NREL
NATIONAL RENEWABLE ENERGY LABORATORY

ICEER

Internal Combustion Engine Energy Retention



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National Renewable Energy Laboratory

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Project ID: VSS126

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

Overview

Timeline

Project Start Date: 10/1/2013

Project End Date: 9/30/2015
(pending phase 2 go/no-go)

Percent Complete: 25%

Budget

DOE FY14 Project Funding to NREL: $200k

(No FY13 project funding)

Barriers Addressed

- Risk aversion
- Lack of standardized test protocols
- Constant advances in technology

Partners

- Argonne National Laboratory: collection of dynamometer data and input on modeling
- USCAR OEMs: active conversations on the topic through VSATT meetings and direct engagement
- NREL is lead for the analysis project

USCAR = United States Council for Automotive Research
OEM = original equipment manufacturer
VSATT = Vehicle Systems Analysis Technical Team

Relevance for DOE Fuel-Saving Mission

The "Cold-Start" Penalty: Consider the following…

- ICEs presently included in **>99%** of US LD powertrains and anticipated to remain in the majority of vehicles in even the most aggressive long-term market projections
- CV efficiency improvement of **1%** would have the same fuel use impact as taking **2,470,000** cars off the road
- Laboratory cold-start effects have been observed to increase fuel use on the order of **10%**
  - (FTP bag 1+2 vs. bag 3+4)
- ICE loses majority of thermal energy in **<1 hr** following key-off

***Data from ANL D3**

Vehicle	UDDS Cold Start Penalty
2012 Ford F150	15%
2009 Jetta	13%
2011 Sonata Hybrid	13%
2012 Fiat 500	13%
2012 Fusion	13%
2013 Sonata	12%
2012 Chrysler 300	12%
2010 Fusion Hybrid	10%
2013 Altima	10%
2012 Focus	10%

*247M vehicles in operation as of 2013 (Polk)
ICE = internal combustion engine
LD = light duty
CV = conventional vehicle

ANL = Argonne National Laboratory
D3 = Downloadable Dynamometer Database
UDDS = Urban Dynamometer Driving Schedule
FTP = Federal Test Procedure

Relevance for Addressing Barriers

- **Risk aversion**
  - Project may reveal benefits attainable with relatively low incremental cost
  - Good cost/benefit ratio = Low hanging fruit
- **Lack of standardized test protocols**
  - The standard CAFE and 5-cycle window sticker test procedure may not fully capture all energy retention benefit elements
    - Helpful role for national lab to demonstrate where off-cycle benefits may exist
    - Holistic modeling approach will consider travel histories with several consecutive driving/parking sequences linked back-to-back
- **Constant advances in technology**
  - Modular programming technique will allow for new component maps and thermal control strategies to be evaluated in real time as technology advances

CAFE = Corporate Average Fuel Economy

Objectives

- **Conduct a holistic assessment of cold-start penalties in ICEs to benchmark real-world fuel economy for…**
  - DOE and regulatory bodies interested in real-world fuel saving potential
  - OEMs concerned with meeting CAFE requirements (via on- and off-cycle credit)

- **Specifically, NREL will answer…**
  - What is the real-world effect of engine cold-starts considering:
    - Thermally sensitive engine fuel rate maps
    - Representative mixes of driving behavior
    - In-use distributions of trip length and dwell times
    - Seasonal ambient temperature variations
  - To what extent can thermally engineered ICE systems mitigate cold-start penalties in the real-world?

Milestones

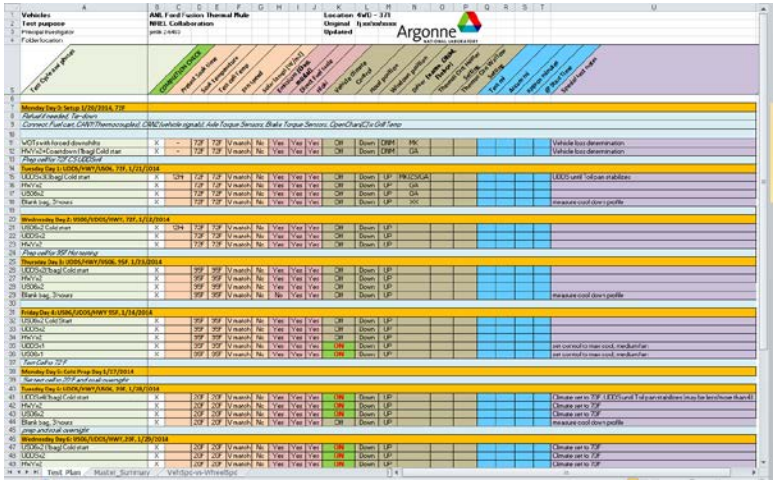
Date	Milestone or Go/No-Go Decision	Description	Status (as of April 2014)
12/31/2013	Milestone	Present at VSATT Deep Dive Meeting	Completed
3/31/2014	Milestone	Progress summary	Completed
6/30/2014	Milestone	Progress summary	On Track
7/31/2014	Milestone	Summary report on U.S. LDV cold start fuel use and potential for energy savings by engineering ICE balance of plant for heat retention	On Track
9/30/2014	Go/No-Go Decision	Sufficient fuel savings demonstrated by the analysis to proceed with the testing and validation activity in FY15.	On Track

