Simulation and Evaluation of the Air-Conditioning System in Electric Vehicles

Nissan Leaf as a case study

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Resumo

Neste trabalho, implementou-se um modelo no AVL Cuise com o objetivo de simular um veículo elétrico o mais próximo possível do Nissan Leaf 2013 utilizando a informação disponível sobre o veículo. Após modelar e calibrar os componentes no AVL Cruise, foi utilizado o software KULI, desenvolvido pela empresa MAGNA, funcionando como interface externa de modo a se poder implementar o sistema de ar condicionado no modelo implementado no AVL Cruise.

O consumo e autonomia foram avaliados para vários ciclos de condução, tais como, *New European Driving Cycle* (NEDC), *Urban Dynamometer Driving Schedule* (UDDS), *Highway Fuel Economy Driving Schedule* (HWFET), *Supplemental Federal Test Procedure* (US06) para simular condução agressiva, *Supplemental Federal Test Procedure* (SC03) para testar ar condicionado, *Worldwide harmonized Light vehicles Test Cycle* (WLTC), e os resultados foram comparados com os encontrados na literatura.

No geral, os resultados obtidos foram próximos dos encontrados na literatura sem ar condicionado usando o AVL Cruise e com ar condicionado usando o AVL Cruise em conjunto com o KULI. Concluiu-se que o sistema de ar condicionado pode reduzir a autonomia do veículo entre 12 % e 25 % em condições extremas.

Palavras-chave

Ar Condicionado, Veículo Elétrico, AVL Cruise, KULI, Simulação.

Abstract

In this work, it was implemented a model in AVL Cruise in order to simulate an electric vehicle as close as possible to Nissan Leaf 2013 with the information published for the vehicle. After modelling and calibrating the components in AVL Cruise it was included KULI software from MAGNA as an interface to implement the air-conditioning system to the model in AVL Cruise.

Range and consumption were evaluated for driving schedules such as New European Driving Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFET), Supplemental Federal Test Procedure for aggressive driving style (US06), Supplemental Federal Test Procedure for air-conditioning testing (SC03) and Worldwide harmonized Light vehicles Test Cycle (WLTC) and the results with and without air-conditioning system were compared to those found in literature.

In general, the results obtained were close to those found in literature without A/C using AVL Cruise and with A/C using AVL Cruise with KULI. It was found that air-conditioning system can reduce the vehicle range from 12 % to 25 % in extreme conditions.

Keywords

Air-conditioning, Electric Vehicle, AVL Cruise, KULI, Simulation.

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Abbreviations

AC Alternate Current

ANL Argonne National Laboratory

A/C Air-conditioning system

BEV Battery Electric Vehicle

CO Carbon Monoxide

CO_2 Carbon Dioxide

COP Coefficient of Performance

DC Direct Current

DoD Depth of Discharge

EPA Environmental Protection Agency of United States. In this text EPA solely is also a reference to driving cycle tests made by this agency to homologate cars in US.

FWD Front Wheel Drive

GWP Global Warming Potential

HFC-134a hydrofluorcarbon (HFC) refrigerant fluid, 1,1,1,2 Tetrafluoroetano

HFO-1234yf hydrofluoroolefin (HFO) refrigerant fluid, 2,3,3,3-Tetrafluoropropene

HVAC Heating, Ventilation and Air-conditioning

HWFET Highway Fuel Economy Driving Schedule (U.S. EPA)

ICE Internal combustion engine

INL Idaho National Laboratory

MAC Mobile air-conditioning system

MCT Multi Cycle Test based in SAE Standard J1634

NEDC New European Driving Cycles

NHTSA National Highway Traffic Safety Administration (of U.S.)

NO_x Nitrogen Oxides

NREL National Renewable Energy Laboratory (of U.S.)

ODE Ordinary Differential Equation

PDM Power Delivery Module

PMR Power-to-mass ratio

RDE Particulate Real Drive Emissions

SAE Society of Automotive Engineers

SC03 Supplemental Federal Test Procedure (Air-conditioning schedule, U.S. EPA)

SOC State of Charge (battery)

SoH State of Health (battery)

SO_x Sulfur Oxides

UDDS Urban Dynamometer Driving Schedule (U.S. EPA)

U.S. United States of America

US06 Supplemental Federal Test Procedure (Aggressive schedule, U.S. EPA)

WLTC Worldwide harmonized Light vehicles Test Cycle

WLTP Worldwide harmonized Light vehicles Test Procedure

VSS Variable Step Size

1 Introduction

1.1 Motivation

In the last decades, a concerning about pollution has been growing. With the increase in population and in a need for transportation and mobility, the number of vehicles used in the world rapidly increased. With that grown quickly came the concern for the human being in term of hazardous emissions namely CO_2 which contributes to global warming and NO_x gases which are toxic to the human being, among others such as CO, SO_x and soot.

Electric vehicles were developed in the last years and today almost every brand have presented, for example Nissan, BMW, VW, Renault, Tesla, or intend to present, for example Mercedes-Benz [1], Audi [2], a full electric vehicle. The main objective of electric vehicles is, first of all, to create a sustainable way of mobility in order to decrease the levels of pollution emitted by the transportation sector in all world. And second, with the increasing concern about pollution, the European Commission introduced the World harmonized Light Vehicle Test Procedure (WLTP) as the necessary procedure to homologate new vehicles after 1st September 2019 and electric and hybrid vehicles may be the only option to consider by manufactures to complete successfully the test procedure.

Battery Electric Vehicles (BEV) undergo a series of challenges. The goals for electric vehicles are range, energy efficiency, comfort and easy maintenance and the main restrictions are weight and cost. Battery in electric vehicles is one of the main issues and the most important, and yet to be developed, component. Its efficiency for extreme temperatures need to be accounted as well as battery life vs n^{er} of cycles or battery life vs Depth of Discharge (DoD). Besides these factors, there are few battery external factors that influence battery performance and consequently vehicle range, which are driving style, vehicle coasting and auxiliary vehicles components. One of this components, which can be the main auxiliary consumer in a BEV is the air-conditioning compressor.

Air-conditioning system can have a huge impact in BEV decreasing its range in extreme conditions by 13 % [3]. Besides that, air-conditioning can be harmful for the environment. In 2012 EPA and NHTSA [4] estimated that in U.S.A. the air-conditioning system was responsible for 3.9% of the total greenhouse gas emissions of cars and light trucks. However measures have been taken about air-conditioning system leakages and it is mandatory in European Union [5] since January 2017 that the refrigerant fluid has a Global Warming Potential (GWP) below 150. One of the solutions found was to use R1234yf, which GWP is 4, as a refrigerant fluid. However, many vehicles in the market still use R134a, which GWP is above 1300.

1.2 Objective

The objective of this work is to simulate the influence of the air-conditioning system in electric vehicles using Nissan Leaf as a case study.

Exploring AVL Cruise, one will try to develop a model in order to implement an electric vehicle as close as possible to Nissan Leaf 2013 with the information published for the vehicle and available from the literature. After modelling the components in AVL Cruise, one will calibrate the results without air-conditioning system with the data published for Nissan Leaf 2013. After calibrating, the main goal is to include a new interface in AVL Cruise, a software named KULI from MAGNA with the objective of implementing the air-conditioning system in the vehicle model defined.

Lastly, one will compare results for vehicle model designed in AVL Cruise with KULI interface with the data published. The differences in range and consumption for vehicle model with and without air-conditioning module will be discussed for driving schedules such as New European Driving Cycle (NEDC), Urban Dynamometer Driving Schedule (UDDS), Highway Fuel Economy Driving Schedule (HWFET), Supplemental Federal Test Procedure for Aggressive driving style (US06), Supplemental Federal Test Procedure for Air-conditioning Testing (SC03) and Worldwide harmonized Light vehicles Test Cycle (WLTC).

1.3 Document Structure

This document is organized in 6 chapters described briefly below.

2 State of the Art

The vehicle air-conditioning system is described, which factors influence its performance and what measures were taken in terms of improving A/C efficiency. The impacts of the vehicle A/C in emissions and consumption are also addressed.

In the last sub-chapter it is addressed what are the differences in the A/C system of battery electric vehicles and how much does it impact the battery and ultimately vehicle consumption and range.

3 Methodology

In this chapter, it is presented the vehicle case study and the simulation parameters used to model it. The methods used to simulate some of the components are discussed in this chapter for both AVL Cruise and KULI. At the end of the chapter, it is presented the driving cycles used during simulation.

4 Results and Discussion

In calibration sub-chapter, results are initially used to calibrate the model both with and without air-conditioning system with real data from the literature. Results for driving schedules are presented in Results sub chapter. In Validation the results obtained are compared with data gathered experimentally in vehicle tests.

5 Conclusion

It is presented the final conclusions for the work done in terms of what one determined for air-conditioning influence on vehicle model defined in AVL Cruise and KULI.

6 Future Work

Finally, one presents some considerations to be addressed and improved in future works.

2 State of the Art

2.1 Vehicle Air-Conditioning System

In 2012, EPA (Environmental Protection Agency, United States) and NHTSA (National Highway Transportation Agency) [4] estimated that 95% of new cars and light trucks in U.S.A. were equipped with mobile air-conditioning systems (MAC). Nowadays, every new vehicle has its own air-conditioning system which is utterly important in terms of passenger comfort. However, air-conditioning system impacts the energy consumption of every vehicle especially in electric vehicles where it decreases the vehicle range [3, 6].

In fig. 2.1 it is presented the basics of the air-conditioning system inside a vehicle, left part is the front of the car, the right part is near the passengers, the arrows represent the air flow. Air from the outside flows through the condenser and its speed depends on the fan rotation speed, air absorbs heat in the condenser where the cooling fluid (usually R134a in vehicles previous 2017 and R1234yf for new vehicles) undergoes a change of phase from gas to liquid. In the expansion valve, the cooling fluid will undergo a pressure drop and consequently decrease its temperature, in the evaporator the air will flow through the tubes and lose some heat to the cooling fluid. The air passes through the evaporator fans and goes to the cabin while the cooling fluid will go to the compressor where the cycle will once again begin.

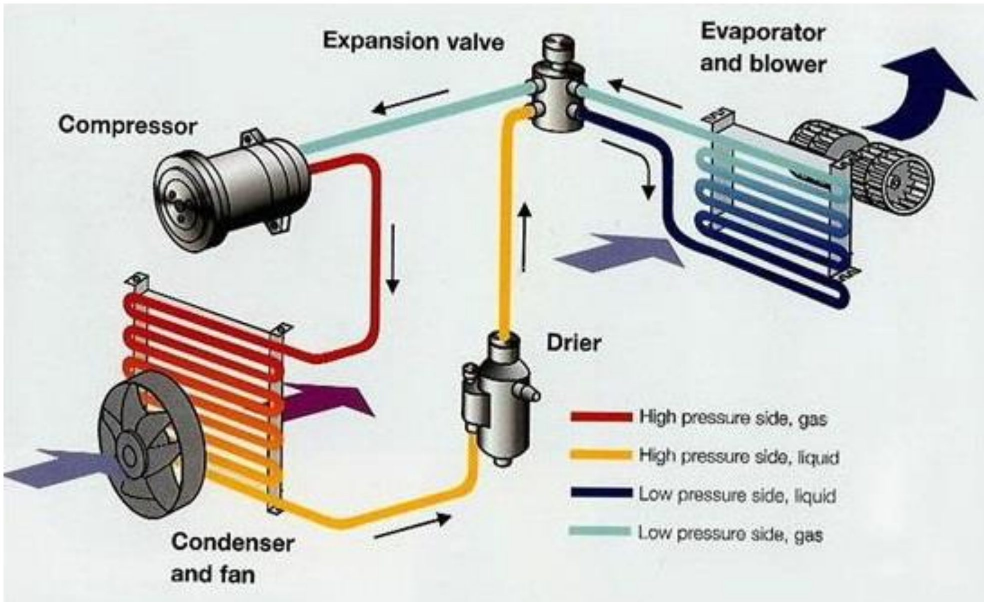


Figure 2.1– Vehicle air-conditioning system representation

The compressor is usually mechanically connected to the engine with a belt, however in electric vehicles the compressor is powered by the vehicle high voltage battery. Usually, the DC current from the battery passes through an inverter and powers an AC motor which powers the compressor itself. In the compressor there is also a connection with the 12 V battery which powers the control unit of the compressor and electric motor and its sensors.

2.1.1 Factors influencing the air-conditioning energy consumption

Air-conditioning (A/C) system energy consumption depends on many factors. Shete [7] in his study about air-conditioning load on engine defined some factors that can contribute to an increase of energy consumption such as climatic conditions, cabin conditions and the contribution of both to thermal load, compressor speed and the overall efficiency of the A/C system.

Compressor Speed

The most common used compressor in air-conditioning system is the mechanical belt-driven compressor which is connected to the engine by a belt and its speed is dependent on the engine rotation speed. The mechanical compressor adds load directly in the engine when air-conditioning system is working.

With the intensive development of electric and hybrid vehicles in the last decade, the development of electric compressors for the air-conditioning system has been growing. With an electric compressor, the compressor speed is not dependent on the engine speed thus better temperature control inside the cabin can be achieved and also better efficiency [8].

Air-conditioning System Efficiency

Dahlan *et al.* [9] in their comparative study between electric compressor powered by the car's 12 V lead-acid battery and the conventional belt-driven compressor concluded that electric compressors have lower energy consumption, better temperature distribution because the speed is independent of engine speed, and can be regulated depending on the cooling load necessary inside the car. With electrical compressors, a high thermal comfort can be achieved. In short, electrical compressors have lower fuel consumption and thus lower pollutant emissions.

For the evaporator blower and condenser fan the energy is usually supplied by the 12 V DC Battery. Datta *et al.* [10] studied the influence of variances in state-of-charge of the battery on coefficient of performance (COP) and cooling capacity. To do a continuously work, the evaporator blower and the condenser fan need an input of power from the 12 V battery which is charged by the alternator connected to the engine in IC engine vehicles or by the high voltage battery in electric vehicles. Datta *et al.* [10] stated that the reduction of air flow, which affects the performance of condenser and evaporator, "follows a particular trend as it is caused by the fall of battery voltage". It is concluded that there is a temperature and pressure increase in the condenser with the decrease of the air flow and in the evaporator there is no relevant pressure drop but there is a decrease in outlet temperature which has to be taken into account considering it can damage the compressor. In terms of cooling capacity, while the battery is discharging it was found that there is a reduction in cooling capacity of about 35 %, associated with a 30 % increase load on the compressor and a drop in COP up to 50 %.

Daviran *et al.* [11] in a study comparing the performance of refrigerant HFO-1234yf and HFC-134a in automotive air-conditioning systems made several conclusions such as, during condensation and evaporation, HFO-1234yf presents a smaller pressure drop thus it performs better than HFC-134a and HFO-1234yf can enhance compressor lifetime comparatively to HFC-134a due to a lower pressure ratio and lower discharge temperature of compressor. Performing the experiment with constant mass flow rate, Daviran *et al.* obtained a COP 18 % higher using HFO-1234yf, however at constant cooling capacity, the mass flow rate of HFO-1234yf is 27 % higher than of HFC-134a and for identical cooling capacity, COP of HFO-1234yf is 1.3 to 5 % lower. In [11] Daviran *et al.* concluded also that as the working pressure of HFO-1234yf is lower that of HFC-134a a thicker pipe system can be used which can minimize costs. Besides that, HFC-134a has been banned in European Union for new light cars and light trucks since January 1st 2017 [5] and HFO-1234yf has been presented as a vial substitute not only for light vehicles but also for all range of vehicles in the future.

Thermic Load between Cabin and Climatic Conditions

Thermic load influences the design of the air-conditioning system, namely, its size is related to the maximum thermal load in vehicle, which happens for the maximum temperature that cabin will reach while in direct contact with sun light [12].

In [13] the impact of cabin temperature is discussed and it's acknowledged that the temperature necessary to cool down a vehicle cabin can have a huge impact in electric vehicle range. It is proposed some measures to reduce thermal load such as cabin ventilation during soak and advanced glazing which is also discussed in [14]. Vehicle insulation [15] and reflective vehicle painting [16] are also methods discussed to reduce thermal load.

2.1.2 Impact of air-conditioning system

Fuel Consumption

The Air-conditioning system in a vehicle is considered the most significant in terms of auxiliary loads on engine. In a study about fuel used by air-conditioning systems in U.S. [17] and supported by NREL, Johnson pointed that in U.S., every year, it is consumed by vehicle air-conditioning systems 27 billion litres of gasoline, equivalent to 10 % of U.S. imported crude oil.

Emissions

From the works done so far, it is inconclusive on how much the air-conditioning system affects emissions because that depends on a many factors such as type of vehicle, external and internal load, driver's profile and many others mention above. In EPA and NHTSA [4], it is discussed that air-conditioning system contributes mainly in two forms of pollution. First, there are leakages in the system which may occur in components such as seals, gaskets, and can increase due to the wear of these components and also in accidents, which can contribute to a major fluid leakage. In case of leakage, decreasing its impacts also mean use a fluid with a lower GWP, such as HFO-1234yf, or design new components which in most scenarios is way more expensive. Usually it is used HFC-134a in most type of vehicles, and HFO-1234yf in all new cars and light trucks in Europe since 1st January 2017 (mandatory GWP below 150 and established in directive 2006/40/EC [5]). HFC-134a can contribute more than three hundred times than HFO-1234yf to global warming due to the values of GWP of 1300 against 4, respectively.

The second form is related to the extra load that air-conditioning system does on the engine, thus emissions are done by the additional fuel that is consumed when the air-conditioning system is running. So the amount of pollutants is related to the amount of fuel used. Knowing the load that A/C system does on the engine and knowing the engine, the amount of fuel and pollutants can be determined. EPA [4] collected data from 2012 to 2016 and stated that the load of the A/C system on the engine contributed indirectly to 3.9 % of the total greenhouse gas emissions from cars and light trucks in United States of America.

In BEV, only leakages contribute to harmful emissions from A/C system in a tank to wheel analysis. Its influence in battery electric vehicles will be addressed in next sub-chapter.

2.2 Impact of HVAC system in Battery Electric Vehicles

Heat, Ventilation and Air-Conditioning system (HVAC) in electric vehicles is one of the major contributors to reduce vehicle range and increase vehicle consumption. As referred previously, in battery electric vehicles (BEV) the compressor of the air-conditioning system is powered by the high voltage battery which means that it is dependent from battery performance, namely its temperature and SOC. Thus, in electric vehicles the battery undergoes a series of challenges from the need of power to vehicle movement through the electric machine, to power other devices such as the air-conditioning compressor. Every component that it is powered by the battery can impact greatly vehicle performance as well the battery life time.

In electric vehicles, there is no heat generated by the engine to be used for heating, thus power is consumed from the battery by heating coils which has a major impact in power consumption. This impact is greater for lower temperature and can reduce vehicle range by values around 13 % [3]. In Faruque and Vatanparvar's work [3] it is pointed that a Tesla Model S with 60 kWh can have a range loss of 13 % due to the HVAC system at the ambient temperature of -20 ºC, it has the shortest range loss (4 %) at the ambient temperature of 10 ºC and the range loss increases to around 12 % for an ambient temperature close to 45 ºC, which means that in extreme temperatures, HVAC system can have a huge impact.

Faruque [3] also presents a comparison between BEV and internal combustion engine vehicles (ICEV) and states that power consumption of HVAC system can reach 20 % which is more significant than in ICEV where can be up to 9 %. This factor, together with all electric devices in the vehicle (such has lamps, radio, monitors, gadgets) can lead to an increase battery stress and then decrease State-of-Health (SoH) and consequently decrease total range available over time. Bäuml [6] states that in the worst case the driving range can be reduced by 50 % while heating the passenger compartment in full electric vehicles.

3 Methodology

AVL Cruise developed by AVL was selected to simulate a pure electric vehicle (or battery electric vehicle BEV). First the vehicle, based on Nissan Leaf, was set without the air-conditioning module. The implementation parameters are described below and those were validated comparing with INL Document [18], which is for a 2013 Nissan Leaf Vehicle test and supported by US Department of Energy in Vehicle Technologies Program. It was conducted a series of tests in the dynamometer and in track. For calibration of the model, test and validation one run those tests which include driving cycle runs (UDDS, HWFET, US06 and SC06, which belong to EPA Driving tests and described further in this text). And track tests such as acceleration and maximum speed.

After the calibration and validation without A/C, validation took place for A/C integration. One tried to simulate and validate A/C system using a software named KULI, from MAGNA. KULI is an "automotive thermal management software" [19] which has an interface with AVL Cruise and allows the user to set the A/C system in KULI and obtain results in AVL Cruise with the model designed for the vehicle previously.

Besides INL Nissan Leaf Testing, one tried also to compare electricity consumption and range results with New European Driving Cycle (NEDC) driving cycle and estimate also for Worldwide harmonized Light vehicles Test Procedure (WLPT).

3.1 Vehicle specifications

The vehicle specifications were based on the Nissan Leaf 2013, which has the characteristics described below in table 3.1. Almost all data was collected from [18], except NEDC range and energy consumption and other data elements which were collected from Nissan Portuguese Website [19]. After each parameter the reference is presented from where the data was collected.

Figure 3.1 represents power unit of Nissan Leaf which includes High Voltage Battery in the middle and is placed below the vehicle occupants and driver seats and at the front there are Power Delivery Module (PDM), Inverter, Motor and Reduction Drive, as represented in figure 3.2.

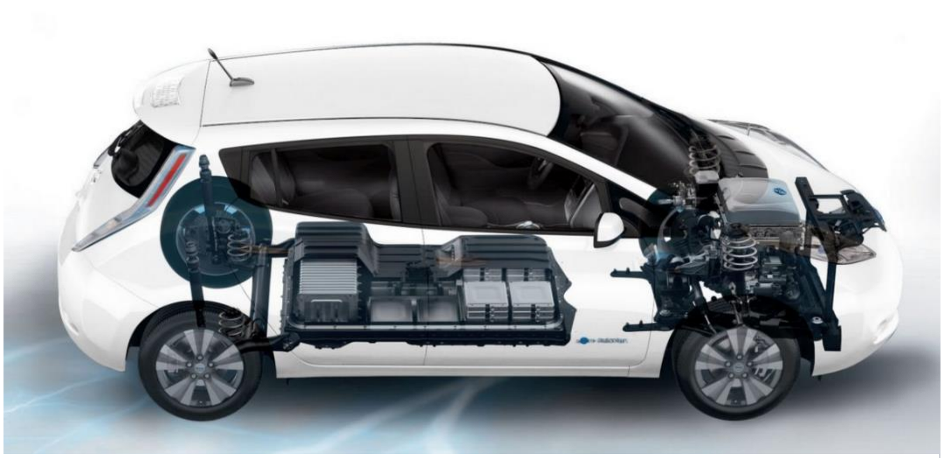


Figure 3.1 - Nissan Leaf with transparent view to the high voltage battery (in centre) and to power unit (in front) [21].

Table 3.1 - Nissan Leaf 2013 Specifications.

Vehicle Specifications	
Type	Battery Electric Vehicle (BEV)
Class	Midsize Car
EPA Energy Consumption	16.8/21.1/18.6 kWh/100 km (City/Highway/Combined)
NEDC Energy Consumption	15 kWh/100 km [20]
EPA Range	135 km (84 mi) [18]
NEDC Range	199 km (120 mi) [20]
Vehicle Maximum Speed	144 km/h [20]
Tire and Wheels	205/55R16 [20]
Electrical Machine [20]	
Type	Permanent Magnet AC Synchronous
Max. Power	80 kW (3008 – 10 000 rpm)
Max. Torque	254 Nm (0-3008 rpm)
Maximum Speed	10 500 rpm
Transmission [18]	
Type	Automatic Fixed Gear
Final Drive Ratio	7.9
Traction	FWD
Battery [18]	
Type	Lithium-Ion (LiO)
Number of Cell	192
Cell configuration	2 Parallel, 96 Series
Nominal Cell Voltage	3.7 V
Nominal System Voltage	364.8 V
Rated Pack capacity	66.2 Ah
Rated pack Energy	24 kWh
Weight of Pack	290 kg
Weights [18]	
Design Curb Weight	1486 kg
Delivered Curb Weight	1498 kg
Distribution F/R (%)	58/42
Dimensions	
Wheelbase	2700 mm [20]
Height	1550 mm [20]
Ground Clearance	160 mm [18]

Aerodynamics [20]	
Cd for 16'’tire	0.29
Cd for 17'’tire	0.28

Figure 3.3 represent the curve torque vs electric machine speed [rpm]. Torque is maximum (approximately 254 N.m) from the beginning and starts to decrease at 3008 rpm [20], where the power starts to be maximum (approximately 80 kW) until 10 000 rpm.

Nissan Leaf battery is composed by four cells integrated in each model and as a whole it includes 48 modules placed in series.

Figure 3.2 - Nissan Leaf Power Unit (PDM, Inverter, Electrical Machine and Reduction Gear; Top, Middle and last two below, respectively).

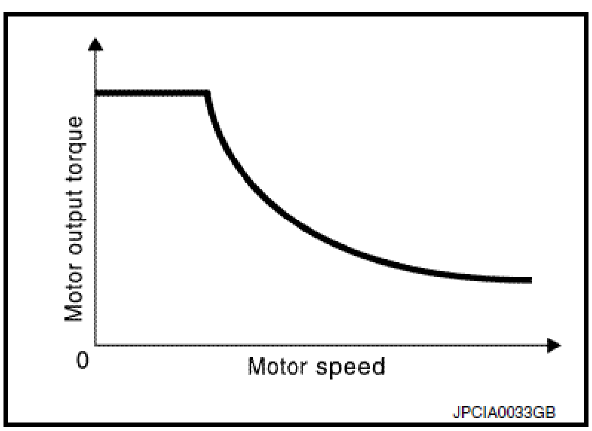


Figure 3.3 - Torque Curve type for Nissan Leaf electric machine.

3.2 Simulation Software

The vehicle model for simulation was done in two phases. First it was only used AVL Cruise and it was calculated all data without considering air-conditioning system. In the second phase, an air-conditioning model from Magna KULI was integrated with AVL Cruise which has an interface that enables the processing of data between the two software and presents the final data in AVL Cruise.

3.2.1 AVL CRUISE

In this topic one will present the model and data used in AVL Cruise. Some of the equations used by the model itself and assumptions made will also be presented. In Annex B are the figures from AVL Cruise for some modules used.

In AVL Cruise, it was used the model of the figure 3.4.

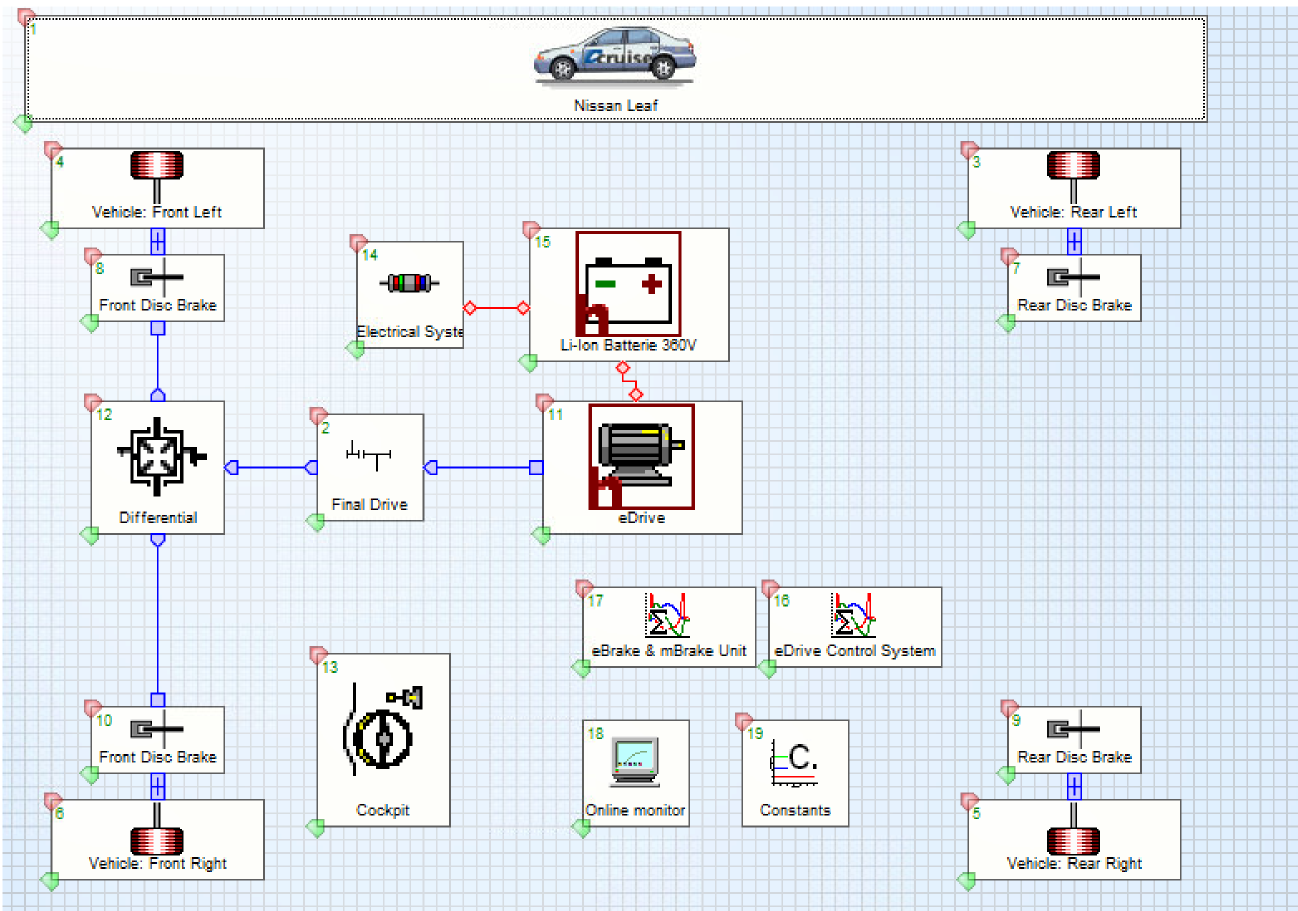


Figure 3.4 - Nissan Leaf model in AVL Cruise without air-conditioning module.

The inputs for the vehicle module are presented in table 3.2.

Table 3.2 – Vehicle module inputs.

Vehicle Body Dimensions[1]	
Distance from Hitch to Front Axle [mm]	3468
Height of Support Point at Bench Test[2] [mm]	517
Wheel Base [mm]	2700
Load Dependent Characteristics	
Distance of Gravity Centre[1] [mm]	1134
Height of Gravity Centre[1] [mm]	517
Tyre Pressure [bar]	2.48
Nominal Weight	
Curb Weight [kg]	1474
Gross Weight [kg]	1945
Air Coefficient	
Frontal Area [m^2]	2.27
Drag coefficient	0.29

Drag coefficient of 0.29 corresponds to wheel's rims of 16 inches and was found in Nissan Leaf catalogue in [20].

For wheels modules, a few parameters were not changed. Wheel inertia moment and wheel slip were considered the default already in the module. However, wheel slip was not considered in calculation tasks. For rolling radius, AVL Cruise has incorporated a calculation task which has as inputs tire dimensions, in this case 205/55R16, and calculates static and dynamic rolling radius and respective circumferences. Although all four parameters can be calculated, the user only have to introduce in software two of them which in this case stating rolling radius and dynamic rolling radius were used as inputs. In AVL Cruise User's Guide [22] is also mentioned that static rolling radius is not used for calculation. Wheel slip was not considered in calculation.

To define rolling resistance, it was used SAE Coast Down method which is a procedure defined by SAE Standard J2263 and consists in the determination of the road load applied to the vehicle while travelling from 115 km/h to 15 km/h with transmission in neutral [23]. It results in a model for road load force as function of speed and it allows to test any vehicle in dynamometer with rolling resistance defined by the model determined previously allowing to get more accurate results (for example for driving cycles runs).

[1] Vehicle dimensions such as Distance from Hitch to front axle and height of support point at bench test, Height of support point at test bench, etc., where estimated from figure A.1 in annex A.

[2] Support point at bench test was considered at same height as gravity centre to avoid moment.

The procedure uses reference conditions of 20 ºC, 98.21 kPa, dry and level road with no wind and no precipitation [23].

In Nissan Leaf, the constants were obtained in the track tests done by INL [24] and then used for dynamometer testing. To determine those constants for Coast Down method, a balance of forces was used (Eq. 1).

Since the mass of the vehicle is known, it is performed in track usually six runs in each direction [24] to determine a profile variation of velocity in time (in the closest conditions possible described by the SAE standard above).

$$\sum F = m \times a = m \frac{\partial V}{\partial t} \ (Eq. 1)$$

Then, the forces to stop slow down the vehicle from 115 km/h to 15 km/h are defined as road load which is defined as a 2nd degree equation as follows in equation 2 from [24],

$$F_{roadload} = A + B \times V + C \times V^2 = m \frac{\partial V}{\partial t} \ (Eq. 2)$$

where the last term in (Eq. 2) is obtained with experimental data from track tests. These equations account friction losses (A), rolling resistance losses (B) and aerodynamic forces (C). The parameters obtained in [18] for Nissan Leaf 2013 were:

A = 141.940 N

B = 0.32015 N/(km/h)

C = 0.0304704 N/(km/h)^2

With the methodology used by AVL Cruise, and presented in fig. B.3 in Annex B, these constants originated unrealistic results, usually consumption values three times higher.

To determine the most accurate values to input, one used the calculation task presented in AVL Cruise named Brake/Coast/Thrust, set the parameters of SAE Standard 2263 [23], with velocity starting at 115 km/h until 15 km/h and as a result AVL calculated the resistance constants A, B and C. The objective was, by trial and error, to set the constants in Wheels Module and obtain the output constants with AVL Cruise calculation task the closest one can get to INL results of Nissan Leaf Track Testing [18]. The resistance constants calculated in the simulation task are represented in fig. B3 in Annex B and table 3.3 which represents the differences between constants calculated by AVL Cruise calculation task and by INL in [18].

Table 3.4 represents the inputs for wheel modules, with all wheels with equal inputs.

Table 3.3 - Comparison between values obtained in simulation task in AVL Cruise and by INL [18] during track test.

AVL Cruise Results	*INL[10] Track Testing*	*Difference*	*Criteria*
141.8595872 N	141.940 N	-0.081	<0.1
0.3154992 N/(km/h)	0.32015 N/(km/h)	-0.005	<0.01
0.0299745 N/(km/h)^2	0.0304704 N/(km/h)^2	-0.0005	<0.001

Table 3.4 - Wheel module input (equal for all wheels).

Wheel	
Inertia Moment [kg.m²]	0.1431
Rolling Radius [mm]	
Static Rolling Radius	291 (input)
Circumference	1828.41 (auto)
Dynamic Rolling Radius	307 (input)
Circumference	1928.94 (auto)
Rolling Resistance using SAE Coastdown Method	
Parameter a [N]	35.8
Parameter b [N/(km/h)]	0.08
Parameter c [N/ (km/h)²]	0
α	0
β	0

Parameter c is zero for best correspondence with experimental results because AVL Cruise uses the input C_d in Vehicle module (table 3.2) to calculate aerodynamic resistance. A value greater than zero for c would imply an aerodynamic resistance calculated more than once.

Exponents α and β, pressure sensitivity exponent and load sensitivity exponent respectively, were set to zero. Both of their influence is taken into account in the constants used. However, without setting exponent values, it is not possible to determine tire pressure or vertical load influence in vehicle calculations, this thus means that, for all calculations, the same tire pressure and same weight were used.

For brakes, disc brakes where considered and data for disc brakes are presented in table 3.5. For brake piston surface data was obtained from Nissan Leaf 2013 Brakes Service Manual using master cylinder diameter value. For specific brake factor, 1 is used for disc brakes [22]. For efficiency, inertia moment and effective friction radius, the default AVL Cruise values where used due to lack of data.

