Impact of Battery Management on Fuel Efficiency Validity

2012 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Overview

- **Timeline**

  Light-duty Vehicles
  - Leverage existing test data to examine battery energy versus fueling trends
  - Examine recent vehicle data for opportunities to improve performance
  - Assess current procedures

  MD/HD Vehicles
  - Integrate LD findings with MD/HD
  - Perform simulation study of MD/HD energy trends
  - Support SAE J2711 with analysis

- **Budget**
  - FY 2012 $150k
    - $75k Vehicle Testing and Analysis
    - $75k Modeling and Simulation

- **DOE strategic goals/barriers addressed**
  - **F:** Constant advances in technology
  - **D:** Lack of standardized test protocols
  - **E:** Computational models, design and simulation methodologies

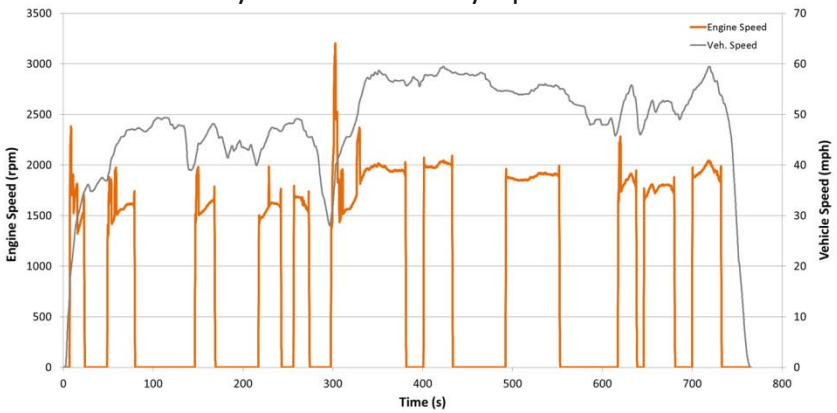
- **Partners**
  - DOE and other National Laboratories
  - SAE J2711 working group
    - OEMs
    - National Laboratories
    - Other regulatory agencies

Relevance: Battery Energy Management Impacts Fuel Economy

Recent light-duty vehicle trends require the reassessment of battery usage versus fuel consumption and further investigation of battery management issues

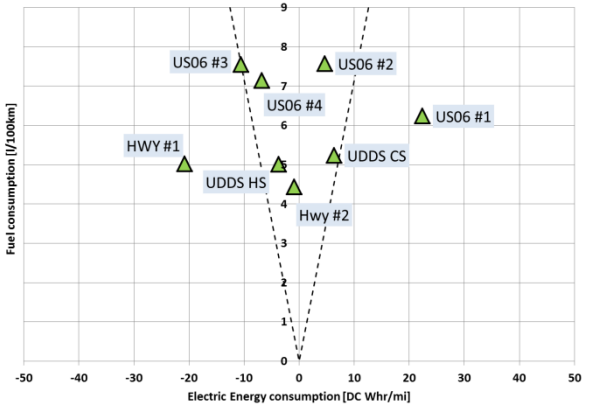
More engine-off operation

Hyundai Sonata Hwy Operation



Larger On-board Energy Storage

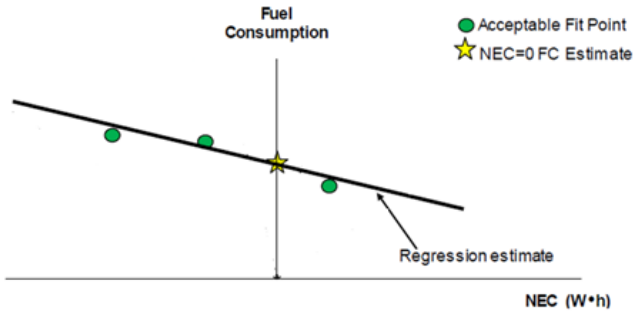
Volt Charge Sustaining Fuel Consumption vs. Energy



- Net Energy Change (NEC) is becoming an important metric for correcting certain fuel consumption tests
  - ✓ Robustness to battery SOC estimation issues
  - ✓ Does not force charge-correction over a cycle
  - ✓ Reduces allowable variation due to 1% window

- SAE J1711 includes procedure for NEC correction for LD HEVs/PHEVs running in charge sustaining mode

Basic NEC Correction Procedure



NEC correction is the current direction for the SAE J2711 MD/HD Vehicle Assessment Procedure

Approach/Strategy: Evaluate NEC Trends and Battery Management Issues related to Fuel Economy

