2012FY Data Collection for Improved Cold Temperature Thermal Modeling

2012 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Project ID #VSS080

Overview

Timeline

- 1Q 2011 - current
  - Complete evaluation of Gen 2 Prius
  - Complete evaluation of 2010MY Gen 3 Prius
  - Began testing of 2011MY Ford Fusion thermal test vehicle
- 60% complete

Barriers

- **A:** Risk Aversion
- **F:** Constant advances in technology
- **E:** Computational models, design and simulation methodologies

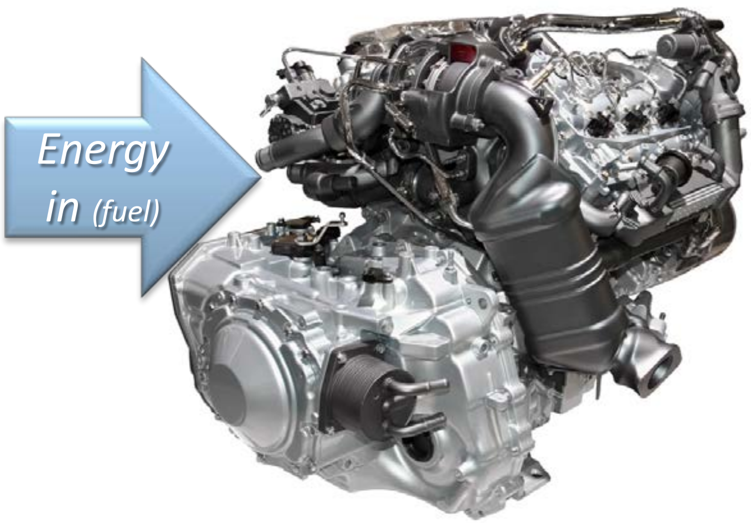
Budget

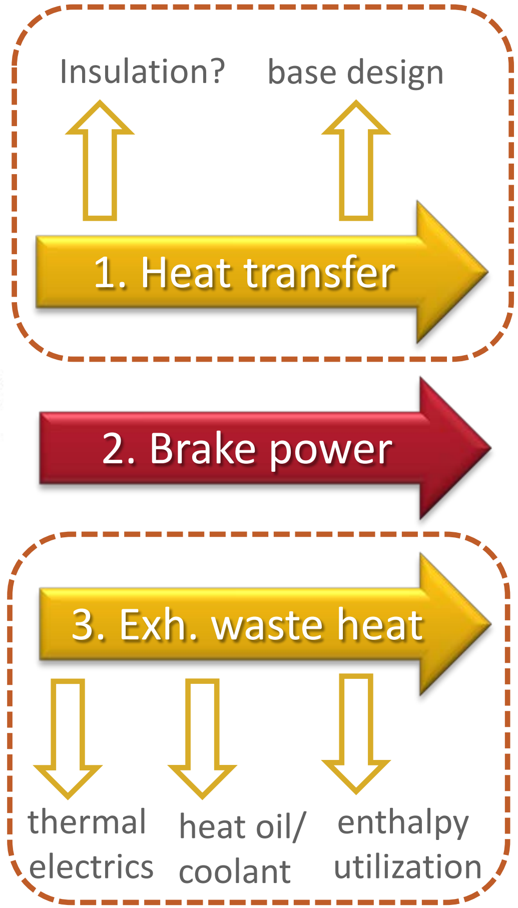
- Total project funding
  - FY11 funding: $300k
  - FY12 funding: $250k

Partners

- Environment Canada
- Oak Ridge National Laboratory
- Argonne – M&S

Relevance: Waste Energy Decreases Efficiency and is Impacted by Ambient Temperature





Research Questions:
- How sensitive is fueling to ambient temperature?
- What is the correct thermal signal to use for efficiency?
- Can fundamental design changes dramatically improve heat transfer losses?

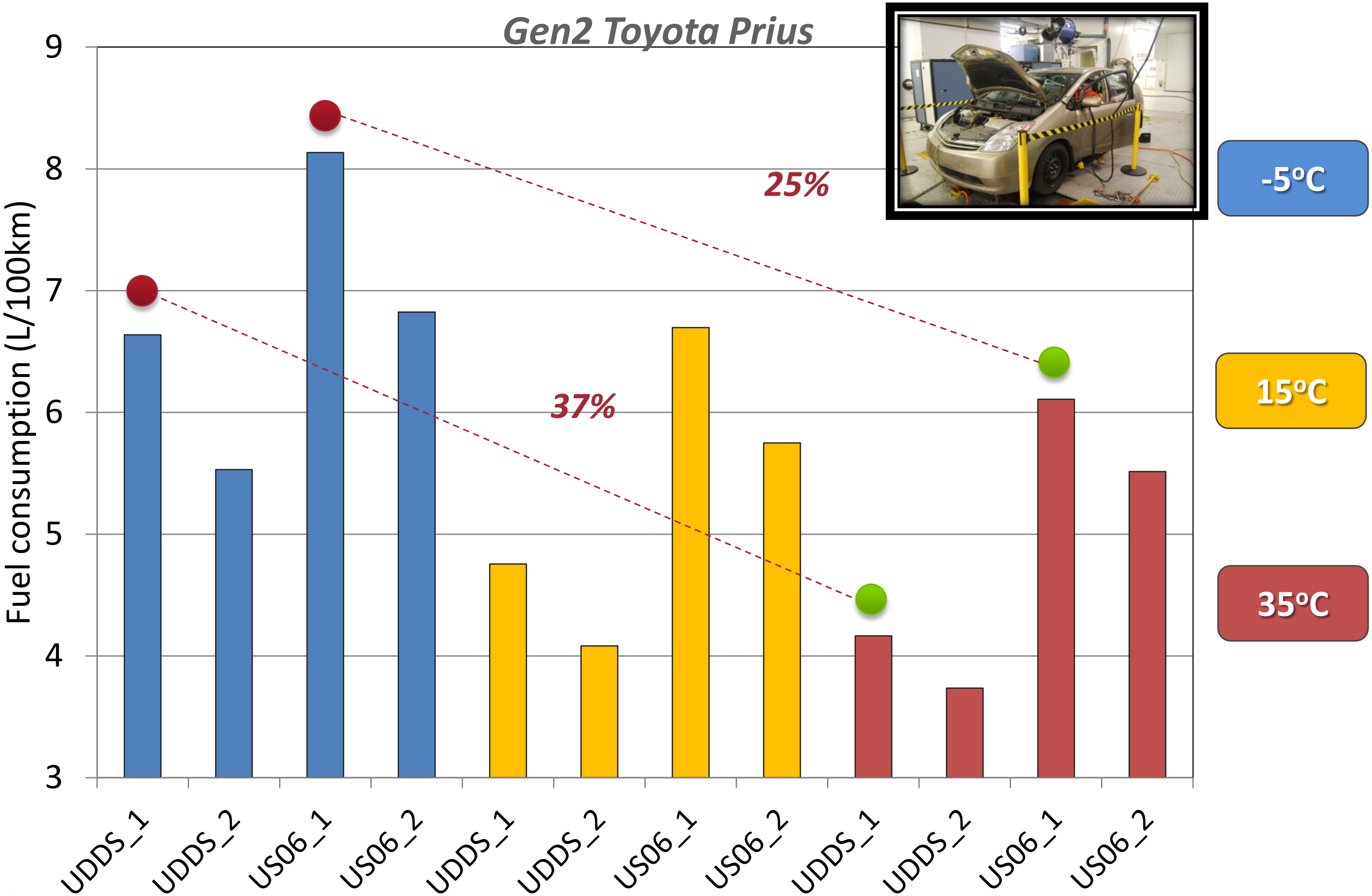
Research Questions:
- What/how to estimate available exhaust energy for recovery?
- Where should recovered energy be utilized?

