ANALYSIS OF ENERGY FLOW IN A CITROËN C-ZERO

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ABSTRACT

ANALYSIS OF ENERGY FLOW IN A CITROËN C-ZERO

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The Automotive Institute of the HAN University of Applied Sciences in Arnhem, is specialised in automotive engineering. To keep up with current innovations, the educational program requires the implementation of electric vehicles to extend their existing course material.

In this report is described, how the energy consumptions of components is distributed in electric vehicles, by analysing the energy flow in a Citroën C-ZERO. The CAN-bus in the vehicle is used to disclose settings and sensor readings, by evaluating and visualising its data. An interface and underlying software to acquire the data have been developed to enable real-time data acquisition and visualisation. In collaboration, a system was developed to attach additional sensors to the CAN-bus, enabling monitoring of the energy consumption of individual subcomponents.

By using dynamometer tests, the characteristics of the electric motor and its regeneration behaviour have been analysed and validated. The outcome of the tests show that the developed system and obtained results are worthy, to provide insight into the energy distribution in electric vehicles.

DECLARATION

I hereby certify that this report constitutes my own product, that where the language of others is set forth, quotation marks so indicate, and that appropriate credit is given where I have used the language, ideas expressions or writings of another.

I declare that the report describes my original work that has not previously been presented for the award of any other degree of any institution.

Signed,

Harrie Willem Noorlander

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LIST OF ABBREVIATIONS

API	Application Program Interface
CAN	Controller Area Network
ESP	Electronic stability control
EV(s)	Electric Vehicle(s)
HAN	Hogeschool van Arnhem en Nijmegen (HAN University of Applied Sciences)
ICE	Internal Combustion Engine
ID	Identifier
OBD	On-board Diagnostics
SoC	State of Charge
USB	Universal Serial Bus
Wi-Fi	Wireless Fidelity

LIST OF UNITS

V	Volt
A	Ampere
Ah	Ampere-hour
W	Watt
bhp	Brake horse power
km	Kilometre
km/h	Kilometres per hour
rpm	Revolutions per minute

I. RATIONALE

This first chapter of the graduation report contains the problem definition and research question. It starts with a general introduction to describe the current situation followed by the desired outcome and reason for the research. Ultimately, the research question covering the scope of the project and problem definition is given.

A. INTRODUCTION

Electric vehicles (EVs) are becoming more common in the automotive industry. Although the internal combustion engine (ICE) is replaced with an electric motor, other components are still similar. In order to keep up with this current innovation, the Automotive Institute of the HAN University of Applied Sciences in Arnhem, wants to implement EVs into the educational program, to update their existing course material. The reason for this particular research is to provide new course material.

Nowadays vehicles and especially EVs, like the Citroën C-ZERO, contain various electrical components, which require electrical power from the battery, see Figure 1. Each component has its own characteristics and specifications and individually takes part in the overall consumption. Another similarity is that the C-ZERO uses a CAN-bus for communication, here both sensors and controllers provide information and data, coming from different components in the vehicle.

Another similarity in comparison to modern vehicles is that the C-ZERO contains sensors. Whether the data from the sensors on the CAN-bus provides the right data to analyse the energy flow, or if additional sensors are required, has to be investigated. Various power-consuming components, such as the heater, air-conditioning, radio and other components, will require monitoring, in order to analyse the energy flow. As the range of a Citroën C-ZERO is limited by its battery capacity, using the heater or radio, will result in additional energy consumption, which subsequently decreases the reachable range of the vehicle.

Figure 1: Citroën C-ZERO

B. DESIRED SITUATION

The desired result is a system, with an interface to provide a visual representation of the energy consumption of individual subcomponents. Therefore, a system needs to be developed to allow the energy distribution in an EV to be analysed. The goal is to provide new groundwork for the Automotive Institute at the HAN University of Applied Sciences in Arnhem. So they can further extend their already existing course material, by implementing EVs to their educational program.

C. RESEARCH MOTIVATION

As previously mentioned in the introduction, the automotive industry is in constant development of new techniques to provide alternative solutions to keep up with current energy demands. Educational programs, such as provided by the Automotive Institute at the HAN University of Applied Sciences, in Arnhem, need to keep up with those current innovations. Currently there is no system available to analyse the energy flow in EVs, therefore the development of a system is required to provide a solution for this problem.

D. RESEARCH QUESTION

This research combines the data from the CAN-bus, the implementation of additional sensors and measurements from the dynameters, for analysing the behaviour concerning the energy flow in the Citroën C-ZERO. The primarily goal of this research is to develop a system, which is able to provide an overview of the power consumption of specific components inside the vehicle. Hereby, enabling the education to gain more understanding about the behaviour of EVs, and therefore providing new material for the education, to update their existing course material. Coming to the central research question for this project:

How can the energy flow of a Citroën C-ZERO be analysed and the data be visually represented, to provide new material for the education to update their existing course material?

With the following logical differentiated sub-questions:

How can the CAN-bus data be acquired and visually represented?

Which parameters are readily available on the CAN-bus?

How can the obtained results be verified and validated?

II. SITUATIONAL & THEORETICAL ANALYSIS

The situational and theoretical analysis outlines the facts and figures by further expanding on the information given in the rationale from the previous chapter, focussing on collecting and summarising different theories.

A. CITROËN C-ZERO

Citroën donated a Citroën C-ZERO to the HAN [1]. This vehicle has been on the road as a test vehicle, for two years. As explained in the reference the vehicle is available for various research purposes, such as this graduation project. However, because the vehicle has been a test vehicle, testing is now limited to indoor testing only, because of insurance restrictions of the vehicle. Furthermore, no allowance for driving around the parking limits the possibility to extend the research to include outside factors. Therefore the outdoor environment is not within the scope of this research project.

Regarding the system that needs to be developed in order to determine the power consumption of individual subcomponents in the vehicle, the implementation has to be non-invasive and non-destructive. The vehicle has to stay operational, throughout the research and thereafter.

Besides the aforementioned vehicle, the HAN also owns and facilitates equipment, such as a dynamometer, to obtain measurement- and validation data. My personal task is to acquire and visualise the data, to determine the energy flow, which includes the development of an interface and underlying software, for the sensor system, to analyse the energy flow in the Citroën C-ZERO.

Within the domain of the automotive department the tools for conducting the research, as well as the required information are both available and the request from the client is sufficiently clear. Allowing new methods with already existing knowledge and information to be combined within a new domain. By analysing the CAN-bus data, and revealing which information already is provided by the CAN-bus, to see which parameters will require additional monitoring. The HAN suspects, additional current and voltage sensors will be required.

B. REBADGING

The developer of the Citroën C-ZERO is Mitsubishi, however the vehicles in Europe are being sold as the Citroën C-ZERO and Peugeot iOn. Apart from some exterior differences the Citroën C-ZERO is almost identical to the Mitsubishi i-MiEV and Peugeot Ion, as they all have the same drivetrain, electrical motor and batteries [2]. Therefore research based on those vehicles can disclose additional information, however as there are some dissimilarities, caution is required while using the other vehicles in this research.

As an example, the Mitsubishi i-MiEV has additional shifter positions, to apply different settings, intended for city driving, hilly terrain and flat terrain. Proper use of this option enables kinetic and potential energy to be returned to the battery more efficiently [3]. This option is not available in the Citroën C-ZERO, either this option has been disabled by Citroën or possibly automated or locked in a default setting.

Another difference between the Mitsubishi i-Miev and the Citroën C-ZERO is the presence of an additional feature in the C-ZERO called Citroën Connect [4]. This enables roadside and emergency assistance in case of an accident using a built-in SIM card and a GPS module.

The Citroën Connect feature is most likely secured and will not be easily accessible for the use in this research. Combining the outdoor restriction of the vehicle with the potential to use the GPS data to access location information also limits its usefulness within this research.

C. SPECIFICATIONS

The specifications from the manufacturer show that the motor drive system installed in the Citroën C-ZERO, is manufactured by Meidensha Corporation [5]. The motor and the controller operates at 330V and are water-cooled. The motor is a permanent magnet motor rated at 25 kW with a maximum rated output of 47 kW or 64 bhp from 3.000 to 6.000 rpm with an maximum torque of 180 Nm from 0 to 2.000 rpm. The power is transmitted to the rear axle via a single speed reduction gear, with a reduction ratio of 6,066, weighting 23 kg.

The ratings given by the manufacturer are well within the range of the dynamometer. Although the dynamometer can handle much more than the Citroën C-ZERO should be able to provide it allows verification of the specifications from the manufacturer. Because the dynamometer is oversized it will not provide very accurate data as its excessive range limits the sensitivity.

The power in the Citroën C-ZERO comes from a lithium-ion battery pack, called the traction battery pack. The pack consists of 88 lithium-ion manganese oxide cells, in series, manufactured by Lithium Energy Japan [6]. The battery pack consists out of 10 modules Lithium-Ion (8-cell type) and 2 modules of Lithium-Ion (4-cell type). In Figure 2 a single LEV50 cell as well as a module of eight cells is represented. The nominal voltage of a single cell is 3.7 V with 50 Ah capacity. Specifications show a total capacity of 14.5 kWh with a total supply voltage of approximately 330 V. However, $88 * 50\ Ah * 3.7\ V = 16.5\ kWh$, the difference between the capacity from the specification and the calculated capacity can be theoretical versus usable capacity. The pack is about 240 kg and air cooled located in the bottom of the vehicle. The cells are resistant to partial recharges, therefore it is not required to completely recharge before using the vehicle [2,7]. This is useful for doing regeneration test on the dynamometer, as the cells will only be partially recharged.

The battery pack does not only supply the motor, but also allows the motor to regenerate electricity while decelerating the vehicle, here losing the accelerator pedal induces the regeneration. This regeneration causes the traction battery to refill, which is useful to extend the range of the vehicle, as the brakes are not dissipating all of the energy. In addition to supplying power to the electric motor, the traction battery also supplies the heating and air conditioning. All other electrical components are powered by the axillary battery, this 12V battery is charged by the traction battery using a DC/DC converter, converting the 330V DC to 12V DC [8].

Figure 2: LEV50 Cell and 8-cell module

D. LIMITING FACTORS

In EVs, the cabin heat comes from air conditioning or coil heated air, whereas traditional petrol powered vehicles use the excess heat from the combustion is used to heat up the air. Heating up an EV, to avoid mist on the windscreen, also has impact on the range, due to energy consumption [9].

The reachable range with a fully charged battery is limited by several factors, as mentioned before there is the heating, but also outside factors such as the aerodynamics of the vehicle and under-inflation of the tires result in added friction. Regarding the tire pressure, the user manual mentions the presence of an indicator on the dashboard, which warns the driver, in case low tire pressure is observed. The tire pressure, but also the use of ancillaries have influence on the reachable range of the vehicle [8]. Besides mentioning the tire inflation, the user instruction manual also contains many other side notes, mentioning to limit electrical consumption where possible, to optimise the range of the vehicle, for example by switching of the demisting/defrosting of the rear screen and door mirrors as soon as appropriate.

As already mentioned before, apart from electrical consumption, there is also the vehicle aerodynamic which results in additional friction, this counter force increases as the speed increases, therefore high speed results in more losses. Here both computer modelling or wind tunnel testing as well as road tests can be used to obtain measurements, however testing the vehicle in a wind tunnel or performing computer modelling will require additional skills and are also very time consuming. As a result, the aerodynamic losses do not have to be taken into account for mapping the energy distribution.