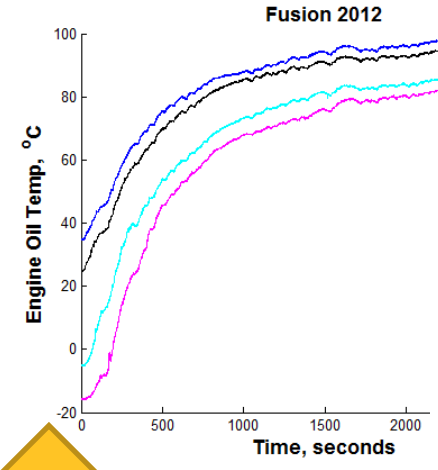
Approach: Engine/Powertrain Thermal Behavior

Conventional car in FY14; Extend to HEV and light trucks in FY15

- NREL coordinating with ANL's APRF in the collection of dynamometer data from a highly instrumented Ford Fusion
- ANL tests vehicle over a comprehensive matrix of drive cycle, ambient temperature, and initial thermal conditions
- NREL uses operational data and in-use responses to train models capable of evaluating large matrices of real-world usage scenarios

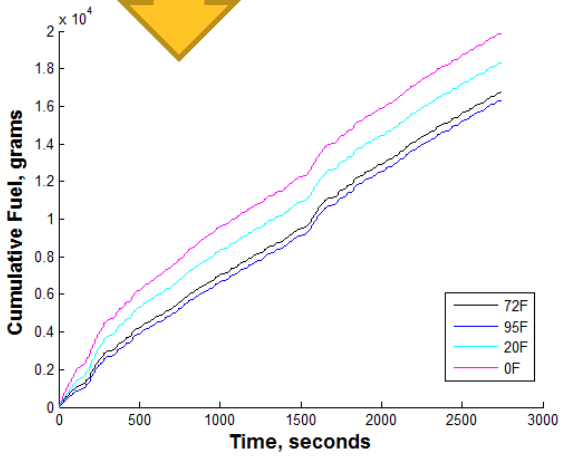
Photo credit: ANL APRF





Warm-up temps at various ambient conditions
(data collected by ANL APRF)

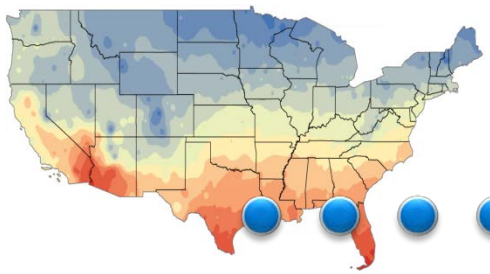
Fuel use at various ambient conditions
(data collected by ANL APRF)



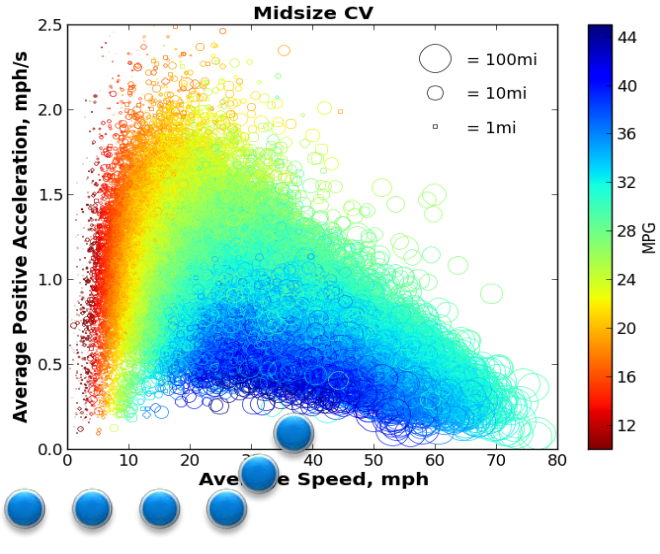
APRF = Advanced Powertrain Research Facility
HEV = hybrid electric vehicle

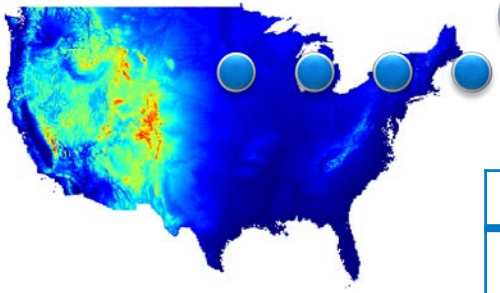
Approach: Real-World Fuel Economy

Exercise calibrated models over a large sweep of usage conditions to evaluate the interplay between travel time, driving behavior, ambient temperature, road grade, and ICE thermal response



Transportation Secure Data Center



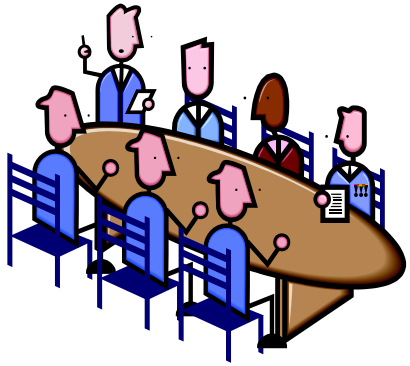


USGS = United States Geological Survey
TDSC = Transportation Secure Data Center
TMY = Typical Meteorological Year
FASTSim – Future Automotive Systems Technology Simulator

Data Element	Source	Notes
Drive Cycles/ Trip Distributions	NREL Transportation Secure Data Center	The TSDC houses hundreds of thousands of real-world drive cycles from vehicles across the country.
Climate Data	NREL National Solar Radiation Database	Home to TMYs from hundreds of U.S. locations, each containing hourly climate data.
Elevation/ Road Grade	USGS National Elevation Dataset	Raw USGS elevations are filtered to remove anomalous data and produce smooth road grade curves.

