



## **Investigation of Load Profiles of Lithium-ion batteries for Electric Vehicle Applications**

Chadchai Srisurangkul

National Metal and Materials Technology Center, 114 Thailand Science Park, Phahonyothin Rd. Klong 1, Klong Luang,  
Pathumthani 12120 Thailand

\*Corresponding Author: Tel: +66 2 564 6500 ext. 4731, Fax: +66 2 564 6332,

E-mail: chadchas@mtec.or.th

### **Abstract**

Vehicle electrification become and continues to be the major trend in the automotive industry and a main part of this is batteries. Unfortunately the battery testing presently does not represent the real-world condition, in which the battery load profile comprises complex charge-discharge wave. Therefore in this study, the load profile of batteries for electric vehicles was investigated. An integrated simulation and testing approach is used to predict the battery load. In simulation the battery load profile is calculated based on the utilization of vehicle and battery model. The present vehicle and battery model are developed using a vehicle dynamics technique and equivalent circuit modeling technique respectively, whereas the model development is focused on a specific vehicle which converts conventional propulsion into pure electric propulsion. The results are demonstrated through the current profile of advanced batteries subjected to standard driving cycles. With this approach, the battery loads correspond to actual driving condition or any driving cycle can be predicted and can be used for battery testing. This creates a new aspect to evaluate advanced batteries for power train application.

**Keywords:** Current Profile, Vehicle Modeling, Battery Modeling, Driving Cycle

### **1. Introduction**

All major car manufacturers are planning to bring out electric cars in the near future. This trend drives the development of high power batteries such as lithium-ion batteries. Although lithium-ion batteries are widely used for electric vehicles, there is no testing standard for those batteries [10]. The battery test profiles presently base on constant current or step response technique which does not represent the real-world condition. They may be used to investigate

some battery parameters but still not suite to investigate, for example, the battery life or heat generation. It is not suitable to use as tool for design battery subsystem such as battery thermal management.

This paper describes an approach to determine the battery load profile comprising complex charge-discharge wave from real-world driving cycle.

## 2. Vehicle Dynamics Modeling

The vehicle dynamic model can be derived from Newton's second law considering all the forces applied upon the vehicle. It should be noted that only the longitudinal dynamic is sufficient to investigate the battery load profile. With this the complex and uncertain parameters as well as the simulation time can be reduced.

The total resistance forces acting on the vehicle are rolling resistance, aerodynamic resistance, and grade resistance force, as demonstrated in Fig. 1.

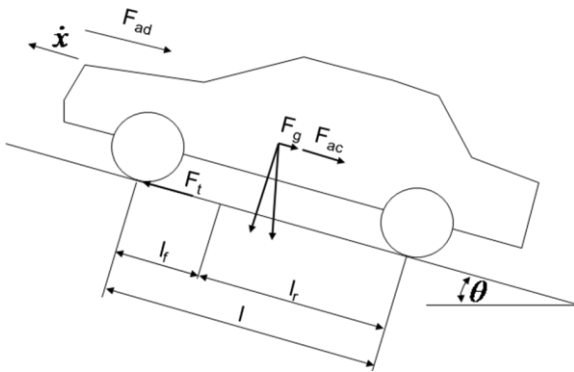


Fig. 1 Resistance force acting on the vehicle

Hence, the vehicle dynamic equation can be obtained as

$$F_t = F_{roll} + F_g + F_{ad} + F_{ac} \quad \text{Eq. (1)}$$

$$F_t = mg(f_0 + f_1 \dot{x}) \text{sgn}(\dot{x}) + mg \sin \theta + 0.5 \rho C_d A_f (\dot{x} + \dot{x}_0)^2 \text{sgn}(\dot{x}) + (m + \frac{J_{red}}{r^2}) \ddot{x}$$

where  $F_{roll}$  is rolling resistance,  $F_{ad}$  is the aerodynamic resistance,  $F_g$  is the grade resistance,  $m$  is the vehicle mass,  $g$  is the natural acceleration,  $\theta$  is the angle of grade,  $f_0$  and  $f_1$  are the rolling coefficients,  $\rho$  is the air density,  $C_d$  is the aerodynamic drag coefficient,  $A_f$  is the vehicle frontal area,  $\dot{x}_0$  is the wind

speed,  $\dot{x}$  is the vehicle speed, and  $J_{red}$  is the reduced mass moment of inertia at wheel.