E. RANGE

Theoretically, the C-ZERO can reach a top speed of 80 mph and has a range of around 93 miles, which corresponds to about 130 km/h and 150 kilometres respectively. But according to other sources the range can go down to 60 or even 40 miles during the winter [4]. The Electric Car Guide offers a detailed overview, where ranges from the Nissan LEAF and the Mitsubishi i-MiEV are shown, as represented in Table 1 [10]. This table shows that the i-MiEV does not reach the official driving range from to the European NEDC test.

Coming back to the ability to regenerate energy using the electric motor, one might think it compensates the use of friction brakes and regenerative braking potentially increases the service life of the brakes. A case study analysing the regenerative braking efficiency, shows over 20% energy reduction with using regenerative braking. As this feature takes a major role in the energy flow, researching the regeneration behaviour of the vehicle has to be taken into account in analysing the energy flow [11].

Test	**Nissan LEAF**	**Mitsubishi i-MiEV**
Official range (European NEDC test)	124 miles (200 km)	93 miles (150 km)
Official range (US EPA test)	75 miles (121 km)	62 miles (100 km)
City centre driving	98 miles (156 km)	91 miles (147 km)
Urban/extra urban	82 miles (131 km)	79 miles (126 km)
Cross country roads	74 miles (118 km)	75 miles (120 km)
Cross country roads – fast driving	48 miles (77 km)	46 miles (74 km)
Dual carriageway/freeway eco driving	69 miles (110 km)	68 miles (109 km)
Dual carriageway/freeway normal driving	52 miles (83 km)	51 miles (82 km)

Table 1: Range tests of the Mitsubishi i-MiEV

F. FUSES

As commonly used in the automotive industry, a variety of blade fuses is implemented to protect the electrical installation including wiring. These fuses and to avoid damage in case something goes wrong, by cutting off the electrical installation from the power supply, when the rated current is reached.

Within the Citroën C-ZERO there are two fuse boxes, one under the dashboard with 26 fuse holders and another one located in the front compartment with 20 fuse holders. Using the user manual an overview of all the fuses has been compiled, represented in Appendix A, Table 11 [8]. In this table, the functions give a general description about the different components, which are connected to the axillary battery. The ratings ranging from 7.5 A to 40 A, providing an indication of the tolerated current rating. From here, the different subcomponents in the vehicle can be distinguished, providing a foundation to identify the components within the vehicle.

The maximum expected range for a fully charged battery with no auxiliary equipment on is 150 km. As the fully charged traction battery holds 14.5 kWh, and with this capacity the vehicle should be able to reach about 150 km, the consumption comes to roughly 100 Wh per kilometre. Assuming here the speed is a constant 60 km/h it would take 2.5 hours before the battery is depleted.

For installed components like the heated seat, there is no current rating provided. To provide an estimation of the range reduction when the heated seat is on, the fuse rating of the fuse in holder 17 under the dashboard is used. This fuse is rated 20 A, with about 12 V from the auxiliary battery, this feature can consume a maximum of 240 W before the fuse will melt.

Enabling the heated seat feature reduces this range as follows; enabling just this feature for one hour decreases the capacity by 240 Wh. Therefore in 2.5 hours it would consume 600 Wh, which corresponds to 6 km, equal to 4% of its total range. This example shows that enabling this feature limits the range significantly.Although has to be mentioned that the rated current of the device itself will be lower than the fuse rating, therefore the actual outcome will be less. Also the calculation does not take into account the efficiency of the inverter or the capacity of the auxiliary battery, therefore the calculation is inaccurate and serves as an example.

G. CAN-BUS

The CAN-bus is a network, which enables communication between components within the vehicle, according to the manufacture technical documentation, there are three CAN-busses present in the C-ZERO. This documentation also provides schematic drawings and tables indicating connected devices and routes [12]. Both wired and wireless solutions are available to read-out CAN messages and transfer them to a computer. Due to the quantity of messages, Bluetooth is to slow, thus only USB or the more expensive Wi-Fi standard remains.

A connection to the CAN-bus can be established using the OBD (On-board Diagnostics) port, with a female 16-pin (2x8 J1962) connector. In the Citroën C-ZERO this connector is located directly under the steering wheel. The pin out of the connector is standardised, thus the terminals to link to the CAN bus are defined. A PCAN-USB developed by PEAK System, can convert the binary signal coming from the CAN-bus and transfer it to a computer via an USB connector, the pin-out and connector are represented in Figure 3 and Figure 4 respectively. Hereafter, using its application program interface (API), computer software can be developed to read the CAN messages on the CAN-bus.

The PCAN-USB adapter enables connectivity to the CAN network via USB. The ODB pin-out is represented in Table 2, whereas the pin-out of 9-pin D-sub connector on the PCAN-USB is represented in Table 3. Here Figure 5 and Figure 6 correspondingly represent the PCAN Pin-out and PCAN-USB adapter.

Pin	Signal	Description
2	J1850 Bus+	J1850 Bus+
4	CGND	Chassis ground
5	SGND	Signal ground
6	CAN High	J-2284
7	K-LINE	ISO/DIS 14230-4
10	J1850 Bus-	J1850 Bus-
14	CAN Low	J-2284
15	L-LINE	ISO/DIS 14230-4
16	+12V	Battery power

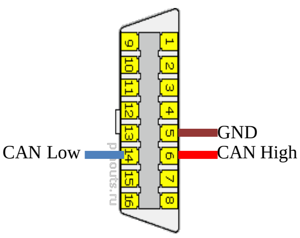


Figure 3: ODB Pin-out


Figure 4: ODB connector

Table 2: ODB-II / J1962 connector, pin-out

Pin	Signal	Description
1	+5V	Optional
2	CAN_L	CAN Low
3	GND	Ground
6	GND	Ground
7	CAN_H	CAN High
9	+5V	Optional

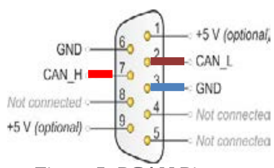


Figure 5: PCAN Pin-out


Figure 6: PCAN-USB

Table 3: PCAN-USB / 9 pin D-sub connector, pin-out

H. LIGHTING

Regarding the lighting of the vehicle the details represented in Table 4, were obtained from the Citroën C-ZERO user manual [8]. Here the exterior lighting from both the front, rear and side of the vehicle are represented. Comparing the ratings of the fuses in Appendix: A, to the power consumption of the lighting from Table 4, indicates that using the ratings from the fuses for further calculations to indicate power consumption is not recommended as they are inaccurate. However, the fuse ratings can still be used to indicate what the maximum allowed consumption would be for selecting sensors.

Front lamps			Rear lamps		
Function	**Type**	**Rating**	**Function**	**Type**	**Rating**
Direction indicators	W21W	21 W	Brake lamps / Side lamps	-	21 W / 15 W or LEDs
Side lamps	W5W	5 W	Direction indicators	WY21W	21 W
Main beam headlamps	HB3	60 W	Reversing lamps	W21W	21 W
Dipped beam headlamps	H11	55W	Fog lamp	W21W	21 W
Front fog lamps	H8	35 W	Third brake lamp	W5W	5 W
Daytime running lamps	P13W	13 W	Number plate lamp	W5W	5 W

Table 4: Lighting of the Citroën C-ZERO

I. HEATING & VENTILATION

In order to analyse the energy flow of the Citroën C-ZERO, many different variables are present where some of those variables might have direct relations with one another. As already mentioned before the heating is one them. For example, the air conditioning is related to the temperature and requires electrical energy to function, using it will decrease the available amount of energy. The heating and ventilation in the Citroën C-ZERO are user controlled by three vertical aligned dials on the dashboard, represented in Figure 7. With the dial on top the desired temperate can be adjusted, the middle dial controls the air ventilation speed, and the dial on the bottom changes the ventilation direction. The control dials do not have quantifications, for example the heating dial only has a 'H' for hot and a 'C' for cold. The heating for EVs in comparison to ICE vehicles does not come from excess heat, but comes from coil heated air, thus heating reduces the range.

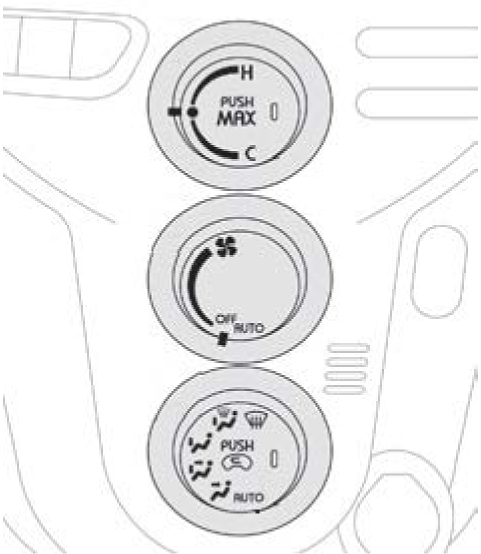


Figure 7: Heating and Ventilation dials

III. CONCEPTUAL MODEL

The previous chapter provided theoretical insight, regarding the energy distribution within the vehicle. Using that information, this chapter describes a conceptual model for a system to acquire data for quantisation and visualisation of the energy distribution of individual components within the Citroën C-ZERO.

A. CONCEPT DESIGN

To quantify and visualise, the energy consumption of individual subcomponents, in the C-ZERO, real-time measurements will be required. The measurements will need to be acquired by analysing the vehicle CAN-bus and by implementing additional sensors. Since the manufacturer, Citroën, does not disclose those details, reverse engineering is necessary to attain the required data.

As each subcomponent has different characteristics and most likely, they will not consume electrical energy continuously, it requires investigation into the cause of specific behaviours of individual subcomponents. Therefore, to avoid doing excessive measurements, components with a low energy consumption will be neglected, and they will not be taken into account in mapping the energy flow.

To acquire the measurements, the research can be divided into two parts, firstly there is the development of an interface and underlying software to acquire the data and secondly the development of a measurement system to measure the energy consumption of individual subcomponents.

B. DATA ACQUISITION

To avoid the implementation of potential unnecessary sensors has to be started with the development of a system to receive and analyse CAN messages from the CAN-bus. This system will disclose which components are already providing usable information for quantifying and visualising the energy distribution. While simultaneously, a measurement system to measure the voltages and currents of individual subcomponents has to be developed. Although my personal task mostly involves the development of a system to acquire and analyse CAN message, by programming the underlying software and corresponding user interface for the visual representation, there remains a direct involvement and collaboration with the other task.

To satisfy to the non-invasive and non-destructive condition, so called clamp meters allow measurements by clamping around the electrical conductor, after which it is able to measure the electric current in the conductor without having to make physical contact or having to disconnect it [13].

Taking into account that the Citroën C-ZERO is relatively small and nearly all of the electrical components and connections are tightly packed together, hence not easily accessible, central locations such as the fuse boxes are convenient. Here the connection to the individual electrical subcomponents is relatively easy to access. Table 11 in the Appendix provides an overview of the fuses and their functions.

Aside from the various subcomponents, which are required to be measured, there is the electric motor for accelerating the vehicle. Here the dynameters can be used to acquire first hand data to reveal the characteristics and specifications of the electric motor. As this motor is one of the main power consuming components in the vehicle, while not standing still, it is the most important components that needs to be analysed to map the energy flow in the Citroën C-ZERO.

IV. RESEARCH DESIGN

In the research design chapter it is described, what had to be done in order to get to the results, but also the different steps that haven been executed to get to the results, hereby using the conceptual model explained in the previous chapter.

A. OVERVIEW

The energy flow of the Citroën C-ZERO has to be monitored, therefore various subcomponents have to be identified and analysed, the behaviour, characteristics and specifications of those components will need to be visually represented and the results gathered throughout the research will have to be validated.