Approach: Industry Engagement/Feedback

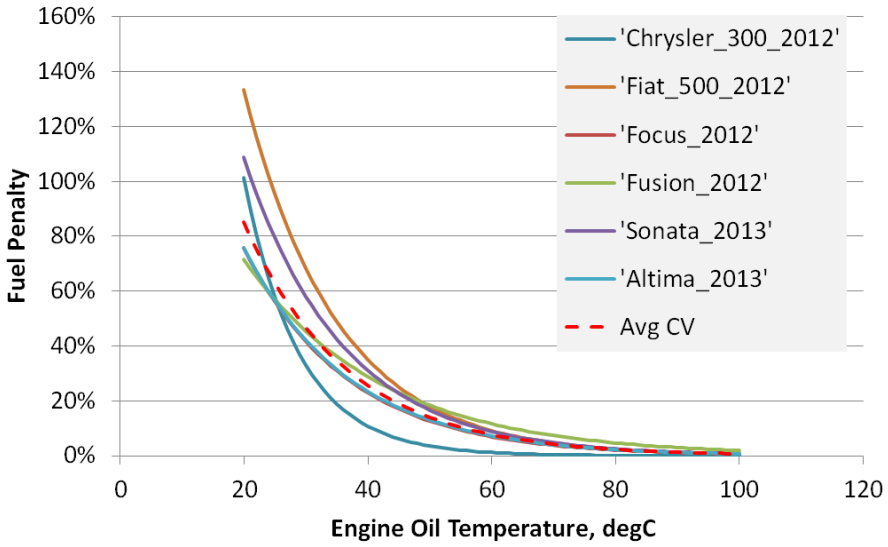
- **Updates shared with attendees of VSATT meetings, including representatives from USCAR OEMs and National Labs**
  - Chrysler, Ford, GM
  - DOE
  - ANL, INL, ORNL

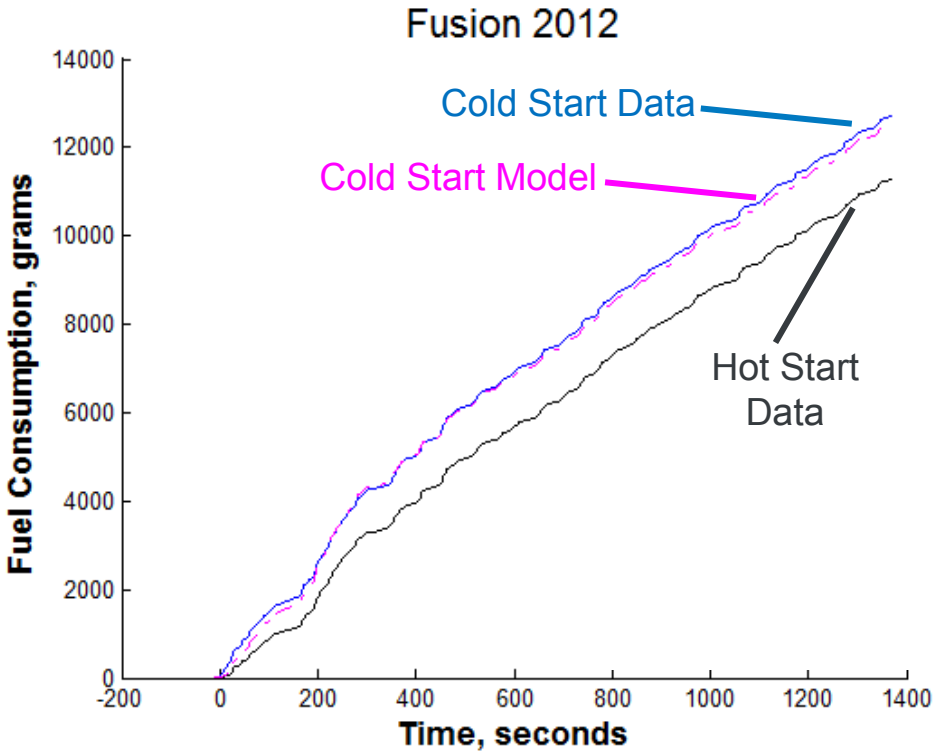


ANL = Argonne National Laboratory
INL = Idaho National Laboratory
ORNL = Oak Ridge National Laboratory

Technical Accomplishments and Progress

- Exponential relationship between engine oil temperature and fuel rate penalty has been observed in the data
- These fuel penalty curves are then fit using a constrained nonlinear optimization routine
- Method has been shown to provide reasonably accurate estimates of cumulative fueling rates
- Future refinements will isolate enrichment fuel use following ignition from remainder of drive cycle