- **Suite of analysis to investigate NEC versus fueling trends**
  - Investigate existing LD vehicle data for battery NEC trends and sensitivities
    - Focus on recent in-depth research vehicles
  - Assess vehicle-level opportunities for improved performance related to battery management issues
  - Evaluate existing LD test procedures for irregularities

- **Preliminary evaluation of MD/HD vehicle NEC trends and implications**

  Larger battery size, increased diversity of driving style, wide range of technologies

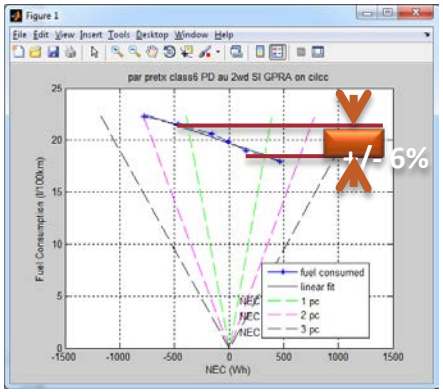
  - Leverage LD findings and analysis for preliminary MD/HD insights
  - Support and inform SAE J2711 test procedure development
  - Collaborate with Argonne Modeling and Simulation group to perform preliminary evaluation of MD/HD NEC versus fueling trends
    - Minimal HEV data available for public assessment and analysis

Approach/Strategy: Use Simulation to assess NEC versus Fuel Consumption Trends for MD/HD vehicles

Investigate applicability for a wide range of vehicles (linearity, error)

- SI, CI, Degree of hybridization, Engine, Motor, Battery size, technology, control logic…
- Important for new fuel consumption requirements for electrified MD/HD vehicles

	CILCC	HWFET	Truck UDDS
Class 2	?	?	?
Class 6	?	?	?
Class 8	?	?	?



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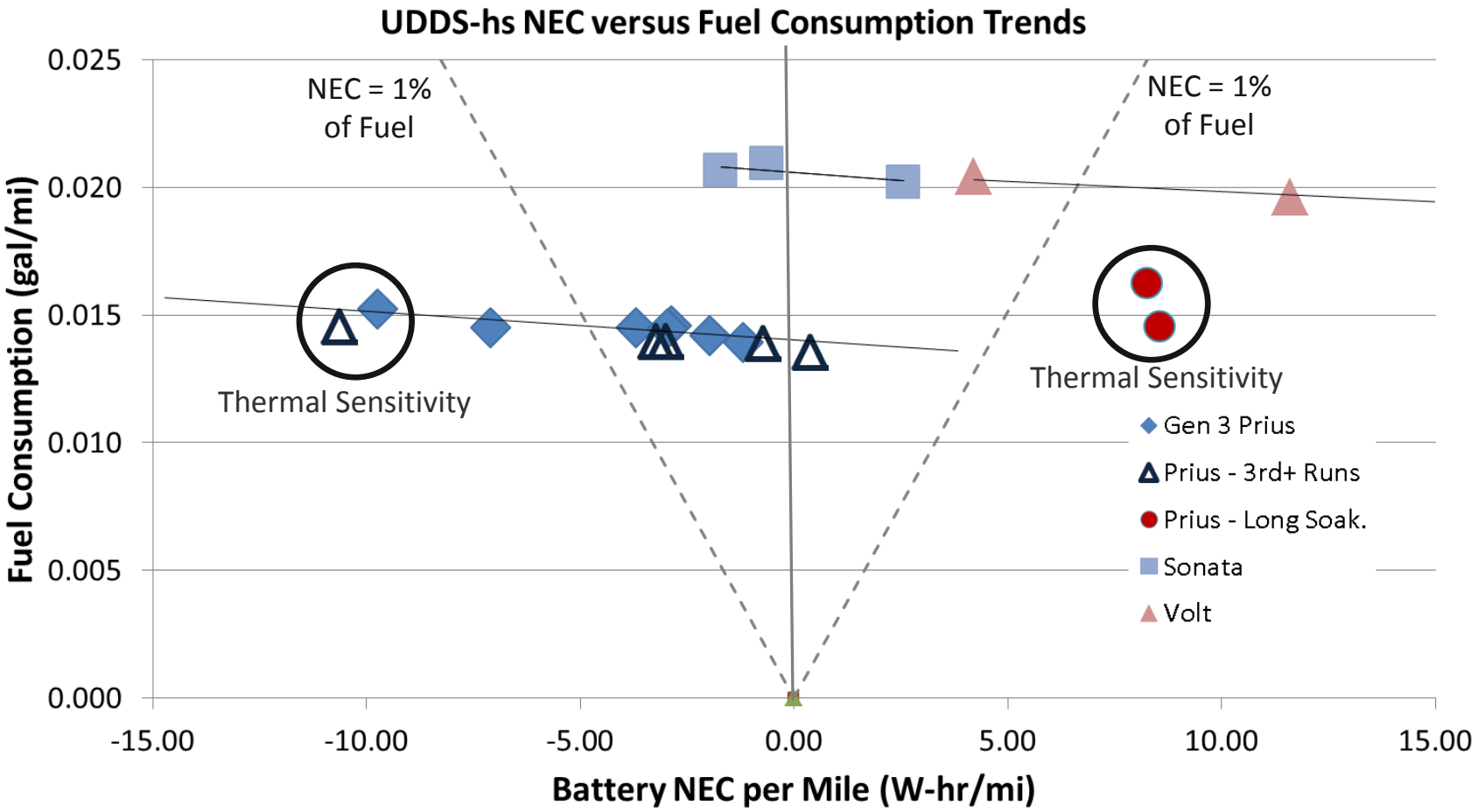
Accomplishments: NEC vs. FC for Recent LD Vehicles

