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Development of a Novel Method for Lithium-Ion Battery Testing on Heavy- Duty Vehicles

Pontus Svens

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Abstract

Increasing demands for lower environmental impact from vehicles, including heavy-duty vehicles, have driven several vehicle manufacturers to consider adding hybrid electrical vehicles (HEV's) to the product portfolio. Present research on batteries for HEV's is mainly focused on lithium-ion battery chemistries, since lithium-ion batteries has the most promising technical potential compared to other types of batteries. However, the uncertainty regarding battery lifetime combined with a high battery cost can have a negative impact on large scale commercialisation of heavy-duty hybrid vehicles in the near future.

A large part of present lithium-ion battery research is focused on new materials, but there is also research focusing on ageing of already established lithium-ion battery chemistries. Cycle ageing of batteries often includes complete charging and discharging of batteries or the use of standardized test cycles. Battery cycling in real HEV applications is however quite different compared to this kind of laboratory testing, and real life testing on vehicles is a way of verifying the soundness of laboratory ageing.

The aim of this study was to develop a test method suitable for real life testing of lithium-ion batteries for heavy-duty HEV-usage, with the purpose of investigating the correlation of battery ageing and usage in real life applications. This concept study includes both cell level battery cycling and performance testing on board vehicles. The performance tests consist of discharge capacity measurements and hybrid pulse power characterization (HPPC) tests. The main feature of this test equipment is that it is designed to be used on conventional vehicles, emulating an HEV environment for the tested battery. The functionality of the equipment was verified on a heavy-duty HEV with satisfying results. Results from real life testing of 8 batteries using the developed test equipment on four conventional heavy-duty trucks shows that the concept of comparing battery ageing with battery usage has a most promising potential to be used as a tool when optimizing battery usage vs. lifetime. Initial results from this real life study shows significant differences in state of charge (SOC) and power distributions between cycled batteries, but so far only small differences in ageing. Lithium-ion batteries of the type lithium manganese spinel/lithium titanate (LMO/LTO) were used in this study.

Sammanfattning

Ökande krav på minskad miljöpåverkan från fordon, inklusive tunga fordon, har drivit flera fordonstillverkare till att addera hybridiserade fordon till produktportföljen. Forskning på hybridfordonsbatterier är idag huvudsakligen inriktad på litiumjonbatterikemier, vilken har den mest lovande tekniska potentialen jämfört med andra typer av batterikemier. Det finns idag en risk att osäkerheten kring litiumjonbatteriers livslängd i kombination med en hög batterikostnad kan ha en negativ inverkan på en storskalig kommersialisering av tunga hybridfordon inom den närmsta framtiden.

En stor del av batteriforskningen är inriktad på nya material, men det finns även forskning som fokuserar på åldring av redan etablerade litiumjonbatterikemier. Vid åldringsprov används ofta standardiserade testcykler eller cykler där batterierna blir fullständigt laddade och urladdade. Cykling av batterier i verkliga förhållanden skiljer sig dock från den typen av laboratorietester och provning på fordon är därför ett sätt att kontrollera att laboratorieprovning ger relevanta resultat gällande åldring.

Syftet med denna studie var att utveckla en testmetodik lämplig för provning av litiumjonbatterier för tunga hybridfordon i verklig drift, med syfte att undersöka kopplingen mellan batteriers åldrande och hur det används. Detta koncept inkluderar battericykling på cellnivå och möjligheten att utföra batteriprestandatester på fordon, där prestandatesterna består av kapacitetsprov och pulsprov. Den viktigaste egenskapen hos den utvecklade testmetodiken är att provning sker på konventionella fordon genom att emulera en hybridmiljö för det testade batteriet. Funktionaliteten hos den utvecklade testutrustningen verifierades på en tung hybridlastbil med goda resultat. Resultaten från en fältstudie av 8 batterier på 4 lastbilar där den utvecklade testutrustningen användes påvisar att testmetodiken har en lovande potential att kunna användas som ett verktyg vid optimering av utnyttjandegrad och livslängd för HEV-batterier. De initiala resultaten från denna fältstudie påvisar skillnader i laddningsgradsfördelning och batterieffektfordelning mellan cyklade batterier, men ännu bara små skillnader i åldring. Litiumjonbatterier av typen litiummanganspinel/litiumtitanat (LMO/LTO) användes i denna studie.

List of papers

- I. **Novel Field Test Equipment for Lithium-Ion Batteries in Hybrid Electrical Vehicle Applications**
Pontus Svens, Johan Lindström, Olle Gelin, Mårten Behm and Göran Lindbergh
Published in *Energies* 2011;**4**: 741-57

- II. **HEV lithium-ion battery testing and driving cycle analysis in a heavy-duty truck field study**
P. Svens, J. Lindström, M. Behm and G. Lindbergh
Manuscript submitted to *ECS Transactions*

Division of work between authors

In Paper I, programming of the software for the electronic control unit was done by Olle Gelin. All experiments and the writing were done by Pontus Svens for both papers.

“Kunde det verkligen i ett civiliserat land finnas människor, karlar rentav, som inte hade den ringaste kännedom om elektrokemiska processer?”

Citation from the book ”Adam och Eva” by Arto Paasilinna

Table of contents

1	Introduction	1
1.1	Hybrid electrical vehicle technology	1
1.2	Driving forces for heavy-duty HEV's	2
1.3	The battery system in hybrid electrical vehicles	4
1.4	Battery lifetime testing.....	6
1.5	Previous work.....	7
1.6	Aim of this work	7
2	Materials and equipment	8
2.1	Materials	8
2.2	Laboratory equipment	8
3	Development and verification.....	8
3.1	Test equipment design concept.....	8
3.2	Hardware.....	9
3.3	Software.....	13
3.3.1	Measurements	13
3.4	Mounting.....	13
3.5	Test equipment verification.....	14
3.6	Onboard battery performance testing	16
3.7	Measurement data collection	18
4	Results from field tests	19

4.1	Drive cycle analysis.....	19
4.2	Battery performance.....	23
5	Discussion	25
6	Conclusions	26
7	Acknowledgements	28
8	References	29

1 INTRODUCTION

1.1 HYBRID ELECTRICAL VEHICLE TECHNOLOGY

UNECE has suggested that a hybrid electrical vehicle, HEV, should be defined as follows:

“Hybrid electric vehicle (HEV)” means a vehicle that, for the purpose of mechanical propulsion, draws energy from both of the following on-vehicle sources of stored energy/power:
- *a consumable fuel*
- *an electrical energy/power storage device (e.g.: battery, capacitor, flywheel/generator etc.)”[1]*

This definition implies that there are two energy storages onboard an HEV. Figure 1 shows the two main types of hybridization, the parallel and the serial hybrid systems. [2].

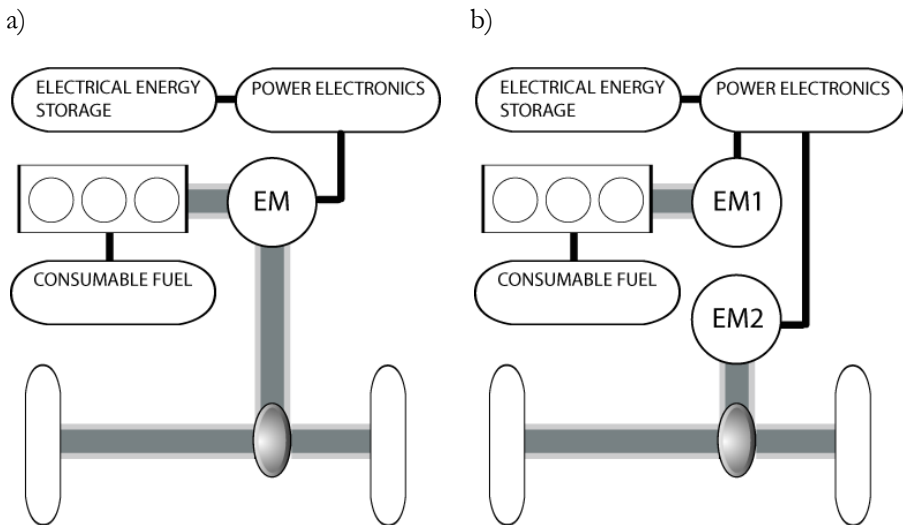


Figure 1. a) Parallel hybrid system b) Serial hybrid system

These two concepts can also be combined which is done in for example the Toyota Prius. The parallel hybrid vehicle system has, besides the conventional internal combustion engine (ICE) and the fuel, an electrical motor (EM) and an electrical energy storage. The electrical energy is transferred bidirectionally between the electrical energy storage and the EM via the power electronics.