The vehicle considered in this work is the two year used HONDA Jazz that will be converted to a pure electric vehicle. The existing engine will be replaced with a 40kW new developing motor. The vehicle uses a 100 cell lithium-ion battery (type: LiFeYPO4) as power source. The total capacity is 60Ah. The vehicle uses the original transmission modified to use the 3<sup>rd</sup> gear ratio. The vehicle specification is shown in Table 1.

Table. 1 Vehicle specification

| No. | Parameter                          | Value/Description                   |
|-----|------------------------------------|-------------------------------------|
| 1   | Curb. weight                       | 1050 (kg)                           |
| 2   | Weight distribution (% front/rear) | 62/38 (%)                           |
| 3   | Wheelbase                          | 2.5 (m)                             |
| 4   | Drag coefficient                   | 0.35                                |
| 5   | Frontal area                       | 2.18 (m <sup>2</sup> )              |
| 6   | transmission                       | 5 speed manual gearbox              |
| 7   | Gear ratio (1,2,3,4,5)             | 3.461, 1.869, 1.303<br>1.054, 0.853 |
| 8   | Final drive ratio                  | 4.294                               |
| 9   | Tire size                          | 175/65R15                           |
| 10  | Motor                              | PMSM, 40 (kW) continuous power      |
| 11  | Battery type                       | LiFeYPO4                            |
| 12  | Battery Capacity                   | 60 (Ah)                             |
| 13  | Number of cells                    | 100 (cells)                         |
| 14  | Battery weight                     | 230 (kg), total                     |

To implement vehicle system simulations there are various types of mathematical models available. In this work the

vehicle model was created by using a transient effort-flow refer to [1]. Effort-flow in the model refers to the combinations of torque/angular speed, force/velocity and voltage/current.

The basic configuration of the electric vehicle used for simulation is illustrated in Fig. 2. Overall system is modeled in a MATLAB/Simulink environment.

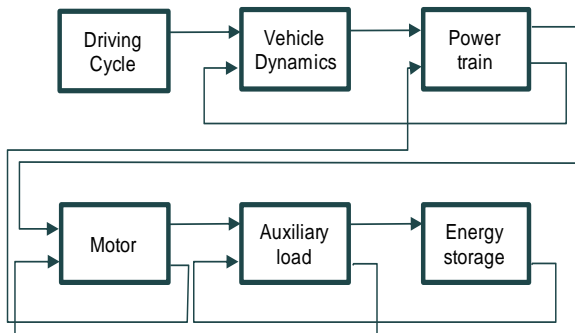


Fig. 2 Electric vehicle configuration

Vehicle system models typically contain a mix of empirical data, engineering assumptions, and physical based parameter and algorithms. Driven by the need for fast simulation times, complex components such as motor are typically simulated using empirical data in form of lookup maps. For example, the electric motor is modeled using an efficiency map handled as a 2-D lookup table indexed by rotor speed and torque. This map is generally obtained via experiments. In our case the efficiency map of electric motor is unknown because the motor is presently constructing. Therefore the scaling of torque to provide the required maximum power has been done. This type of scaling is valid only for the same motor type and in the neighborhood near the actual parameter. The efficiency map of the electric motor is shown in Fig. 3.

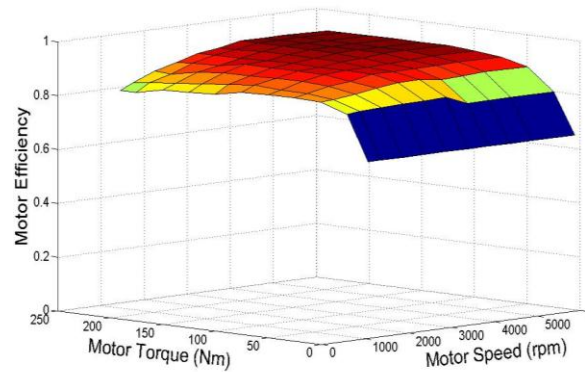


Fig. 3 Efficiency map of the electric motor

### 3. Battery Modeling

#### 3.1. Battery Model

A battery model calculates the battery variables like current, voltage, and the battery temperature. The battery is modeled as an equivalent circuit with a battery internal resistance, as shown in Fig. 4. The model uses data from experiment described in the next section.

