SIMULATED REAL-WORLD ENERGY IMPACTS OF A THERMALLY SENSITIVE POWERTRAIN CONSIDERING VISCOUS LOSSES AND ENRICHMENT

Eric Wood, Jeffrey Gonder, Sean Lopp
National Renewable Energy Laboratory

Forrest Jehlik
Argonne National Laboratory

SAE Thermal Management Systems Symposium
Sept 23, 2014 – Denver, Colorado

NREL/PR-5400-62443
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Your MPG Will Vary…

- **Several factors influence fuel economy, including:**
  - Drive cycle (speed, acceleration, idle time)
  - Road grade
  - Vehicle thermal state (hot start vs. cold start)
  - Ambient conditions
  - Cabin HVAC loads
- **This effort seeks to improve understanding of real-world fuel economy by combining large datasets of operating conditions with high fidelity vehicle models supported by comprehensive test data to:**
  - Improve public understanding of fuel economy variation
  - Inform industry testing procedures
  - Identify avenues for OEMs to improve real-world MPG (and earn credit!)

HVAC = heating, ventilation, and air conditioning
OEM = original equipment manufacturer
MPG = miles per gallon

Outline

- **Present dynamometer data from 2011 Ford Fusion tested at Argonne National Laboratory's (ANL's) Advanced Powertrain Research Facility (APRF)**
- **Propose system of equations to describe internal combustion engine (ICE) efficiency relative to thermal state and document goodness of fit**
- **Describe interface between ICE models and NREL's High Performance Computing Environment for drive cycle simulation**
- **Discuss simulated fuel economy sensitivity to drive cycle, thermal state, and ambient conditions**
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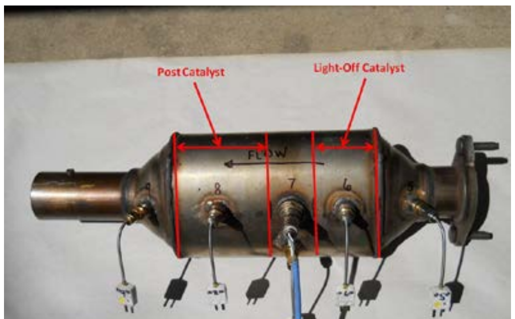
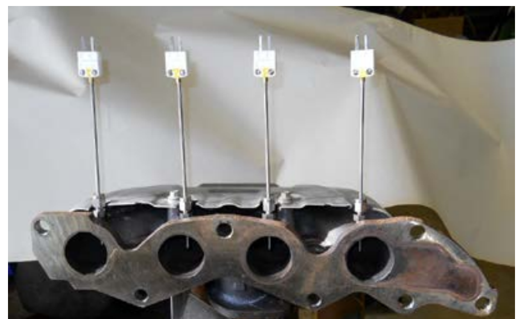
ANL APRF & Vehicle Instrumentation

- **2011 Ford Fusion Thermal Evaluation Vehicle**
  - Four-cylinder, six-speed transmission representative of a modern mid-size vehicle
  - More than 27 thermal channels of data (engine oil, transmission oil, engine coolant, cabin temperatures)

Photos Credit: Forrest Jehlik



Catalyst Temperatures

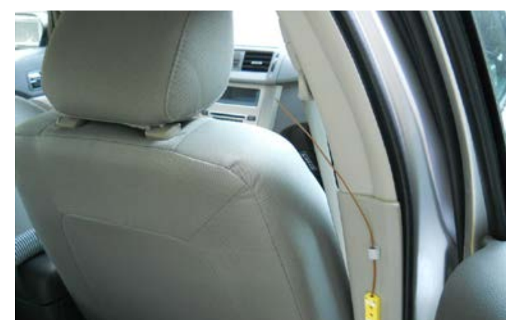


Exhaust Runner Temp

Post-cat. Exhaust Temp

Coolant Flows

Coolant Temperatures



Cabin Temperatures

Fusion Test Matrix

Test matrix designed to cover representative range of drive-cycle conditions, ICE thermal states, and ambient temperatures

Expect wide range of test conditions to provide best and worst case ICE viscosity and enrichment responses

*Enrichment used here to denote incremental fuel rate increase to accelerate catalyst heating in the exhaust line on startup

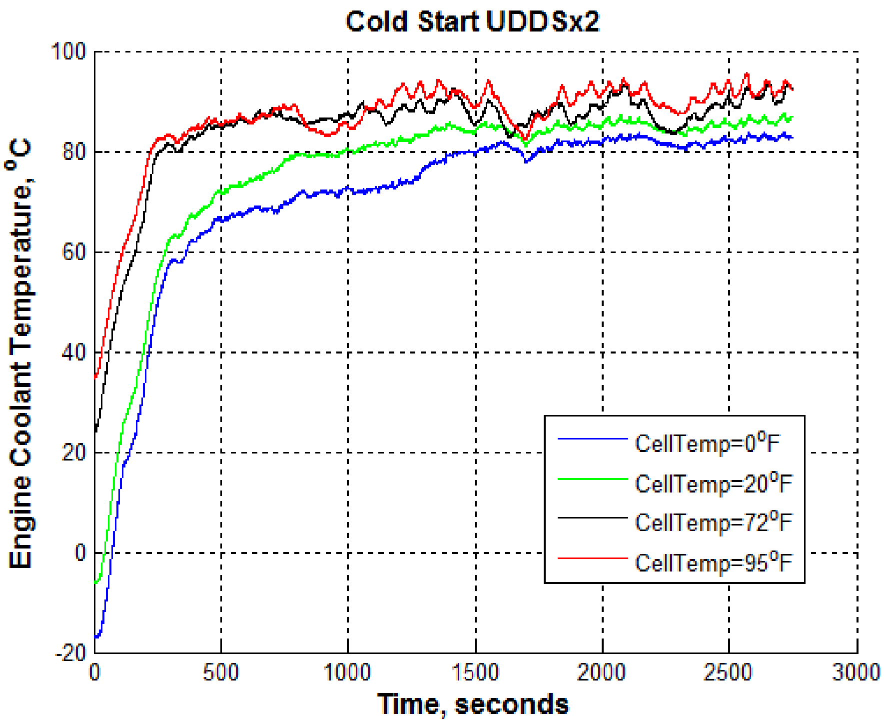
16 tests in total

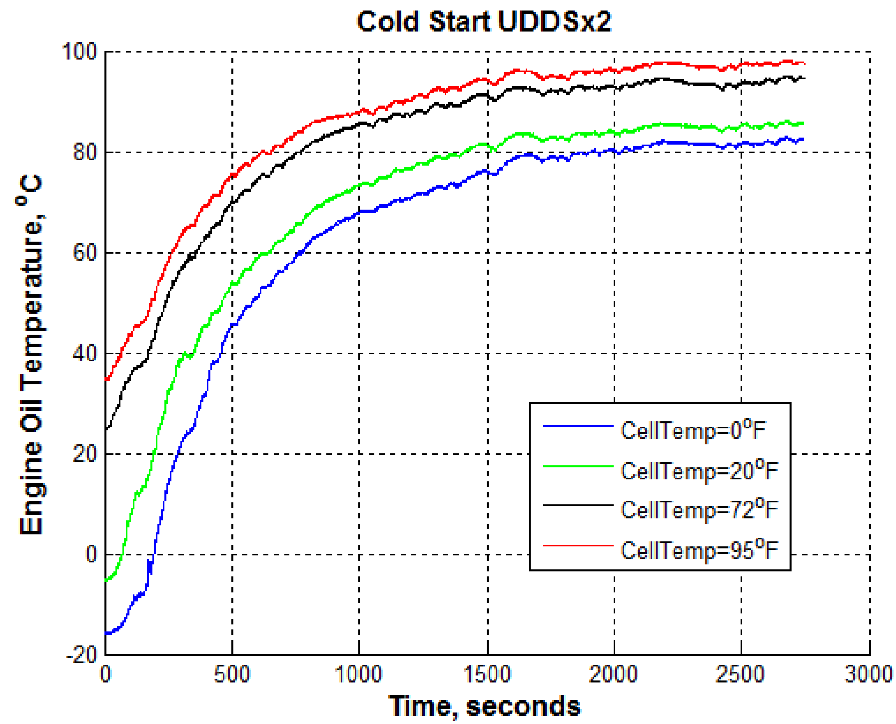
Variable	Values
Drive Cycle	UDDSx2, US06x2
Start Condition	Hot Start, Cold Start
Test Cell Temperature	0°F, 20°F, 72°F, 95°F

