MOBILITY OF THE FUTURE: HYBRID AND ELECTRIC VEHICLES

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Center For Mechatronics and Hybrid Technologies (CMHT)

McMaster Automotive Resource Center (MARC), ON Canada

SPEAKER BACKGROUND

Education

- **Masters of Business Administration (MBA) Candidate (2015-2017)**
  DeGroote School of Business, ON Canada
- **Ph.D. in Mechanical/Mechatronics Engineering (2014)**
  McMaster University, ON Canada – *Battery Management and Control*
- **M.A.Sc. in Mechanical Engineering (2011)**
  McMaster University, ON Canada – *Engine Management and Fault Detection*
- **B.Sc. in Mechatronics Engineering (2007)**
  Ain Shams University – Mechatronics Engineering

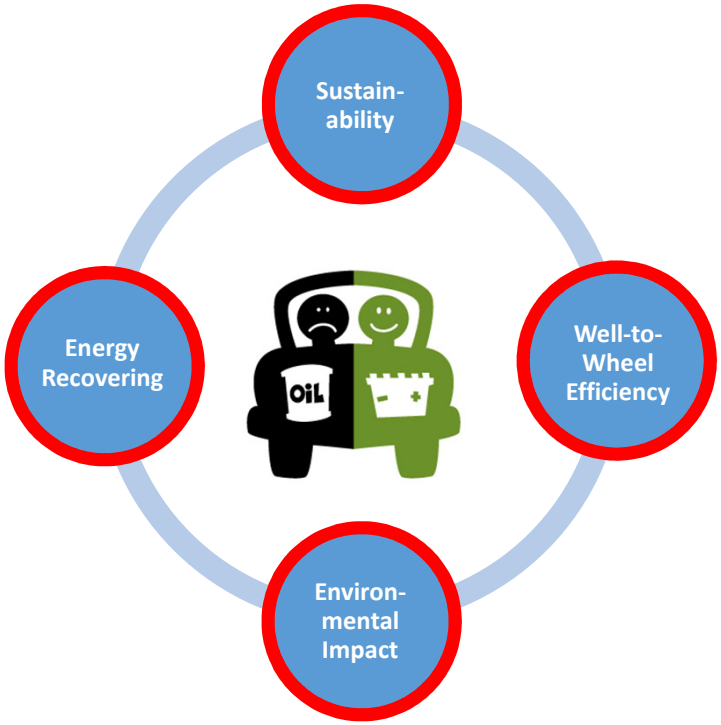
Work Experience

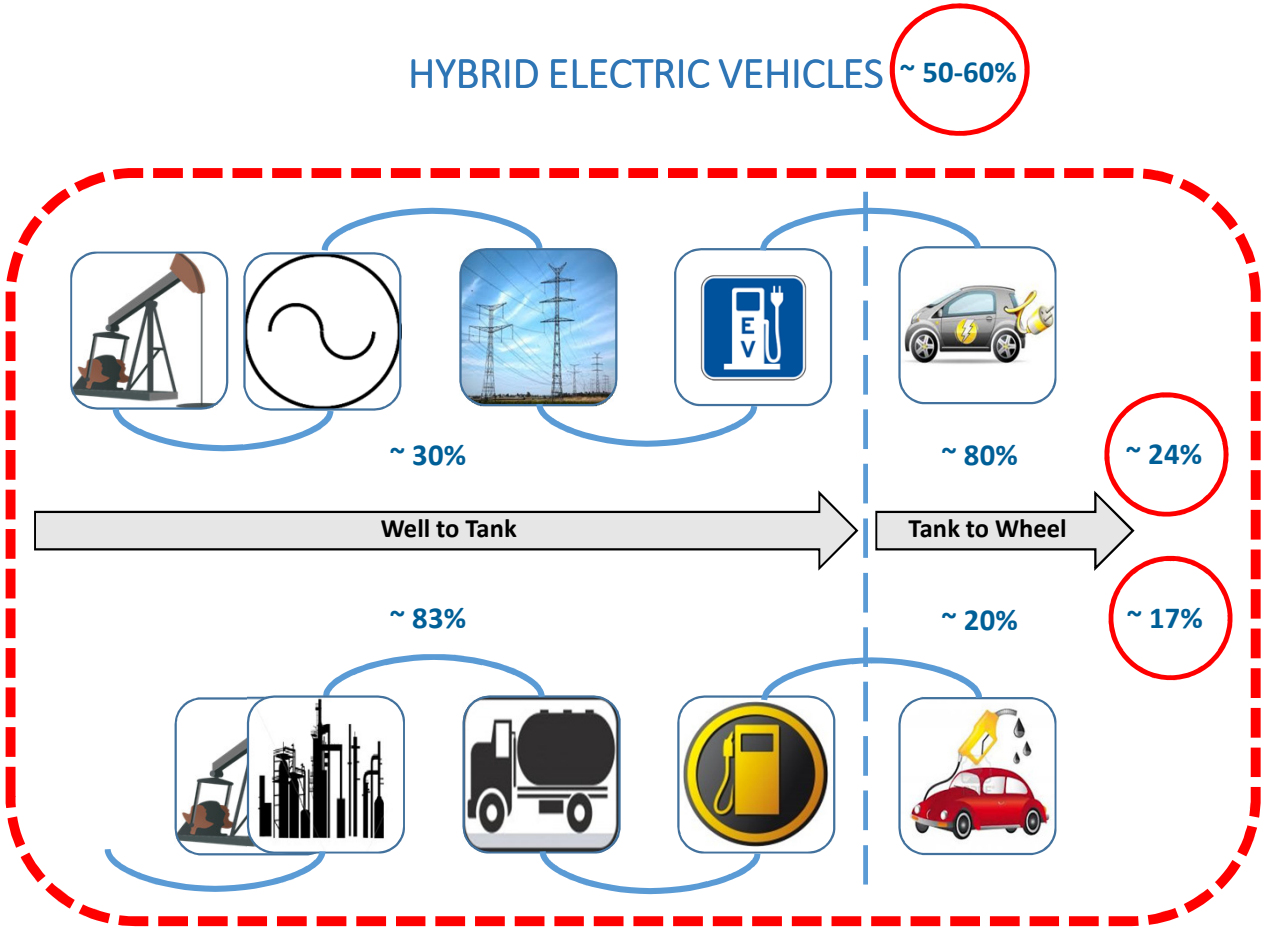
- **Adjunct Professor, McMaster University, ON Canada (2016 – present)**
- Senior Systems Engineering Lead, Samsung SDI America, USA (2015 – 2016)
- Senior Technical Specialist, Fiat Chrysler Automobiles (FCA), ON Canada (2014 – 2015)
- R&D engineer, Ford Powertrain R&D Center, ON Canada (2011 – 2014)
- Teacher Assistant, Ain Shams University (2007 – 2009)

AGENDA

- **Why Electric Vehicles?**
- **Paradigm shift in transportation**
- **Hybrid Vehicles Configurations**
- **Mechatronics Engineering in the Automotive Industry**
- **Case Study: Battery Management Systems (BMS)**
  - Battery Modeling
  - Battery Aging
  - State of Charge Estimation
  - State of Health Estimation
- **Alternative Technologies**

WHY ELECTRIC VEHICLES?





http://nextbigfuture.com/2009/04/direct-conversion-of-nuclear-power-to.html

PARADIGM SHIFT IN TRANSPORTATION

Not sustainable – Transportation 1.0

Sustainable – Transportation 2.0

More Efficient, cleaner, greener

ICE

- Not efficient – Efficiency of approximately 20%

More Electric Vehicles

- **Electrification less than 20%** – Non-propulsion Electric components
- Electrically assisted power steering, electrically driven air-conditioning, electromechanical valve control

Hybrid Electric Vehicles

- Micro hybrids, mild hybrids, power (full) hybrids, and energy hybrids
- hybridization factor is ratio between its peak electrical power and peak total electrical and mechanical power

Plug-In Electric Vehicles

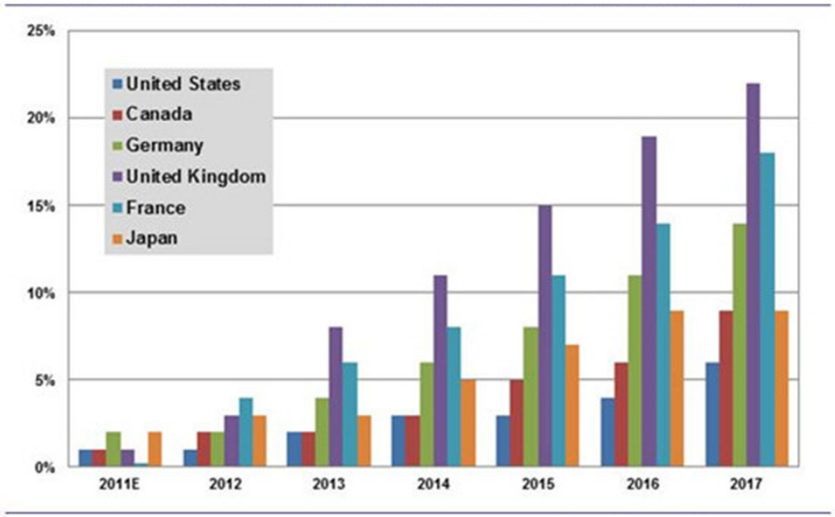
- Dual fuel vehicles – Most Promising

All Electric Vehicles

- **Electrification level 100%** – Ultimate form

PARADIGM SHIFT IN TRANSPORTATION

- HEVs market will form **8%** of the **global passenger vehicle** segment by **2020**
- **PHEVs** will become one of the main forms of transportation in Canada and across the globe by **2030**
- In five years, advanced electric-drive vehicles will exceed **15%** of the global new vehicle market
- This means production of at least **7.5 million units per year**

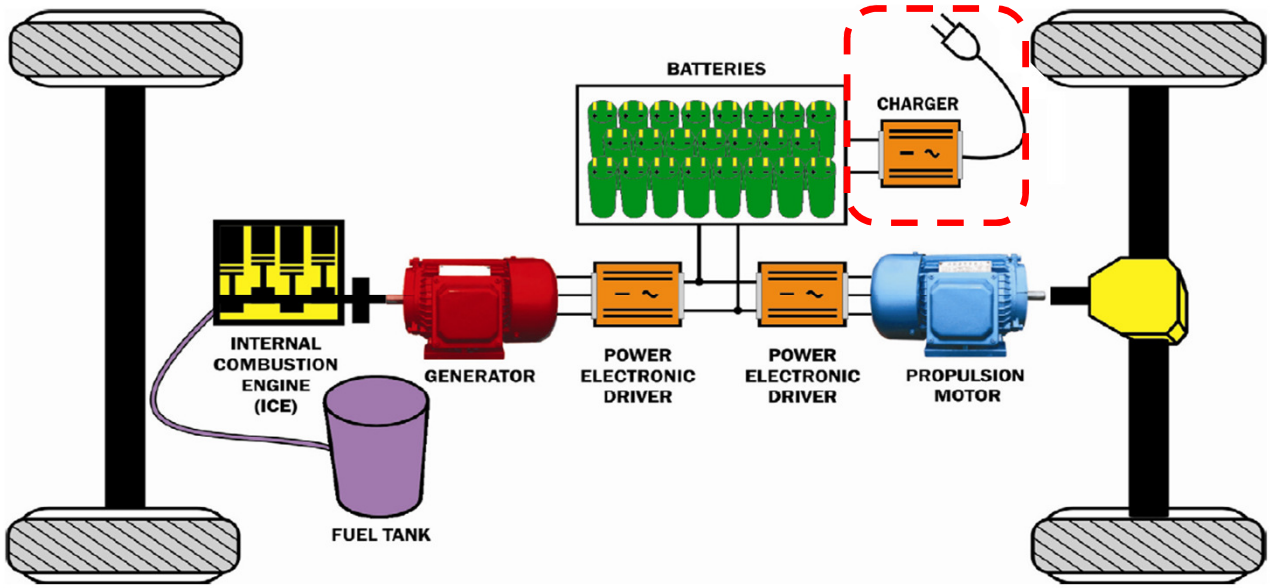


(Source: Pike Research)

HEVs POWERTRAIN CONFIGURATIONS: SERIES HYBRID EV

- Engine is **mechanically decoupled** from the wheels
- Power is delivered by the electric motor while the engine drives an electric generator
- Generator charges the batteries which drives the electric motor