When the EM is propelling the vehicle, by itself or in parallel with the ICE, the electrical energy storage is discharged. The electrical energy storage is charged when the EM is used instead of the mechanical brakes when breaking the vehicle or by using excess power from the ICE while the vehicle is propelled. The serial hybrid system has an additional EM compared to the parallel hybrid system. In addition, there is no mechanical connection between the ICE and the wheels. In this case, the ICE is only powering EM1 which works like a generator producing electrical power that in turn is used for propelling the vehicle via EM2, or for charging the electrical energy storage. In addition to mechanical braking, heavy-duty vehicles have other possible ways of braking: engine, exhaust and retarder braking [3]. In a heavy-duty parallel HEV, EM-braking can be used in combination with each of those methods. The parallel hybrid is a less costly system compared to the serial hybrid system since fewer components are needed. For example, only one EM is needed in a parallel hybrid, and it can also be smaller compared to the EM in a serial hybrid. Another advantage with the parallel hybrid is a higher total efficiency due to fewer energy conversions. Due to those reasons, parallel hybridization is most common for heavy-duty vehicles. However, since serial hybridization provides a better flexibility regarding placement of the components, it is sometimes used in buses to optimize the available space for passengers.

1.2 DRIVING FORCES FOR HEV'S

Even if emissions from each individual vehicle have been considerably reduced during the last decades [4, 5], emissions from the transport sector worldwide has increased considerably with the growing number of vehicles [6, 7]. To be able to handle this, new vehicle technologies such as hybridization have started to emerge. The introduction of HEV's to the market has the potential of significantly reducing tail pipe emissions. The reduction of vehicle fuel consumption, and hence lowered CO₂-emission, has historically followed emission legalisations. In Europe for example, vehicle emission regulations have been used since 1988, starting with directive 88/77/EEC for vehicles with diesel engines and directive 88/76/EEC for vehicles with petrol engines [8, 9]. The present European emission standard is called Euro 5, and it was introduced in late 2008. The introduction of the vehicle emission standard Euro 5 addressed a lowered NO_x limit compared to the former Euro 4 standard [10, 11]. The upcoming Euro 6 standard is meant to be introduced in 2013. For diesel vehicles lowered emission levels of both hydrocarbons and

NO_x will be introduced. The goal for European vehicle manufacturers that produce heavy-duty vehicles with an allowed total weight over 12000 kg (class N3 vehicles) is to meet the Euro 6 standard using existing and mature technology such as exhaust gas regulation (EGR), selective catalytic reduction (SCR) and particle filters. Even if hybridization is not needed to meet the Euro 6 standard, experts are convinced that hybridization will play an important role in vehicle technology in the future [12-15].

Another benefit with hybridization is the potential of reducing local emissions, for example decreasing inner city air pollution by introducing hybrid buses, a fact that London politicians have become aware of. The regional traffic company in London, Transport for London (TfL) will gradually change all inner city buses in London to hybrid buses. At present, 56 hybrid buses from VOLVO, Wright, ADL and Optare are in use and an order for 50 additional hybrid buses was placed in the spring 2010. By 2011, 300 hybrid buses are planned to be in operation in London, and starting from 2012 all new buses will be hybrids [15, 16]. Other cities are following this trend of introducing hybrid city buses. For example, a test fleet of 6 ethanol hybrid buses from Scania CV AB was evaluated by the regional traffic company in Stockholm (SL) between 2009 and early 2010. The fuel consumption for the tested hybrid buses were predicted to be lowered by 25 % compared to conventional buses operating the same route, and in combination with ethanol fuel, the emissions of fossil CO₂ had the potential of being reduced with 90% [17]. The outcome of the tests showed a reduction of fuel consumption by 11% to 19% compared to the corresponding conventional bus, depending on driving cycle [18]

The motivation for transportation companies to choose hybrid vehicles instead of conventional vehicles needs to be both economical and environmental. Fuel savings is obviously a major driving force and hence the additional cost for the hybrid system needs to be low enough to achieve a reasonably short payback time. Companies that have a policy to be “green” could also improve their public image by having hybrid vehicles in the fleet. Even if there is a potential for reducing CO₂-emissions by using for example ethanol as fuel, a global study performed by the company Arthur D. Little regarding the usage of different fuel types and hybridization of heavy-duty vehicles predicts that diesel fuel still will be the dominating source of energy for the transport sector in 2020 [19]. However, the trend in this study is that the usage of alternative fuels

will increase while diesel fuel usage will stagnate, or even decline. Furthermore, hybridization is predicted to be an increasing technology for heavy-duty vehicles where the majority of hybridization will be within city buses and distribution trucks. The study also concludes that the major obstacle for hybrid vehicle development is the additional energy storage; the HEV- battery system.

1.3 THE BATTERY SYSTEM IN HYBRID ELECTRICAL VEHICLES

An HEV-battery system basically consists of a number of battery cells with individual monitoring and cell balancing system and a cooling system placed in a rigid container. The cell monitoring and balancing systems keep all cell voltages within operating limits and the cooling system guarantees operation within temperature limits. Today the most promising battery technology for both passenger car HEV's and heavy-duty HEV's is lithium-ion battery systems. This is due to the high energy and power densities compared to other battery technologies, such as lead-acid and nickel-metal hydride (NiMH).

The lithium-ion battery is also known as the “rocking-chair” battery since lithium-ions (Li^+) are moving between the electrodes during charge and discharge without being reduced to metallic form. This incorporation of lithium-ions into the crystal structure of the electrode materials is called intercalation. Figure 2 shows the principle of the lithium-ion battery during discharge, displaying the negative and the positive electrode with the electrolyte soaked separator in between.

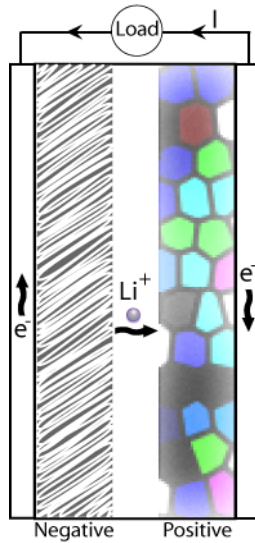


Figure 2. *Principle of a lithium-ion battery during discharge*

During discharge, an oxidation process is present at the negative electrode and a reduction process at the positive. Electrons are hence generated at the negative and consumed at the positive electrode. This produces an electric current that travels from the positive to the negative electrode via an external load. Simultaneously, the lithium-ions that are deintercalated at the negative electrode travel in the electrolyte through the separator to be intercalated into the positive electrode.

Research on lithium-ion batteries started already in the 1970's, but it took until 1990 for the breakthrough that lead to commercialization and market introduction by Sony Corporation [20]. Some examples of technical issues with those early lithium-ion batteries intended for consumer electronics were short lifetime and safety. Although present lithium-ion batteries are safer and have improved lifetime, the operating environment and the usage of the batteries in an HEV are quite different compared to consumer electronics applications. This requires new strategies regarding usage of the batteries to obtain optimal performance and long lifetime in HEV applications.

One general issue with battery systems for HEV's is the high cost [13, 21]. Even with an estimated cost for a lithium-ion battery system as low as

\$300/kWh, the growth for light-duty HEV's is predicted to be rather small for the next 30 years [12, 13]. Another major issue with battery systems for HEV's in general is battery ageing [22]. This is even more problematic for heavy-duty hybrid vehicles compared to for example hybrid passenger cars since the run-time is much higher in the previous case. A battery pack is most likely not predicted to last the whole lifetime of a heavy-duty HEV, and due to high battery cost, one or several battery pack replacements could jeopardize the business case for a heavy-duty HEV compared to the corresponding conventional vehicle. It is hence of great importance that battery lifetime estimations are accurate and that battery usage is optimized for long life.