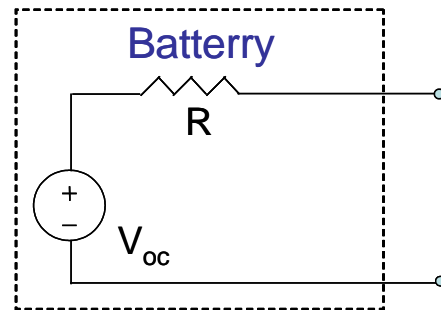


Fig. 4 Battery Model

The model consists of voltage source generating an open-circuit voltage (OCV) and a resistor representing the internal resistance (R). Both parameters can be described as a function of state of charge (SOC) and temperature. The internal resistance is considered separately between charge and discharge process.

The state of charge was estimated by coulomb counting (current based SOC estimation). The SOC is obtained by measuring the current flowing into and out of a battery and

integrating this current over time and then subtracting it from the charge in a fully charged battery [4]. The other methods of SOC determination can be found in [5].

The temperature is obtained by using battery thermal model which describes the heat transfer process. The heat is generated from battery due to electrochemical reactions and resistive heating which causes increased battery temperature [6]. In practice the heat dissipation is best estimated from values of the current and voltage [7], according to

$$P = i (V_{oc} - V) \quad \text{Eq. (2)}$$

where  $V$  is the instantaneous cell potential,  $V_{oc}$  is the open-circuit voltage.

The heat dissipation is conducted from the internal battery to the battery case and then convected from the case's surface to the air.

### 3.2. Experiment Setup

To characterize battery parameters for its model, the step response technique [8] was employed. The tests were carried out on the testing system as shown in Fig. 5.

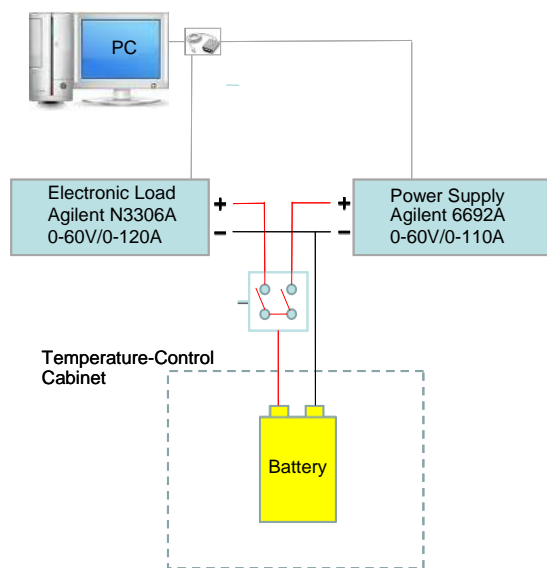


Fig. 5 Testing system configuration

The system consists mainly of power supply and electronic load which connected to PC via GPIB. The output voltage range and the maximum current rating of those machines are 0-60Vdc and 120A respectively. Labview was used to define the test procedure and log data.

The tested specimen is a 5 cell series connected LiFeYPO4 with a capacity of 60 Ah. The battery core is covered by poly-propylene case which has low thermal conductivity. During the test the battery was placed in a temperature-control cabinet. The test cycles is shown in Fig. 6-7.