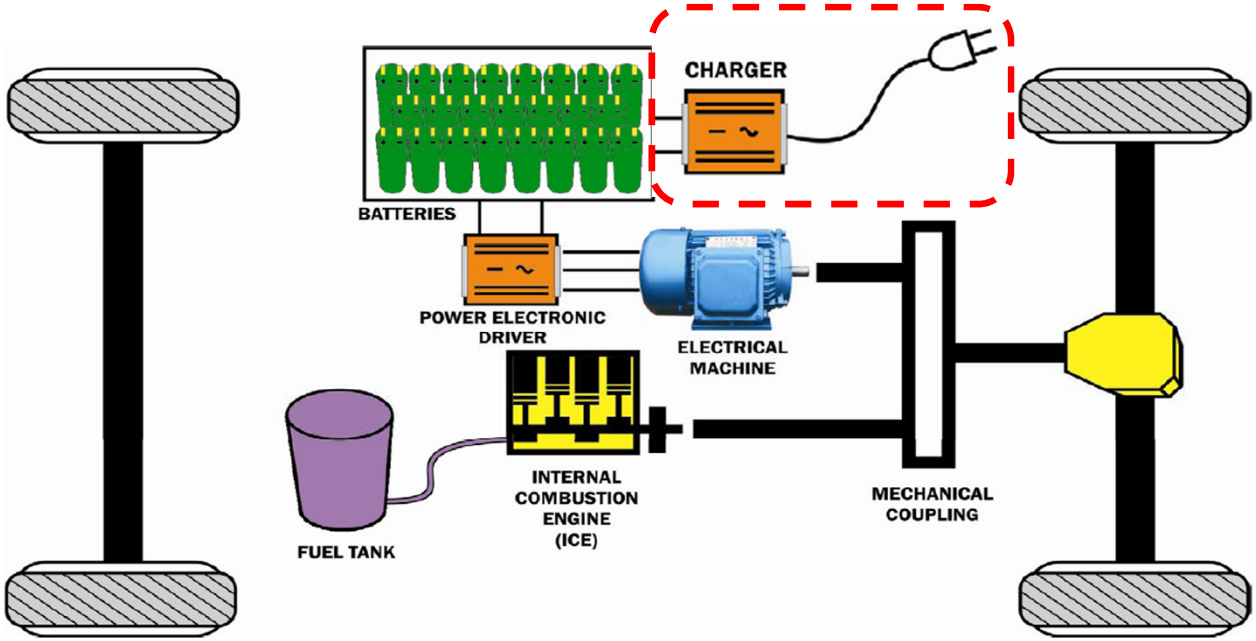
PLUG-IN HYBRID – SERIES CONFIGURATION



HEVs POWERTRAIN CONFIGURATIONS: PARALLEL HYBRID EV

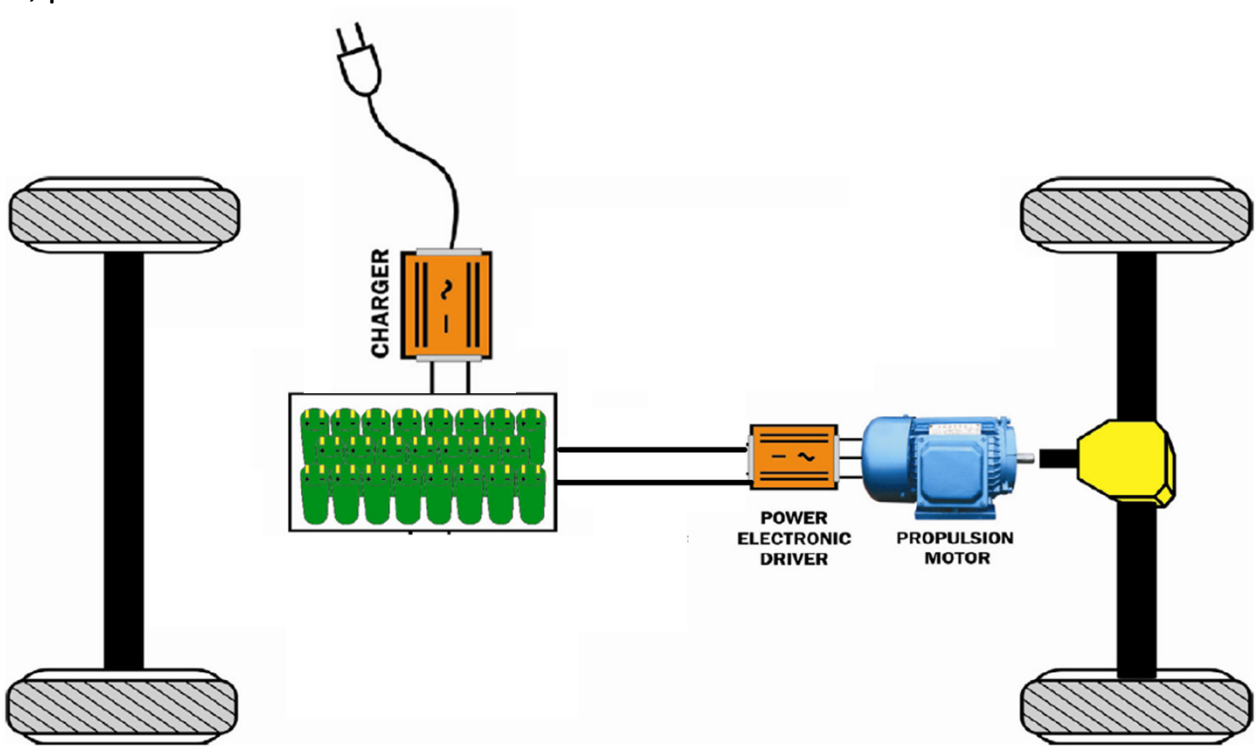
- The **engine and electric motor** are **coupled** to drive the vehicle

PLUG-IN HYBRID – PARALLEL CONFIGURATION

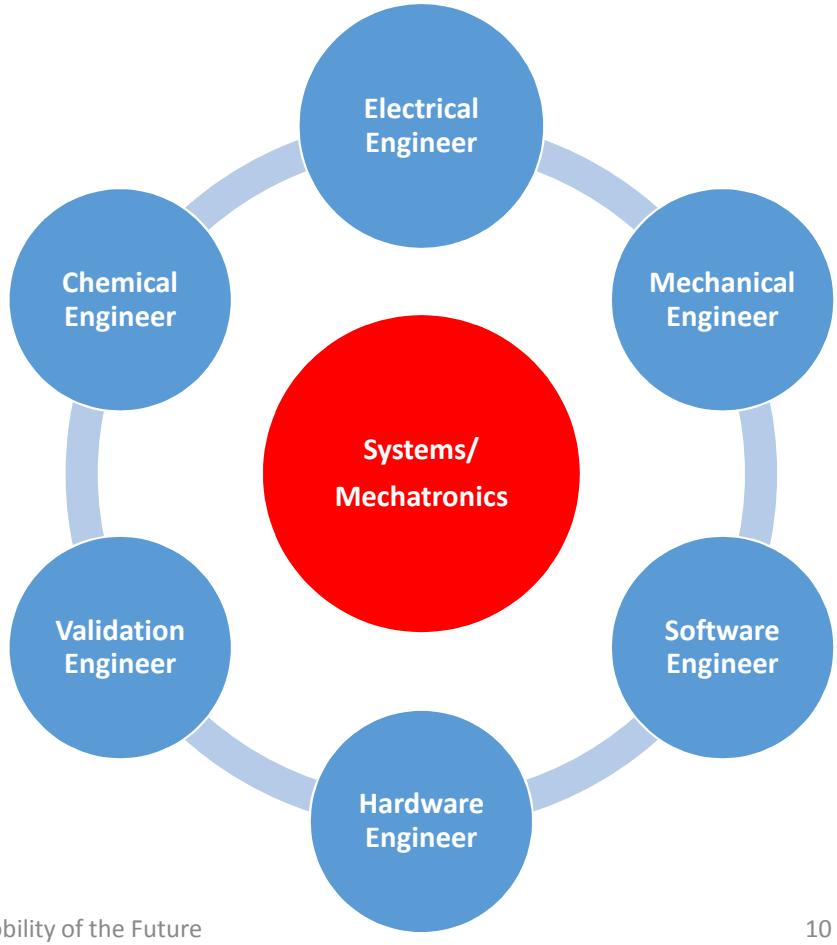


HEVs POWERTRAIN CONFIGURATIONS: BATTERY ELECTRIC VEHICLES (BEV)

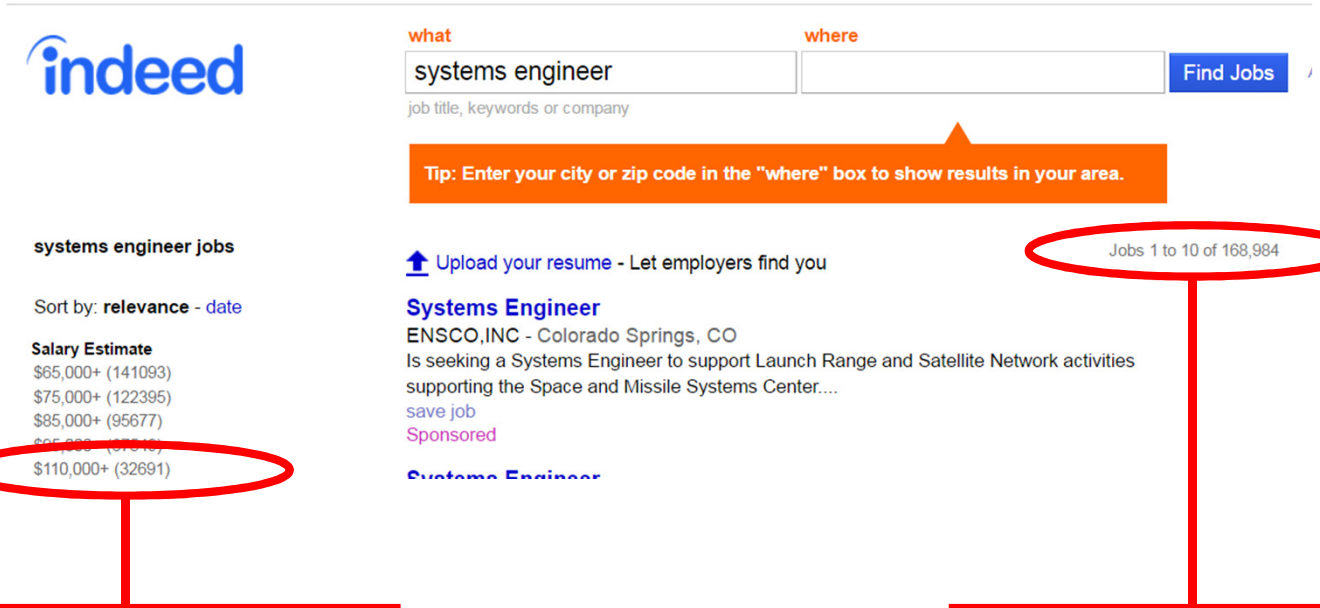
- No engine exists, pure electrified vehicles



MECHATRONICS ENGINEERING: AUTOMOTIVE INDUSTRY



MECHATRONICS ENGINEERING: JOB MARKET IN U.S.