Energy in

- *1) ~33% (loss, heat transfer)*
- ***2) ~33% (brake power)***
- *3) ~33% (loss, exhaust waste)*

Recent Vehicles Using Exhaust Heat Recovery:
- Toyota Prius – Exhaust to engine coolant
- Hyundai Sonata – Exhaust to trans. oil

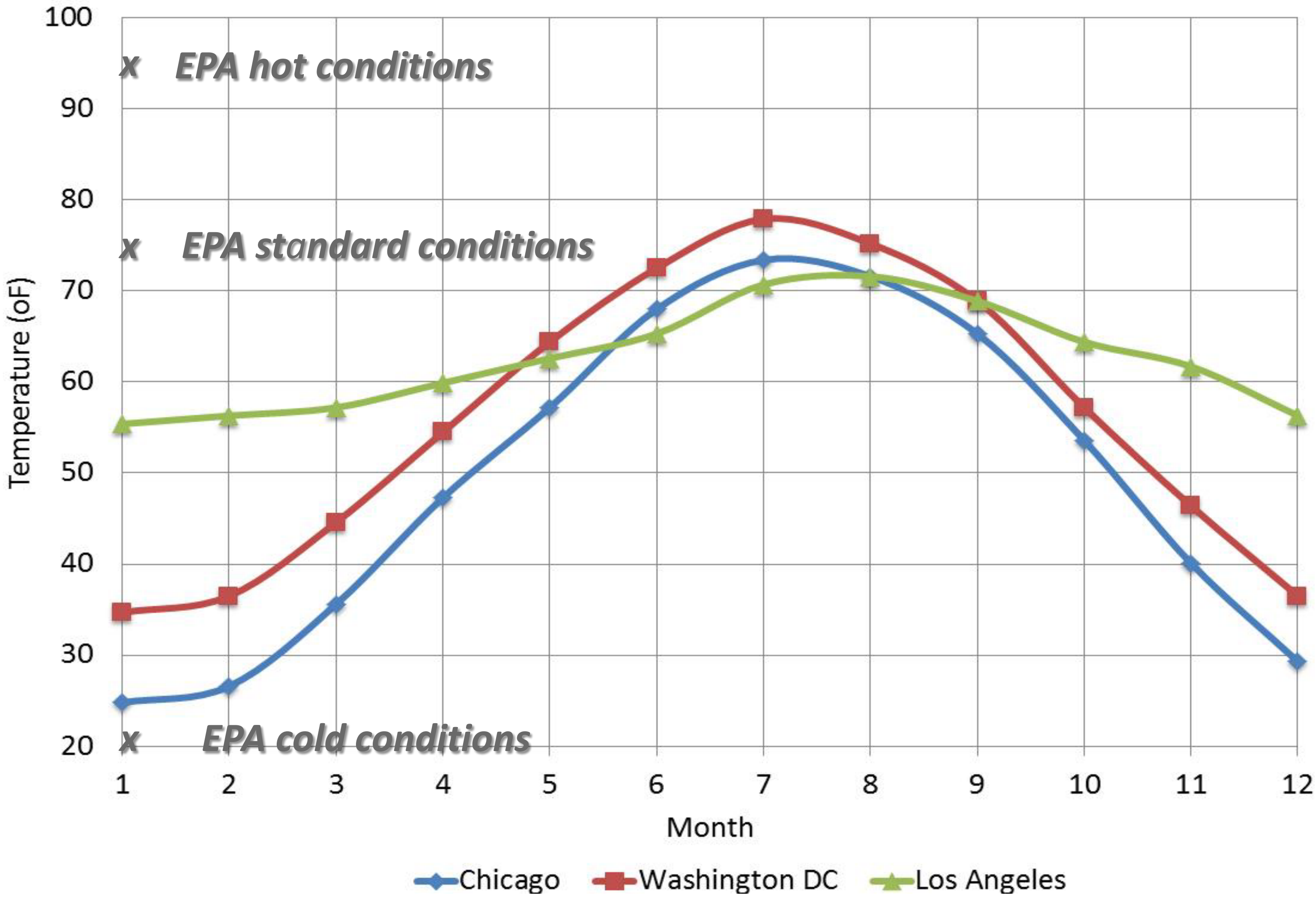
Relevance: Previous Testing Has Shown Large Fuel Economy Reductions At Cold Temperatures