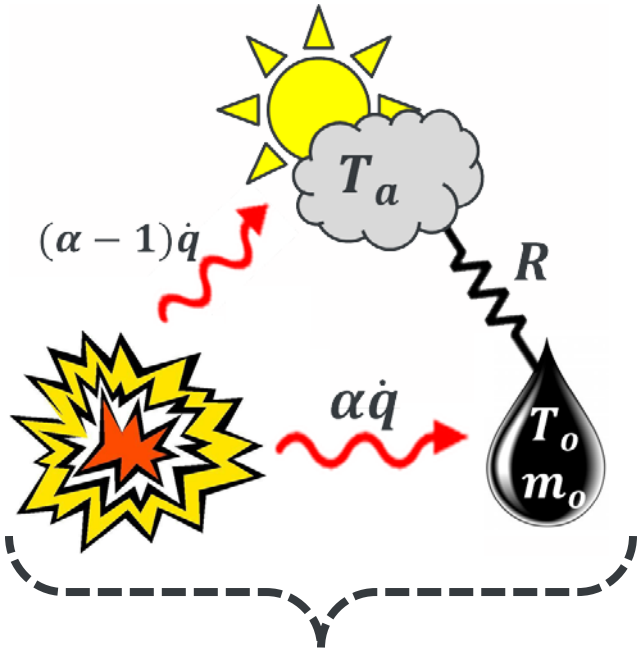




Initial Results

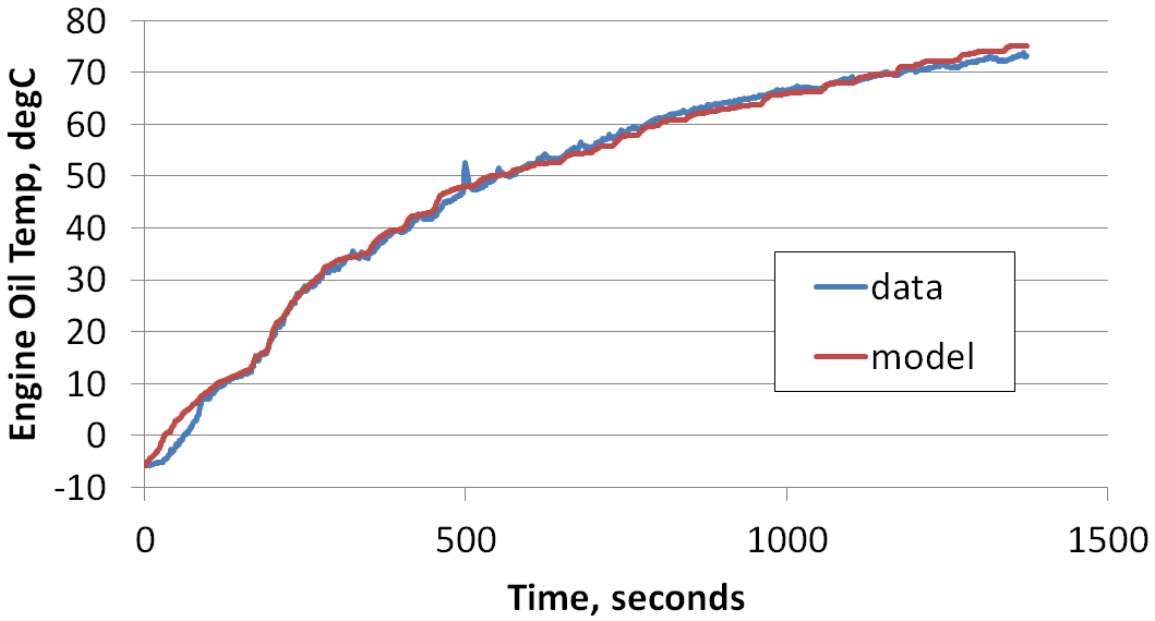
Model to be refined during remainder of project