Credit: Forrest Jehlik

Fusion Test Data

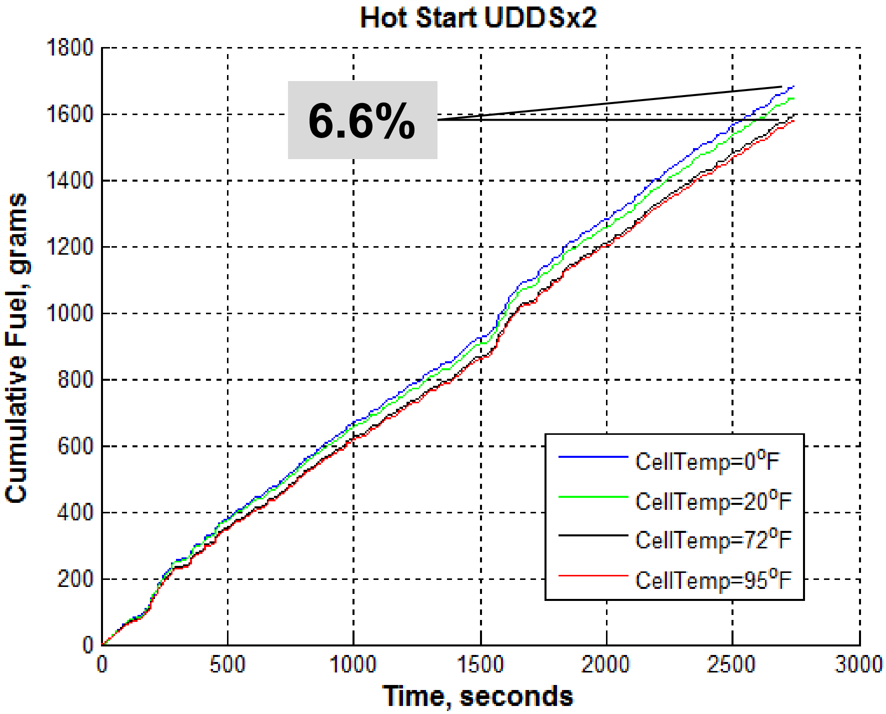
- Thermal response of engine coolant and engine oil is presented for cold-start Urban Dynamometer Driving Schedule (UDDS) cycles over a sweep of ambient conditions
- Oil response lags coolant with both fluids reaching steady-state temperatures that are dependent on ambient conditions

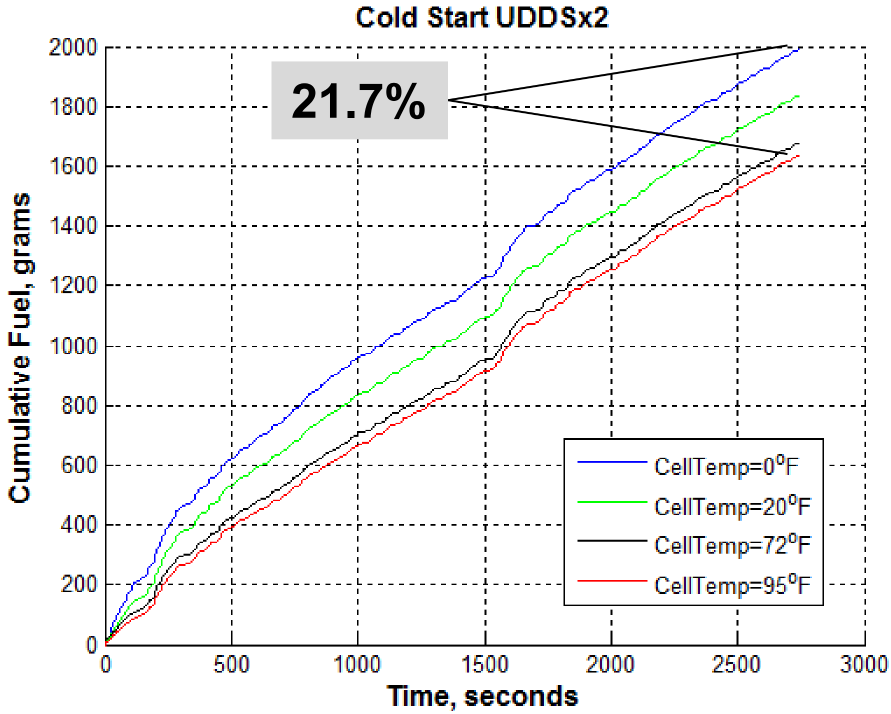




Fusion Test Data

- Powertrain thermal state significantly impacts fuel consumption with both hot- and cold-start cycles experiencing penalties relative to hot ambient conditions
- The real-world impact of cold starts and cold operating conditions is highly drive-cycle and climate dependent





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ICE Thermal Model: System of Equations

Sub-Model	Governing Equation	Supporting Equations
Engine Efficiency	$fuel = f_1(P_{out}, T_{oil}) + f_2(T_{cat})$ $f_1(P_{out}, T_{oil}) = a_0 + a_{1,1}{P_{out}}^3 + a_{1,2}{P_{out}}^2 + a_{1,3}P_{out} + a_{2,1}{dT_{oil}}^3 + a_{2,2}{dT_{oil}}^2 + a_{2,3}dT_{oil} + a_{3,1}{P_{out}}^3{dT_{oil}}^3 + a_{3,2}{P_{out}}^2{dT_{oil}}^2 + a_{3,3}P_{out}dT_{oil}$ $f_2(T_{cat}) = \max(0, a_1 * (e^{a_2*(T_{cat}-a_3)} - 1))$	$dT_{oil} = T_0 - T_{oil}$
Catalyst Temperature	$\dot{T}_{cat} = \frac{h(T_{amb} - T_{cat}) + \alpha(P_{out} - P_{in})}{m_{cat}}$	$h = a_{h1}v_{veh} + a_{h2}$ $\alpha = a_{\alpha 1}T_{cat} + a_{\alpha 2}$
Oil Temperature	$\dot{T}_{oil} = \frac{h_1(T_{amb} - T_{oil}) + h_2(T_{cool} - T_{oil}) + \alpha(P_{out} - P_{in})}{m_{oil}}$	$h_1 = a_1 v_{veh} + a_2$
Coolant Temperature	$\dot{T}_{cool} = \frac{h_1(T_{amb} - T_{cool}) + h_2(T_{oil} - T_{cool}) + \alpha(P_{out} - P_{in})}{m_{cool}}$	$if\ T_{cool} < T_{set}:$ $h_1 = a_1 v_{veh} + a_2$ $else:$ $h_1 = a_3 v_{veh} + a_4$

System of equations developed to capture primary system dynamics

ICE Thermal Model: System of Equations

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Catalyst Temperature	$\dot{T}_{cat} = \frac{h(T_{amb} - T_{cat}) + \alpha(P_{out} - P_{in})}{m_{cat}}$	$h = a_{h1} v_{veh} + a_{h2}$ $\alpha = a_{\alpha 1} T_{cat} + a_{\alpha 2}$
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Engine Efficiency Model

Model Structure

$$fuel = f_1(P_{out}, T_{oil}) + f_2(T_{cat})$$

$$f_1(P_{out}, T_{oil}) = a_0 + a_{1,1}{P_{out}}^3 + a_{1,2}{P_{out}}^2 + a_{1,3}P_{out} + a_{2,1}{dT_{oil}}^3 + a_{2,2}{dT_{oil}}^2 + a_{2,3}dT_{oil} + a_{3,1}{P_{out}}^3{dT_{oil}}^3 + a_{3,2}{P_{out}}^2{dT_{oil}}^2 + a_{3,3}P_{out}dT_{oil}$$

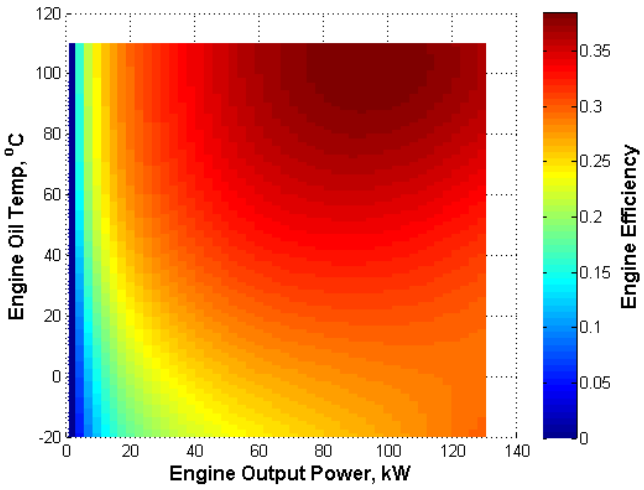
$$f_2(T_{cat}) = \max(0, a_1 * (e^{a_2*(T_{cat}-a_3)} - 1))$$