The electric motor, air-conditioning and heating are the components connected to the traction battery. Whereas, the 12V auxiliary battery on the other hand is used to power all the other electrical components, such as radio and lights. As information concerning the energy flow should be available on the CAN-bus in the vehicle, this is the place to start. The CAN-bus data will be acquired using a PCAN-USB, provided by the HAN. The results from those findings will expose which addition component will require monitoring. Hereafter a measurement system will need to be developed in order to measure the energy consumption of the additional components.

Several components will consume small amounts of energy, to avoid doing unnecessary measurement the focus will be on the energy consumption of the major subcomponents in the vehicle. On the other hand, measurements need to be non-invasive and non-destructive, ensuring safety and maintaining usability of the vehicle. The energy measurement system needs to be able to measure both voltages and currents, because those parameters can vary depending on the energy level of the battery and the measured components.

B. QUANTIFICATION

Vehicles with an internal combustion engines for the propulsion of the vehicle, usually have a tachometer to inform the driver about the revolutions per second of the engine. In the Citroën C-ZERO there is no such tachometer, but another indicator, the so-called energy consumption / generation indicator, informs the driver of the level of energy consumption or generation of the traction battery. This indicator is visible in Figure 8 and uses a red needle to indicate its state. However, this indicator is unquantified, as it only has a Charge, Eco and Power marker. Knowing, the actual value from the indicator, allows the energy flow to be analysed more precisely, quantifying the individual markers on the indicator provides insight into the energy consumption.

Likewise, other components such as the heating, air-conditioning and lighting, which can be set to different settings depending on the preferences of the driver, lack quantification, therefore making the quantification of the individual components essential for the analysis of the energy flow.

Figure 8: Citroën C-ZERO Dashboard

C. DATA ACQUISITION

For the visual representation of the CAN messages, special hardware along with compatible software are required. Here, for acquiring and visualising the data on the vehicle CAN-bus, a PCAN-USB adapter is used in combination with LabVIEW as the programming environment.

The driver and its API supplied PEAK system, to operate the PCAN-USB, support many different programming languages, including LabVIEW. As the HAN is already familiar with this way of programming and its dynameters use it as well, they encouraged the use of LabVIEW. Given that the API provided by PEAK system supports this way programming, a program and interface will have to be developed to read the CAN messages from the CAN-bus in LabVIEW.

A system needs to be developed to acquire and store the data regarding the energy flow of the vehicle. This system has to visually represent the energy flow to provide a clear and detailed overview of the energy consumptions. In addition, the system has to be capable of determining the power-consumption of various power demanding parts, where the energy flow can be analysed. Hereby providing the education with the information required in order to update their course material with providing an overview of which parts are depleting the battery.

D. MEASUREMENT SYSTEM

The DC to AC converter that drives the motor, converts the DC coming from the battery to AC for the motor, is not 100% efficient. In order to determine its efficiency, in both the generating and regenerating state, the dynameters will be used to monitor the output power of the motor. This requires a workshop to get to know how to operate the dynameters, as well as reservation of the facilities. Likewise, the DC to DC converter for charging the auxiliary battery also has inefficiency, which needs to be taken into account in the energy flow.

Using the fuse boxes a subsystem can be disabled by removing its corresponding fuse, hereby ensuring no energy is consumed by its components, but also gives the ability to measure the specific subsystem separated from the rest of the vehicle. To determine the current and voltage of the individual subcomponents, measurements can be taken here, using so called fuse testers, represented in Figure 9. These devices are available and allow the measurement of the current and voltage across its corresponding subcomponent, by replacing its fuse. Clamps will be used, to get the current and voltage values from its inductor, different types of clamps are available, including clamps capable of measuring AC and DC voltage and current.

Due to circumstances, several factors related to the energy flow can not be tested, because there is no allowance to test the vehicle outside on the public road. For example, determining the resistance caused by the aerodynamics of the vehicle, as well as real world testing of the heating system are not possible. Factors limiting the circumstances will not have to be measured by the measurement system.

Figure 9: Fuse tester (buddy)

V. RESEARCH RESULTS

In this chapter the developed software for both acquiring and processing the CAN-messages from the CAN-bus and the gathered results as well as the conducted measurements are described.

A. THE VEHICLE CAN-BUSSES

As mentioned in paragraph G of the Situational & Theoretical analysis three different CAN-busses should be present in the Citroën C-ZERO. Using PCAN-USB and PCAN-View, testing the ODB port revealed incoming CAN-messages from up to 52 different identifiers. By, using the documentation provided from the maintenance manual, other locations were tested to find other the CAN-busses.

Firstly a multimeter was used to measure the voltage on the pins of detachable connectors, if the voltage is in between 3 and 4 V it is a possibly a CAN High signal, whereas a voltage between 1.5 and 2.5 V can be a CAN Low signal. To confirm if it indeed is a CAN signal a digital oscilloscope was used to visualize its signal. From this visual representation of the incoming signal the presence of a CAN signal could be conformed.

The detected CAN-busses on various locations in the vehicle revealed the same CAN identifiers, thereafter a conductivity test confirmed that the detected CAN-busses were using the same conductor, and also the presence of only one single CAN-bus. It might be that the information given in the maintenance guide does not apply to this C-ZERO or that the busses have been combined together, resulting into a joined network.

As a result for the remaining part of the research only one CAN location will need to be monitored. Here has been chosen to use the OBD port for further analysis, because this one is most easily accessible from the cabin. Using the information provided in Table 2 and Table 3, the corresponding pins are connected to one another using a twisted pair cable, to reduce interference and noise, to transfer the signal from the OBD connector to the PCAN connector and transfer the signal to the computer.

B. LABVIEW AND PCAN-USB

For the visual representation of the CAN messages, hardware and compatible software are required. For acquiring and visualising the data on the vehicle CAN-bus, a PCAN-USB adapter in combination with LabVIEW as the programming environment were used to acquire the CAN-messages.

1. INITIALISATION

To acquire data in LabVIEW, PEAK system, the manufacturer from PCAN-USB supplied the drivers and API for the development of the application. The API includes a library file named PCANBasic.dll; this library contains the different functions to send commands to the device. The first step is to initialise the CAN bus, by specifying the USBBUS and Baud rate to PCAN_USBBUS1 and 500k respectively, this is done by using the Call Library Function with the Function name CAN_Initialize. This function returns the TPCANHandle required for other functions to recognise the device.

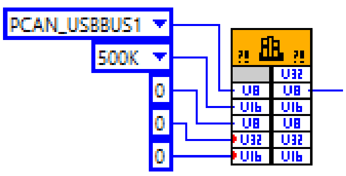


Figure 10: Call Library Function

2. Acquisition

Subsequently, after the device initialisation, the TPCANHandle is passed into a loop, where the CAN_Read function is configured and used to receive a CAN message, represented in Figure 11. This function also requires two input cluster to configure the corresponding outputs, similar to the CAN_Initialize function there is the TPCHandle, but most important here, is the TPCANMsg which containing CAN-message. The other two outputs are the TPCANStatus and TPCANTimestamp. The output of TPCANTimestamp is converted, by combining the TickCount from the operating system itself, using a formula, to return the actual time the message has been received. If the TPCANStatus indicates a received message, the loop continues and the TPCANMsG output and timestamp are passed into a case loop, where depending on the type of message, the data is bundled and formatted into a cluster array, to contain the timestamp, identifier, type, length and the data from the CAN message.

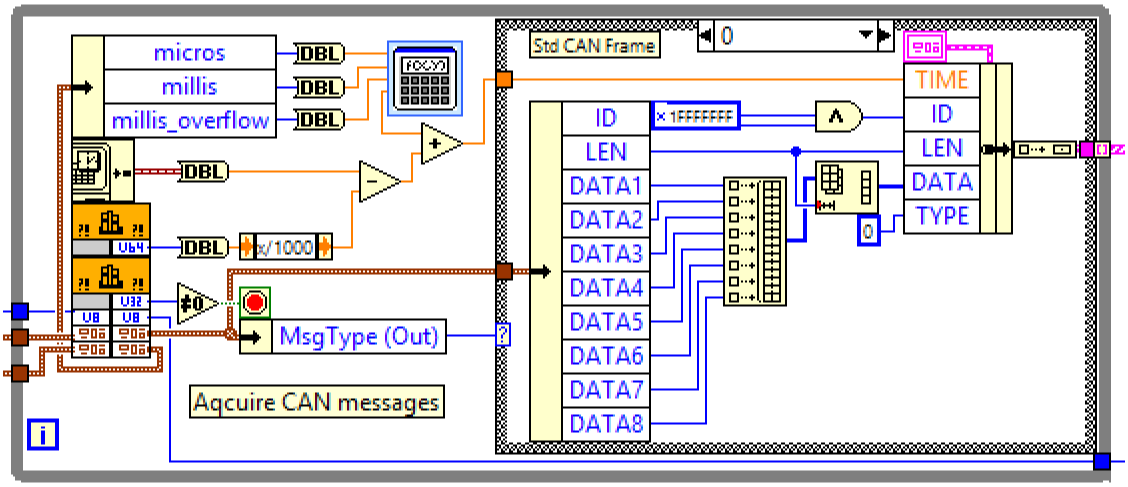


Figure 11: CAN-message acquisition

The amount of data in a CAN messages is carrying is determined by the value set in the LEN (length) section of the CAN message. For a standard CAN message the maximum is 8 data bytes, numbered from zero to seven. For the remaining part of this report, bytes will be denoted by surrounding the corresponding byte with square brackets. Each of the data-bytes consists of 8 bits, so a total of 64 bits per CAN message. A bit is binary value, therefore it can only be in one out of two states, being either ON or OFF, represented by a 1 or a 0 respectively. In a byte consisting of 8 bits, each bit can be represented as 2^n, where n is the bit number, counted from right to left. Using this property one single byte can have up to 28 (256) different states, ranging from 0 to 255 when represented in decimal form.

3. Extended Identifier

The ID (identifier) in the CAN messages identify the transmitting device, where a low value identifier has a higher priority. A standard CAN message had an 11 bit identifier, whereas an extended message has a 29 bit identifier. To ensure compatibility between one another, a standard identifier can be extended by applying binary logic, using the logical “and” operator with hexadecimal value 1FFFFFFF, represented in Figure 12. The hexadecimal format is used, because this is the standard numerical notation for identifiers in A CAN-message, therefore throughout the remaining part of this report identifiers will be denote with an ‘x’ before the identifier value.

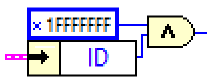


Figure 12: Extending identifier

4. Uninitialisation

Outside of the loop of the CAN_Read function, the user can stop the program by clicking the stop button on the user interface or by pressing ESC on the keyboard. After a stop action, the device is uninitialised by using the CAN_Uninitialize function, represented in Figure 13. This function requires the TPCANHandle to identify the device that needs to be uninitialised. When the program is stopped without using the uninitialisation function errors can occur and the next time the program runs, it will take longer to start.

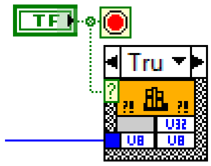


Figure 13: CAN_Uninitialize

5. Indexation

To keep a clear overview of the incoming CAN-messages they need to be indexed in order to sort the messages, as each identifier refreshes at a rate of about 100 Hz. The output from the acquisition is sorted using the identifier from the CAN-messages, the identifier is used to categorise the incoming messages, because the identifier is a constant, whereas the rest of the data in the message varies depending on the time and content of the data enclosed in each message.