Technical Accomplishments and Progress



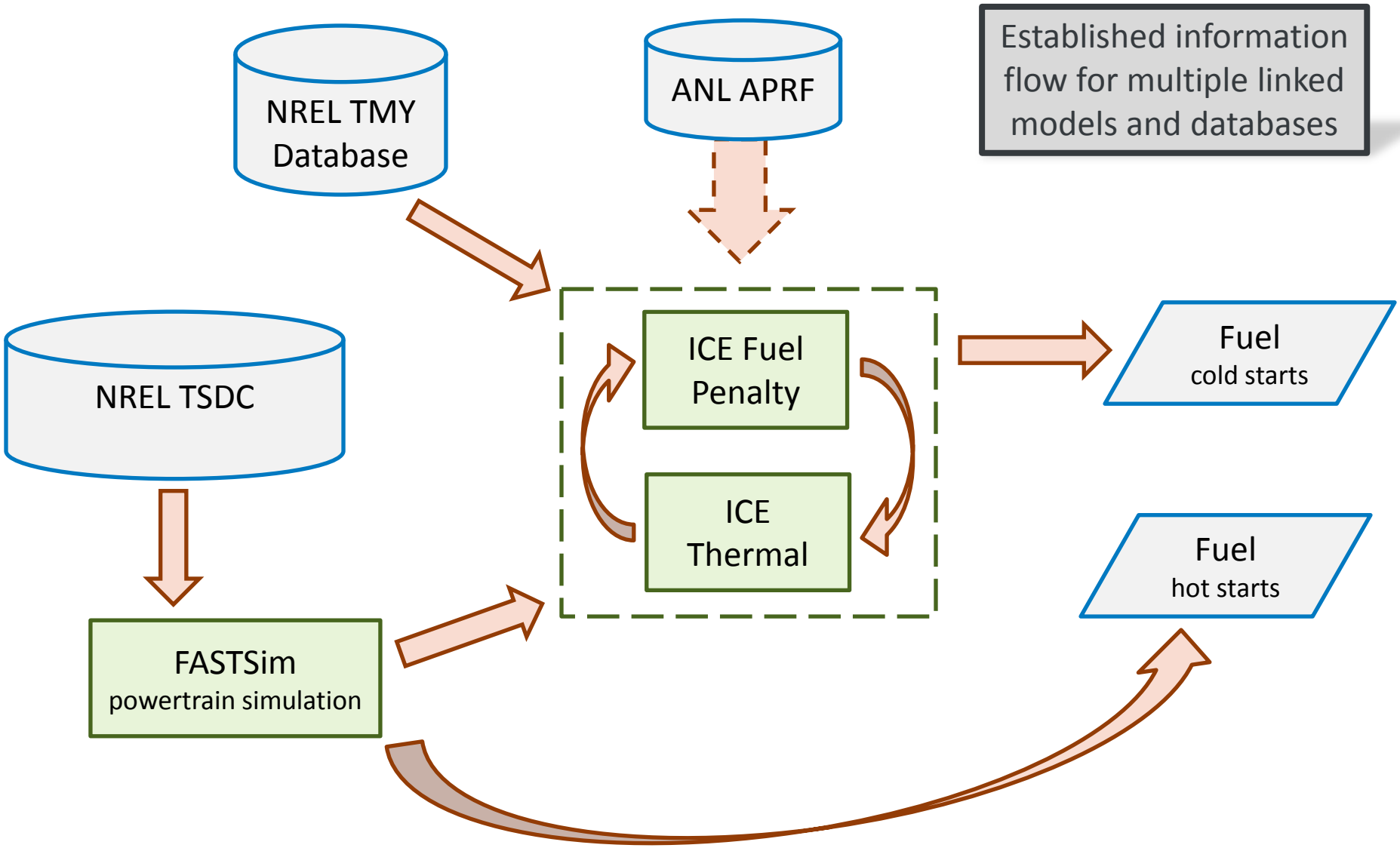
For model fitting assume
Known: q(t), T_o(t), T_a(t)
Unknown: α, m_o, R

- Lumped capacitance thermal model of ICE is employed and calibrated to dynamometer data showing reasonable levels of accuracy
- Future refinements will consider convective losses as a function of vehicle speed and equivalent models of catalytic converter, engine coolant, and transmission fluid



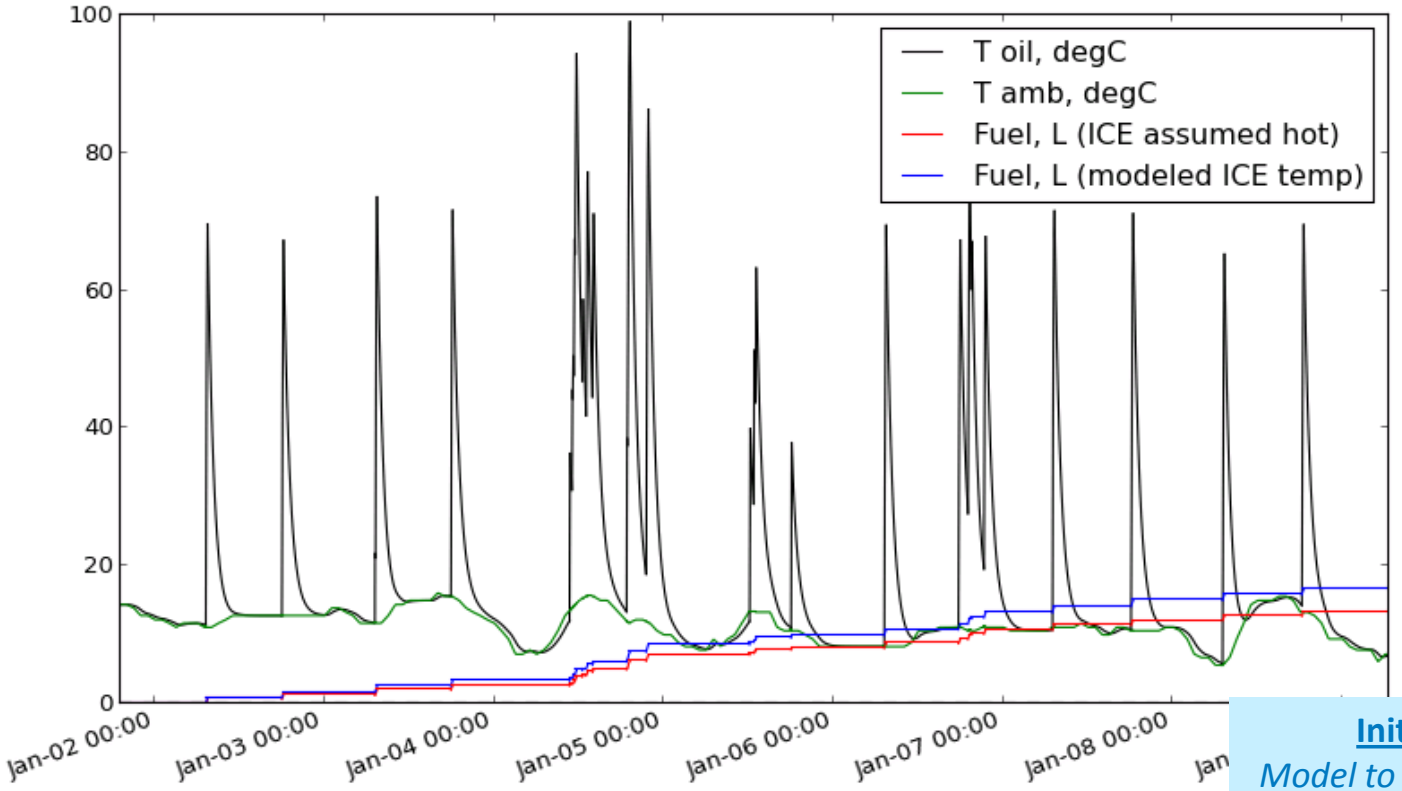
Initial Results
Model to be refined during remainder of project