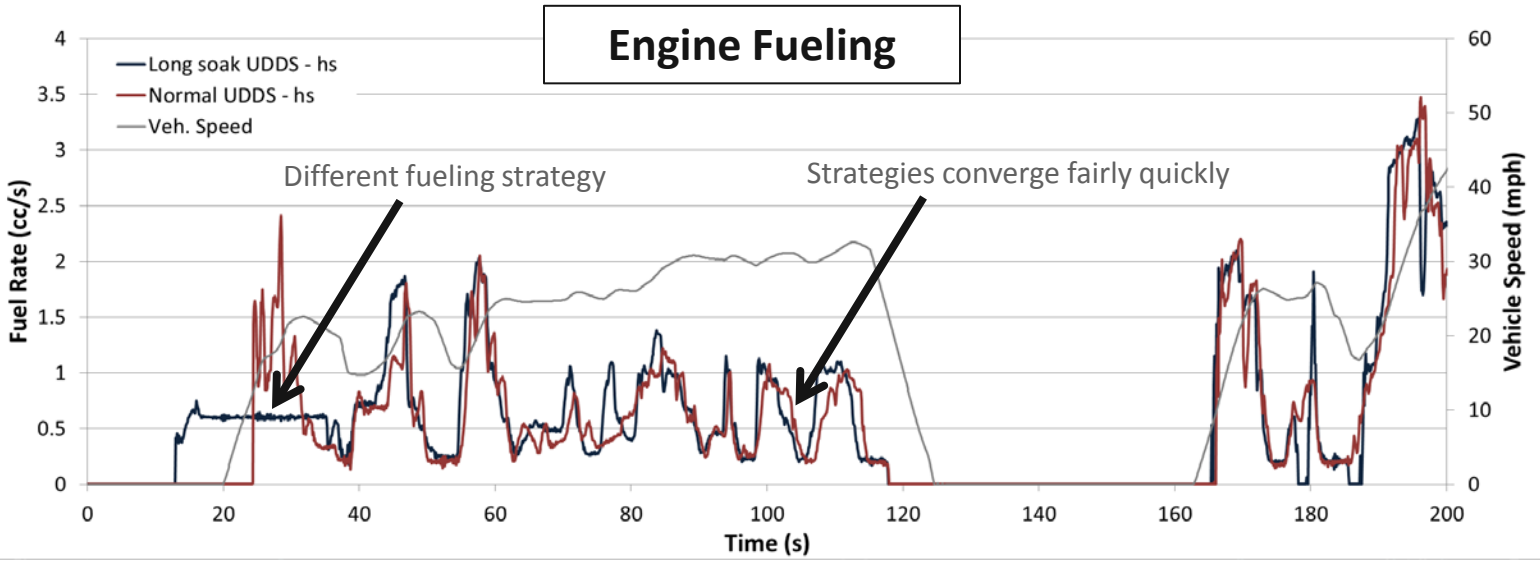
Analysis of recent vehicles shows similar trends to previous with some new cautions

