Data Collection for Improved Cold Temperature Thermal Modeling and Strategy Development

2011 DOE Hydrogen and Vehicle Technologies Annual Merit Review

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Argonne National Laboratory

Sponsored by Lee Slezak

Project ID # VSS050

U.S. Department of Energy

Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Overview

Timeline

- 1Q 2010-current
- 50% complete
  - Complete evaluation of Gen 2 Prius
  - Begun evaluation of 2010MY Gen 3 Prius
  - Leverages APRF benchmarking and Environment Canada vehicle testing

Barriers

- Barriers addressed
  - Cold ambient testing shows significant fuel consumption increase (w/o creature comforts)
  - Engineered solutions could have potential drastic petroleum use reduction

Budget

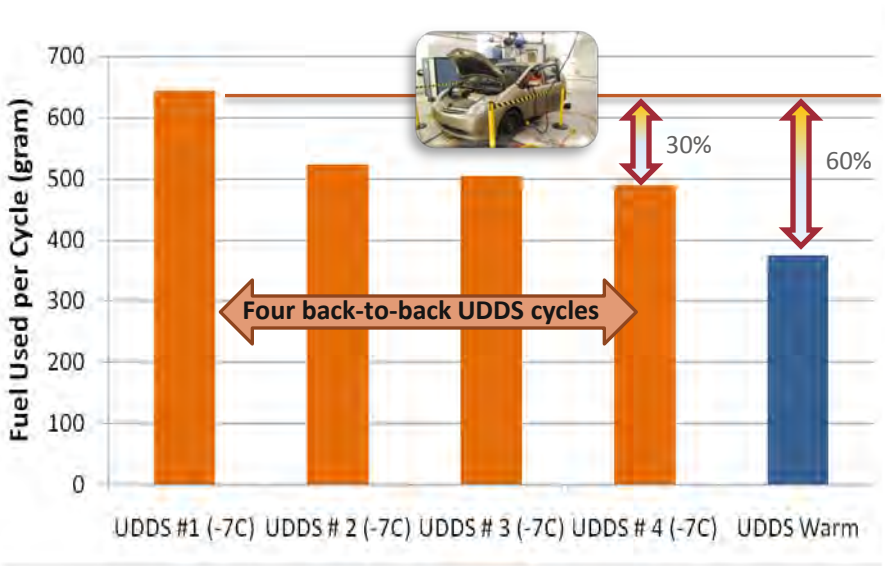
- Total project funding
  - FY10 funding: $200k
  - FY11 funding: $300k