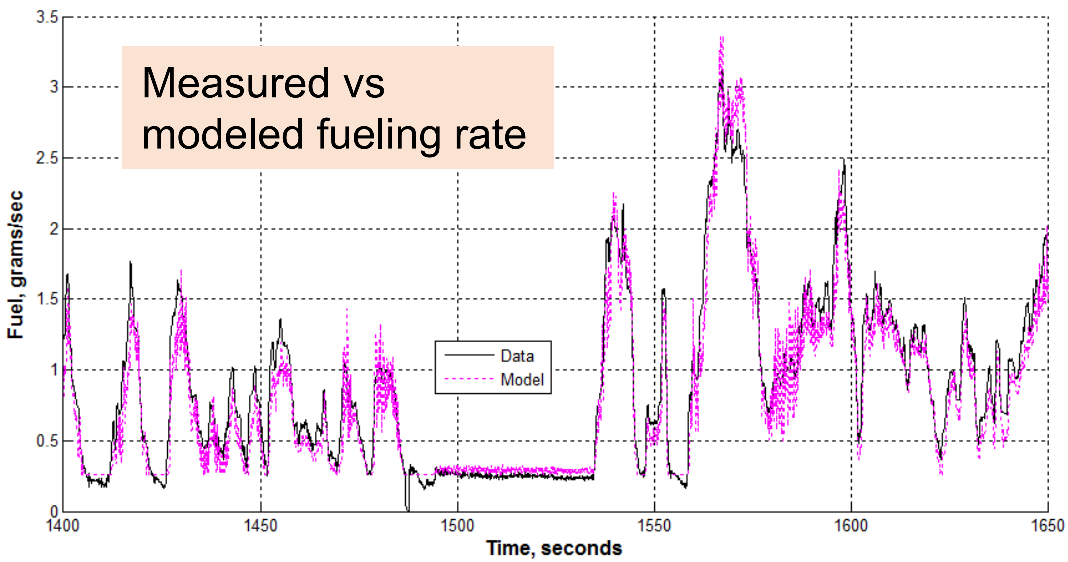
$$dT_{oil} = T_0 - T_{oil}$$

Goodness of fit statistics

(predictive accuracy of model to be evaluated relative to 5 cycle test data by end of FY14)

Cumulative Fuel Error				
	UDDS		US06	
Ambient Temp	Cold Start	Hot Start	Cold Start	Hot Start
0F	-3.9%	1.5%	-5.0%	2.5%
20F	0.5%	1.9%	2.5%	5.2%
72F	-1.7%	-1.3%	-0.5%	-0.9%
95F	-4.1%	-2.0%	-0.5%	-2.8%





Catalyst Thermal Model

Model Structure

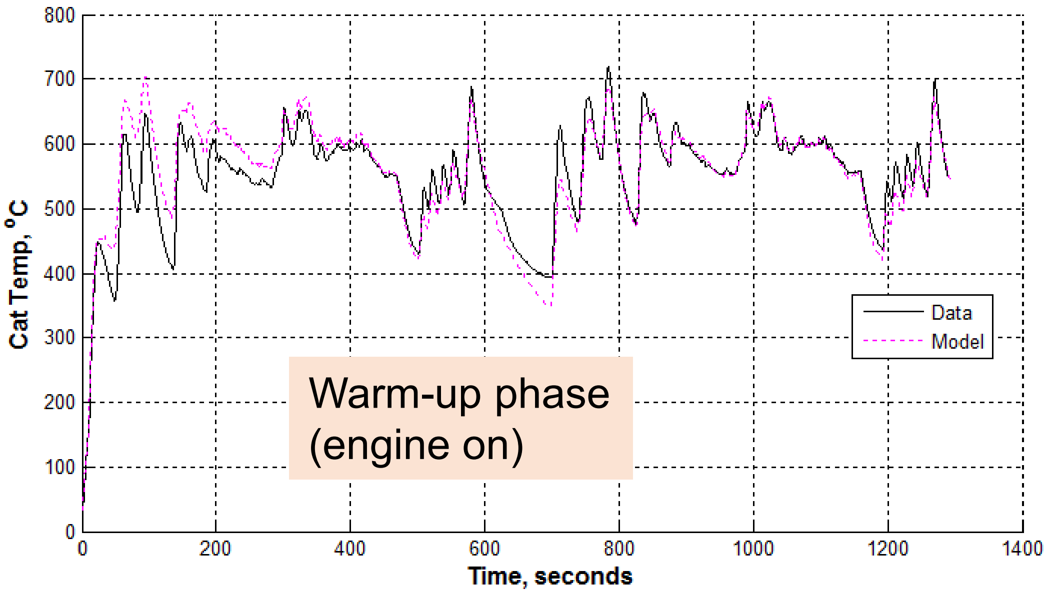
$$\dot{T}_{cat} = \frac{h(T_{amb} - T_{cat}) + \alpha(P_{out} - P_{in})}{m_{cat}}$$

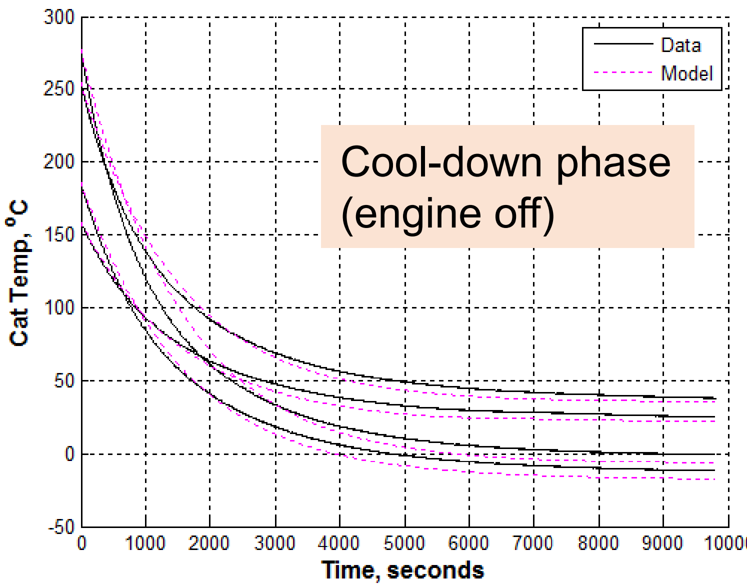
$$h = a_{h1} v_{veh} + a_{h2} \qquad \alpha = a_{\alpha 1} T_{cat} + a_{\alpha 2}$$

Goodness of fit statistics

(predictive accuracy of model to be evaluated relative to 5 cycle test data by end of FY14)

Instantaneous RMS Error (deg C)				
	UDDS		US06	
Ambient Temp	Cold Start	Hot Start	Cold Start	Hot Start
0F	69.5	26.9	70.3	24.4
20F	54.5	24.8	53.5	23.6
72F	37.5	19.8	50.1	24.6
95F	34.6	20.0	38.4	24.6





Oil Thermal Model

Model Structure

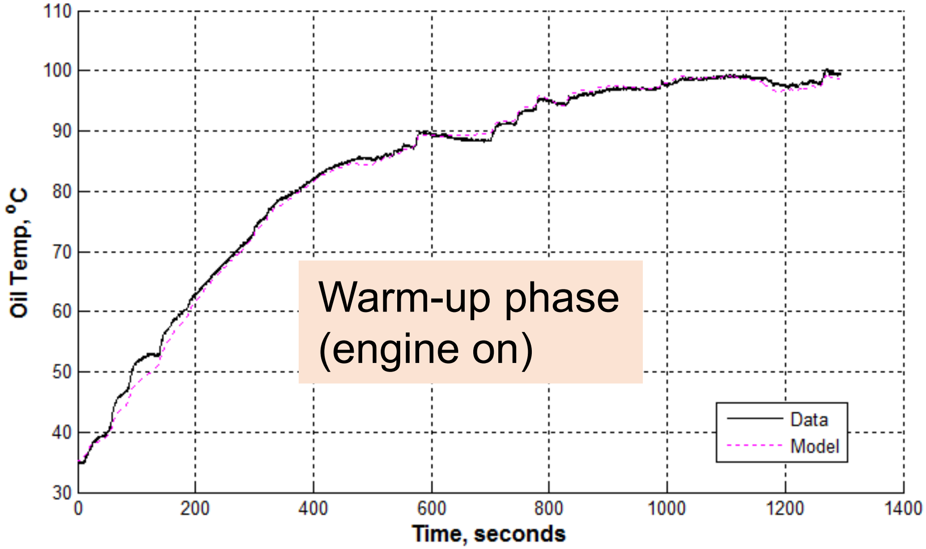
$$\dot{T}_{oil} = \frac{h_1(T_{amb} - T_{oil}) + h_2(T_{cool} - T_{oil}) + \alpha(P_{out} - P_{in})}{m_{oil}}$$

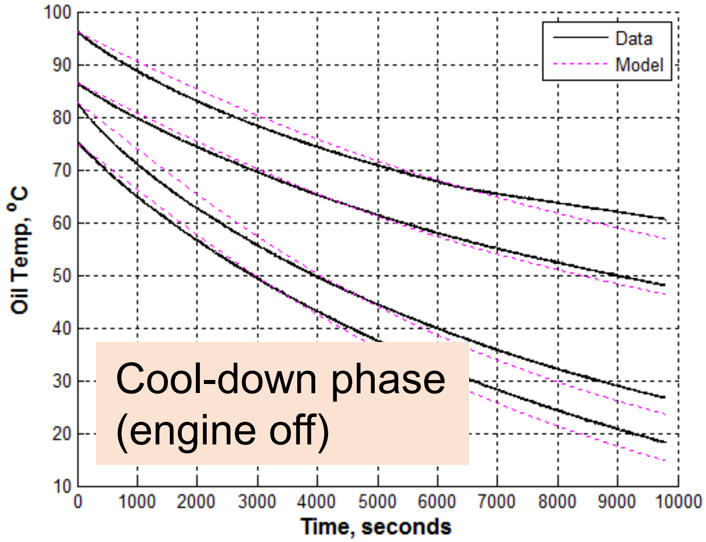
$$h_1 = a_1 v_{veh} + a_2$$

Goodness of fit statistics

(predictive accuracy of model to be evaluated relative to 5 cycle test data by end of FY14)