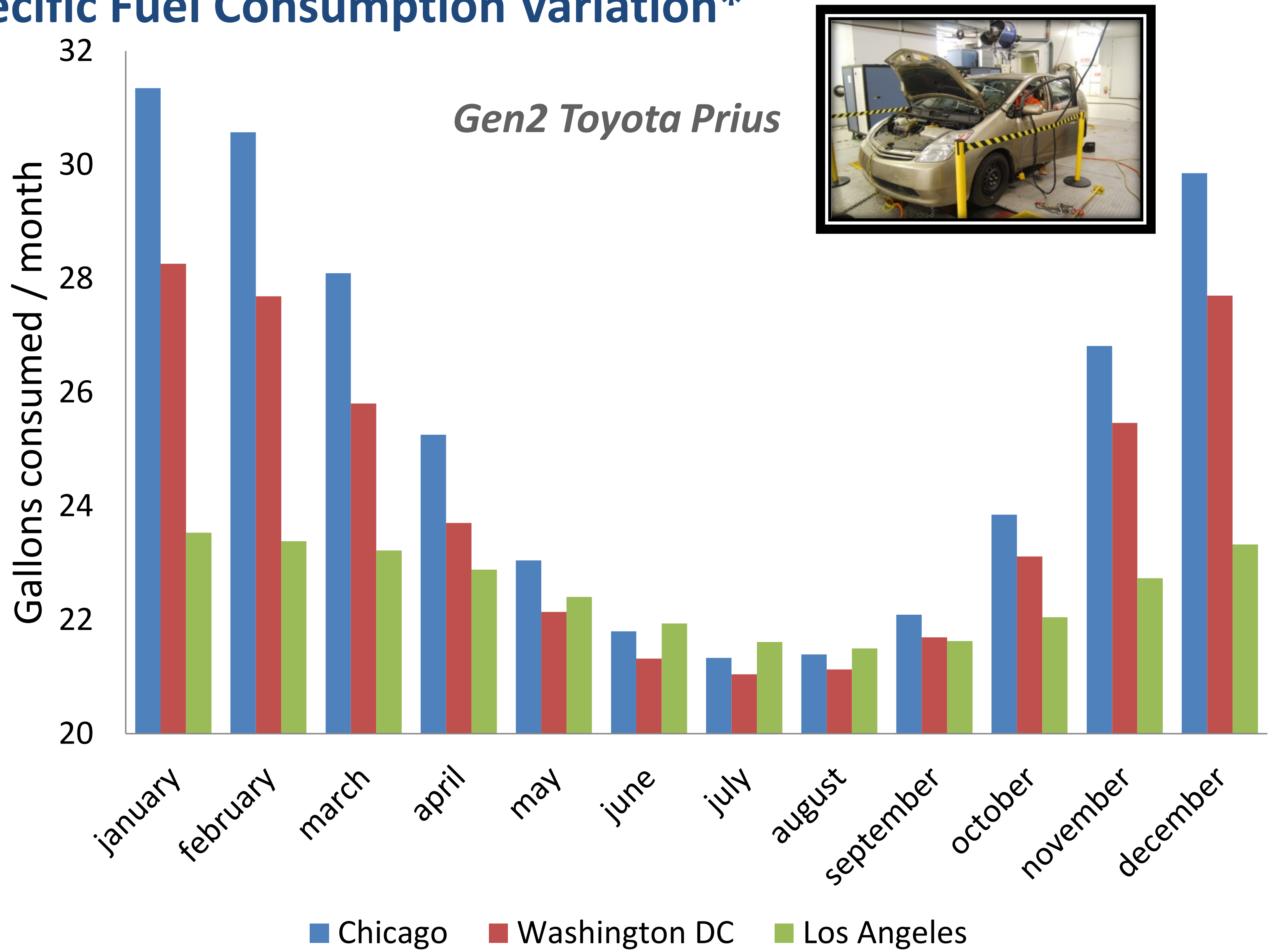
Results shown are trends from experimental data.

Relevance: Vehicles Operate in Seasonal Temperature Variations

Understanding fuel consumption across a broad range of ambient temperatures provides unique insight into real-world fuel consumption



Relevance: Cold Operation Results in Significant and Location Specific Fuel Consumption Variation*



*Results assume 15,000 annual miles driven. Results shown do not account for air conditioning losses at higher ambient temperatures.

Approach: Generate Experimental Data Across a Range of Ambient Temperatures and Evaluate Sensitivities and Trends

- **2011 Ford Fusion (non-hybrid) thermal testing mule**

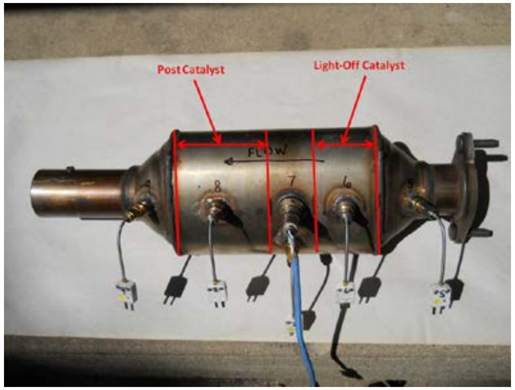
Thermal conditioning cart

- Instrument vehicle for thermal nodes
- Conduct tests over broad ambient temperature conditions
- Conduct tests over broad speed/load conditions
- Utilize thermal conditioning cart to separate coolant/oil temperature effects
- Refine techniques to estimate powertrain efficiency versus ambient conditions
- Publish and utilize a simplified model for vehicle assessment and efficiency studies

Approach: Extensive Vehicle Thermal Instrumentation

- **2011 Ford Fusion Thermal Evaluation Vehicle:**
  - 4-cylinder, 6-speed transmission representative of a modern mid-size vehicle
  - 27+ thermal channels of data (engine oil, transmission oil, engine coolant, cabin temperatures)

Catalyst Temperatures

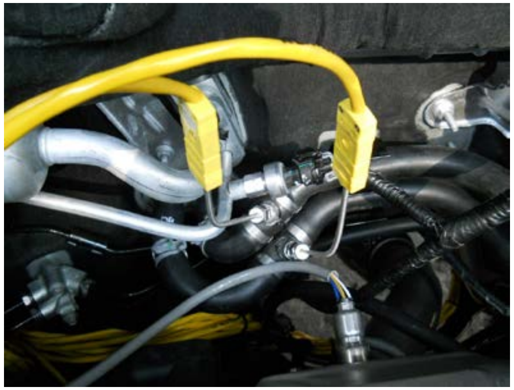


Exhaust Runner Temperature

Post-cat. Exhaust Temperatures

Coolant Flows

Coolant Temperatures

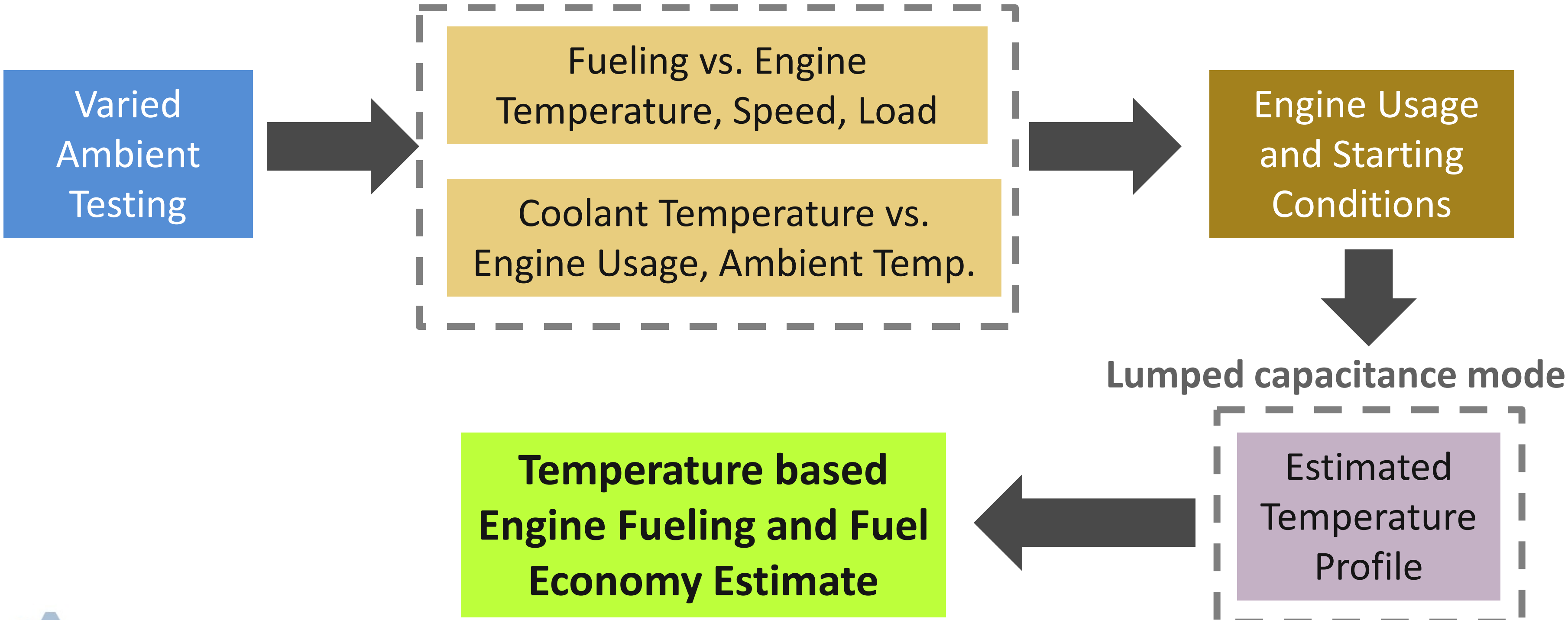


Cabin Temperatures

Approach: Leverage and Refine Previous Fueling and Temperature Prediction Models and Methodology