6. Representation

A Multicolumn Listbox is used for the visual representation of the incoming CAN-messages, in this table the identifiers are used to sort the incoming messages, as described in the previous chapter. The table contains a clear overview of the incoming data, including the Time Stamp, ID, Bytes and DATA.

The table needs to be initialised at the start of the program, using its property node, represented in Figure 14. Initialising the table provides the possibility to implement checkboxes to select specific identifiers for logging the incoming data to a text file. In the header row of the table there is an extra checkbox to allow checking all checkboxes simultaneously.

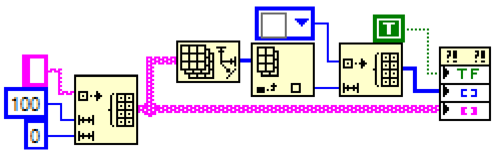


Figure 14: Multicolomn Listbox initialization

Checking a checkbox is processed in the first case of the Even Structure, represented in Figure 15. The Event Structure changes events by placing a checkmark in the corresponding checkbox, this way the user is aware of the identifiers that have been selected.

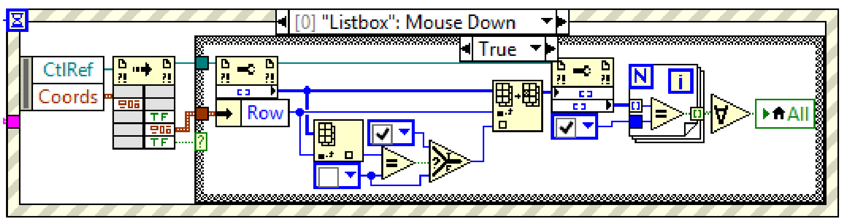


Figure 15: Event Structure, checkbox

C. DATA ANALYSER

Selecting a row in the Multicolumn Listbox, instead of a checkbox, selects the corresponding identifier for analysing the data part of the message. Here the individual data bytes are represented in both binary and hexadecimal format, respectively represented in Figure 16, with ‘b’ for binary and ‘x’ for hexadecimal. On the left of the decimal representation the user can see which identifier has been selected from the table. Directly above of the different numerical formats also eight horizontal sliders are implemented to provide a visual appealing way of representing the value of the corresponding data byte.

Beneath the numerical formats is a so-called Waveform Chart, on the left a list where an independent byte can be selected. Subsequently after the selection, the data values are plotted onto the graph to provide a historical timeline of the corresponding byte value.

Using the data analyser the data in a CAN message from a specific identifier can be visually analysed, from which the meaning of the data can be disclosed. The following paragraphs will explain different cases for identifiers where results have been found in its data content.

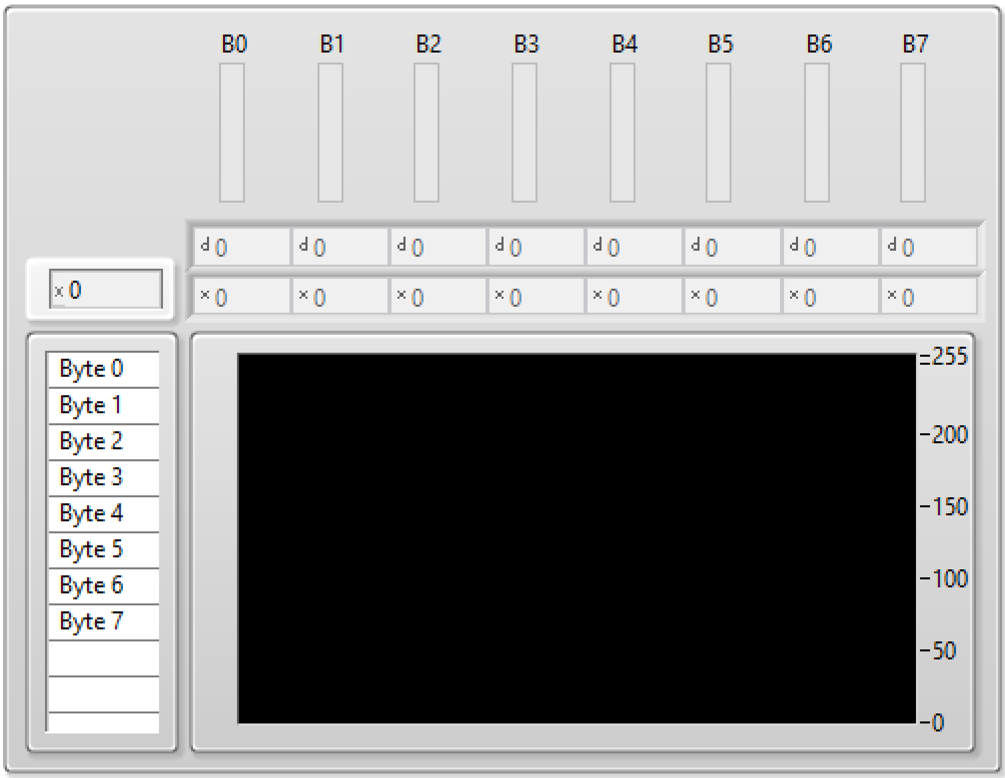


Figure 16: CAN-Data Analyser

D. CELL VOLTAGES AND TEMPERATURES

The identifiers x6E1, x6E2, x6E3 and x6E4 contain the individual cell voltages and temperatures, from all the 88 lithium ion cells in the traction battery. For each identifier there is a case structure to process the data. Byte[0] of each identifier iterates from 1 to 12, where each iteration contains data values at the other bytes.

1. Cell Voltages

For identifiers x6E1 and x6E2 each iteration contains two voltage readings. Whereas for identifier x6E3 and x6E4 the 6^{th} and the 12^{th} iteration do not contain readings. Identifiers x6E1 and x6E2 contain 24 voltage readings each, while x6E3 and x6E4 contain 20 readings each.

Each voltage value is comprised in a pair of bytes, where byte[4] and byte[5] are a pair and byte[6] and byte[7] form pairs. To get the value representing the voltage of a specific cell, for each iteration the first byte of the pair needs to be multiplied by 256 and added to the value of the second byte and subsequently divided by 100.

$$\frac{\mathrm{byte}[4] * 256\ +\ \mathrm{byte}[5]}{100}\ and\ \frac{byte[6] * 256 + \mathrm{byte}[7]}{100} = Cell\ voltage$$

Here the byte[4] and byte[6] can be either one or zero, whereas the last byte[5] and byte[7] can be 0 to 256. The output from the formula can range from 0.00 to 5.12, which fits within the theatrical operating limits of the lithium ion cells, as 4.2 volts represents 100% SoC with fully charged cells and 2.5 volts represents 0% SoC empty cells.

Figure 17 presents a bar graph containing all 88 cell voltage measurements, the y-axis represents the voltage scale, whereas the x-axis contains the cell numbering. The digital indicators on the right of the graph display the mean, maximum and minimum measured cell voltages.

Coming back to the data acquisition, when one of the aforementioned identifier is received and recognised by its case structure in LabVIEW, the corresponding bytes are put into the equation. The resulting value is placed in a pre-initialised array, containing all the readings for that particular identifier. Hereafter the arrays from the other identifiers are combined into a larger pre-initialised array, which contains all the 88 voltage values.

The array containing all the measurements is used to represent the voltage readings in a bar graph, from this plot all the voltages can be seen. When all voltages are equal to one another, the cells are balanced. Furthermore, this graph also shows the state of charge of each individual cell, but can also indicate malfunctioning cells, when they behave differently in comparison to other cells.

Furthermore, as all the cells are connected in series, the sum of the individual cell voltages represents the total output voltage from the traction battery. Using the aforementioned information, the nominal output voltage is 330 V, whereas a fully charged battery pack delivers about 370V and an empty battery will provide 220 V.

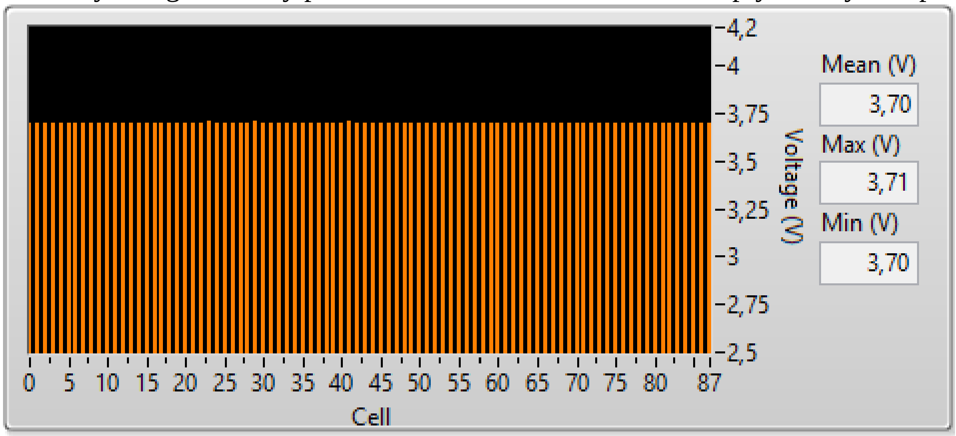


Figure 17: Cell voltage indicator

2. Cell Temperatures

Besides the individual cell voltages some of the identifiers also contain temperature readings from the battery pack, however here a total of 66 readings are present, where identifier x6E1 contains 24 measurements, x6E2 a total of 22 measurement and x6E3 the remaining 20.

For identifier x6E1 byte[2] and byte[3] of all 12 iteration contain the temperature value, hence x6E1 yields 24 temperature readings. To get the temperature in degrees Celsius an offset of 50 needs to be removed from its value contained in the data byte. Identifier x6E2, containing 22 temperature readings, does not contain measurements in the byte[3] for iterations 6 and 12. Whereas x6E3 does not contain measurements in both byte[3] and byte[4].

Figure 18 gives a visual representation of the temperature measurements, similar to Figure 17 the bar graph the x-axis contains the measurement number, whereas the y-axis contains the temperature measurement in degrees Celsius. Here the digital indicators present the mean, maximum and minimum recorded temperature.

Similar to the cell voltages the values of each iteration are passed into an array and combined into a larger array to represent the outcome in a bar graph. In comparison to the cell voltages, the cell temperature readings are not that sensitive, as its step size for the temperatures are only whole values, whereas the voltages have a much larger precision of two decimal figures.

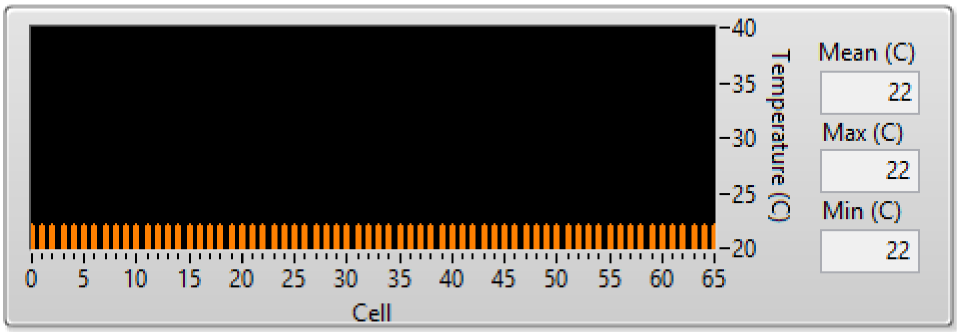


Figure 18: Cell temperature indicator

E. BATTERY VOLTAGE AND CURRENT

CAN-messages with identifier x373 contains more readings regarding the battery pack, namely the voltage and current readings. The values for these readings are contained in byte[2] to byte[5], where byte[4] and byte[5] represent the voltage, which is calculated using the formula presented below.

$$\text{Battery voltage} = (\text{byte}[4] * 256 + \text{byte}[5])/10$$

Similar to the individual cell voltage calculation, here byte[4] is either zero or one, after multiplication it representing either 0 or 256, whereas byte[5] yield the remaining part of the voltage value. After the dividing by ten, the resulting output is the voltage value ranging between 0 and 512 V.