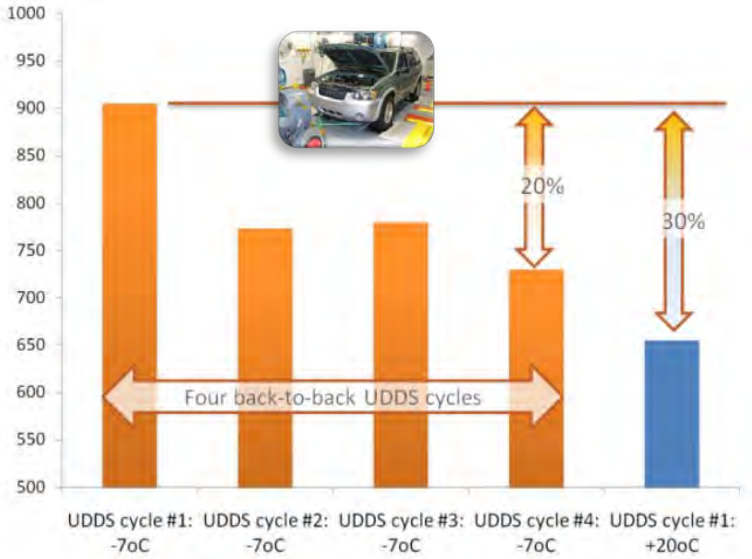
Partners

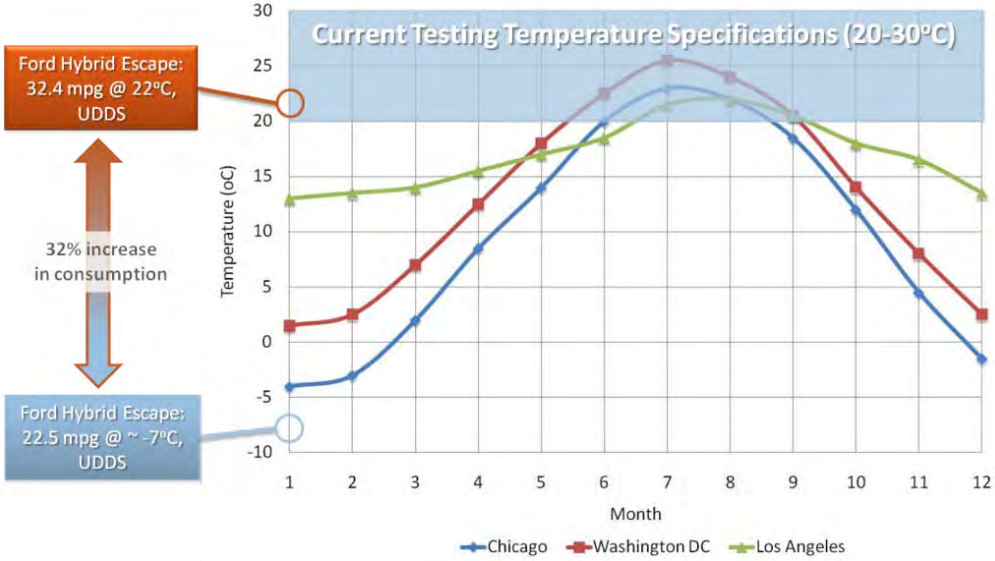
- Environment Canada

Relevance: Cold ambient temp greatly reduces hybrid fuel economy

Majority of fuel economy testing does not reflect real world ambient conditions



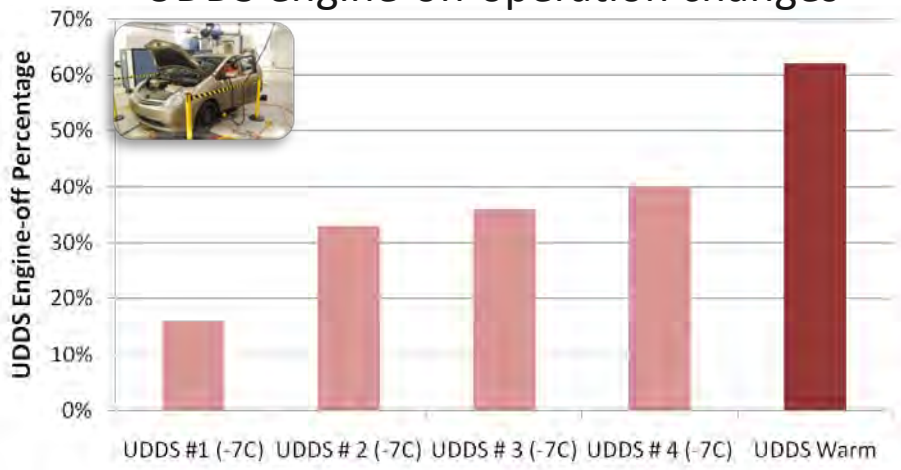




Relevance: Cold operation impacts vehicle operation and efficiency

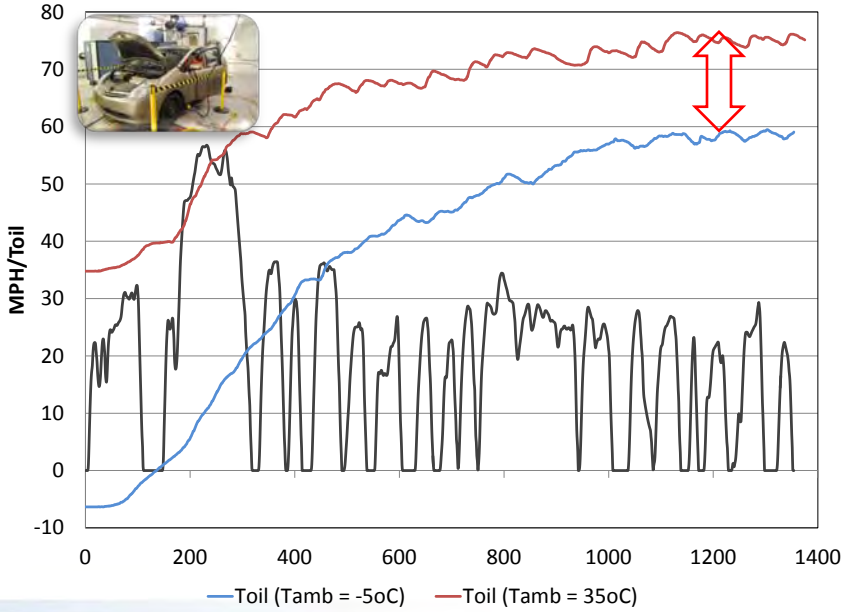
Engine-off operation changes dramatically under cold ambient conditions and during vehicle warm-up

UDDS engine-off operation changes



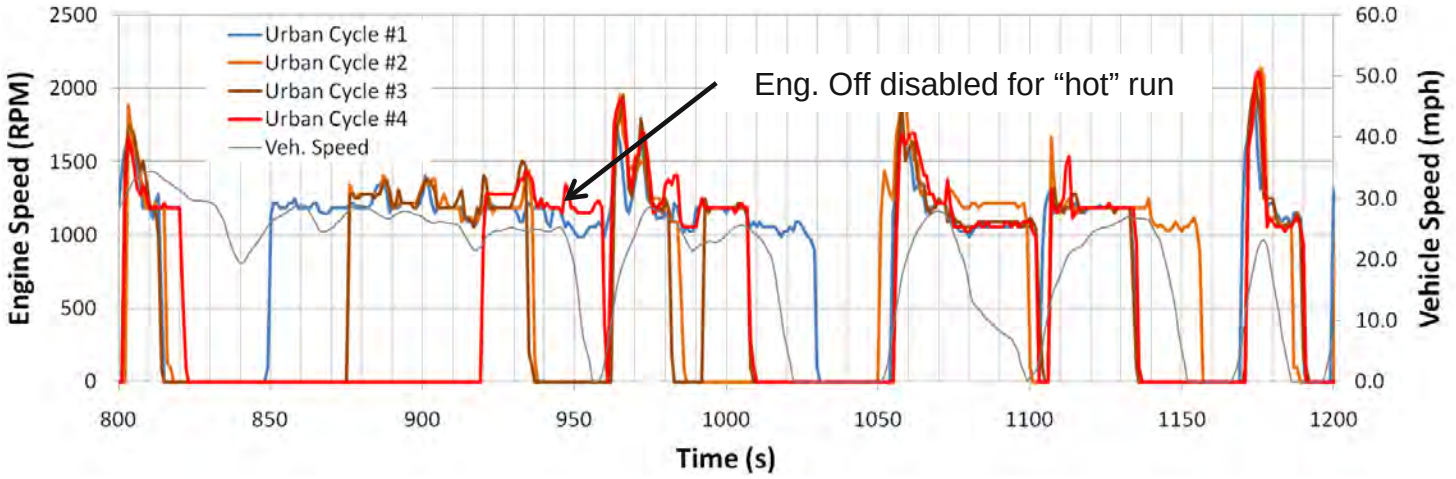
Engine efficiency differs throughout the entire warm-up period as a function of ambient temperature

Steady state temperature reduced

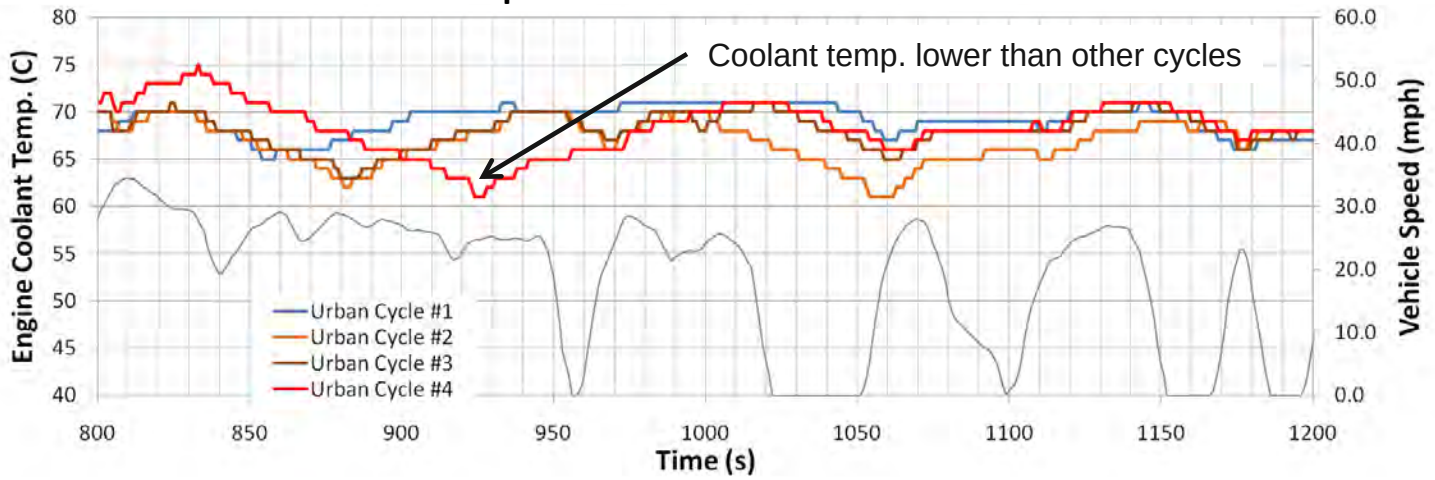


Relevance: Cold ambient operation still affects vehicle controls after initial warm-up