Table 3.5 - Disc Brake module input.

Disc Brake	***Front***	***Rear***
Brake Piston Surface[mm²]	62.67	62.67
Specific Brake Factor	1	1
Efficiency (default)	0.99	0.99
Inertia moment (default)	0.02	0.02
Friction Coefficient	0.25	0.25
Effective Friction Radius [mm] (default)	130	130

Though, for friction coefficient, one used a value of 0.25 which is value inside a range of experimental values determined by literature such as, El-Tayeb [25] in a study about the performance of frictional brake pads.

For Nissan Leaf, a transaxle component is used, which means that the single ratio transmission and the differential module are “integrated”. However, because one has no data values, a differential module developed by AVL Cruise was used and values are represented in table 3.6.

Table 3.6 - Differential module.

Differential	
Differential lock	locked
Torque Spit Factor	1
Inertial Moment I	0.015
Inertia Moment Out 1	0.015
Inertia Moment Out 2	0.015
Efficiency	0.96

Values for single ratio transmission module are represented in table 6. Transmission ratio data is obtain from INL report [10], Inertia moments are default values defined by AVL Cruise and efficiency was set to 0.97.

Table 3.7 - Single Ratio transmission module.

Single Transmission Ratio	
Transmission Ratio	7.9
Inertia Moment In/Out	0.01/0.015 (Default Values)
Efficiency	0.97

For electric machine, one only found the range for max power and for max torque from Nissan Leaf Brochure [20]. With the max values and the shape, a characteristic curve was designed.

To input the characteristic Torque curve for the electric machine, an approximation function was used based on the curve of Figure 3.3. With maximum Torque of 254 N.m from 0 to 3008 rpm and using the first point for the curve at 3008 rpm and 254 N.m, assuming a profile of $1/(x^2)$, one got an approximation curve described by equation 3,

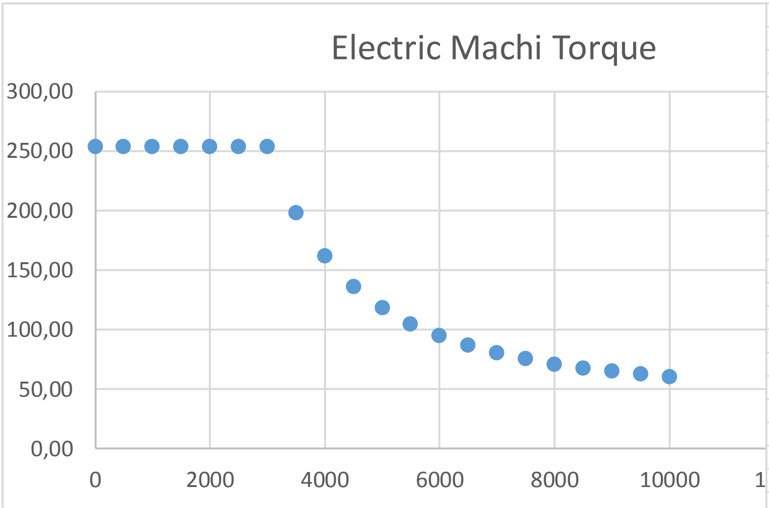
$$T = \frac{1924885135}{x^2} + 41.25 \quad (Eq. 3)$$

with x being motor rpm.

The constraints for determine the equation were:

- Point x=3008 rpm and T=254 N.m is an equation point.

- The curve tends to 60.5 N.m at x=10 000 rpm which was estimated from fig. 3.3 geometrically assuming maximum corresponds to 254 N.m. The function is represented in fig 3.5.



RPM	Torque
1,00E-04	254,00
500	254,00
1000	254,00
1500	254,00
2000	254,00
2500	254,00
3008	254,00
3500	198,39
4000	161,57
4500	136,32
5000	118,26
5500	104,89
6000	94,73
6500	86,82
7000	80,54
7500	75,48
8000	71,34
8500	67,90
9000	65,02
9500	62,59
10000	60,51

Figure 3.5 -Experimental torque map for Electric Machine own estimations.

Table 3.8 represents the AVL Cruise inputs for electric machine. In Maps and Curves was set the option "overall" to account the work as motor and generator for electric machine. The torque map was set the one in figure 3.5 for motor and the symmetric for generator which was similar to the model already presented in AVL Cruise. Data for inertia moment and drag torque was left default from the model made by AVL Cruise. The same applies to thermal inputs where thermal calculation for electrical machine was not considered due to the lack of values.

Table 3.8 - Electric machine module.

Electric Machine	
Type of Machine	Permanent Magnet Synchronous Machine
Characteristic Maps and Curves	Overall
Nominal Voltage [V]	364.8 [18]
Maximum Speed [rpm]	10 000 [20]
Inertia Moment	1E-4 Default
Drag Torque at Maximum Speed	0 Default
Thermal Model	Default Values

For battery module, AVL uses input for each cell and it was found in data that the constitution of the battery was 192 cells with the configuration of 2 parallel and 96 in series. After a series of unrealistic results, one decided to set the voltage for cell voltage done by [26] which is a work done recently (2016) by INL about 2011 Nissan's Leaf Battery and which cell voltage and charge of the battery don't vary much comparing with 2013 Nissan's Leaf battery The inputs of 1 cell per cell-row and 96 cell rows were the ones that lead to the closest results comparing with experimental data. The maximum charge was assumed equally distributed per cell which is 66.2 Ah divided by 96 cells.

For thermal module no data was found, so it was used default values. With lack of data one was not able to simulate the influence of temperature of the battery in vehicle performance which made impossible to determine accurate results for vehicle performance under temperatures different than battery normal temperature such as, for example, cold weather.

Resistance and capacitance were considered constant in battery properties and it was used a model designed by AVL for idle voltage for charge and discharge. Table 3.9 present the inputs for the battery module.

Table 3.9 – Battery module.

High Voltage Battery	
Maximum Charge [Ah]	0.6896
Initial Charge [%]	100
Nominal Voltage [V]	3.7
Maximum Voltage [V]	4.2
Minimum Voltage [V]	2.5
Number of Cells per Cell-Row	1
Number of Cell-Rows	96
Operating Temperature [ºC]	25
Mass of a Cell [kg]	2.35
Specific Heat Transition [W/K]	0.006
Specific Heat Capacity [J/(kg.K)]	0.4
Internal Charge Resistance [Ohm]	0.8
Internal Discharged Resistance [Ohm]	0.6

The last module is the electrical consumer which is used to simulate the electrical consumption of some components in the vehicle. The module used was defined by AVL and the inputs are in table 3.10.

Table 3.10 - Electrical consumer module.

Electrical consumer	
Nominal Voltage [V]	364.8
Threshold value	0.5

Calculation Task

In AVL Cruise the simulation was performed using a method named VSS (variable step size) Implicit Euler+ for calculation without air-conditioning and Quasi-stationary 2 for air-conditioning system calculation. For VSS Implicit Euler+ the maximum simulation time step was set to 0.05 s.

VSS Implicit Euler+ is usually the method used as default in cruise and it is based in implicit Euler step. In VSS Implicit Euler+, the step size is controlled using a priori step size control. In the preparation of next time step, it is gathered information from the components about changes or instabilities and it adapts step size accordingly. To solve the nonlinear ordinary differential equations

$$\dot{y} = f(t,y) \quad (Eq.4)$$

$$y(0) = y_0 (Eq.5)$$

the ODE is reformulated to an integral equation

$$y = y_0 + \int_0^t f(\tau, y)d\tau \quad (Eq.6)$$

and discretized with trapezoid rule

$$y_{n+1} - \frac{t_{n+1} - t_n}{2} f(t_{n+1}, y_{n+1}) = y_n + \frac{t_{n+1} - t_n}{2} f(t_n, y_n) \quad (Eq.7)$$

solved for each time step [22].

For Quasi-stationary 2, it “reformulates the equation system to an optimization problem using an adapted Quasi-Newton method” [12]. The ODE is discretized, as the simulation above, by implicit Euler Method

$$\frac{y_n - y_{n-1}}{t_n} = f(t_n, y_n) \quad (Eq.8)$$

Quasi-stationary simulation, works like reverse engineering. For example, being given the vehicle velocity the acceleration and required torques are calculated [22]. For calculation using KULI interface, only a quasi-stationary method can be selected for calculation in AVL Cruise.

The parameters used are the ones recommend by AVL in User’s Guide [22]. For calculation accuracy it is used high option (1e-6), and maximum simulation time step of 0.05 s. In quasi-stationary calculation it is recommended a time interval of 1 s for cycle run and cruising and 0.25 s for all other tasks. However one used 0.25 s due to the difficulty of simulate perfectly some of the driving schedules. For velocity interval it is recommended 0.5 km/h.

3.2.2 KULI Software

KULI is a software developed by MAGNA and the main goal is energy management optimization. It can simulate vehicle cooling systems and allows to calculate components temperature, heat losses, power losses, etc. It can predict the influences of vehicle heat exchangers such as engine oil cooler, air-conditioning condenser, transmission air cooler amongst others, which can impact vehicle performance and passenger comfort inside the cabin.

In this work the main objective was to incorporate a model of vehicle air-conditioning system and determine how much it influences vehicle range, consumption and try to obtained close results to those determined experimental by INL [18]. Next it will be presented the model one used and which components were considered.

KULI Model

For modelling air-conditioning module, the components are presented in figure 3.6.

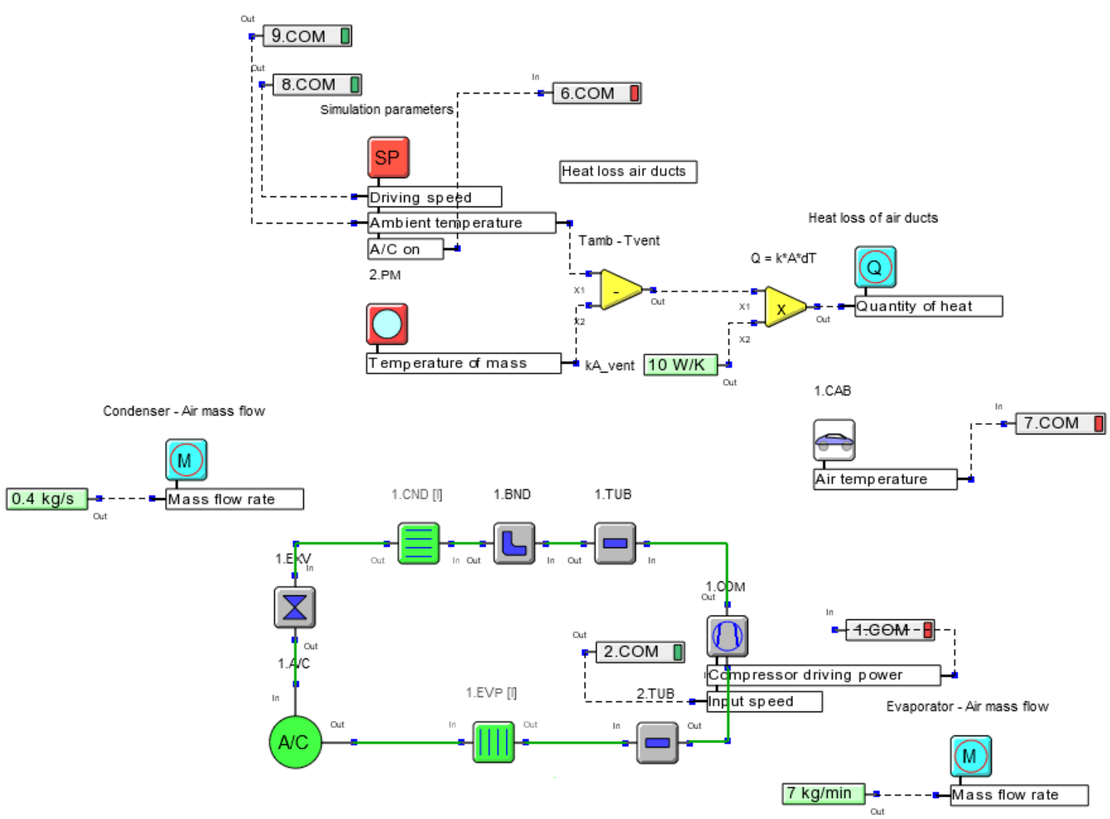


Figure 3.6 - KULI model used for air-conditioning system influence and all its components.

This model includes compressor, condenser, expansion valve and evaporator, at bottom. At the right side are the cabin conditions. At the top, are the simulation parameters used, right of it is a simple calculation to account heat loss between evaporator and vehicle cabin. Air flow rate at the condenser (middle left) and air flow rate at evaporator (bottom right) are also accounted.

KULI is a very complex software and to run a simulation starting from zero, many parameters are necessary and about Nissan Leaf air-conditioning system there are almost no public data available. To overcome this difficulty, one decided to use a KULI example model and input a simulation parameters and define some working constraints.

To simulate the results obtained by INL [20] the first main objective was to set the target temperature to 22.2 ºC (72 ºF) because in the air-conditioning test the conditions were ambient temperature at 35 ºC (95 ºF) with a solar load of 850 W/ m^2 and the air-conditioning was set to auto at 22.2 ºC (72 ºF).

The air-conditioning model is the green circuit in the fig. 3.6 and contains the evaporator, compressor, condenser and expansion valve. An example for how complex and how far the user can “personalize” the elements are represented in fig. C.1 to C.6 in Annex C for the evaporator used.

Each COM represented in fig. 3.6 are defined by the user and represent data in KULI that are inputs or outputs. In this models the inputs (data that comes from AVL Cruise) are vehicle speed (8.COM), ambient temperature (9.COM) and compressor Speed (2.COM). For outputs in KULI model there are A/C status on/off (6.COM), cabin temperature (7.COM) and compressor driving power (1.COM).

For the compressor it was assumed a constant speed of 2000 rpm which is an input from AVL Cruise. KULI then calculates the compressor driving power necessary to lower the temperature which is then sent to AVL Cruise and allows to calculate torque and consumption in Cruise Model.

In Cabin model, represented in fig 3.7, were set the values for initial temperature and the values to simulate solar radiation.

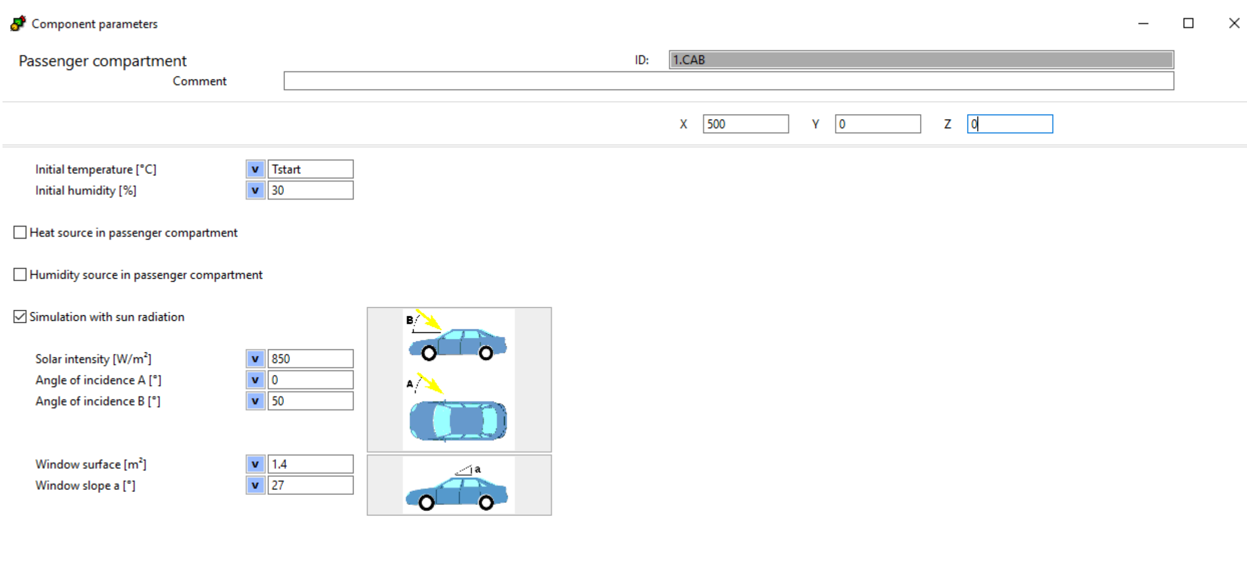


Figure 3.7 - Cabin Compartment inputs in KULI.

Tstart represents the initial temperature and it is defined in Simulation Parameters which an example is presented in figure 3.8, it is defined as 35 ºC for the first driving schedule and at the final temperature of the previous driving schedule during the simulation.. At the beginning of A/C simulation the starting value is 35 ºC but all parameters may change after each simulation since each cycle is run one at each time. The parameters RPM Engine, Driving Speed, Warm-up temperature and ambient temperature cannot be removed from the table but are not considered in simulation. RPM Engine is usually considered to use compressor speed, engine dependent which in this case does not apply. Driving speed and ambient temperature are inputs from AVL Cruise, Warm-up temperature is a temperature offset between ambient air and KULI air inlet path and was not considered. The only parameter used is A/C on/off which is always

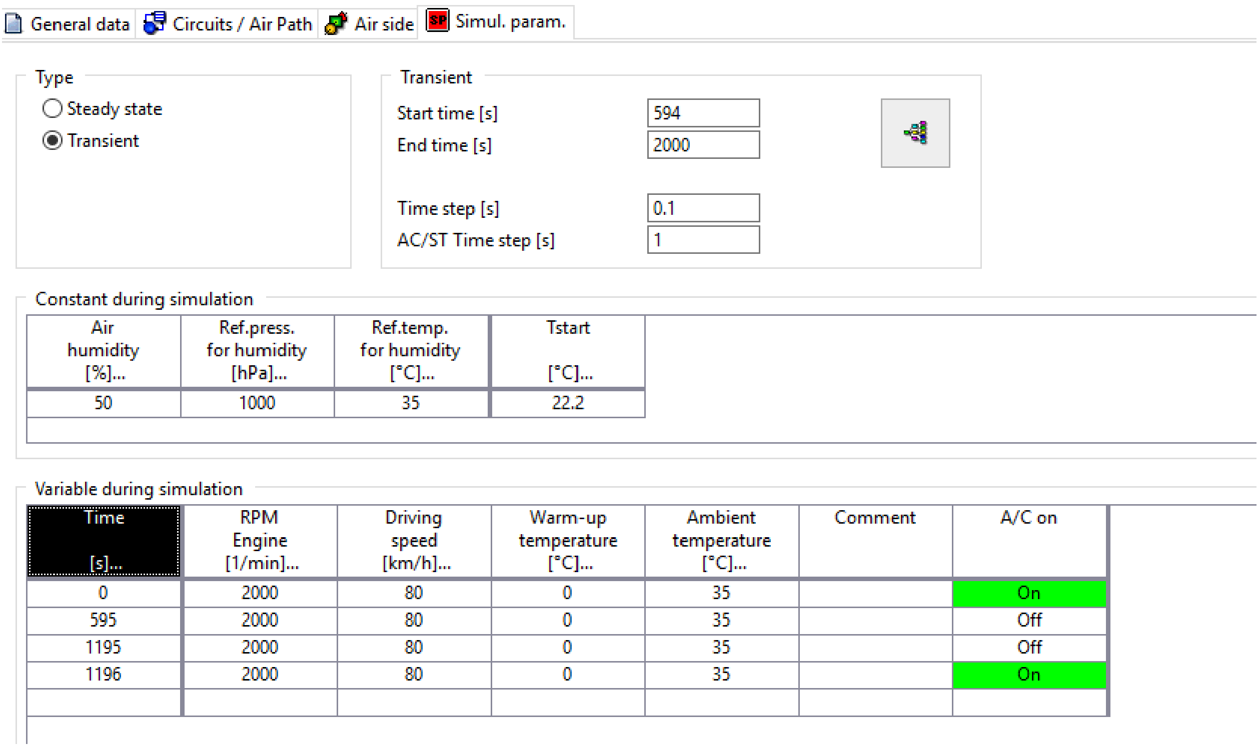


Figure 3.8 - Simulation parameters in KULI. Values are an example.

on except when running SC03 driving schedule twice, separated by a 10 minutes soaking at 35 ºC and 850 W/m^2.

The type was set for transient for accounting time exchanging in data. Steady state is not possible for interface calculation with AVL Cruise. Start time is the first time where temperature calculations will start and end time where it will finish. If one choose start time and end time at 0, KULI will assume steady state. A/C will be on with a constant cabin temperature and constant compressor driving power (for constant input speed).

KULI model also accounts for losses between evaporator and cabin using a simplified model for heat conduction calculation using equation

$$Q = k.A.dT \quad (Eq.9)$$

where k.A is assumed constant and equal to 10 W/m and temperature variation is the difference at each time step between ambient temperature and the temperature of the material between evaporator and cabin.

Figure 3.9 presents the model in AVL Cruise with some modifications to the one in figure 3.4. To allow an interface with KULI software one had to add some modules which are inside the rectangles.

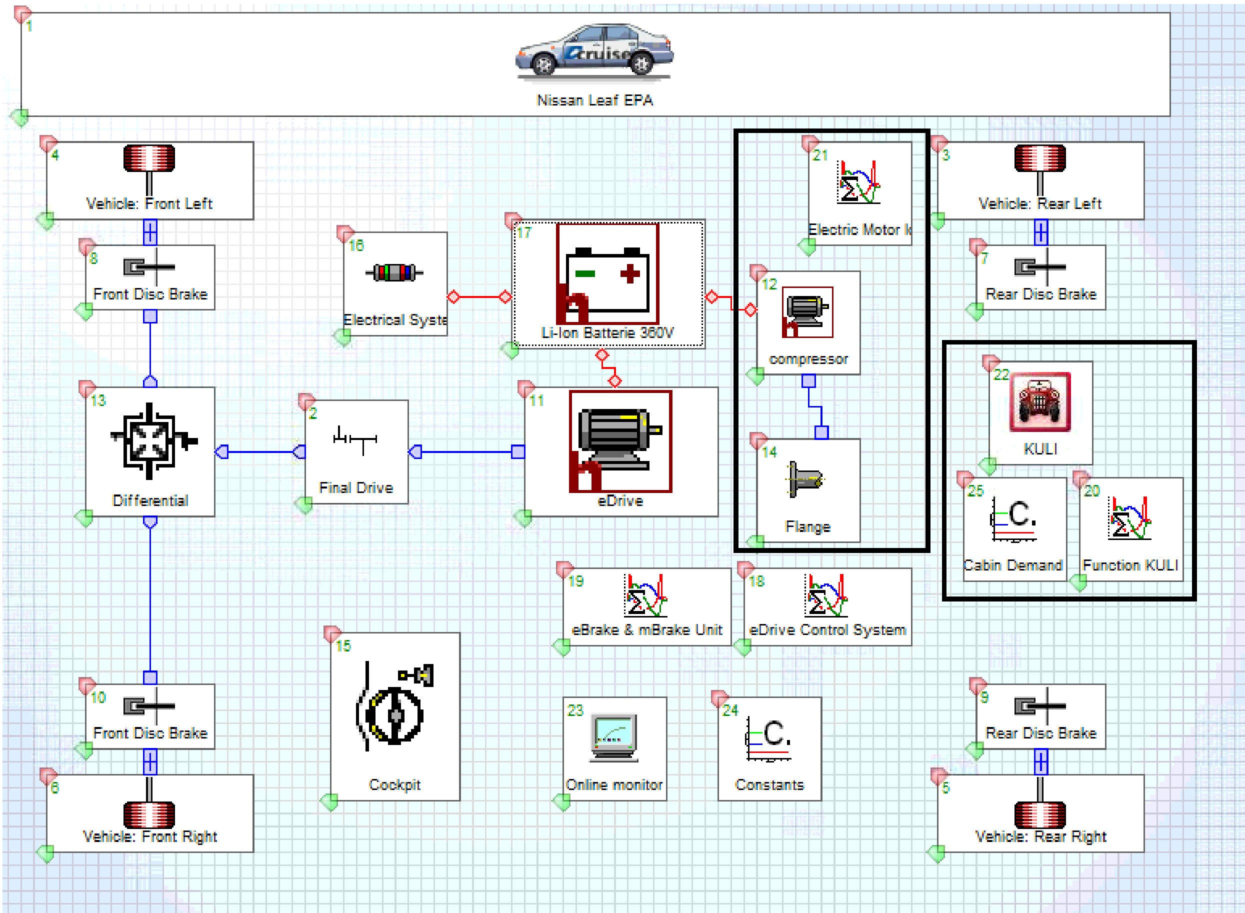


Figure 3.9 - AVL Cruise Model with all components used for KULI interface.

At the right there is the KULI module interface which includes all inputs and outputs referred previously and presented in figure 3.10, there is a module for constants which include user defined compressor speed and max torque for compressor A/C. In Function KULI module it is used compressor speed and compressor driving power to determine torque using the expression:

$$T = -\frac{P \times 60}{2\pi \times N} \quad (Eq. 10)$$

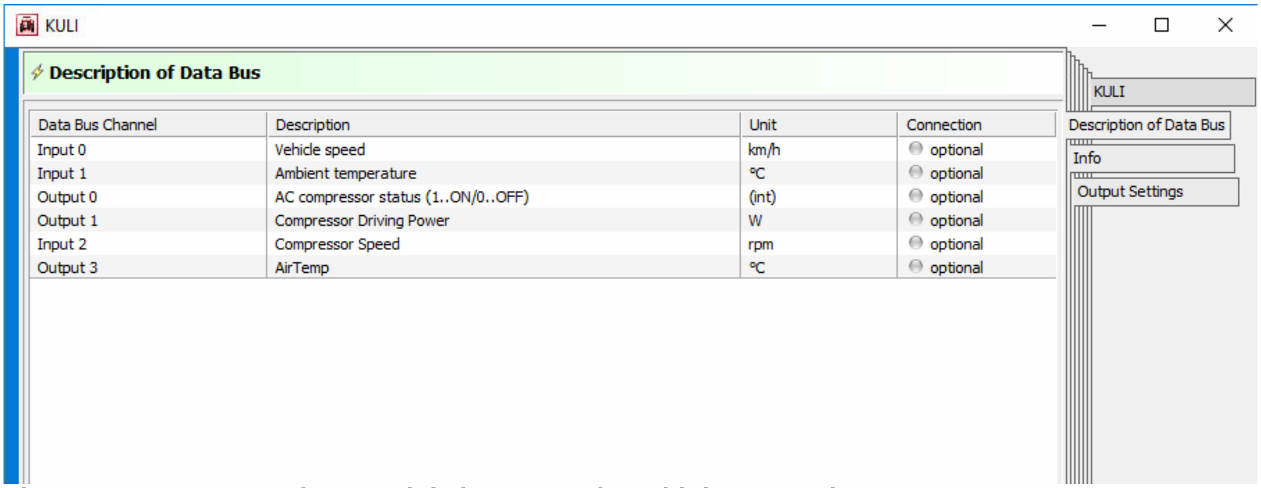


Figure 3.10 - KULI Interface module in AVL Cruise with inputs and outputs

The negative signal is due to the fact that the torque will be used as a “consumed” torque in Flange Module. Flange module uses the torque as an input to represent in AVL Cruise the compressor itself which is connected to the electrical machine. In this case, the electric machine used as an approximation for the electric motor plus the inverter that powers the compressor in the majority of electrical vehicles. The parameters were tuned to get results identically to the compressor obtain in KULI software which means that for the necessary torque, the electric machine that powers compressor in AVL Cruise has to have values of speed and mechanical power close to those determine in KULI. The differences will be discussed in 4.1 Calibration. The control variable for the compressor electrical machine was defined as a relation between the max torque of the machine and the necessary torque for the compressor and it is defined in a function named Electrical Motor Load.

Calculation Task

For calculation task, it was recommended by KULI that the time step was the same as the AVL Cruise while using both interfaces. The time step used in KULI was 0.25 s.

3.3 Simulated Driving Cycles

3.3.1 New European Driving Cycle (NEDC)

The New European Driving Cycle testing protocol is the procedure used to regulate cars in European Union and it is legally based in Regulation (EC) No 715/2007 for light passenger and commercial vehicles. It is divided in 4 urban cycles and an extra urban cycle as shown in fig. 3.11.

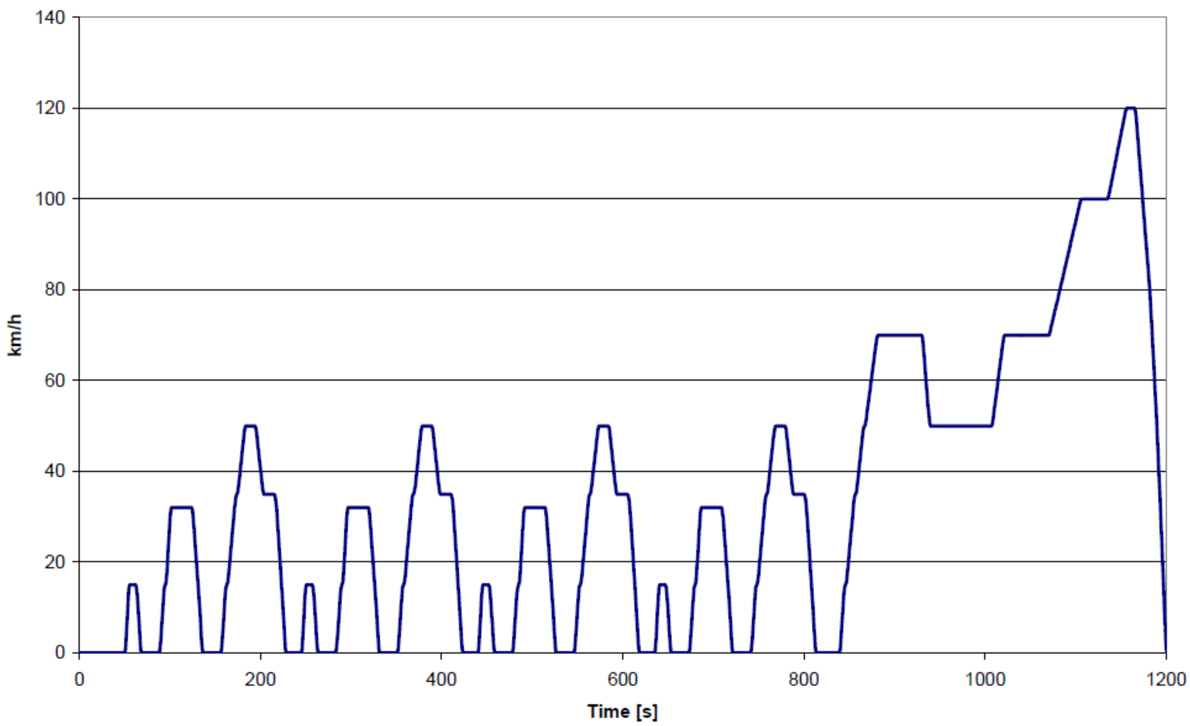


Figure 3.11 – NEDC velocity profile. First 4 Urban driving cycles and then an extra urban cycle from [27]

Although it is the procedure to regulate cars in Europe, it doesn't represent accurately the consumption in real drive. NEDC doesn't consider auxiliary consumers like, for example, air-conditioning system [28]. In "100 Tips to Beat New European Driving Cycle", Stenner and Lienkamp suggest various ways to reduce consumption in this cycle such as increasing tire pressure, reducing way, removing auxiliary units such as air-conditioning systems, in some cases even removing the alternator [28]. As said above air-conditioning system is the auxiliary unit with the biggest impact in the vehicle consumption and in electric vehicles it can reduce the range of the battery by 13 %.

The NEDC cycle undergoes a series of restrictions. In terms of vehicle, we find in Annex 9 of [29] for example, that auxiliary devices "shall be off except those required for testing and usual daytime operation of the vehicle"; tire pressure must be the specified by vehicle manufacturer when the tires are at ambient temperature and the viscosity of oils used in mechanicals parts should be the same specified by manufacturer.

3.3.2 U.S. EPA Driving Schedules

In this work, the simulation cycles for EPA Driving Cycles are based in “Chassis Dynamometer Testing Reference Document” [24] which is based in SAE Standard J1634 from October 2012 and uses a Modified Multi Cycle Test that consists in:

UDDS #1 Cold Start

HWFET #1

UDDS #2 Hot Start

US06 #1

Steady State Speed @ 88.6 km/h (55 mph)

US06 #2

UDDS #3 Hot start

HWFET #2

UDDS #4 Hot Start

Steady state speed until 0 % of SOC @ 88.6 km/h (55 mph)

This order is presented in [24].The figure 3.12 represent the Multi Cycle Test from J1634. In this work it was used the expanded version of the MCT which includes the US06 cycle and the order is described above. The calculation for driving range was done following this sequence and for an ambient temperature of 22.2 ºC (72º F). In July 2017, the Standard J1634 was revised to the actual version which adds an appendix with guidance on BEV five cycle testing with examples [30].

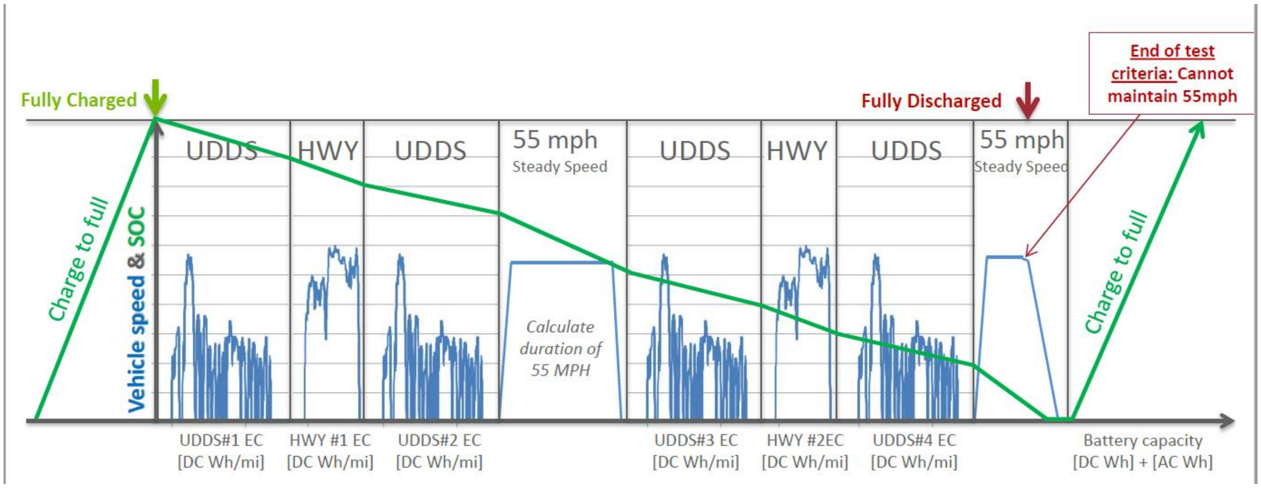


Figure 3.12 - Multi Cycle Test to determine range and energy consumption. Figure from [23].

Figures 3.13 to 3.16 represent the four driving schedules that are integrated in Multi Cycle Test.