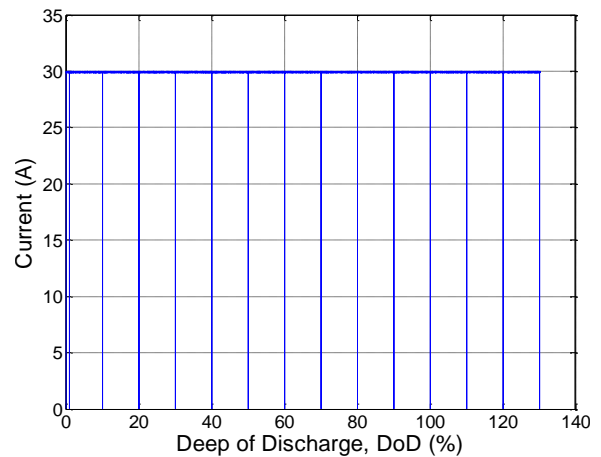


Fig. 6 Battery test cycle as function of DoD

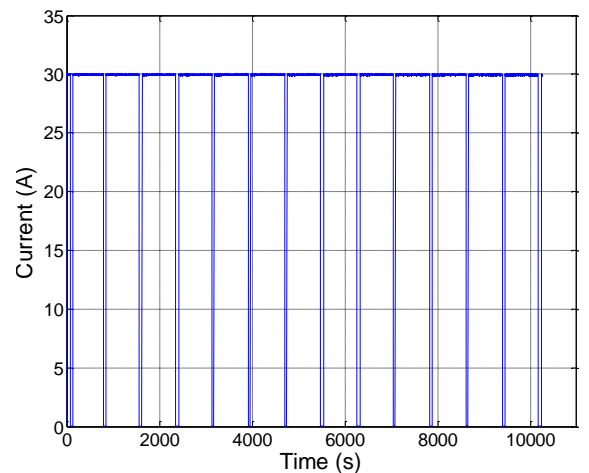


Fig. 7 Battery test cycle as function of time

The test started with the discharge process. For each test cycle the constant current of 0.5C (30A) is applied and was paused for one

minute at every 10% change in state of charge. Measurements were taken every 200ms. The test was performed at temperature of 5°C, 25°C and 40°C. Some initial cycles were applied to ensure that the battery reaches stable behavior.

The voltage response during the pause period is used in order to determine the battery internal resistance. An example of the voltage response during pause period is shown in Fig. 8.

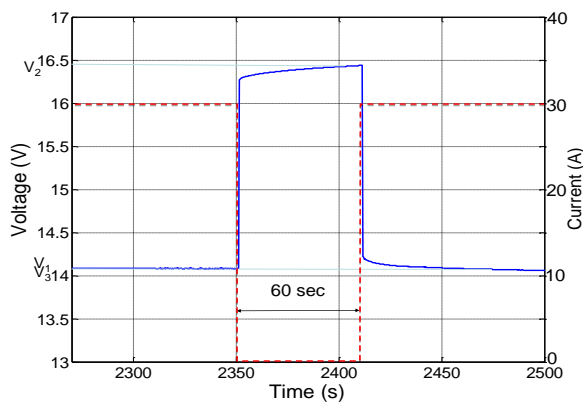


Fig. 8 Example of the voltage response

$V_1$ ,  $V_2$ , and  $V_3$  in Fig. 8 are easily measured. Both the resistance and the open-circuit voltage (OCV) are assumed to be constant over the pulse period. Voltage different at the beginning of the pulse is also assumed at the end of the pulse. The internal resistance after analysis the test data is shown in Fig. 9. For other methods for resistance estimation can be found in [11].

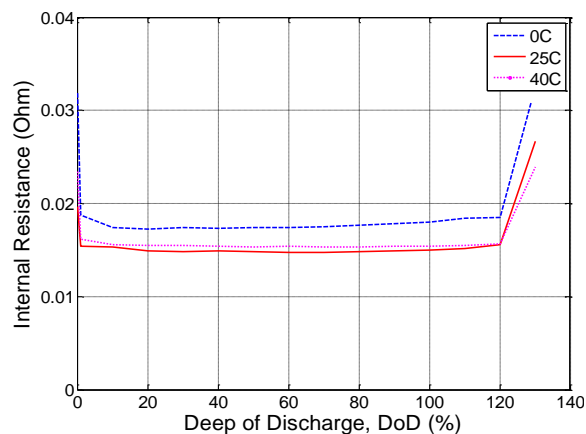


Fig. 9 Internal resistance in case of discharge

## 4. Simulation

### 4.1 Driving Cycle and Battery Load Cycle

Through the battery load profile of real-world driving cycles is the aim of this work, the standard driving cycles with transient characteristic was used to test our model. The transient cycles give more dynamic changing in load and are based upon real-world data. UDDS, NYCC and CSC cycles are three examples of transient driving cycle used to define the battery load profile. They were chosen because they are based upon real-world driving and content a high portion of with non-aggressive urban and suburban routes that are suitable for electric vehicles. UDDS cycle describes an urban route with cold start and transient phase, NYCC cycle represents an urban route through New York and CSC cycle describes a city suburban route with lower average speed than UDDS cycle. Fig. 10 shows UDDS cycle as an example.