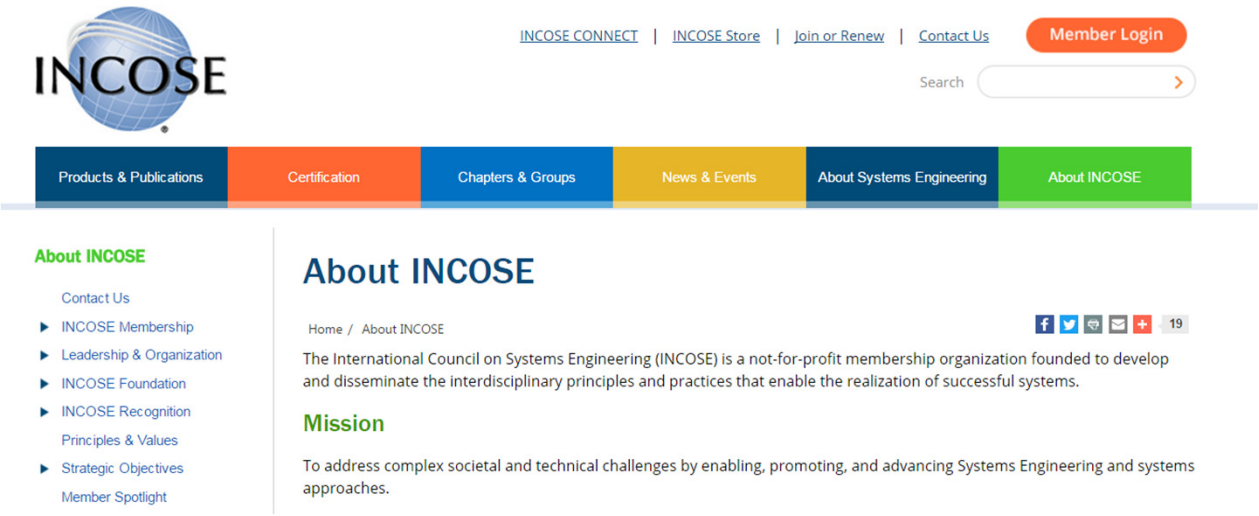


Salary Range: 65K-110K USD

 # Openings: 168,984

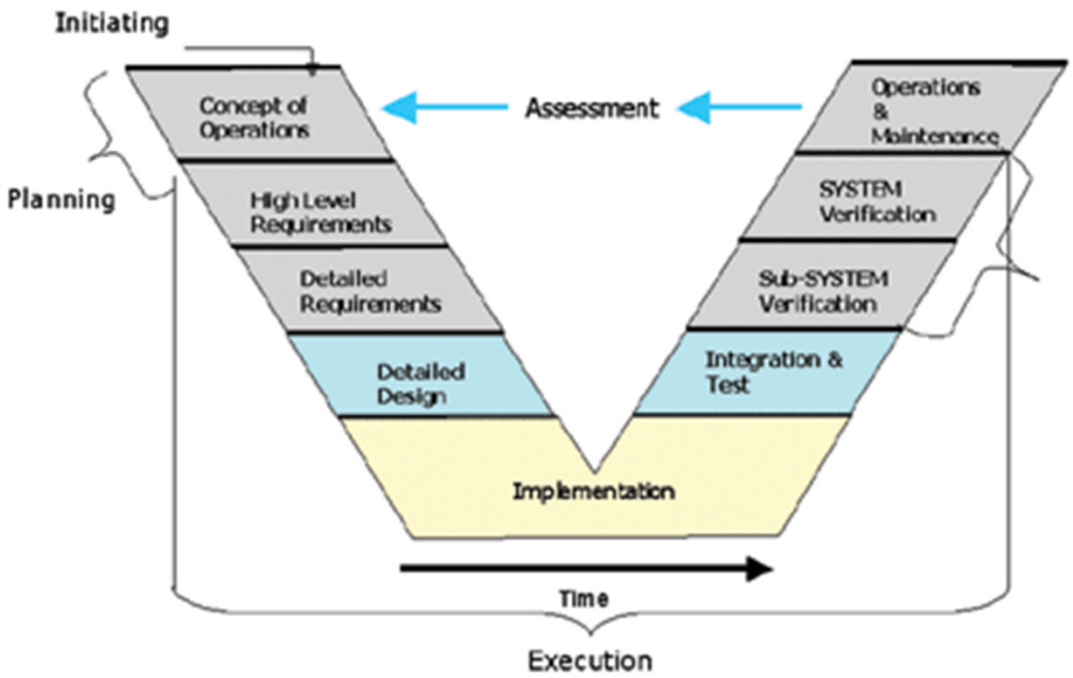
MECHATRONICS ENGINEERING: INTERNATIONAL COUNCIL ON SYSTEMS ENGINEERING (INCOSE)

http://www.incose.org/



V PROCESS MODEL:

- Represents a structured process for guiding project development from its conception through design, implementation, operations.
- This approach increases the probability of producing a successful outcome and minimizes the project budget and schedule.

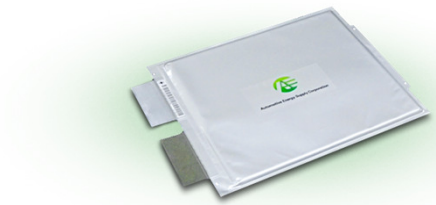


CASE STUDY: BATTERY MANAGEMENT SYSTEM

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE

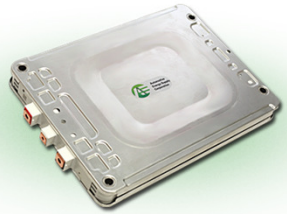
Battery cell:

- Smallest packaged form of a battery
- Voltage ranges from 1 - 6V



Module

- Modules are formed by connecting cells in series and parallel configurations
- Cells are contained in metal case to protect them



Pack

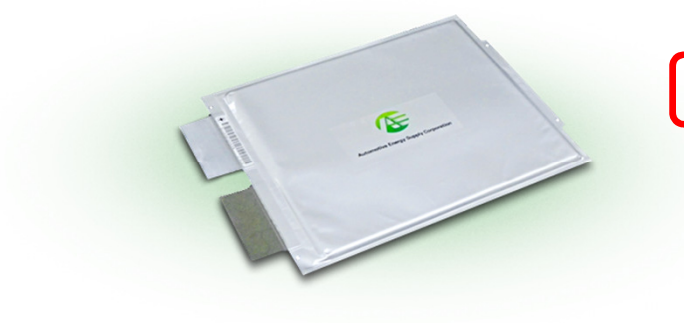
- Assembled by connecting a group of battery modules together in series or parallel

http://www.eco-aesc-lb.com/en/product/liion_ev/
http://blog.cafefoundation.org/less-expensive-batteries-may-lead-to-more-homebuilt-electric-airplanes/

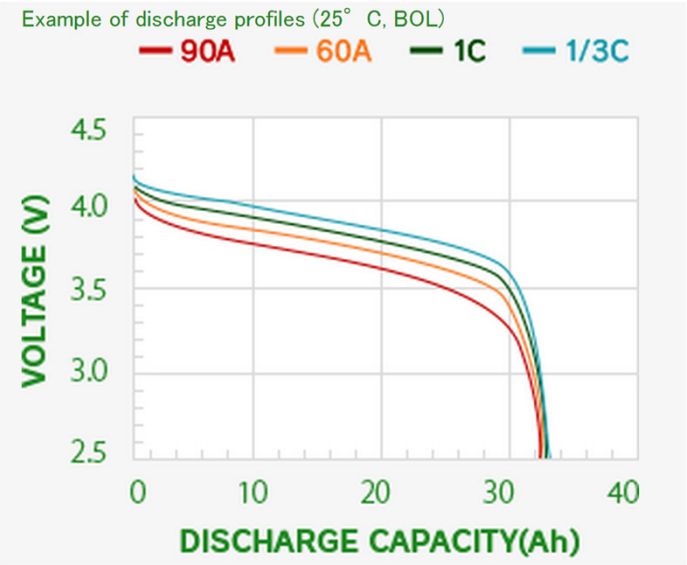
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE NISSAN LEAF BATTERY PACK

Cell

- Cells should provide **long life span**, **strong heat dissipation** and **high energy density**
- Lithium Manganese Oxide cells



Cell Type		Laminate Type
Cathode Active Material		LMO with LNO
Anode Active Material		Graphite
Rated Capacity (0.3C)		32.5 Ah
Nominal Voltage		3.75 V
Exterior Dimensions	Length	290mm
	Width	216mm
	Weight	787 g
Energy Density		317Wh/L 157Wh/kg



http://www.eco-aesc-lb.com/en/product/liion_ev/

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE

Module

- The EV modules adopted in the Nissan Leaf and other vehicles feature a **2-series, 2-parallel** formation
- The case functions are used to **protect the cells from vibration**
- It improves the **pack design flexibility** because of its **simple** and **compact** shape

Number of Cells		4
Structure		2 parallel, 2 series
Exterior Dimensions	Length	303 mm
	Width	223mm
	Height	35mm
Weight		3.8 kg

http://www.eco-aesc-lb.com/en/product/liion_ev/

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE

Pack

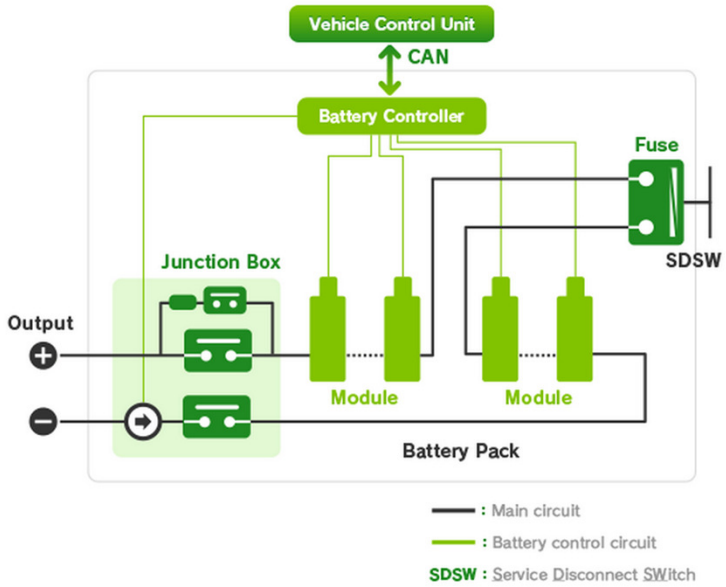
- The pack is formed by installing a **battery management system**, **sensors**, and **housing**
- For Nissan Leaf, battery pack is formed by connecting **48 modules** in series with 360V, capacity of 24kWh
- The pack can be designed with a shape suitable to be installed under the vehicle floor

Number of Modules	48
Nominal Voltage	360V
Capacity	24kWh

http://www.eco-aesc-lb.com/en/product/liion_ev/

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SYSTEM STRUCTURE

- **Voltage, current** and **temperature** are monitored by sensors from each module
- Data is sent from the battery controller (**BMS**) to the **vehicle control unit** via CAN
- During maintenance, the circuit is interrupted by operating the SDSW (**Service Disconnect Switch**)

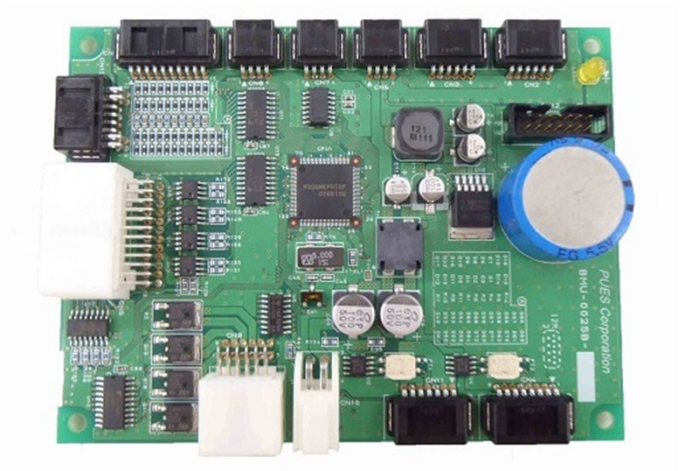


http://www.eco-aesc-lb.com/en/product/liion_ev/

http://www.greencarreports.com/image/100409382_lithium-ion-battery-pack-for-2014-chevrolet-spark-ev-electric-car

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY PACK MONITORING

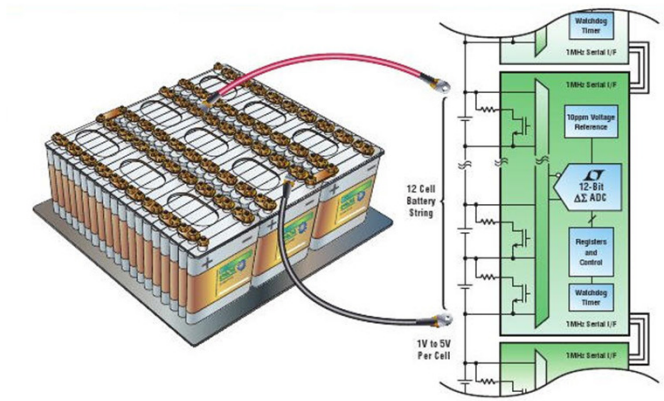
- A Battery Management System (BMS) is employed to actively monitor and protect the cells in real-time.
- The BMS accurately monitor cell voltage, current, temperatures, impedance and other variables of the cells.
- The BMS performs several functions:
  - Cell Monitoring
  - Supervising Battery Pack Behavior
  - Cell Balancing
  - Fuel Gauging (SOC Estimation)



http://www.pues.co.jp/en/products-en/390.html

CASE STUDY/BATTERY MANAGEMENT SYSTEM: CELL SUPERVISORY CIRCUIT (CSC)

- The BMS consists of the ECU (micro-controller) or the brain along with the CSC (Cell Supervisory circuit) (Cell Module)
- The CSC is attached to each module to measure individual cell voltages.
- The CSC has balancing resistors used to dissipate current into them to maintain all cells at the same state of charge.
- The CSC measurements are sent to the ECU (brain) for decision making.