UDDS (Urban Driving Cycle)

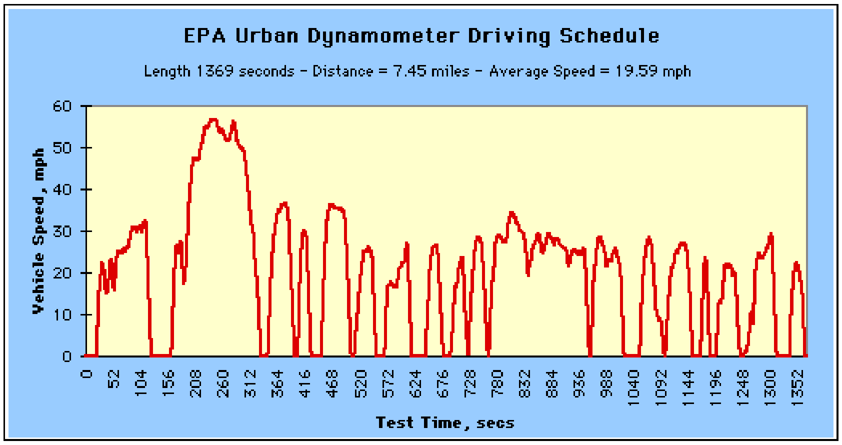


Figure 3.13 - Urban Dynamometer Driving Schedule (UDDS) from [31].

HWFET (Highway Driving Cycle)

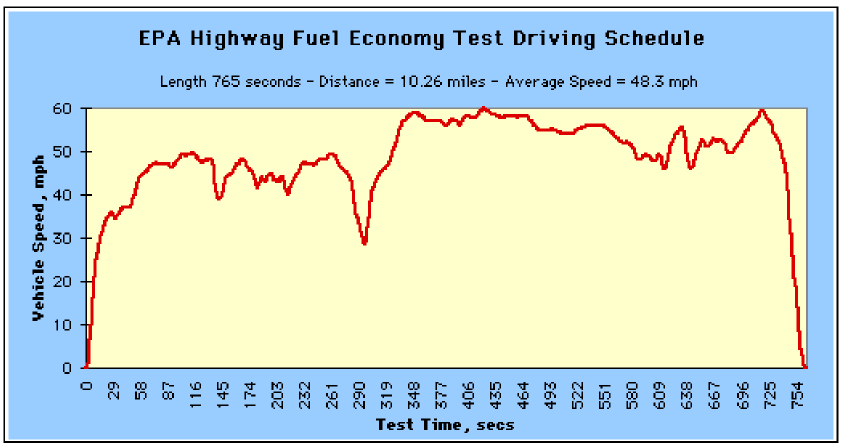


Figure 3.14 - Highway fuel Economy Driving Schedule (HWFET) from [31].

US06 (Supplemental Federal Test Procedure)

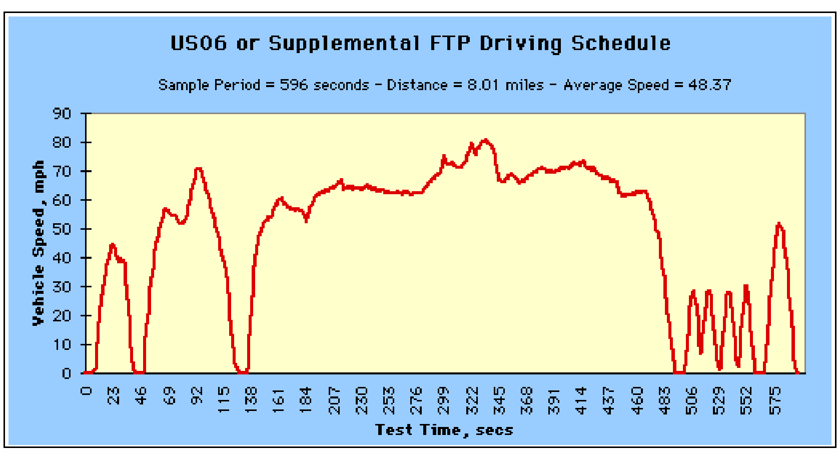


Figure 3.15 – "Aggressive" Driving Schedule (US06) from [31].

SC03 (Supplemental Federal Test Procedure)

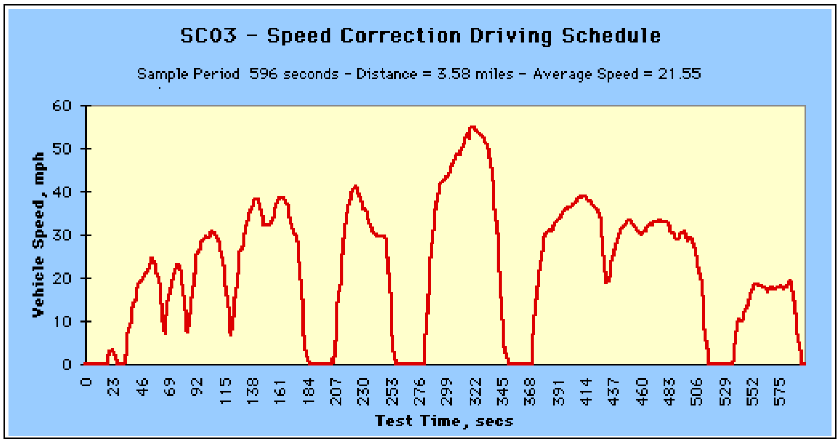


Figure 3.16 – "Air-conditioning" Driving Schedule (SC03) from [31].

Driving Schedules from figure 3.13 to 3.15 are used in the multi cycle run without air-conditioning system, SC03 from figure 3.16 is also used for air-conditioning testing along with the other cycles.

For air-conditioning system there is also a Multi Cycle Test but has some differences from the represented in fig. 3.12. For battery electric vehicles the battery is charged to full during a temperature soak at 35ºC. And the main difference is the existence of an 850W/m^2 radiant load to simulate solar radiation. The test consists in [24]:

UDDS #1 Cold Start

HWFET #1

UDDS #2 Hot Start

US06 #1

SC03 x2 (with 10 min interval between)

Steady State Speed @ 88.6 km/h (55 mph)

US06 #2

UDDS #3 Hot start

HWFET #2

UDDS #4 Hot Start

Steady state speed until 0% of SOC @ 88.6 km/h (55 mph)

The objectives of the Multi cycle test are to determine the usable battery energy, the amount of energy recharged (AC energy from the grid to the vehicle) and to calculate the consumption and range of the vehicle [24].

3.3.3 Worldwide Harmonized Light Vehicles Test Procedure (WLTP)

In order to suppress the major differences between the results in terms of consumption and emissions between driving schedules, specially NEDC, and the real world, there is some efforts going on to create new driving tests that can give close results to what it is actually consumed and emitted. This test is Worldwide Harmonized Light Vehicles Test Procedure (WLTP) and it is already recommended by European Commission since May 2017 to replace NEDC and "from 1 September 2019 all new passenger cars placed on the Union market are to be tested in accordance with the WLTP" [33].

The test divides vehicles for category which are dependent of Power-to-mass Ratio (PMR) which represents the ratio between power output (W) and vehicle curb weight (kg) and vehicle max velocity. The most common light vehicles in Europe are Class 3b with maximum velocity greater than 120 km/h and a PMR greater than 34, where it is included Nissan Leaf 2013 with maximum velocity of 144 km/h and a PWR of 54.The driving cycle used for simulation is represented in figure 3.17.

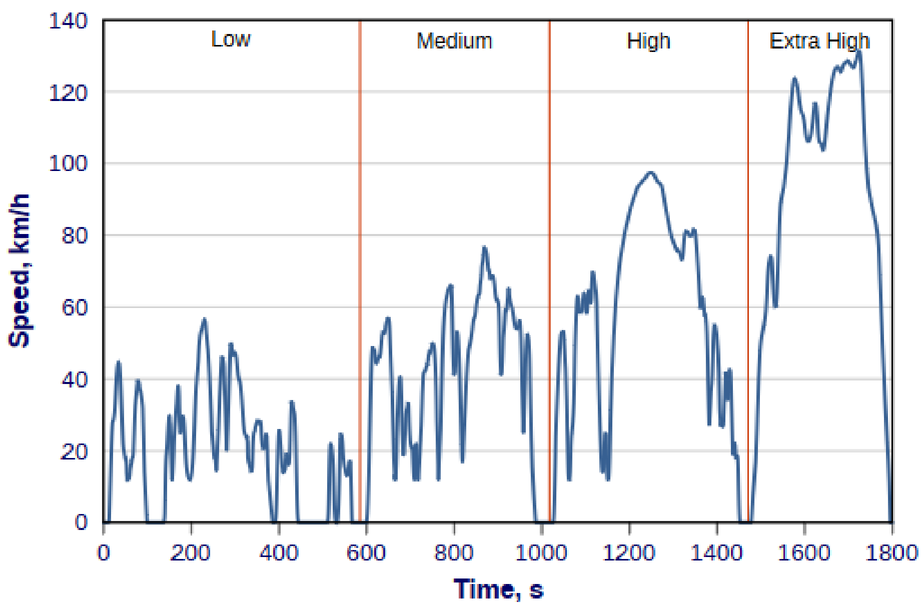


Figure 3.17 - WLTC for vehicle class 3b from [32].

4 Results and Discussion

In 4.1 it is made the calibration of some of the components and methods used. In 4.2.1 results will be presented for the same tests done by INL in [18] for 2013 Nissan Leaf Test first using a model in AVL Cruise described in 3.2.1 and without air-conditioning system. In 4.2.2 it is presented cycle runs with a model using AVL Cruise and Magna KULI which allows to integrate air-conditioning system into the previous model. Tests with simulation cycles will be performed and posteriorly compared with and without A/C in 4.3 to the results obtained in [18]. For EPA Cycles it is used the procedure described by SAE standard J1634 to determine vehicle range and consumption.

4.1 Calibration

Vehicle resistance, as described in methodology chapter, was defined using SAE Coastdown Method. To determine the values in order to obtain realistic results as those obtained in [18], one performed in AVL Cruise the test done in track used to determine the constants for the equation used in the model which is explained in 3.2.1. The results obtained are shown in table 3.3. Figure 4.1 represents the results for Coastdown test with the constants used in AVL and presented in figure B.1.

*** RESULTS ***

Measuring Points VELOCITY

Velocity <km/h>	Gear <->	Time <s>	Distance <m>	Speed <1/min>	Measured Speed Ratio <->
115.00	0	0.00	0.00	7849.74	0.00
110.00	0	3.87	120.76	7508.45	0.00
105.00	0	7.99	243.79	7167.16	0.00
100.00	0	12.39	369.02	6825.86	0.00
95.00	0	17.09	496.35	6484.57	0.00
90.00	0	22.12	625.65	6143.28	0.00
85.00	0	27.52	756.71	5801.98	0.00
80.00	0	33.30	889.26	5460.69	0.00
75.00	0	39.52	1022.97	5119.40	0.00
70.00	0	46.19	1157.38	4778.10	0.00
65.00	0	53.37	1291.94	4436.81	0.00
60.00	0	61.09	1425.94	4095.52	0.00
55.00	0	69.40	1558.51	3754.22	0.00
50.00	0	78.33	1688.62	3412.93	0.00
45.00	0	87.91	1815.02	3071.64	0.00
40.00	0	98.19	1936.23	2730.35	0.00
35.00	0	109.17	2050.58	2389.05	0.00
30.00	0	120.88	2156.18	2047.76	0.00
25.00	0	133.30	2250.97	1706.47	0.00
20.00	0	146.40	2332.81	1365.17	0.00
15.00	0	160.14	2399.53	1023.88	0.00

Resistance Function Coefficients

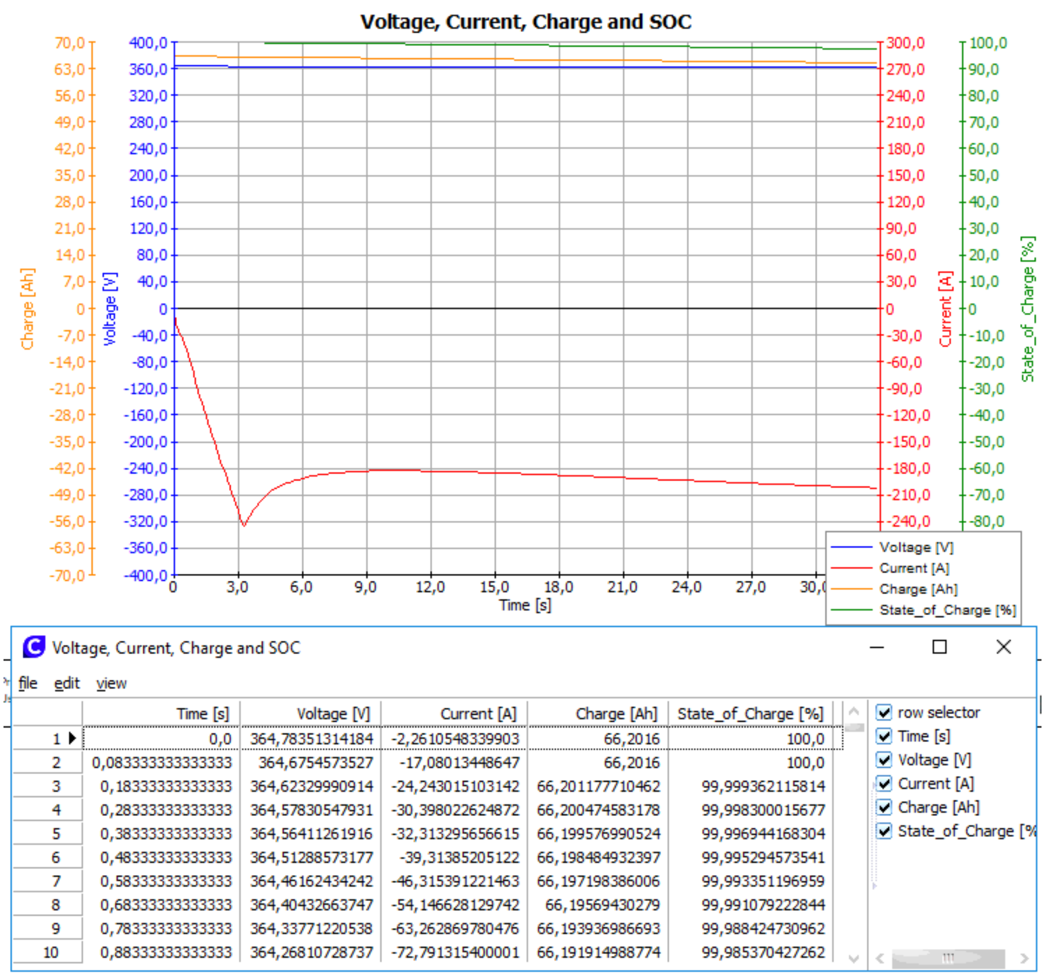
Constant Part: 141.8595872 <N>
Linear Part: 0.3154992 <N/(km/h)>
Square Part: 0.0299745 <N/(km/h)^2>

Figure 4.1 - Results for function coefficients to use in SAE Coastdown Method from AVL Cruise.

In terms of battery calibration, for battery initial values one used the battery results for velocity test (fig. 4.2). These results need to be evaluated because the AVL Cruise inputs are for are battery cell values and the specifications are for battery pack. For initial results one obtained for charge 66.2 Ah, voltage 364.78 V from fig 4.2 and doing the calculation to determine Pack Energy using eq 11, one obtains 24.15 kWh.

$$Pack\ Energy\ [kWh] = Nominal\ Voltage\ [V] \times Charge\ [Ah] \quad \text{(Eq. 11)}$$

The values for Nissan Leaf are presented in table 3.1 and are for battery charge 66.2 Ah, voltage 364.8 V and for rated pack energy 24 kWh, which are very close to those used for initialization.



	Time [s]	Voltage [V]	Current [A]	Charge [Ah]	State_of_Charge [%]
1	0,0	364,78351314184	-2,2610548339903	66,2016	100,0
2	0,0833333333333333	364,6754573527	-17,08013448647	66,2016	100,0
3	0,18333333333333	364,62329990914	-24,243015103142	66,201177710462	99,999362115814
4	0,28333333333333	364,57830547931	-30,398022624872	66,200474583178	99,998300015677
5	0,38333333333333	364,56411261916	-32,313295656615	66,199576990524	99,996944168304
6	0,48333333333333	364,51288573177	-39,31385205122	66,198484932397	99,995294573541
7	0,58333333333333	364,46162434242	-46,315391221463	66,197198386006	99,993351196959
8	0,68333333333333	364,40432663747	-54,146628129742	66,19569430279	99,991079222844
9	0,78333333333333	364,33771220538	-63,262869780476	66,193936986693	99,988424730962
10	0,88333333333333	364,26810728737	-72,791315400001	66,191914988774	99,985370427262

Figure 4.2 - Battery results for maximum velocity test to evaluate battery initial values.

In terms of vehicle calibration, it was used vehicle top speed test and vehicle full throttle acceleration test. Performance for full throttle acceleration test is presented in fig. 4.3. From 0 to 60 mph, the time was 11.58 s and the results table is shown in fig. 4.4 which measure the time every 10 mph until 60 mph mark was reached. This value is close to the obtain by INL [18] of 10.6 s and it is below they performance goal which was 13.5 s

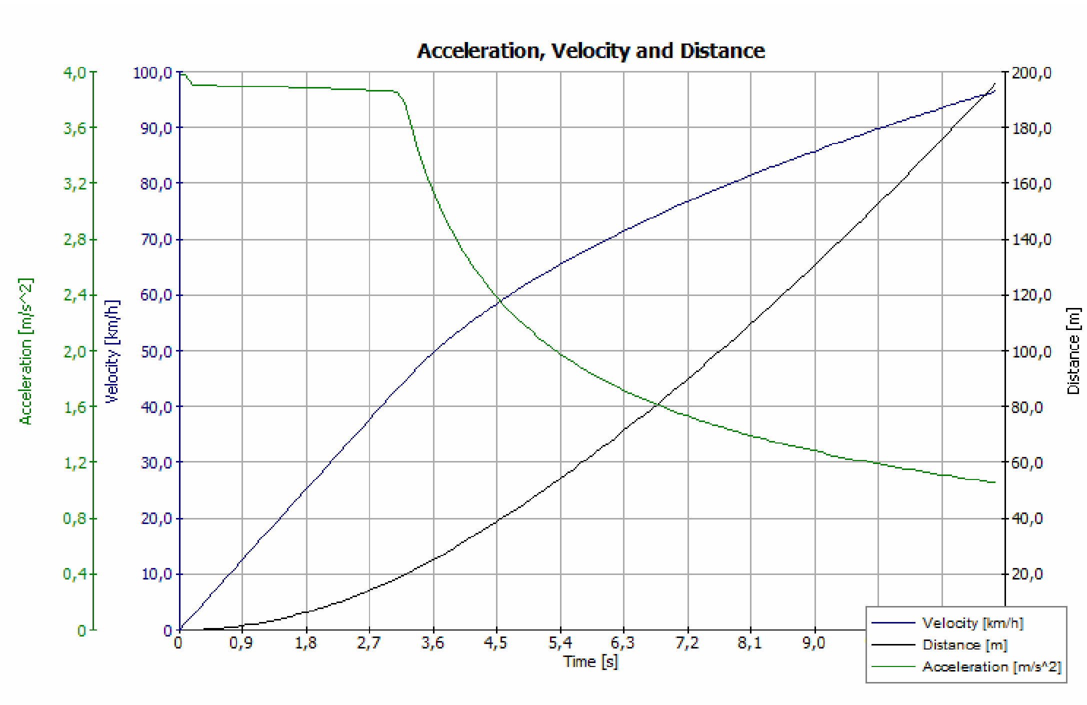


Figure 4.3 - Acceleration, velocity and distance profile for full throttle acceleration from 0 to 60 mph (0 – 96.6 km/h).

Measuring Points VELOCITY

Velocity <km/h>	Gear <->	Time <s>	Distance <m>	Speed <1/min>	Measured Speed Ratio <->
16.09	1	1.14	2.57	1098.52	0.00
32.19	1	2.29	10.28	2197.03	0.00
48.28	1	3.47	23.53	3295.55	0.00
64.37	1	5.24	51.48	4394.06	0.00
80.47	1	7.90	105.39	5492.58	0.00
96.56	1	11.58	196.22	6591.10	0.00

Figure 4.4 - Results for time and distance for a velocity step of 10 mph from 0 to 60 mph (in km/h).

Acceleration test allows also to calibrate battery in terms of peak power during full throttle acceleration. Figure 4.5 represents the maximum reached output power (as red) and its negative due to a convention used for “work” done by battery current. The peak for battery output power is 89.06 kW and it is close to the peak power from the battery obtained in [18], which was 87.1 kW. There is a 2.2 % difference.

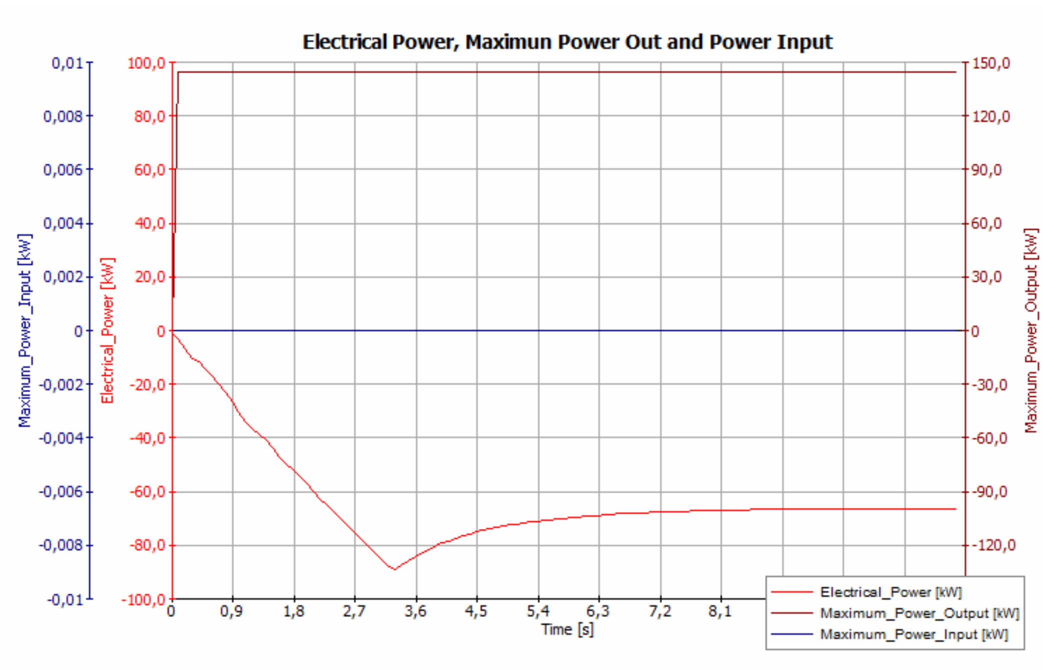


Figure 4.5 - Electric power output during full throttle acceleration from 0 to 60 mph.

For max speed the results are presented in fig. 4.6. Starting from rest, the maximum speed was reached before 1.61 km (1 mi) mark and was 146.69 km/h which is very close to the result obtained by INL [18] of 146.51 km/h. The difference is less than 0.2 %. For the speed trap at 402.34 m (1/4 mile) the velocity obtained with AVL was 118.12 km/h with a difference of 5.3 % when comparing with [18] which at quarter mile mark the velocity was 124.78 km/h.

```
Start Velocity:              0.00 <km/h>
Final Velocity:            146.69 <km/h>

*** RESULTS ***

Measuring Points DISTANCE
-------------------------
                                                                        Measured
  Distance      Gear         Time      Velocity          Speed       Speed Ratio
     <m>        <->           <s>         <km/h>         <1/min>         <->
  402.34         1          18.45        118.12         8063.00          0.00
  804.67         1          29.54        141.41         9652.30          0.00
```

Figure 4.6 - Results for speed traps at 402.34 m (1/4 mile) and 804.67 (1/2 mile).

The velocity profile (fig. 4.7) follows the expectation of an electric vehicle with a better acceleration at the beginning due to the maximum torque availability from the beginning from the electric machine and it decreases in the increase of vehicle velocity. The function stops when the maximum speed of the electrical machine is reached, in this case, 10 000 rpm.

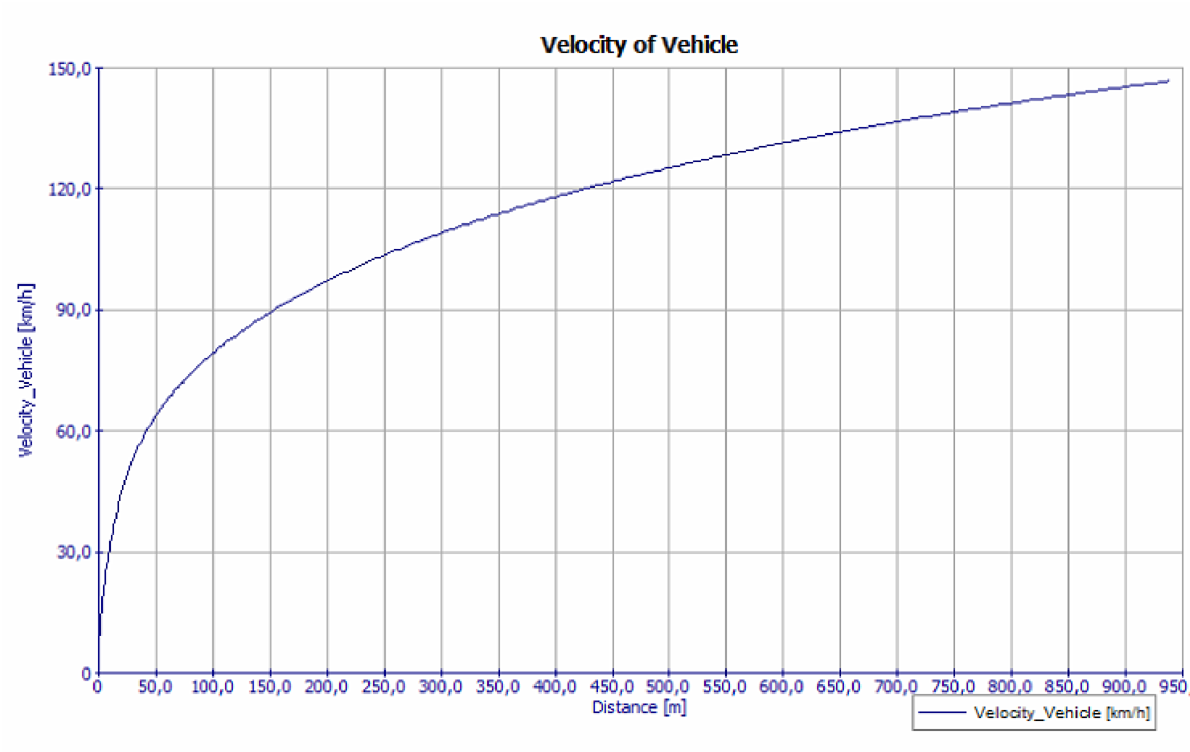


Figure 4.7 - Velocity vs distance profile for full throttle acceleration.

As referred in 3.3.2 it was used an approximation model to simulate the compressor for A/C using AVL cruise with KULI Interface. In an electric vehicle the compressor is powered by an AC motor which uses current from high voltage battery after passing an inverter. In this case the approximation done in AVL Cruise was to assume that the compressor (which is represented by the flange module in fig. 3.9) is mechanically connected to an electric machine which is powered directly from the high voltage battery.

To make this approximation, one had to verify if the power output from the electric machine and its speed were close to those obtained in KULI compressor results. The electric machine parameters were tuned in order to verify this constraints, power and speed, for a given torque needed by the compressor. Power is an output from KULI software and corresponds to compressor driving power, while compressor speed is a user input in this case defined in AVL Cruise Cabin Demand Temperature module (fig. 3.9).

Figure 4.8 represents the compressor driving power obtained in KULI calculation (around 1720 W in the constant part) which is slightly higher than the obtained in the module used for electric machine which in the constant part which it's around 1670 W. Electric machine designed in AVL has a power of around 3 % lower than calculated by KULI as the necessary to power compressor. The lower power in the electric machine contributes with a small error for consumption and can be explained with its lower speed (approximately 1930 rpm in the constant part) comparing to the 2000 rpm as an input initially. Data from KULI compressor driving power and electric machine outputs are presented in figure 4.8 and figure 4.9 respectively.

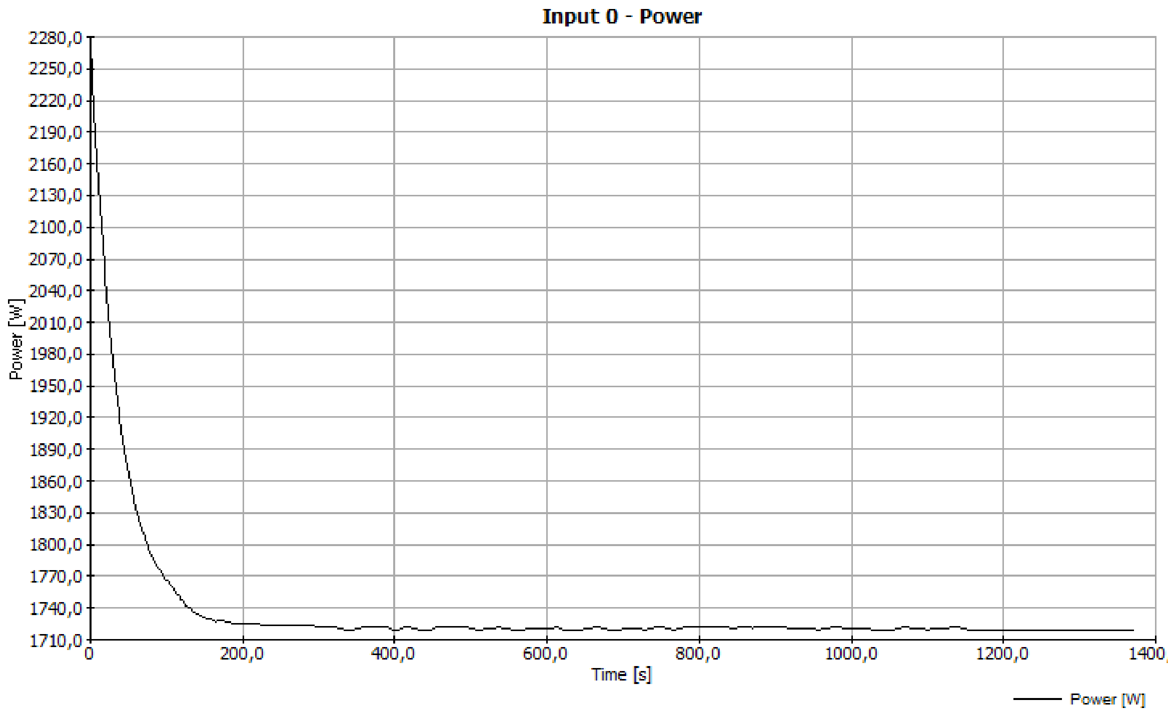


Figure 4.8 - Compressor driving power output from KULI for UDDS first cycle run with A/C on.

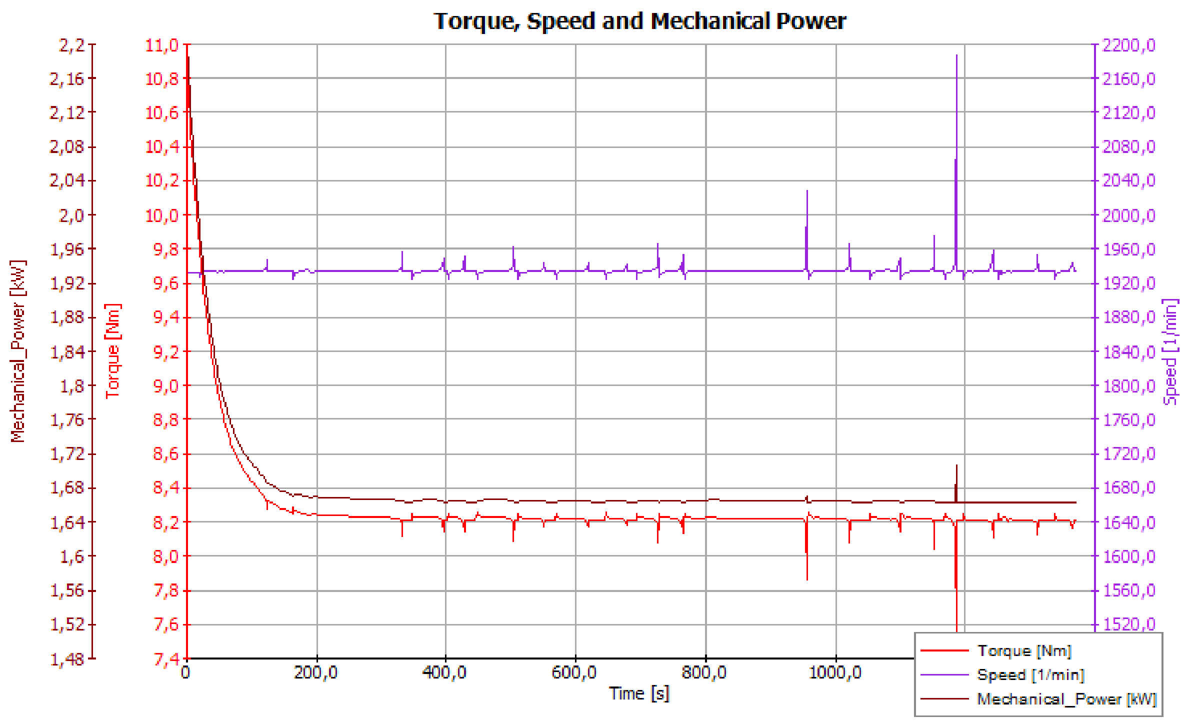


Figure 4.9 - Results for power, torque and speed for electric machine that powers compressor for UDDS first cycle run with A/C on.

4.2 Results

4.2.1 Results without air-conditioning system for EPA Driving Schedules

Following the procedure described in 3.3.2, table 4.1 presents the results for each cycle consumption and the SOC initial and final for each cycle run. The cycles were simulated individually in AVL Cruise and the final SOC was set as the initial SOC of the following cycle.

As thermal effects on battery behaviour were not considered (see 4.3), four UDDS cycles at hot start were simulated to calculate final range (instead of one UDDS at cold start and three UDDS at hot start). The effects on this approximation will be discussed further in Chapter 4.3 Validation.

Table 4.1 - Results for consumption and State of Charge following the Multi Cycle Test procedure described in 3.3.2.

Driving Cycle	***Consumption [kWh/100km]***	***Consumption [kWh]***	***Initial SOC [%]***	***Final SOC [%]***
UDDS #1 Cold Start	13.45	1.618	100	93.28
HWFET #1	15.36	2.528	93.28	82.70
UDDS #2 hot start	13.37	1.609	82.70	75.91
US06 #1	19.24	2.486	75.91	65.33
55 mph	17.24	3.569	65.33	50
US06 #2	19.20	2.480	50	39.20
UDDS #3 hot start	13.19	1.586	39.20	32.25
HWFET #2	15.25	2.511	32.25	21.16
UDDS #4 hot start	13.11	1.578	21.16	14.13
55 mph until SOC = 0	17.23	3.145	14.13	0
Total	-	**23.11**	-	-

During the simulation it was assumed a constant ambient temperature of 22.2 ºC (72 ºF).

For the first cycle run, UDDS #1, fig. 4.10 presents the velocity, acceleration and distance profile and fig. 4.11 presents the battery's SOC, charge, current and voltage. For the other cycles, the results are presented in Annex D unless there is relevant information to add.