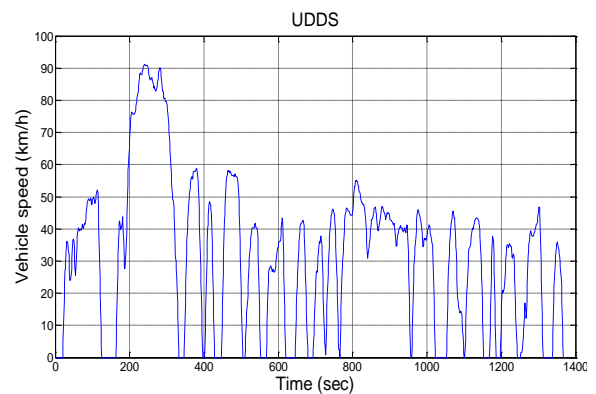


Fig. 10 An example UDDS cycle

A battery load profile used by the vehicle can be determined by using one of these driving cycles as an input to the simulation. The load profile results are shown in Fig. 11-13. The simulation was set up with a full battery and a temperature of 25°C.

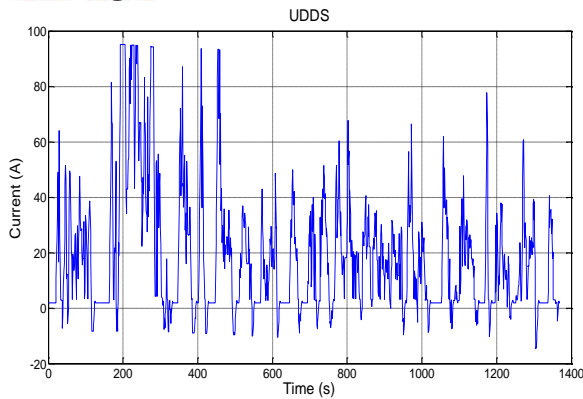


Fig. 11 Battery load profile, UDDS

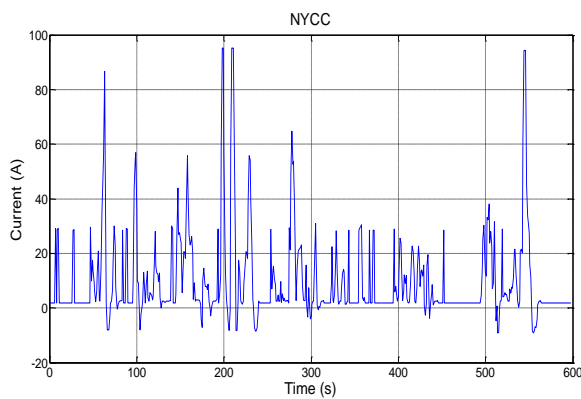


Fig. 12 Battery load profile, NYCC

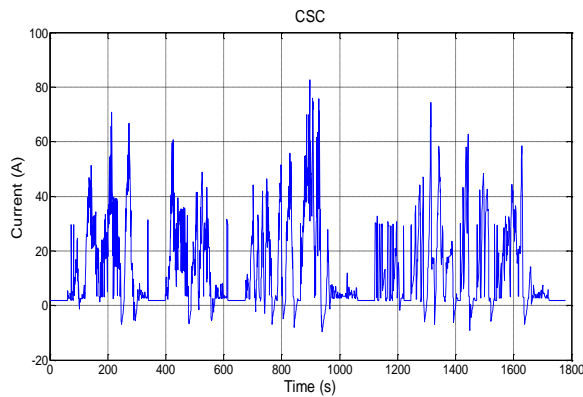


Fig. 13 Battery load profile, CSC

#### 4.2 Cycle Filtration

In the practice the high dynamic load cannot use directly due to the limited capability of battery testing machines. To enable the use of widely available battery testing machines the minimum sampling period of load profile for input to the testing machine should be 2 seconds and the profile should be rectangular wave. To meet these requirements the battery load profile from

the vehicle dynamic simulation must be filtered while still maintaining the typical load characteristic. The filter model with filter and stair-step function was developed for this purpose. It performs an online analysis to meet the requirement of hardware in the loop simulation in the future. Fig. 14 shows a close up view of a portion of the filtered and unfiltered load profile for UDDS cycle.

