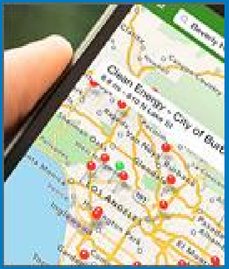
Analyzing Real-World Light Duty Vehicle Efficiency Benefits





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National Renewable Energy Laboratory
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Project ID VSS155

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

Overview

Timeline

- **Project start date:** 10/1/2014
- **Project end date:** 9/30/2016
- **Percent complete:** 70%

Budget

- **Total project funding (FY15-FY16):**
  - DOE share: $425k
  - Contractor share: NA
- (Also builds off of FY14 project on Internal Combustion Engine Energy Retention, and off of many years of work with real-world driving cycles)

Barriers

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

Partners

- Argonne National Laboratory: laboratory/field testing support
- USCAR OEMs: involvement through VSATT meetings and "vehicle usage parameter" working group
- NREL is lead for the analysis project

OEM = original equipment manufacturer
USCAR = U.S. Council for Automotive Research
VSATT = Vehicle Systems Analysis Technical Team

Objectives and Overall Relevance

- **Evaluate real-world fuel saving opportunities for technologies difficult to assess with standard certification cycles**
  - DOE and regulatory bodies want to maximize real-world fuel savings
  - Manufacturers want to get credit for actual fuel savings achieved
- **Strong interest shown by the "Quantifying Vehicle Usage Parameters" multi-lab/OEM workgroup; e.g. technologies:**
  - Engine encapsulation
  - Start/stop
  - High-efficiency alternators
  - High-efficiency lighting
  - Glazing technology
  - Connected vehicle applications

- **Build on existing DOE lab capabilities for objective evaluation of energy efficiency technologies**
- **Expand assessment using large datasets to capture real-world distributions of on-road operating conditions**
  - Drive cycles, road grade, ambient temperature, solar loads, national vehicle miles traveled (VMT)

Relevance for Addressing Barriers

- **Risk aversion**
  - NREL's role as a national laboratory makes it an ideal independent evaluator of real-world fuel savings
- **Lack of standardized test protocols**
  - Existing chassis dynamometer test procedures for window sticker fuel economy and CAFE compliance do not fully capture benefits of all technologies (e.g., start/stop, engine encapsulation, connected and automated vehicles)
- **Constant advances in technology**
  - Methodologies developed under this activity could be extended to future technology iterations and consideration for off-cycle credits

CAFE = Corporate Average Fuel Economy requirements

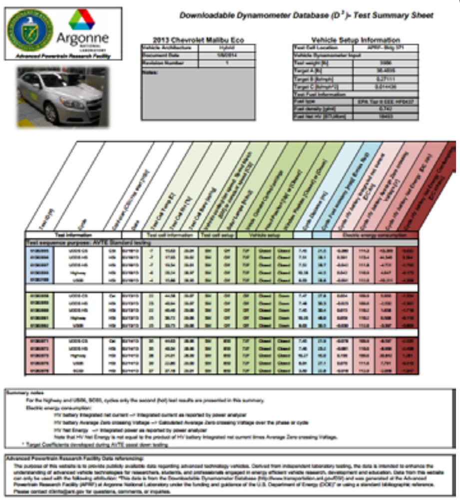
FY16 Milestones

Date	Description	Status (as of April 2016)
6/10/2015	2015 AMR Presentation on Project Status and Plan	Completed
8/30/2015	Summary Report to DOE on Prototyped Methodology for Aggregating Real-World Fuel Economy Impacts	Completed
10/14/2015	Present at VSATT Deep Dive Meeting	Completed
12/31/2015	Summary Report to DOE on On-Road Validation for Real-World Fuel Economy Modeling	Completed
4/6/2016	Present at VSATT Bi-Monthly Meeting	Completed
6/8/2016	2016 AMR Presentation on Project Accomplishments and Next Steps	On Track
6/10/2016	Summary Report to DOE Real-World Modeling Enhancements (in areas such as aggregation of road grade impacts, HVAC modeling, transmission and other driveline thermal impacts)	On Track
8/31/2016	Summary Report to DOE on Refined Procedure for Real-World/Off-Cycle Impact Calculations	On Track

HVAC = heating, ventilating and air conditioning

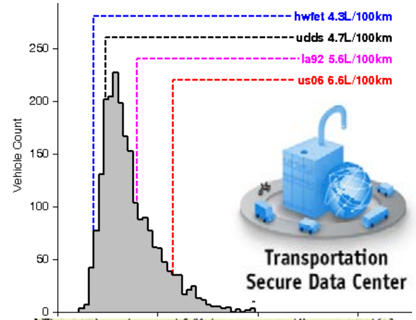
Approach: Testing- and Model-Based Evaluation