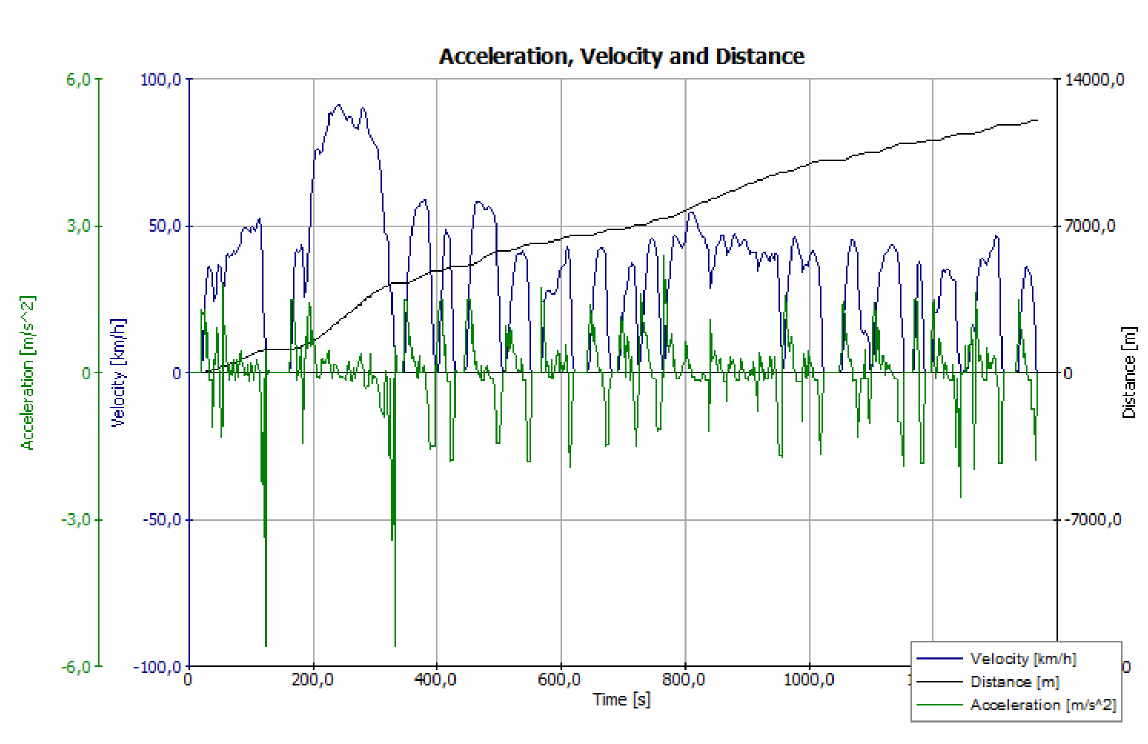


Figure 4.10 - Acceleration, velocity and distance for first Urban Dynamometer Driving Schedule (UDDS) run, UDDS#1.

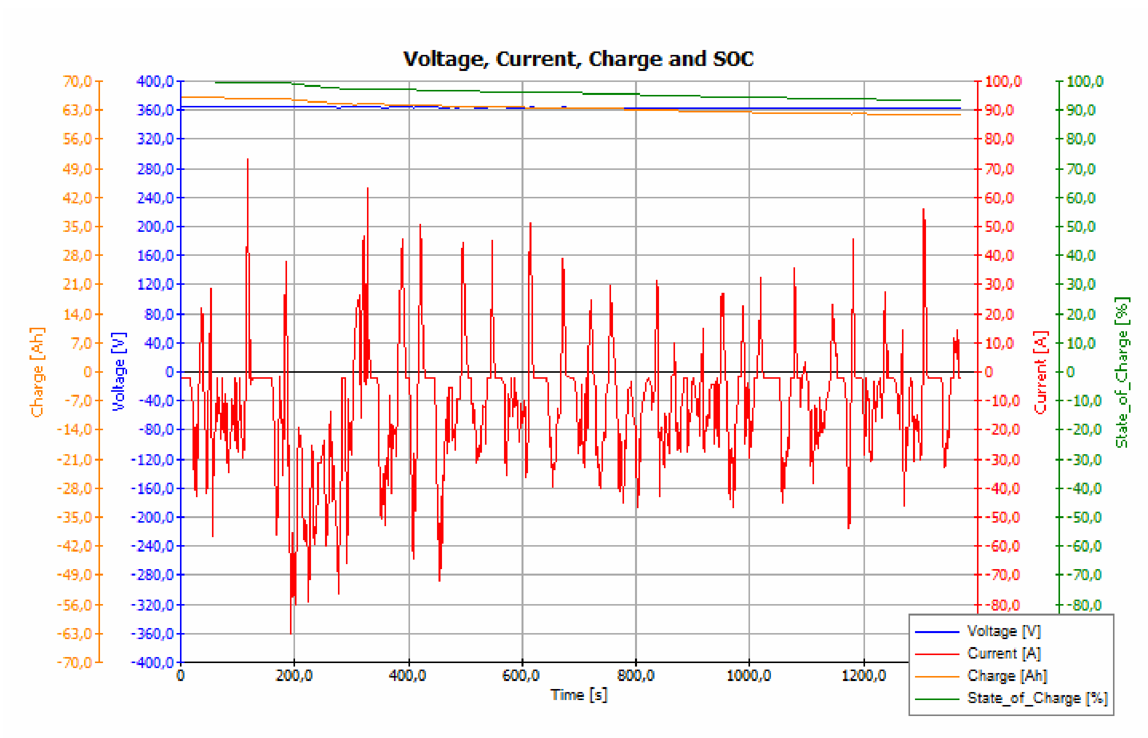


Figure 4.11 - High voltage battery results for first UDDS run, UDDS #1.

The velocity profile in fig. 4.12 is very close to the objective one presented in fig. 3.13. Comparing fig. 4.10 and 4.11 one can also check the recharge battery function in the model is working correctly from the positive peak values in battery in fig. 4.11 at the same instances as great decelerations in fig. 4.10.

As we can see in table 4.1, the total amount of consumed energy during cycle running was 23.11 kWh which is very close to the rated pack energy announced by Nissan [20] which is 24 kWh. The driving cycles used (figures 3.13 to 3.15) were inputs in task folder>cycle run>profile in AVL Cruise along with a steady state speed run of 88.6 km/h (55 mph) to run multi cycle test.

To calculate the vehicle range it was used the cycle type mean value. The formula is:

$$\frac{Total\ Consumption}{\frac{\sum Cycle\ Type\ Consumption}{Nº\ of\ same\ cycle\ run}} \times 100 \quad (Eq.11)$$

which uses total consumption in kW and the sum of cycle type consumption in kWh/100km.
For example for UDDS values in table 4.1, the mean value for consumption is given by

$$UDDS\ Mean\ Consumption = \frac{(13.45 + 13.37 + 13.19 + 13.11)}{4} = 13.28\ kWh/100km$$

with the total consumption of 23.11 kW, we get for range 174 km in city. Following the same procedure, table 4.2 presents the range calculated for electric vehicle model in AVL Cruise.

Table 4.2 - Results for range in city, highway and aggressive tests using data of table 4.1.

Cycle	***Average Consumption [kWh/100km]***	***Range [km(mile)]***
City (UDDS)	13.28	174 (108)
Highway (HWFET)	15.31	150.9 (94)
Aggressive (US06)	19.22	120.2 (75)

4.2.2 Results with air-conditioning system for EPA Driving Schedules

For this test, the procedure is presented in 3.3.2. The test is done after 12h soaking period with the car at temperature conditions for the test with A/C on. During the test the ambient temperature is 35 ºC (95 ºF) and it is exposed to an 850 W/m^2 radiant energy to simulate the incidence of solar radiation. Air-conditioning testing includes in the MCT run a SC03 test which is done twice and with a 10 minutes interval where the vehicle is exposed to radiant energy.

As in 4.2.1, each simulation will be done individually and some of the final results (Final SOC and Final Cabin Temperature) will be the starting values for the next cycle run. Table 4.3 presents the results for multi cycle testing with air-conditioning system. The starting temperature will be 35 ºC in the cabin until it reaches 22.2 ºC (72 ºF). After that, temperature will stay constant with A/C on which means that compressor driving power will be constant. For simulation and to ease processes, compressor speed was assumed constant and equal to 2000 rpm.

Table 4.3 - Results for Multi Cycle Testing with air-conditioning system at 35 ºC with 850 W/m^2 of radiation flux

Driving Cycle	*Consumption [kWh/100km]*	*Consumption [kWh]*	*Initial SOC [%]*	*Final SOC [%]*	*Initial Cabin Temp [ºC]*	*Final Cabin Temperature [ºC]*
UDDS #1 *Cold Start*	17.94	2,151	100	91.06	35	22.2
HWFET #1	17.50	2.888	91.06	78.95	22.2	22.2
UDDS #2 *hot start*	17.79	2.133	78.95	69.92	22.2	22.2
US06 #1	23.56	3.033	69.92	56.95	22.2	22.2
SC03 x2 *with 10 min interval*	18.47	2.128	56.95	47.77	22.2	22.7
US06 #2	23.93	3.080	47.77	34.34	22.7	22.2
UDDS #3 *hot start*	17.71	2.124	34.34	24.99	22.2	22.2
HWFET #2	17.39	2.870	24.99	12.23	22.2	22.2
UDDS #4 *hot start*	17.62	2.113	12.23	2.75	22.2	22.2
55 mph *until SOC = 0 %*		0.610	2.75	0	22.2	22.2
Total	-	**23.13**	-	-		

Next, one will present battery results and in some cases compressor driving power, electric machine output and cabin temperature. First it is simulated the Urban Dynamometer Driving Schedule (UDDS).

Figure 4.12 represents the battery performance for the first UDDS, the first cycle starts at 100 % SOC, with starting charge at 66.2 Ah and nominal voltage a 364.8 V. As referred above, the final SOC of each cycle will be the initial SOC of the next one.

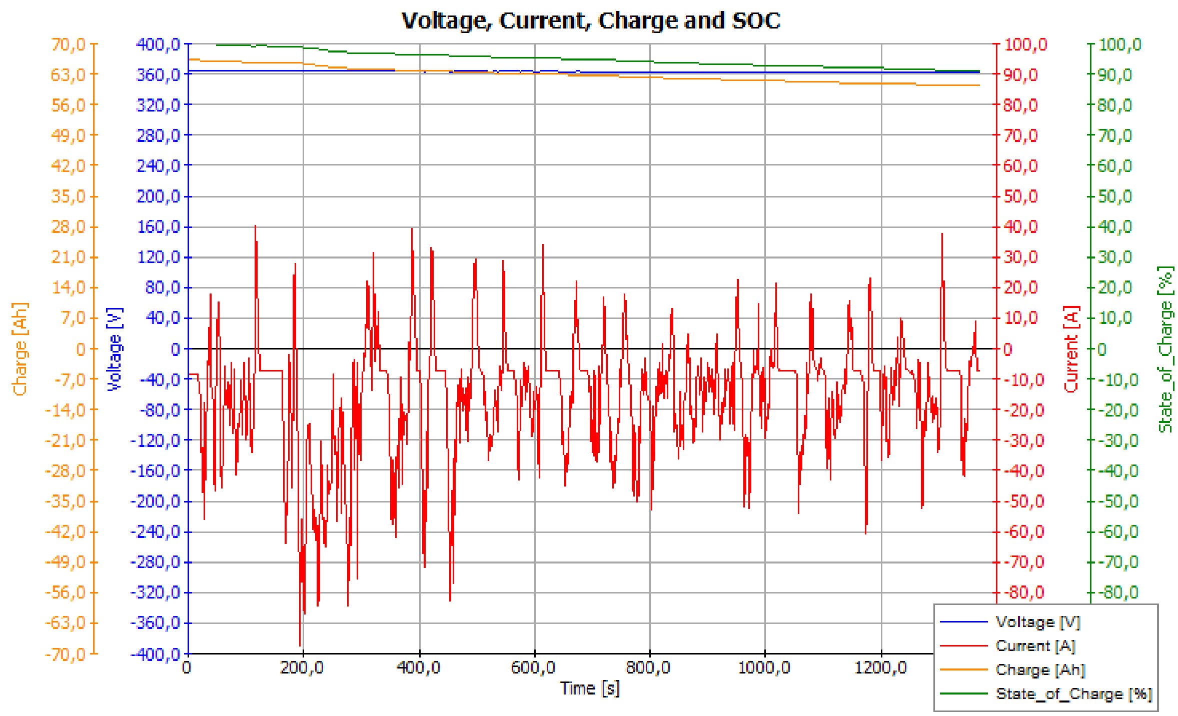


Figure 4.12 - High voltage battery results for the first UDDS run with A/C module.

Figure 4.13 represents the cabin temperature profile for the first cycle run. The starting temperature is 35 ºC (95 ºF) and it is assumed that all components start at this temperature. The temperature decreases until the desired temperature is reached which is 22.2 ºC (72 ºF). This target temperature was selected because it is the temperature for air-conditioning system used in the tests performed by INL [18]. After the target temperature is reached, the A/C system (namely the compressor) will work at steady state in order to simulate a constant desired cabin temperature.

Fig. 4.14 represents the steady cabin temperature during the first HWFET cycle and fig. 4.15 represents the output from KULI software for the compressor driving power working at steady-state. After the temperature reach the desired temperature of 22.2 ºC, which happened during the first driving schedule, the air-conditioning will work at steady state. One assumed that all driving cycles are simulated within an interval which there is no temperature increase between.

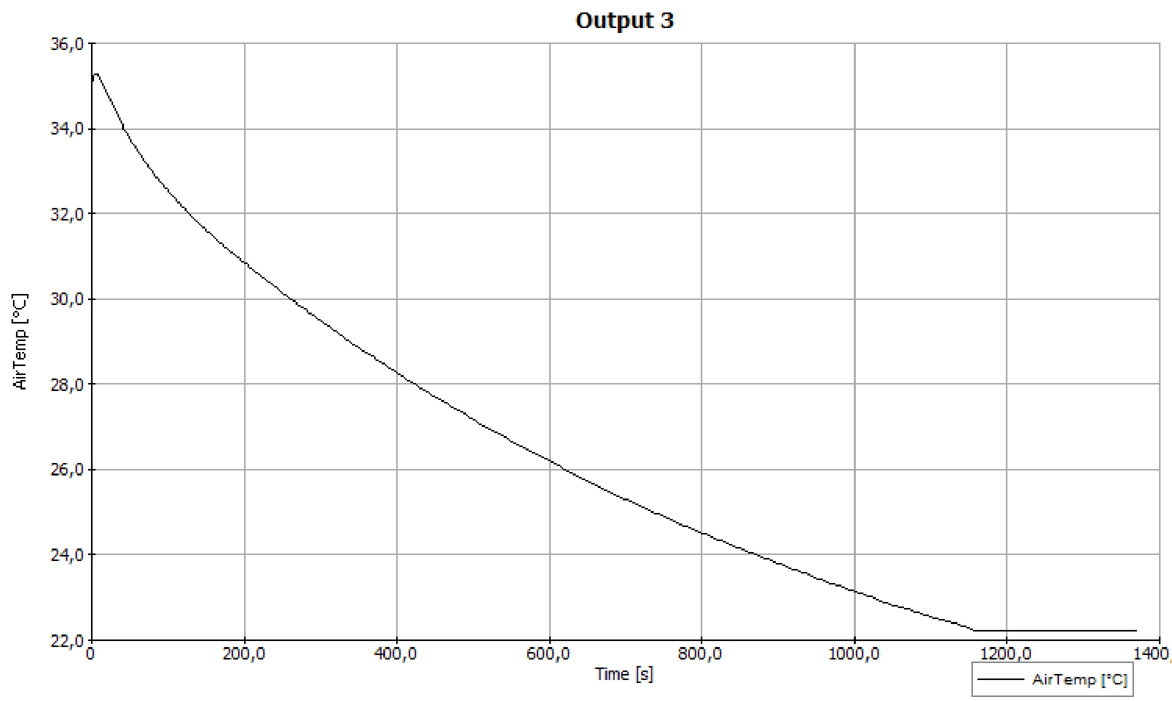


Figure 4.13 - Cabin air temperature in first UDDS cycle run starting at 35 ºC until 22.2 ºC.

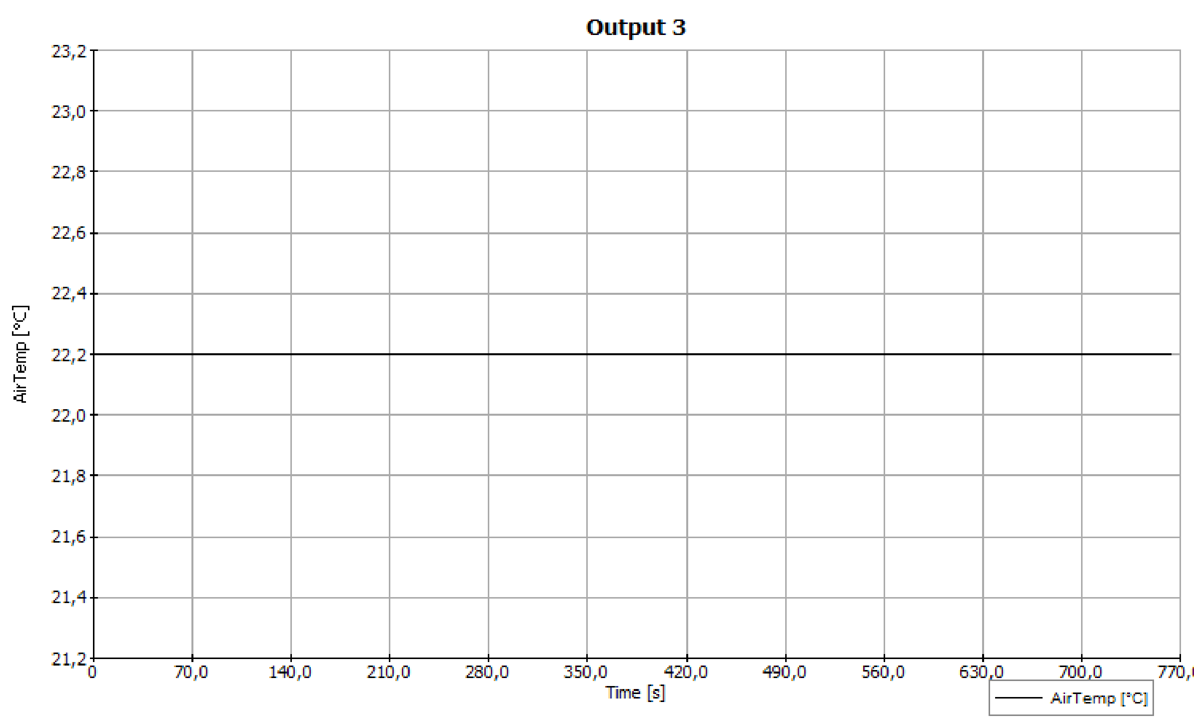


Figure 4.14 - Cabin air temperature during second cycle run (HWFET #1) steady at 22.2 ºC.

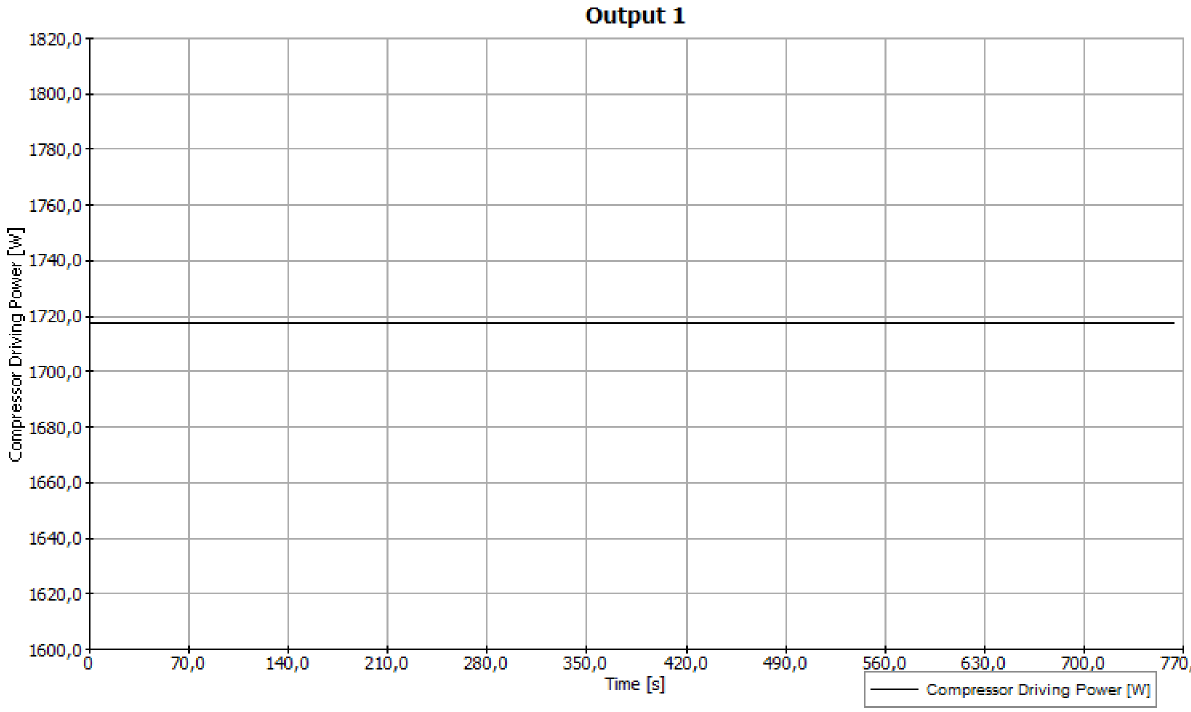


Figure 4.15 - Compressor driving power for second cycle run (HWFET #1) at steady state.

In air-conditioning test cycle, the cycle is performed twice with an interval of 10 minutes with ignition off, ambient temperature of 35 ºC and a simulated solar radiation flux of 850 W/m^2. The objective is to determine the influence of air-conditioning impact on performance and cabin demand temperature. The cycle velocity profile is represented in fig. 4.16.

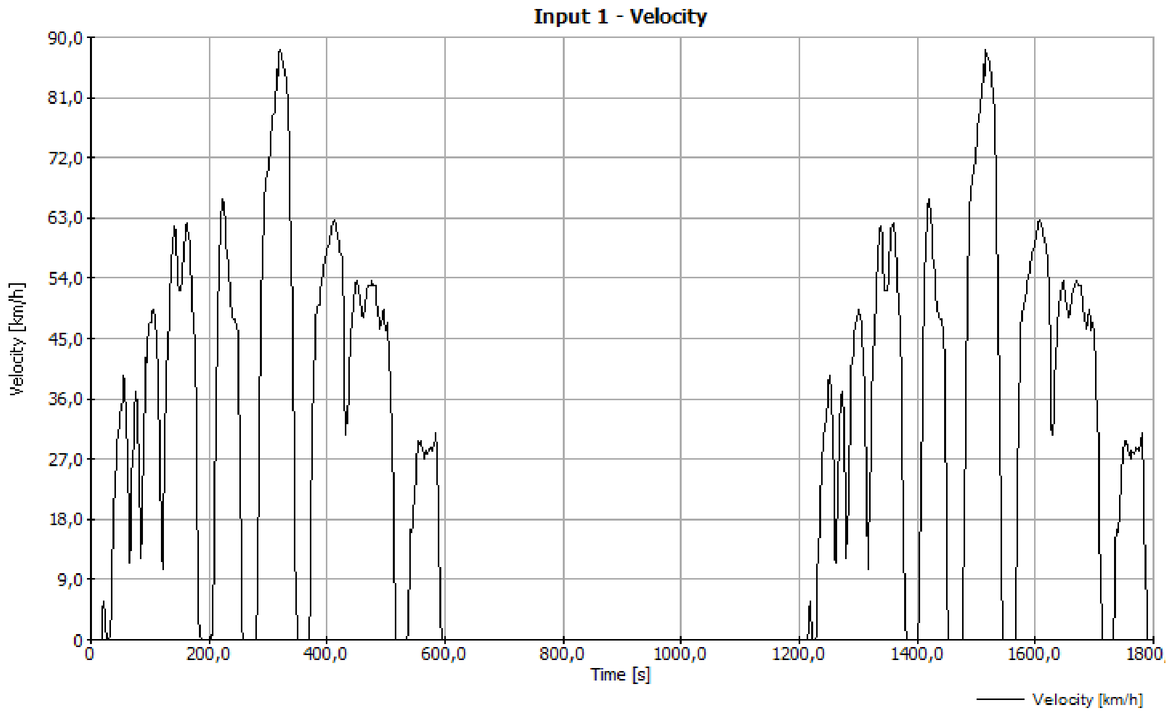


Figure 4.16 - Velocity profile for SC03 dual cycle run.

Figure 4.17 represents the battery results for the simulation test and figure 4.18 shows the temperature variation inside the cabin. In the SC03 the temperature decreases while the A/C is working. After the car stops, the A/C is turned off and the cabin temperature increases due to the simulated solar radiation inside the test zone and the ambient temperature. With the start of the second SC03 run, the temperature starts to decrease again following the profile of figure 4.13 at the initialization cycle with 35 ºC inside the cabin.

The battery results for the next driving schedules until the end of the MCT are presented in Annex D. Fig. D.16 represents the second US06 schedule, fig. D.17 represents battery results for the third UDDS, fig. D.18 the battery results for the second HWFET and finally fig. D.19 the forth UDDS. After all driving schedules, the vehicle starts a constant speed test at 88.6 km/h (55 mph) until full battery depletion represented in fig. D.20.

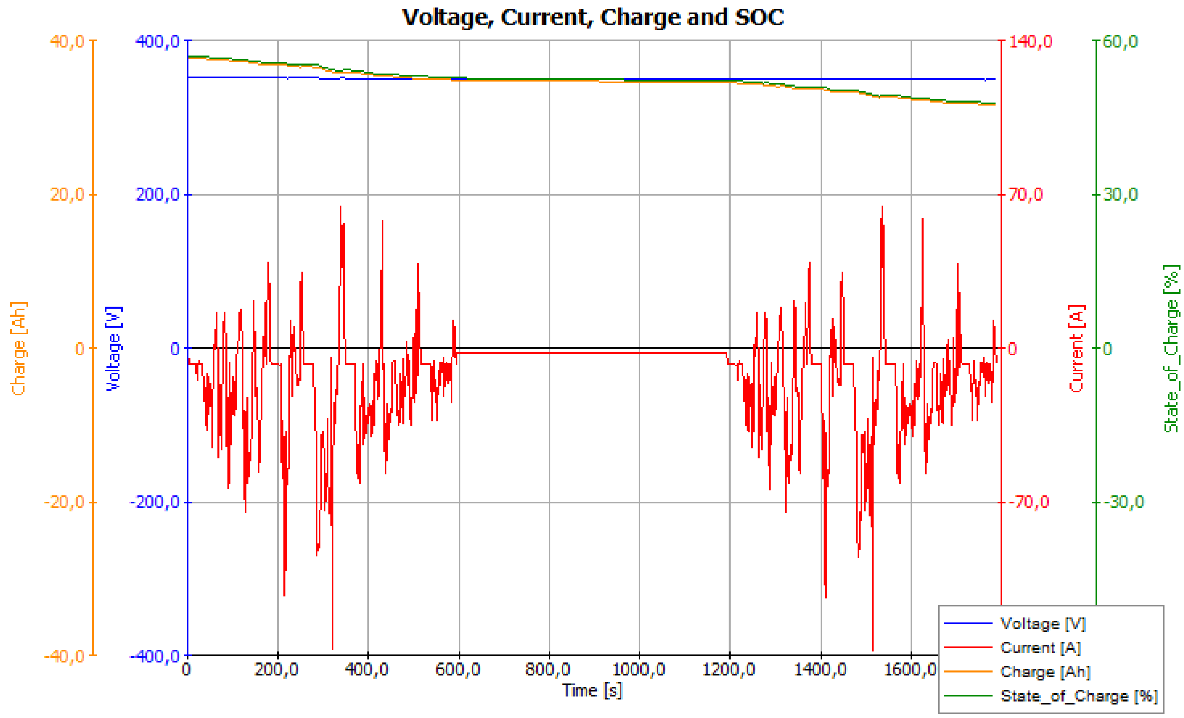


Figure 4.17 - High voltage battery results for SC03 simulation with 10 minutes interval.

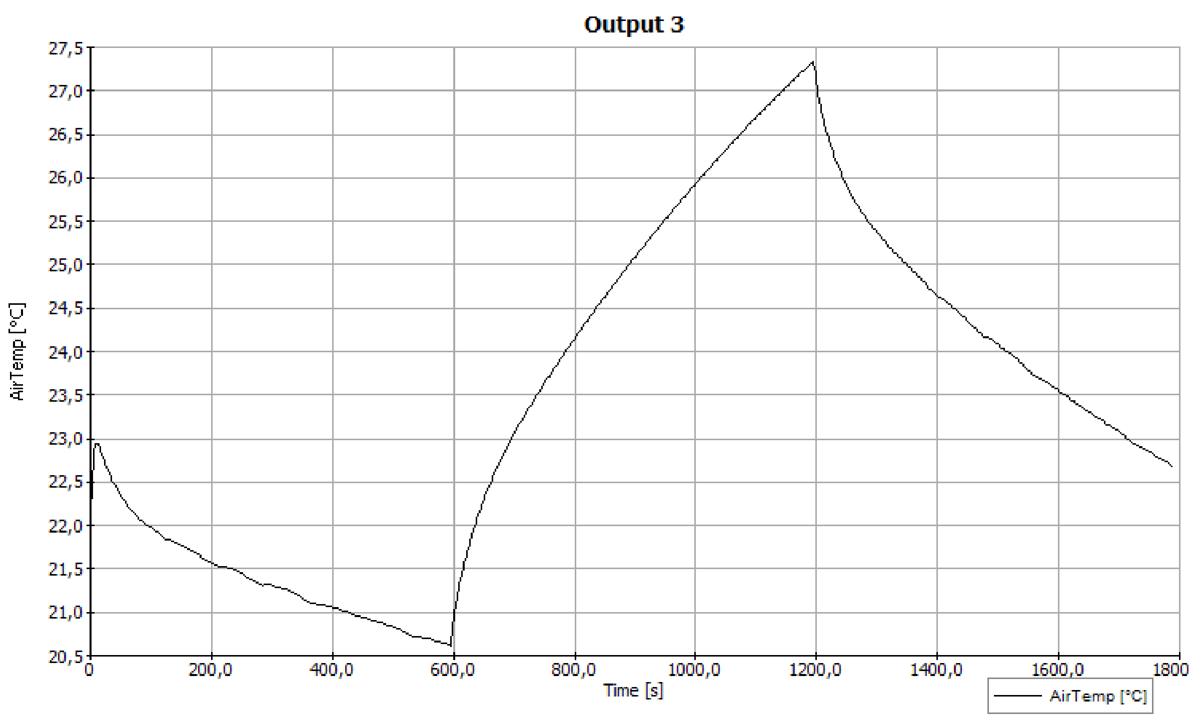


Figure 4.18 - Cabin temperature variation during SC03 dual test.

Using the same method for calculate range, presented in 4.2.1, it is obtained for simulation the following values presented in table 4.4.

Table 4.4 - Results for range in city, highway, aggressive and air-conditioning tests using data of table 4.3.

Cycle	***Average Consumption [kWh/100km]***	***Range [km]***
City (UDDS)	17.77	130.2
Highway (HWFET)	17.45	132.6
Aggressive (US06)	23.75	97.4
Air-Conditioning (SC03)	18.47	125.2

4.3 Validation

The main goal in this chapter is to understand if both models used present close results in terms of vehicle consumption and range in order to compare to the results obtained in the vehicle test by INL [18]. If those results are close enough, one can then compare which influence has the air-conditioning system in the electric vehicle.

For vehicle tests without A/C system with the conditions set by EPA to homologate vehicles in United States and presented in 3.3.2 U.S. EPA Driving Schedules, the results obtained in dynamometer test for the model based on NISSAN Leaf 2013 are presented in table 4.4 after a conversion to SI units of the values presented in [18].

Table 4.5 - Results for dynamometer tests for Urban (UDDS), Highway (HWFET) and Aggressive (US06) driving cycles at 22.2 ºC (72 ºF).

Driving Schedule	***Consumption [kWh/100km]***
UDDS (Cold Start)	13.15
UDDS (Hot Start)	12.51
HWFET	14.96
US06	19.98

As discussed in 4.2.1, the results presented in table 4.5, are mean values for each driving schedule except for cold start UDDS which is the first one running. UDDS (Hot Start) consumption is a mean value of three UDDS runs, HWFET and US06 are ran twice.

Comparing with the results obtained in AVL Cruise simulation (table 4.2), one obtain the differences shown in table 4.5

Table 4.6 – Electricity consumption comparison between data from INL [18] and results from AVL Cruise.

Driving Schedules	***Consumption INL[18] [kWh/100km]***	***Consumption AVL Cruise [kWh/100km]***	***Difference (%)***
UDDS (Cold Start)	13.15	13.45	2.2 %
UDDS (Hot Start)	12.51	13.22	5.4 %
HWFET	14.96	15.31	2.3 %
US06	19.98	19.22	(4) %

Values for range are presented in table 4.6 and its calculation is presented in 4.2.1, table 4.2. Again second row is a value converted to SI units.

Table 4.7 - Results comparison for NISSAN Leaf range between data from INL [18] and AVL Cruise results.

Type of range	*Range INL[18] [km]*	*Range Calculated [km]*	*Difference [%]*
City	178.5	174	2.5 %
Highway	149.2	150.9	(1.1) %
US06	109.8	120.2	(9.5) %

In terms of consumption, the results are close to those obtained by INL [18] and since many parameters were tuned because there was no data available and the uncertainty can lead to misguiding results, this results were not too different. Nevertheless, in terms of cold start and hot start difference, the values differ only slightly, only two tenths of kWh/100km comparing with six tenths obtained by INL. This fact may seem negligible but there is a reason for this error. During the simulation, one was unsuccessful to simulate the influences of cold start and temperature in battery performance. Even with extreme values for temperature in battery and with battery temperature changing during cycle, none of the options tried (resistance and capacitance constant, temperature dependent or temperature and SOC depend) seemed to sort any effect in consumption. For every run the influences of temperature in battery performance were then neglected, so one should expect for cold start UDDS a value slightly higher for consumption. The temperature influence can also explain the better range obtained for Aggressive US06 where the battery temperature is expected to rise with the acceleration pedal load. The increase in temperature of the battery will decrease its efficiency increasing the consumption and then decrease its range.

Although the influence of temperature was not considered, there is a slightly difference in consumption for the same driving schedule with different SOC. For example for UDDS one got from table 4.2 for UDDS #2 a consumption of 13.37 kWh/100km, for UDDS #3, 13.19 kWh/100km and for UDDS #4, 13.11 kWh/100km. This values are not constant because there is a small variation in battery nominal voltage with SOC, which diminishes when SOC tend to zero.

With air-conditioning system on, set to auto 22.2 ºC (72 ºF), with an ambient temperature of 35 ºC (75 ºF) and a solar load of 850 W/m^2, the results obtained by INL [18] were as follow in table 4.7, converted once again to SI units.

Table 4.8 - Results for dynamometer tests for Urban (UDDS), Highway (HWFET), Aggressive (US06) and Air-Conditioning (SC03) driving cycles at 35 ºC (95 ºF) plus a 850 W/m^2 solar load.

Driving Schedule	*Consumption [kWh/100]*
UDDS (Cold Start)	18.23
UDDS (Hot Start)	17.05
HWFET	16.90
US06	22.35
SC03	17.97

Table 4.9 compares the results from table 4.8 with those obtained in AVL Cruise simulation with the integration of KULI software from table 4.3.

Table 4.9 – Electricity consumption comparison between data from INL [18] and results from AVL Cruise with KULI interface.

Driving Schedules	*Consumption [18] [kWh/100km]*	*Consumption AVL Cruise [kWh/100km]*	*Difference (%)*
UDDS (Cold Start)	18.23	17.94	(1.6) %
UDDS (Hot Start)	17.05	17.71	3.9 %
HWFET	16.90	17.45	3.3 %
US06	22.35	23.75	6.3 %
SC03	17.97	18.47	2.8 %

As expected, with air-conditioning system, results are slightly higher from those measured by INL which goes in the same line as the results without air-conditioning system. However, the value for UDDS consumption at cold start is lower than the measured value experimentally.