Instantaneous RMS Error (deg C)				
	UDDS		US06	
Ambient Temp	Cold Start	Hot Start	Cold Start	Hot Start
0F	5.2	7.2	5.4	2.0
20F	4.9	4.1	5.5	1.9
72F	5.7	6.1	8.5	2.5
95F	6.3	8.1	6.7	4.6





Coolant Thermal Model

Model Structure

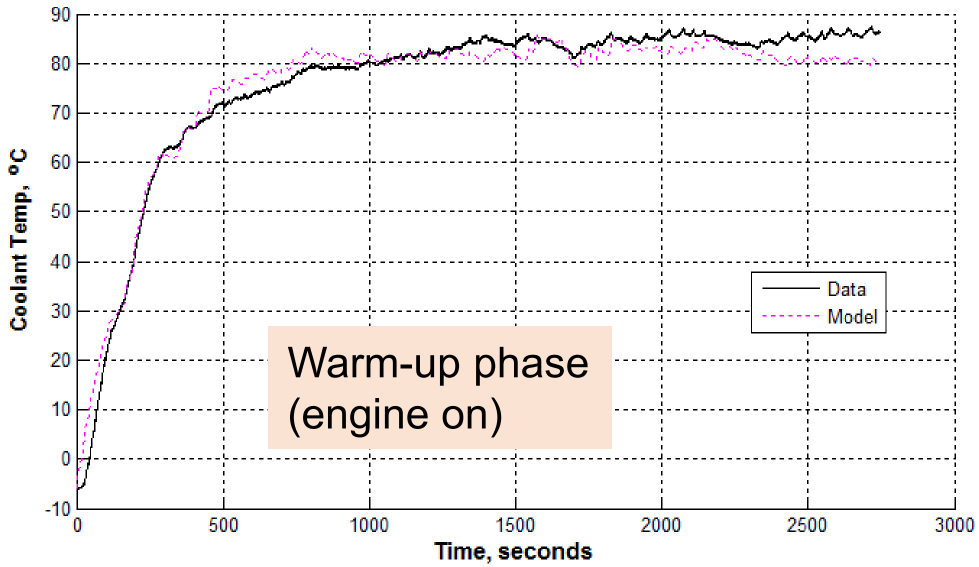
$$\dot{T}_{cool} = \frac{h_1(T_{amb} - T_{cool}) + h_2(T_{oil} - T_{cool}) + \alpha(P_{out} - P_{in})}{m_{cool}}$$

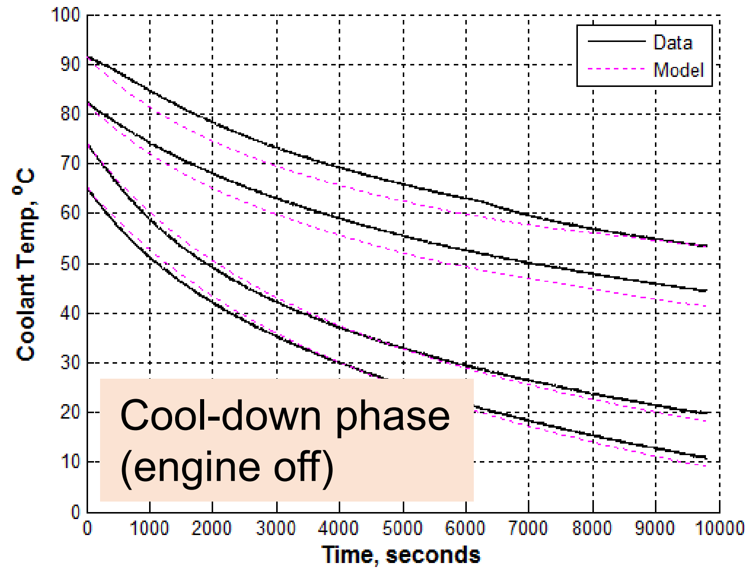
$$
\begin{aligned}
&if\ T_{cool} < T_{set}: \\
&\quad h_1 = a_1 v_{veh} + a_2 \\
&else: \\
&\quad h_1 = a_3 v_{veh} + a_4
\end{aligned}
$$

Goodness of fit statistics

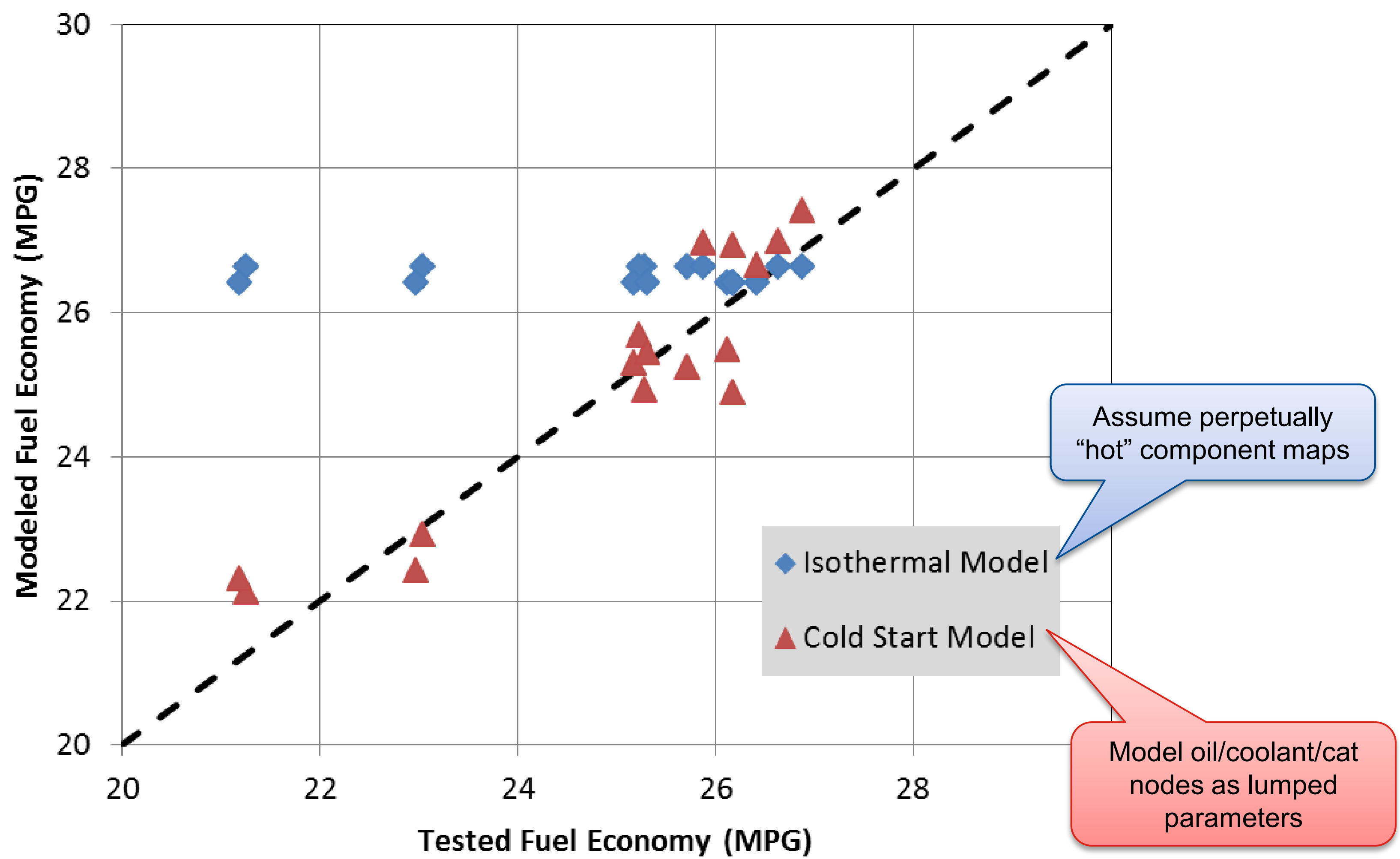
(predictive accuracy of model to be evaluated relative to 5 cycle test data by end of FY14)

Instantaneous RMS Error (deg C)				
	UDDS		US06	
Ambient Temp	Cold Start	Hot Start	Cold Start	Hot Start
0F	7.0	9.2	7.4	3.9
20F	5.1	5.4	6.9	3.3
72F	6.8	4.3	12.5	5.9
95F	6.5	6.0	10.9	9.1