The current reading is enclose in bytes[2] and byte[3], applying the formula given below, result in a two decimal figure, representing the current in ampere (A).

$$\text{Battery current} = (\text{byte}[2] * 256 + \text{byte}[3] - 128 * 256)/100$$

The case structure for processing the Voltage and Current readings from the battery is represented in Figure 19, in this case structure the corresponding power consumption in Watts is to be calculated by multiplying the two outcomes form the previous explained calculations. The result of this equation can either be positive or negative depending whether the battery is being charged or discharged, a negative result indicates discharge and a positive result indicates a charging state of the battery. All the aforementioned results are displayed on the user interface as represented in Figure 20; here the chart contains the calculated power on the y-axis, which automatically scales to fit the calculated value.

The individual cells are connected in series, thus the output voltage of the stack is the sum of the each cell voltage. However, comparing the sum of the individual cells to the result obtained from the voltage calculation above, a noticeable difference of about 10% is observed. This difference can be caused due to several factors, one of them is that it could be that the calculation is not 100% accurate, or it could also be that the sensor is placed after the motor controller.

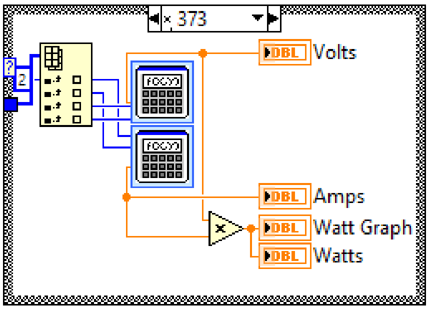


Figure 19: Identifier 373 (Voltage and Current)

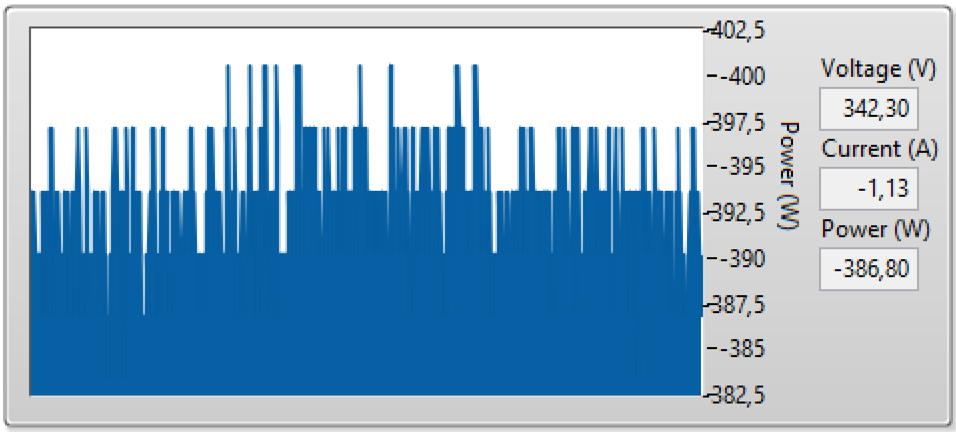


Figure 20: Voltage and Current readings indicators

F. STATE OF CHARGE (S0C)

The SoC represents the remaining capacity, indicated with a fuel indicator on the dashboard of the vehicle, noticeable in the top left corner of Figure 8. The indicator on the dashboard has 15 markers to indicate the remaining capacity of the battery. As the total battery capacity of the battery pack is about 14.5 kWh each bar represents approximately 1 kWh.

This indicator is equivalent to the byte[1] of identifier x374, to obtain the remaining capacity in percentages, the byte value needs to be decreased by ten, to remove the offset and subsequently divided by two, to output a range from 0 to 100 %, with steps of 0.5% each. The formula is given below, and the user interface representation in Figure 21.

$$SoC = \frac{\text{byte}[1] - 10}{2}$$

Given that fully charged cells contain 50 Ah or 14.5 kWh, the remaining capacity of the battery in Ah is calculated, by multiplying the SoC by 0.5. Whereas, multiplication by the battery pack voltage, explained in paragraph E. Battery Voltage and Current, results in the remaining capacity in Wh, the corresponding calculation in LabVIEW is represented in Figure 22.

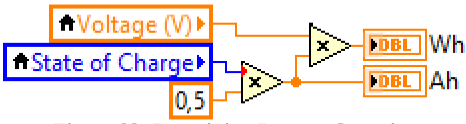


Figure 22: Remaining Battery Capacity

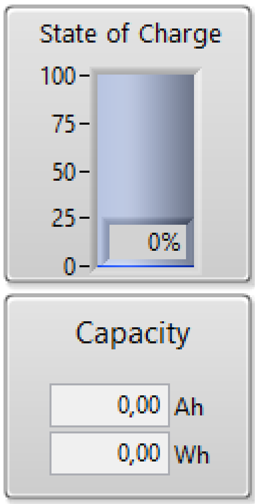


Figure 21: SoC and Capacity

G. IGNITION SWITCH

The ignition switch has four positions, as represented in Table 5. The position of this switch can be altered using the ignition key from the vehicle, which enables the driver to start the vehicle. In order to drive the Ready indicator on the dashboard needs to be on. Byte[0] from identifier 424 on the CAN bus, holds the information in order to determine the position of the switch, where the first two bits of the byte contain the binary values corresponding to the decimal value given in Table 5.

Position	State	Value	Description	Power Consumption
1	LOCK	0	The steering is locked.	No readings possible
2	ACC	1	The ancillaries (radio, 12V socket …) can be used.	240W
3	ON	3	Ignition on.	240W
4	START	2	“Ready” lamp on. Motor ready to drive vehicle.	430W

Table 5: Ignition switch

Using the power consumption readings from the Battery Voltage and Current chapter, the results regarding to the consumptions, represented in the last column were gathered. There is an idle power consumption of about 430W, without the use of extra appliances such as heating or radio, although it has to be noted here, that by default daytime running lamps are on. This means that the battery discharges within 34 hours. The corresponding state of the ignition switch is represented using a dial indicator on the user interface as represented in Figure 23.

Figure 23: Ignition position indicator

H. HEATING AND VENTILATION

The heating and ventilation in the vehicle can be controlled manually or automatically, using three different dials located on the dashboard in-between the driver and passenger seats. The corresponding representation on the user interface and the logical functions to disclose the settings are explained in the following paragraphs and respectively represented in Figure 24 and Figure 25.

The first dial is the temperature dial, this dial has 13 possible positions, ranging from low 'L' to high 'H'. Secondly, there is the airflow dial, with 10 possible levels from off till full speed and an automatic mode. The third dial is the air distribution control, which has six different settings including an automatic option. Each of the dials can be pressed to enable MAX, for maximum heating, A/C to enable air-conditioning and the third dial can be pressed to enable the air recirculation.

All those settings can be obtained from identifier x3A4, on the byte[0] and byte[1], where the heating and all dials pressed are stored in the byte[0], and the other two dial positions are stored in the byte[1]. The corresponding settings are on a binary level, so binary logic and bit shifting are required to obtain results.

The heating dial settings are contained in the first four bits of byte[0], as a result, applying logic 'and' with byte[0] and decimal 15 provides a usable output, with a decimal range from 0 to 15. Changing the dial settings, changes the byte[0] value from 1 to 13, representing L to H on the dial. Pressing the dial changes the sixth bit of byte[0], therefore a logical 'and' and a comparison to decimal 32 yield a Boolean output indicating the dial has been pressed and the heating respectively goes to MAX. Here the electrical consumption for the heating ranges from to 6 kW, obtained using the power consumption indicator.

The ventilation dial settings are contained in the byte[1], similar to the heating dial the first four bits store the settings, therefore the same logic applies. However here the byte value ranges from 0 to 8 and indicate OFF till full speed on the actual dial. Pressing this dial changes the eight bit of byte[0], correspondingly a comparison and logical 'and' with decimal number 128 reveals the dial press and enables the air-conditioning. The corresponding consumption show that the ventilation takes up to 180W or 270W in MAX mode, whereas enabling the air-conditioning ranges till 800W.

Lastly is the air distribution controls, stored in the last 4 bits byte [1]. Bit shifting is applied, in order to obtain a usable decimal format, by using a logical shift of four. Its result represents the corresponding settings, a press on this dial changes the seventh bit if the byte[0]. A comparison and logical 'and' to decimal number 64 reveals if the recirculation is on or off.

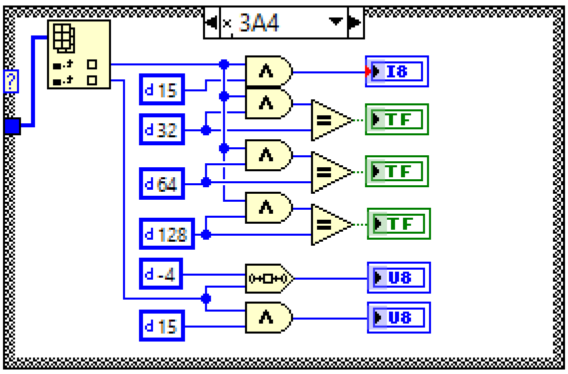


Figure 25: x3A4, heating, ventilation and air distribution

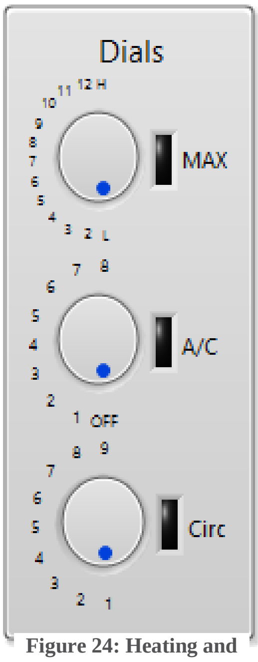


Figure 24: Heating and Ventilation Dials representation

I. LIGHTING CONTROLS

Table 4 in subchapter Lighting in the Situational & Theoretical analysis already provided an overview concerning the lighting of the vehicle. To dive more deeply into the actual power consumption, identifier x424 also discloses the different lighting setting. The different available options disclose the power consumption for each setting using the consumption reading from the subchapter Battery Voltage and Current, the consumption readings are represented in Table 6 below.

Position	Description	Power Consumption
1	Headlights (included taillights)	220W
2	Beam (plus beam)	175W
3	AB lights AV + AR	125W
4	Stop lights	30W
5	Warning lights	140W (modulated 50%)

Table 6: Lightning consumptions

J. DRIVE SELECTOR & PEDAL POSITIONS

In total three identifiers have been found for the pedal positions, as there are only two pedals in the Citroën C-ZERO. Two of them belong to the brake pedal, whereas the other identifier belongs to the accelerator pedal. The position of the drive selector is enclosed in another indentifier. On the interface, the indicators for these identifiers are represented using horizontal sliders and digital indicators, represented in Figure 26.