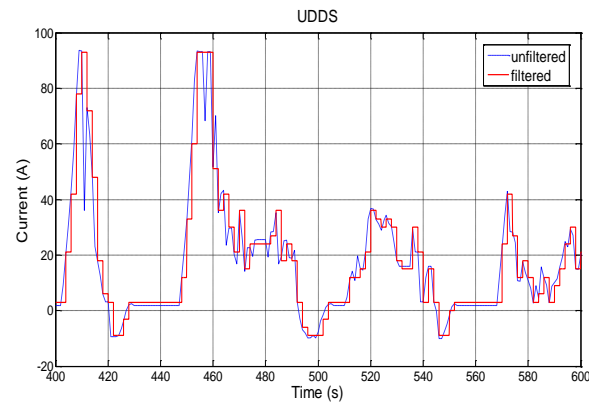


Fig. 14 Unfiltered and filtered battery load profile

The peak current of unfiltered and filtered profile are 95.06 A and 96 A, while the average current are 18.85 A and 18.64 A respectively. This guarantees correctness and stability of the filter model.

Fig. 15-17 shows the distribution of the filtered battery load profile for all three driving cycles.

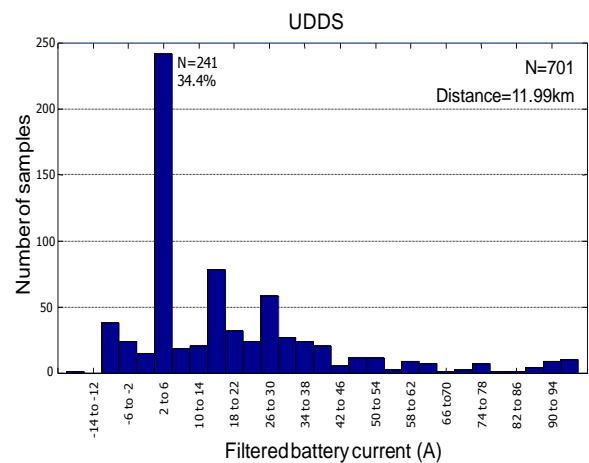


Fig. 15 Load distribution of UDDS cycle

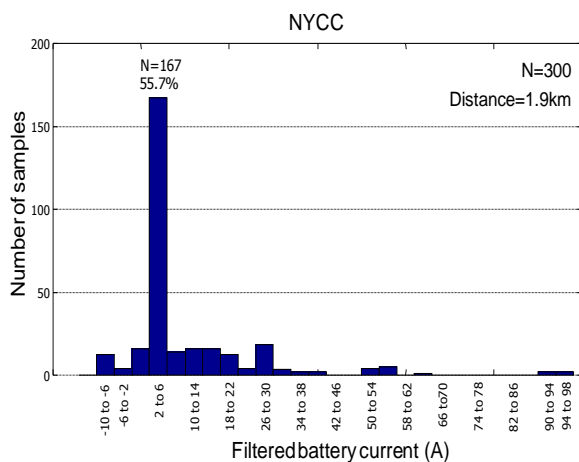


Fig. 16 Load distribution of NYCC cycle

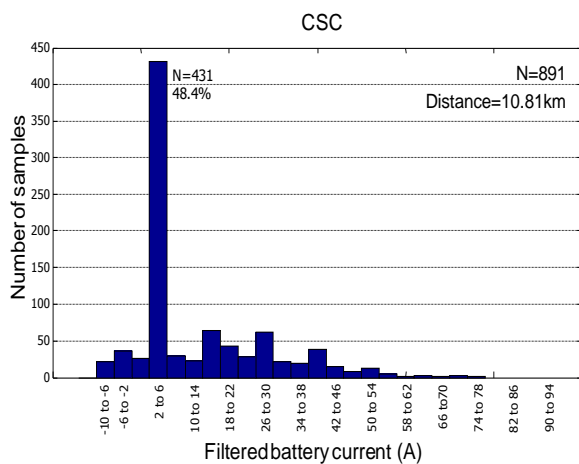


Fig. 17 Load distribution of CSC cycle

All three driving cycles have the most common current value with in the same range. For UDDS cycle the battery current varies widely between -15 and 96 A, whereas the most common value lies between 2 to 6 A. NYCC and CSC cycles show narrower current distribution than the UDDS cycle. The vehicle takes current from the battery at 2 to 6 A through about half of route.

### 5. Conclusion

The present paper examined the battery load profile of a vehicle driving in the real world. To predict the battery load a vehicle system simulation was developed while many tests have

been done to provide input parameters for the simulation.

The vehicle dynamic model and the battery model are a core of this vehicle system simulation. In the vehicle dynamic model only the longitudinal dynamic is sufficient to investigate the battery load profile, while an equivalent circuit with an internal resistance is considered in the battery model.

The experiment has been conducted to get the battery properties. The test methodology relies on the current pulse relaxation technique to determine the battery characteristics.

Accordingly, using this methodology, the battery load profile correspond to actual driving condition or any driving cycle can be predicted and can be used for battery testing. This creates a new aspect to evaluate advanced batteries for power train application.