Technical Accomplishments and Progress



Technical Accomplishments and Progress

- **Used fully integrated model to step through one week of representative travel from TSDC vehicle**
- **Overlaid ambient conditions from Los Angeles, and tracked cumulative fuel consumption assuming both:**
  - Hot ICE conditions
  - Mix of cold, warm, and hot starts according to modeled ICE temperature

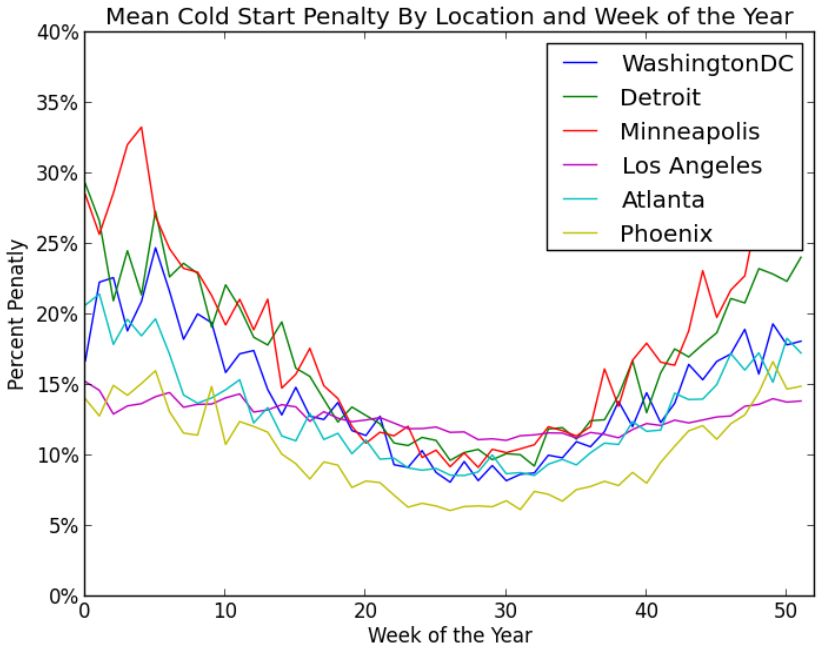


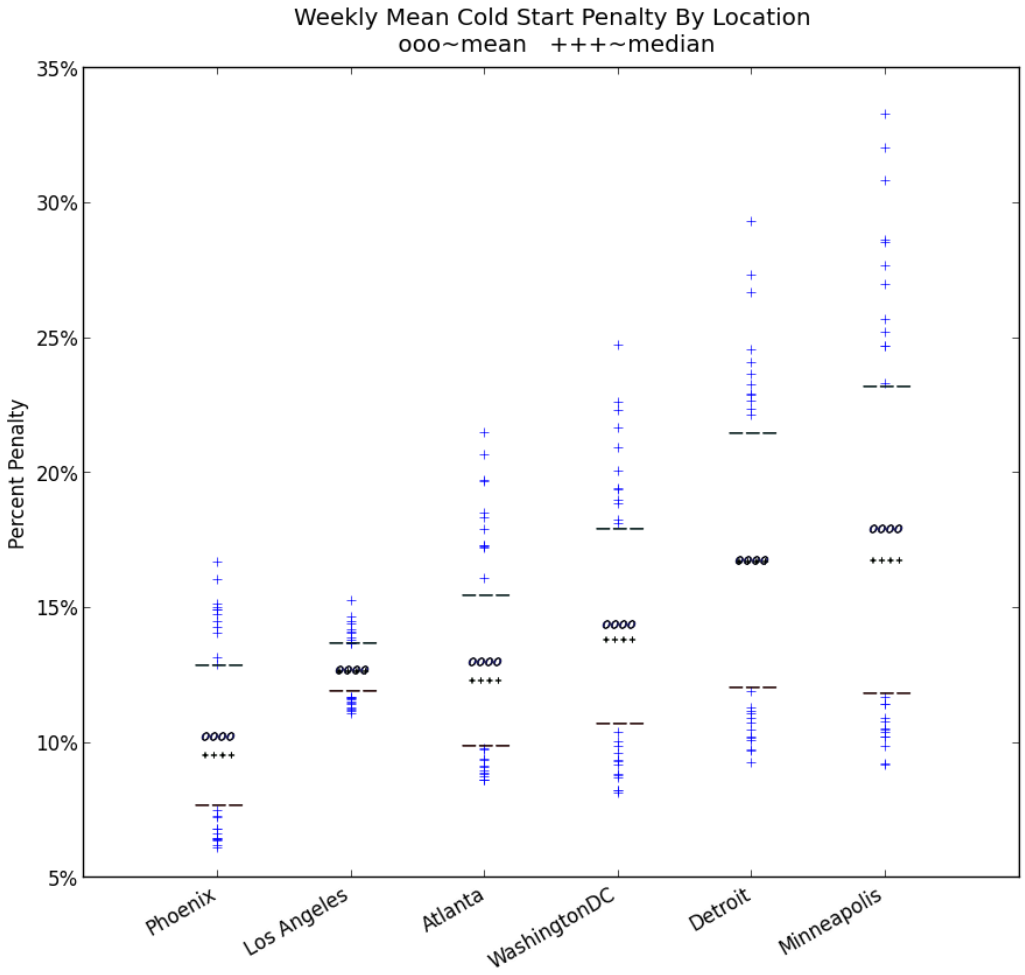
Initial Results

Model to be refined during remainder of project

Technical Accomplishments and Progress

- **Evaluated model over large matrix of conditions**
  - Week-long TSDC histories from ~2,000 vehicles
  - Climates from six representative metropolitan areas