Model Error for All 16 Test Cycles



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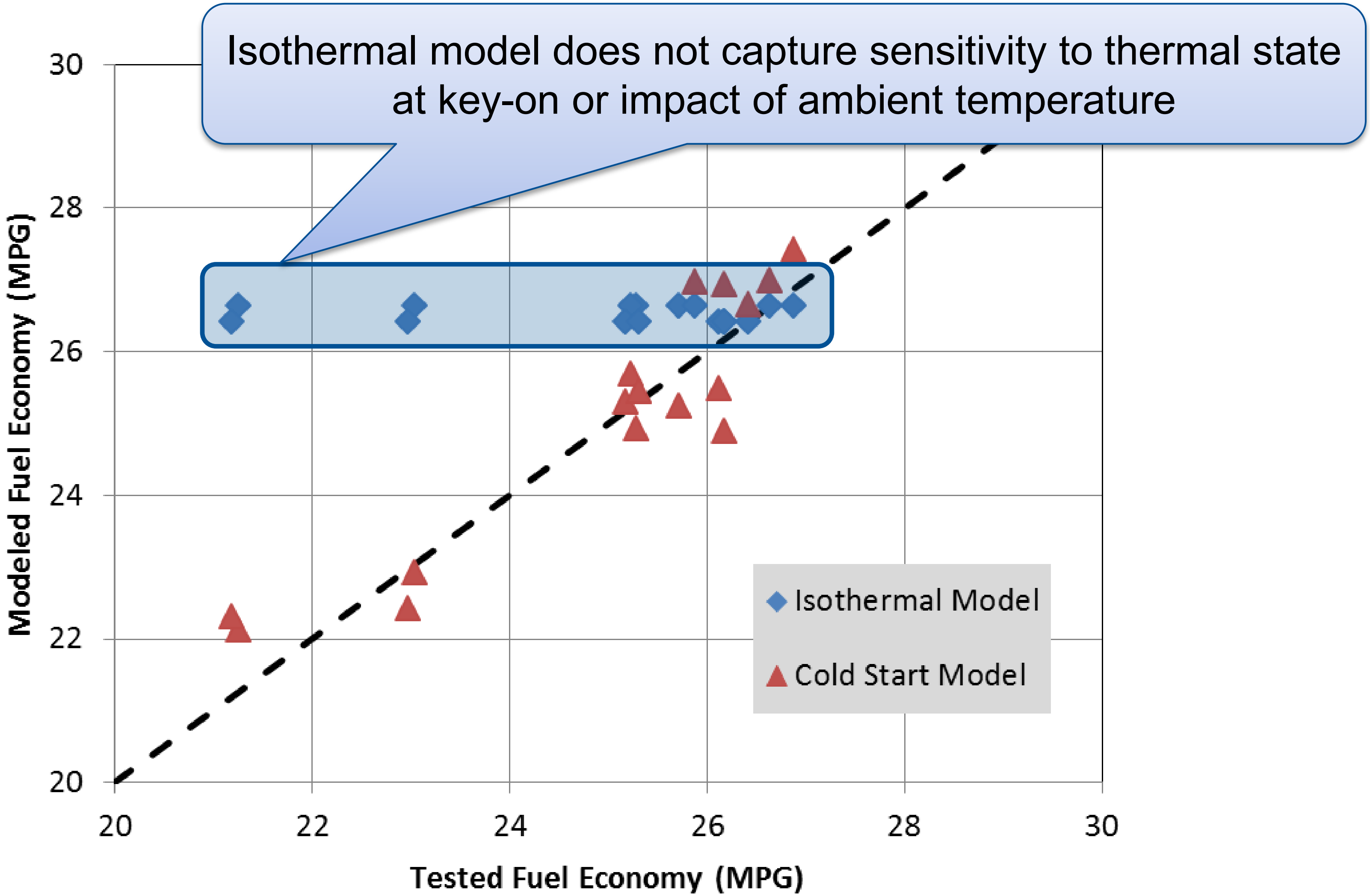
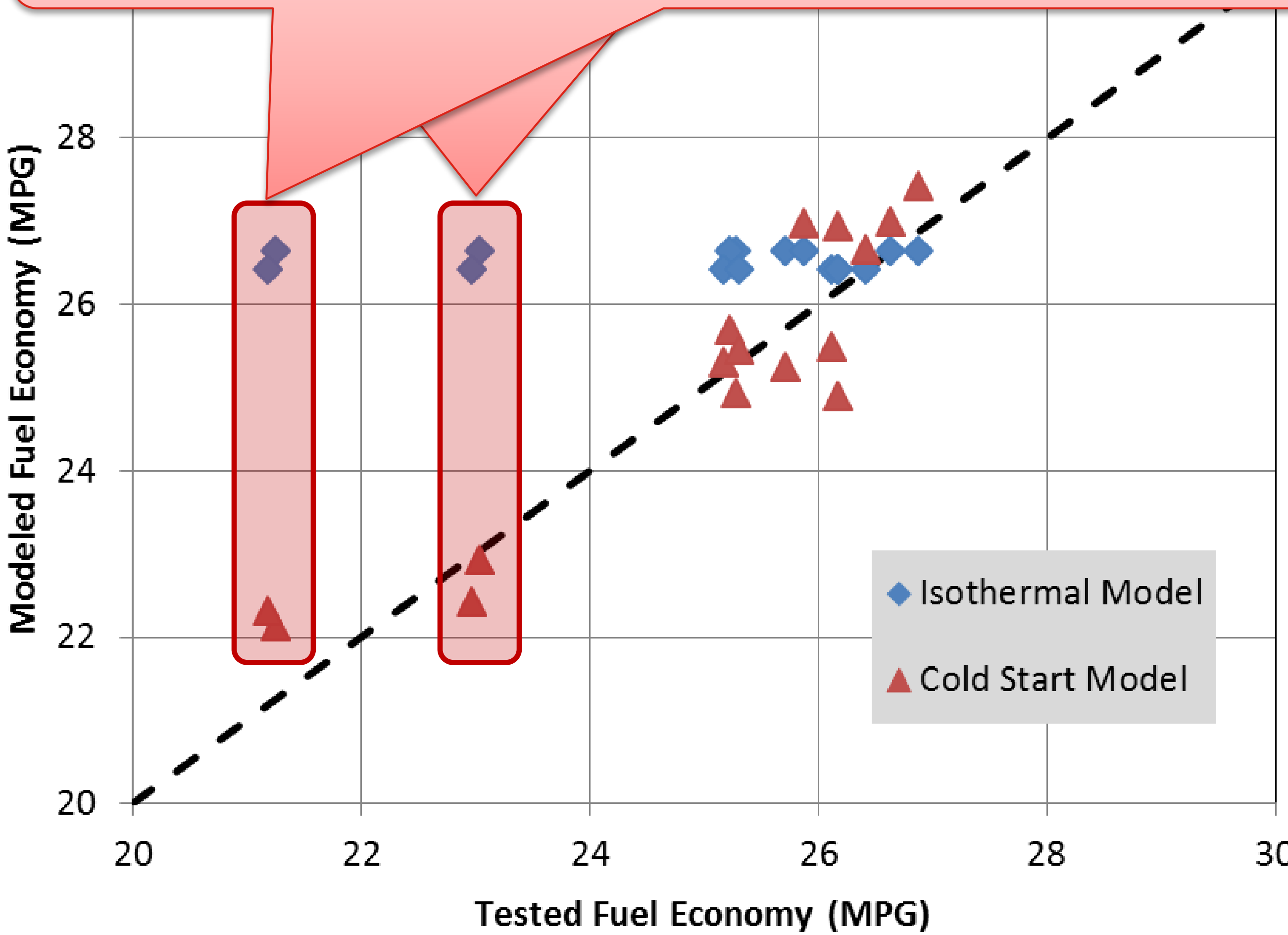


Model Error for All 16 Test Cycles

Model error is significantly reduced (especially under cold start conditions) by incorporating simple lumped capacitance thermal models



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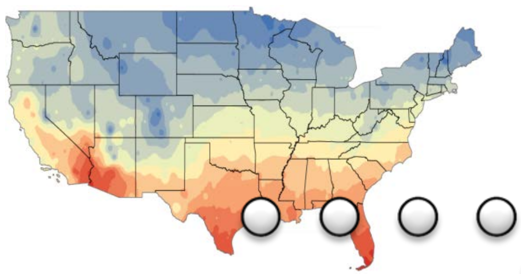
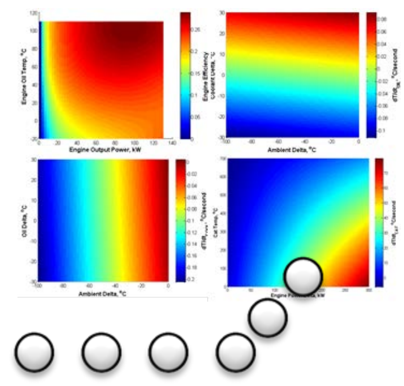
Modeling Environment