### 6. References

- [1] Gao, D.W., Mi, C. and Emadi, A. (2007). Modeling and Simulation of Electric and Hybrid Vehicles, *Proceedings of the IEEE*, vol.95(4), April 2007, pp. 729 – 745.
- [2] Johnson, V.H., Pesaran, A.A. (2000). Temperature-Dependent Battery Models for High-Power Lithium-Ion Batteries, paper presented in *the 17<sup>th</sup> Electric Vehicle Symposium*, Montreal, Canada.
- [3] Johnson, V.H. (2002). Battery performance models in ADVISOR, *Journal of Power Sources*, vol.110, pp. 321 – 329.
- [4] Bergveld, H.J., Kruijt, W.S., Notten, P.H.L. (2002). *Battery Management Systems: Design by Modelling*, Philips Research Book Series Volume 1, ISBN: 1402008325, Springer



- [5] Pop, V., Bergveld, H.J., Danilov, D., Regtien, P.P.L., Notten, P.H.L. (2008). *Battery Management Systems: Accurate State-of-Charge Indication for Battery-Powered Applications*, Philips Research Book Series Volume 9, ISBN: 1402069448, Springer
- [6] Pesaran, A.A. (2002). Battery thermal models for hybrid vehicle simulations, *Journal of Power Sources*, vol.110, pp. 377 – 382.
- [7] PCM Thermal Control of Nickel-Hydrogen Batteries, Division of Technical Services and Planning, PL-TR-93-1075, Energy Science Laboratories Inc., *Final Report 1993*
- [8] Doerffel, D. (2007). Testing and Characterisation of Large High-Energy Lithium-Ion Batteries for Electric and Hybrid Electric Vehicles, *PhD Thesis*, University of Southampton
- [9] Duvall, M.S. (2005). Battery Evaluation for Plug-In Hybrid Electric Vehicles, *Vehicle Power and Propulsion, IEEE Conference*, pp. 338 – 343.
- [10] Morita, K., Akai, M., Hirose, H. (2009). Development of Cycle Life Test Profiles of Lithium-ion Batteries for Plug-in Hybrid Electric Vehicles, *EVS24 International Battery, Hybrid and Fuel Cell Electric Vehicle Symposium*
- [11] Schweiger, H.G., Obeidi, O., Komesker, O., Raschke, A., Schiemann, M., Zehner, C., Gehnen, M., Keller, M., Birke, P. (2010), Comparison of Several Methods for Determining the Internal Resistance of Lithium Ion Cells, *Sensors 2010, 10*, ISSN 1424-8220, pp. 5604 – 5625.