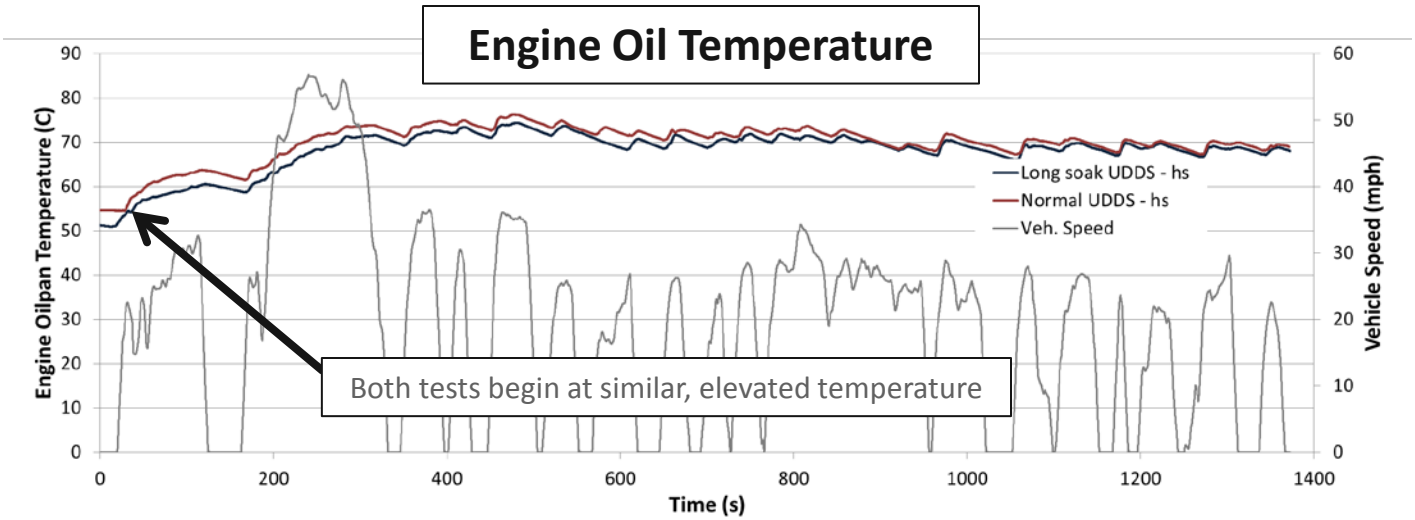
- 1% battery NEC tolerance equates to ~8% fuel economy on the UDDS
- Recent vehicles have a similar FC versus NEC trend, but differences exist
- Several Prius test points highlight sensitivity to vehicle thermal conditions



Accomplishments: Investigation of Thermal Sensitivity to NEC

New vehicles seem particularly sensitive to thermal state, which is important for assessing NEC versus fuel consumption trends