1.4 BATTERY LIFETIME TESTING

To ensure optimal HEV-battery lifetime, it is important to understand how the batteries are aged by performing tests in the lab and in real life. Battery ageing in the lab can be performed by continuously running tests that cycle between full charge and full discharge or by using specific test cycles that intend to be closer to the actual usage. There are several standardized test cycles available from different organizations, for example ISO, USABC and EUCAR [23-25]. Since ageing of batteries is time consuming different ways of accelerating ageing can be used to shorten the test time, e.g. elevated battery temperature or increased allowed battery voltage span. Using elevated temperature to accelerate battery ageing is however problematic since certain chemical reactions depending on battery chemistry are more temperature dependent than others [22]. This could make a battery age differently compared to real life usage and would hence not give a correct estimation of the lifetime. Even if battery testing in the laboratory is performed at a similar temperature compared to real life applications, a laboratory test cycle is not completely reflecting how a HEV-battery is used in real applications. One problem with estimating battery lifetime from laboratory measurements is that the usage of the battery can have a large spread in the real application if the hybrid vehicle strategy is allowing that. To handle this, testing can be performed on an estimated worst case scenario to have a marginal for the spread of battery usage. Results from too harsh testing could however lead to a too intense battery service plan for the customer that would add unnecessary cost. A method for estimating battery lifetime more accurately could for example result in extended time between battery services and consequently lowered cost for the customer.

1.5 PREVIOUS WORK

Results published on battery ageing from real life tests have in the past mainly focused on NiMH-batteries, since those batteries up to now have been the best choice for hybrid passenger car manufacturers (e.g. Toyota and Honda). There are only a handful of publications available regarding real life studies on lithium-ion batteries for propulsion of vehicles, and nothing on heavy-duty vehicles. Liaw et. al. have published several articles on real life studies on plug-in hybrids, focusing on driving cycle analysis (DCA) in their work [26-29]. A large study on HEV-battery ageing was performed by Idaho National Lab (INL) between 2001 and 2005. The HEV's in that test were equipped with NiMH-batteries and battery capacity loss was calculated from measurements at the beginning and at the end of the test [30, 31].

1.6 AIM OF THIS WORK

The overall aim for this work was to develop a method that can be used as a tool when trying to minimize the long term cost of a hybrid battery system on a heavy-duty HEV. The method needs to take into account how battery ageing and vehicle usage are correlated to be able to aid hybrid battery system optimization. Only using conventional laboratory measurements to perform this task is however problematic since battery usage can have a large spread in real application if the hybrid vehicle strategy allows for that. Real life battery testing onboard vehicles is hence an important complement to the laboratory measurements. In addition, by performing onboard battery testing on conventional vehicles a better availability of vehicles is obtained, and by scaling down the onboard testing to cell level both cost and test time benefits can be obtained compared to full scale HEV testing. Another big advantage with single cell testing on conventional vehicles is the possibility to periodically perform onboard battery performance measurements during a test, something that is usually not possible when testing on full scale HEV's. However, this concept will exclude some parameters that can influence battery ageing compared to full scale pack tests. For example, SOC-level differences and temperature differences between cells in a pack will not be addressed. Hence, this test method should be considered to be a complement to laboratory testing and tests on HEV's rather than a substitute.

This work demonstrates a tool for easier real life battery testing and provides a method that can make it easier to perform battery lifetime estimations connected to battery usage on HEV's.

2 MATERIALS AND EQUIPMENT

2.1 MATERIALS

The batteries used in the design phase of the test equipment were commercial graphite/lithium iron phosphate (LFP/C) cells rated to 3.6Ah. Batteries used for real life testing were commercial lithium manganese spinel /lithium titanate (LMO/LTO) cells rated to 3.1Ah.

2.2 LABORATORY EQUIPMENT

Initial battery capacity measurements as well as the final capacity measurements on the batteries in the field test were performed using a Solartron SI 1287 potentiostat. The batteries were placed in a BIA MiniBox MTH4-30 or a Firlabo SP260BVEHF temperature chamber during initial measurements.

The validation of the battery heating performance was executed in a BIA MiniBox MTH4-30 temperature chamber, and the temperature measurement was done with a thermocouple of type K connected to a NI 9219 data acquisition device.

3 DEVELOPMENT AND VERIFICATION

The test equipment used for the real time battery cycling was specified, designed, manufactured and verified within this project. The purpose of the test equipment is to perform real life cell level battery testing on heavy-duty vehicles to a low cost and with relatively short lead time.

3.1 TEST EQUIPMENT DESIGN CONCEPT

The real life battery test method for heavy-duty vehicles is based on the concept that the existing starter battery in the vehicle can be used for both charging and discharging the tested battery cell. Using this available electrical power together with vehicle sensor information obtained from the internal

communication network, called Controller Area Network (CAN), made it possible to emulate an HEV-environment for a battery cell [32]. The test equipment hardware consists of three parts; (1) the electronic control unit (ECU), which contains software for converting vehicle sensor data to corresponding battery currents, (2) the battery management unit (BMU), which contains hardware and software performing battery cycling and measurements, along with data storage handling, and (3), the device under test (DUT) which includes the tested battery cell, two temperature sensors, eight heating resistors and one aluminum holder. The concept is depicted in figure 3.

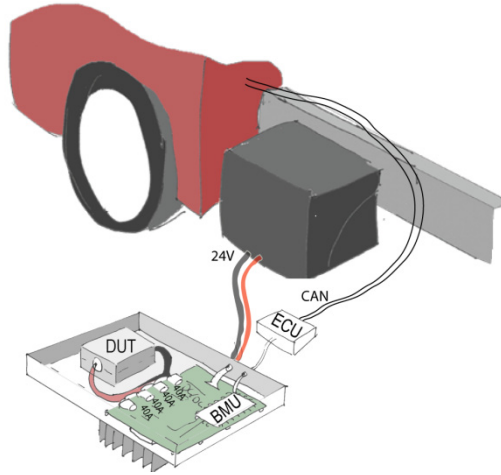


Figure 3. Overview of the HEV-emulator concept using available electric power from the vehicle starter battery to cycle the tested battery cell (DUT) controlled via sensor information available from vehicle CAN-communication network
Illustration: Olle Gelin

Vehicle sensor information on CAN is continuously monitored and this information makes it possible to cycle the tested battery in real time with a current depending on the vehicle driving pattern. This concept has the possibility to obtain information about battery ageing in a more cost efficient way compared to using full scale HEV's.

3.2 HARDWARE

The system was designed so that the communication with the vehicle was handled solely by the ECU and all battery cell interactions were handled by the BMU. This division enables hybrid vehicle specific software to be exclusively

implemented in the ECU, making it possible to use the BMU together with other HEV software systems.

The main parts of the BMU hardware are the power electronics in the form of a step-up, step-down DC/DC-converter, the microprocessor and the memory card, all placed on the same printed circuit board (PCB), as shown in figure 4a.

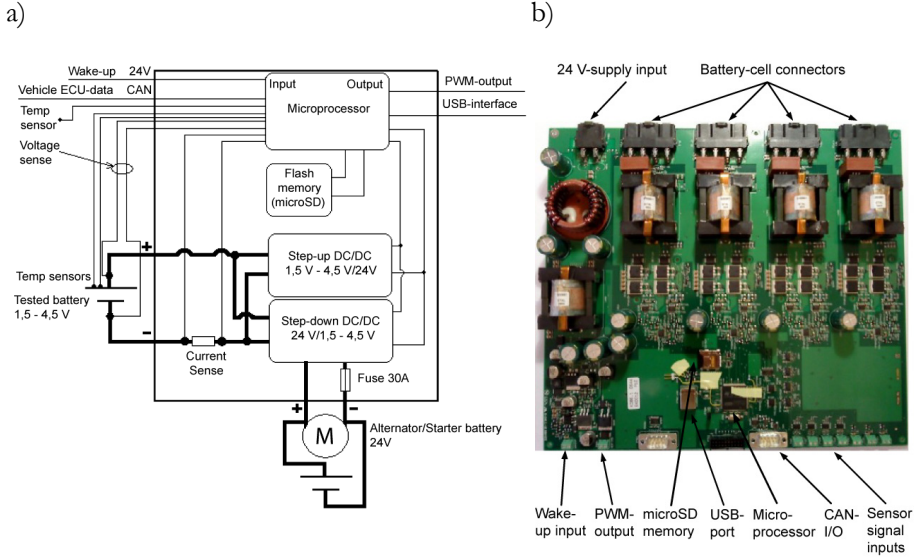


Figure 4. (a) BMU schematic and (b) BMU hardware layout

Figure 4b shows the BMU hardware layout with the main parts and essential inputs and outputs marked.

The BMU is activated via the wake-up port and the tested battery cell is connected to the four connectors in the top of figure 4b. The parameters that are sent from the ECU for controlling the battery cycling (current level, min and max voltage levels), are received via the CAN I/O port. The communication between the ECU and the BMU is done through CAN.