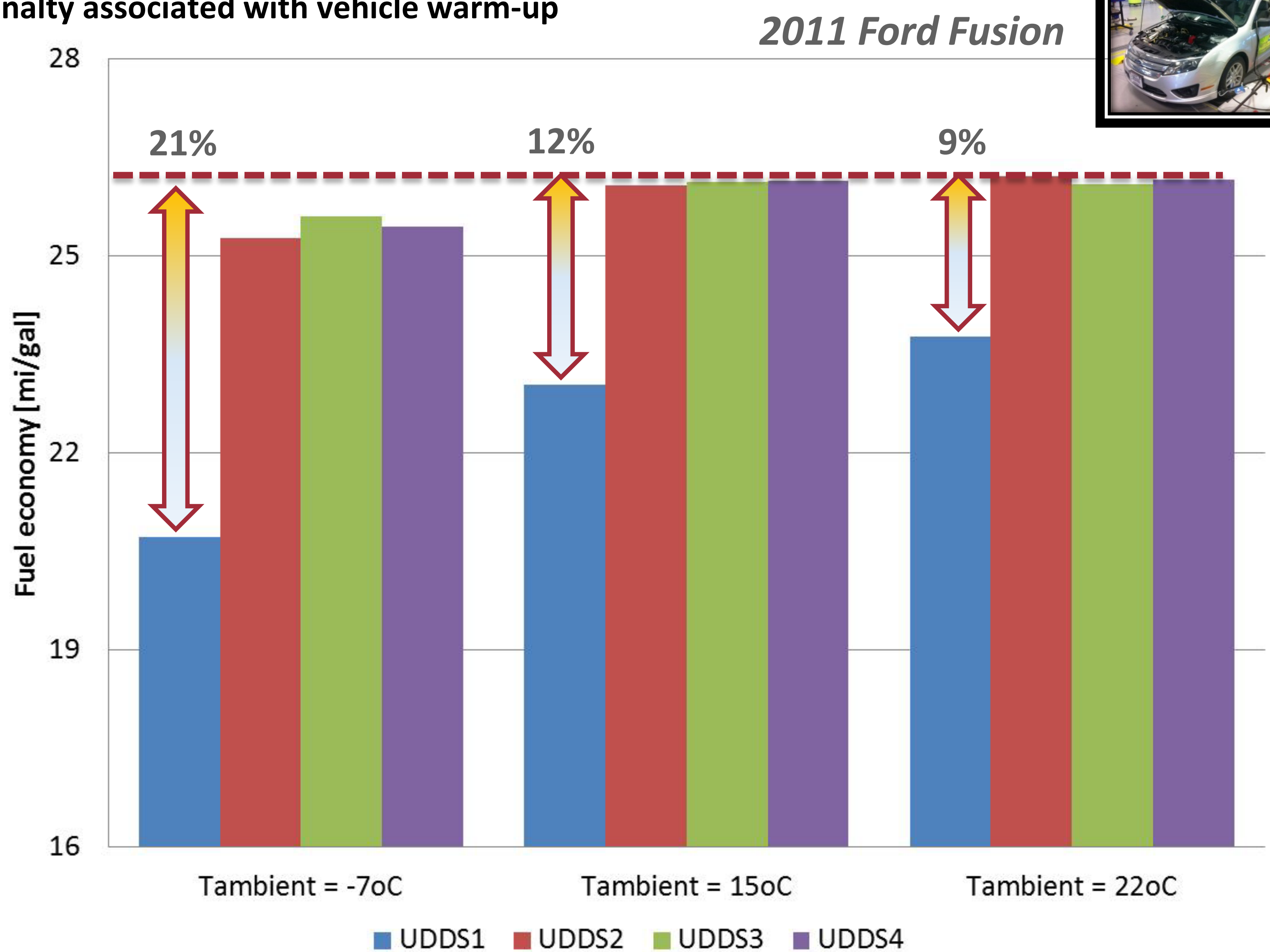
- **Refine modeling methodology to estimate engine efficiency at varied temperatures**
- **Estimate engine thermal state using ambient temperature and engine load**
  - Methodology uses response surface and empirical data-fitting techniques
  - Techniques result in simplified general models

Response Surface Methodology Model (RSM) –
MY 2004 and MY 2010 Toyota Prius and MY 2011 Ford Fusion