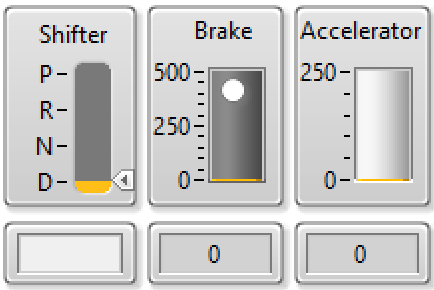


Figure 26: Drive Selector and Pedal Positions indicators.

1. Drive Selector

The drive selector in the Citroën C-ZERO, is located between the two front seats, allowing the driver to select different positions, being; P, R, N and D. When changing the drive selector position, the corresponding indicator is displayed on the instrument panel, next to the remaining battery capacity indicator, represented on the dashboard in Figure 8. On the interface the position is represented using a slider as well as a string representation represented on the left in Figure 26

The state of the drive selector is obtained from byte[0] of identifier x418, analysing the corresponding byte revealed the corresponding values for the shifter position. The matching decimal values for each position are represented in Table 7. Extracting the value from the data and passing it into a case structure with the matching values results in the output of the corresponding state of the drive selector.

Position	Value
D Drive	68
P Park	80
R Reverse	82
N Neutral	78

Table 7: Drive Selector

2. Brake pedal

The identifiers for the brake pedal are x208 and x231, for x208 byte[2] and byte[3] byte provide information regarding the pedal position. Byte[3] byte goes from 0 to 255, whereas the byte[2] byte increases by one when the byte[3] goes from 255 to 0. Byte[2] has an initial value of 96, to get an output value starting at 0, when the brake pedal is not pressed, the initial value is subtracted to remove the offset and subsequently multiplied by 255 and added to the value of the byte[3] to provide the output, resulting in a value between 0 and 500.

$$(byte[2] - 96) * 255 + \text{byte}[3] = \text{Brake pedal position}$$

Identifier, x231 discloses when the brake is being pressed, when the byte[3] byte is equal to 2, it lights up the brake lights, represented with a boolean indicator in Figure 26. Even though identifier x208 can still have zero output, powering the brake light consumes about 30W of power. Pressing the brake pedal also actuates the vacuum pump, reading the power consumption shows an increase of 70 Watt, so the vacuum pump consumes about 40 Watt as the stop light consume the other 30 when applying the brakes.

3. Accelerator pedal

The accelerator pedal in de C-ZERO provides input for the motor and motor controller to either accelerate or decelerate the vehicle. The corresponding identifier is x210, where byte[2] ranges from 0 to 250, here 0 corresponds to an untouched accelerator pedal and 250 a fully pressed accelerator pedal.

In the interface, there is an implemented option to simulate the power consumption of the motor, represented in Figure 27. Assuming a linear relationship between the accelerator pedal position and the consumption, with a maximum consumption of 47 kW, multiplying the output value of the accelerator pedal position by 188 simulates the power consumption. Although assuming a linear relation is false, no other direct relation was found and no other data could be found to measure the individual consumption of the motor. Adding this to value of the consumption measured in the Battery Voltage and Current section, results in a simulated total energy consumption while the vehicle is not moving. Dividing the total energy consumption by the remaining capacity left in the battery, provides an indication of how much battery time is left in minutes with the current pedal position.

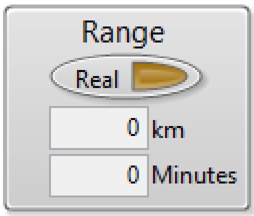


Figure 27: Range estimator

K. Range indicator

As introduced using Figure 27, there is an indicator on the dashboard of the Citroën C-ZERO to display the estimated amount of kilometres the vehicle should be able to reach. Identifier x346 stores the corresponding number of the range in byte[7] of CAN-messages. The value of the byte directly corresponds to the decimal value on the dashboard, therefore it only displays decimal value between 0 and 256. Although the message and corresponding byte value refreshes at approximately 100Hz, it takes time before the value on the indicator updates to display a new value when the power consumption is changed.

L. STEERING WHEEL ANGLE

The angle in which the steering wheel is positioned can be revealed from identifier x236, where byte[0] and byte[1], allow the angle of the steering wheel to be determined using the formula presented below. The output of this formula is degrees, where a straightforward position is 0°, here steering to right gives a positive output, whereas steering to the left provides a negative output.

$$Steering\ Wheel\ Angle = -\frac{\left((byte[0] * 256) + \mathrm{byte}[1]\right) - 4096}{2}$$

Respectively using the outcome of the formula the steering wheel angle indicators on the interface are a dial and a digital indicator, as represented in Figure 28. Here the dial corresponds to the current direction of the steering wheel whereas the digital indicator represents the angle in degrees.

Figure 28: Steering Angle indicator

M. POWER STEERING CONSUMPTION

Power steering helps drivers to manoeuvre the vehicle with less force, providing a bit of comfort, by providing addition force to physical input on steering wheel. This system requires power from the battery but also sensor data, described in paragraph L Steering Wheel Angle, to determine the position of the steering wheel.

Identifier x2F2 contains the power consumption in byte[0]. The byte value ranges from 0 to 60, dividing the value by two gives the power consumption in A. Multiplication by the 14 V coming from the auxiliary battery provides the consumption in Watt. Figure 29 represents the LabVIEW representation.

$$\frac{byte[0]}{2} * 14 = Power\ steering\ consumption\ (W)$$

Locking the power steering, by completely steering to the left or right shows a maximum power consumption of approximately 420 W. Although with normal usage only a small momentarily increase of the power consumption is observed.

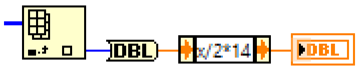


Figure 29: Power steering calculation

N. MOTOR RPM

The motor rpm is enclosed in the last two bytes, byte[7] and byte[8] of identifier x298, the respective value is obtained by the formula below. Figure 31 in paragraph O. Speed and ODO-Meter, represents the rpm value using a gauge and a digital indicator, here the indicator values of the gauge have been set to multiples of 1000.

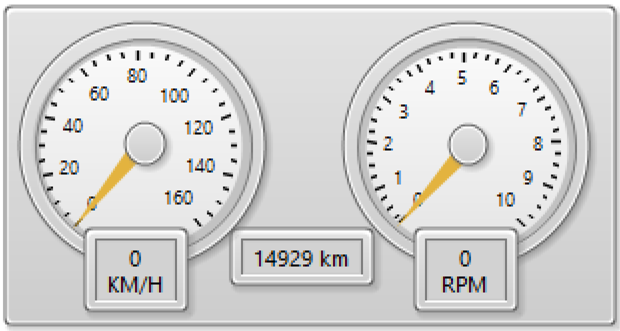


Figure 30: Speed, ODO and RPM

$$[7] * 256 + [8] - 10000$$

Since no other gears than forward and backward are present, the fixed gear ratio and wheel circumference determine the wheel speed. The rear wheel sizes of the Citroën C-ZERO are 175/55 R15, corresponding to a tire width of 175mm, rim size of 15 inches and a ratio width to height of 55 %. Based on the aforementioned specification, using the formula below the resulting tire circumference is 1801.7 mm.

$$\left(\frac{55}{100} * 175 * 2 + 15 * 25.4\right) * \pi = 1801.7\,mm = 1.8017\,m$$

Using the aforementioned information, combining the tire circumference, the motor rpm data and the reduction gear ratio ultimately the wheel speed in km/h can be calculated for a given motor rpm, using the formula below.

$$\left(\frac{1147 * \pi * rpm}{202200}\right) = wheel\ speed\ in\ km/h$$

Visa versa the motor rpm at any given speed in km/h can be calculated using the following formula.

$$\left(\frac{202200 * wheel\ speed}{1147 * \pi}\right) = motor\ rpm$$

O. SPEED AND ODO-METER

The speed displayed on the dashboard is stored in byte[1] of identifier x412, here the corresponding decimal value is does not contain any significant figures. In Figure 31 the gauge and digital indicator correspondingly represent the speed in km/h.

The odometer consists of a pair of 3 conscutive bytes, specifically byte[2], byte[3], and byte[4], here the formula below discloses its value. Using this formula its value is represented in Figure 31 between the speed and rpm indicators.

$$byte[2] * 65536 + byte[3] * 256 + byte[4] = Odometer$$

P. REAR WINDOWS DEFROSTER

The state of the rear window defroster can also be obtained from identifier x424, here the fourth bit of byte[6] changes from zero to one when active, and respectively from one to zero when inactive. A logical 'and' in combination with decimal 8 results in the respective Boolean output to indicate the state. An active rear window defroster has a constant consumption of about 170W. Multiplying the consumption with the logic output of the gives the corresponding consumption, represented in Figure 30.

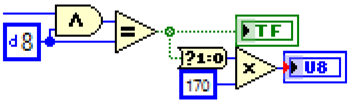


Figure 31: x424 Rear Window Defroster

Q. DOORS

The Citroën C-ZERO is a five door vehicle, the first to bits of the byte[2] from identifier x424 are related to the doors in the vehicle, which serve to indicate whether the driver or a passenger is open or closed. The binary output has three possible cases, firstly all doors are closed, secondly only one or more passenger doors are open and lastly the driver door is open. In the first case the first and second bit are both zero representing decimal 0, in the second case only the first bit is active, representing decimal 1 and in the third case both bits are active, representing decimal value 3. The different cases, states, binary representation and corresponding decimal value are represented in Table 8.

Case	State	Binary	Decimal
1	Doors closed	00	0
2	Passenger open	01	1
3	Diver open	11	3

Table 8: Door state representation

SUMMARY

Using the functionalities of the API provided by PEAK system, a system has been developed as previously described in chapter C. Data Analyser in the Research results section of this report. This system enables the analysis of the CAN-messages on the CAN-bus, which resulted into the finding of the identifiers in Table 9. This table contains all the identifiers along with the title of the chapter and chapter and page numbers.

Identifier	Description	Chapter	Page
x6E1 - x6E4	Cell Voltages	D.1	24
x6E1 - x6E4	Cell Temperatures	D.2	25
x373	Battery Voltage and Current	E	26
x374	State of Charge	F	27
x424	Ignition Switch	G	27
x3A4	Heating and Ventilation	H	28
x424	Lighting Controls	I	29
x418	Drive Selector	J.1	29
x208	Brake pedal	J.2	30
x231	Brake pedal indicator	J.2	30
x210	Accelerator pedal	J.3	30
x346	Range indicator	K	30
x236	Steering Wheel Angle	L	31
x298	Motor RPM	N	32
x412	Speed and ODO-Meter	O	32
x424	Rear Windows Defroster	P	33
x424	Doors	Q	33

Table 9: CAN Identifiers

For a visual representation of the identifiers, a user interface and underlying software have been realised in LabVIEW. By processes the incoming CAN-messages and subsequently visually represents multiple different sets of parameters on the user interface. This interface provides an overview of the electrical consumptions of various components along with several other indicators as represented in Figure 32. Apart from the visual representation the developed software also has the capability to log the incoming messages and corresponding output values to a file.

Utilizing the CAN messages and user interface an overview of the power consumptions from different components has been composed. The overview represented in Table 10, contains the maximum power consumption, but also the default consumption for the different states of the ignition switch.

Device/function	Consumption
Ignition ACC/ON	240 W
Ignition Start/Ready	430 W
Radio	20 W
Lights	100 W
Rear Windows Defroster	170 W
Power steering	420 W
Air-conditioning	800 W
Heating	6.000 W
Traction	55.000 W

Table 10: Consumption overview

A complete overview of the user interface in LabVIEW is represented in Figure 32. In addition to the already provided sub parts of the interface, in this figure also the consumption overview and part for logging to a file is show.