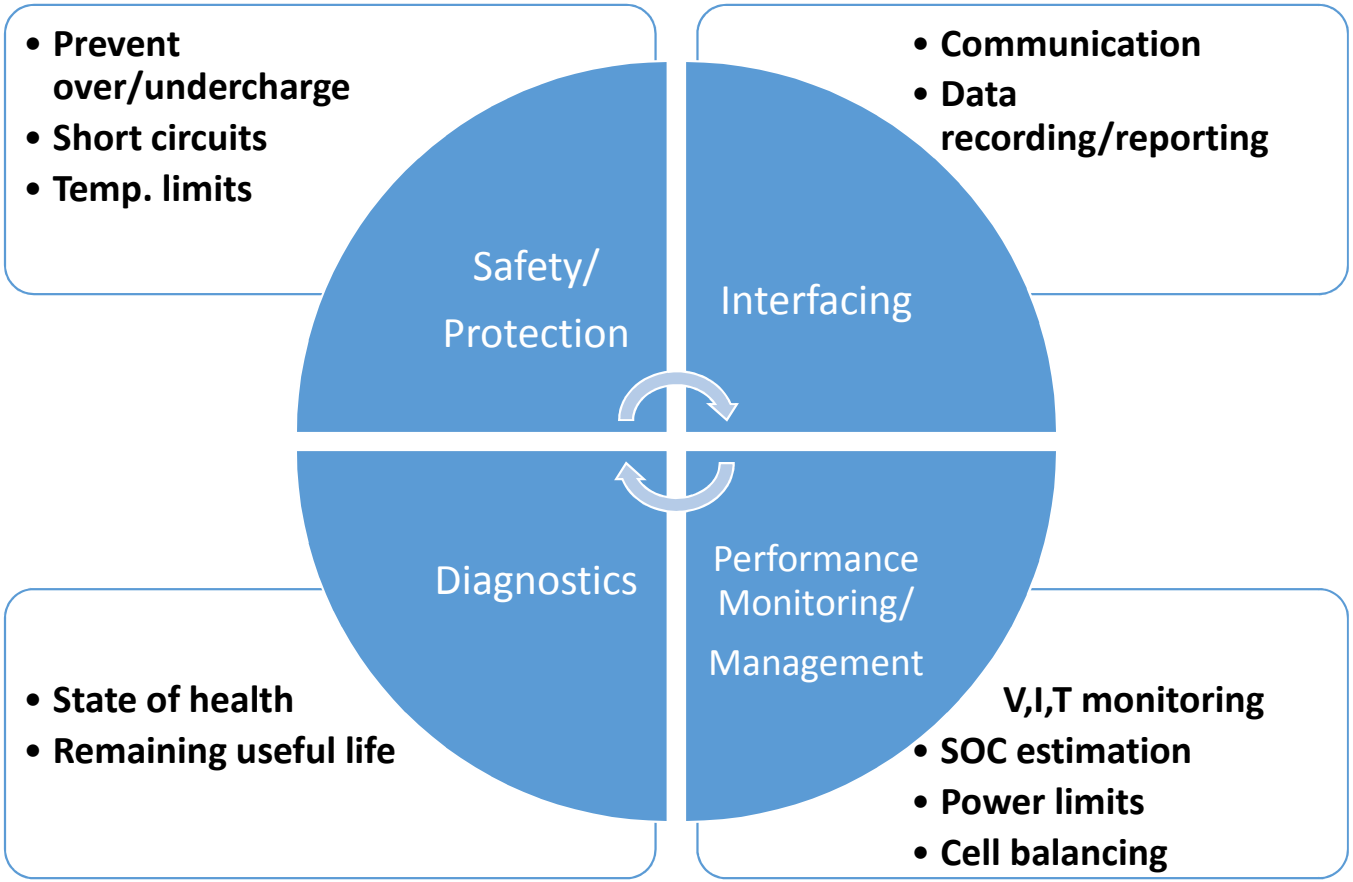


Rugged IC for Hybrid/Electric Vehicles & Battery Backup Systems

http://ams.com/eng/Products/Battery-Management/Cell-Supervision-Circuits

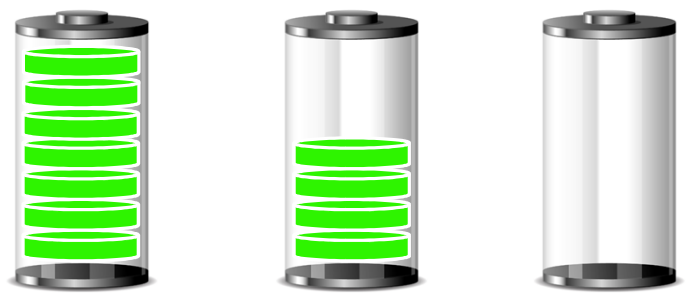
https://www.dspace.com/shared/data/pdf/2011/Elektronik_Automotive_July_2011_01_110811_E_ebook.pdf

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS



CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS: BATTERY STATE OF CHARGE (%) ESTIMATION

- Equivalent to fuel gauge in conventional vehicles
- Represents **battery current capacity** as a **percentage of maximum capacity**
- **SOC is calculated using coulomb counting/current integration**

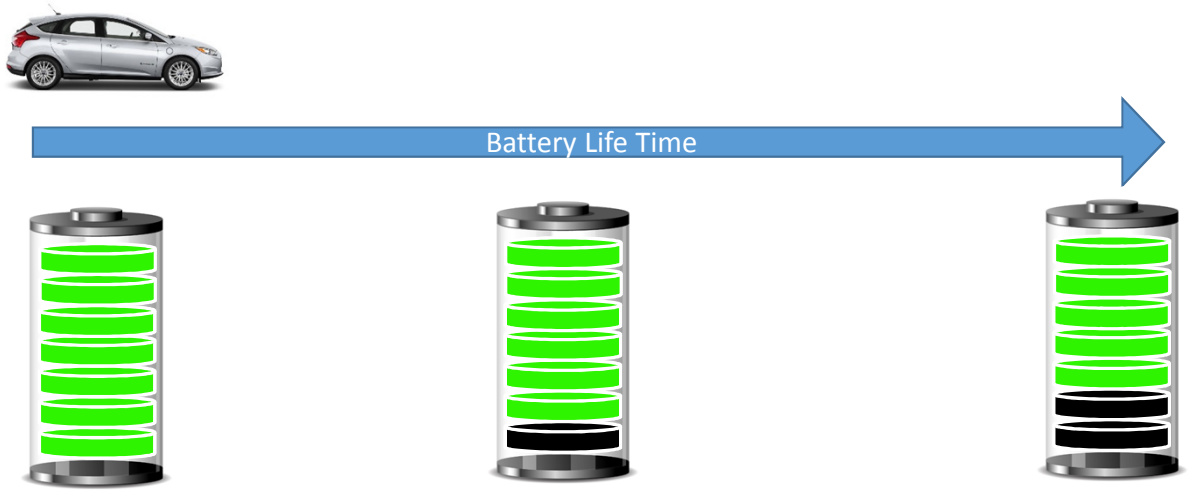


Battery SOC = 100% **Battery SOC = 50%** **Battery SOC = 0%**

*"However, while there exist sensors to accurately **measure** a gasoline level in a tank, there is no sensor available to measure SOC. Instead, SOC must be **estimated** from physical measurements by some algorithm."*

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS: STATE OF HEALTH ESTIMATION

- **Battery SOC and SOH?**



Fresh Battery
Life Fraction (LF)= 0

Model 1

Capacity = 100%

Midlife Battery
LF = 0.5

Model 2

Capacity = 90%

Aged Battery
LF = 1

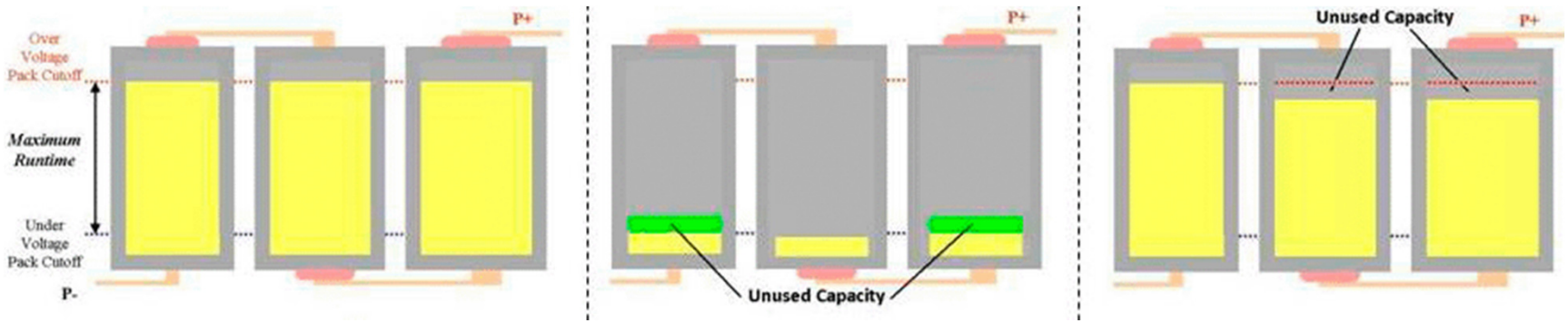
Model 3

Capacity = 80%

- ***EVs are Relatively new, some time is required to assess the estimators in real-world operating conditions***

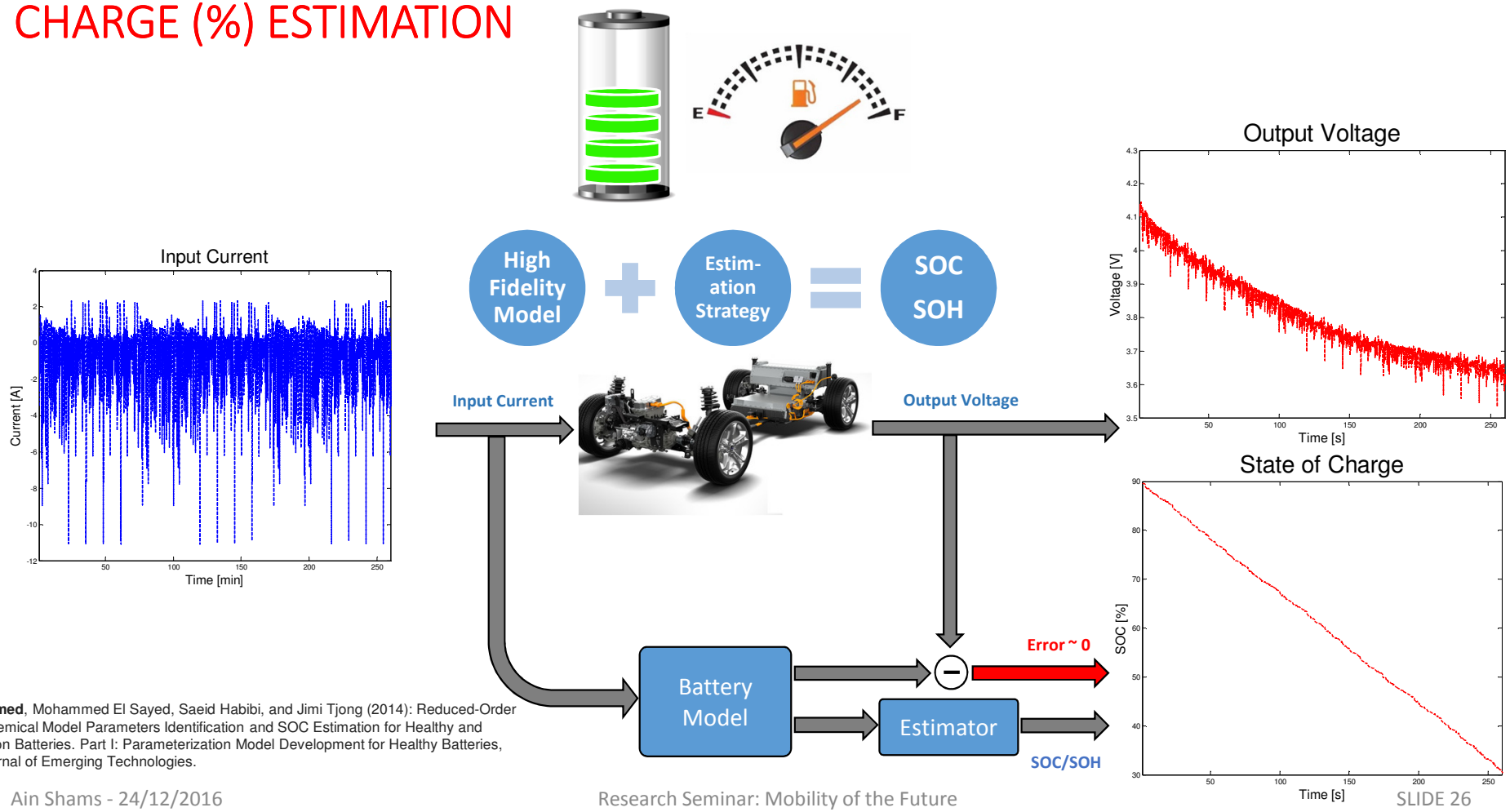
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BMS KEY FUNCTIONS: CELL BALANCING

- After many charging/discharging cycles, cells may become **out of balance**
- Cells vary due to **manufacturing differences**, **columbic efficiencies**, and **capacities**
- Cells may limit the **discharge ability** of the pack if their SOC is much lower than remaining cells



http://www.eetimes.com/document.asp?doc_id=1272951

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY STATE OF CHARGE (%) ESTIMATION



Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part I: Parameterization Model Development for Healthy Batteries, IEEE Journal of Emerging Technologies.