Accomplishments: Quantify Ambient Temp Impact On Efficiency

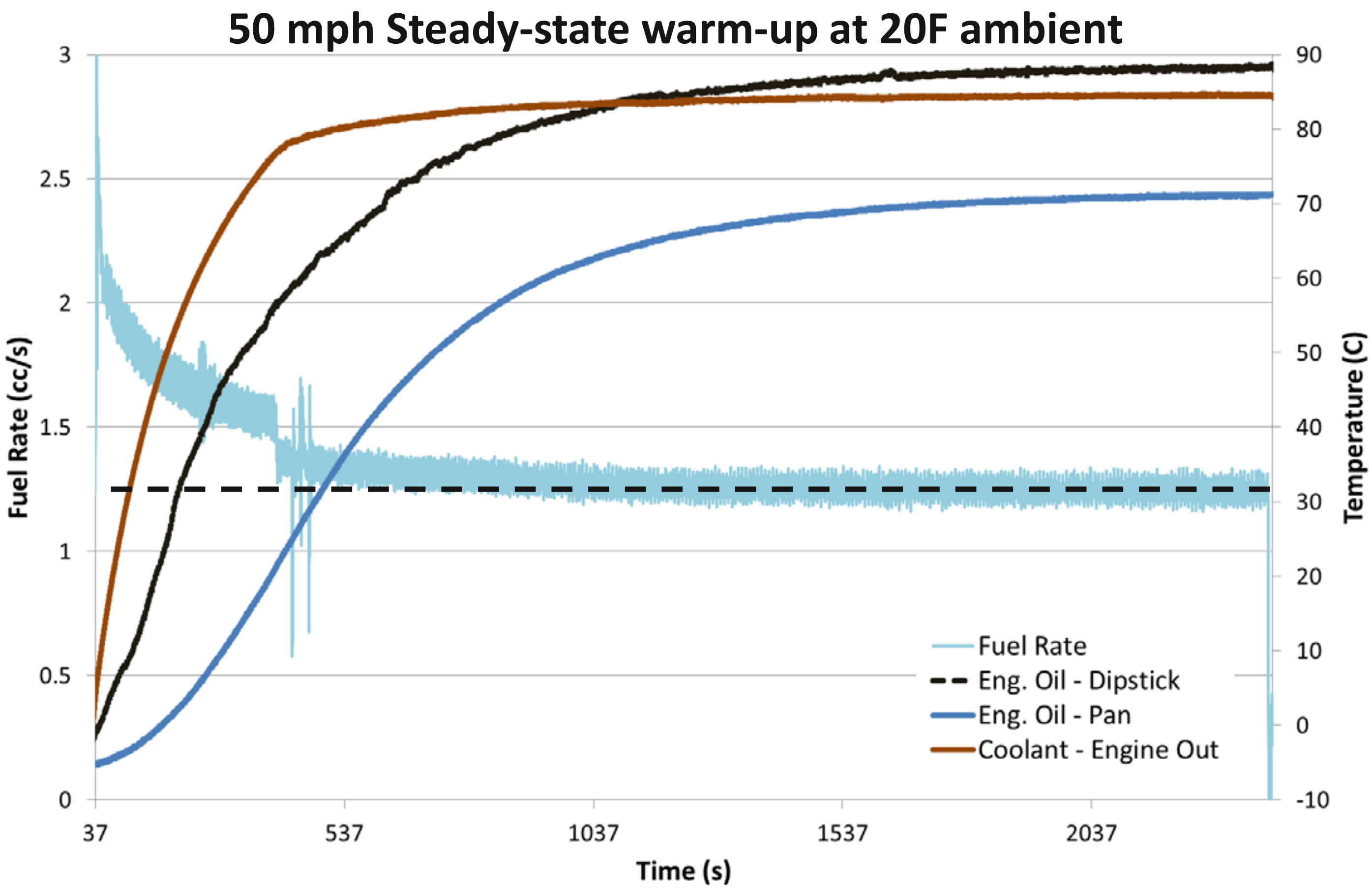
- **Cold temperature testing shows a dramatic increase in the penalty associated with vehicle warm-up**



Accomplishments: Expanded Thermal Signal Evaluation Methodology

Vehicle warm-up during steady-state operation at cold temperature provides useful insight into possible signals for efficiency estimation

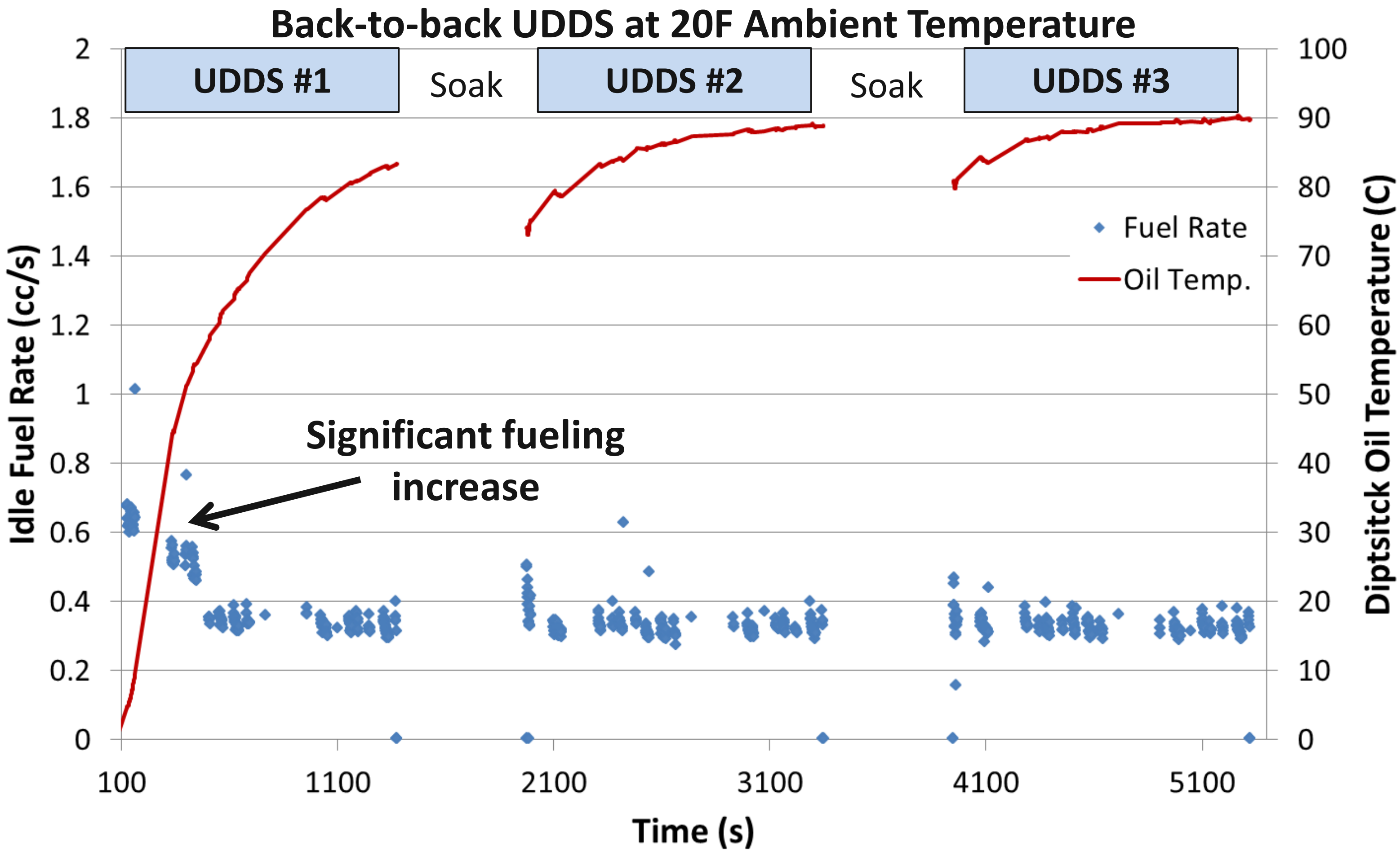
- Oil temperature appears to be better correlated with fueling trends during warm-up
- Sizable difference exits between oil-pan and dipstick temperature… particularly at colder temperatures
- Many other temperatures and operating points provide additional insight (i.e. heater core impact @ cold)