Three NTC-temperature sensors can be connected to the BMU and a pulse width modulated (PWM) output signal is available.

The power electronics part of the BMU is essentially a two-quadrant, four-phase DC/DC converter with high efficiency. This two-quadrant design

permits bidirectional power flow (positive and negative currents) that allows the battery cell to be both charged and discharged. This DC/DC converter is controlled and monitored by the microprocessor, which in turn is controlled by the ECU via the CAN-interface. The connection to the tested battery cell is split into four outputs; enabling four equal currents with synchronous phases shifted 90 degrees from each other to minimize disturbances. When the four current leads are connected together at the battery cell, switching disturbances are theoretically cancelled out. Each current phase provides a maximum of ± 40 A and is controlled by a regulator circuit.

Power is taken from the 24 V-system during charging and power will be delivered back to the 24 V-system during discharging. This approach requires that the vehicle electrical system has the capacity to both deliver and receive the needed power without getting disturbances in vehicle performance.

The BMU was manufactured by the company Elektronikonsult AB, Sweden and the component cost for this part is less than 2000 € [33].

The DUT consists of two battery cells, two temperature sensors attached to opposite sides of one battery, and eight serial-connected power resistors, all placed in an aluminum casing (figure 5). One cell is cycled while the other only is calendar aged and used as reference. The power resistors are used for heating the battery when necessary, to be able to resemble a true HEV-battery temperature. Power resistors are connected to the analogue output on the BMU, which can deliver a PWM signal with a power level adjustable between 0 W and ca. 100 W at 8 Ω , with a resolution of 0.5 %.

Since the battery housing is placed in contact with the aluminum casing containing the BMU and the DUT, the battery is also indirectly cooled by the air flow around the casing when the vehicle is moving.

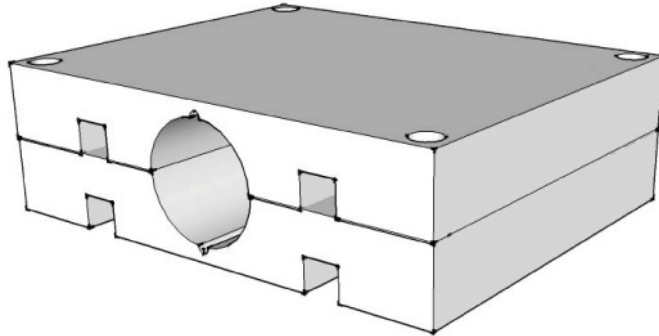


Figure 5. *Example of a battery housing with place for cylindrical battery and temperature sensors (circular opening), and power resistors (square openings).*

The BMU, DUT and cables (including fuses on power cables), are placed in the aluminum casing as seen in figure 6. The BMU is connected to the casing via an aluminum heat bridge to ensure cooling of the power transistors.

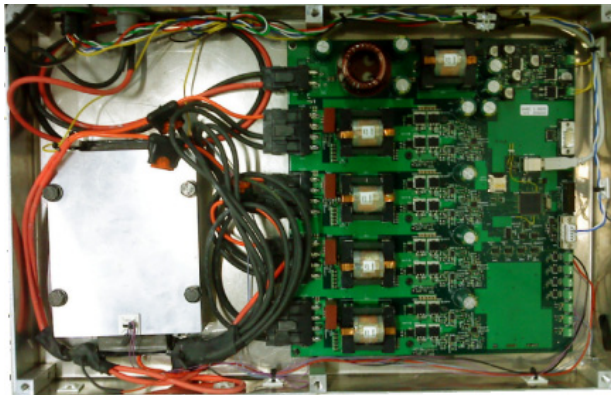


Figure 6. *Assembly of the BMU, DUT and connecting cables in an aluminum casing*

3.3 SOFTWARE

The software in the ECU essentially converts real time sensor data from the vehicle to a signal controlling the current through the tested battery cell. This current should correspond to the current in an HEV-battery. The hybrid strategy software from a Scania hybrid truck was chosen to be the foundation of the software in the ECU. The hybrid strategy software makes decisions about how to apply the available electrical motor (EM) power in the HEV into the drive train, based on information about vehicle and battery status, e.g., vehicle speed and acceleration, and battery SOC and temperature. Since HEV-specific components are missing in conventional trucks, those components have to be emulated by software in the test equipment. The signals needed are generated using vehicle sensor information available in conventional trucks.

3.3.1 MEASUREMENTS

The voltage of the tested cell is measured and recorded with a sample rate of 10 Hz and an accuracy of ± 0.01 V. The input voltage from the truck side is also measured but not stored since this information only is used to detect low or high truck voltage to ensure controlled equipment shut-down if this parameter is out of limits. Four integrated current sensors are used, one for each current phase. The maximum current level is ± 160 A, i.e. the sum of the currents in all phases. The measurement accuracy is ± 0.1 A and the current is stored with a sample rate of 10 Hz. Two temperature sensors are used for measuring battery surface temperatures and one sensor is used for measuring the temperature inside the aluminum casing. The measurement range is -40 °C to $+80$ °C, the measurement sample rate 0.1 Hz and the accuracy ± 0.5 °C.

3.4 MOUNTING

The test equipment is mounted on the starter battery box connected to the frame of the Scania truck (figure 7). The ECU is placed in the cabin, close to the connection point for the CAN-communication. The place for the ECU was chosen to avoid unnecessarily long cables, hence minimizing the risk of collecting disturbing signals during communication. In this way, potential disturbances on the CAN-path between the ECU and the BMU would only affect the test system, not other systems in the truck.

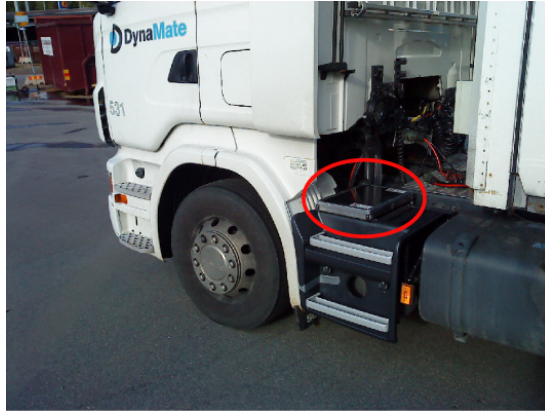


Figure 7. Test equipment (encircled) placed on top of the battery box of a conventional Scania truck

3.5 TEST EQUIPMENT VERIFICATION

Verification of the test equipment was done on a Scania HEV truck. This test made it possible to compare the current through the tested battery with an actual HEV-battery pack current. The result from the test run is presented in figure 8

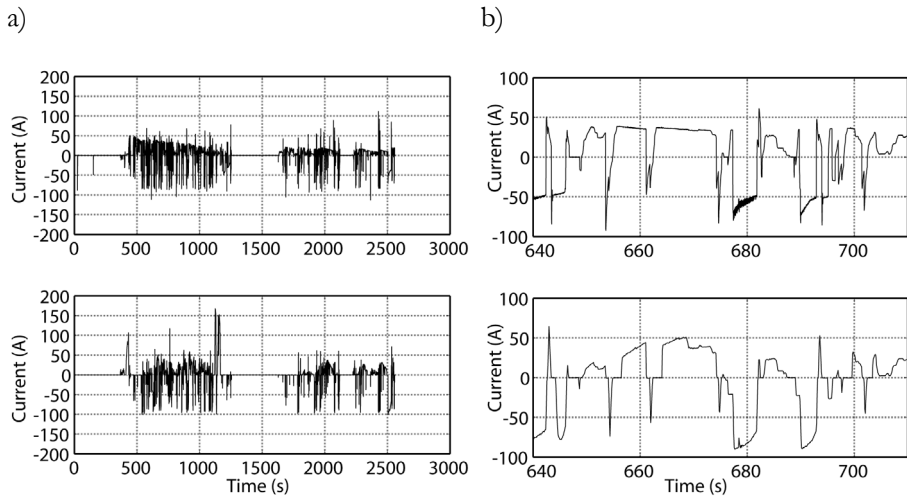


Figure 8. Current through the tested battery cell (upper plots) and current through the HEV battery pack (lower plots). (a) A test run of about 45 minutes. (b) Magnification of the test run (a) between 640 s and 710 s.