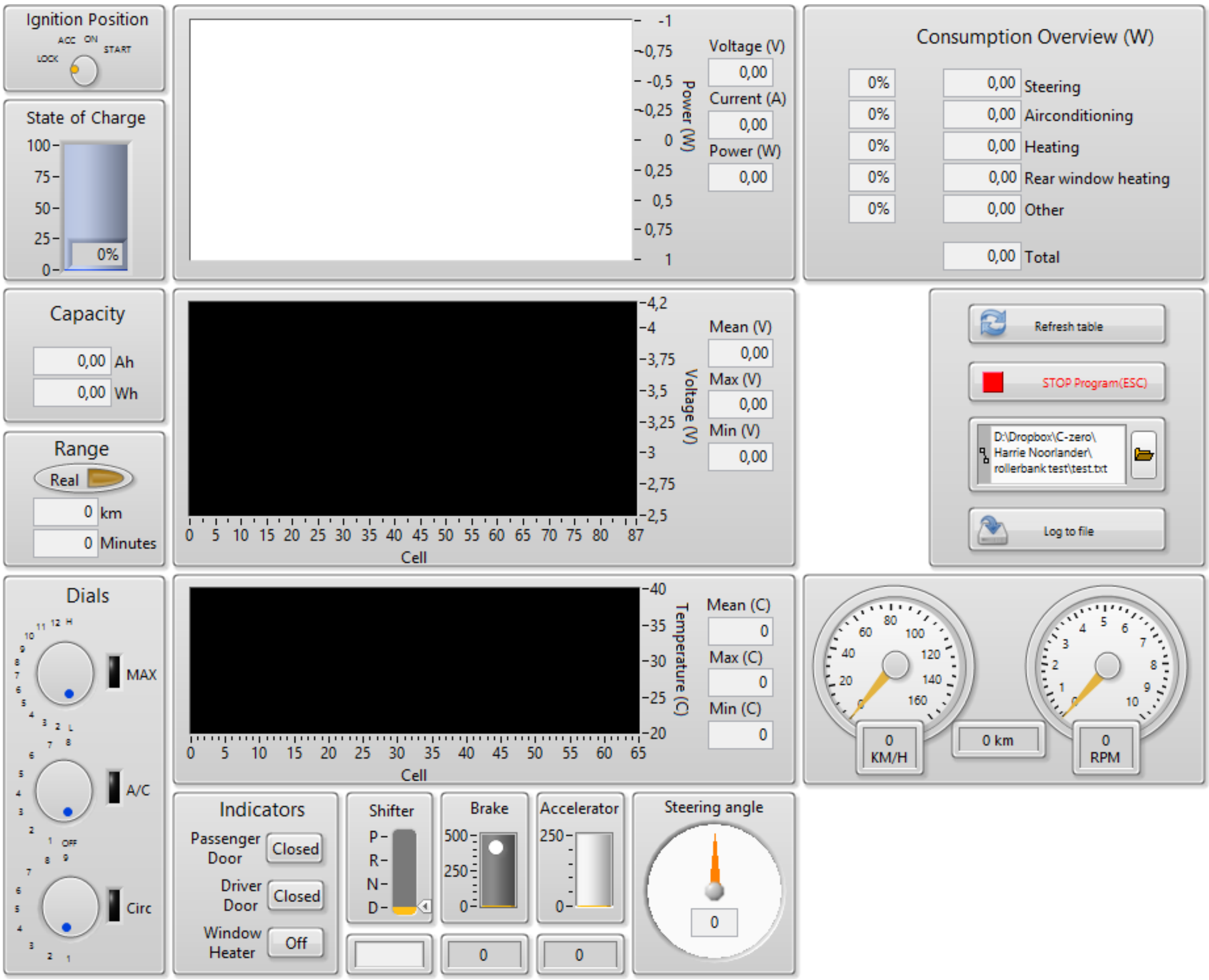


Figure 32: User Interface, reading overview

VI. VALADATION

The measurements from the acquisition system developed in LabVIEW were validated, by comparing them to the readings from DiagBox. Furthermore, a series of dynamometer tests have been executed to validate the measurements regarding the traction part of the vehicle.

1. DiagBox

DiagBox is the official system from Citroën and Peugeot for diagnosing their vehicles. With this software, parameters can be selected and monitored. At PSA Peugeot Citroën Académie Nederland in Nieuwegein a Citroën C-ZERO and the diagnosing system were used for validation[12].

Comparing the processing speed and accuracy of the two systems shows that the self-developed system in LabVIEW is faster and more accurate, compared to the DiagBox interface with a delay of about 5 seconds. Unfortunately, this system does not disclose formulas or identifiers from the CAN-messages, only a given name for the selected parameter and its corresponding output.

Using the DiagBox software the identifier and formula for the power consumption for power steering was found. This parameter has later on been implemented into the LabVIEW software by adding an additional case structure, see paragraph M in the Research results section.

A difference between the sum of the individual cell voltages and the measured voltage from Chapter E. Battery Voltage and Current was noticed. Comparing the output of the cell voltages from DiagBox to those from LabVIEW showed an offset of 0.12V for each cell. After the offset was added into the formula to get the cell voltages an identical result was displayed.

Although the DiagBox software had many capabilities its functionality was limited, for example some indicators such as open door indicators or rear windows heating could not be displayed. In addition the DiagBox software does not have the ability to log its readings. Therefore comparing of the results had to be done manually.

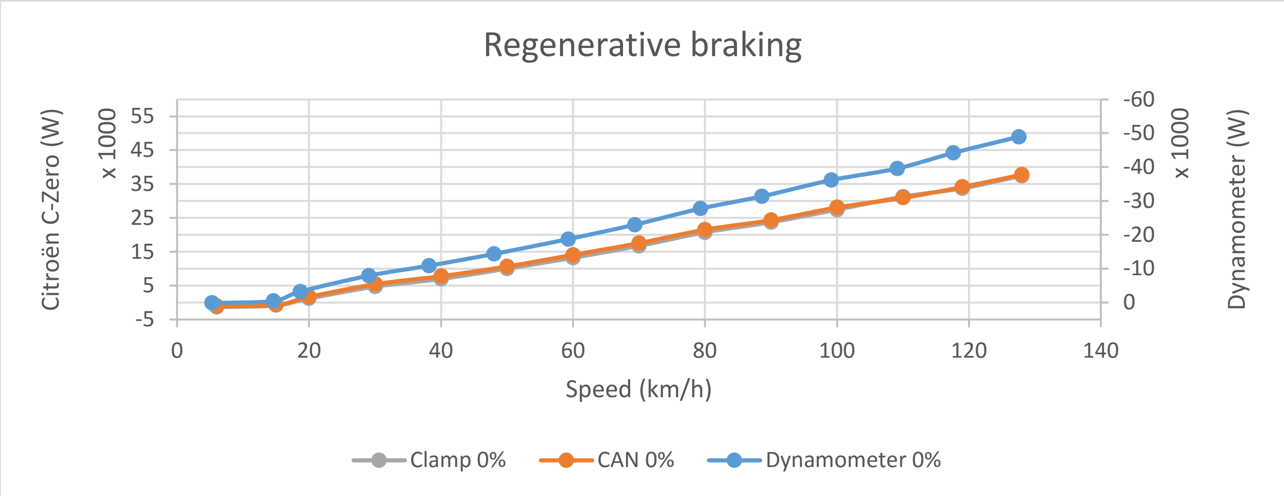
The remaining results were validated, and showed equal outcomes, however the accuracy from DiagBox was sometimes lower. The lower accuracy seems to be the result of only using the first byte of a byte pair.

2. Dynamometer

For the dynamometer tests, the rear wheels of the Citroën C-ZERO were places on the dynamometer to investigate the motor and controller characteristics of the vehicle. Using a current clamp, the amperage from the traction battery to the motor controller was measured. The readings from this clamp was displayed and recorded using a multimeter. The used current clamp was a Fluke 80i-110s. To get the power consumption the voltage reading from the CAN-bus, which was validated using DiagBox was used in order to avoid harming the high voltage cables.

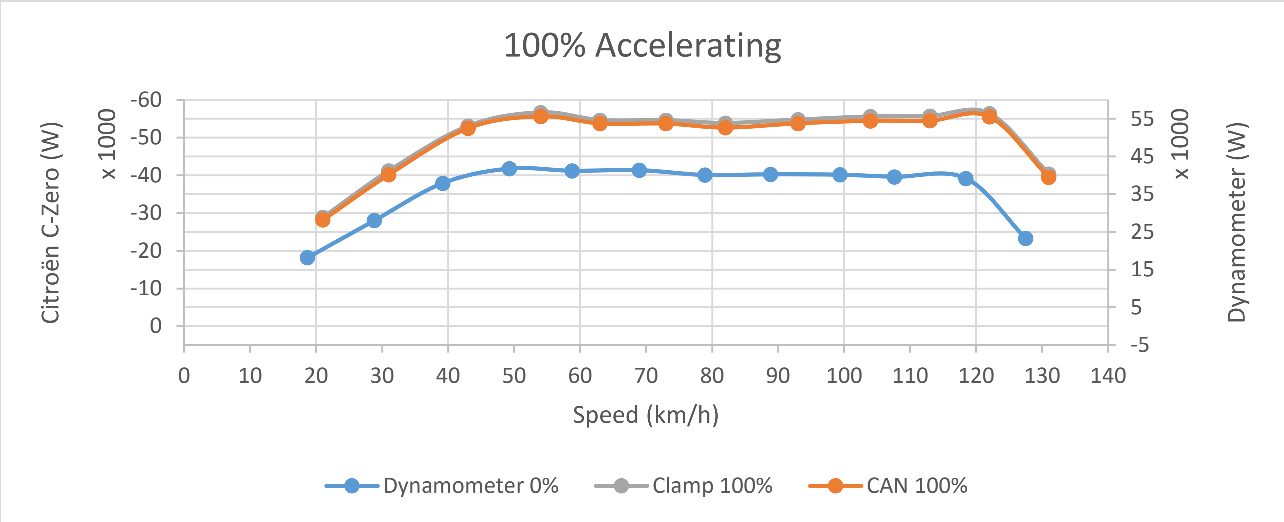
Using the dynamometer, three series of test were executed, firstly a regenerative test, secondly a 100% acceleration test and thirdly a 60% acceleration test. Each series the dynamometer was set to maintain a specified constant speed and ESP was disabled, as the front wheels were not rotating. In the corresponding graphs, the x-axes represent specified speeds recorded by the dynamometer and the rear wheels of the Citroën C-ZERO. On the primary y-axes on the right hand side the respective in- and output powers from the dynamometer are represented, whereas the secondary y-axis on the left provides the powers recorded using the current clamp as well as the CAN-bus reading from the developed LabVIEW program.

In the regenerative braking test, the dynamometer drives the wheels of the Citroën C-ZERO at specified speeds, here neither the brake or accelerator pedal is being pressed. In Graph 1 a negative power is observed for the dynamometer, as it is providing energy, whereas the Citroën C-ZERO measurement is positive, as it is gaining energy and respectively charging its cells in the battery pack. From the graphical representation can be seen that all three measurements follow the same trend, where the clamp and CAN-bus measurement are almost identical. An increasing difference in power as the speed increases is noticeable, at nearly 130 km/h the CAN-bus and clamp measurement indicate nearly 38 kW, whereas the dynamometer is almost at 49 kW.