Accomplishments: Idle Efficiency Greatly Reduced At Cold Temp

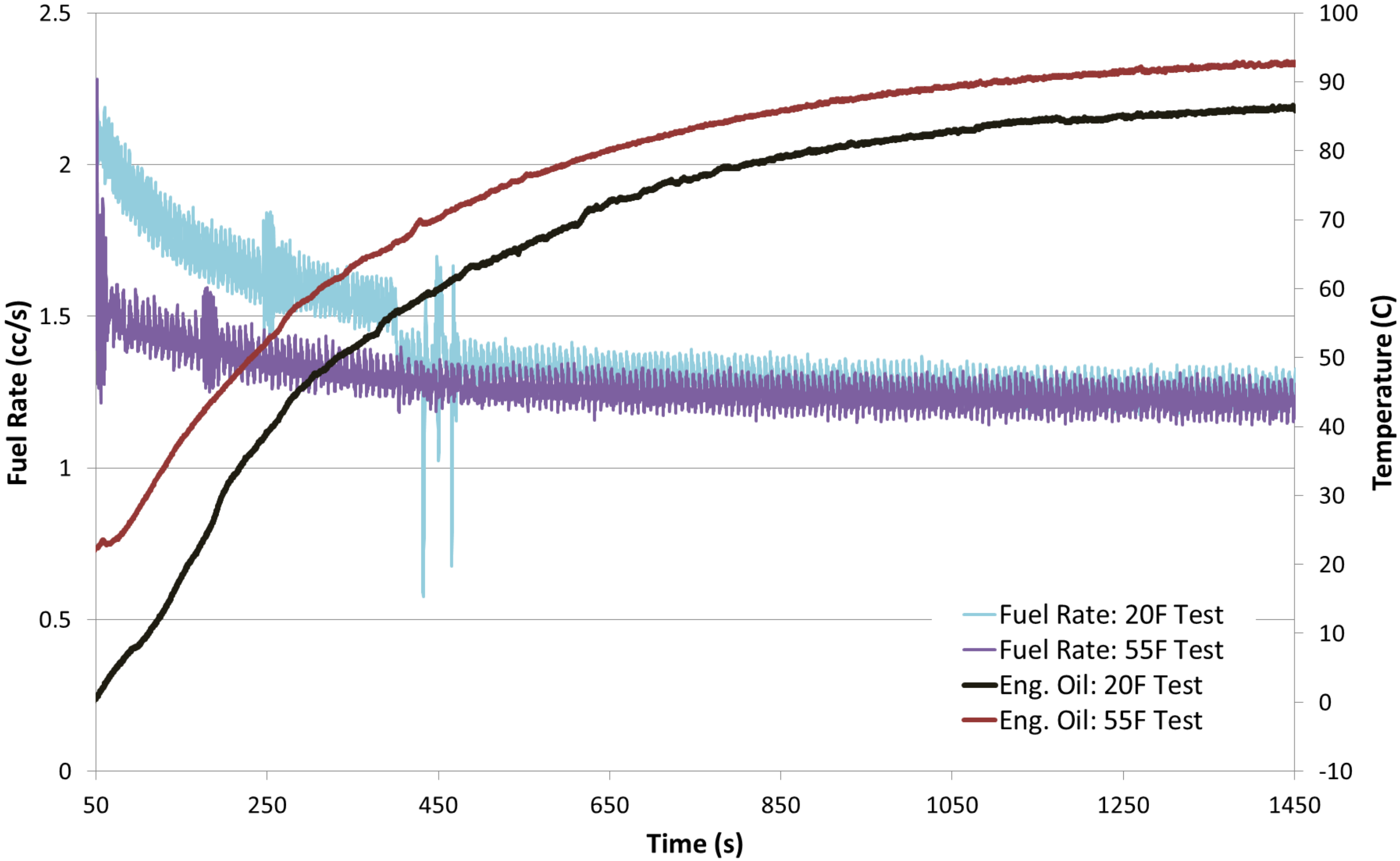
During very cold operation (20F) idle fueling changes dramatically as vehicle warms from initial engine start during back-to-back UDDS cycles

- Understanding idle fuel consumptions over a range of temperatures is critical to estimating real-world fuel consumption for a conventional vehicle
- Assessment of hybridization benefits are also closely tied to idle fuel consumption



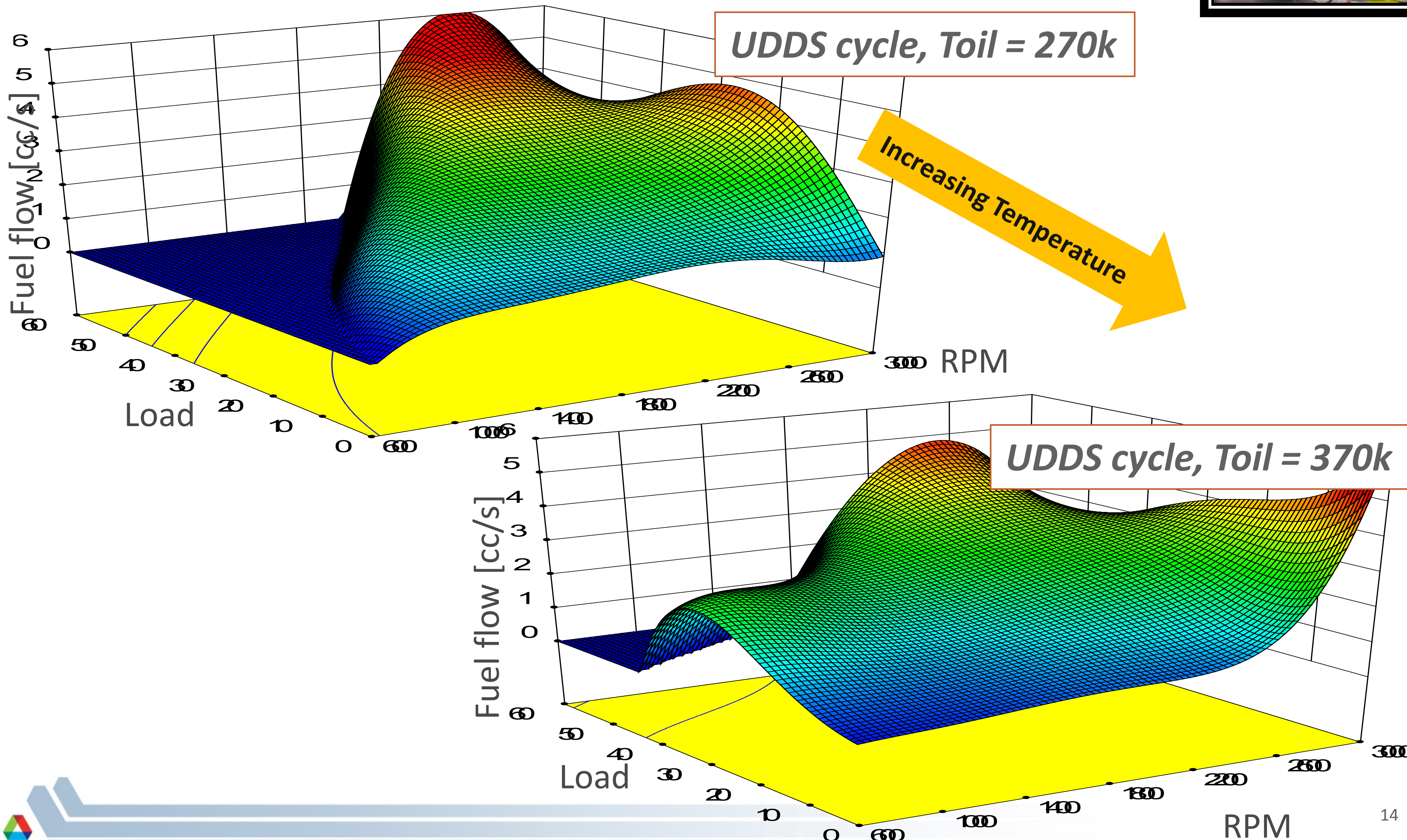
Accomplishments: Direct Impact of Ambient Temp Effect On Efficiency