The value for UDDS consumption at Cold Start can be explained with the starting cabin temperature and ambient temperature. Comparing with the value without A/C, the consumption is greater due mainly to two factors: first the A/C is on and working at maximum power while trying to remove vehicle heat and bring the temperature down from 35 ºC to 22 ºC and the second one, which was not considered by AVL Cruise as discussed previously, the starting temperature of the battery was at 35 ºC which is above its operating temperature and tend to increase during the cycle due to acceleration load. Thus, only the air-conditioning system influences the increase in consumption in the model used and the greater ambient temperature has no effect in this simulation. Accounting for temperature impact on battery performance one should get higher results with the model used.

At last, table 4.10 shows a comparison between range results calculated for all EPA driving schedules with and without A/C.

Table 4.10- Comparison between range values for simulations with and without A/C for EPA driving schedules simulated.

Driving Schedule	*Range without A/C [km]*	*Range with A/C [km]*	*Difference [%]*
UDDS	174	130.2	25.2
HWFET	150.9	132.6	12.4
US06	120.2	97.4	19
SC03	-	125.2	-

From table 4.10, it's clear that the main impact of the air-conditioning system is in the urban type cycle UDDS. Although the range without A/C is calculated at ambient temperature of 22.2 ºC and the range for air-conditioning system was calculated for moderately extreme conditions with 35 ºC with solar radiation, the results presented suggest that the air-conditioning system can impact from 12 % to 25 % in extreme conditions.

4.4 Other Simulations

4.4.1 New European Driving Cycle (NEDC)

4.4.1.1 NEDC without air-conditioning system

For vehicle test in New European Driving Cycle run (described in 3.3.1) the vehicle model is represented in 3.2.1. For this cycle all mechanical consumers are removed and the air-conditioning system is not accounted.

For NEDC, the calculation was done using SOC target to 0 %, this means that NEDC was continuously run until there was no more battery charge for another cycle. The total range is the total energy consumed doing all repetition cycles dividing by the distance travelled plus an extrapolation for the percentage of SOC left.

Figure 4.19 represents the battery values of current, nominal voltage, SOC starting at 100 % and battery total charge. The final value of SOC is 6.33 % after 13 complete NEDC runs. Consumption in average was 15.19 kWh/100 km. When comparing with the announced values (see 3.1) there is a difference of 0.19 kWh/100km.

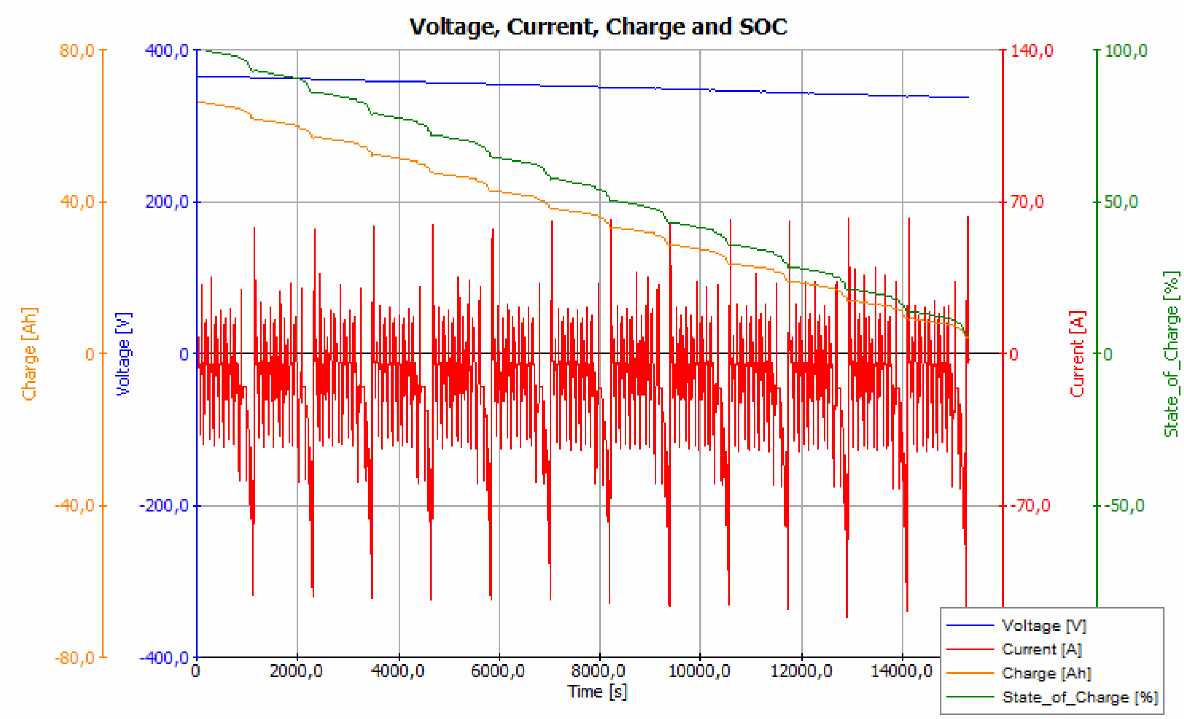


Figure 4.19 - Results for NEDC multiple run starting at 100% SOC. Total battery values.

In figure 4.20 is represented the distance travelled as well as velocity and acceleration profiles. From there we can get the total distance of 142 889 km from SOC of 100 % to 6.33 %. Extrapolating one gets the total range for the vehicle simulated in NEDC of 152 545 km. Although the result for consumption is very close, the result for range calculated is 152 km and the announced by Nissan [20] is 199 km. The calculated value is almost 25 % less than the one announced.

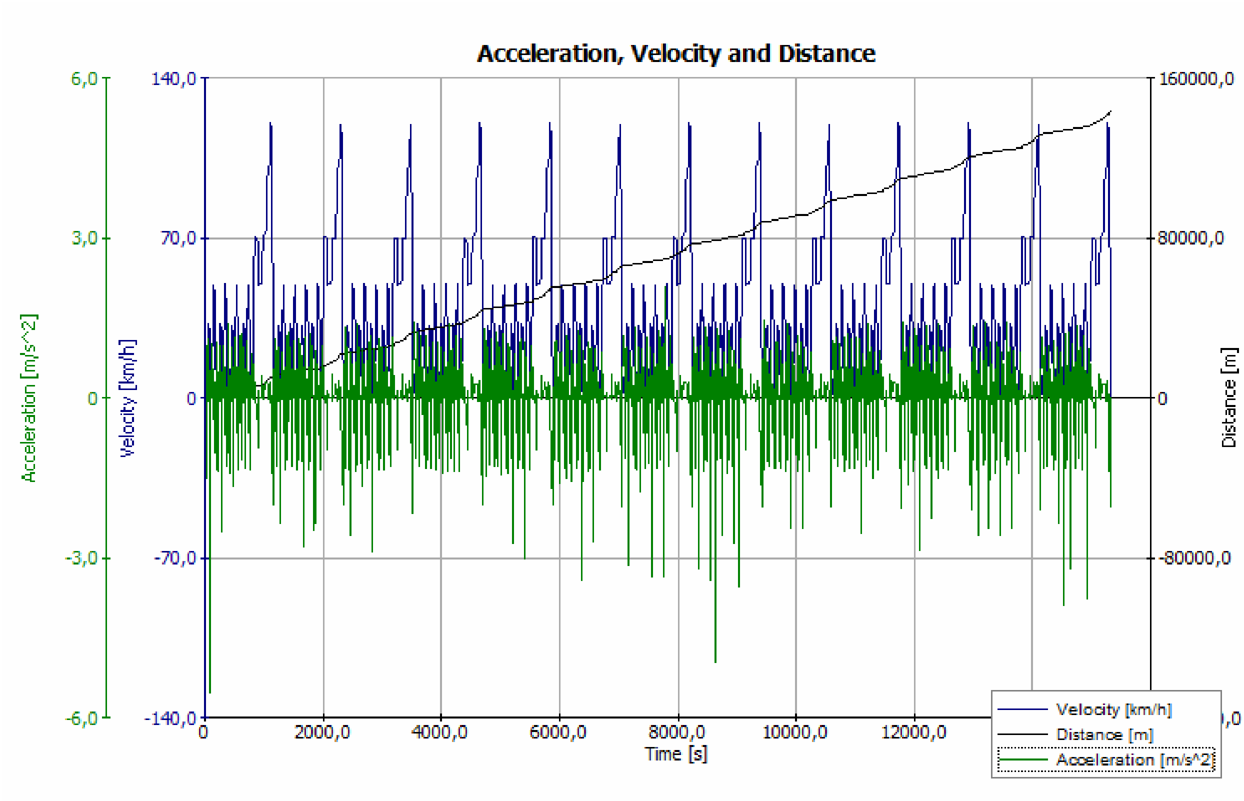


Figure 4.20 - Velocity, acceleration and distance travelled for multiple NEDC complete runs.

4.4.1.2 NEDC with air-conditioning system

The results presented here are merely informative since there is no results published from vehicles companies with the influence of air-conditioning system in NEDC. The conditions set were ambient temperature of 35 ºC and a target cabin temperature of 22 ºC. The objective is to compare with the values obtained in 4.4.1.1 and see how much does air-conditioning system impacts consumption and range.

Figure 4.21 represents the battery performance for NEDC with air-conditioning on, the cycle was only run a single time because the simulation method quasi stationary 2 (necessary for KULI interface) does not allow a simulation with SOC target which was done previously on the simulation of NEDC without air-conditioning system. The consumption calculated was 19.86 kWh/100 km which is much greater than the determined without A/C (15.19 kWh/100 km). This means that in the simulated performed air-conditioning system starting at a temperature of 35 ºC has a huge impact in consumption at its impact is close to 31 %. To calculate the total range, an extrapolation was made using the final SOC of 90.9 % for a single cycle.

Using the distance of 11.013 km for a single NEDC one gets a value for range of approximately 121 km (which is not true and with this simulation one got less consumption values when SOC tend to 0, though is an approximation by excess).

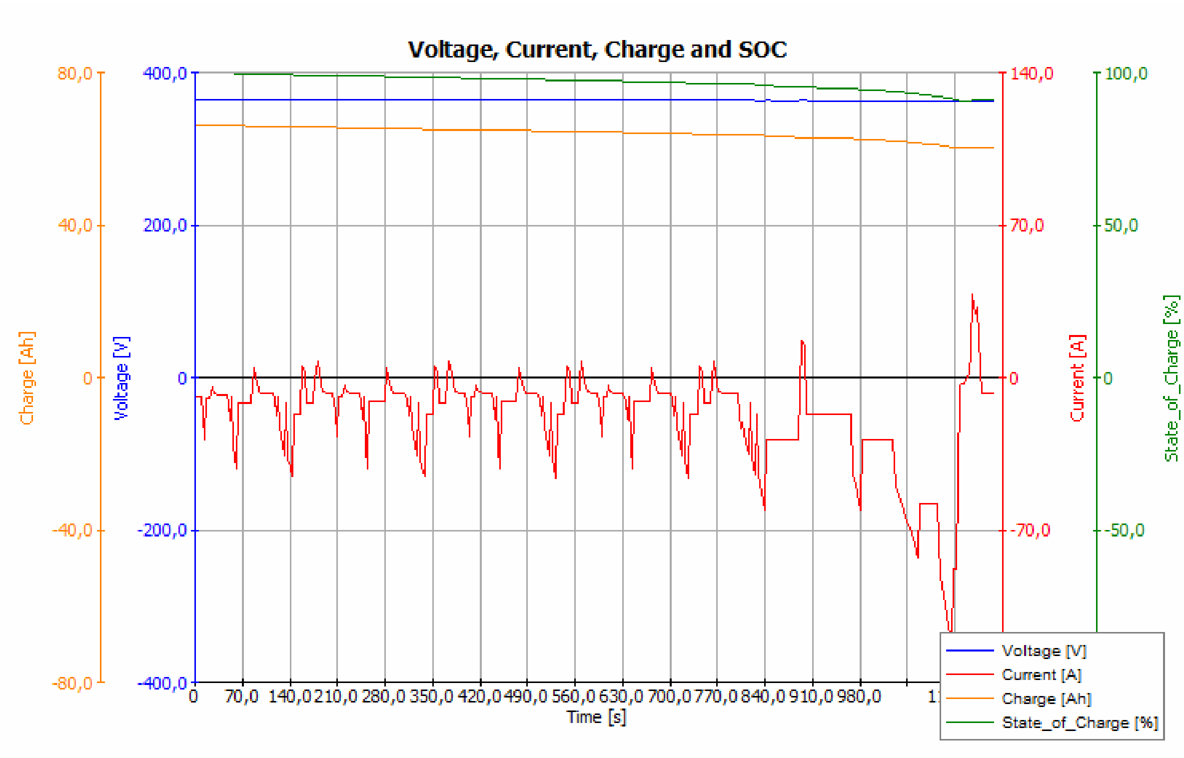


Figure 4.21 - High voltage battery results for NEDC with A/C on.

4.4.2 World harmonized Light vehicle Test Procedure (WLTP)

4.2.2.1 WLTP without air-conditioning system

For WLTP, the test cycle is described in 3.3.3. The simulation without air-conditioning is performed in AVL Cruise and the simulation conditions are described in 3.2.1.

In fig. 4.22 is represented the driving cycle WLTC which AVL Cruise can simulate faithfully to the actual cycle presented in 3.3.3. For this single cycle run the consumption was 16.39 kWh/100 km. Battery performance is showed in fig.4.23 where results for voltage, current charge and SOC are presented. As expected the battery drains much faster for the high speed cycle which in this figure can be identified by the large slope in SOC and the large values (in module) of current.

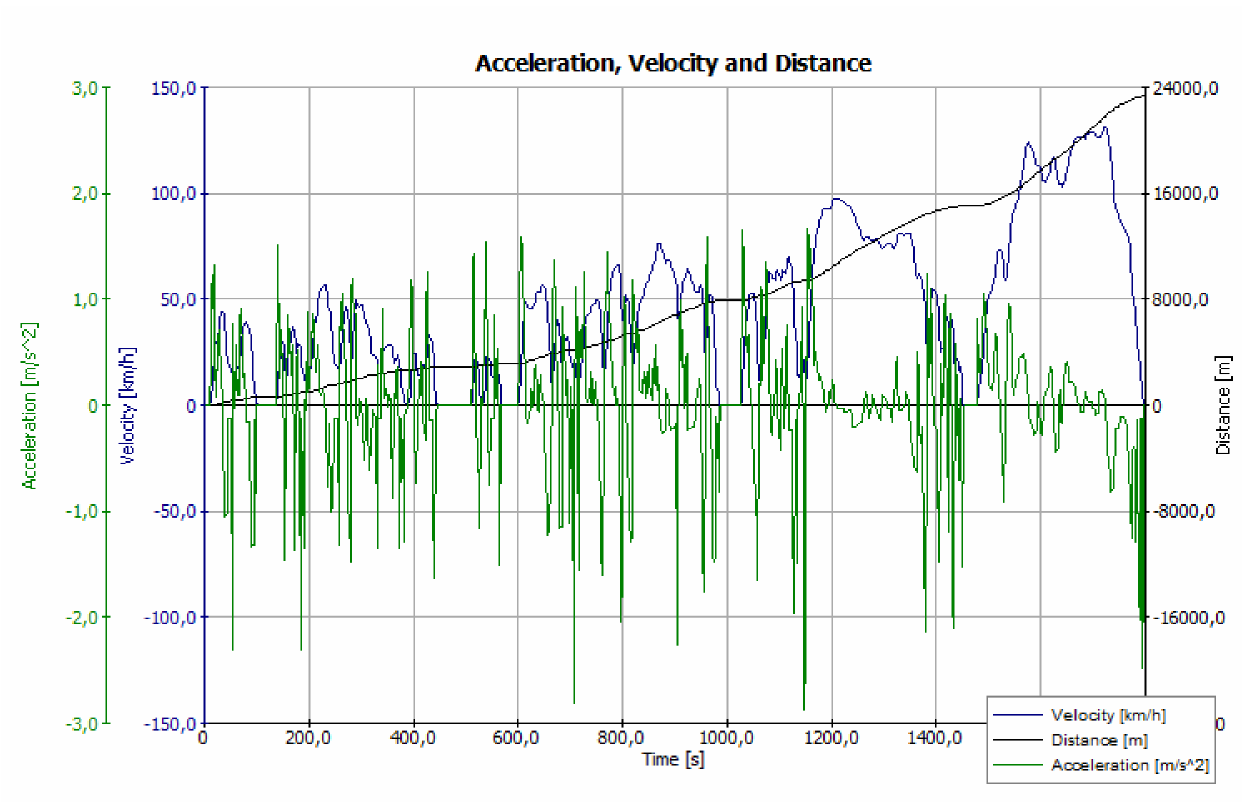


Figure 4.22 - Acceleration, velocity and distance of a single World harmonized Light vehicle Test Cycle (WLTC).

For calculation of vehicle range, one performed a calculation task in AVL Cruise using a SOC target of 0 % starting at 100 %, determined the travelled distance and extrapolated for the percentage of SOC left. The calculation stops when the SOC is not able to run a complete WLTC. The results for battery performance for a full discharge are presented in fig. 4.24.

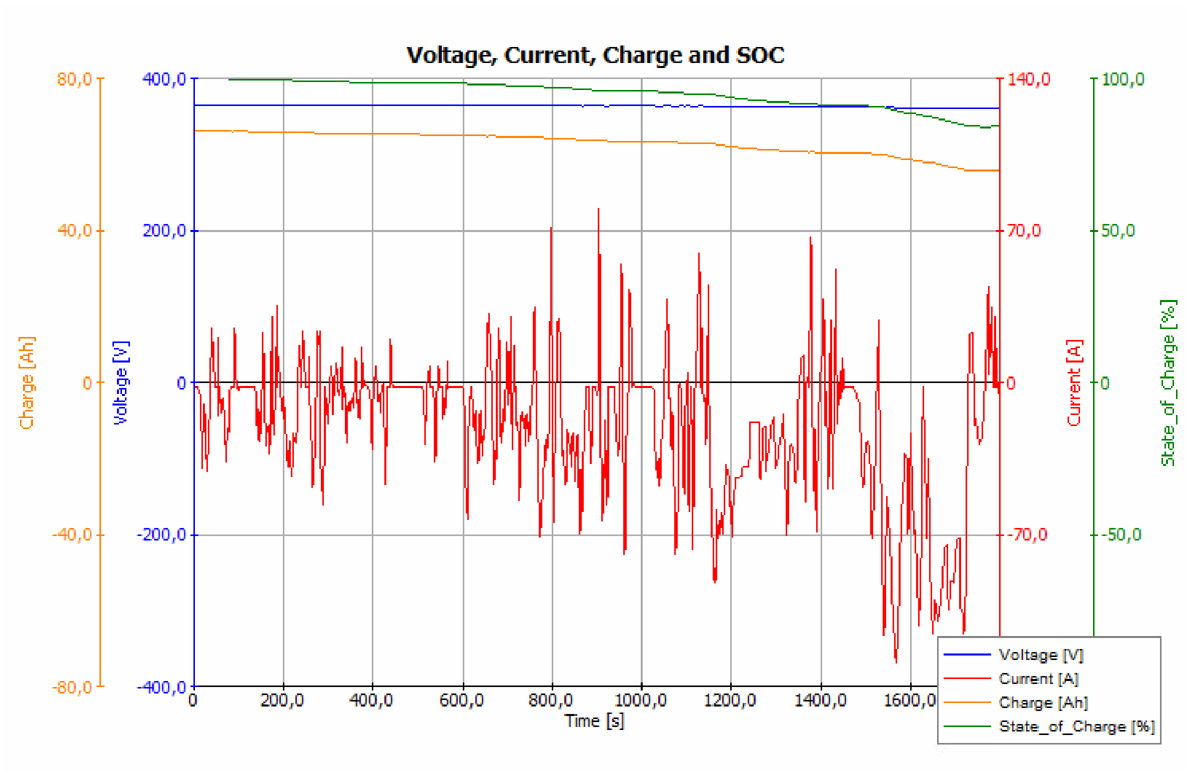


Figure 4.23 - High voltage battery results for a single WLTC.

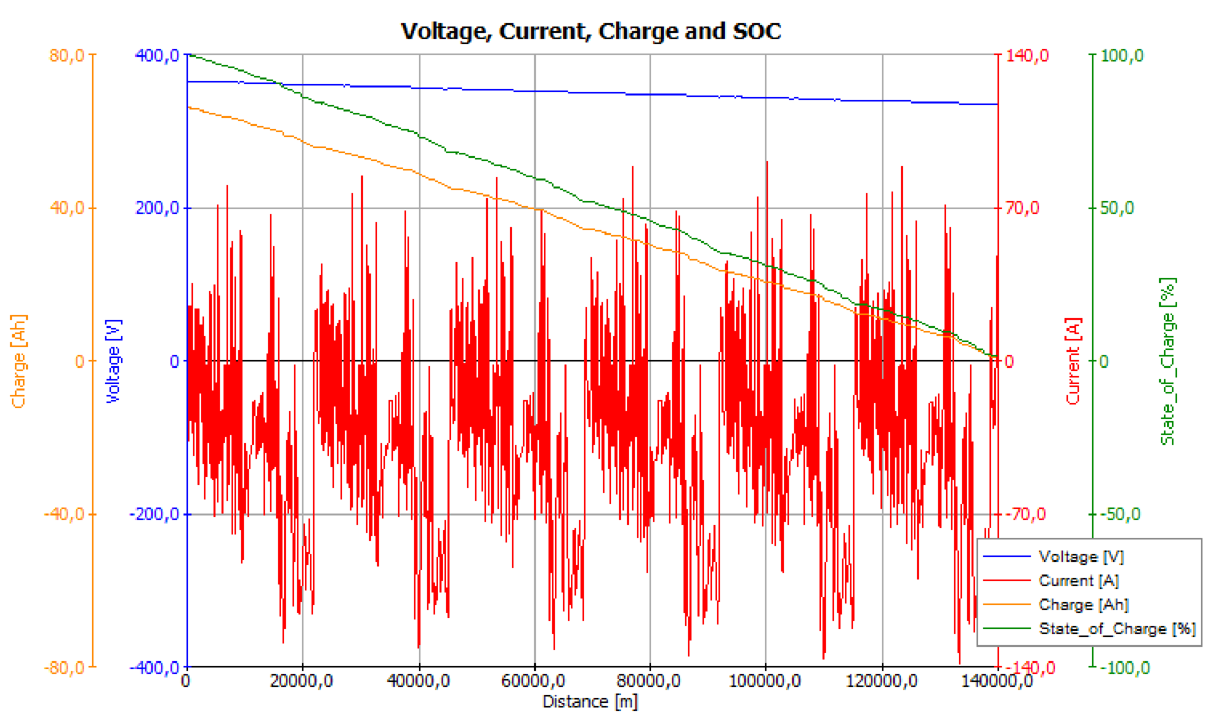


Figure 4.24 - High voltage battery performance running multiple WLTC driving cycles until full depletion.

From SOC 100 % to 1.6 %, the vehicle model was able to complete 6 full WLTC driving cycles with a total range of 139.9 km and a mean consumption of 16.27 kWh/100 km. Extrapolating for the last 1.6 % one gets a total range of approximately 142 km.

Comparing with the results for NEDC, there is an increase in consumption as expected but only around 1kWh/100km, and thus there is a slightly decrease in range calculated. For NEDC one calculated 152 km and for WLTC 142 km. The difference is not big for the values calculated. However, the announced value for Nissan Leaf in NEDC is 199 km which makes a difference in values of 28.6 %. In this vehicle model one did not get a close value for range in NEDC vs calculated, although the value for energy consumption was very similar (difference of 0.19 kWh/100 km).

4.2.2.2 WLTP with air-conditioning system

The World harmonized Light vehicle Test cycle, which its velocity profile is represented in fig. 4.25, was simulated with the model developed for air-conditioning system. During a single simulation of the driving cycle, the total consumption was 4.692 kWh with a travelled distance of 23.26 km which represents a mean consumption value of 20.17 kWh/100 km.

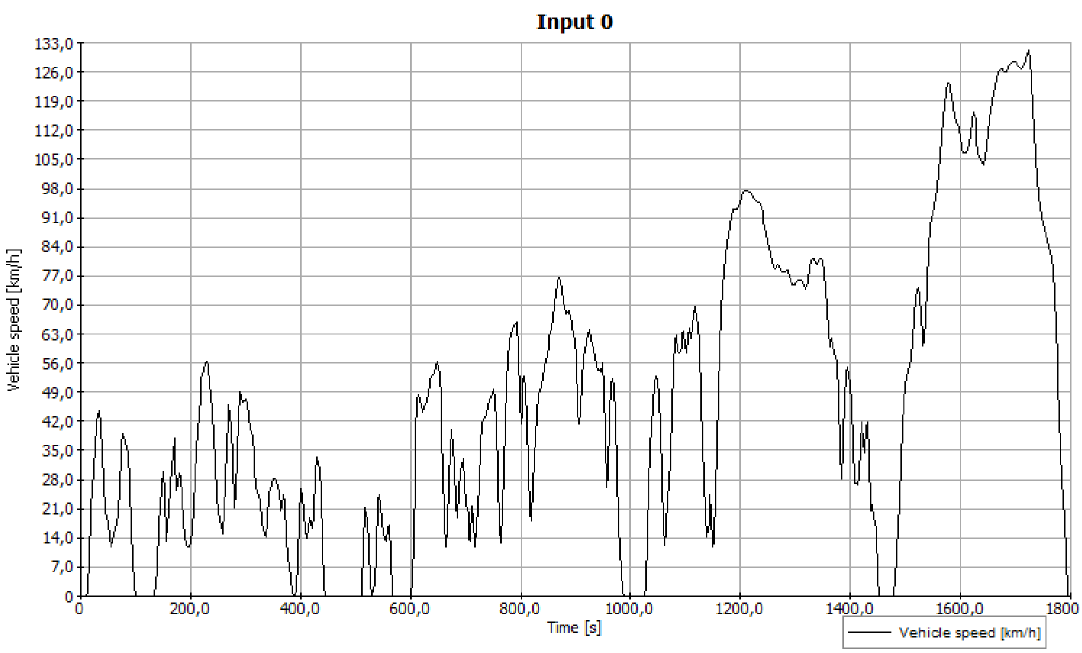


Figure 4.25 - Velocity profile of a World harmonized Light vehicle Test Cycle (WLTC).

The initial SOC was 100 % and the final SOC value was 80.4 %. High voltage battery results for a single cycle are presented in fig. 4.26. Fig. 4.27 represent the compressor values for power, torque and speed during the simulation of WLTC with A/C on. Doing an extrapolation, assuming that all the cycles until battery depletion have the same value of consumption (which is not true and with this simulation one got less consumption values when SOC tend to 0, though is an approximation by excess) the value for range obtained is 118.7 km.

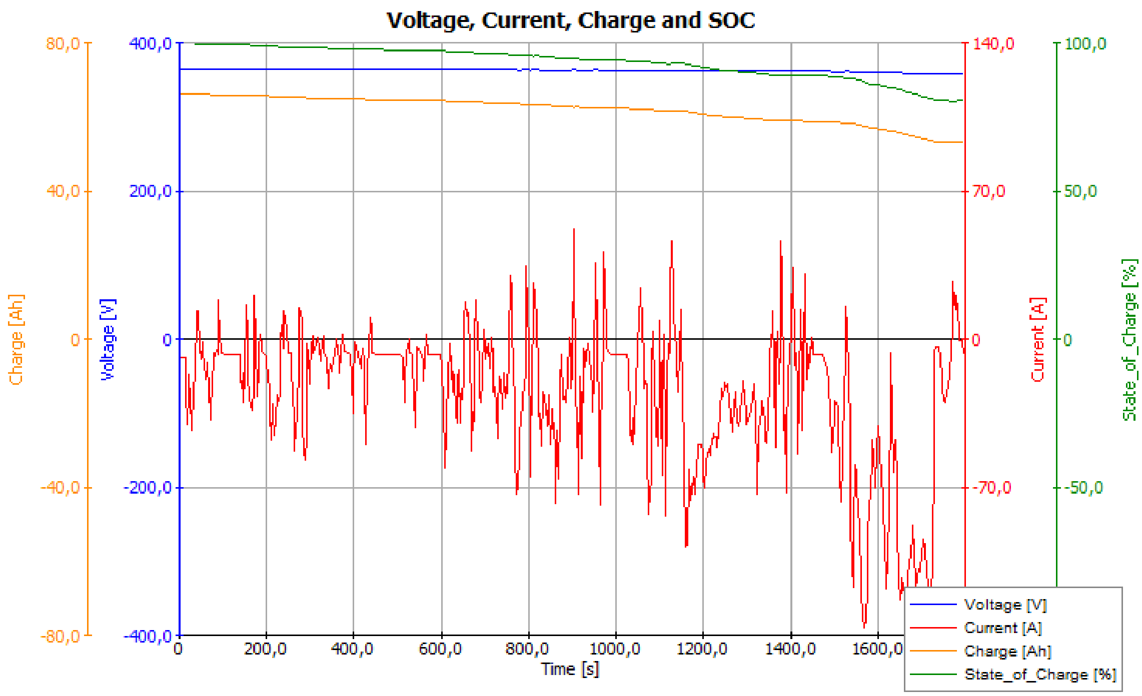


Figure 4.26 - High voltage battery results for WLTC with A/C module.

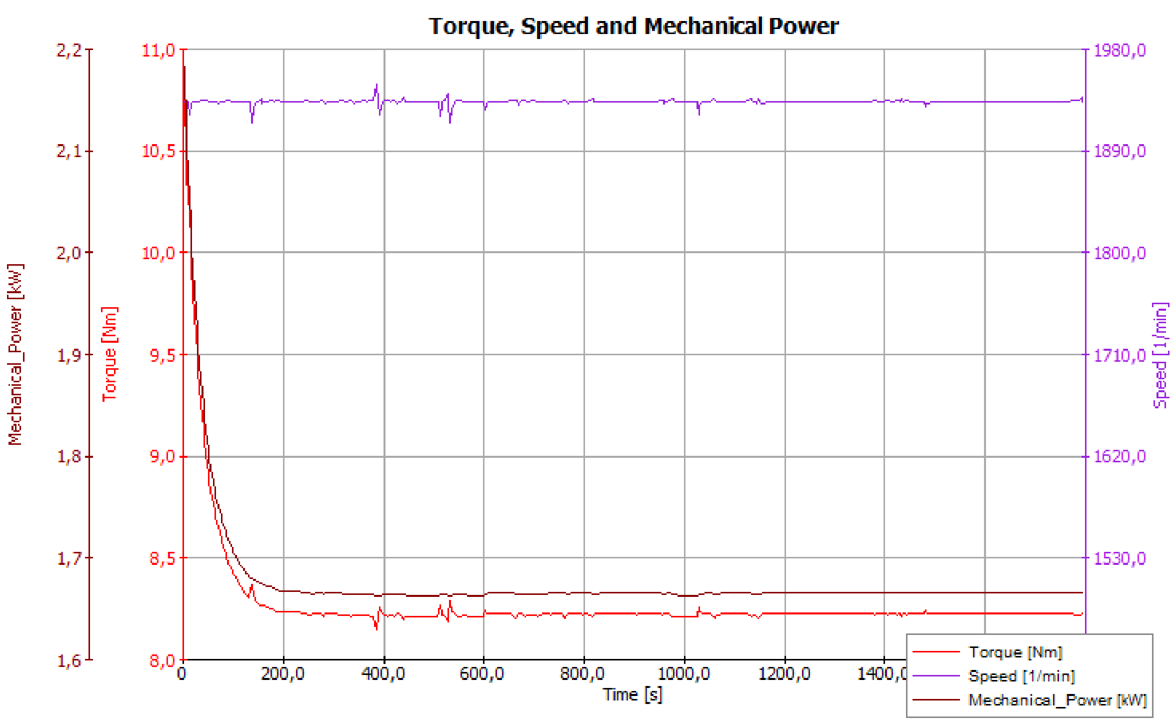


Figure 4.27 - Results for power, torque and speed for electric machine that powers compressor for WLTC with A/C on.

4.4.3 Discussion

A final comparison between vehicle range with and without air-conditioning system for all driving schedules simulated is presented in table 4.11.

There is a decrease in vehicle range for all driving schedules (as expected) and those increases are higher in driving schedules that try to replicate urban conditions such as UDDS, part of NEDC and part of WLTC. UDDS is the driving schedule with the biggest impact of air-conditioning system which can decrease the range in 25 %. In a global way, air-conditioning system can decrease the range of the electric vehicle in 12 to 25 %.

Table 4.11 - Results for range for all driving schedules simulated.

Driving Schedule	***Range without A/C [km]***	***Range with A/C [km]***	***Difference [%]***
NEDC	152	121	20.4
UDDS	174	130.2	25.2
HWFET	150.9	132.6	12.4
US06	120.2	97.4	19
SC03	-	125.2	-
WLTC	142	118.7	16.4

5 Conclusion

In the last decades, a concerning about pollution has been growing. With the increase in population and in a need for transportation and mobility, the number of used vehicles in the world rapidly increased. With that grown quickly came the concern for the human being in term of hazardous emissions namely CO_2 which contributes to global warming and NO_x gases which are toxic to the human being. A series of measures has been undertaken by vehicle manufacturers and in the top of those measures are included hybrid vehicles and battery electric vehicles. With the crescent concerning, European commission decided at May 2017 that after September 2019 all new vehicles have to pass the new World harmonized Light vehicle Test Procedure (WLTP) in order to be homologated in European Union.

In this work it was study the influence of air-conditioning in electric vehicles consumption and range for New European Driving Cycle (NEDC), Environmental Protection Agency of United States (EPA) Driving Schedules and for the new World harmonized Light vehicle driving Schedule (WLTP).

The definition of the model was initially done with AVL Cruise software which is a very good tool to model the vehicle and results were obtained in terms of electricity consumption and range. Starting with the definition of the vehicle based in Nissan Leaf 2013 and tried to replicate the results obtained experimentally in NEDC by Nissan itself and the results obtained by INL and ANL in track and dynamometer results. The first results obtained in terms of coasting test, acceleration maximum speed and some cycle runs were used to calibrate the model and one got close results.

For NEDC the consumption simulated in AVL Cruise is 0.19 kWh /100 km greater than the value announced by Nissan. In terms of maximum speed, acceleration and peak power from the battery the results are close to the measured by INL. In EPA driving schedules the results for consumption were also close with 5.4% increase for UDDS, 2.3 % increase for HWFET and a decrease of 4 % for US06. For range one got a decrease of 2.5 % in UDDS and increases of 1.1% in HWFET and 9.5 % in US06.

In order to simulate air-conditioning system, one had to find other software because it is not possible with AVL Cruise alone. KULI developed by MAGNA was the software chosen due to its already implemented interface in AVL Cruise. KULI is a very complex and complete software which allows to change many parameters from geometry of the components to almost every design parameter. With the model developed, the consumption results obtained with air-conditioning system were slightly higher, in the same line as before, than the results published (3.9 % for UDDS, 3.3 % for HWFET, 6.3 % for US06 and 2.8 % for SC03).

At last, comparing results obtained during the simulation with and without A/C for all driving schedules and although the range without A/C is calculated at ambient temperature of 22.2 ºC and the range for air-conditioning system was calculated for moderately extreme conditions with 35 ºC with solar radiation, the results presented suggest that the air-conditioning system can impact from 12 % to 25 % in extreme conditions.

6 Future Work

With the new normative arriving and the need to pass WLTP test to homologate light vehicles in European Union an intense effort need to be made by manufacturers in their vehicles. That effort may include electric vehicles by the majority of car manufacturers and new electric vehicles to be developed need to respect normatives and it should be accounted all types of driving conditions and styles across all member states.