Usage Oscillation Due to Engine-off Cool-down to Ambient



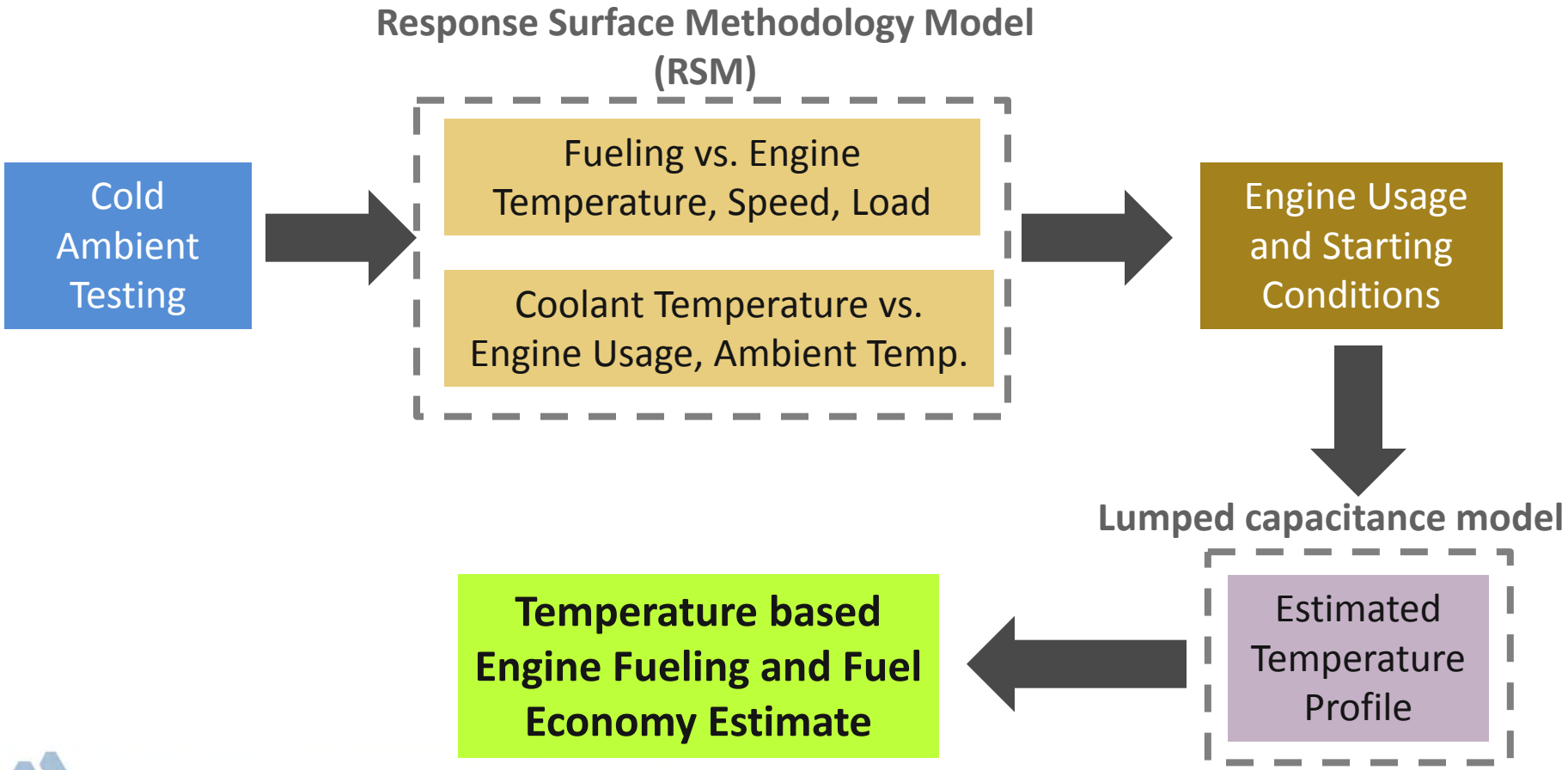
Coolant Temperature Oscillation Due to Cool-down



*** Cool-down issue is even larger for PHEVs**

Approach: Combine RSM fueling map with temp prediction model

- **Simple methodology to estimate the impact of cold engine temperature on engine efficiency and estimate engine thermal state given usage and ambient temperature**
  - Current methodology uses coolant temperature, but can be generalized to other temperatures
  - Methodology uses response surface and empirical data-fitting techniques
  - Techniques result in simplified general models

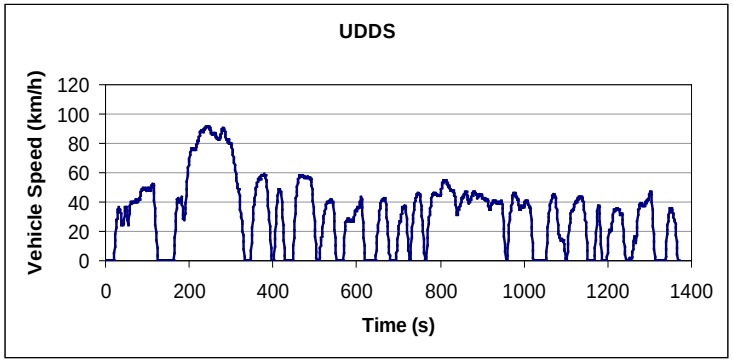


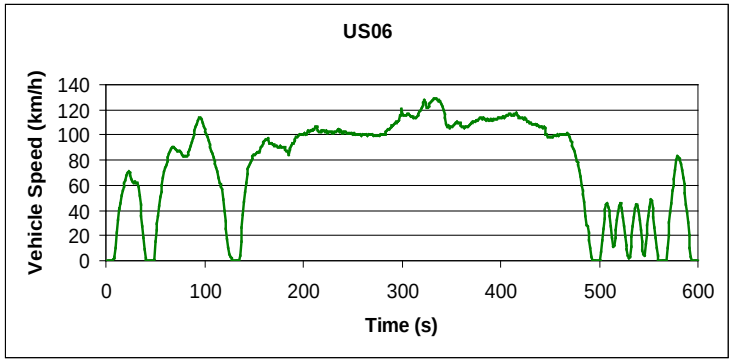
Approach: Experimental setup

- **Hymotion Prius was used for vehicle testing and methodology development**

Signal	Description	Notes
Vehicle Speed	Dynamometer/ CAN measured	Drive trace measurement
Engine RPM	CAN/ spark frequency	Model input
Brake Torque	CAN	Flywheel torque, model input
T_oil	Dipstick thermocouple	Model input
T_coolant	CAN	Model input
Fuel Flow	Emissions Bench carbon count	Model input