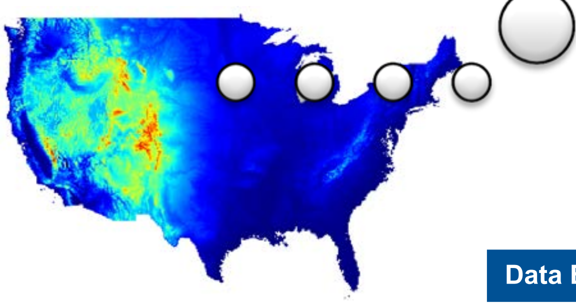
Exercise calibrated models over a large sweep of usage conditions to evaluate the interplay between travel time, driving behavior, ambient temperature, road grade, and ICE thermal response



Transportation
Secure Data Center

ICE Thermal Model

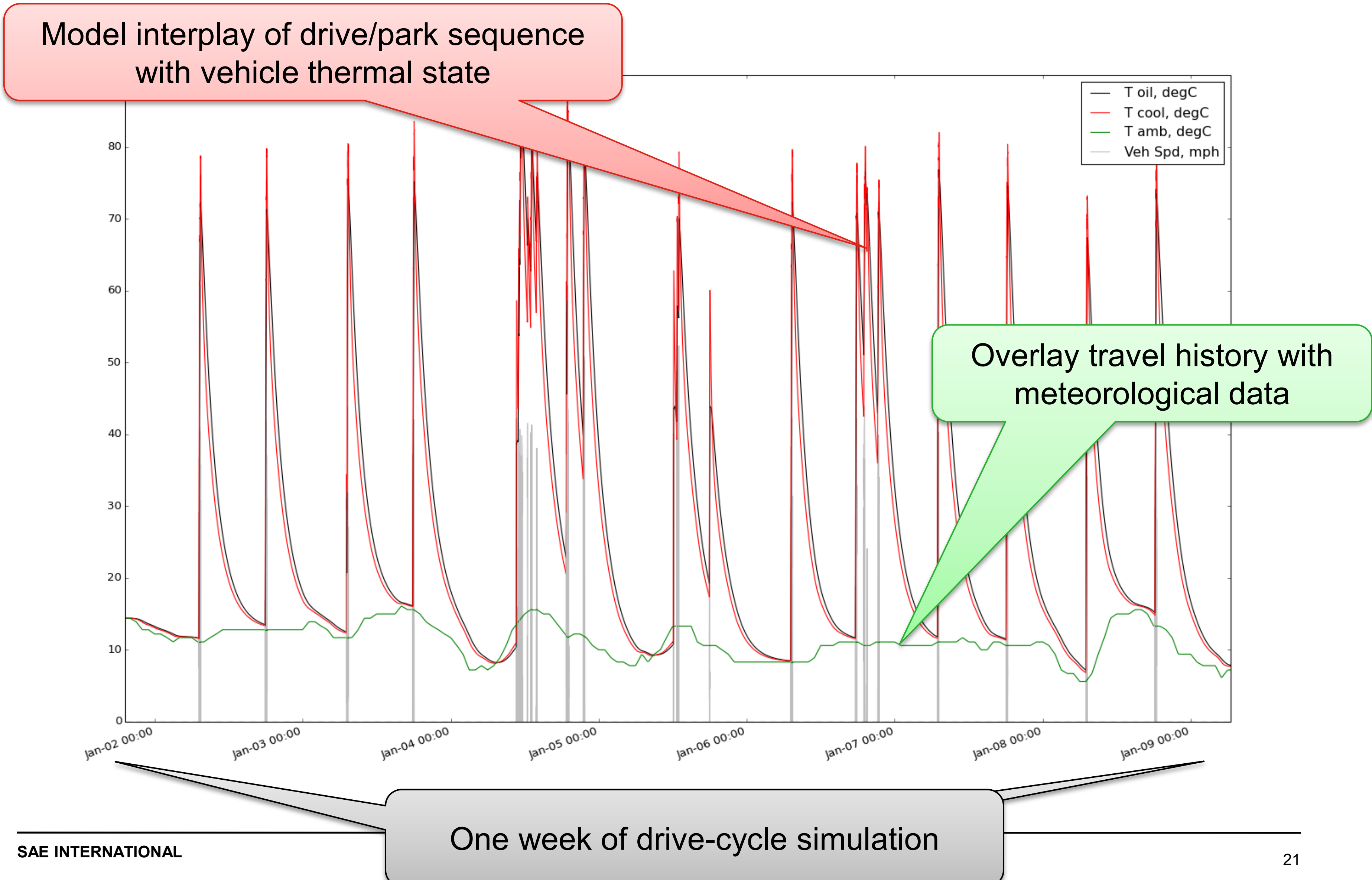




Data Element	Source	Notes
Drive Cycles/ Trip Distributions	NREL Transportation Secure Data Center	The TSDC houses hundreds of thousands of real-world drive cycles from vehicles across the country.
Climate Data	NREL National Solar Radiation Database	Home to TMYs from hundreds of U.S. locations, each containing 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.

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

Apply Model to Drive Cycle and Climate Data



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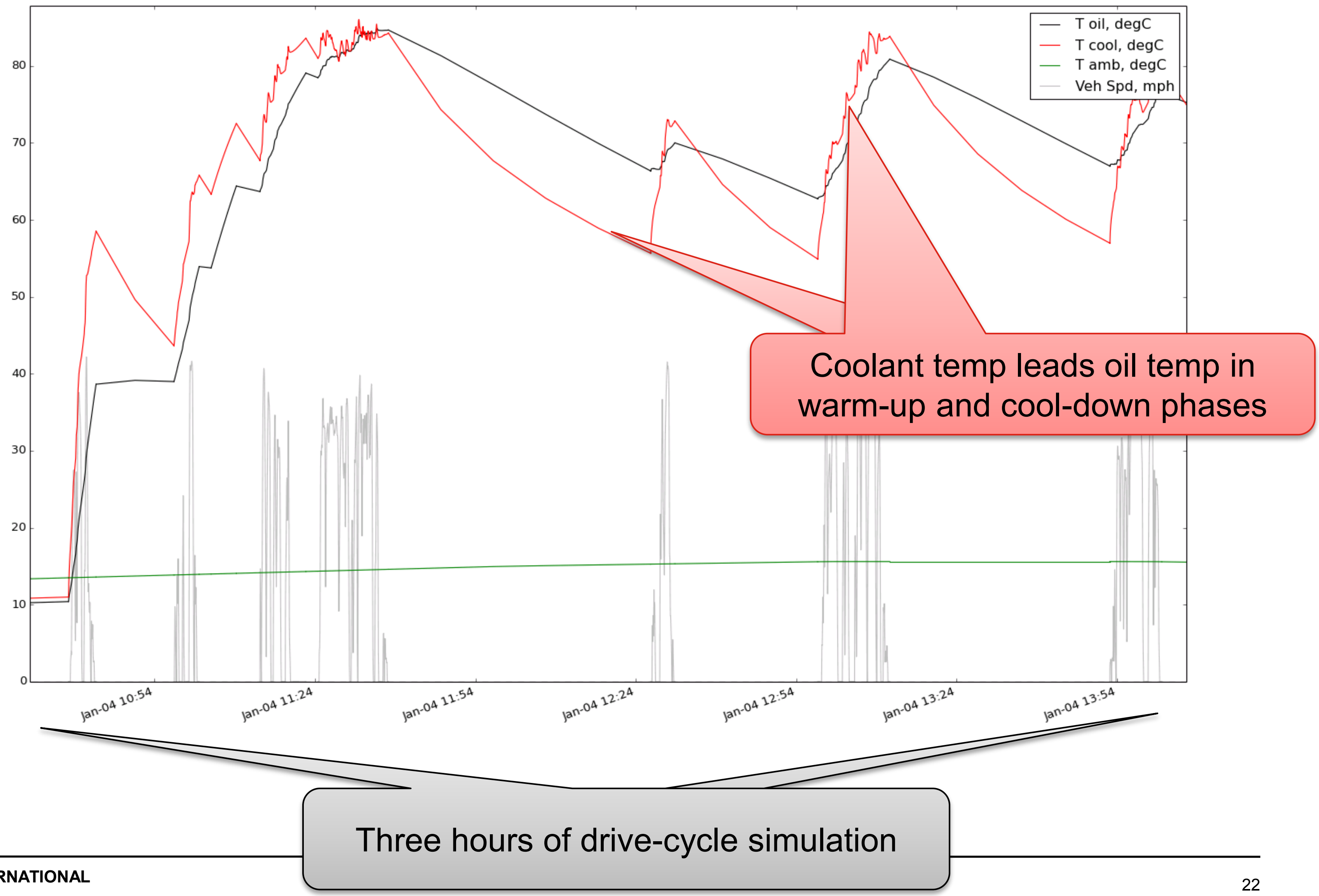