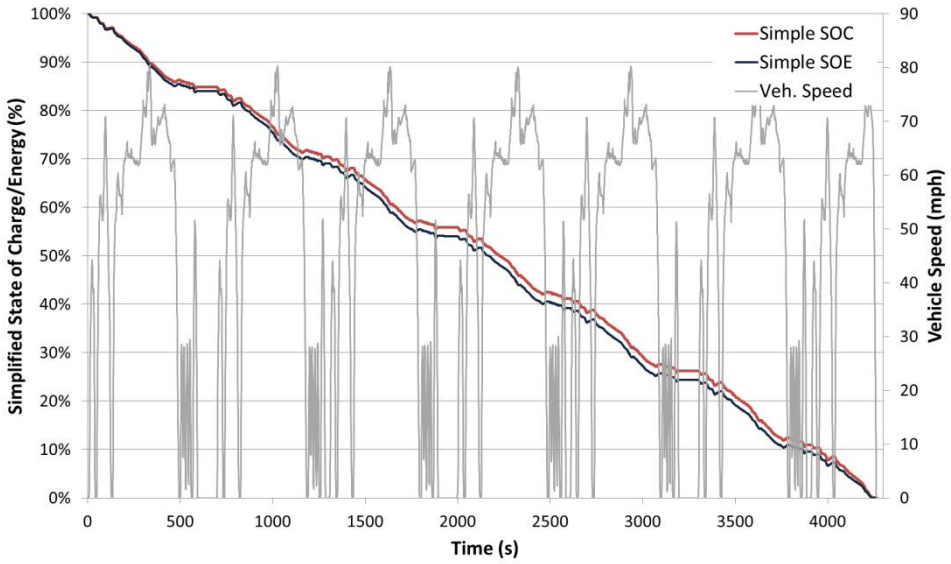


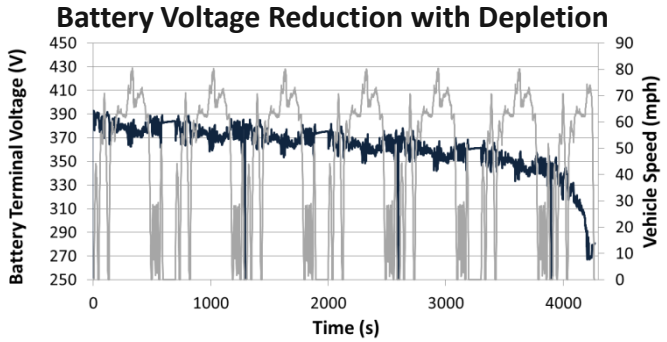


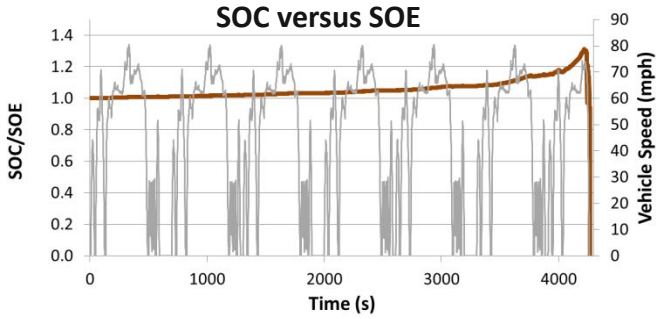
Accomplishments: Preliminary Evaluation of SOC vs. SOE

Differences between state-of-energy (SOE) and state-of-charge (SOC) are important from both a regulatory and a vehicle implementation perspective

- **A very basic SOC vs. SOE example…**

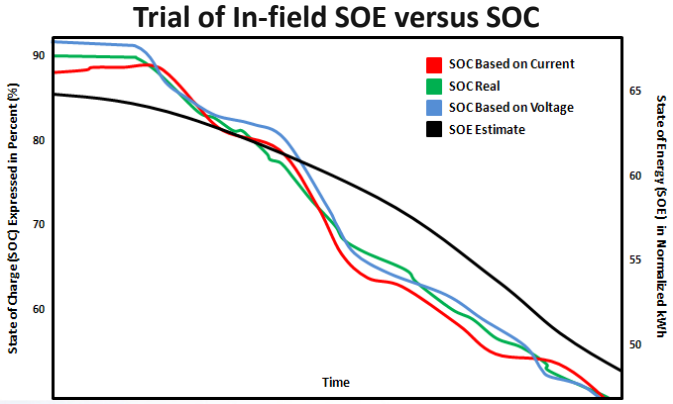






- SOC monitoring is important to prevent over charge/discharge (and for battery assessment)

- SOE likely to track more closely to available energy:
  - ✓ Improved effective range estimation
  - ✓ Robustness to battery degradation/variability
  - ✓ Better incorporation of real-time usage
  - ✓ Less noisy in-situ energy usage estimation



Accomplishments: V_{cycle} Correction for Net Energy Calculation

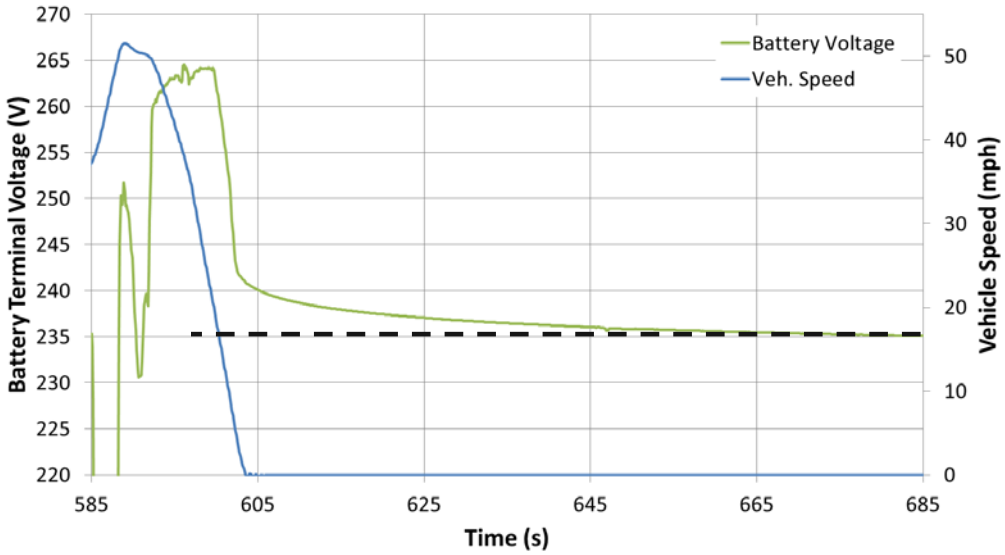
Proposed MD/HD NEC correction procedure requires improved battery voltage estimation