- **Vehicle testing focused on the UDDS and US06 cycles to obtain a cross section of usage**





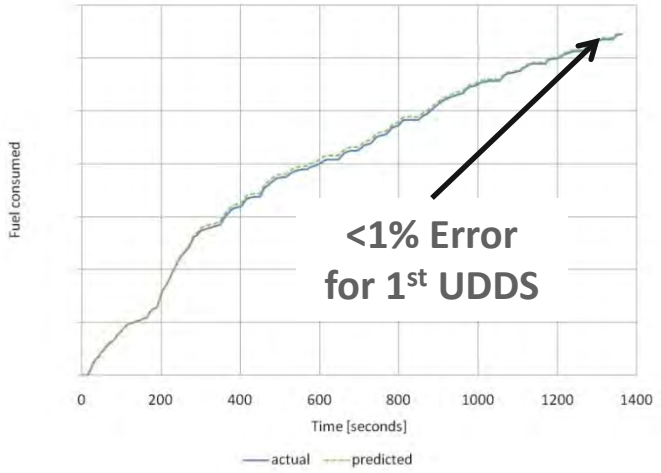
Approach: Data from multiple cycles at varied temperatures

- **Project will develop a methodology for estimating the impact of engine thermal state on engine efficiency during cold ambient operation**
  - Quantifying/qualifying magnitude of losses highlight benefit for engineered solutions
    - Opportunity to greatly reduce all season, real world fuel consumption

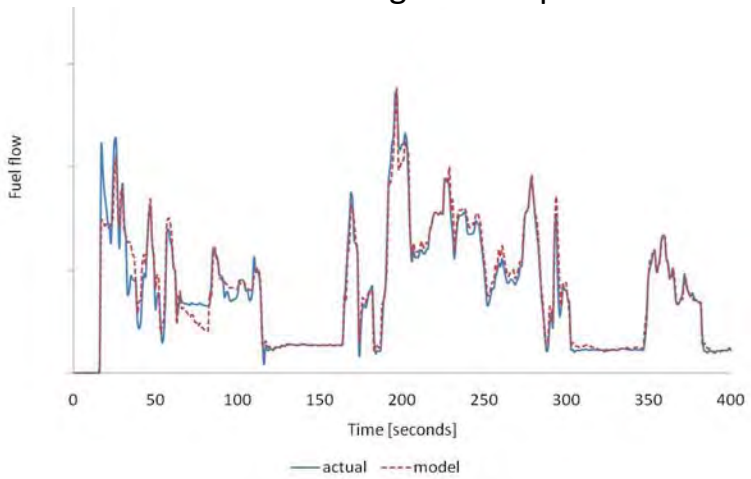
Accomplishments: Fueling map response surface development