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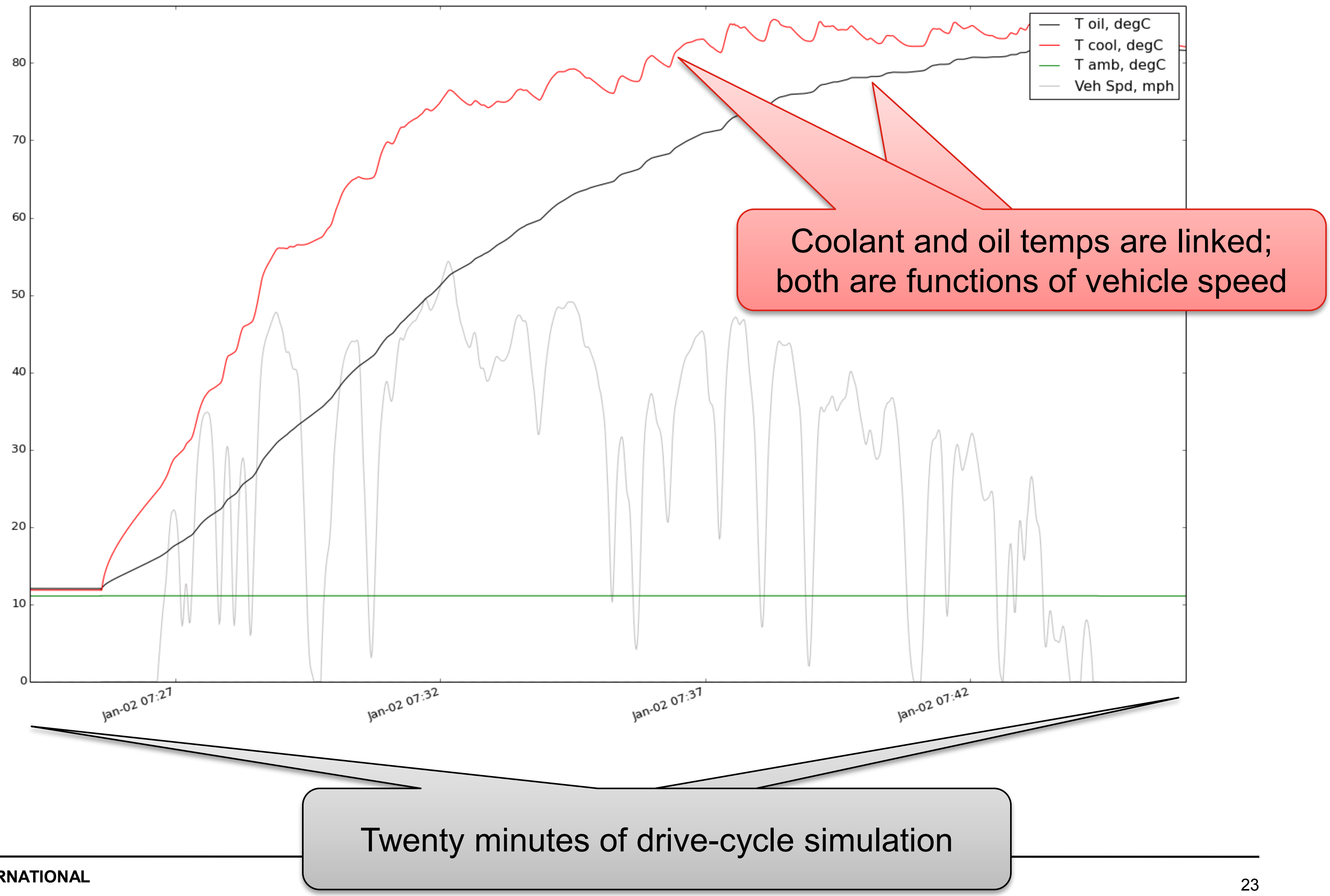

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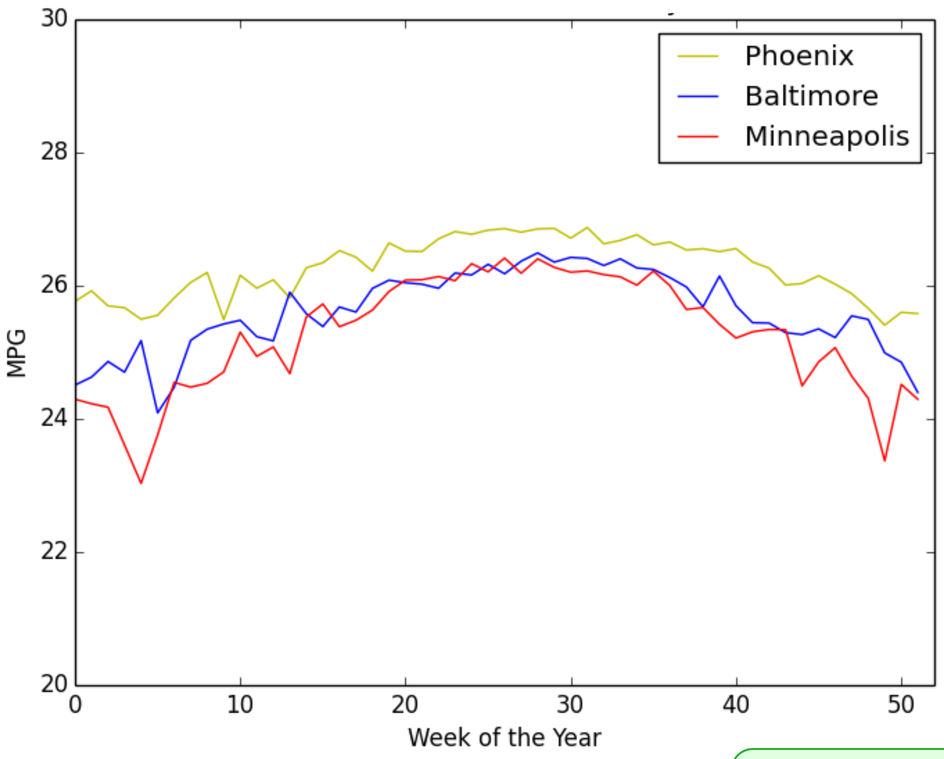
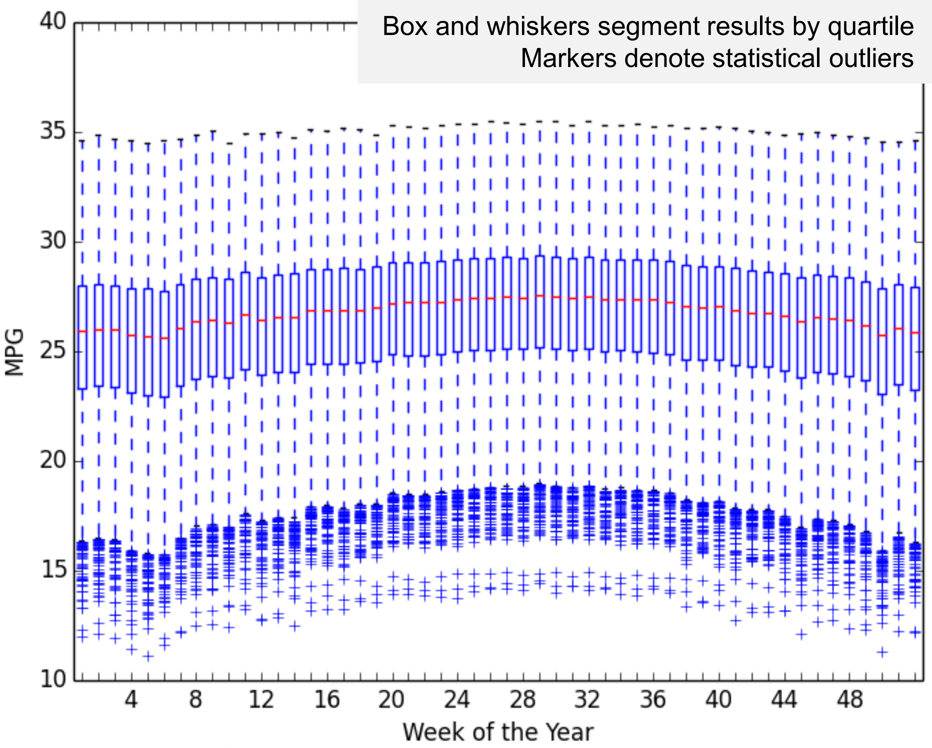
Simulation Results