- **Results reveal sensitivities to time of year, geography, and drive profile**

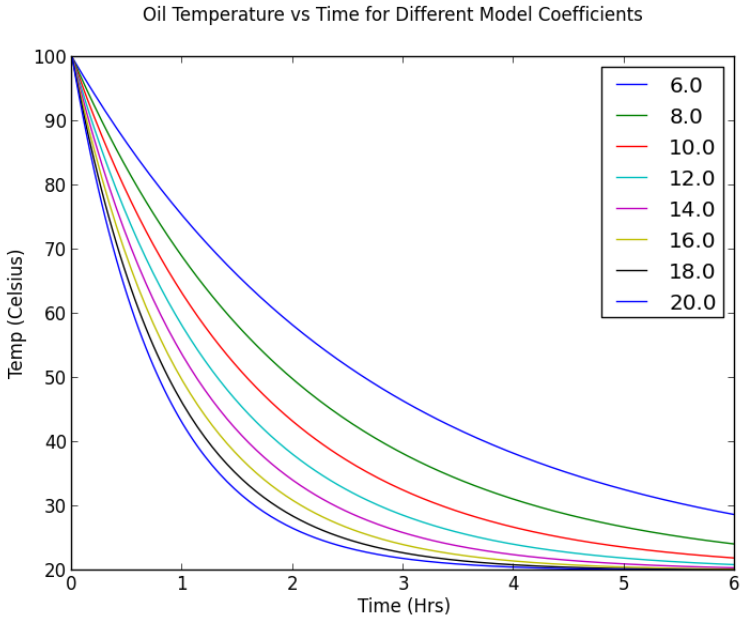


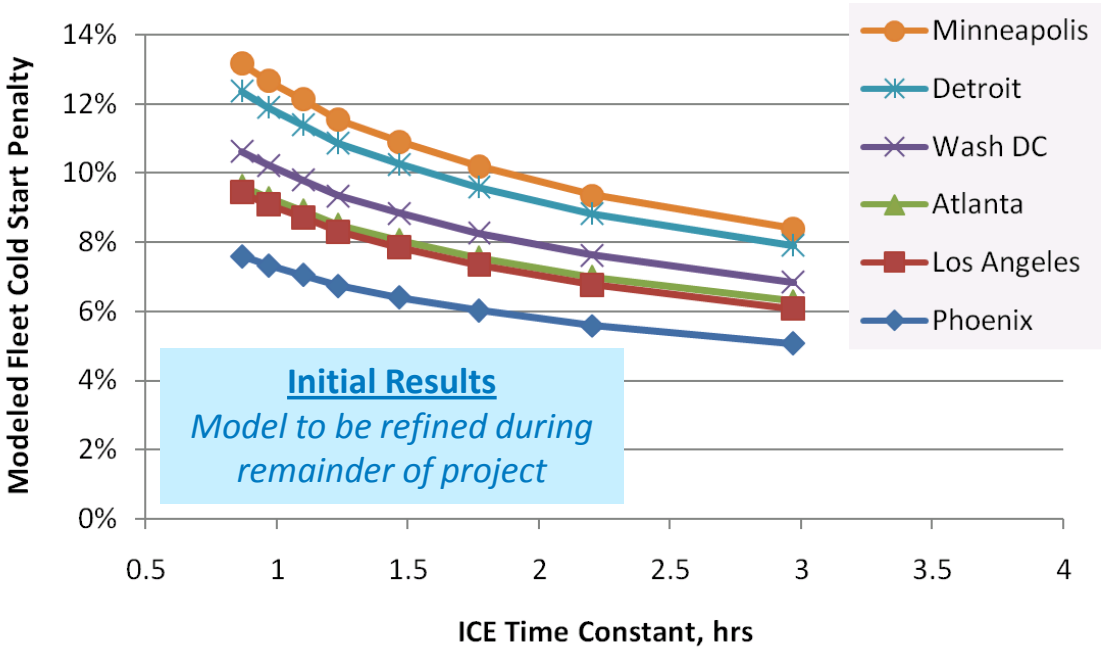


Initial Results
Model to be refined during remainder of project

Technical Accomplishments and Progress

- While quantifying the existing fuel use dedicated to overcoming cold-start penalties is of interest, the greater value of this work lies in estimating the **potential for various technologies to mitigate cold-start fuel use**
- This slide explores the potential fuel savings associated with increasing engine cool-down times from a baseline of approximately one hour
- Results indicate that doubling the ICE time constant could **reduce cumulative fuel use by approximately 2%**