Simulation software companies should in the next years involve themselves in the electric vehicle development and try to accompany the changes, improving their algorithm in terms of new components and its influence in vehicle performance. And since the experimental simulation can be very costly while changing every parameter, numerical simulation may be the only available option.

It is also necessary to perform studies in what are the influences of the WLTP in electric vehicles in terms of what it accounts and what is does not, for example, influences on the battery for aggressive driving or for extreme cold or hot temperatures. A comparison between WLTC test cycle and real driving battery range should also be made in order to obtain real results.

Developments should be performed in terms of legislation to give to the user the real well-to-wheel emissions for every electric vehicle on each market based on electricity production style of each country in order to account real emission values for the test procedure, WLTP in European Union.

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Annexes

Annex A - Vehicle specifications

Vehicles dimensions are shown in the following figure and were estimated using known measures.

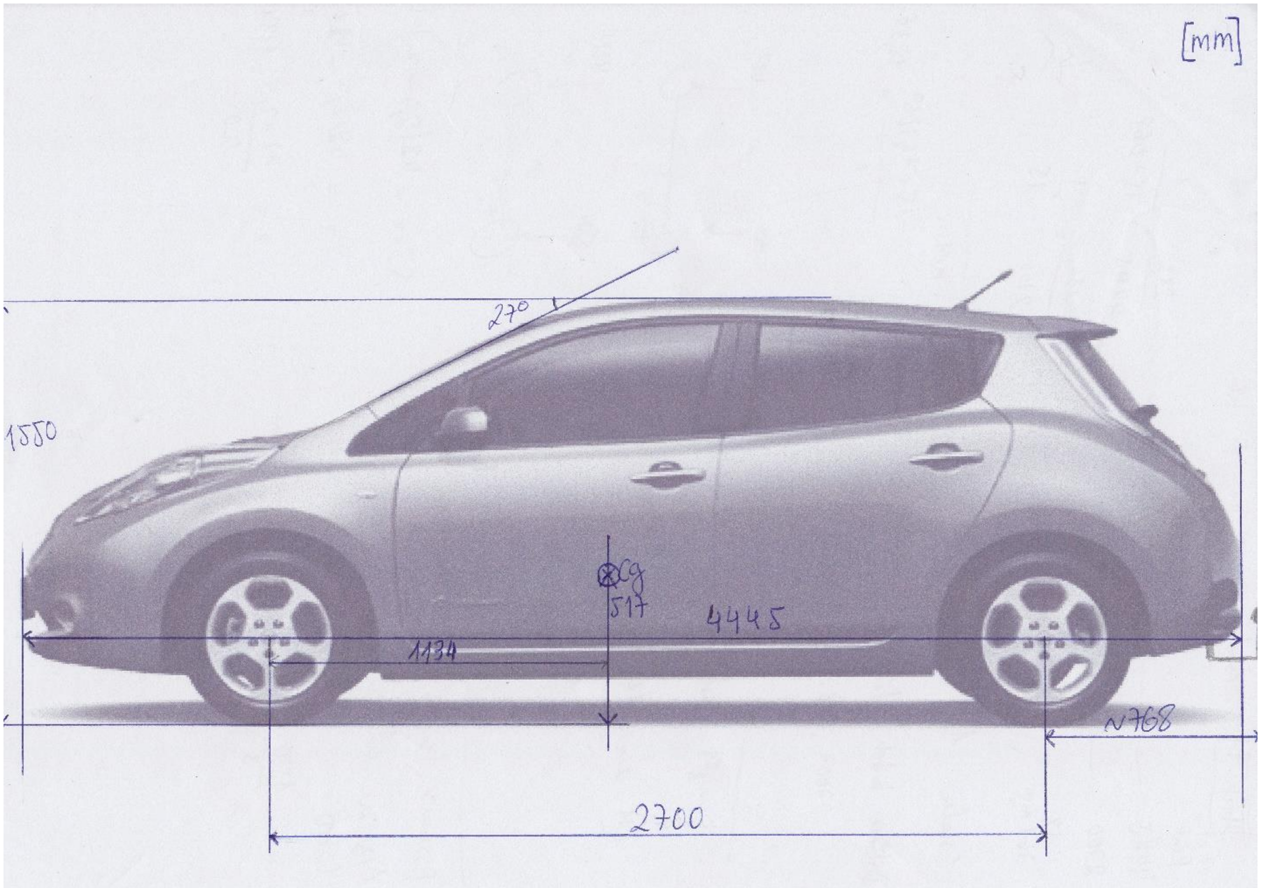

Figure A.1 - Nissan Leaf 2013 dimensions

Annex B – Input Data for AVL Cruise Modules

Here are presented some modules used in AVL Cruise

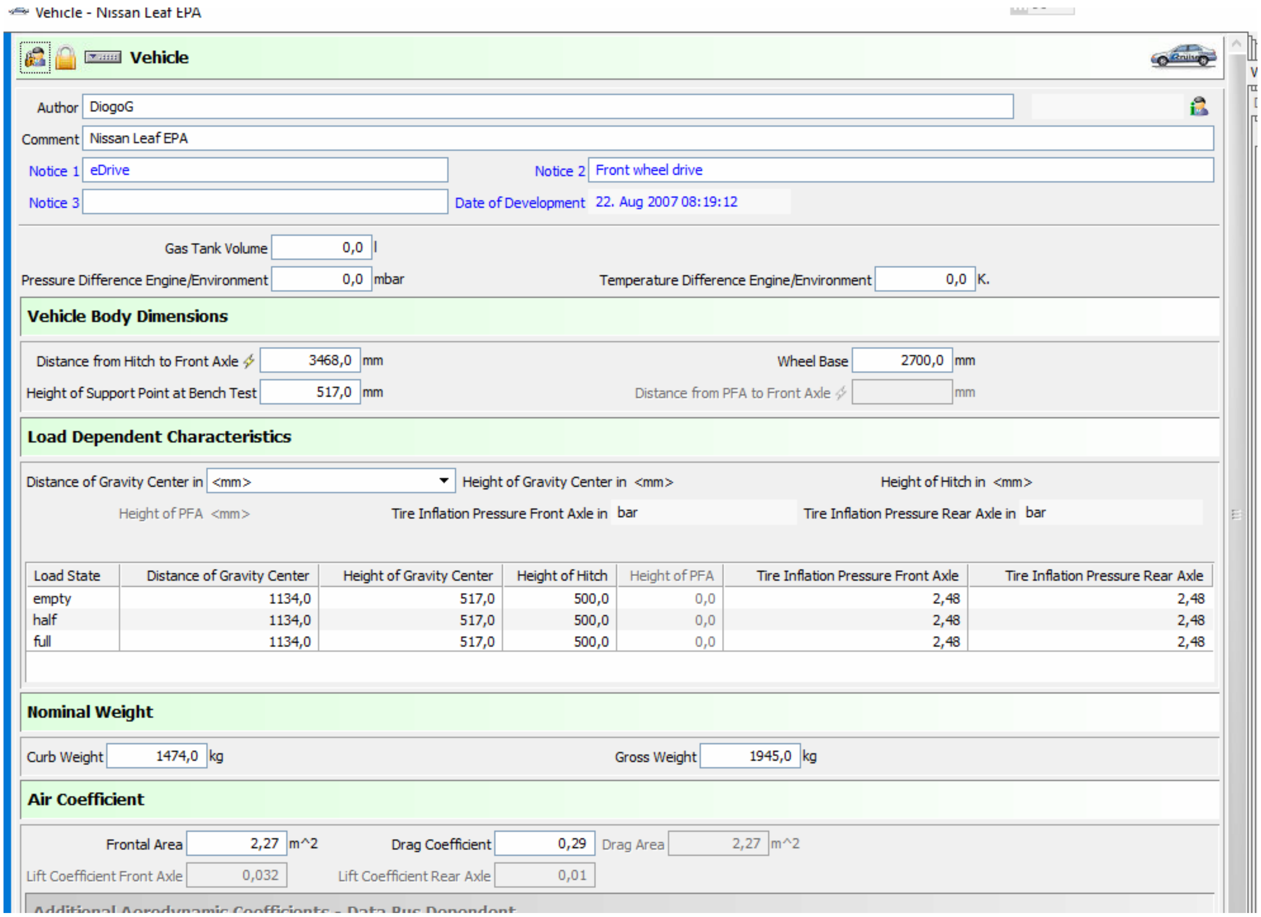

Figure B.1 - Vehicle module inputs.

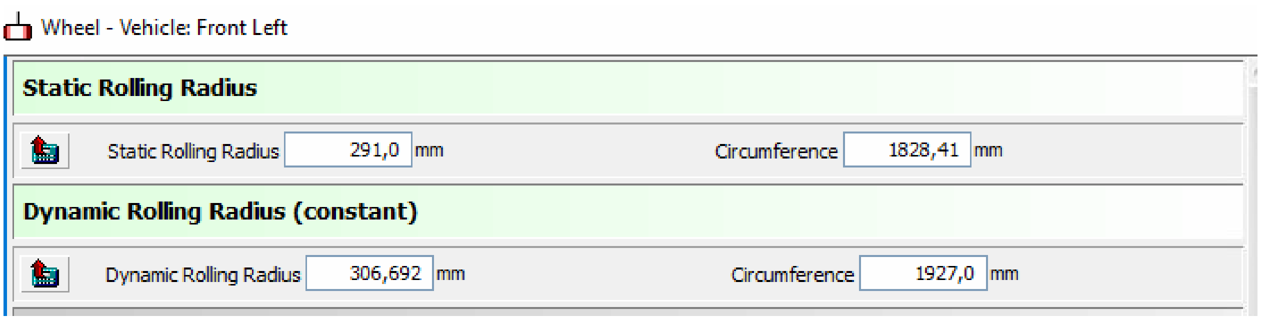

Figure B.2 - Wheel Rolling Radius input.

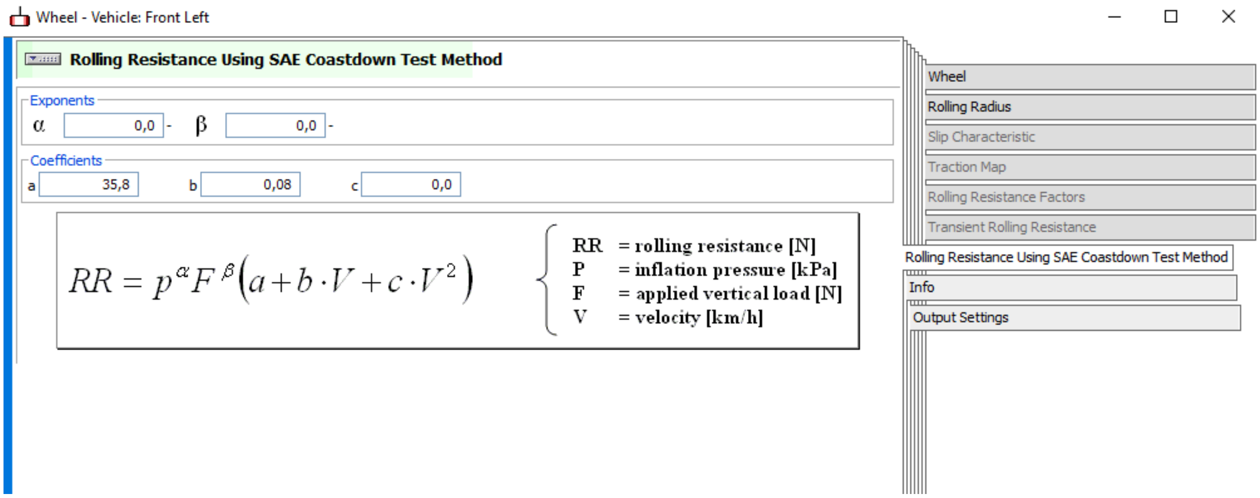

Figure B.3 – Wheel input for SAE Coastdown method.

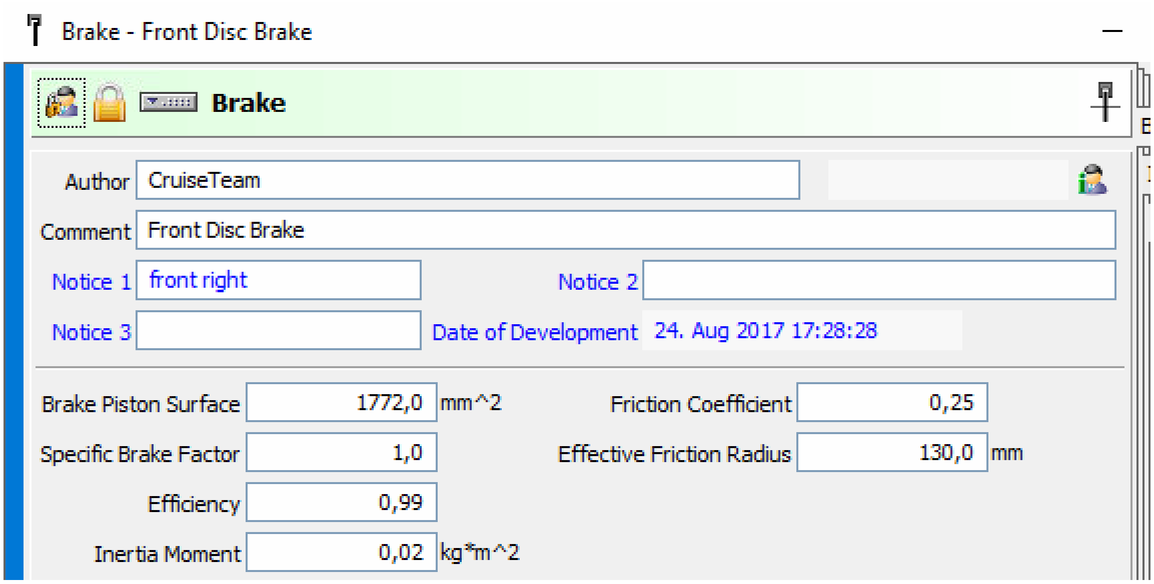

Figure B.4 - Brake module inputs.

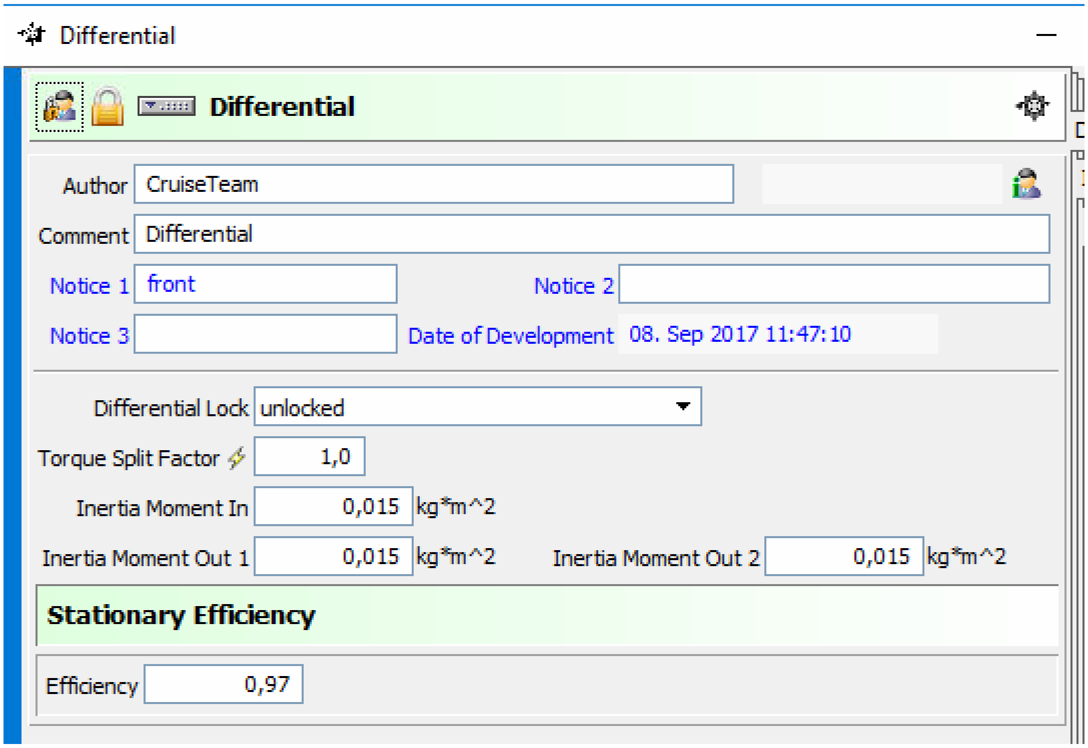

Figure B.5 - Differential module inputs.

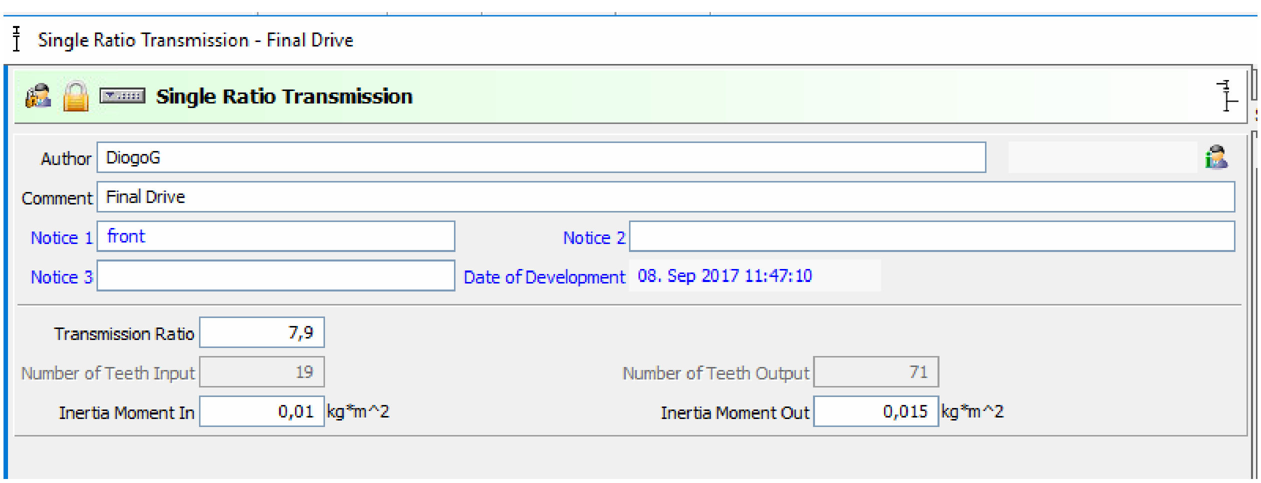

Figure B.6 - Transmission module input.

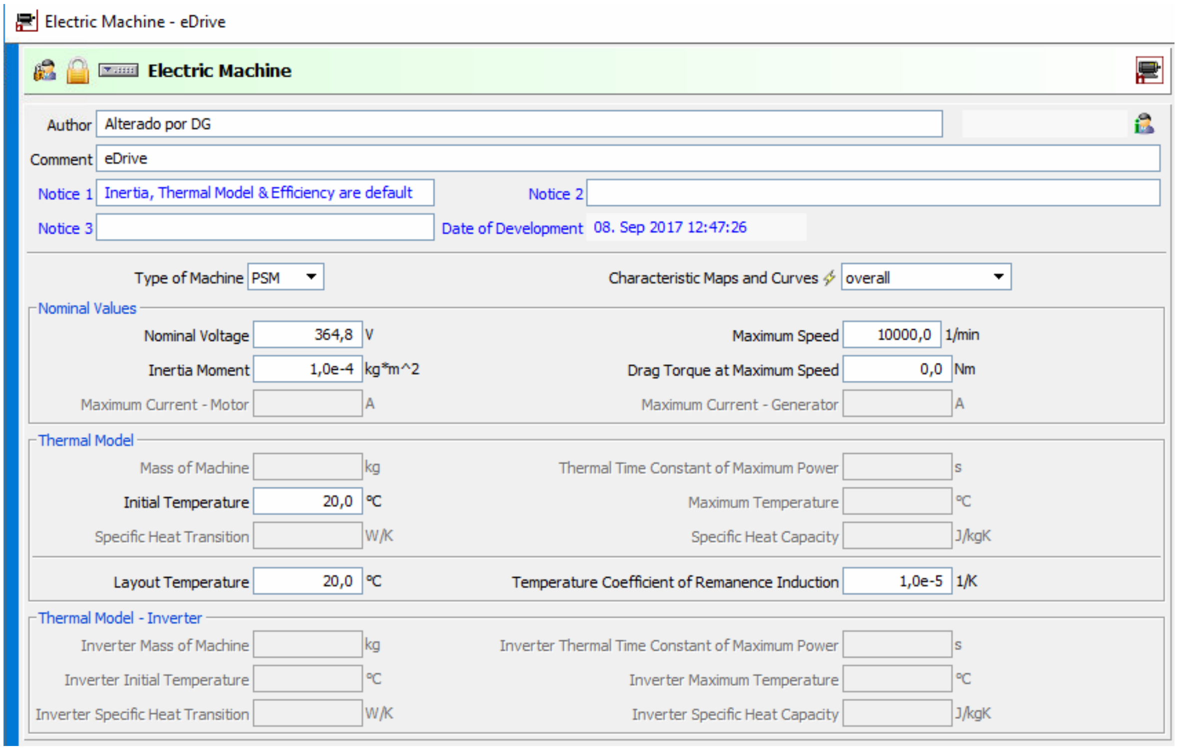

Figure B.7 - Electric machine module inputs.

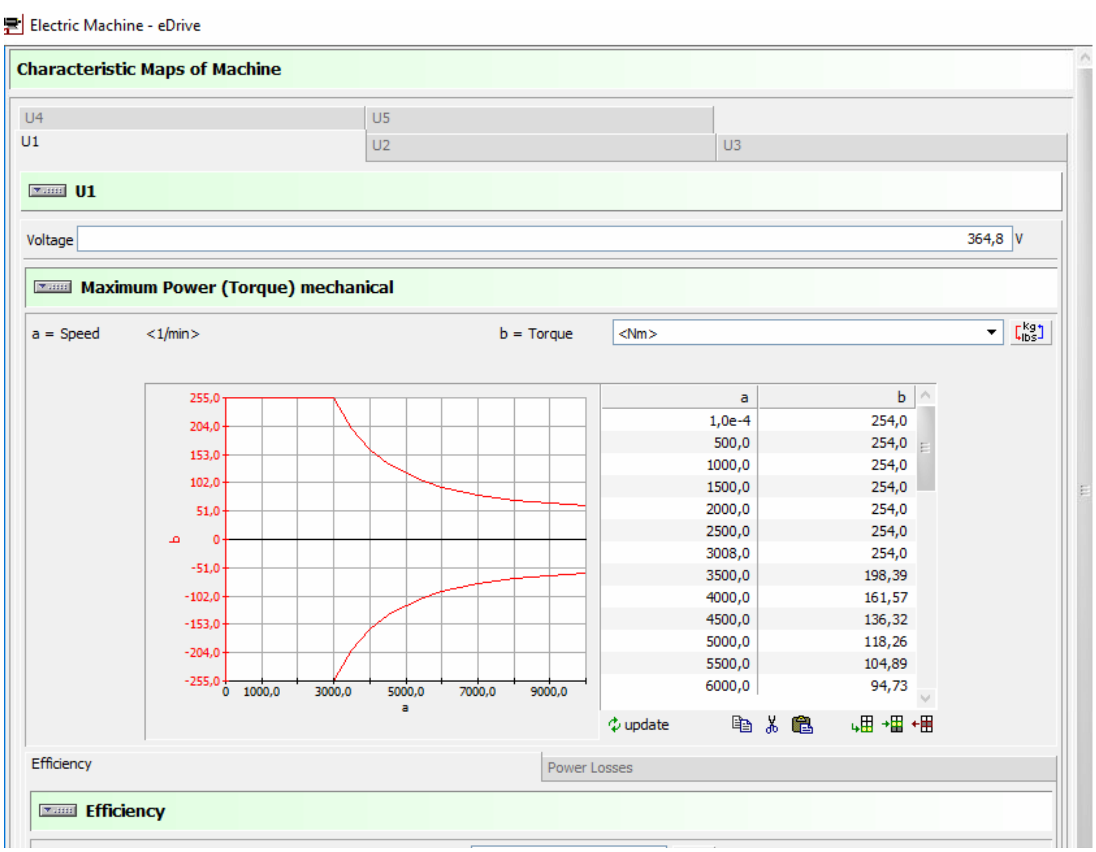

Figure B.8 - Electric machine torque map.

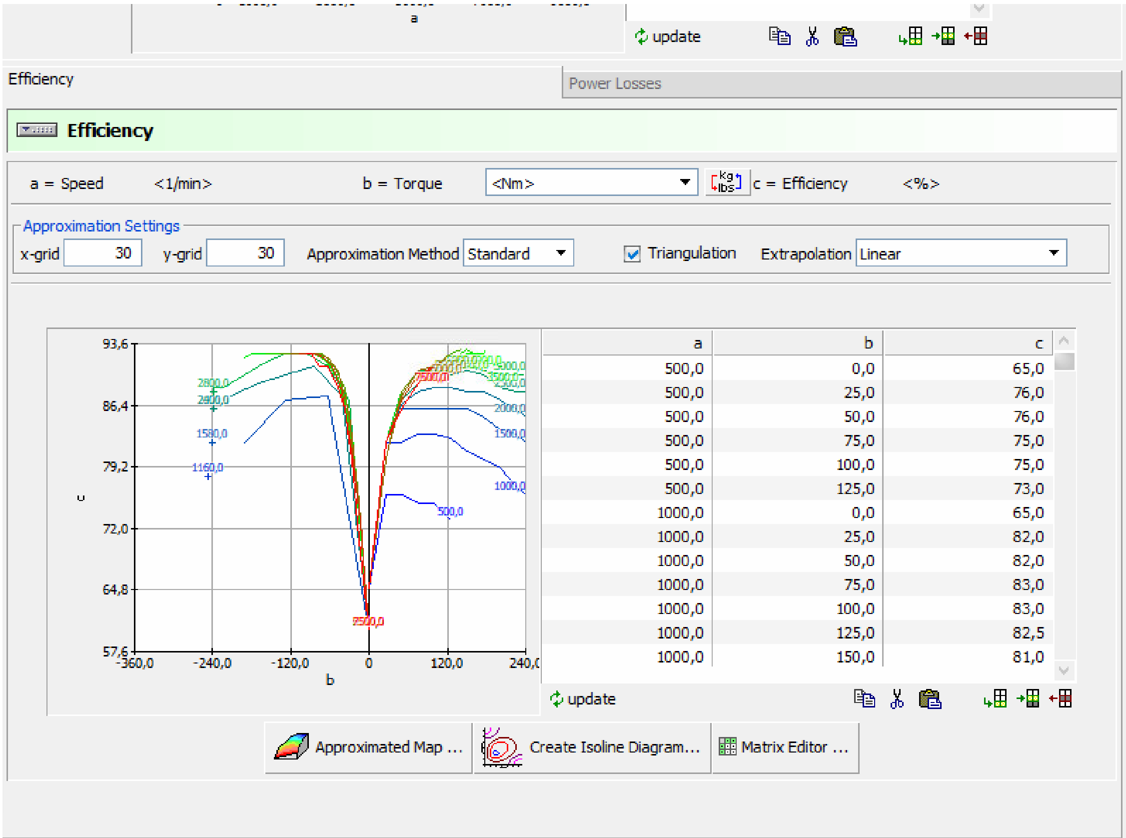

Figure B.9 - Electric machine efficiency map (developed by AVL Cruise).

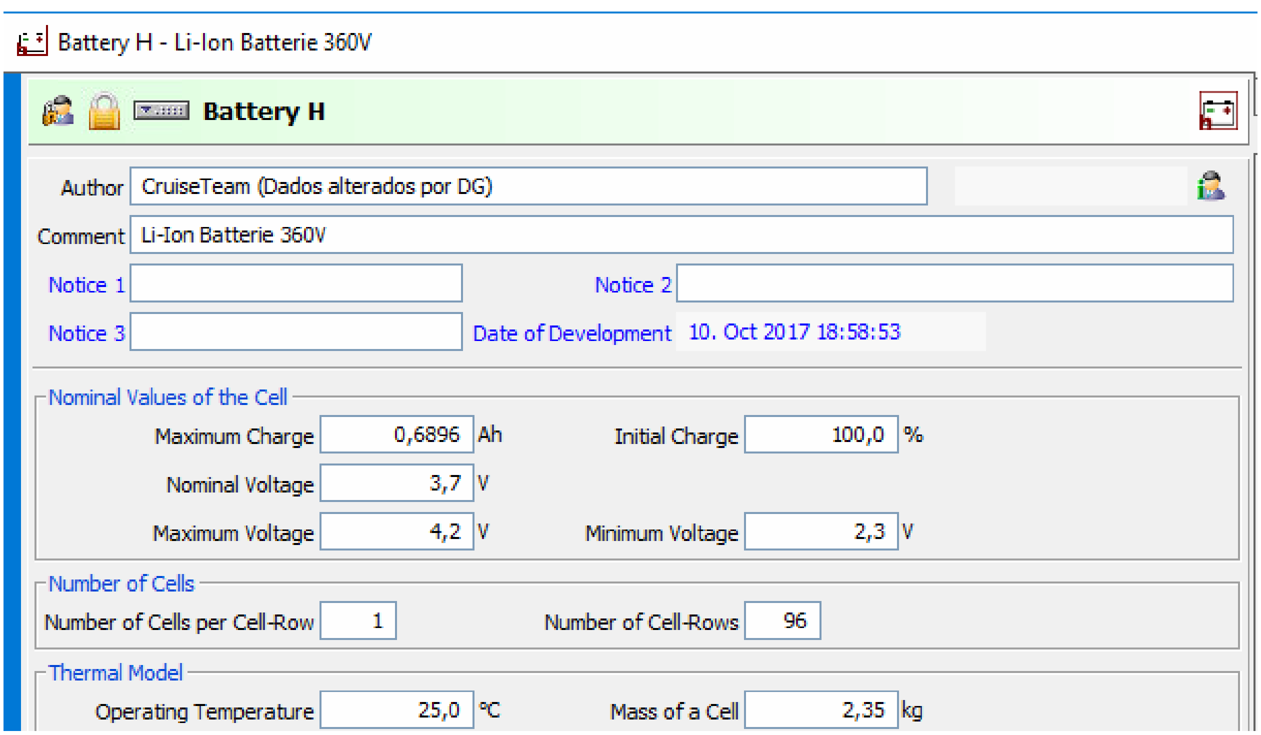

Figure B.10 - Battery module inputs.

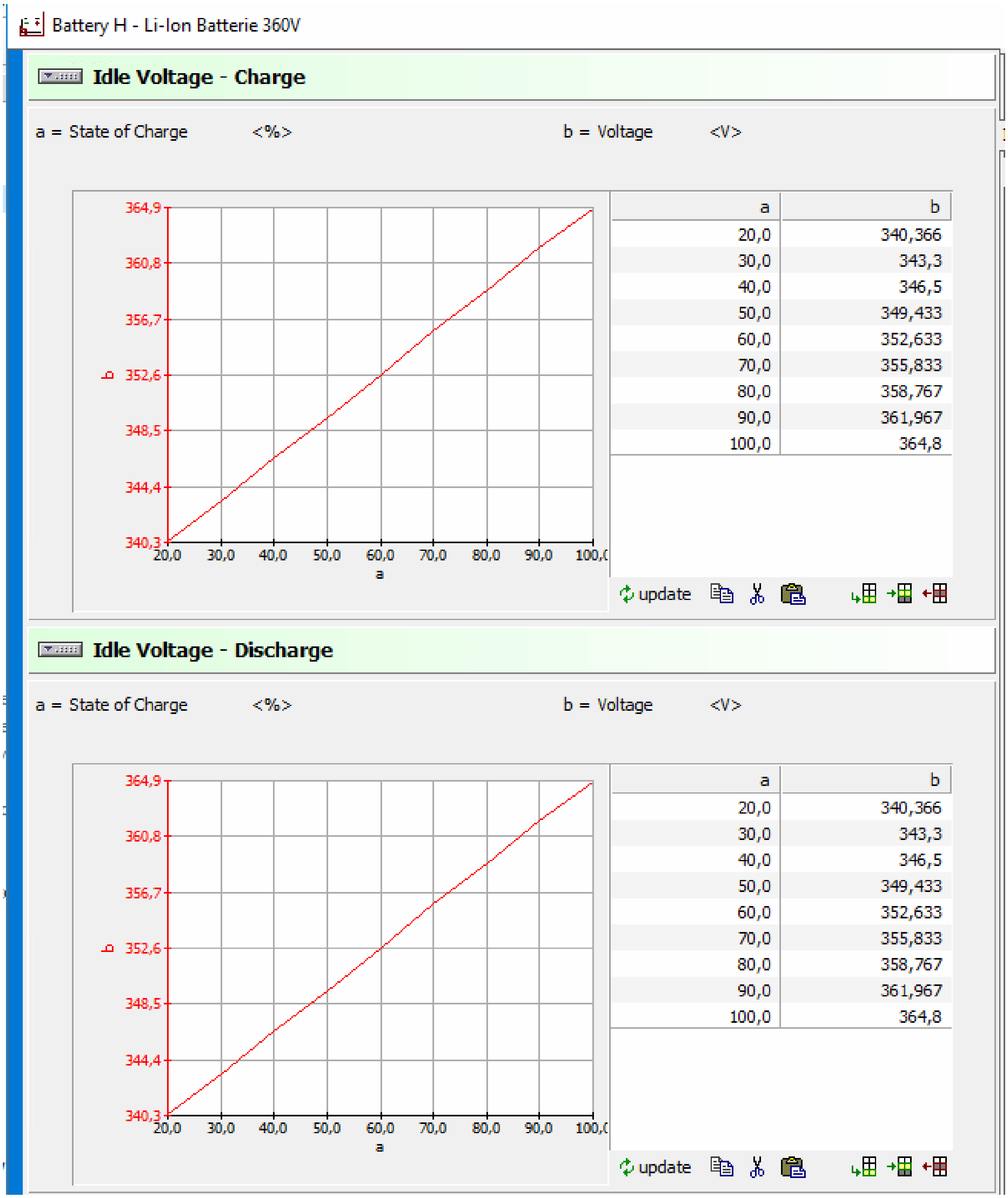

Figure B.11 - Battery values for idle voltage (developed by AVL Cruise).

Annex C – Input Data for KULI Modules

Figure C.1 to C.6 present the inputs for evaporator in KULI software in a model developed by KULI and demonstrates the complexity and the number of inputs available in KULI software.