Zooming in between 640 s and 710 s shows the similarity between the current through the tested battery cell and the HEV-battery current (figure 8b). Comparing the accumulated charge passed through the tested battery cell with the corresponding value for the HEV-battery pack during the test run indicates similar cycling since the difference only was 3 %. This is a satisfying result since the HEV-battery pack consisted of a different battery type than the tested cell. The results also confirm that the emulated hybrid vehicle functions are influencing the tested battery the way they are supposed. For example, current peaks due to gear changes are clearly seen at 654 s, 662 s, 675 s and 702 s in figure 8b, both for the tested battery and the HEV-battery. The conclusion from the verification results is that the test equipment has a most promising potential to be used as an HEV-emulator for batteries placed on conventional vehicles.

The heating capability of the DUT was verified in a temperature chamber. Heating of the DUT starting from both $-18\text{ }^{\circ}\text{C}$ and $-30\text{ }^{\circ}\text{C}$ were performed. The DUT was cooled down to the starting temperature and was kept there for several hours before the heating was started. Figure 9 shows the results from the test.

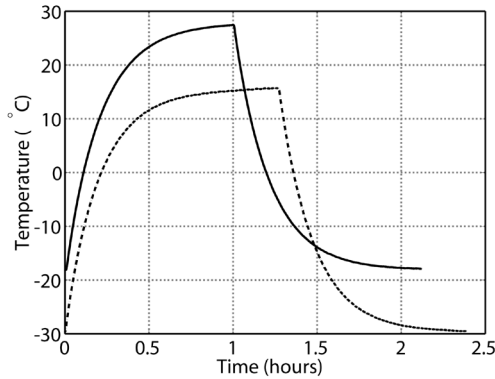


Figure 9. Heating test of the DUT from $-18\text{ }^{\circ}\text{C}$ (solid line) and from $-30\text{ }^{\circ}\text{C}$ (dotted line). The heating was stopped after 1 hour and 1 hour and 15 minutes respectively followed by a cooling period.

It is clearly seen that the DUT can be heated to above $0\text{ }^{\circ}\text{C}$ within half an hour, which is considered to be a short time in this context. When starting from $-18\text{ }^{\circ}\text{C}$, the DUT reaches $10\text{ }^{\circ}\text{C}$ after 12 minutes and when starting from

-30 °C, it reaches 10 °C after 26 minutes. This test was performed without any insulation surrounding the DUT. The use of insulation would clearly decrease the heating time.

3.6 ONBOARD BATTERY PERFORMANCE TESTING

The onboard performance testing consists of a capacity test and a pulse test. The performance testing is starting with the capacity test followed by the pulse test. The tests were chosen to be performed at 25 °C.

The periodic capacity test consists of a constant current/constant voltage (CC/CV) charging procedure followed by a constant current discharging until the lower voltage limit is reached.

Pulse testing was chosen to be performed periodically at three different SOC-levels. The battery cells are discharged completely before pulse testing starts. The cell voltage is always guaranteed to be within limits during testing since a constant voltage (CV) state automatically is entered if a voltage limit is reached. Resistances are calculated from one discharge pulse and one charge pulse, each 18 seconds long. From the pulse test the internal resistance and energy efficiency can be calculated according to a procedure based on the EUCAR High Voltage HEV Traction Battery Test Procedure [24]. For each discharge pulse and charge pulse resistances at different times after pulse start can be calculated, for example at 0.1 s, 2s, 10 s and 18 s. The resistances are calculated as the ratio between the voltage drop and the applied current. The voltage drop is the difference between the voltage at time t and the corresponding open circuit voltage, OCV. The OCV changes during the pulse and this is compensated for according to equation 1.

$$OCV(t) = U(t_0) - \frac{U(t_0) - U(t_2)}{t_1} \cdot t \quad 0 \leq t \leq t_1 \quad [1]$$

The voltage $U(t_2)$ (encircled in Figure 10) is assumed to approximate the OCV at time t_1 . At the beginning of the current pulse at time t_0 the OCV is assumed to be the same as the starting voltage $U(t_0)$. The resistance can hence be calculated from equation 2.

$$R(t) = \frac{OCV(t) - U(t)}{I_{pulse}} \quad t_0 \leq t \leq t_1 \quad [2]$$

Figure 10 shows how the approximate OCV is calculated for different times during the pulse. The charge resistance is calculated analogously to the discharge resistance.

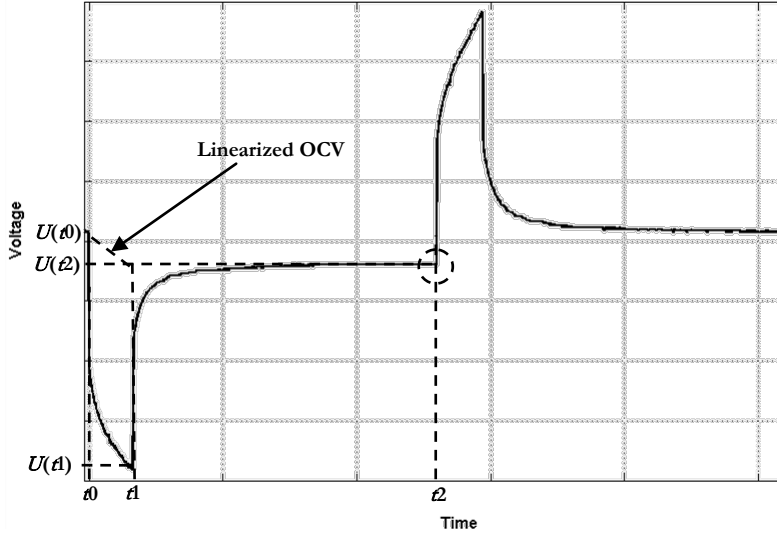


Figure 10. Voltage response from the current pulse used for resistance measurements with graphics showing the linearized OCV

The energy efficiency (η) can be calculated using the charge neutral pulse train in figure 11. Equation 5 describes how the energy efficiency is calculated.

$$\eta = 100 \cdot \frac{\int_{t1}^{t2} U(t) \cdot I(t) dt}{\int_{t1}^{t2} U(t) \cdot I(t) dt} \quad t0 \leq t \leq t2 \quad [3]$$

The nominator represents the discharge energy and the denominator the charge energy.

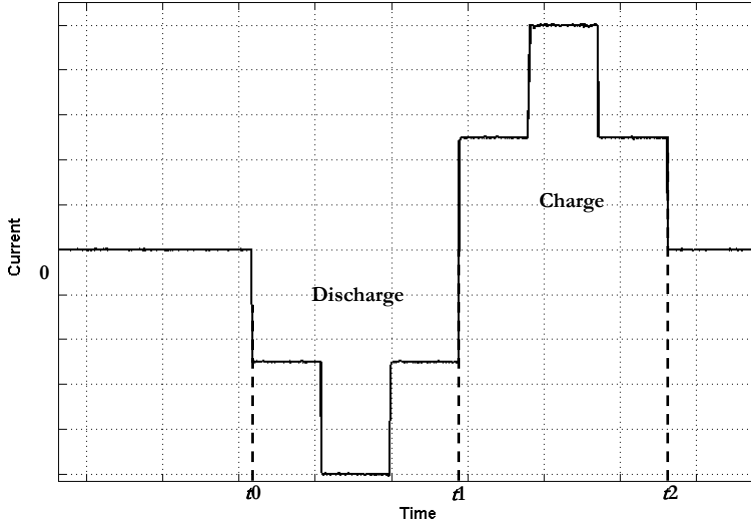


Figure 11 Current pulse used for power efficiency measurements. The time between t_0 and t_1 is 30 s, as well as the time between t_1 and t_2 .

4 MEASUREMENT DATA COLLECTION

It is possible to store battery current and voltage as well as vehicle sensor data on a memory card on the BMU. The memory card slot on the test equipment is compatible with microSD and microSDHC memory cards and the data is saved to the memory card in a binary format to save space. When a test mode is activated, a separate file with those measurements will be generated to make it easier to access battery performance data during evaluation. Since storing all available vehicle sensor data would acquire too large space on the memory card, a choice of what to store had to be made. To make the upcoming data analysis more convenient, some key parameters were chosen to be directly calculated by the ECU software and then stored. Table 1 shows a short description of the parameters chosen to be stored. Figure 12 shows how data from the real life battery cycling is collected and analyzed.