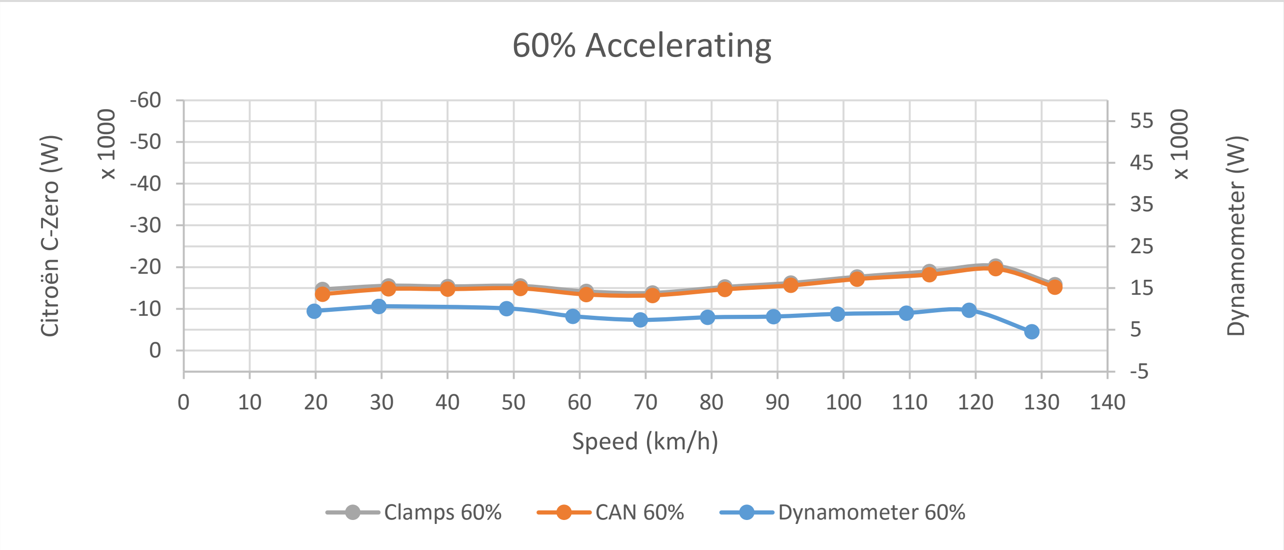
Graph 1: Regenerative braking test results

The second and third test run had similar test settings for the dynamometer, however here the accelerator pedal in the Citroën C-ZERO is 100% pressed for the second run and held at a constant 60% for the third run. As a result, in Graph 2 and Graph 3 a negative power for the Citroën C-ZERO and the positive power for the dynamometer is shown. Also from the results from these two tests a similar difference is noticeable, when comparing the power readings from the dynamometer to the results from CAN-bus and current clamp.



Graph 2: 100% Accelerating test results

Maintaining the same scale throughout all three graphs, allows comparing, from which can be seen that the measured current on the CAN-bus is almost identical to the measurements recorded by the current clamp. Comparing the results from the CAN-bus and clamp to the dynamometer results shows an offset between the power consumption readings. This can be due the inefficiency of the converter between the battery and the motor, but is also partially caused by wheel slip, as some rubber residue behind the vehicle was present after the tests. Also on a dynamometer the tire has two contact points, whereas while driving on the road it would normally only have one. This also adds additional friction causing heat, which can be added to this power loss. Henceforward, there are multiple reasons why there is a difference between the measurements.



Graph 3: 60% Accelerating test results

VII. CONCLUSION

The request from the Automotive Institute of the HAN University of Applied Sciences in Arnhem was to develop a system to enable them to analyse the energy flow in an EV. With the goal to provide new material for the education to update their existing course material. To conduct this research a Citroën C-ZERO was provided. By using a PCAN-USB adapter from PEAK system, the CAN-bus for internal communication has been used to acquire and deciphering data from the ODB connector in the Citroën C-ZERO.

Throughout the project, the developed underlying software and user interface has been tested, improved and optimized to increase its performance. New findings of parameters led to extra functionalities, but also increased its overall complexity, here in Table 9 in the Summary provides an overview of the identifiers.

For the verification and validation various tests have been executed using DiagBox and dynamometer, the validation of the obtained results guarantees reliability of the obtained results. Therefore, the developed system is a success as it can used to accurately analyse the energy flow of the Citroën C-ZERO in real time.

Furthermore, the system allows logging of CAN-messages and is ready to receive additional readings. This compatibility enables the other graduation project to provide sensor data from external connected sensors. Hereby allowing real time monitoring of the energy flow from other devices in the Citroën C-ZERO, which unfortunately due to complexity and time contains is still under development.

VIII. RECOMMENDATIONS

To extend the functionality of the monitoring system, the development of the measurement system has to continue, to allow measurements of the energy flow from other components in the Citroën C-ZERO. The combination of systems provides the ability to monitor the energy flow of specific components in real time, which can be used for practicums.

The performed test on the dynamometer were limited, as it is taken in a controlled laboratory environment. Performing tests on a private road or test circuit takes into account the aerodynamics and rolling resistance. Comparing the results gives a more detailed overview of the efficiencies.

Further testing of untested parameters can be implemented to provide an even more detailed overview, for features such as the windscreen wipers and windshield washer, but also the heated seat option for the driver.

Research and analyses of the heating system to find relationships between air-conditioning and the heater can result in increasing the efficiency of the vehicle, as the energy consumption can be minimised. For example, a warning when the heater is on when the cabin temperature is above a certain threshold. Further development potentially allows full automation to turn off the demisting/defrosting of the windows or the heated seat.

Another recommendation is to research the influence of outside temperatures on the characteristics of the battery, as can be seen in the user manual, the charging time varies with different outside temperatures, hence a low outside temperature might also decrease the performance of the vehicle [8].

Using the gathered results a financial overview, comparing a vehicle with ICE to an EV can provide insight into the costs efficiency, to give a general idea for the students.

Current navigation systems have already been developed to efficiently route vehicles, using the messages on the CAN-bus more options can be implemented. For example, a route specialized for electric vehicles might benefit its reachable range.

Investigating the behaviour of regenerative braking with a fully charged battery pack has not been executed, as this could damage the cells if there is no safety system for dissipating the energy. To extend the analyses of the energy flow this behaviour can be researched. When testing it might be that the regenerative braking will be deactivated.

REFERENCES CITED

1. HAN. Elektrische Citroën C-ZERO in onderwijs en onderzoek HAN Automotive - HAN.nl [Internet]. 2014 [cited 2015 Mar 16]. Available from: http://www.han.nl/opleidingen/bachelor/autotechniek/vt/over-autotechniek/nieuws/nieuws/citroen-c-zero-han-automo/

2. OliNO. Electric Car Citroën C-Zero | OliNo [Internet]. 2010 [cited 2015 Mar 19]. Available from: http://www.olino.org/us/articles/2010/07/22/electric-car-citroen-c-zero

3. 2014 Mitsubishi i-MiEV At-A-Glance [Internet]. Mitsubishi Motors. 2014 [cited 2015 Mar 26]. Available from: http://media.mitsubishicars.com/releases/31f1c4c1-3f67-479a-8bbe-edc0cdebe8b9

4. Ecodrive. eco-drive | Citroën C-Zero [Internet]. 2012 [cited 2015 Mar 18]. Available from: http://www.eco-drive.co.uk/Citroen-C-Zero

5. Kabebayashi T, Itakura H. Motor Drive System for i-MiEV and Standard Type Motor Drive System for Electric Vehicle (EV). MEIDEN Rev [Internet]. 2014;2(161):14–8. Available from: http://www.meidensha.co.jp/review/ereview-201402/article-201402-0014.pdf

6. Litium Energy Japan Steadily Increasing Lithium-ion Battery Production Mitsubishi Motors Selects Batteries for New i-MiEV High-end Model G. GS YUASA [Internet]. 2011;1–3. Available from: http://lithiumenergy.jp/en/newsrelease/pdf/20110706e.pdf

7. Gianfranco P. Lithium-Ion Batteries: Advances and Applications. 1st ed. 2014. p. 228–9.

8. Citroën. Handbook [Internet]. 2014 [cited 2015 Mar 16]. Available from: http://service.citroen.com/ddb/modeles/czero/czero_czero/ed01-14/en_us/contenu/AC-C-ZERO_DAD_01_2014_GB.pdf

9. EvMeerat. Winter Range: Citroen cZero Electric Car and the Heating Issue [Internet]. 2012 [cited 2015 Mar 18]. Available from: http://evmeerkat.com/cz/winter-range-citroen-czero-electric-car-and-the-heating-issue/

10. Boxwell M. The Electric Car Guide - 2015 Edition. Coventry: Greenstream Publishing; 2014.

11. Van Sterkenburg S, Rietveld E, Rieck F, Veenhuizen B, Bosma H. Analysis of regenerative braking efficiency - A case study of two electric vehicles operating in the Rotterdam area. 2011 IEEE Veh Power Propuls Conf VPPC 2011. 2011;

12. Académie PSA Peugeot Citroën. DiagBox. Nieuwegein, The Netherlands; 2015.

13. Hall-effect Open-loop Current Sensor Application [Internet]. Honeywell. 2007 [cited 2015 Apr 9]. Available from: http://sensing.honeywell.com/index.php?ci_id=51431

APPENDIX

A. FUSE HOLDERS, RATINGS AND FUNCTIONS

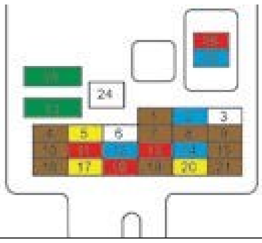
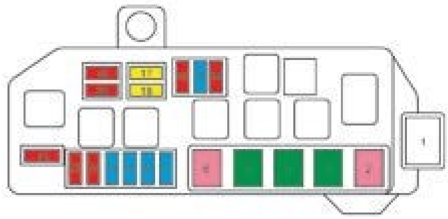
Dashboard fuses			Front compartment fuses		
					
Fuse	Rating	Functions	Fuse	Rating	Functions
1	7.5 A	Left hand front and rear side-lamps	1	-	Not used.
2	15 A	Accessory socket.	2	30 A	Electric motor.
3	-	Not used.	3	40 A	Internal fuse.
4	7.5 A	Starter.	4	40 A	Radiator fan.
5	20 A	Audio system.	5	40 A	Electric windows.
6	-	Not Used.	6	30 A	Vacuum pump.
7	7.5 A	Vehicle equipment, right hand front and rear side-lamps.	7	15 A	Main battery ECU.
			8	15 A	Third brake lamp.
8	7.5 A	Electric door mirrors.	9	15 A	Front fog-lamps.
9	7.5 A	Supervisor controller.	10	15 A	Water pump.
10	7.5 A	Air conditioning.	11	10 A	On-board charger.
11	10 A	Rear fog-lamp.	12	10 A	Direction indicator.
12	15 A	Door locking.	13	10 A	Horn.
13	10 A	Courtesy lamp.	14	10 A	Daytime running lamps.
14	15 A	Rear wiper.	15	15 A	Battery fan.
15	7.5 A	Instrument panel.	16	10 A	Air conditioning compressor.
16	7.5A	Heating.	17	20 A	Right hand dipped beam.
17	20 A	Heated seat.	18	20 A	Left hand dipped beam, headlamp adjuster.
18	10 A	Option.			
19	7.5 A	Door mirror heating.	19	10 A	Right hand main beam.
20	20 A	Windscreen wiper.	20	10 A	Left hand main beam.
21	7.5 A	Airbags.			
22	30 A	Heated rear screen.			
23	30 A	Heating.			
24	-	Not used.			
25	10 A	Radio.			
26	15 A	Passenger compartment fuse.			

Table 11: Fuse holders, ratings and functions.