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING

- **Battery Models Overview**

Level of Details Increase

Lumped-parameters models

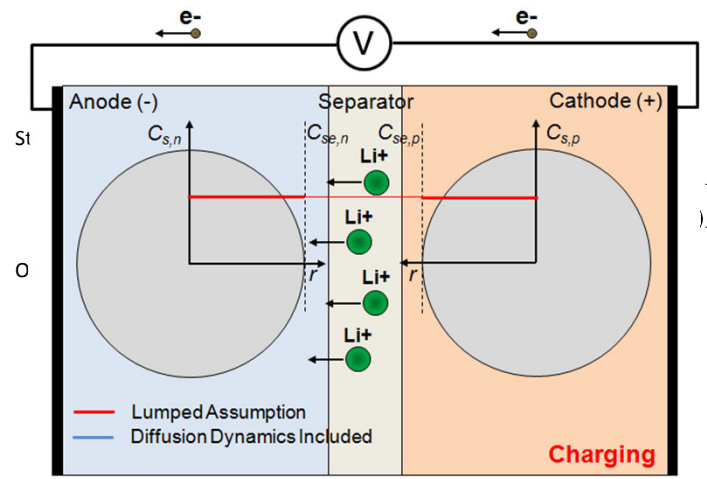
- Empirical models
- Account for hysteresis, polarization T_s, ohmic loss
- No/minimal physical significance/SOH

Equivalent circuit models

- Simple, less parameters to tune
- Easy implementation/Computationally efficient
- No/minimal physical significance/SOH

Electrochemical models

- Model lithium diffusion
- Physical insight of battery SOH
- Large number of parameters
- Hard to obtain these parameters
- Computationally expensive (reduced form)



CASE STUDY/BATTERY MANAGEMENT SYSTEM: EXPERIMENTAL SETUP

Battery Cells

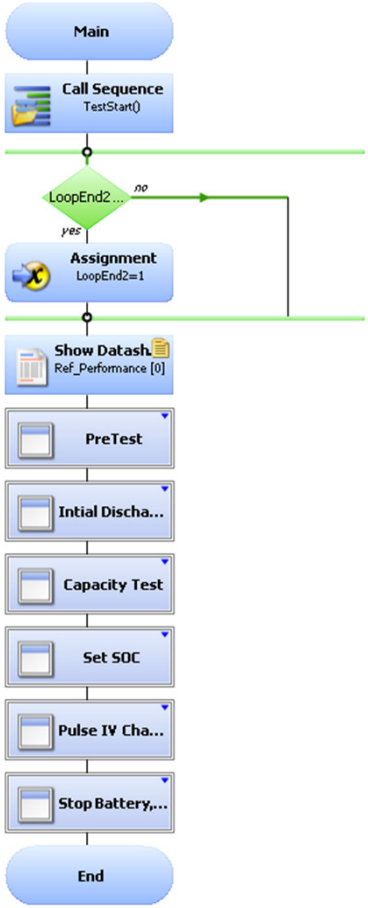
- Mount temperature sensors on each cell

Cyclers/ Chambers

- Chambers: thermally stress cells (-20 to 70°C)
- Independent parallel channels (Ex: 400 A, 20V)

Data Acquisition

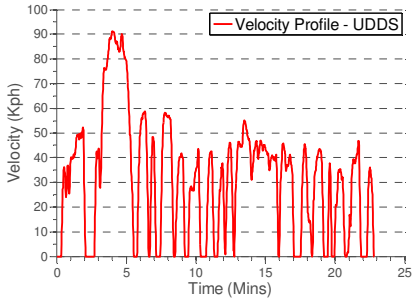
- Software
- Test Procedure

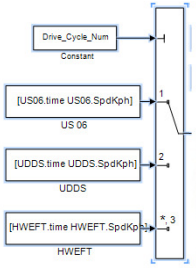


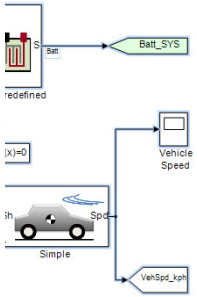
Ryan Ahmed, Jimi Tjong, and Saeid Habibi, "Battery Aging Model Development based on Behavioural and Equivalent Circuit-Based Models", Journal of Power Sources (2014)

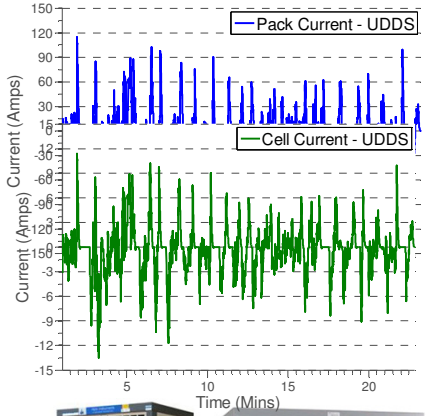
CASE STUDY/BATTERY MANAGEMENT SYSTEM: VELOCITY PROFILE TO CYCLER

- **Generate Velocity Profile to Cycler?**









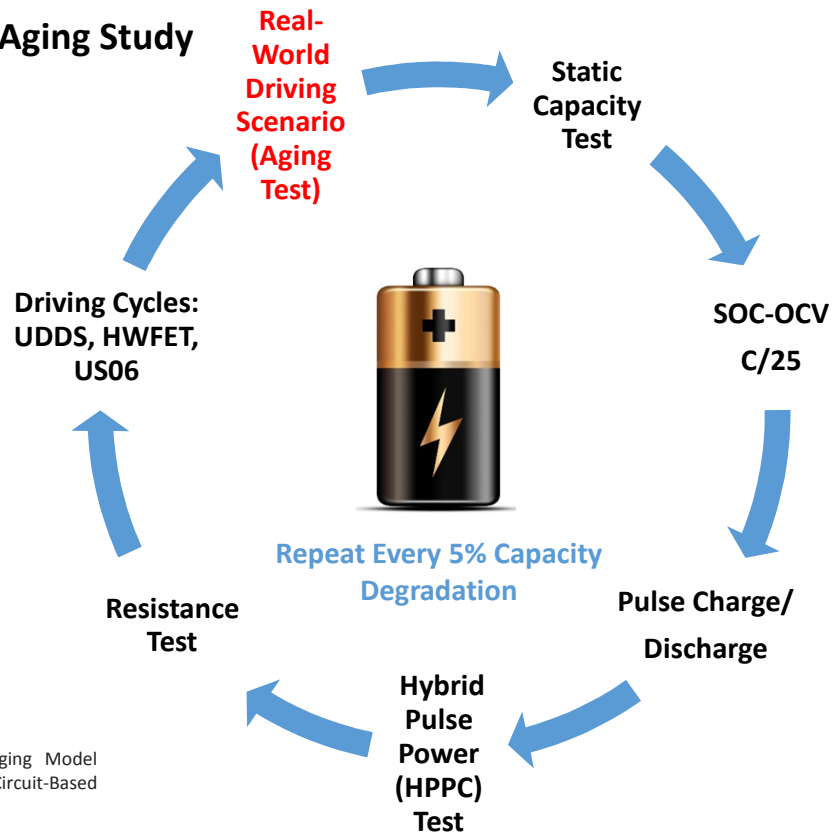
Driving Cycle
- Urban/Highway
- Velocity Profile

Electric Vehicle Model
- Matlab/ Simulink
- Pack level current

Cycler
- Cell-level scaling
- No cell balancing

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- **Aging Model Development: Aging Study**



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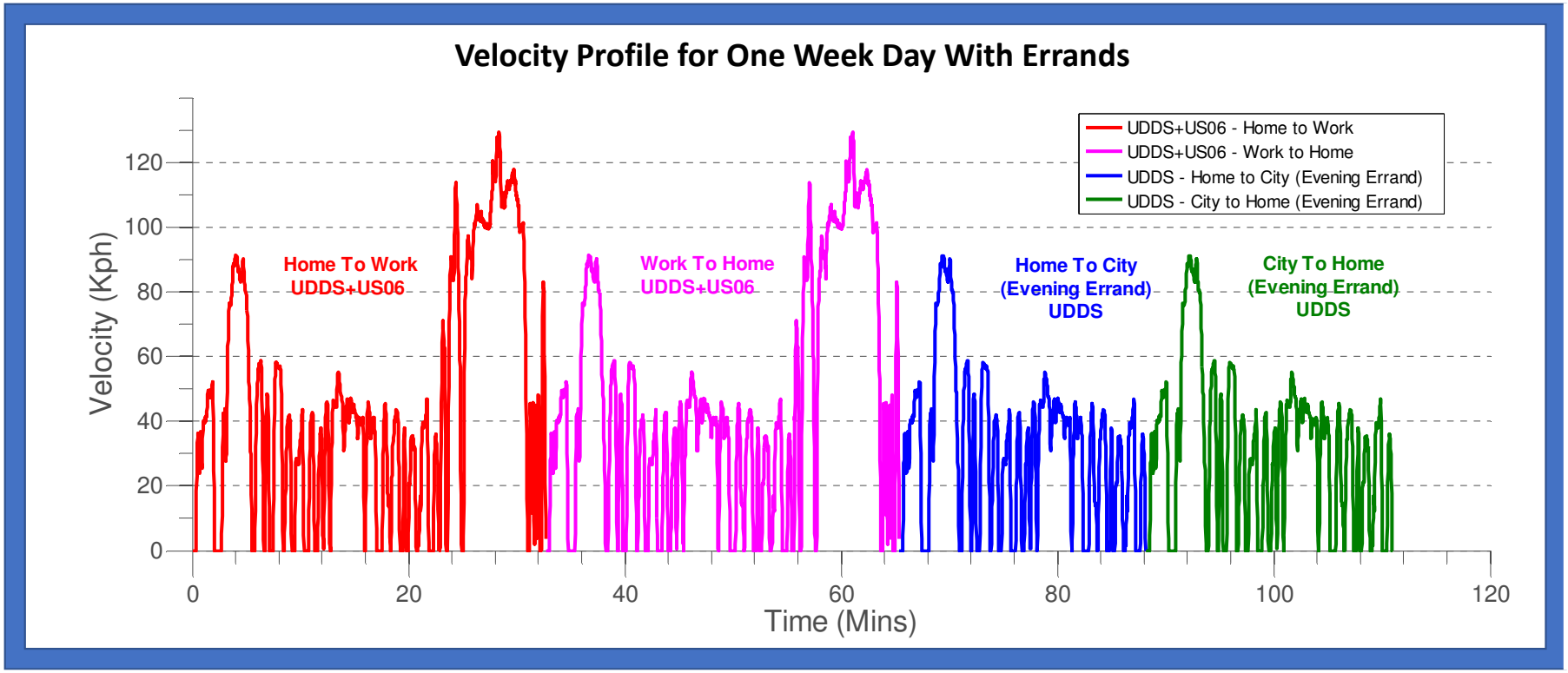
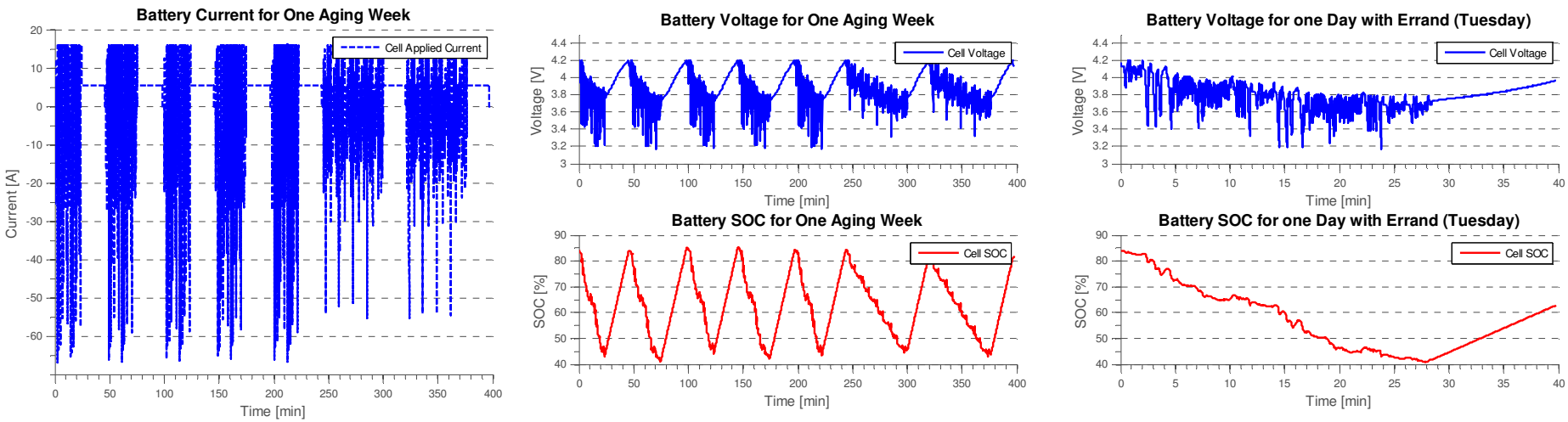
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- **Aging Model Development: Real-World Driving Aging Test**



CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- **Aging Model Development: Experimental Data Sample**



Experiments Running on 24/7 basis for ~ 13 months

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING

ELECTROCHEMICAL BATTERY MODEL

- Solid and electrolyte potentials

$$\frac{\partial}{\partial x} k^{eff} \frac{\partial}{\partial x} \emptyset_e + \frac{\partial}{\partial x} k_D^{eff} \frac{\partial}{\partial x} \ln c_e = -j^{Li}$$

$$\frac{\partial}{\partial x} \sigma^{eff} \frac{\partial}{\partial x} \emptyset_s = j^{Li}$$

- Linear lithium diffusion in electrolyte:

$$\frac{\partial \varepsilon_e c_e}{\partial t} = \frac{\partial}{\partial x}\left(D_e^{eff} \frac{\partial c_e}{\partial x}\right) + \frac{1 - t^0}{F} j^{Li}$$

- Spherical solid diffusion:

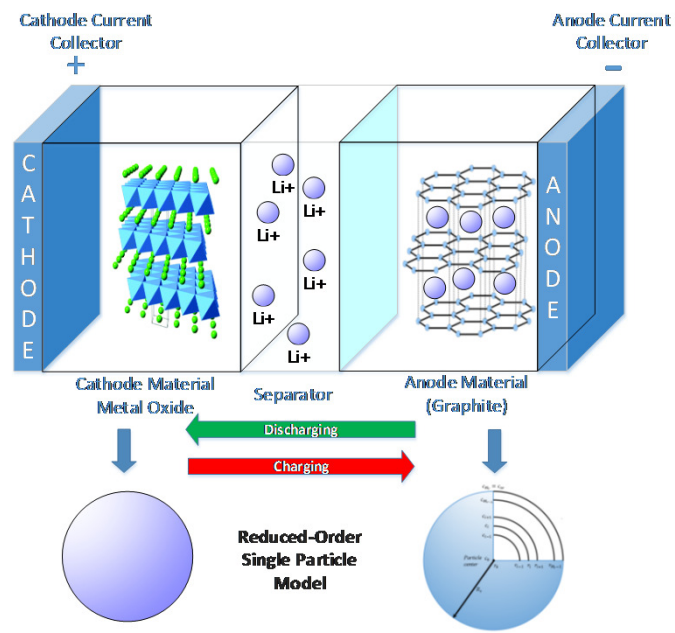
$$\frac{\partial c_s}{\partial t} = \frac{\partial}{\partial r}\left(D_s \frac{\partial c_s}{\partial r}\right)$$

- Terminal Voltage Calculation

$$J^{Li} = a_s j_o [exp\left(\frac{\propto_a F}{RT}\eta\right) - exp(\frac{\propto_c F}{RT}\eta)]$$

$$\eta = \emptyset_s - \emptyset_e - U(c_{se})$$

$$V = \emptyset_s(x = L) - \emptyset_s(x = 0) - R_f I$$



Model Assumptions:

- No aging or capacity fade has been accounted for
- Model parameters assumed to be held constant
- Significant errors at high C-rates (rate capacity/recovery effect)

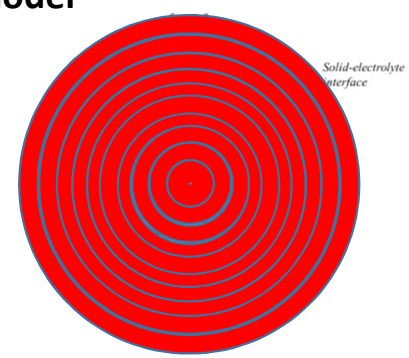
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING

ELECTROCHEMICAL BATTERY MODEL

- **SOC Module: Reduced-Order Electrochemical Model**

$$c_{s,p_{avg}} = \frac{c_T}{V} = \frac{total\ lithium\ concetration}{particle\ volume} = \frac{\sum_{i=1}^{M_r-1} r_i^2 4\pi\Delta r c_i}{\frac{4}{3}\pi(R_s - \Delta r)^3}$$

$$SOC = 100 * \left(\frac{\frac{c_{s,p_{avg}}}{c_{s,max,p}} - \theta_{p0\%}}{\theta_{p100\%} - \theta_{p0\%}}\right)$$



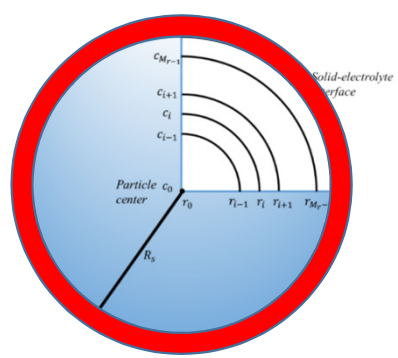
- **Terminal Voltage Module**

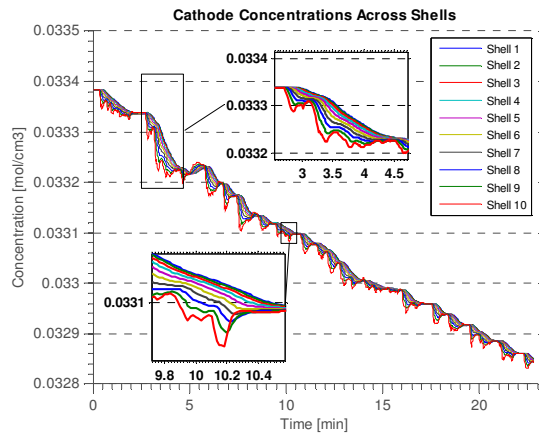
$$\bar{c}_{se,n} = c_{s,max,n}\left(\theta_{n0\%} + \frac{\bar{c}_{se,p} - \theta_{p0\%} c_{s,max,p}}{(\theta_{p100\%} - \theta_{p0\%}) c_{s,max,p}}(\theta_{n100\%} - \theta_{n0\%})\right)$$

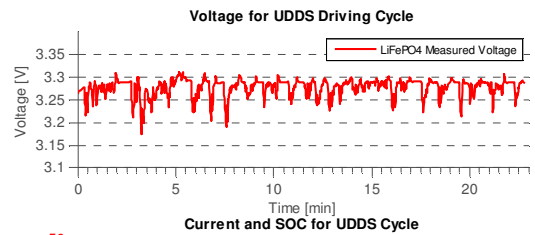
$$\eta_p = \emptyset_{s,p} - \emptyset_{e.p} - U_p(c_{se,p})$$

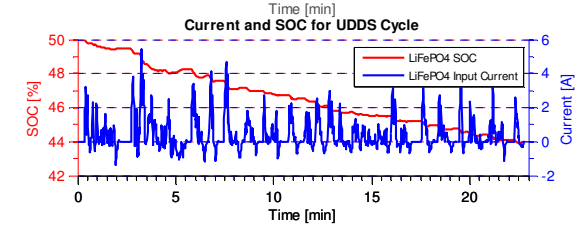
$$\eta_n = \emptyset_{s,n} - \emptyset_{e.n} - U_n(c_{se,n})$$

$$V(t) = (\bar{\eta}_p - \bar{\eta}_n) + (\bar{\emptyset}_{e.p} - \bar{\emptyset}_{e.n}) + (U_P(c_{se,p}) - U_n(c_{se,n})) - R_f I$$





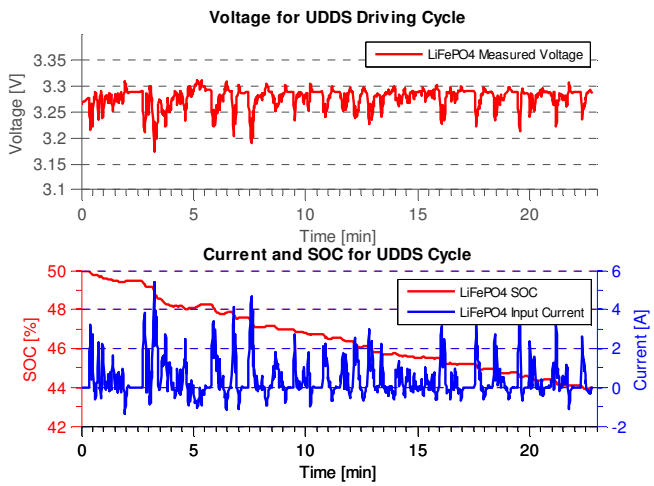


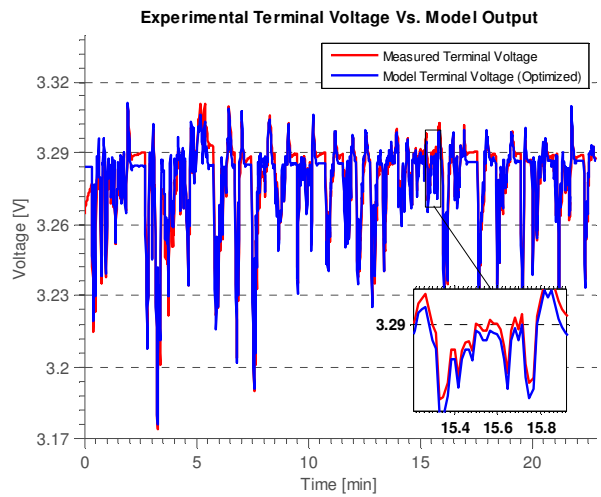


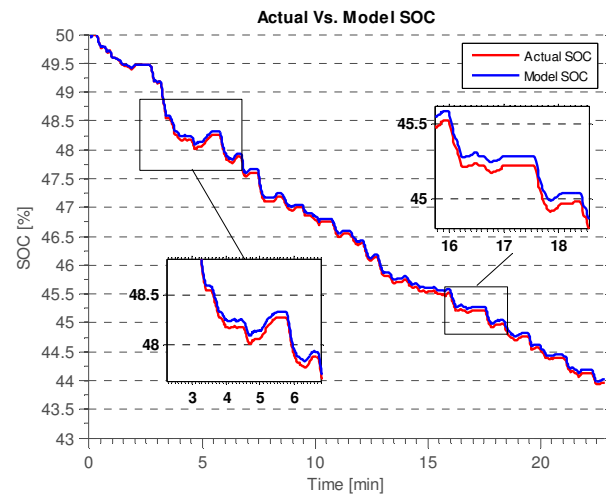
Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part I: Parameterization Model Development for Healthy Batteries, IEEE Journal of Emerging Technologies.

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY MODELING
ELECTROCHEMICAL BATTERY MODEL

- **Model Parameters Fitting**
  - Actual SOC (Arbin Cycler) vs. Model SOC for UDDS Cycle
  - Model Terminal voltage vs. Measured voltage





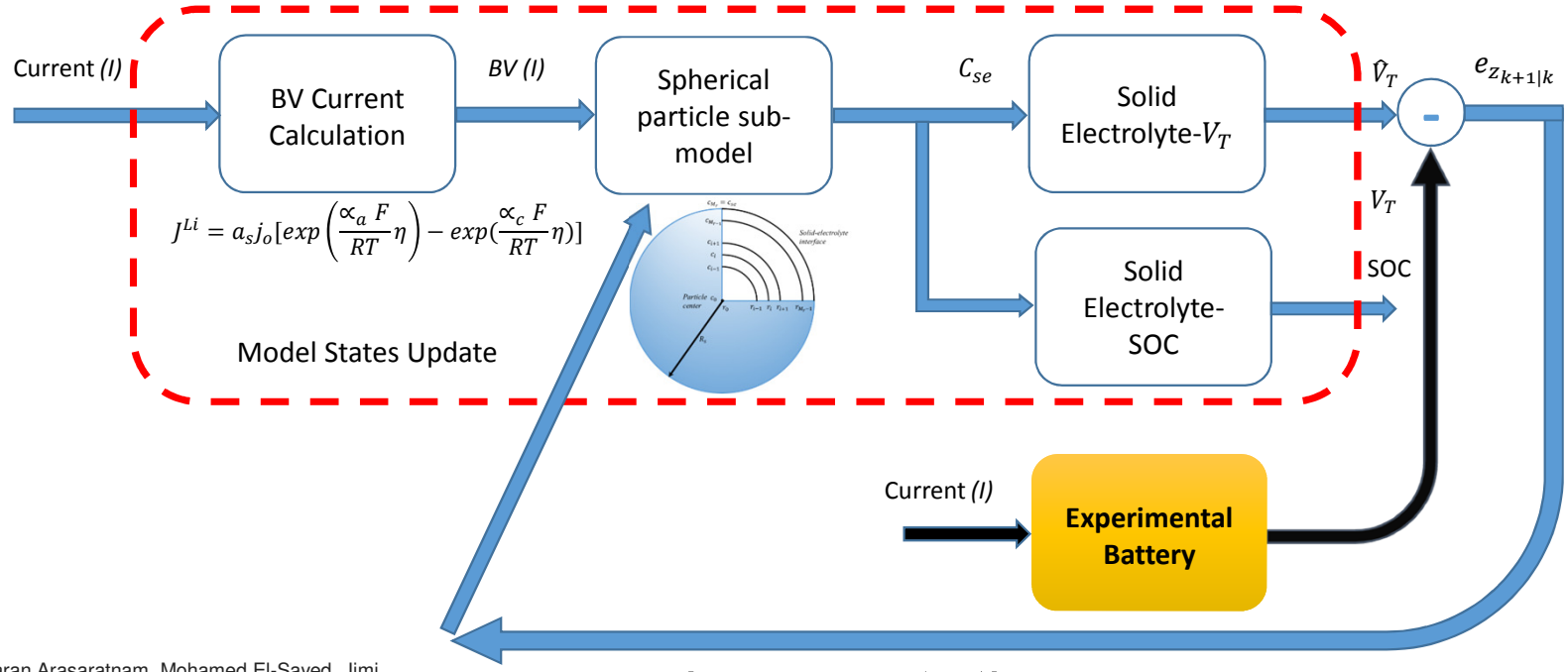


V_T **RMSE (UDDS) = 0.22 mV**

SOC RMSE (UDDS) = 0.0547 %

Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part II: Aged Battery Model and State of Charge Estimation, IEEE Journal of Emerging Technologies, Special Issue on Transportation and Electrification.