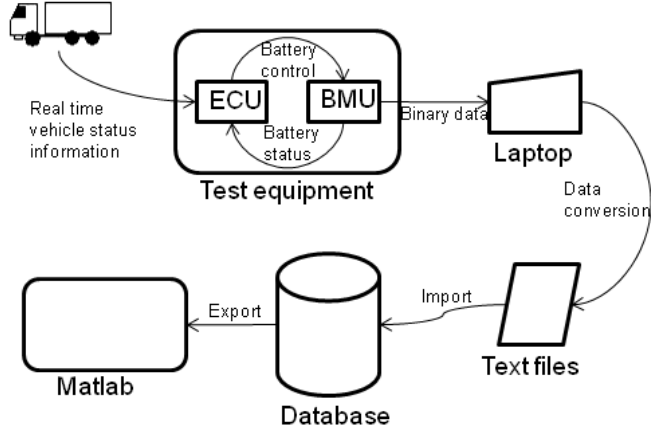


Figure 12 Flowchart describing the real life data collection

5 RESULTS FROM FIELD TESTS

Commercial LMO/LTO lithium-ion battery cells were cycled onboard four heavy trucks from Scania CV AB. Each truck was equipped with two battery cells, one that was cycled and one that was calendar aged. The hybrid strategy implemented in the test equipment was developed for Scania hybrid vehicles and allows high C-rates and large depth of discharge, DOD, to be able to minimize fuel consumption. One main characteristic with this hybrid strategy is to allow higher charging rates than discharging rates. This feature ensures that the battery pack at most times can deliver requested power during acceleration. Since this hybrid strategy is optimized for reducing fuel consumption it will allow DOD and battery power to follow the drive pattern. This variation in SOC and battery power can have a negative impact on battery lifetime, and a future optimization of the hybrid strategy regarding fuel consumption versus battery lifetime is desirable.

5.1 DRIVING CYCLE ANALYSIS

One way of correlating battery usage with how the vehicle is used is by comparing battery parameters like SOC and power with vehicle speed. Figure 13 shows SOC histograms for the cycled batteries in this study.

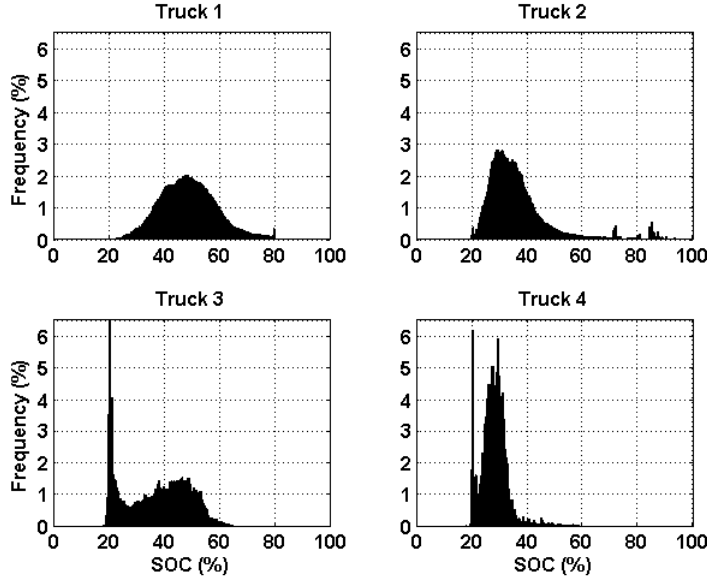


Figure 13. SOC distribution plots. The cell on truck 3 has a truncated peak of 13 % between SOC 19.5 % and 20.0 %. The SOC resolution is 0.5 %.

It is clearly seen from figure 13 that the hybrid strategy allows the battery usage to follow the drive pattern. This is even clearer when comparing SOC distributions in figure 13 with vehicle speed distributions in figure 14. Truck 1 shows an inner city transportation type of drive pattern with obvious peaks at 20 kph and 50 kph. The corresponding SOC in figure 13 shows a smooth SOC distribution centered on 50 %. Truck 2 shows a similar vehicle speed distribution except the lack of obvious peak at 50 kph. However, this should also be considered as an inner city transportation type of drive pattern. The corresponding SOC-distribution is in this case centered on 35 % SOC and has narrower distribution, probably due to a truncation at SOC 20 % (the lower SOC-limit). Trucks 3 and 4 differ however regarding vehicle speed distribution. Both trucks 3 and 4 have narrow peaks at highway speed (around 90 kph). However, during the majority of time the speed is much lower with peaks at 20 kph and 50 kph for both truck 3 and 4. This type of driving pattern is typical for intercity transportation where the vehicles are driving mostly within cities but also travel between cities occasionally.

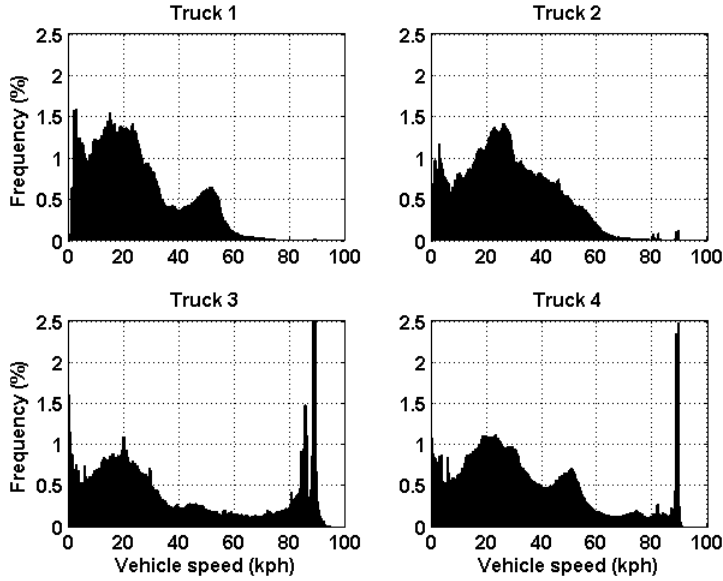


Figure 14. *Vehicle speed distribution plots for the test periods. The plot for truck 3 has a truncated frequency peak of 10 % between 89 kph and 89.5 kph. The speed resolution is 0.5 kph.*

This type of driving pattern gives different SOC behavior compared to the inner city transportation driving pattern. The plots for trucks 3 and 4 in figure 13 shows a more uneven SOC-distribution compared to trucks 1 and 2 and the curves are also moved towards lower SOC-values. The used hybrid strategy tends to drive battery SOC towards the lower limit during highway driving since one target of the strategy is to empty the battery during accelerations to be able to save as much braking energy as possible when braking even with a relatively small battery pack. This behavior is clearly seen for both truck 3 and 4 in figure 13. It is also seen from table 1 that truck 3 has a higher average speed than truck 4 due to more frequent highway driving. The plot for truck 3 in figure 14 has a 10 % peak at 89 kph that is truncated for better visibility. Since truck 3 has done more frequent highway driving compared to the other trucks in the study the average speed is the highest and according to the previous discussion this should lead to more frequent emptying of the cycled battery. This correlates well with the SOC distribution for the cycled battery on truck 3 that has a higher peak at SOC 20 % compared to the other cycled batteries in figure 13. Another interesting battery parameter to look into and to compare with vehicle speed distributions is the battery power. The battery

power also reflects how the hybrid strategy is using the battery and this parameter is also scalable to be compared with hybrid battery pack power. Figure 15 shows cell power distributions for the four trucks. Negative power corresponds to discharging and positive to charging. The power distribution plots reveal peaks around zero current for all cycled cells, which is normal and related to the hybrid strategy that was used.

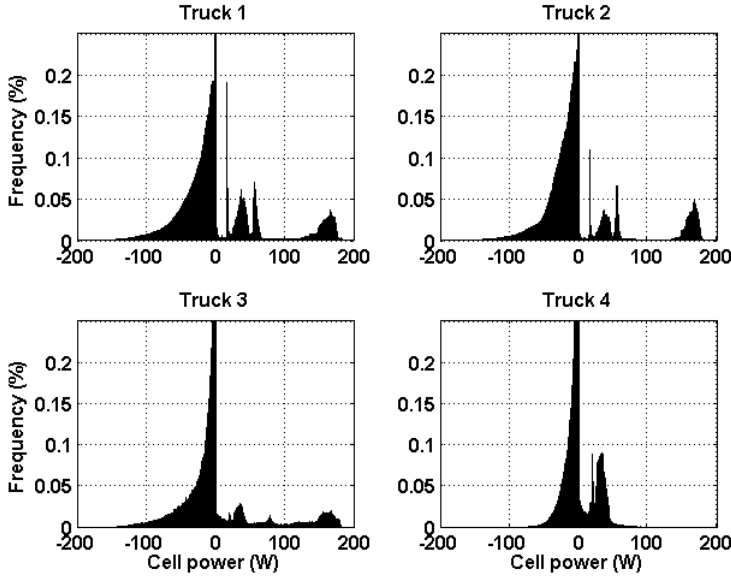


Figure 15 Cell power distribution plots. The resolution is 0.1 %

Figure 15 shows that trucks 1 and 2 have larger positive power peaks above 100 W compared to truck 3 and 4. This is most probably due to more frequent and harder braking for those trucks. The weight of the trucks and how the driver is planning the driving will also affect the positive power distribution. The similarity between the negative power distributions for all trucks shows that the way the batteries are discharged is less sensitive to drive pattern for the used hybrid strategy.