Although initial conditions and heat loss to the environment are dictated by ambient temperature, steady state runs indicate ambient does not significantly impact fuel consumption once vehicle has stabilized

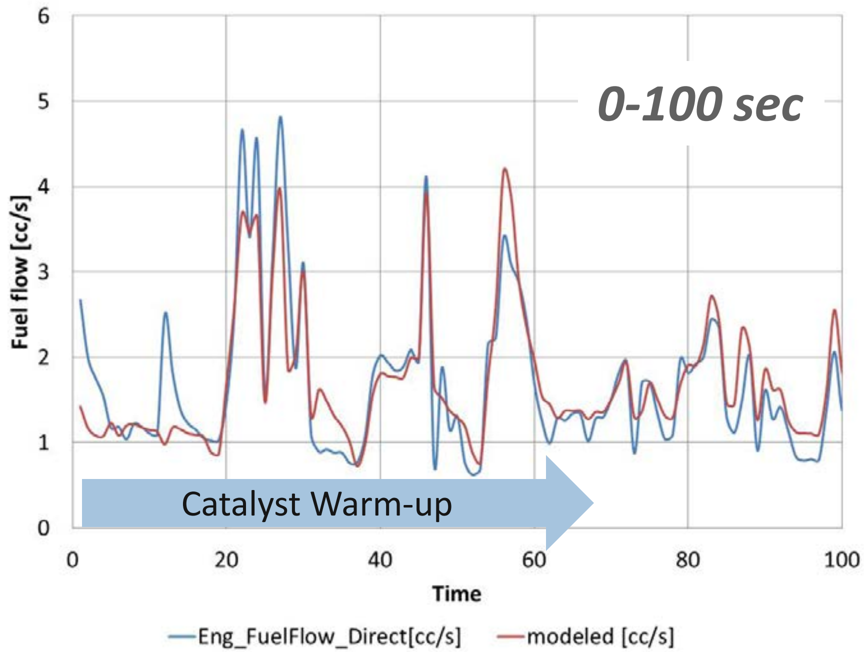


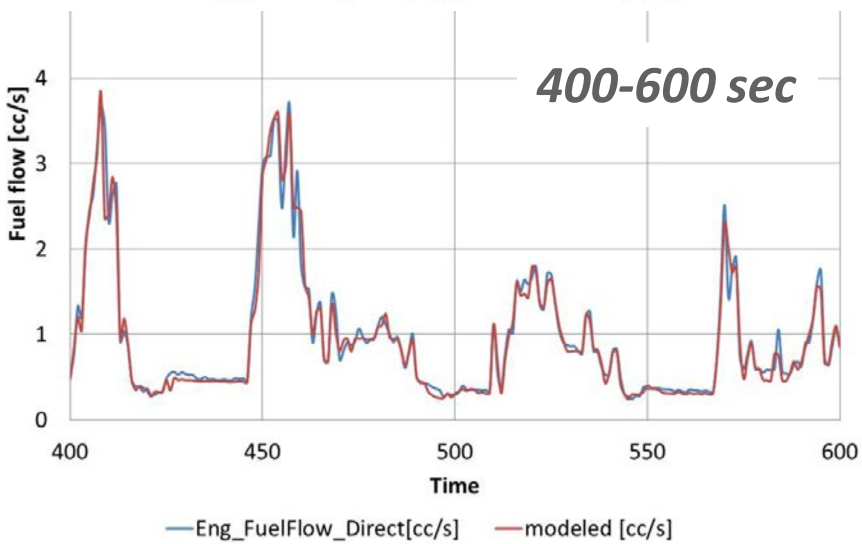
Accomplishments: Utilize Collected Test Data to Develop Oil Temperature Dependent Fueling Model

- Using insights from steady-state testing and data from drive cycle testing, the map estimates fueling as a function of engine speed, load, and oil temperature