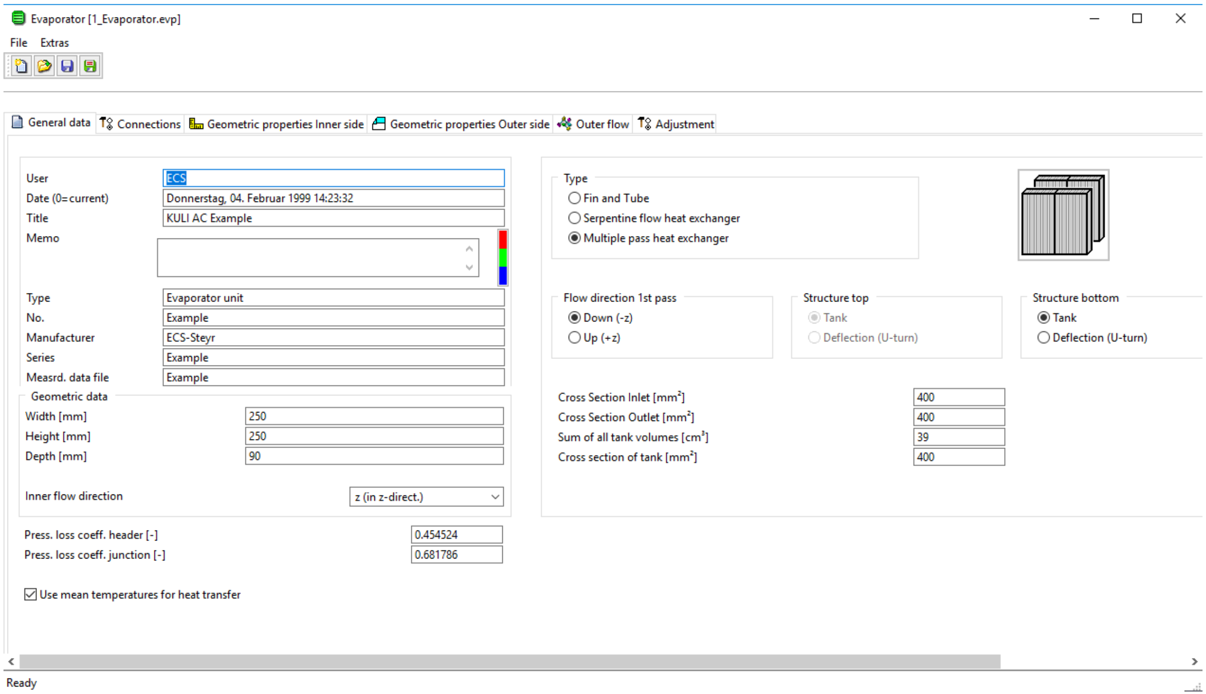

Figure C.1 - Evaporator general data in KULI.

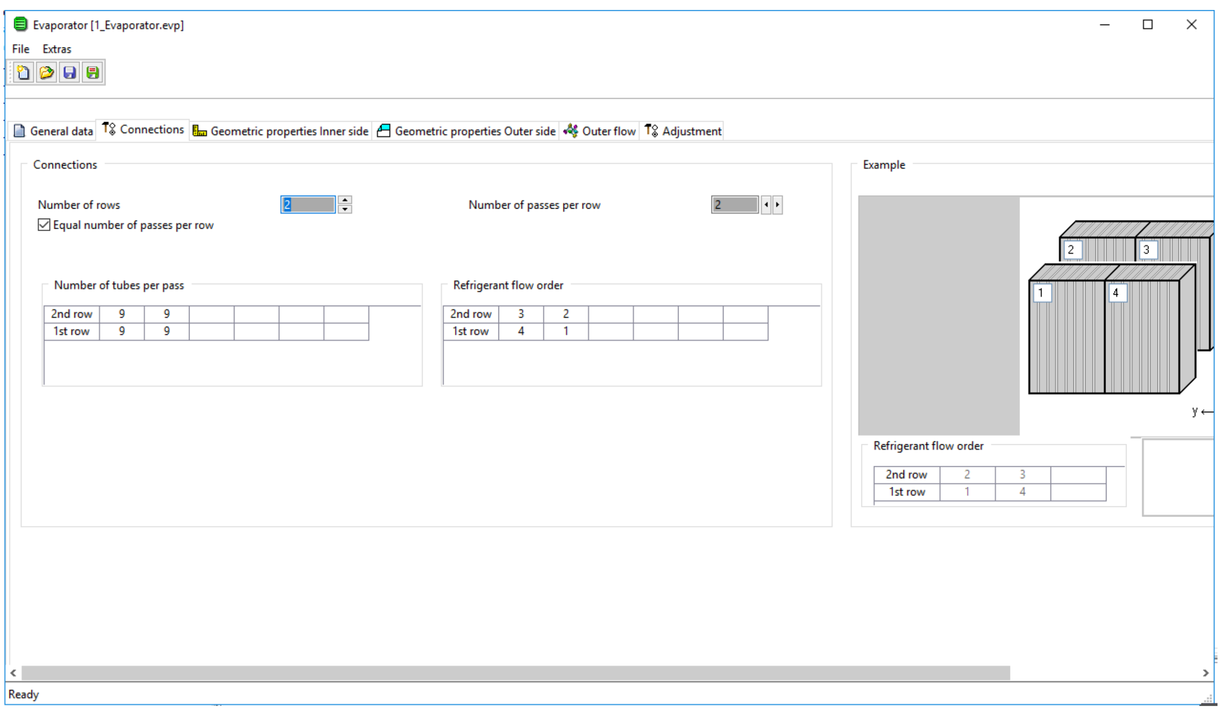

Figure C.2 - Evaporator connections input in KULI.

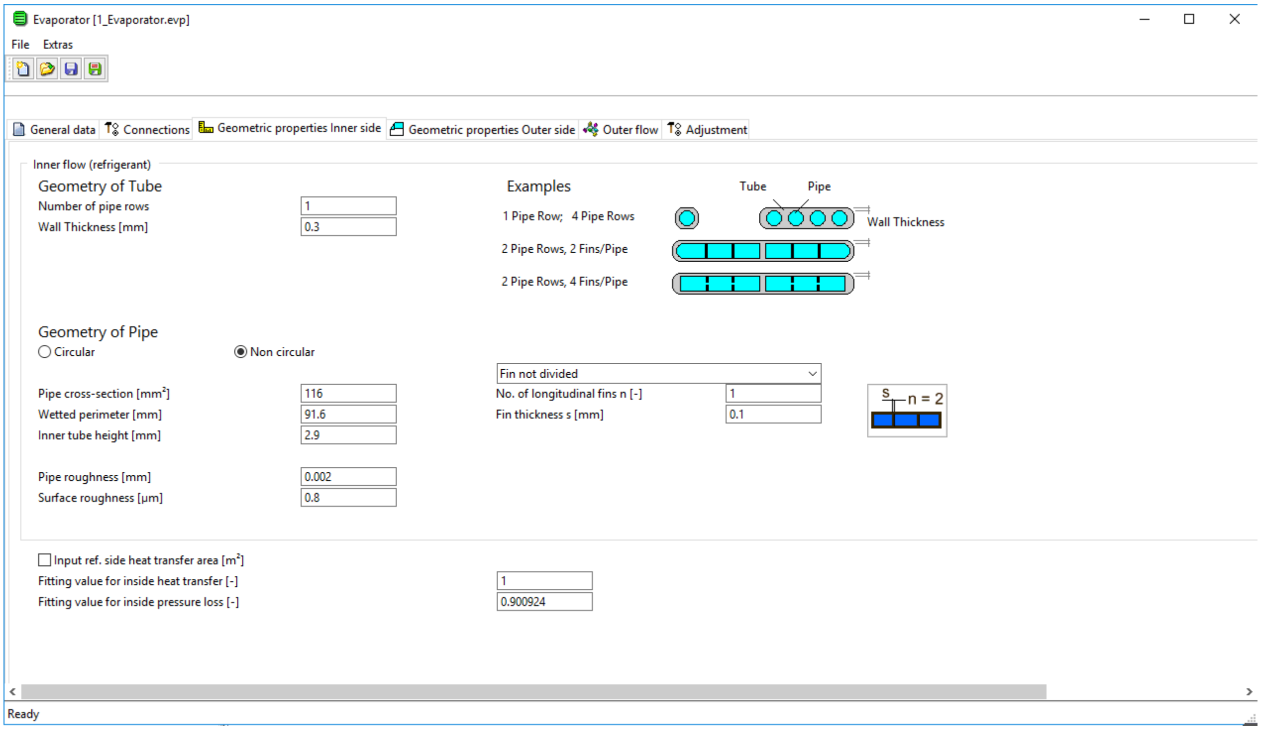

Figure C.3 - Evaporator geometric properties inner side inputs in KULI.

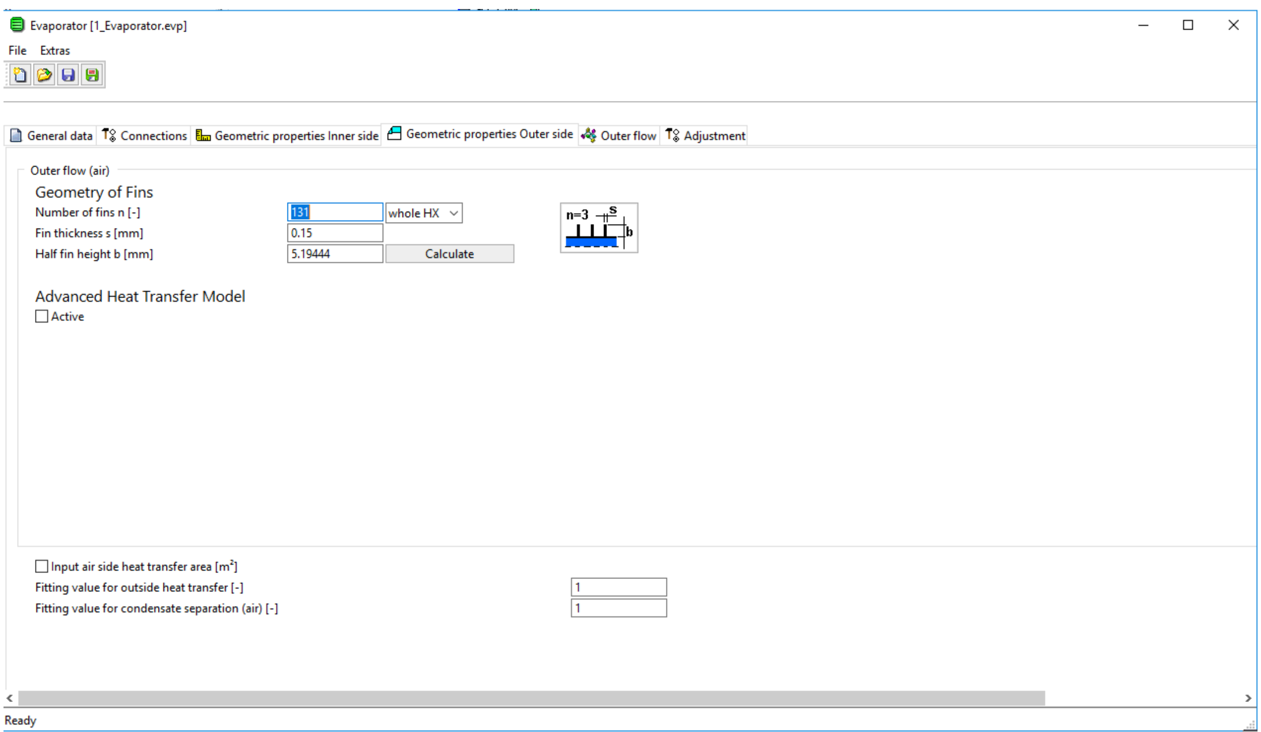

Figure C.4 - Evaporator geometric properties outer side inputs in KULI.

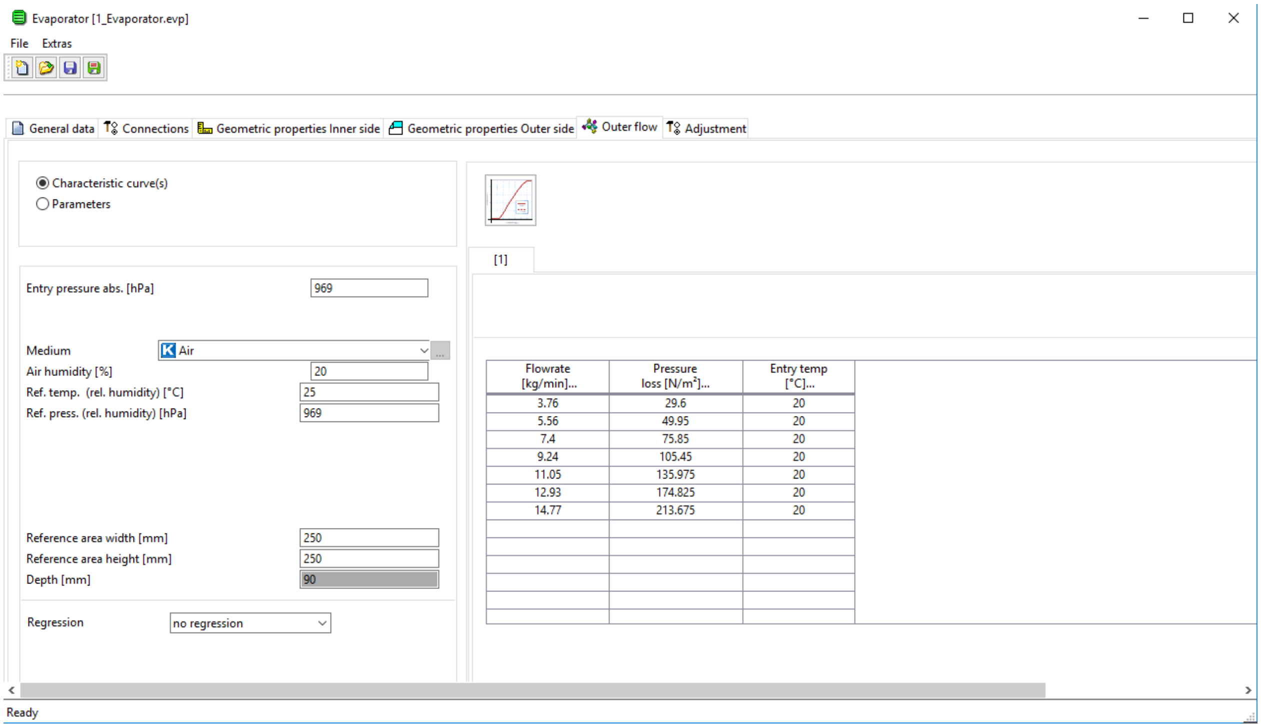

Figure C.5 - Evaporator outer flow inputs from KULI.

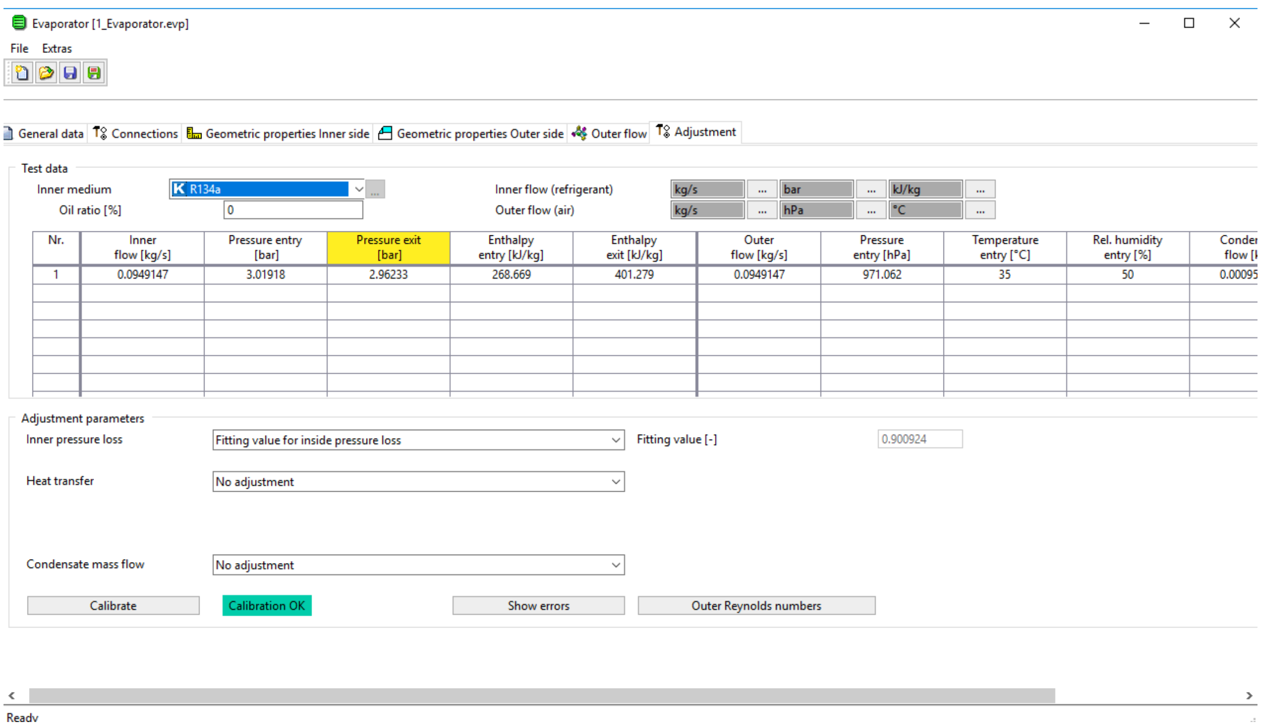

Figure C.6 - Evaporator adjustment inputs from KULI.

Annex D – Results for Driving Cycles

EPA Without Air-conditioning

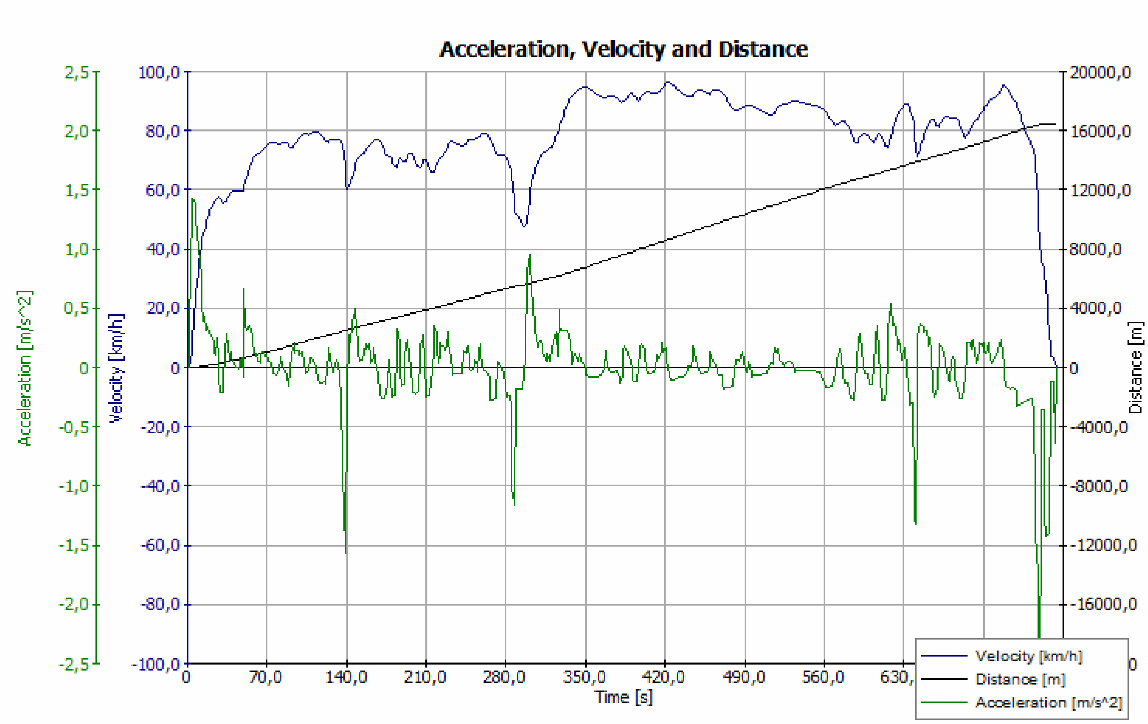

Figure D.1 - Acceleration, velocity and distance for first HWFET run, HWFET #1.

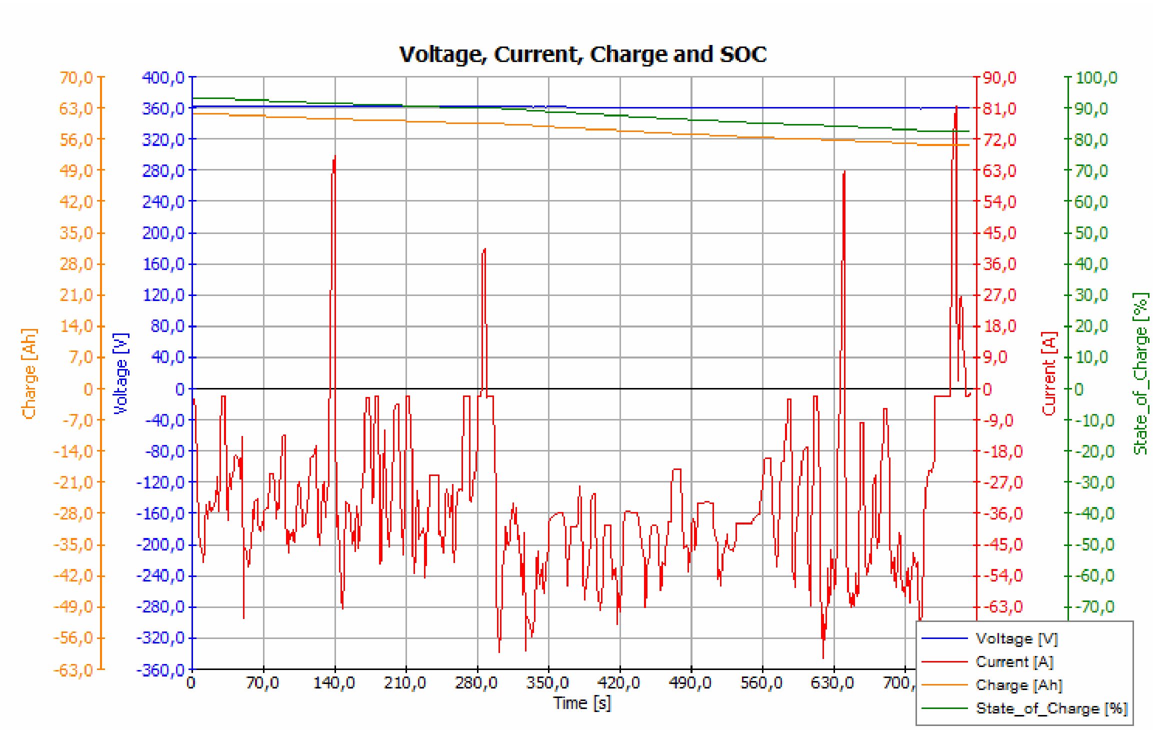

Figure D.2 - High voltage battery results for the first HWFET run, HWFET #1.

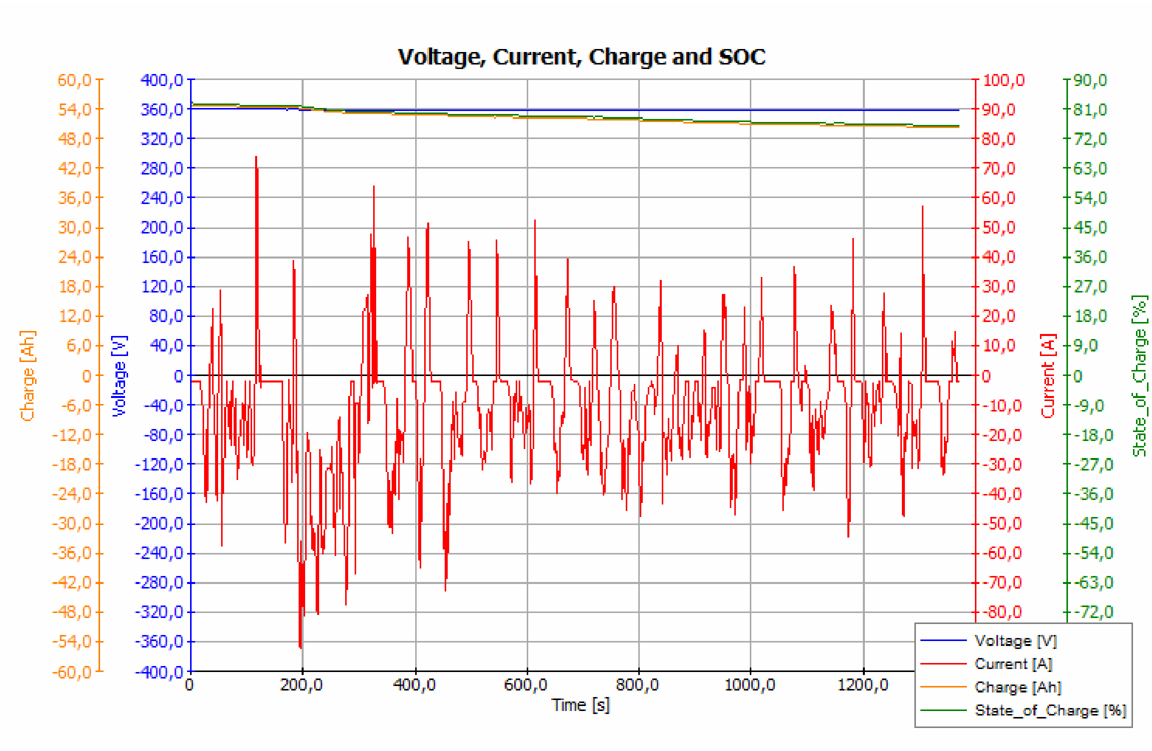

Figure D.3 - High voltage battery results for the second UDDS run, UDDS #2.

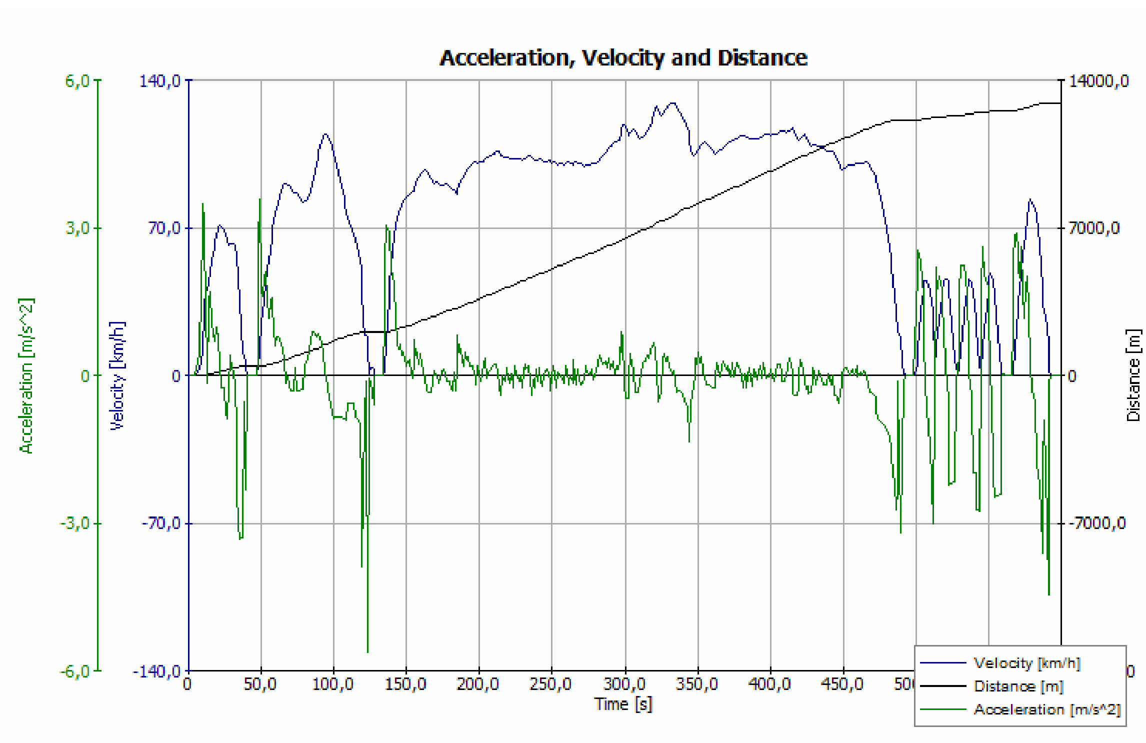

Figure D.4 - Acceleration, velocity and distance of an "Aggressive" driving cycle (US06), US06 #1.

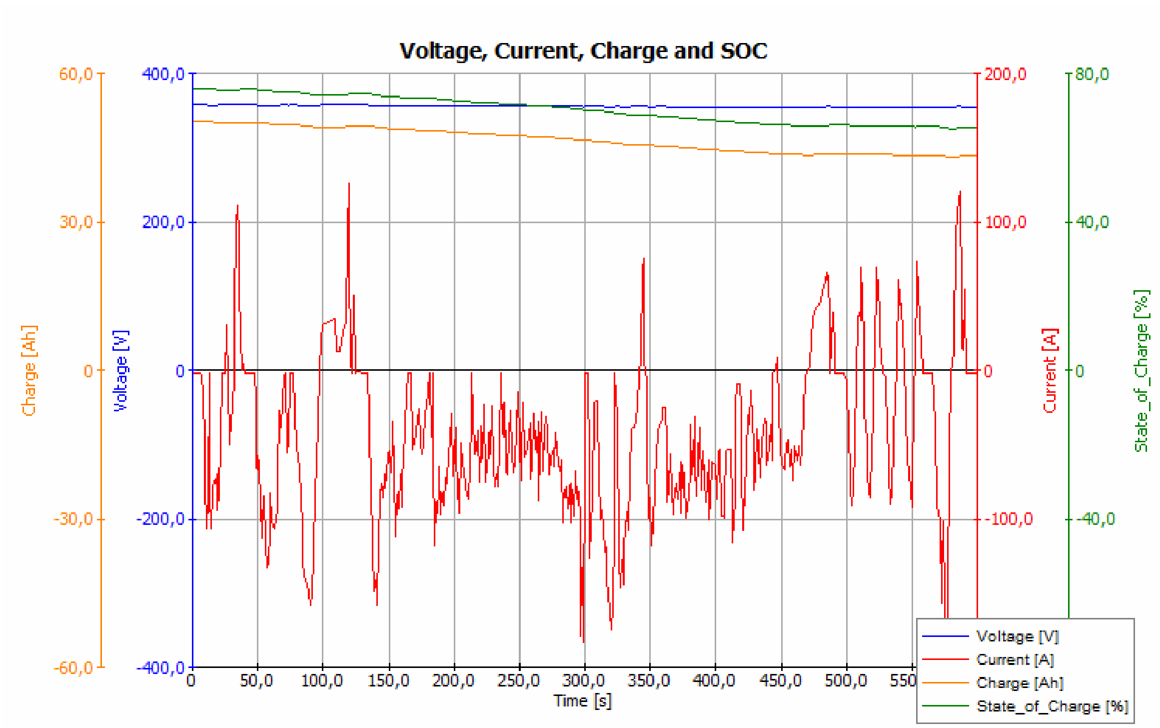

Figure D.5 - High voltage battery results for the first US06 run, US06 #1.

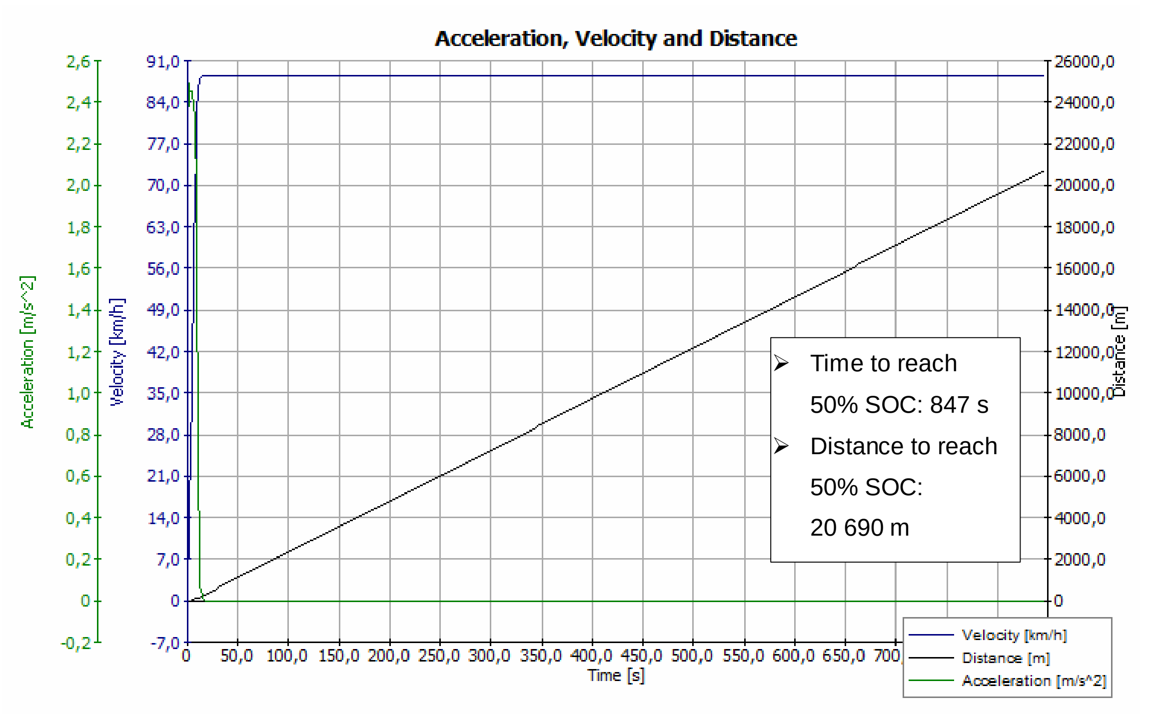

Figure D.6 - Acceleration, velocity and distance of 55mph run at steady state speed.

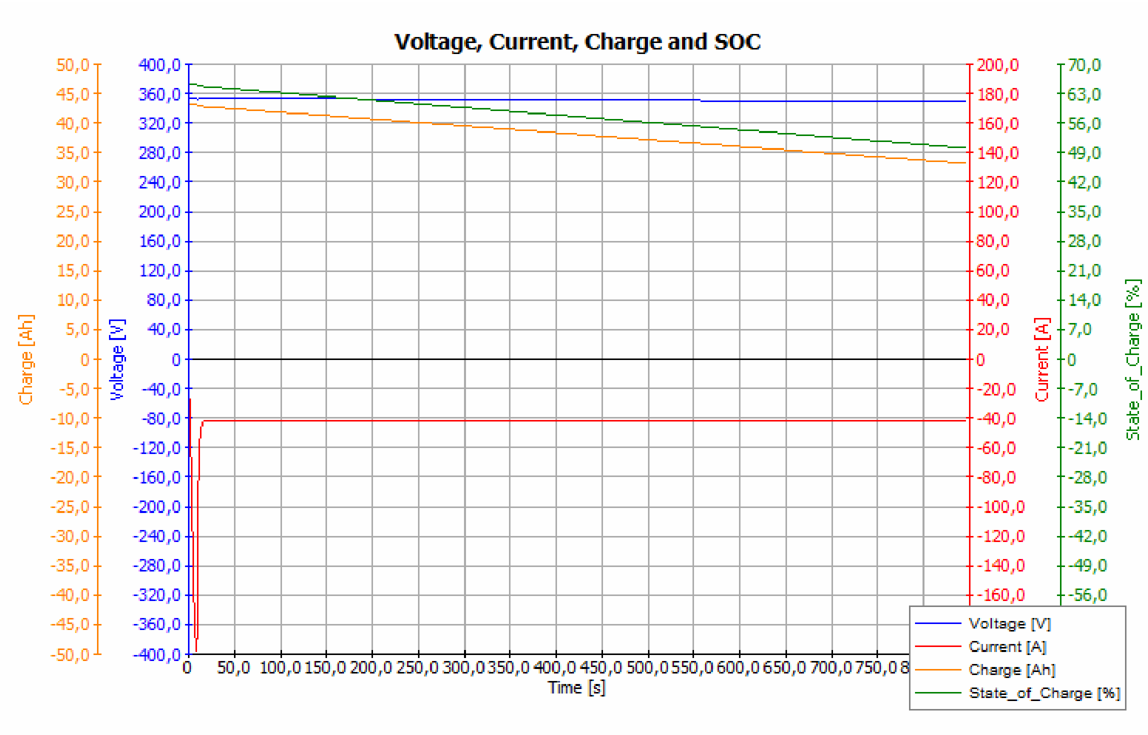

Figure D.7- High voltage battery results for 55 mph steady state speed.