5.2 BATTERY PERFORMANCE

The initial discharge capacities and the capacities at the end of the test periods were measured in the laboratory (23 ± 1 °C, C/20) and are displayed in table 2 in Paper II.

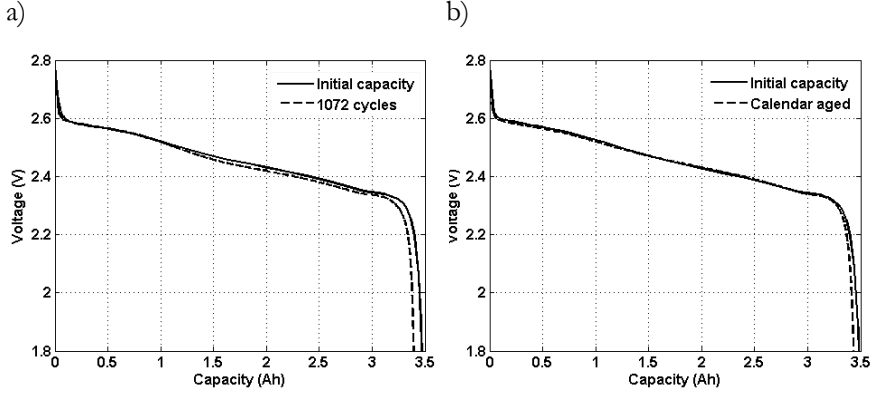


Figure 16. Initial capacity (solid line) compared to aged capacity (dotted line) for the cycled cell (a) and the corresponding calendar aged cell (b) on truck 1

Figure 16 shows the discharge plots for both batteries placed on truck 1. The number of cycles was calculated from the accumulated energy throughput according to equation 4:

$$N_{eq} = \frac{W_{tot}}{2 \cdot U_{nom} \cdot Q_{init}} \quad [4]$$

Where N_{eq} is the equivalent number of full cycles, W_{tot} is the accumulated energy throughput for the cycled cell, U_{nom} is the specified nominal battery voltage and Q_{init} is the measured initial battery capacity. It is from figure 16 and table 2 in Paper II seen that the difference in capacity loss for the cycled cell and the calendar aged cell on truck 1 is small, i.e. 3.00 % vs. 1.18 %. The other cells were cycled less during the study and the difference in capacity loss was accordingly also smaller.

The type of batteries used in this study has an expected cycle life of at least 6000 full cycles according to the battery manufacturers for this type of batteries [36, 37]. A smaller DOD would however result in higher number of equivalent full cycles, N_{eq} . For example, a life estimation done on this battery

type by Toshiba estimates 10 times more cycles at 50 % DOD compared to 100 % DOD (at 45 °C, 10C/10C) [38]. This corresponds to 5 times higher N_{eq} at 50 % DOD. The expected cycle life for the batteries used in this study should hence be about 30000 equivalent full cycles at DOD 50 %. One way of estimating the average DOD for an HEV-battery is to analyze the SOC distribution plots. For example, continuously charging and discharging a battery between two SOC levels would produce a box in the SOC distribution plot. Figure 17 shows an example of this for 50 % DOD (grey box) and 25 % DOD (black box), with SOC centered on 50 %.

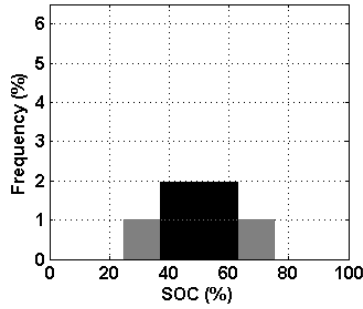


Figure 17. Theoretical distribution plots for continuous cycling around SOC 50 %. DOD 50 % (grey box) and DOD 25 % (black box). The SOC resolution is 0.5 %.

A comparison between the ideal plots in figure 17 and the plots in figure 13 indicates that DOD is less than 50 % for the majority of time for the cycled batteries on all trucks. Based on the simple estimation above, the cells in this test seems to have a potential cycle life of 30000 equivalent full cycles, corresponding to almost 16 years lifetime, using data from the cycled cell on truck 2. This is obviously a highly uncertain value that only should be used as an indication.

Self discharge was detected on the reference cells during the study. The reference cells were charged to around SOC 45 % ($OCV \approx 2.44$ V) before starting the tests. During the test period all reference cells experienced self discharge. For example, reference cell 7 experienced a voltage drop of 55.4 mV corresponding to a self discharge from SOC 46.5 % to 27.3 % and reference cell 10 experienced a voltage drop of 45.6 mV corresponding to a self discharge from SOC 46.0 % to 29.7 %. This quite large self discharge

mechanism still needs to be explained. Self discharging of lithium-ion batteries has different possible explanations, for example electrolyte shuttle mechanisms, electrolyte oxidation at the cathode and transition metal dissolution [34, 35]. It could be possible that the calendar ageing mechanisms is connected to the self discharge.

The earlier described pulse power tests were performed periodically onboard the vehicles during the test period and only small differences in resistance and energy efficiency between initial and final measurements of the cycled batteries can be seen, as shown in table 2 in Paper II. Those differences are most likely related to temperature differences since the cell temperatures can be higher than the desired 25 °C. This is due to the use of passive cooling only.

6 DISCUSSION

The described test equipment is designed to be shut down when the vehicle is turned off. A consequence of this is that no temperature measurements are performed when the vehicle is parked. The lack of temperature data could make it difficult to isolate future cycle ageing from calendar ageing of a cell. To overcome this problem a reference cell that is only calendar aged is placed together with every cycled cell, as discussed earlier. If the functionality to measure battery temperature even when the vehicle is turned off is added to the test equipment, correlation between calendar ageing and vehicle driving and parking conditions could be performed in addition.

Another potential enhancement of the test equipment would be to improve the SOC-estimation algorithm. One way of doing this could be to introduce Kalman-filtering theory. This would enhance the accuracy of calculating SOC for especially battery cells with a flat OCV vs.SOC behavior.

This concept of testing will not include all factors that may cause cell ageing in a HEV battery pack. For example, SOC-level differences caused by unbalance or variation in capacity between cells in a pack as well as temperature variations between cells in a pack will not be addressed.

To identify possible differences in ageing between cells cycled in laboratory and cells cycled on vehicles, post mortem analysis of cells could be compared

at end of life of tested cells. Both electrochemical methods and material analysis methods could be used to perform this analysis.

Even if the presented concept shortens the time of HEV battery testing on vehicles, cycle ageing of batteries is still a slow process. This method of testing could be complemented with different ways of accelerating ageing, for example higher cell temperatures as well as wider SOC and voltage limits.

The described test method should also be possible to use for estimating fuel consumption reduction possibilities for different hybrid strategies and battery packs by translating cell power to battery pack level and comparing that with the needed power for propelling the vehicle. This could be an alternative way of verifying fuel consumption simulations for HEV's.

7 CONCLUSIONS

This work has presented a novel approach to HEV battery testing. This concept includes real life battery cycling on cell level onboard conventional vehicles, including temperature management and the possibility to perform in situ testing. The concept has been proven to give adequate results from initial real life studies.

The core of the test equipment, the battery management unit (BMU), was designed to handle the battery cycling, as well as temperature management and measurement data storage. The functionality of the test equipment was successfully validated in laboratory and on a heavy-duty hybrid truck showing satisfying similarity between currents through the tested battery cell and currents through the hybrid truck battery pack.

By comparing collected real time cell cycling data with vehicle performance data from a fleet of heavy-duty vehicles it was possible to correlate battery usage with driving pattern. For example, by comparing information about battery SOC and power distributions with vehicle speed conclusions about how battery usage depends on driving for a specific hybrid strategy can be drawn. Using this information together with future battery ageing data should make it possible to optimize the battery usage for the specific battery type to obtain as low cycle ageing as possible.