A related outcome of the SOC versus SOE work considers corrections for battery voltage

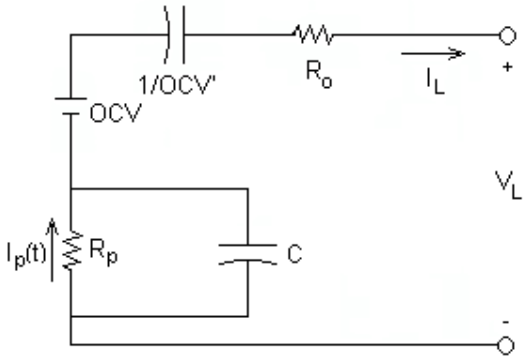
$$\text{Net Energy Change} = \left((A \bullet h)_{final} - (A \bullet h)_{initial}\right) * V_{system}$$

V_{system} will change as battery NEC swings

- Averaging V_{start} and V_{end} is susceptible to settling issues for certain chemistries and requires near zero current
- Zero crossing voltage has issues with usage bias and hysteresis



Proposed correction fits USABC battery model to test data and is more robust to chemistry and usage



Simple Prius (NiMH) example improves estimate by roughly 4%

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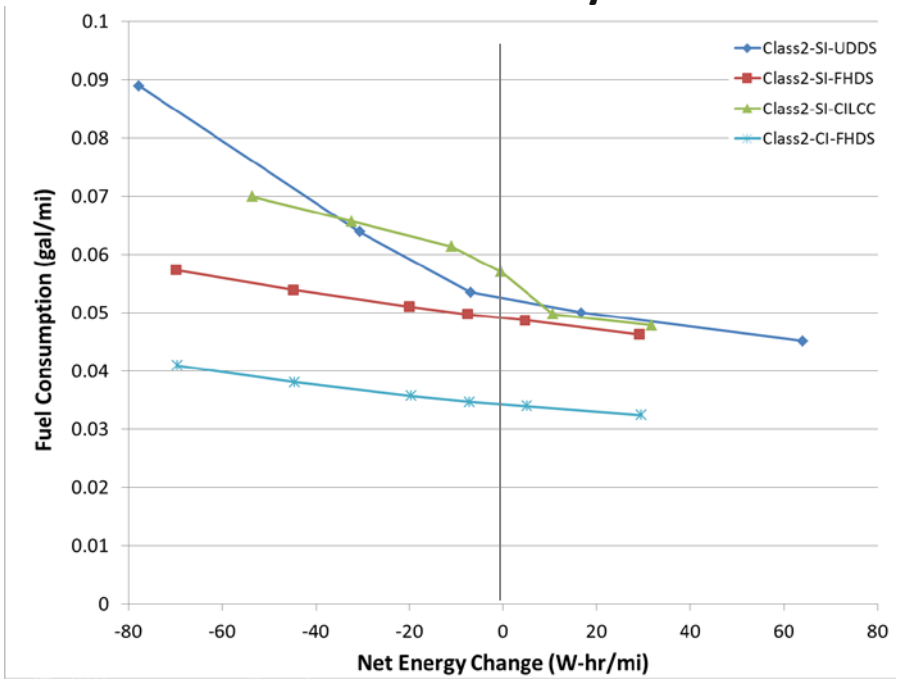
Accomplishments: MD/HD Simulation Study for NEC Correction