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SOC ESTIMATION

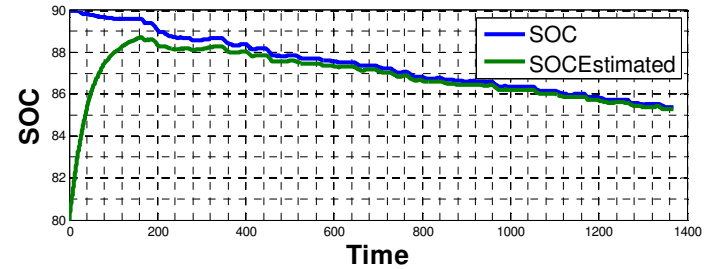


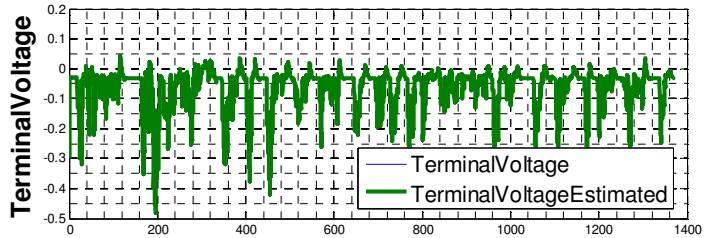
$$K_{k+1} = diag\left[\left(\left|e_{z_{k+1|k}}\right| + \gamma\left|e_{z_{k|k}}\right|\right) \circ sat\left(\frac{e_{z_{k+1|k}}}{\psi}\right)\right] diag\left(e_{z_{k+1|k}}\right)^{-1}$$

Ryan Ahmed, Ienkaran Arasaratnam, Mohamed El-Sayed, Jimi Tjong, and Saeid Habibi, "Online and Offline Parameters Identification and SOC Estimation for Healthy and Aged Electric Vehicle Batteries Based on Equivalent Circuit Models", Journal of Power Sources, 2015.

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY SOC ESTIMATION

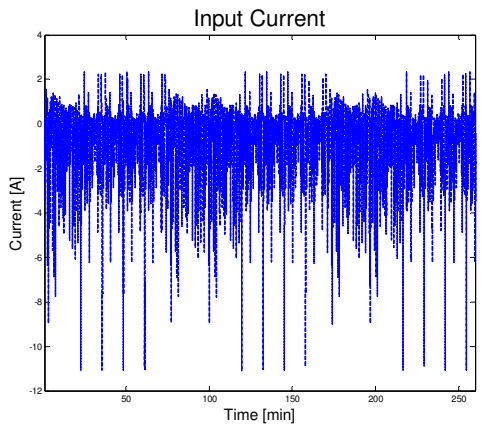
```
for k = 1 : 1 :  ik
    %% Ploting Data
    SOCEstimated              = [SOCEstimated; X(1)];
    %% Calculate Required Parameters.
    SOC      = X(1);
    T        = [R_plus; R_minus; K0; K1; K2; K3; K4];
    CoffB3   = -(eta * DeltaT / Cn);
    %% Linearize Model For Kalman Use.
    [C_x]    = CombinedModel_ComplexDiff(X, T, Current(k),1);
    %% Run Updated Model
    U        = Current(k);
    if Current(k) >= 0
        TerminalVoltage  = K0                          ...
            - (R_plus  * Current(k))      ...
            - K1/SOC                      ...
            - K2*SOC                      ...
            + K3*log(SOC)                 ...
            + K4*log(1-SOC)               ;
    else
        TerminalVoltage  = K0                          ...
            - (R_minus  * Current(k))     ...
            - K1/SOC                      ...
            - K2*SOC                      ...
            + K3*log(SOC)                 ...
            + K4*log(1-SOC)               ;
    end
    %% Calculate Error in States.
    Error_x      = TerminalVoltageActual(k) -  TerminalVoltage;
    %% Time          Update for the state filter.
    A        = 1; B     = CoffB3;
    X        = (A * X) + (B * U);
    P_x      = (A * P_x * A') + Q_x;
    %% Measurement  Update for the state filter.
    KalmanGain_x     = (P_x) * (C_x') * (inv((C_x * P_x * C_x')+( R_x)));
    X                = X + (KalmanGain_x * Error_x);
    P_x              = (eye(n_x,n_x) - (KalmanGain_x * C_x)) * P_x;
    %% Ploting Data
    TerminalVoltageEstimated = [TerminalVoltageEstimated; TerminalVoltage];
```

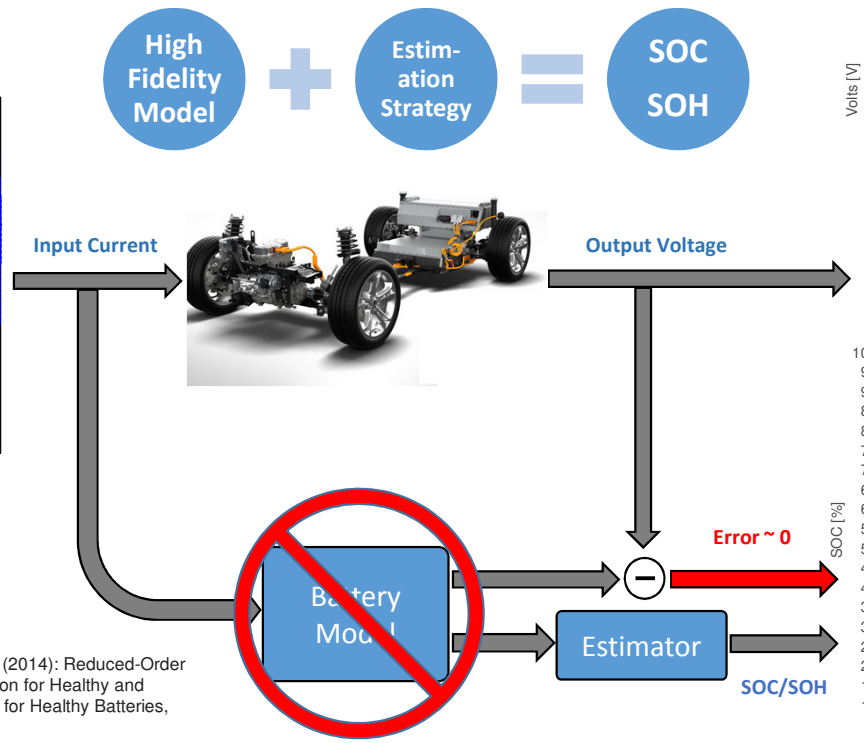


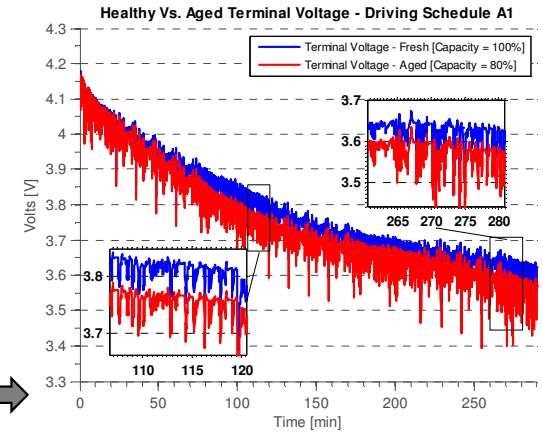


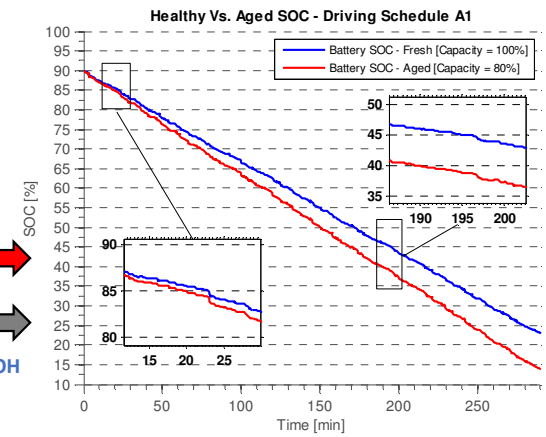
CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY STATE OF HEATLH ESTIMATION

- **Battery models change over the vehicle lifetime**
- **Estimators are used to predict the battery state of health**





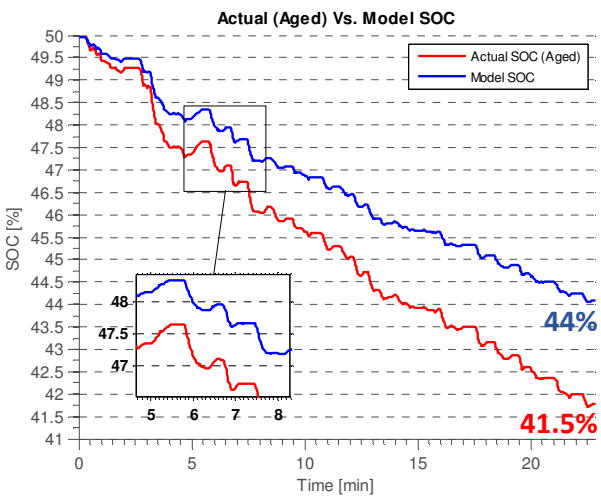


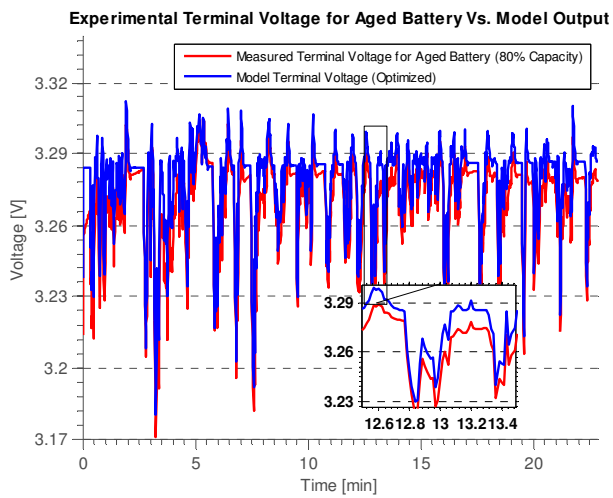


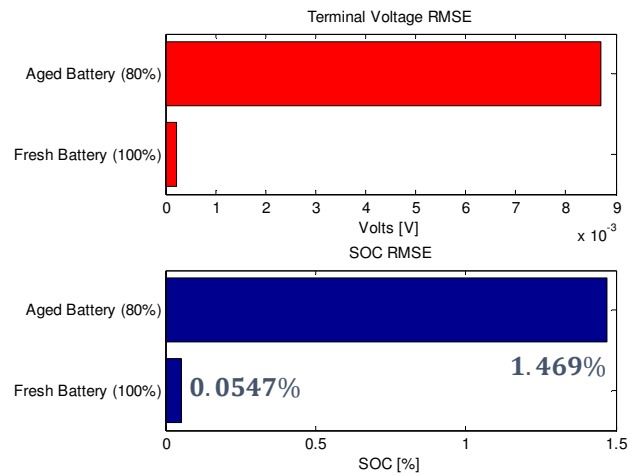
Ryan Ahmed, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part I: Parameterization Model Development for Healthy Batteries, IEEE Journal of Emerging Technologies.

CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

- **Aging Model Development: Do we need model update?**
  - Actual SOC from Aged Battery vs. Model SOC
  - RMSE variations for healthy and aged batteries

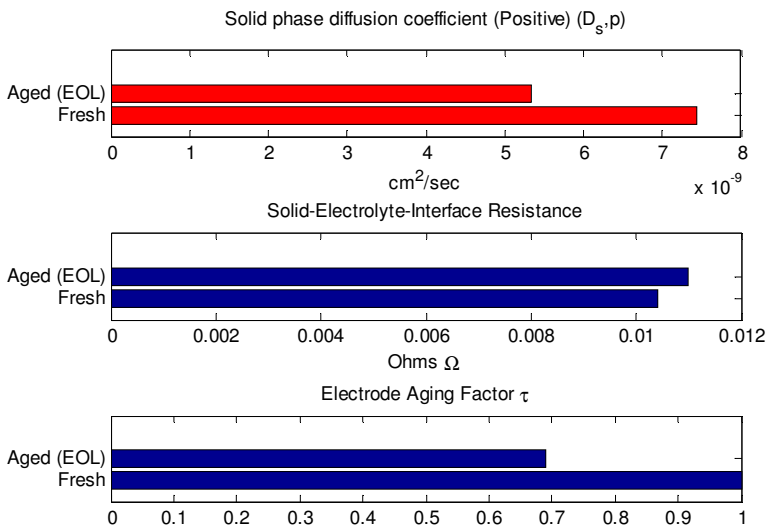


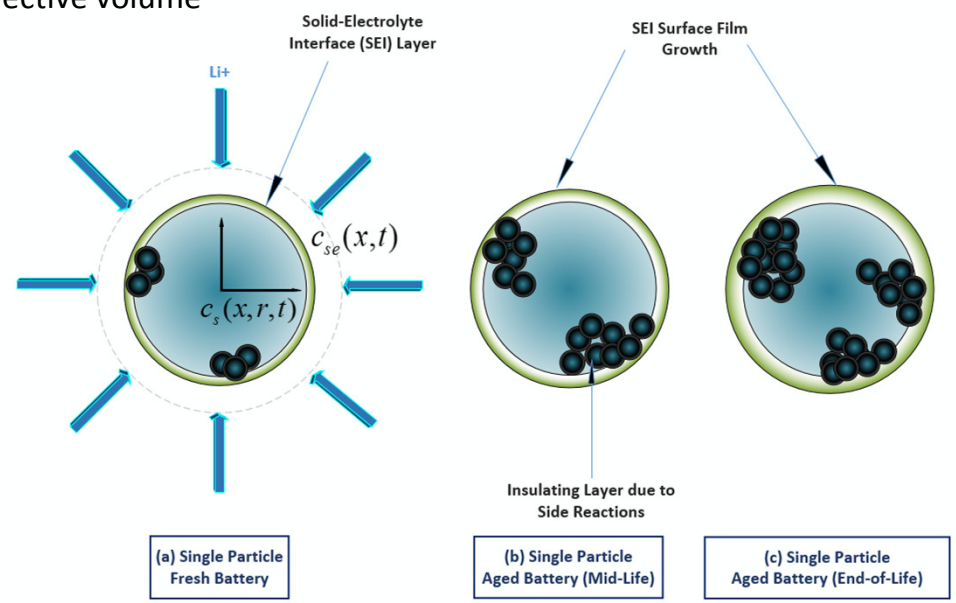




CASE STUDY/BATTERY MANAGEMENT SYSTEM: BATTERY AGING STUDY

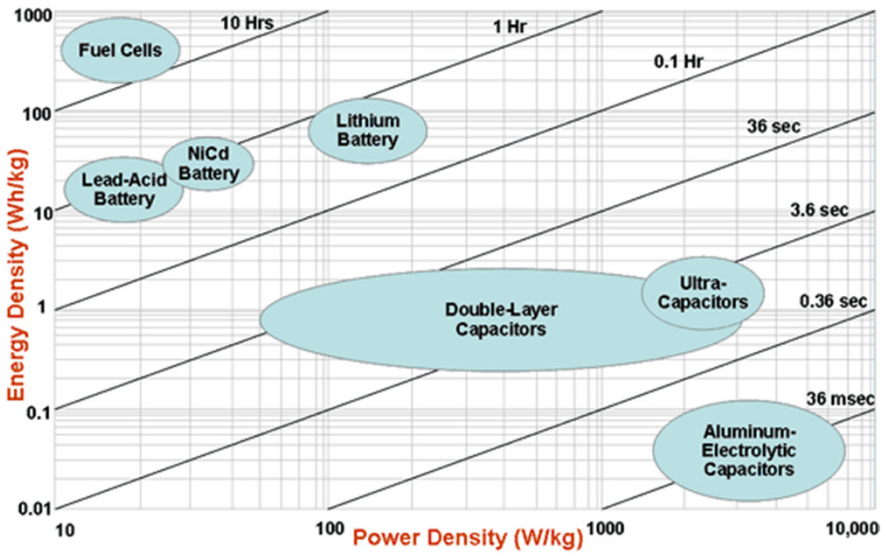
- **Aging Model Development**
  - Model increase in the electrode resistance to accept Li^+
  - Track changes in R_{SEI}, D_s, $OCV - SOC$
  - Introducing: electrode aging factor (τ), electrode effective volume





OTHER TECHNOLOGIES: RAGONE PLOT

- The Ragone plot compares the performance of various electrochemical devices
- **Ultra capacitors provide a high power density** but their storage capacity is very limited thus makes them suitable for capturing **regenerative braking energy** in EV applications
- **Fuel Cells have very high energy density but low power** density limiting their application in EV applications
- Lithium batteries are in between therefore provide a compromise between the two
- A combination of more than one device can be beneficial



Source US Defence Logistics Agency

http://www.mpoweruk.com/performance.htm

OTHER TECHNOLOGIES: ULTRA CAPACITORS

- A **supercapacitors** (**ultracapacitors)** are high-capacity electrochemical capacitor with capacitance values much higher than other capacitors.
- Supercapacitors bridges the gap between electrolytic capacitors and rechargeable batteries.
- They are capable of storing 10 - 100 times more energy per unit volume or mass than electrolytic capacitors.
- They have very high power capability, i.e.: can accept and deliver charge much faster than batteries.
- They have a high cycle life, can withstand great number of charge and discharge cycles than rechargeable batteries.
- However, they have low energy density, they require 10 times more space than conventional batteries for a given charge.
- Supercapacitors are used in regenerative braking, i.e.: applications with many rapid charge/discharge cycles.

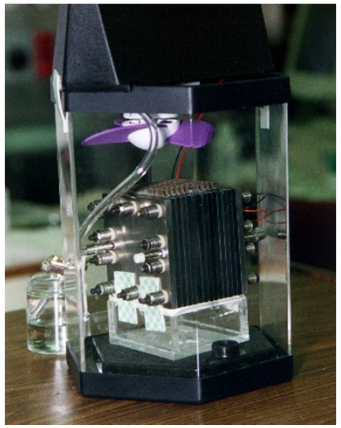
"Supercaps can charge in seconds, without capacity degradation like rechargeable batteries. They can endure virtually unlimited charge cycles"

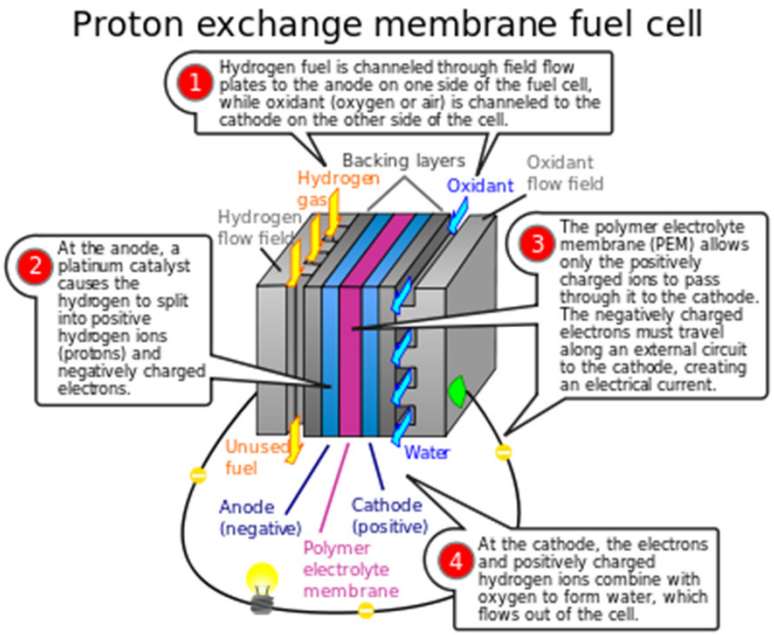
http://www.mouser.com/applications/supercapacitors-hero-automotive/

https://en.wikipedia.org/wiki/Supercapacitor

OTHER TECHNOLOGIES: FUEL CELLS

- A fuel cell converts chemical energy from a fuel into electricity on the fly.
- Fuel cells are different from batteries in requiring a continuous source of fuel and oxygen (or air) to sustain the chemical reaction.
- Check this out: https://www.youtube.com/watch?v=08ZH7vwzzEg





https://en.wikipedia.org/wiki/Fuel_cell

CASE STUDY/BATTERY MANAGEMENT SYSTEM: PUBLICATIONS

1. **Ryan Ahmed**, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part I: Parameterization Model Development for Healthy Batteries, IEEE Journal of Emerging Technologies, Special Issue on Transportation and Electrification. (**Published**).

2. **Ryan Ahmed**, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Reduced-Order Electrochemical Model Parameters Identification and SOC Estimation for Healthy and Aged Li-Ion Batteries. Part II: Aged Battery Model and State of Charge Estimation, IEEE Journal of Emerging Technologies, Special Issue on Transportation and Electrification. (**Published**).

3. Ienkaran Arasaratnam, Jimi Tjong, **Ryan Ahmed** and Saeid Habibi, (2013): Adaptive Temperature Monitoring for Battery Thermal Management, SAE World Congress, Detroit, Michigan. (**Published**).

4. I. Arasaratnam, **Ahmed, Ryan**, M. El-Sayed, S. Habibi, and J. Tjong, (2013): Li-Ion Battery SOC Estimation Using a Bayesian Tracker. SAE World Congress and Exhibition, Detroit, Michigan. (**Published**).

5. M. Farag, **Ryan Ahmed**, S.A. Gadsden, S. Habibi, and J. Tjong, (2012) A Comparative Study of Li-Ion Battery Models and Nonlinear Estimation Techniques. iTEC Conference, Dearborn, Michigan. (won the best paper award at the ITEC Conference). (**Published**).

6. **Ryan Ahmed**, Mohammed El Sayed, Saeid Habibi, and Jimi Tjong (2014): Literature Review of Battery Models, Aging Models, State of Charge, and State of Health Estimation Strategies, Journal of Power Sources. (**Submitted and under review**).

7. **Ryan Ahmed**, Ienkaran Arasaratnam, Mohamed El-Sayed, Jimi Tjong, and Saeid Habibi, “Online and Offline Parameters Identification and SOC Estimation for Healthy and Aged Electric Vehicle Batteries Based on Equivalent Circuit Models”, Journal of Power Sources, 2015.

8. **Ryan Ahmed**, Andrew Gadsden, Mohamed El-Sayed, Jimi Tjong, Saied Habibi, “Aged Battery State of Charge Estimation based on Interacting Multiple Models”, Journal of Power Sources, 2015.

9. **Ryan Ahmed**, S.A. Gadsden, M. El-Sayed, S. Habibi, and J. Tjong, (2013) Artificial Neural Network Training Utilizing the Smooth Variable Structure Filter Estimation Strategy. Journal of the International Neural Network Society. Ref#: NEUNET-D-12-00336. (**Submitted and under review**).

10. Arasaratnam Ienkaran, Jimi Tjong, and **Ryan Ahmed** (2014), Battery Management System in the Bayesian Paradigm: Part I, Transportation and Electrification Conference and Expo, 2014. (**Published**)

CASE STUDY/BATTERY MANAGEMENT SYSTEM: RESEARCH AREAS

Smart embedded controllers

- Artificial Neural Networks
- Optimal HEV controls

Energy storage systems

- Management and control
- Thermal management/packaging
- Modeling, SOC, SOH estimation, and aging

Hybrid battery/Supercap.

- Modeling
- State prediction
- Packaging and integration

Fault detection

- State estimation
- Fault prediction and RUL prediction

THANKS, QUESTIONS?

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