- **Estimated fueling versus temperature and load works well (within 1%)**

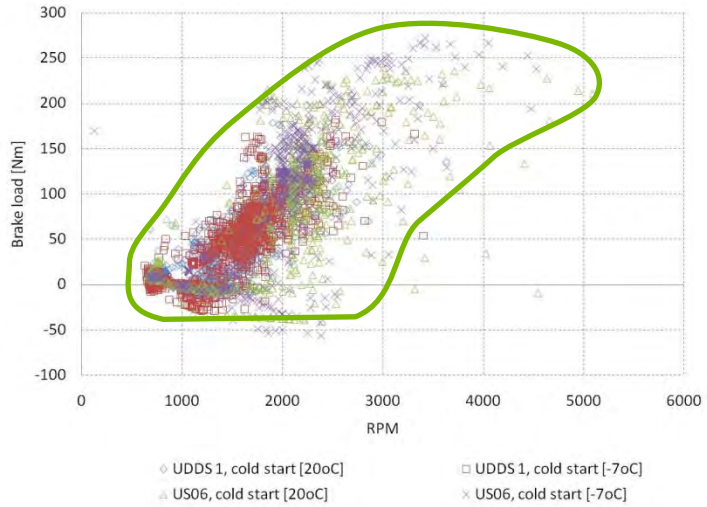
UDDS Estimated vs. Actual Fuel Used

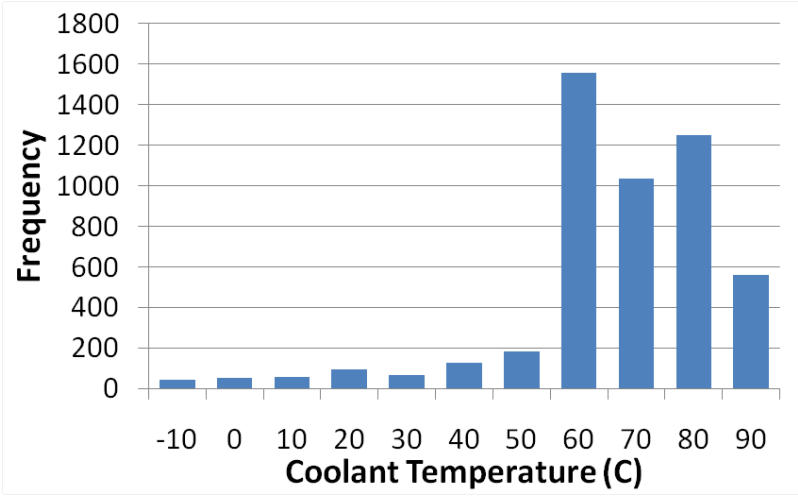


Fuel Rate During Warm-up



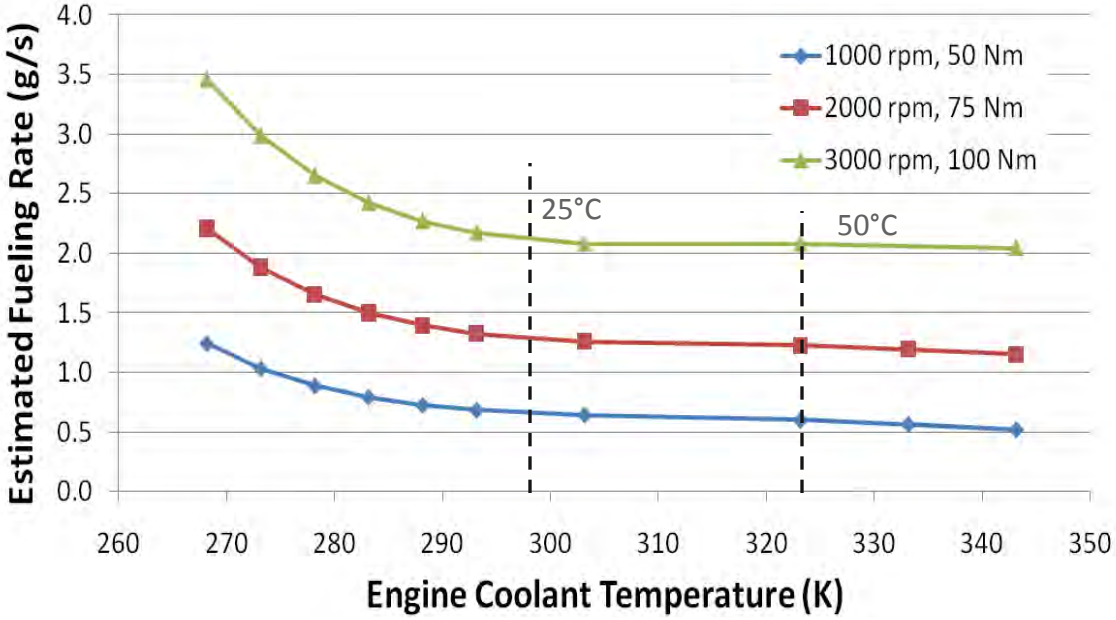
- **For more robust estimations, additional low temperature testing required**



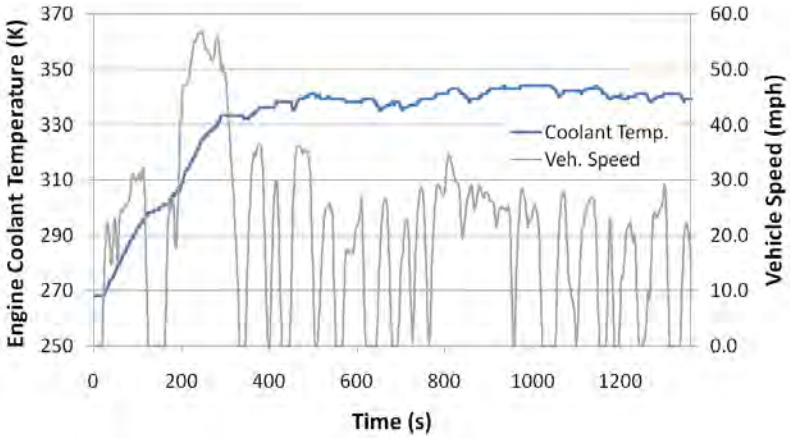


Accomplishments: Fueling rate sensitive to temperature

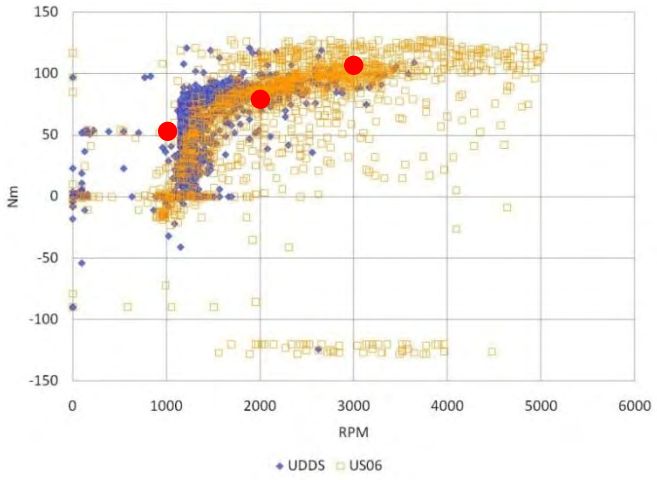
Estimated fueling map shows a strong sensitivity to coolant temperature



UDDS cycle coolant temperature



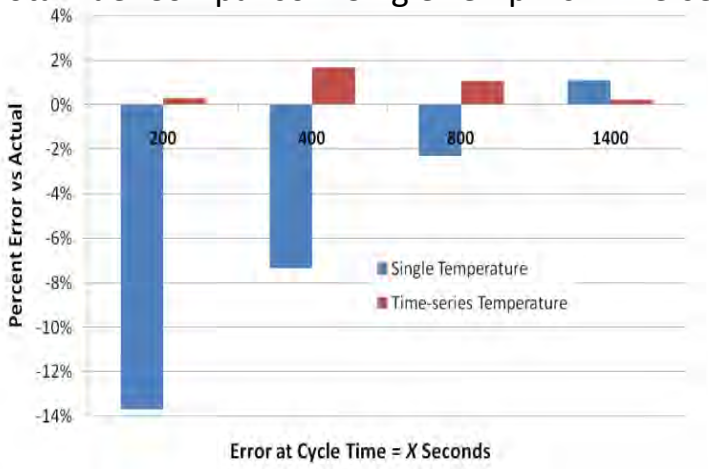
UDDS engine speed/load points



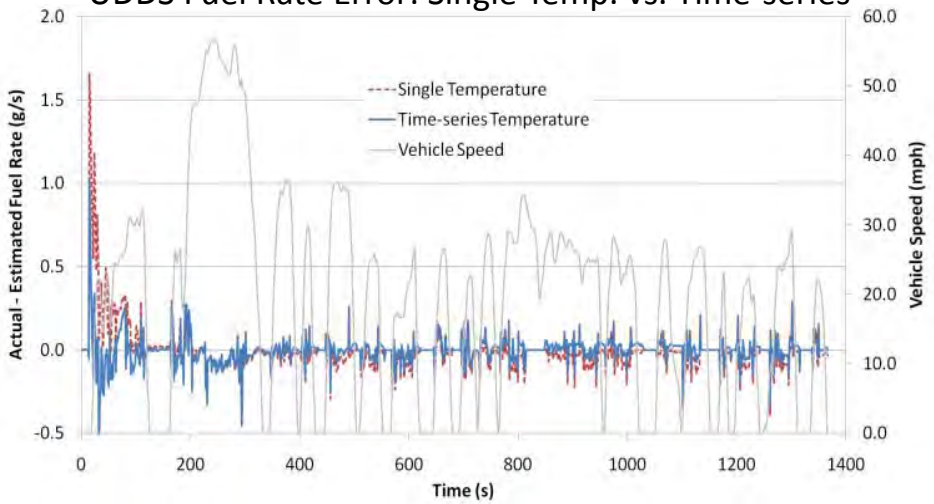
Accomplishments: Temperature resolution sensitivity