Simulated fuel economy by climate data and week of year

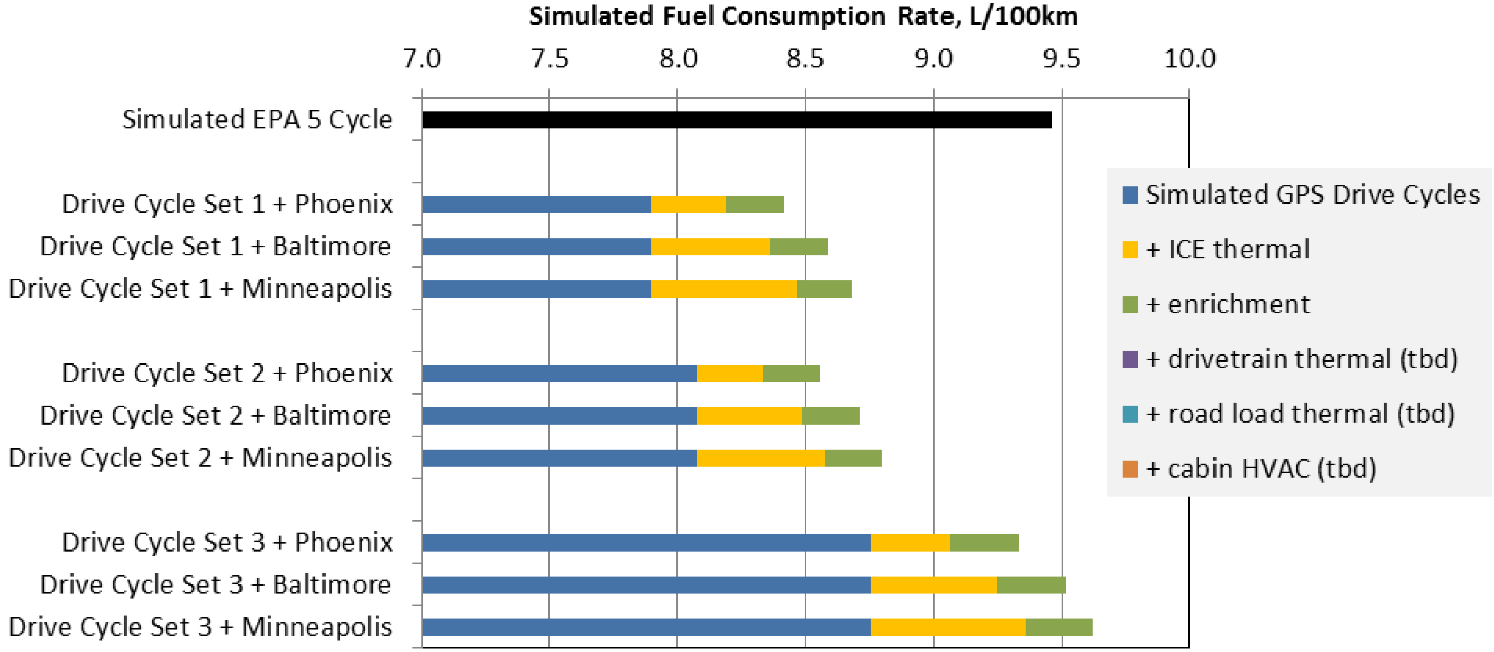


Simulated fuel economy by drive-cycle data and week of year



39M miles of simulated driving in each plot

Simulation Results



- **Aggregate fuel consumption rates reported for hundreds of week-long vehicle histories simulated over matrix of representative drive cycle sets and climates**
- **Engine thermal effects accounted for 4.8% of total simulated fuel consumption**
- **Enrichment effects accounted for 2.7% of total simulated fuel consumption**
- **Results slightly under-predict fuel consumption relative to simulated and adjusted EPA 5-cycle test procedure (additional contributions to be added as future work)**

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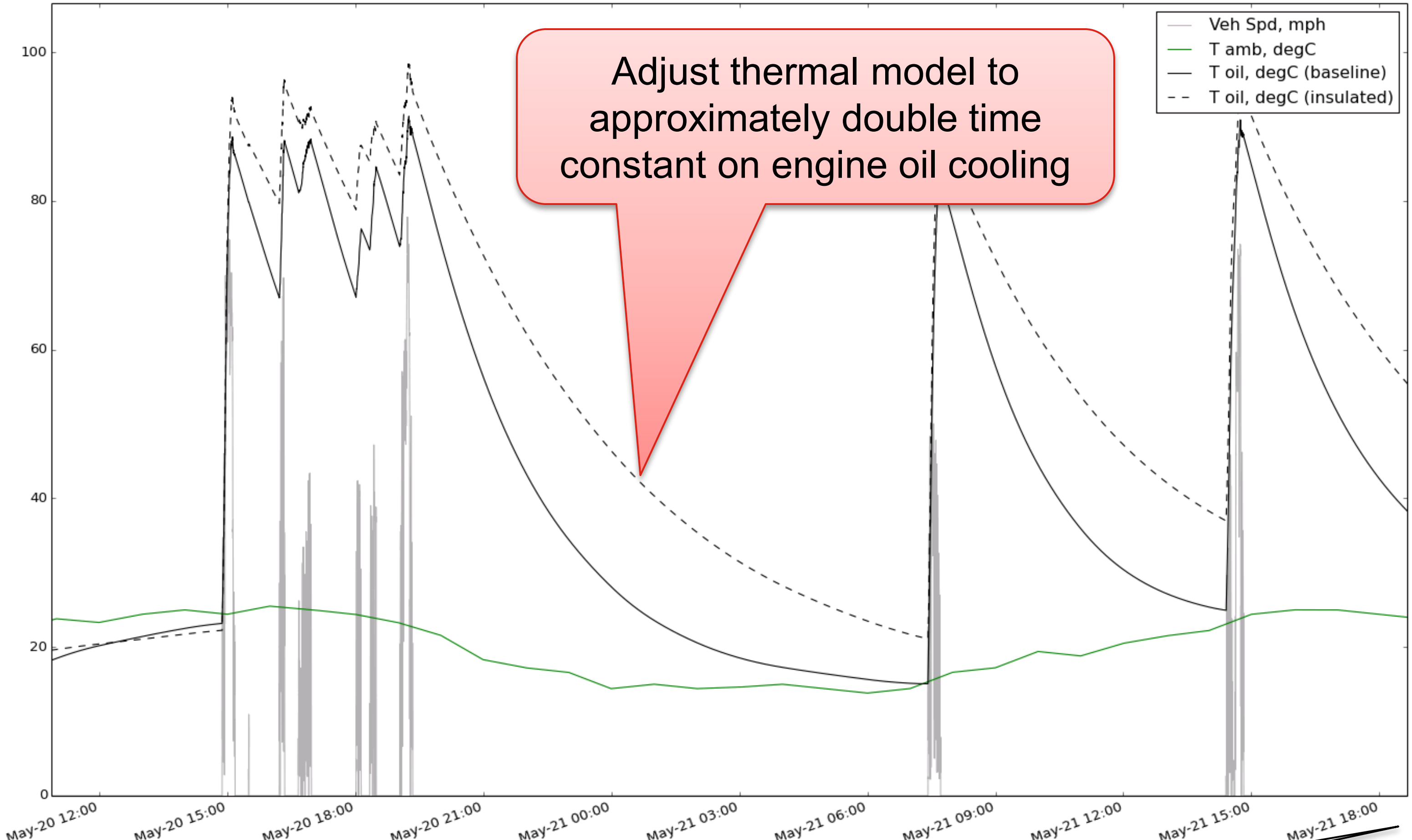
Insulate Engine Oil + Coolant



Adjust thermal model to approximately double time constant on engine oil cooling

Thirty hours of drive-cycle simulation

Insulate Engine Oil + Coolant

- **Insulated model compared to baseline under simulated EPA 5-cycle test procedure and large sweep of real-world drive cycles and climates**

- **Simulated 5-cycle test procedure netted 0.7% fuel economy improvement**
  - Byproduct of reduced warmup time during cold start tests (Federal Test Procedure (FTP) and cold FTP)

- **Simulated real-world cycles resulted in 2.0% average fuel economy improvement**
  - 5^{th} percentile vehicle history: 1.3% improvement
  - 95^{th} percentile vehicle history: 6.6% improvement
  - In addition to reduced warm-up times, real-world drive cycles benefit from higher temperatures at start of drive cycles (due to prolonged cool-down times)

Conclusions & Future Work

- **Preliminary results suggest that the real-world benefit of certain fuel efficiency technologies may differ from that reflected by 5-cycle test procedure**
  - Merging of large drive cycle and climate datasets with vehicle models trained on laboratory test data provides an improved understanding of real-world fuel economy

- **Future work will consider additional…**
  - Real-world effects (drivetrain efficiency at cold temperatures, sensitivity of road load to climate, and cabin HVAC energy requirements)
  - Vehicle models (hybrid electric vehicle, sport utility vehicle, full-size truck)
  - Fuel economy improvement strategies (further component insulation, exhaust heat recovery)

Acknowledgments

- **This work is funded by the DOE Vehicle Technologies Office**

- **We appreciate the support provided by our DOE program managers**
  - Lee Slezak
  - David Anderson

- **Technical questions regarding this work should be directed to Eric Wood at 303.275.3290 or eric.wood@nrel.gov**

Thanks! Questions?