With this concept it is also possible to compare different hybrid strategies on a large fleet of vehicles in a less time consuming and less costly way compared to using full HEV's.

The component and manufacturing costs for the test equipment, excluding the ECU, is estimated to be in the order of 2000 €, which should be considered low in this context.

This method of real life testing of HEV-batteries in real time will be used in my future work. Aged batteries from this type of studies are planned to be analyzed with electrochemical methods as well as using material analysis to reveal ageing mechanisms. Results from those tests are planned to be compared with corresponding results from batteries aged in the lab, seeking for similarities or differences. In the long term, this type of comparisons could help optimizing laboratory cycling to resemble cycling in real life applications in a better way.

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9 REFERENCES

- 1 UNECE: PROPOSAL FOR DRAFT SUPPLEMENT 3 TO THE 05
SERIES OF AMENDMENTS TO REGULATION No. 83
(Emissions of M1 and N1 categories of vehicles). Working document,
UNECE, 2003.
- 2 Emadi A: Handbook of Automotive Power Electronics and Motor
Drives. CRC Press, 2005: p. 21–36.
- 3 Fitch JW: Motor Truck Engineering Handbook, Fourth Edition.
Warrendale, PA, SAE International, 1993: p. 239-300.
- 4 Zamboni G, Capobianco M, Daminelli E: Estimation of road vehicle
exhaust emissions from 1992 to 2010 and comparison with air quality
measurements in Genoa, Italy. Atmospheric Environment. 2009;**43**:
1086-92.
- 5 Beyea J, Stellman SD, Hatch M, Gammon MD: Airborne emissions
from 1961 to 2004 of Benzo a pyrene from US vehicles per km of
travel based on tunnel studies. Environmental Science & Technology.
2008;**42**: 7315-20.
- 6 Mantzos L, Capros P, Kouvaritakis N, Zeka-Paschou M: European
energy and transport trends to 2030. Luxembourg, European
commission directorate-general for energy and transport, 2006.
- 7 Worldometers: Cars produced in the world. 2010.
<http://www.worldometers.info/cars/> (Last accessed June 14 2011).
- 8 Council: Council Directive 88/77/EEC of 3 December 1987 on the
approximation of the laws of the Member States relating to the
measures to be taken against the emission of gaseous pollutants from
diesel engines for use in vehicles. European Union, 1987.
- 9 Council: Council Directive 88/76/EEC of 3 December 1987
amending Directive 70/220/EEC on the approximation of the laws of
the Member States relating to measures to be taken against air
pollution by gases from the engines of motor vehicles. European
Union, 1987.
- 10 J. SP, S. H: EMISSIONS AND FUEL CONSUMPTION FROM
HEAVY DUTY VEHICLES; in COST, (ed) COST 346 - Final
report. Graz, Graz University of Technology, 2005.
- 11 DieselNet: Emission Standards. 2010.
<http://www.dieselnets.com/standards/> (Last accessed June 14 2011).
- 12 Grahn M, Williander M: The role of ICEVs, HEVs, PHEVs, BEVs
and FCVs in achieving stringent CO2 targets: results from global
energy systems modeling; EVS24. Stavanger, Norway, 2009.
- 13 Grahn M, Azar C, Williander MI, Anderson JE, Mueller SA,
Wallington TJ: Fuel and Vehicle Technology Choices for Passenger

- Vehicles in Achieving Stringent CO₂ Targets: Connections between Transportation and Other Energy Sectors. *Environmental Science & Technology*. 2009;**43**: 3365-71.
- 14 Hedenus F, Karlsson S, Azar C, Sprei F: Cost-effective energy carriers for transport - The role of the energy supply system in a carbon-constrained world. *International Journal of Hydrogen Energy*. 2010;**35**: 4638-51.
 - 15 Brown S: Fifty hybrids ordered for London; Bus and Coach. United Kingdom, Steve Rooney, 2010: p. 3.
 - 16 TfL: Hybrid buses fact sheet; in Transport for London, (ed). London, 2010.
 - 17 Hammarberg G: Unika miljöbussar testas i Stockholm; Scania Value. Sweden, Per Hillström, Scania CV AB, 2009.
 - 18 Wikström M, Folkesson A, Alvfors P: Analysis of the fuel economy improvement potential of ethanol hybrid buses The 24th International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental impact of Energy Systems, ECOS. Novi Sad, Serbia, 2011: p. 2220-9.
 - 19 Nilsson PM: How new powertrain technologies will impact the value chain; Truck & Bus world forum. Gothenburg, Sweden, Little, Arthur D., 2008.
 - 20 Brandt K: Historical development of secondary lithium batteries. *Solid State Ionics*. 1994;**69**: 173-83.
 - 21 Anderman M: Value Proposition Analysis for Li Ion Batteries in Automotive Applications; Advanced Automotive Battery & Ultracapacitor Conference. Tampa Convention Centre, Tampa, Florida, 2008.
 - 22 Vetter J, Novak P, Wagner MR, Veit C, Moller KC, Besenhard JO, Winter M, Wohlfahrt-Mehrens M, Vogler C, Hammouche A: Ageing mechanisms in lithium-ion batteries. *Journal of Power Sources*. 2005;**147**: 269-81.
 - 23 ISO: Electrically propelled road vehicles — Test specification for lithium-ion traction battery packs and systems — Part 1: High power applications; ISO/TC 22/SC 21/WG 3 - Lithium Ion traction Batteries. Draft, International Organisation for Standardization, 2010.
 - 24 EUCAR Traction Battery Group: Specification of Test Procedures for Electric Vehicle Traction Batteries. EUCAR, 2005.
 - 25 USABC, DOE National Laboratories: Electric Vehicle Battery Test Procedures Manual Rev 2. 1996.
http://www.uscar.org/commands/files_download.php?files_id=57
 (Last accessed June 16 2011).

- 26 Dubarry M: Analysis of Electric Vehicle Usage of a Hyundai Santa Fe Fleet in Hawaii. *Journal of Asian Electric Vehicles*. 2005;**3**: 657-63.
- 27 Dubarry M, Svoboda V, Hwu R, Liaw BY: A roadmap to understand battery performance in electric and hybrid vehicle operation. *Journal of Power Sources*. 2007;**174**: 366-72.
- 28 Dubarry M: Vehicle Evaluation, Battery Modeling, and Fleet-testing Experiences in Hawaii. *Journal of Asian Electric Vehicles*. 2007;**5**: 1033-42.
- 29 Liaw BY, Dubarry M: From driving cycle analysis to understanding battery performance in real-life electric hybrid vehicle operation. *Journal of Power Sources*. 2007;**174**: 76-88.
- 30 Karner D, Francfort J: Hybrid and plug-in hybrid electric vehicle performance testing by the US Department of Energy Advanced Vehicle Testing Activity. *Journal of Power Sources*. 2007;**174**: 69-75.
- 31 Francfort JE: Hybrid Electric Vehicle and Lithium Polymer NEV Testing. Idaho Falls, Idaho, Idaho National Laboratory, 2005. http://avt.inel.gov/pdf/hev/hev_power_sourcepaper.pdf (Last accessed February 16 2011).
- 32 J1939: Recommended practice for a serial control and communications vehicle network. SAE International, 2009.
- 33 Elektronikkonsult AB. 2011. <http://www.elektronikkonsult.se/home.aspx> (Last accessed November 11 2011).
- 34 Smith AJ, Burns JC, Xiong D, Dahn JR: Interpreting High Precision Coulometry Results on Li-ion Cells. *Journal of The Electrochemical Society*. 2011;**158**: A1136-A42.
- 35 Yazami R, Ozawa Y: A kinetics study of self-discharge of spinel electrodes in Li/LixMn2O4 cells. *Journal of Power Sources*. 2006;**153**: 251-7.
- 36 Toshiba Corporation: SCiB™ A Rechargeable Battery. 2009. <http://www.scib.jp/en/product/spec.htm> (Last accessed September 21 2011).
- 37 Altairnano: Applications for advanced batteries in Microgrid environments. 2010.
- 38 Toshiba Corporation: Proceedings of the fourth international symposia Large Lithium ion battery technology and application; in Menahem A, (ed) Advanced Automotive Battery & Ultracapacitor Conference. Tampa Convention Centre, Tampa, Florida, 2008.