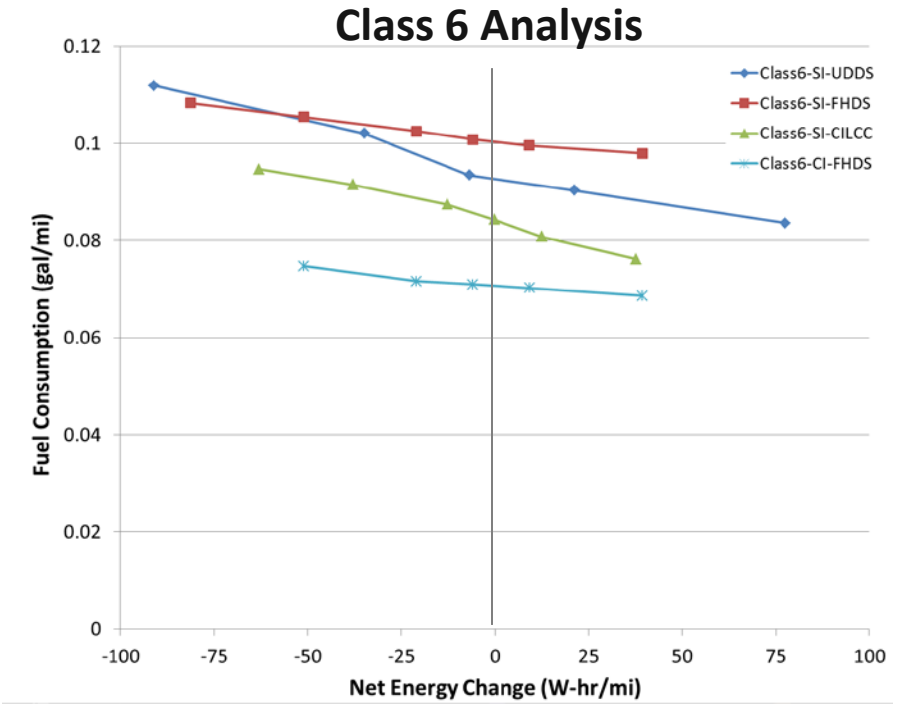
Over 70 runs simulated for a range of cycles and NEC values for Class 2b and 6 vehicles

- Although not considered for SAE 2711, 1% NEC tolerance equates to roughly:
  - 8-20% fuel consumption difference for Class 2b
  - 6-14% fuel consumption difference for Class 6
- CI versus SI does not appear to significantly alter the NEC vs. fuel relationship
- Class 6 vehicle appears to be slightly less sensitive to NEC (for this study)

Class 2b Analysis



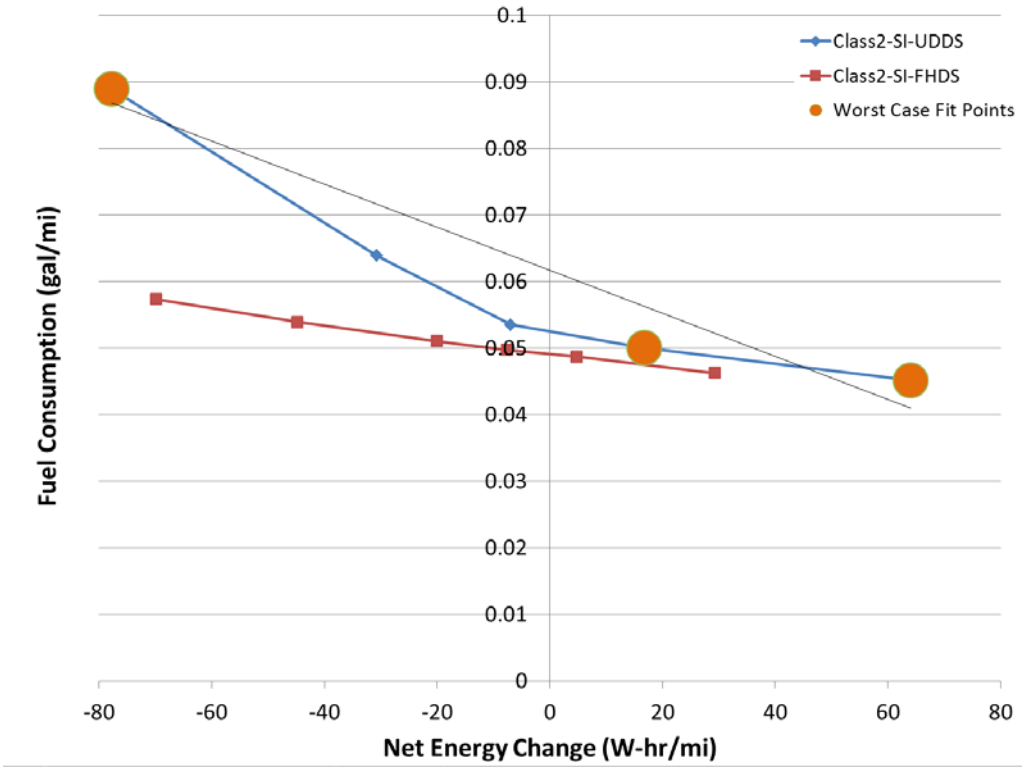
Class 6 Analysis



Accomplishments: MD/HD NEC Correction Error Assessment

What are the possible fuel consumption estimation errors due to NEC non-linearity