- **Using a single temperature does not provide adequate estimation during warm-up**
  - **Necessary to determine the number of points required to adequately reduce error**

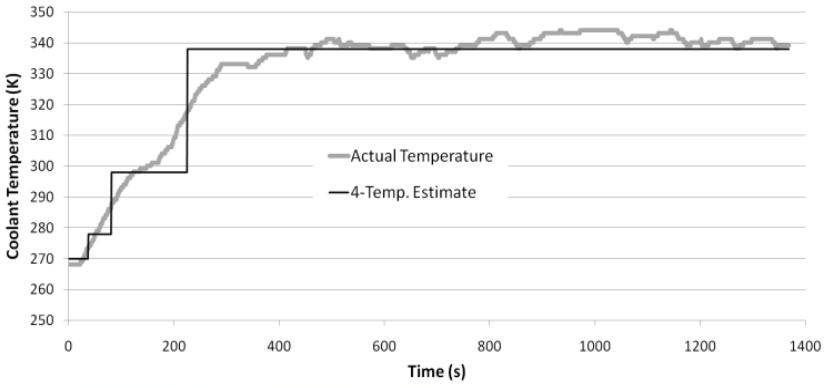
Total Fuel Comparison: Single Temp. vs. Time-series



UDDS Fuel Rate Error: Single Temp. vs. Time-series



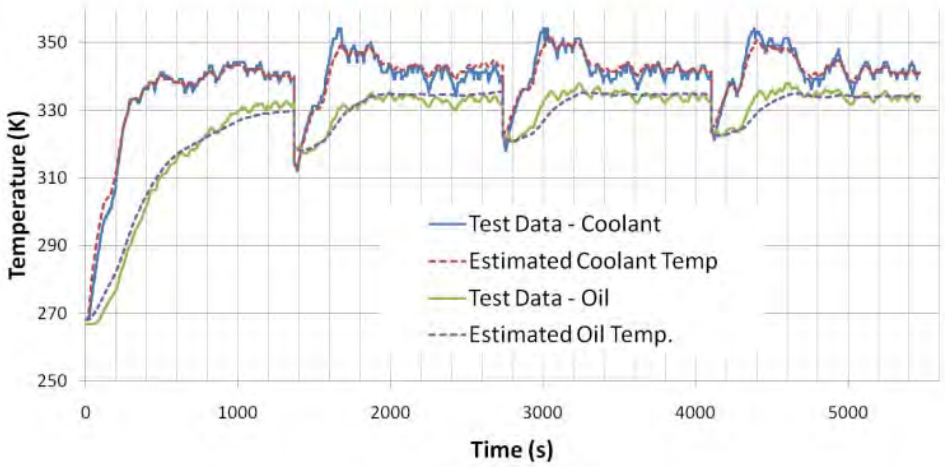
- **In this example, at least four temperatures are needed to evaluate the previous UDDS comparison points within 1%**

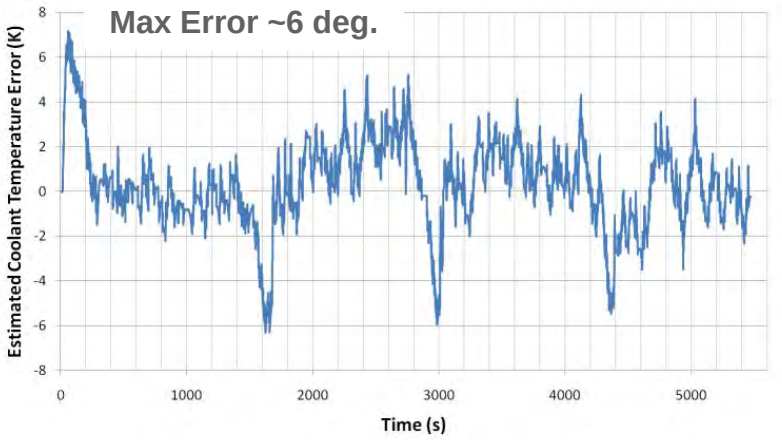


While only 4 points are required, minimal points would not allow for control strategy optimization/ characterization of where losses are most prevalent

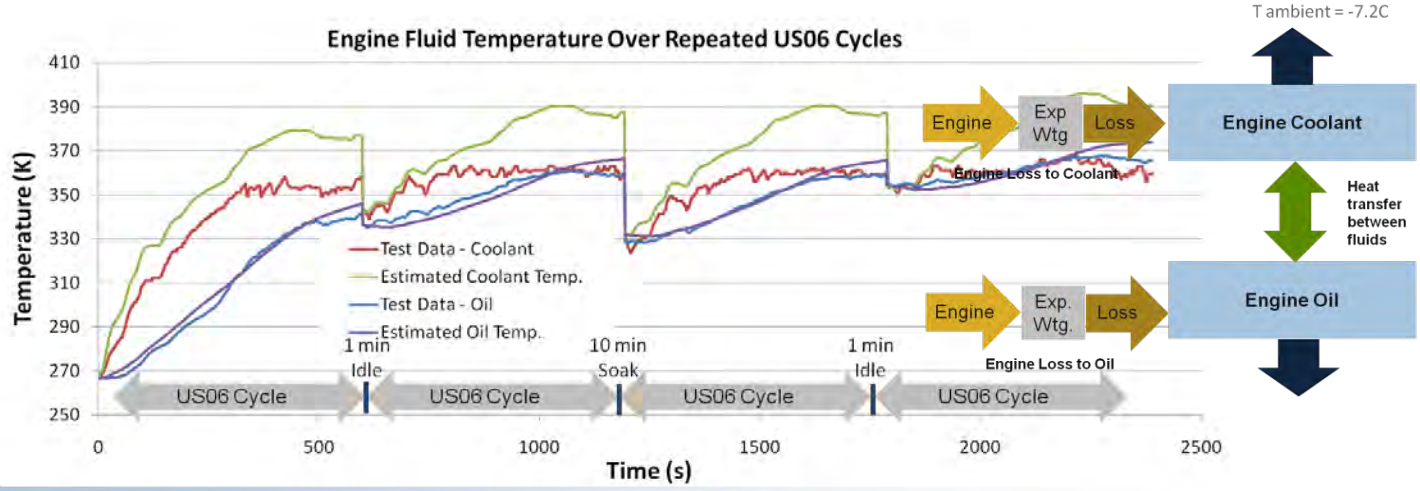
Accomplishments: Estimating thermal state