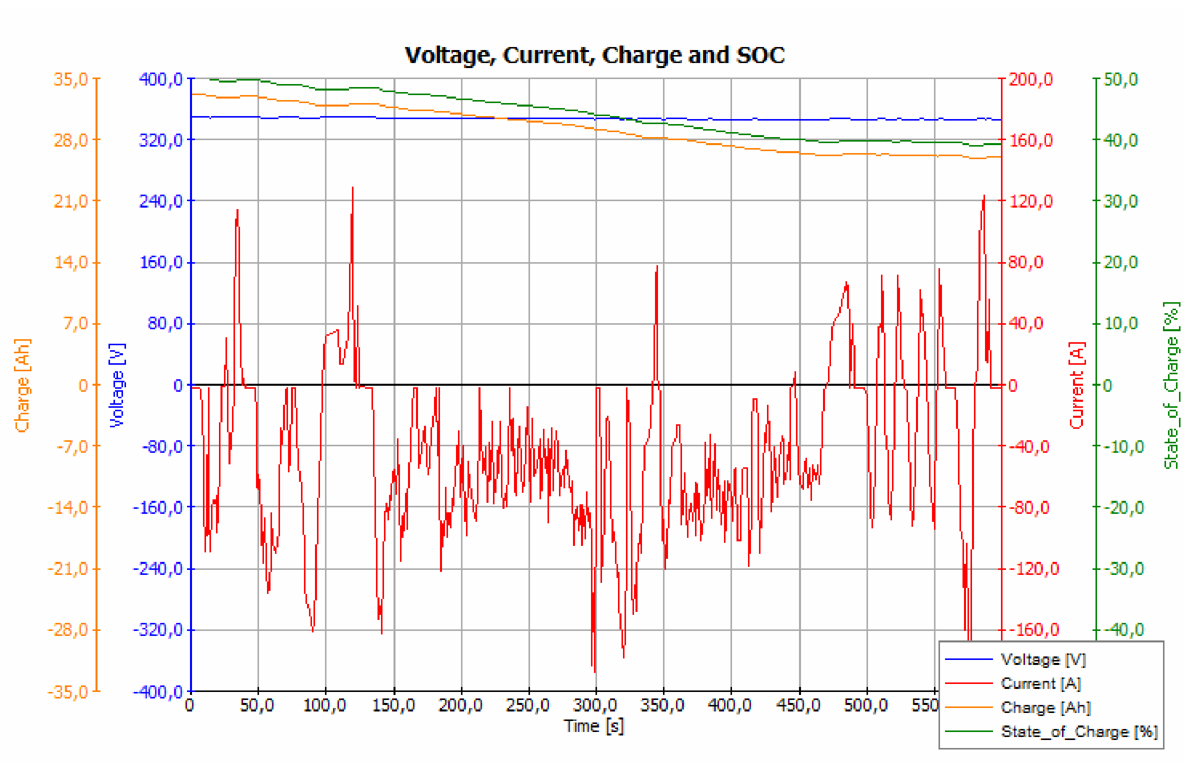

Figure D.8 - High voltage battery results for the second US06 run, US06 #2.

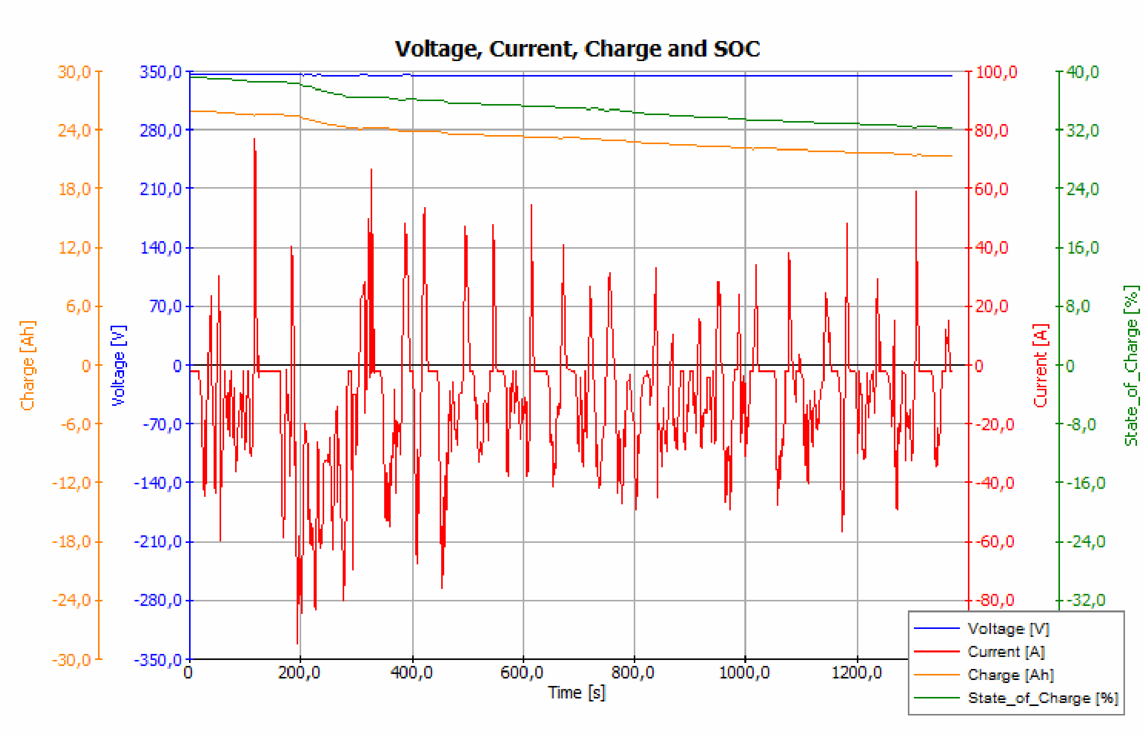

Figure D.9 - High voltage battery results for the third UDDS run, UDDS #3.

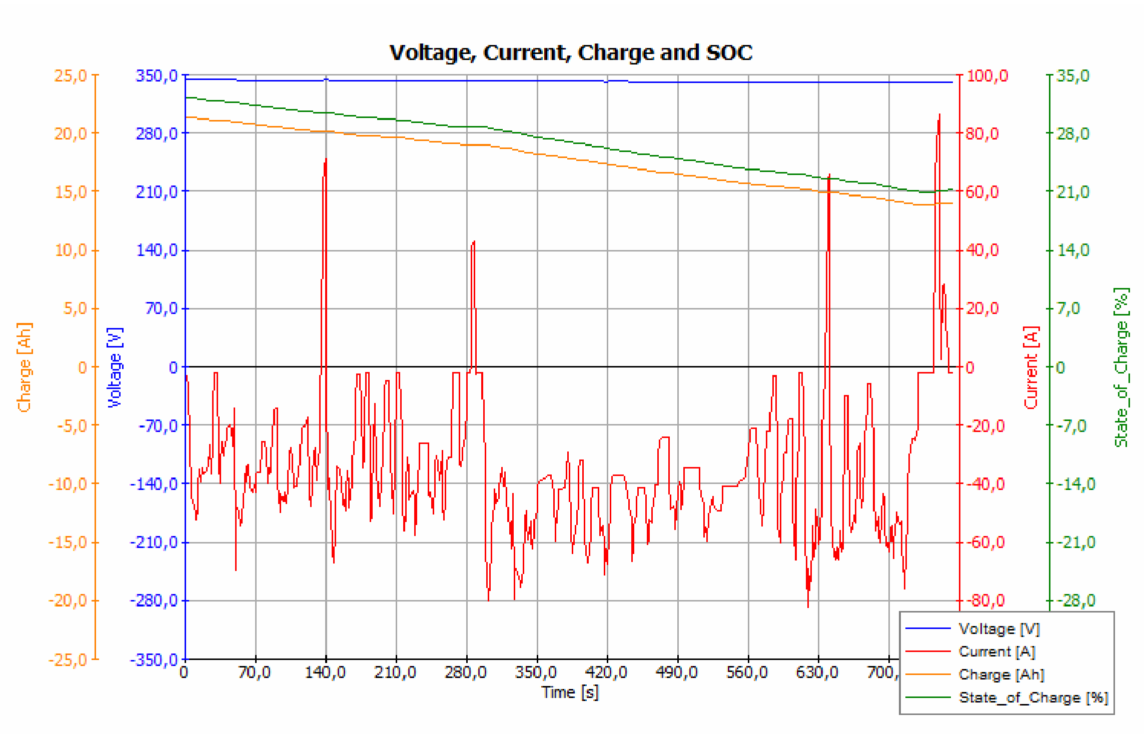

Figure D.10 - High voltage battery results for the second HWFET run, HWFET #2.

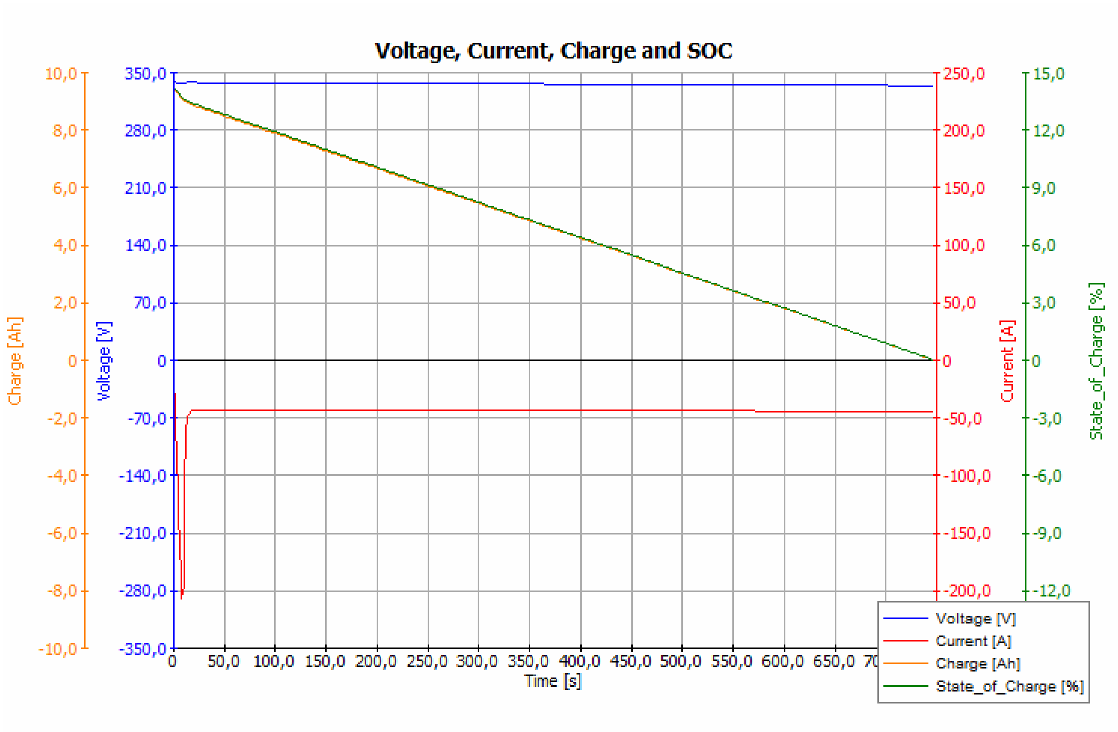

Figure D.11 - High voltage battery results for the fourth UDDS run, UDDS #4.

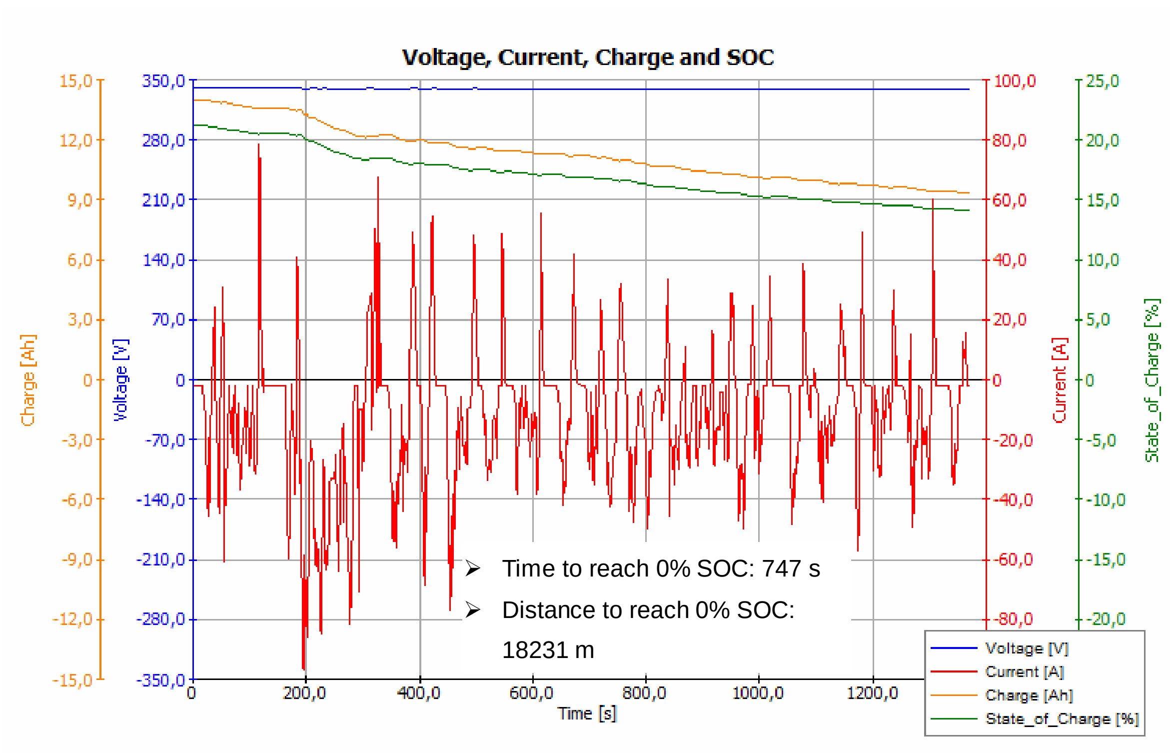

Figure D.12 - High voltage battery results for 55 mph steady state speed

EPA with air-conditioning system

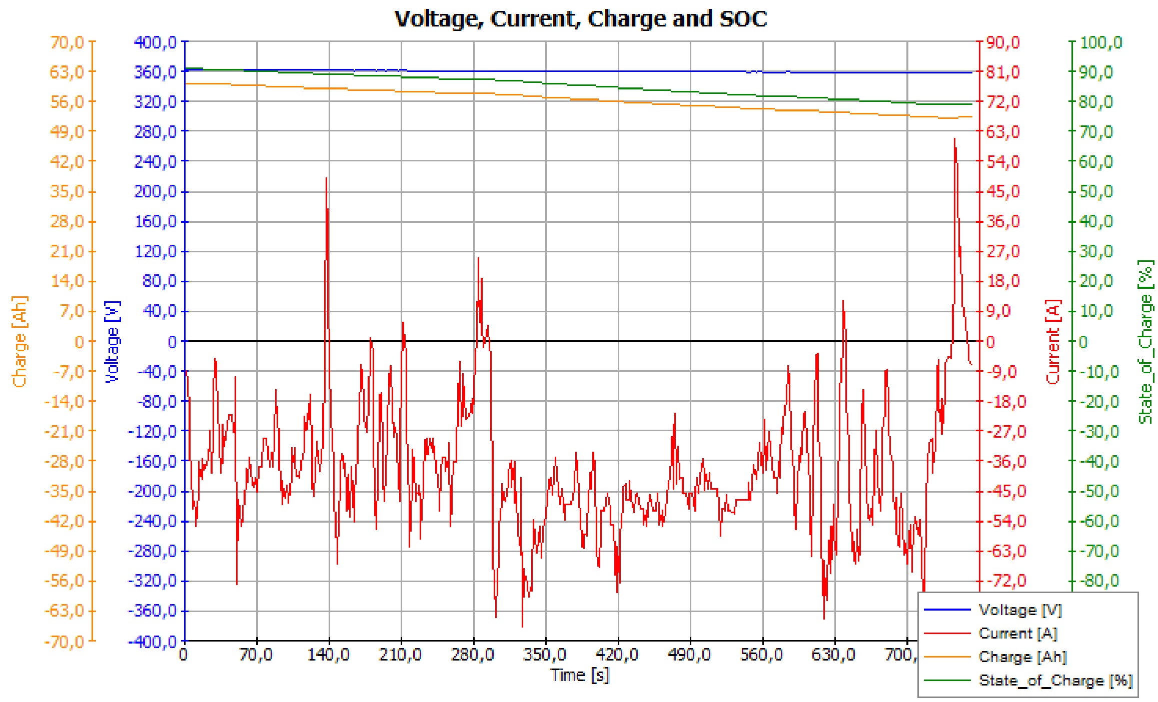

Figure D.13 - High voltage battery results for the first HWFET with A/C module, HWFET #1.

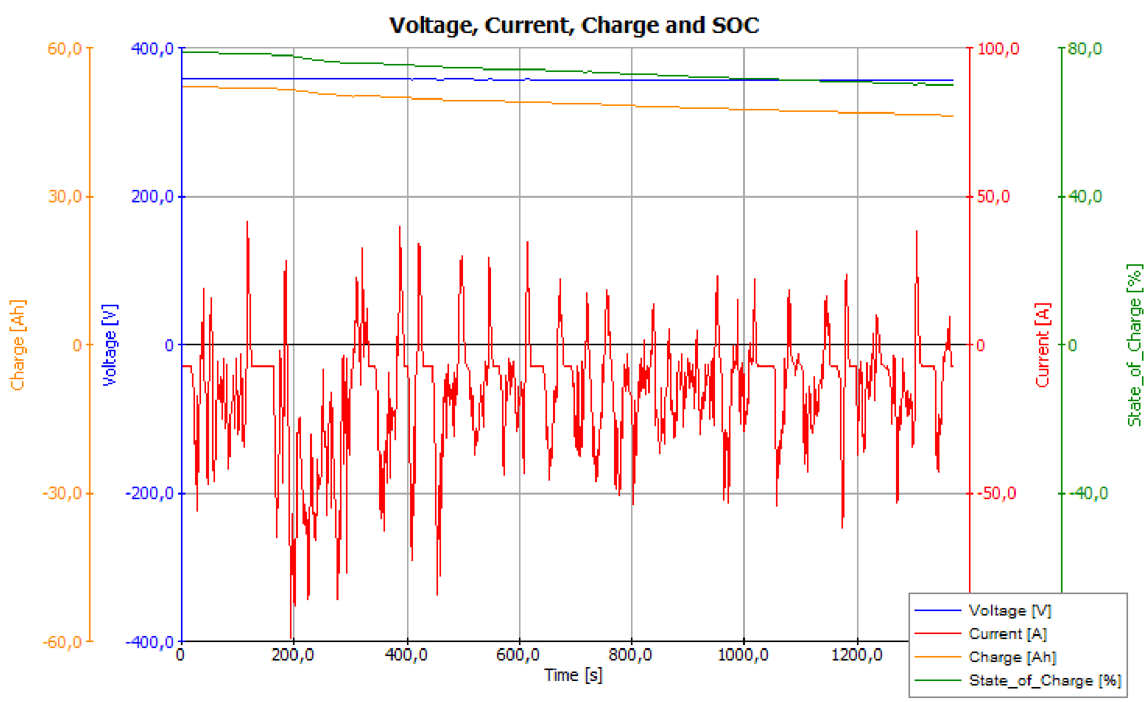

Figure D.14 - High voltage battery results for the second UDDS run with A/C module, UDDS #2.

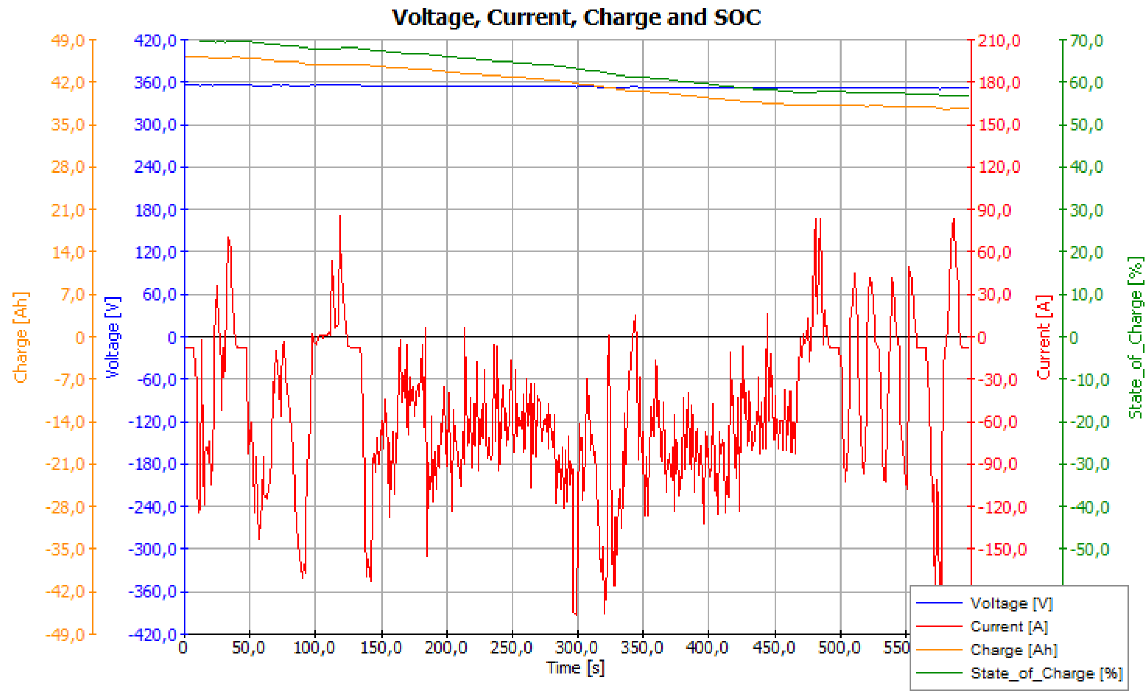

Figure D.15 - High voltage battery results for the first US06 run with A/C module, US06 #1.

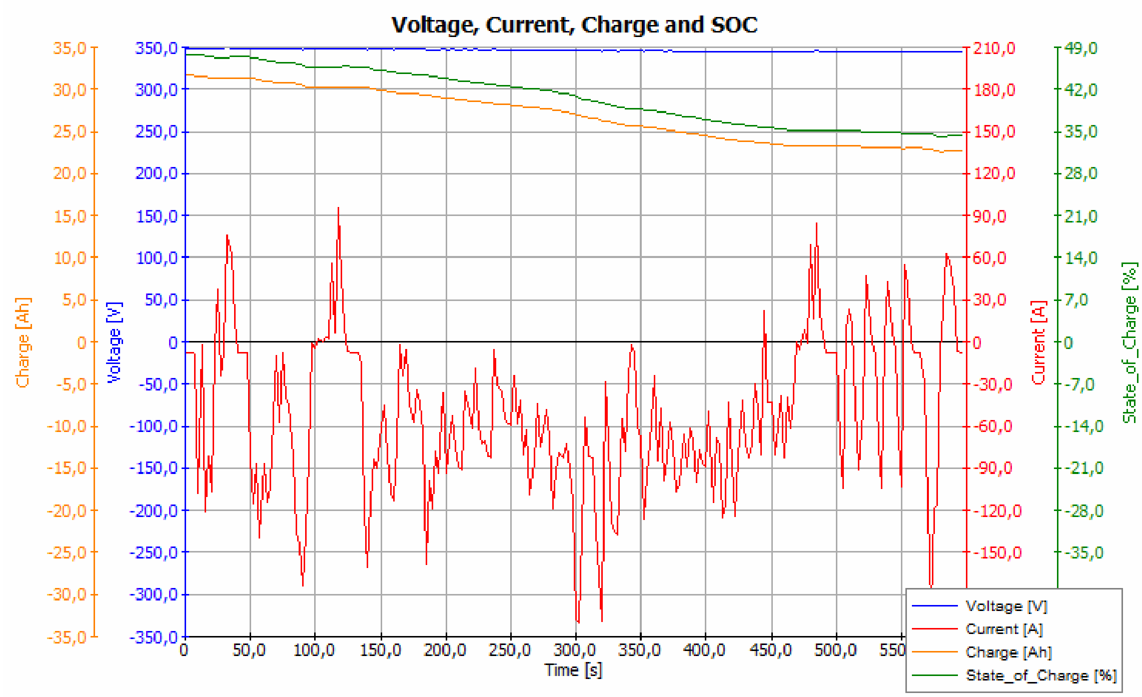

Figure D.16 - High voltage battery results for the second US06 run with A/C module, US06 #2.

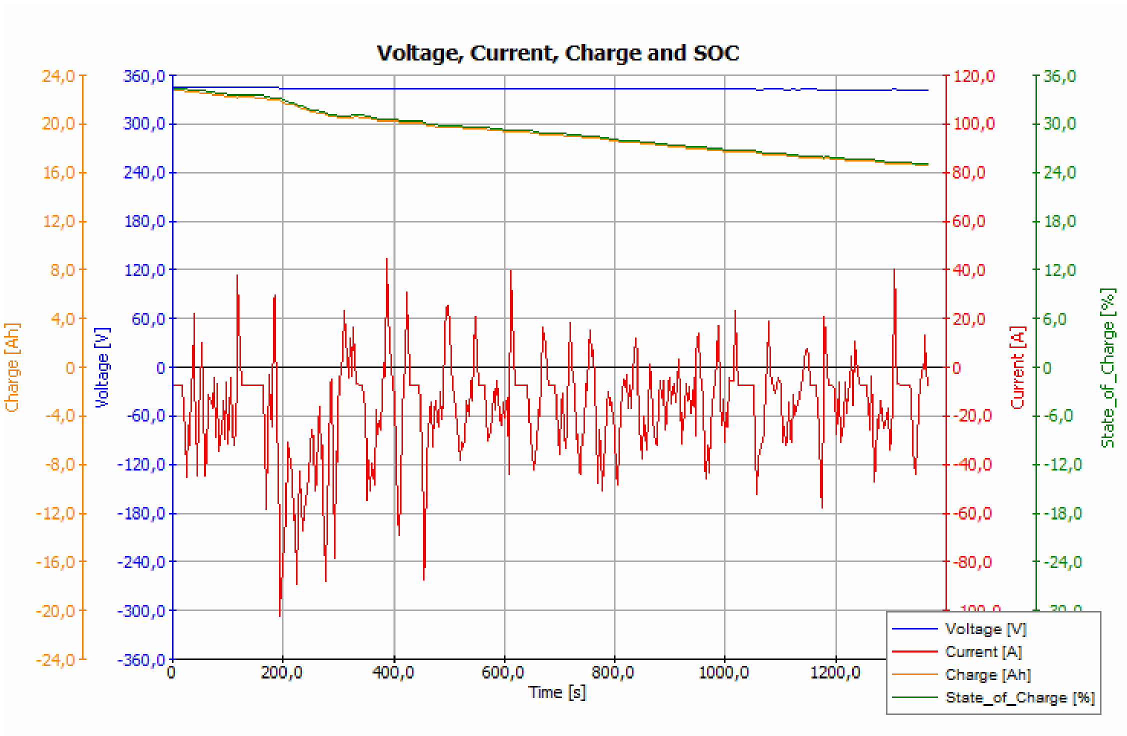

Figure D.17 - High voltage battery results for the third UDDS run with A/C module, UDDS #3.

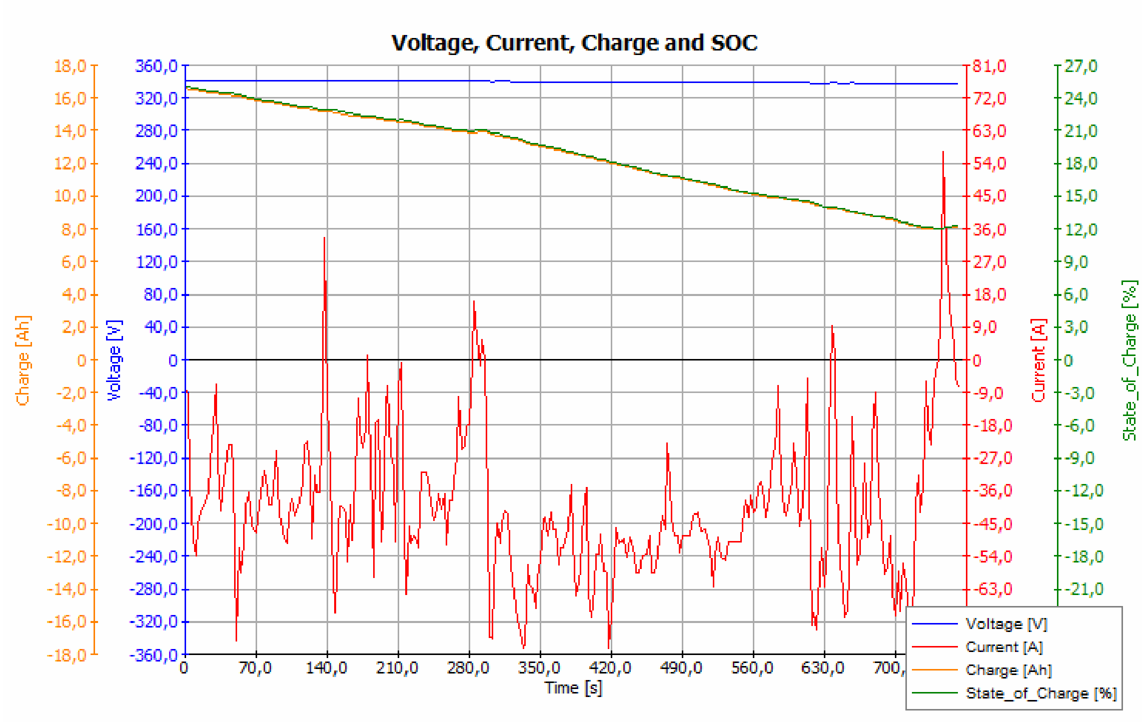

Figure D.18 - High voltage battery results for the second HWFET run with A/C module, HWFET #2.

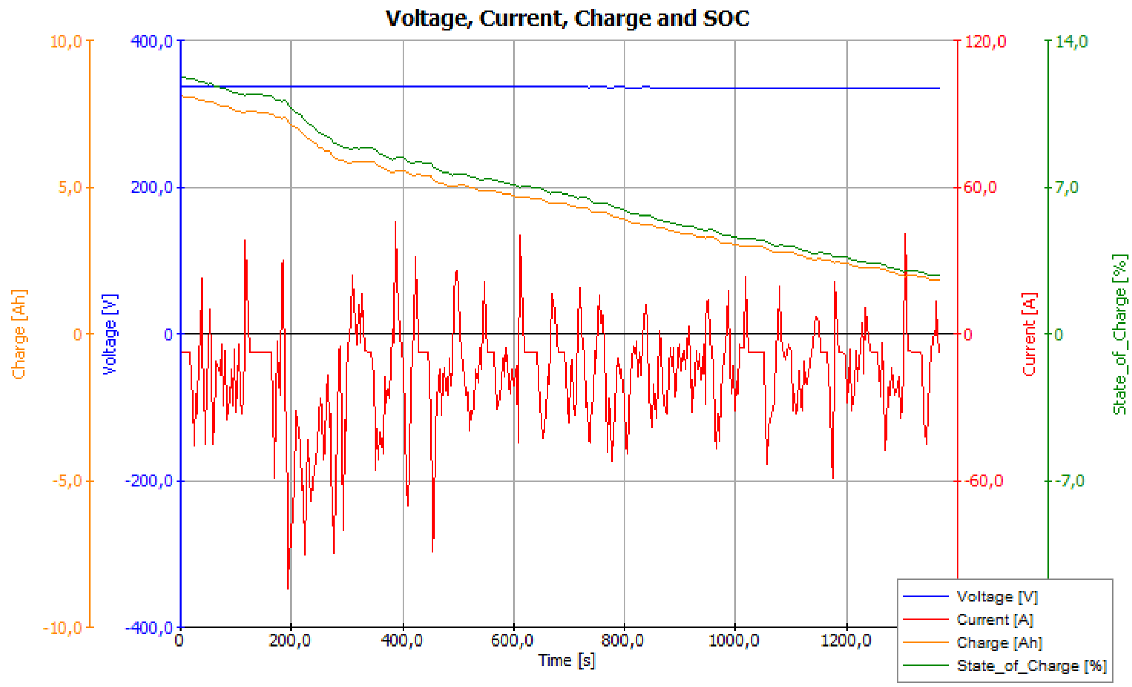

Figure D.19 - High voltage battery results for the fourth UDDS run with A/C module, UDDS #4.

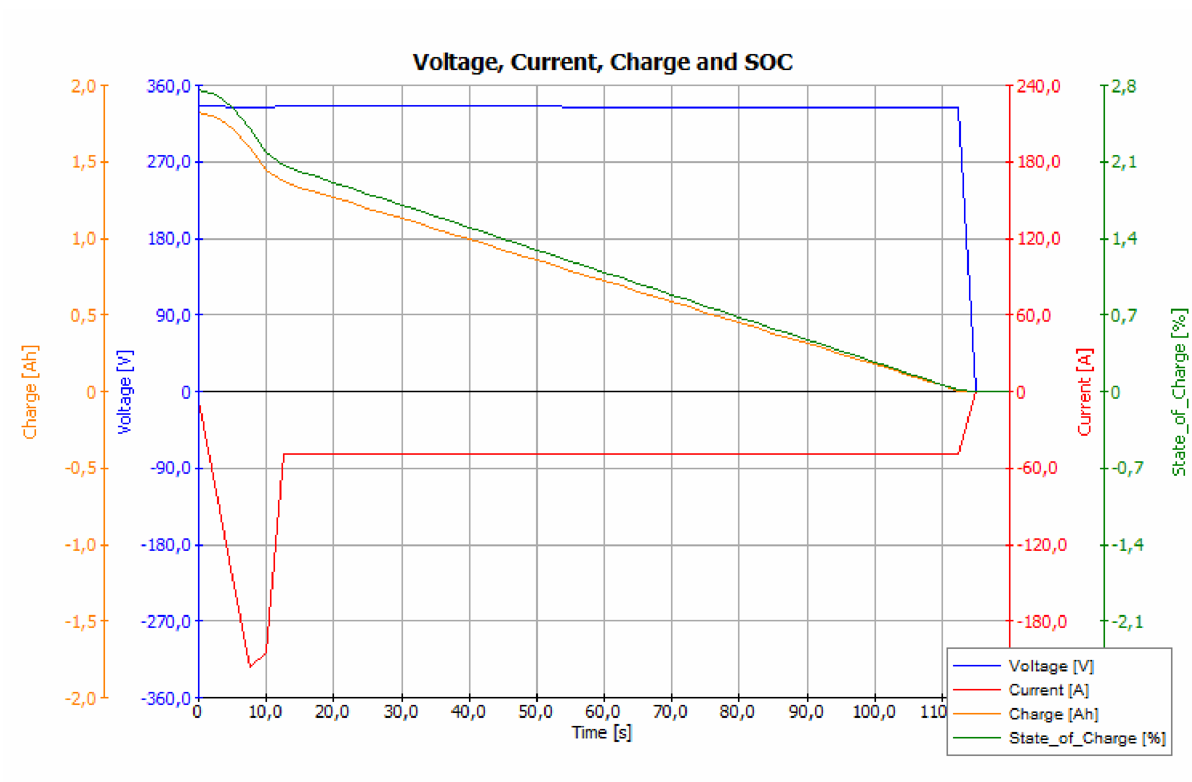

Figure D.20- High voltage battery results for 88.6 km/h (55 mph) until battery depletion with A/C module.