Accomplishments: RSM Fueling Model During 20F UDDS Warm-up





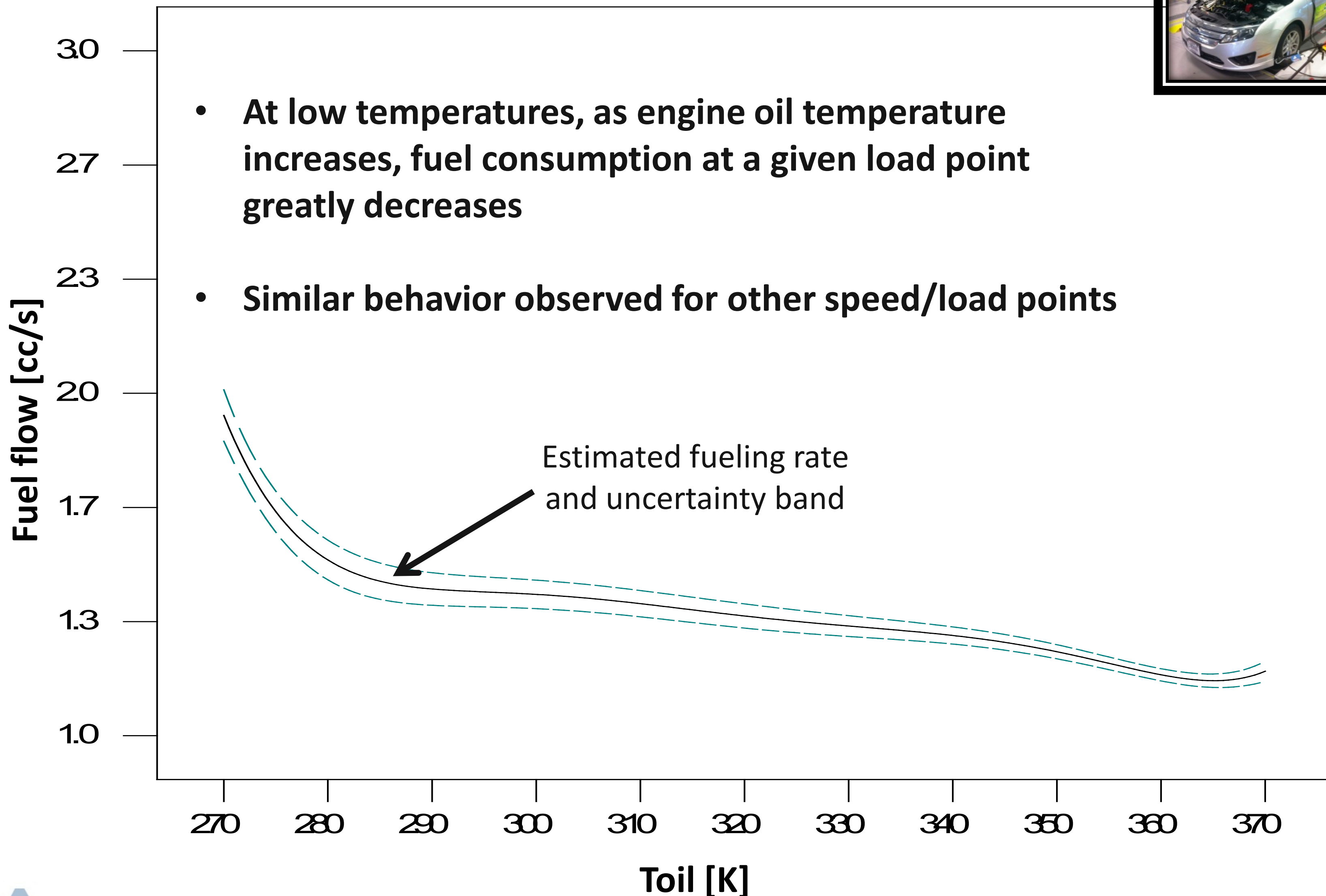
UDDS cycle: 2011 Ford Fusion

- **Fuel flow rate estimated as a function of RPM/load/oil temp.**
- **Excellent accuracy following catalyst light off period (Light-off ~70 seconds at -7^{o}C).**
- **Need to develop technique for improved start-up accuracy.**

Accomplishments: Preliminary Fueling Estimate Incorporates Temp. Effects

@10Nm, 1700RPM *2011 Ford Fusion*

- **At low temperatures, as engine oil temperature increases, fuel consumption at a given load point greatly decreases**
- **Similar behavior observed for other speed/load points**



Collaboration: Significant 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
- Cold/warm testing data collected at APRF

Argonne National Laboratory

Automonie
- Development of thermal capability in models

AUTONOMIE

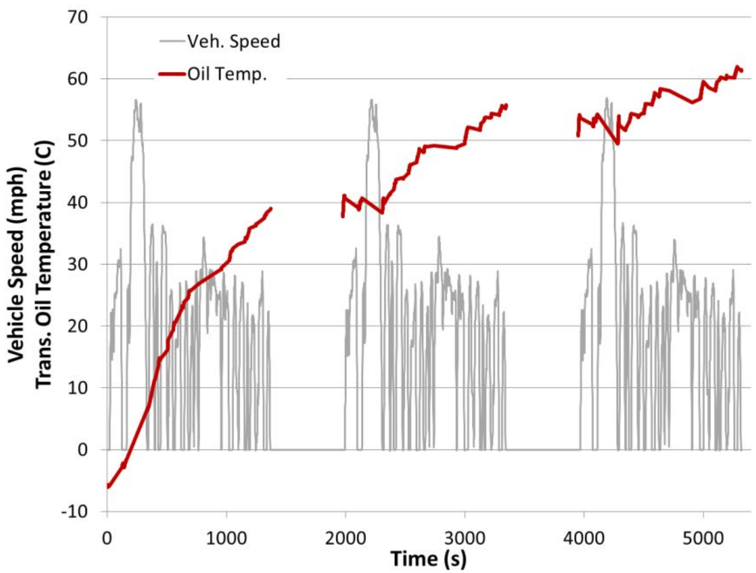
DOE technology evaluation
- Future collaborative potential with ORNL/NREL

NREL ornl Argonne

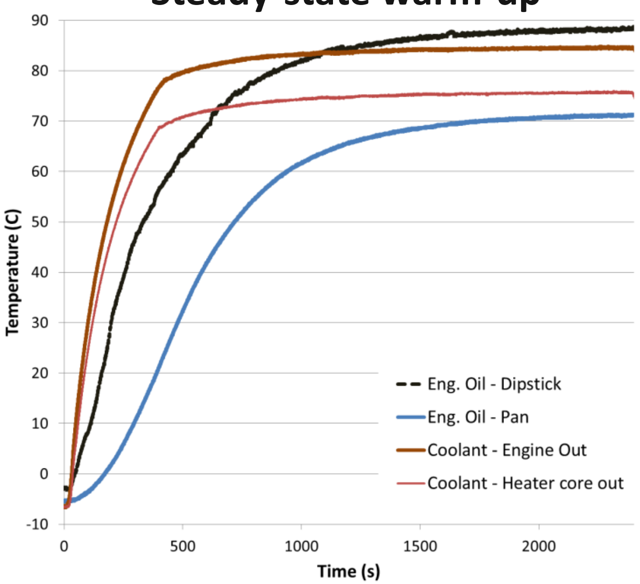
On-going / Future work

- **Preliminary assessment of transmission thermal sensitivity**
  - Automatic transmissions are typically sensitive to ATF viscosity and thus temperature
    - DCTs and synthetic ATF are ways to mitigate these issues, but what is the expected real-world benefit?
  - What are the warm-up characteristics for the transmission oil?
  - What are the relevant inputs in order to estimate transmission oil temperature?
- **Improved data collection methodology for temperature and efficiency estimation**
  - Utilizer conditioning cart for more independent evaluation of different fluids
  - Estimate impacts of heater-core as a major source of heat-loss during cold operation

Transmission Oil Temperature During Back-to-Back UDDSs @ 20F



Coolant and Oil Temperature During Steady-state warm-up



On-going/Future work

- **Improve procedure/techniques for fueling/temperature estimates**
  - Response surface models versus more physical estimates (or a hybrid of both)
- **Define potential for engineered solutions to reduce real world fuel consumption**
  - Utilize thermal sensitivity estimates to focus on effective use of recovered energy
- **Incorporate creature comfort features into modeling effort (NREL)**
- **Incorporate catalyst light off features into modeling effort (ORNL)**
- **Ensure robustness with additional vehicle testing leveraging APRF thermal capability upgrade**
  - Leverage Level-2 research vehicles with exhaust heat recovery to confirm sensitivity analysis and temperature estimation techniques

Prius: Exhaust to Coolant

APRF Thermal Capability

Sonata: Exhaust to Trans. Oil

Summary

- **Vehicle testing procedures do not reflect the full range of ambient conditions**
  - Real-world fuel economy may be overstated due to ambient temperature
  - Methodology developed to predict real seasonal fuel consumption in HEV's
  - Opportunities exist for exhaust heat recovery and other mitigation strategies

- **Refined techniques shown to be representative of experimental data**
  - Response surface fueling rate modeling technique finalized
  - Lumped capacitance temperature modeling technique developed
  - Improved data collection through a mix of steady-state and drive cycle operation Model vs. experimental fuel consumption data within a few %

- **Results demonstrate significant engineering opportunities to reduce petroleum consumption though improved vehicle warm-up and loss mitigation**

- **Further work needs to be complete to assess how much efficiency can be gained and the most effective pathways**