- **Developed technique works well for estimating UDDS coolant temperature**





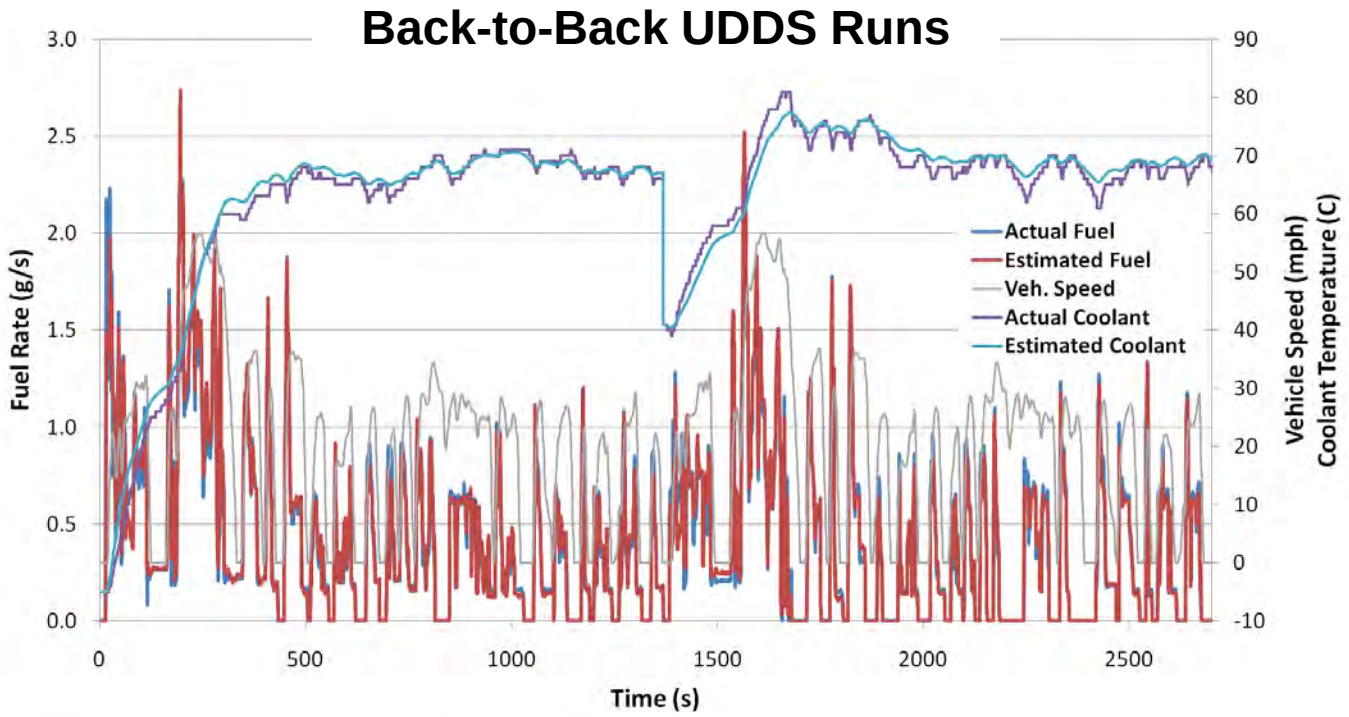
- **During US06 cycle operation, coolant temperature is over estimated due to significant thermostat operation**



Accomplishments: Model works well predicting UDDS/US06

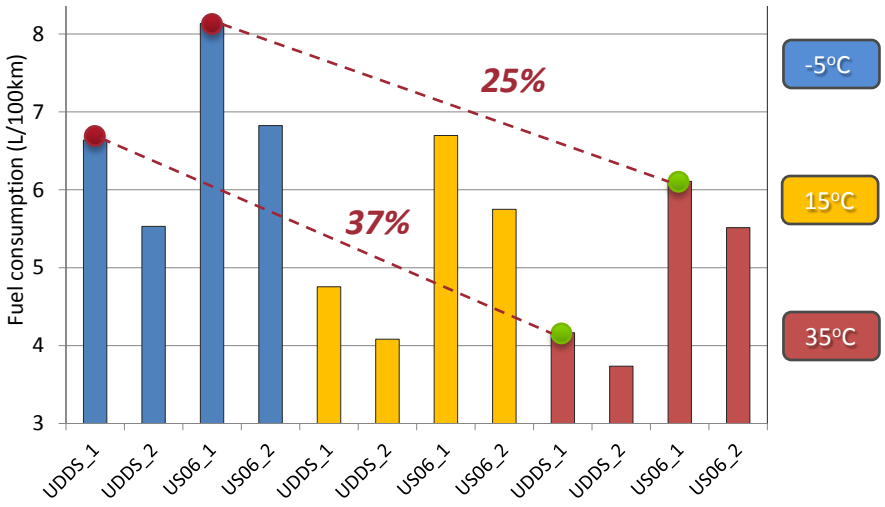
Modeled UDDS and US06 cycles when operating in cold ambient conditions

Cycle	Percent Error of Actual versus Estimated Grams Fuel Used (%)
UDDS #1	1.3
UDDS #2	0.7
US06 #1	3.0
US06 #2	4.4