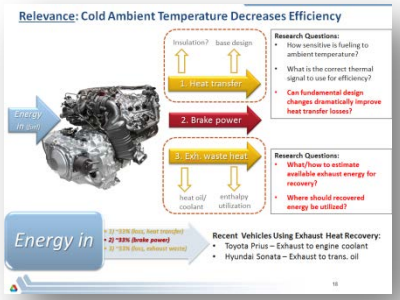


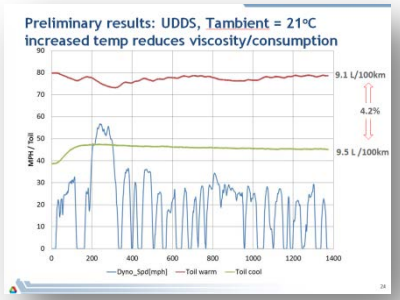
Responses to Previous Year Reviewers' Comments

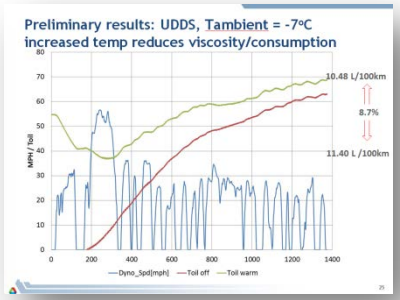
This is a new project and was therefore not reviewed in FY13.

Collaboration and Coordination with Other Institutions

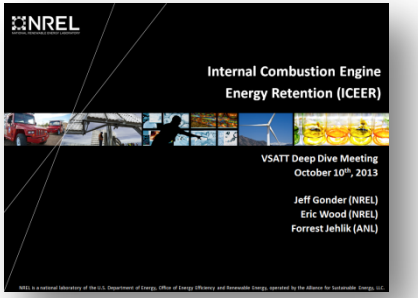
- **Argonne National Laboratory**
  - Collection of dynamometer data to support model development

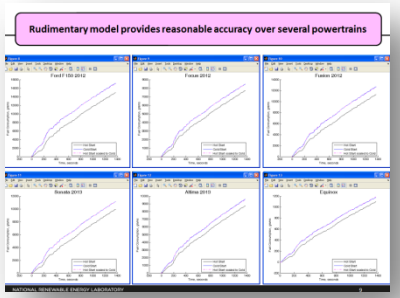


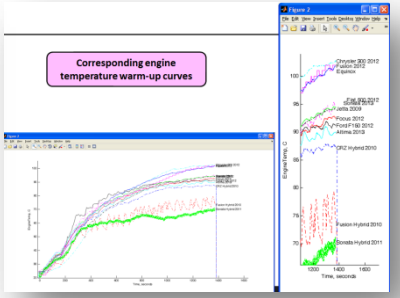




- **USCAR OEMs** (Chrysler, Ford, and GM)
  - Active conversations on the topic through VSATT meetings and direct engagement







Remaining Challenges and Future Work: FY14

Challenges/Barriers

- **Need good confidence in the model**
  - Including ability to isolate different sources of impact
- **Need to determine if/which specific energy retention strategies merit further investigation**
- **Desirable to understand different considerations for different powertrains**

Corresponding Work Plan for Remainder of FY14

- **Increase model fidelity**
  - Fuel: Isolate enrichment fuel penalty from viscous losses
  - Thermal: Thermostat behavior, convective losses as function of vehicle speed
- **Investigate mitigation strategies**
  - Component insulation, exhaust heat recovery
- **Publish in conference proceedings/journal article**
- **Begin exploring effects on HEV powertrain using APRF Prius data**

Remaining Challenges and Future Work: FY15

Challenges/Barriers

- **Need sufficient review/buy in to proceed with prototyping step**
  - Assuming promising initial results continue to hold
- **Comprehensive assessment should also consider…**
  - Other component thermal sensitivities
  - Considerations for different powertrains (including hybrid/plug-in)
  - Considerations for different size vehicles

Corresponding FY15 Future Work Proposal

- **Continue/expand on ANL and OEM collaboration**
- **Develop/evaluate prototypes of promising approach(es), if justified**
  - Improve model validation/refinement with data from prototypes
- **Expand modeling capabilities**
  - Isolate thermal sensitivities of other components (e.g., differential and transmission)
- **Develop equivalent models**
  - Hybrid-electric (intermittent ICE use); Large truck/SUV (more thermal storage)
- **Identify optimal waste heat utilization strategies**
  - Incorporate into prototyping approach, as appropriate

Summary

- **Incremental ICE efficiency improvements have significant aggregate petroleum displacement potential, which is particularly significant as it relates to….**
  - National energy concerns
  - Considering pathways to satisfy CAFE requirements
- **Accurate quantification of real-world fuel use/savings requires integration of detailed testing with high-level analysis, which is accomplished via….**
  - High-resolution test data and model development supported through collaboration with ANL
  - Integration of large-scale datasets providing holistic assessment of vehicle use across representative combinations of driving distributions, road grade, and climate/thermal conditions
- **Aggregating detailed vehicle simulations to fleet-level energy assessment provides context for technology significance and fuel saving potential….**
  - Early results indicate potential for dramatic aggregate fuel savings related to ICE energy retention
- **Continued research will….**
  - Improve model capabilities/fidelity
  - Explore additional powertrains
  - Identify most promising mitigation strategies, and (if supported by the analysis results) develop/evaluate hardware prototypes