- Proposed correction procedure uses 3+ points with at least one + and - NEC point
  - Correction procedure is susceptible to non-linearity in the NEC trend
  - Given this, an additional check of % error from fit points has been proposed



Class 2b	Max Estimated Fuel Consumption Error
UDDS	18%
FHDS	-1%
CLICC	6%

Class 6	Max Estimated Fuel Consumption Error
UDDS	4%
FHDS	1%
CLICC	-1%

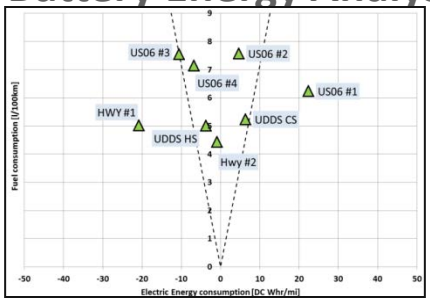
Collaborations and Coordination with Other Institutions

Environment Canada
- Comparison of MD/HD vehicle data
- Collaboration on SAE J2711

J1711 HEV/PHEV vehicle dyno. procedures
J2711 MD/HD vehicle dyno. procedures
- **Cummins**
- **Navistar**
- **Arvin Meritor**
- **Eaton**
- **Allison Transmission**
- **Southwest Research Institute®**
- **ORNL**
- **NREL**

SAE International®

Battery Energy Analysis



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- Support of modeling and simulation with data

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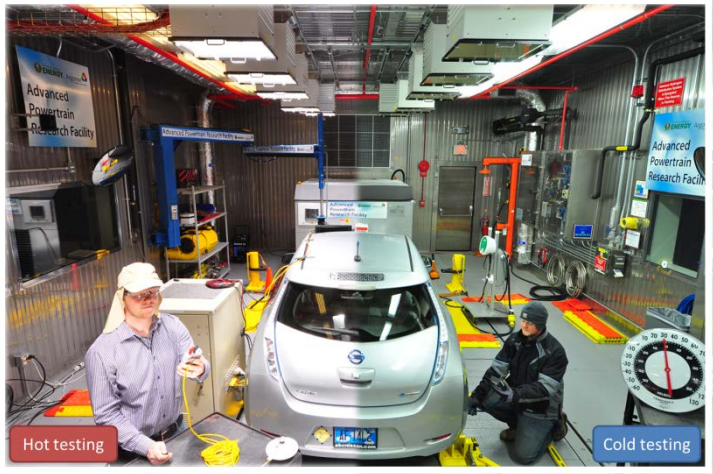
DOE technology evaluation
- DOE requests
- National Lab collaboration

NREL ornl INL Argonne

Future/On-going Work

- **Continuing analysis of light-duty vehicles**
  - Assess emerging technologies through continuing testing and analysis
  - Leverage upgraded APRF to evaluate NEC trends at a wider range of temperatures
  - Continue evaluation of vehicle-level battery SOE versus SOC issues and include state-of-function and state-of-health (collaborate with other disciplines)
  - Identify additional battery management issues impacting fuel consumption (i.e.: conditioning, de-rating, balancing, and thermal management)
  - Outreach and data dissemination – SAE Battery Terminology Working Group

- **Increased analysis and support for MD/HD evaluation procedures**
  - Finalize SAEJ2711 procedural changes
  - Perform additional M&S studies
  - Assess NEC issues with dyno. test data
  - Evaluate MD/HD specific issues
    - Multiple batteries
    - Alternative energy recovery/storage sources
  - Disseminate issues and best practices
    - SAE J1939 – Vehicle Communications Network
    - Support MD/HD regulatory efforts



Summary

In order to support both LD and MD/HD standards development, an extensive study of battery management trends relative to fuel consumption impact was performed using both experimental and simulation data

- Current LD vehicles appear to have similar trends relative to NEC vs. fuel
- For LD certain cases, 1% NEC tolerance equates to roughly 8% fuel economy variability (much larger than current assumptions)
- Preliminary assessment of State-of-Energy versus State-of-Charge has been performed
- A methodology to robustly account for battery “settling” has been developed
- Simulation study has been performed to assess the NEC trends of MD/HD vehicles
  - Helped to evaluate and refine proposed J2711 NEC correction procedure

This effort directly supports standards development which is critical for unbiased technology evaluation and assists in the adoption of advanced vehicles