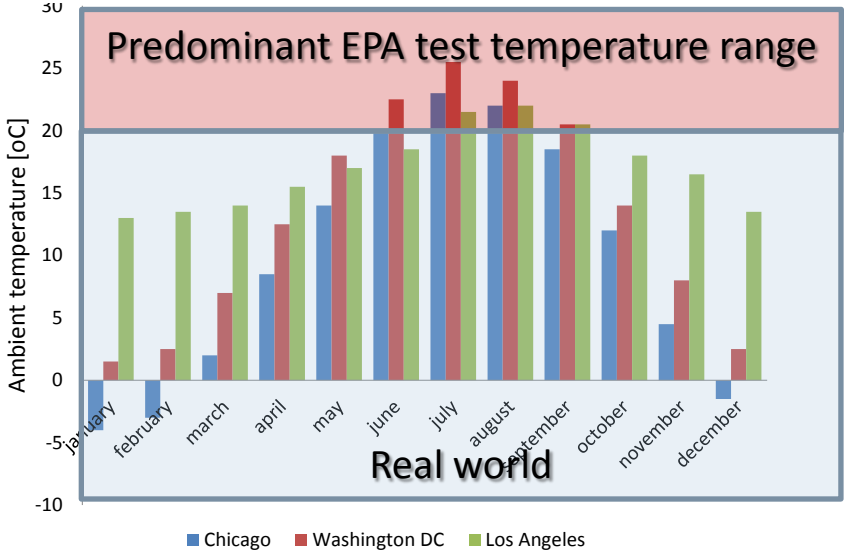


Accomplishments: Early results clearly show large petroleum reduction potential*

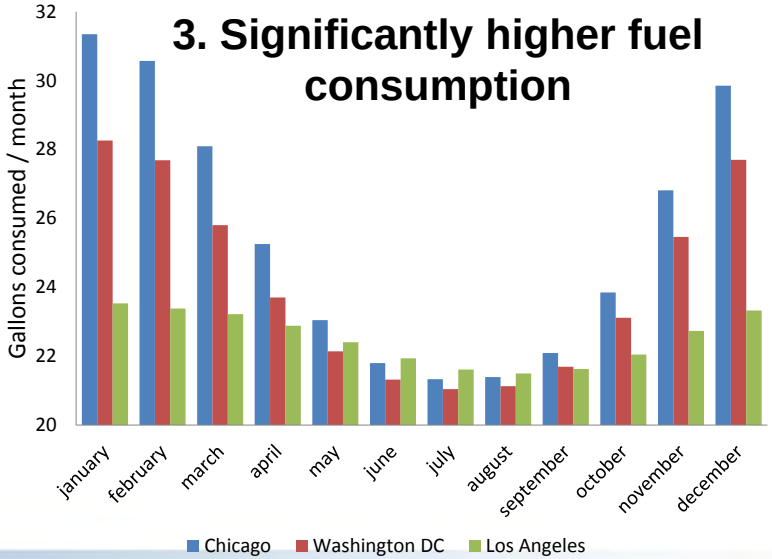
1. Testing at multiple temps…



2. Greater variation in real world…



3. Significantly higher fuel consumption

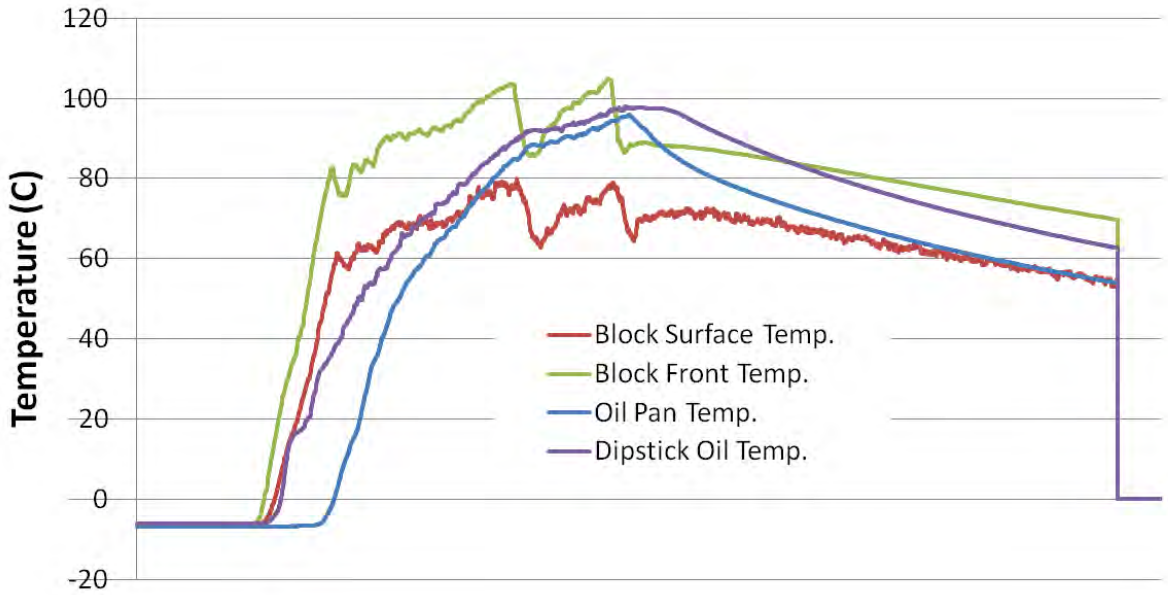


*Results shown are trends from experimental, not modeling data

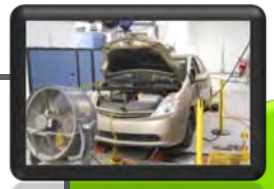
Conclusions/Proposed future work

- **There are still many open issues to investigate**
  - Improve procedure/technique for model development
  - Define potential for engineered solutions to reduce real world fuel consumption
  - Incorporate creature comfort features into modeling effort (NREL)
  - Incorporate catalyst light off features into modeling effort (ORNL)
  - Further investigate thermal linkages between components
  - Ensure robustness with additional vehicle testing leveraging APRF thermal capability upgrade and continuing Environment Canada collaboration

Alternative Temperature Signals and Cool-down



Collaborations and coordination with other institutions



Environment Canada
- Testing and tech support

Environment Canada

J1711 HEV & PHEV test procedures
- Early thermal worked used in guidance

SAE International®

APRF
- Warm testing data collected at APRF
- APRF under construction to begin cold testing

Automonie
- Development of thermal capability in models

AUTONOMIE

DOE technology evaluation
- Future collaborative potential with ORNL/NREL

NREL ornl Argonne NATIONAL LABORATORY

Summary

- Current vehicle testing protocols under represent real world ambient conditions
- Methodology developed to predict real season fuel consumption in HEV's
  - Response surface fueling rate modeling technique finalized
  - Lumped capacitance temperature modeling technique developed
- Modeling shown to be relatively accurate relative to experimental data
  - Model vs. experimental fuel consumption data within a few %
- Results demonstrate significant engineering potential to reduce petroleum consumption
- Further work needs to be complete to assess how much efficiency can be gained and the most effective pathways

Publications

I. "*PHEV Energy Management Strategies at Cold Temperatures with Battery Temperature Rise and Engine Efficiency Improvement Considerations*", Shidore, Neeraj, S., Jehlik, F., Rask, E., SAE World Congress, Detroit, SAE 2011-01-0872

II. "*Development of Variable Temperature Brake Specific Fuel Consumption Engine Maps*", Jehlik, F., Rask, E., SAE Powertrain Fuels and Lube Conference, San Diego, SAE 2010-01-2181

III. "*Simplified Methodology for Modeling Cold Temperature Effects on Engine Efficiency for Hybrid and Plug-in Hybrid Vehicles*", Jehlik, F., Rask, E., Christenson, M., SAE Powertrain Fuels and Lube Conference, San Diego, SAE 2010-01-2213

IV. "*Methodology and Analysis of Determining Plug-In Hybrid Engine Thermal State and Resulting Efficiency*", Jehlik, F., SAE World Congress, Detroit, Mi., SAE 2009-01-13081