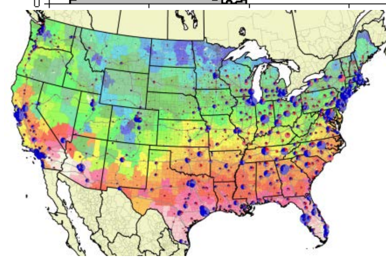
Hundreds of Miles of Laboratory Testing



Purpose: Generate “small” amount of data over comprehensive range of conditions in a controlled environment

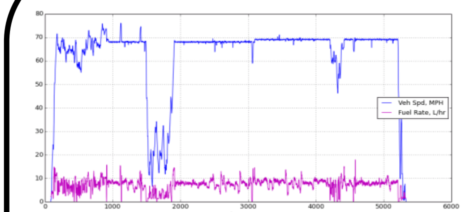
Millions of Miles of Simulated Driving

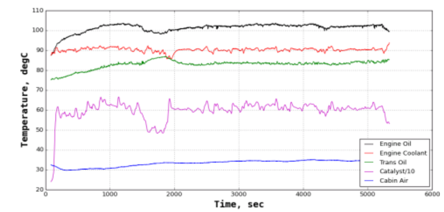




Purpose: Calibrate models to lab data; run over real-world combinations of drive cycles and climate; weight results to generate national average

Thousands of Miles of Real-World Evaluation





Purpose: Sanity check computer models against on-road data from uncontrolled environment

Argonne NATIONAL LABORATORY

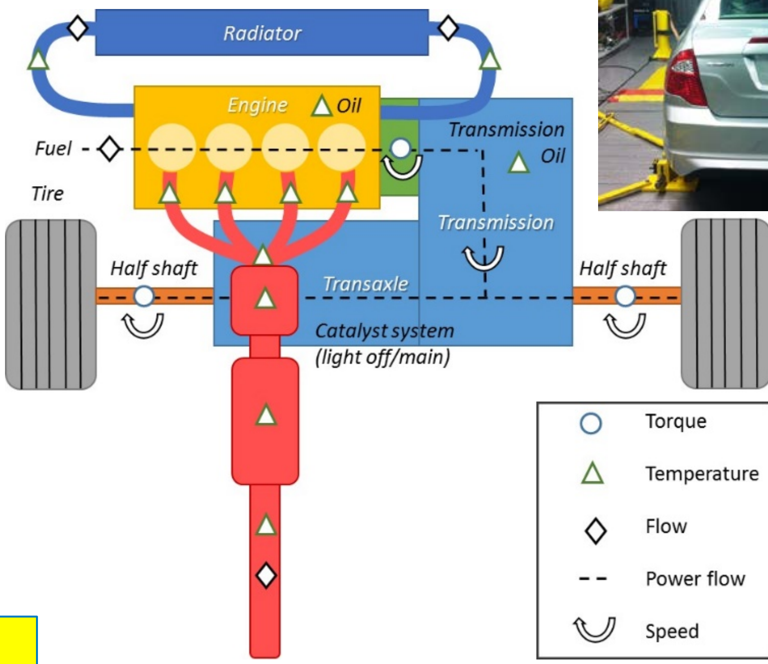
Leveraging Argonne National Laboratory (ANL) work at the Advanced Powertrain Research Facility (APRF) for the laboratory and on-road testing activities

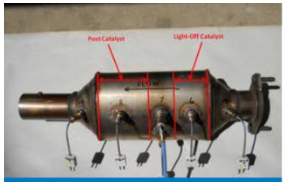
Dynamometer Testing & Model Calibration (Approach)

- **ANL dynamometer data collection**
- **2011 Ford Fusion evaluation vehicle**
  - Four-cylinder, six-speed transmission, representative of a modern mid-size vehicle
  - More than 27 channels of thermal data (engine oil, transmission oil, engine coolant, cabin)
- **Matrix of dynamometer tests over drive cycles, initial thermal conditions, and ambient temperatures**
  - Use to calibrate simplified model for national-level analysis

16 tests total

Variable	Values
Drive Cycle	UDDSx2, US06x2
Start Condition	Hot Start, Cold Start
Test Cell Temperature	-17°C, -7°C, +20°C, +35°C




Catalyst Temperatures


Exhaust Runner Temp


Post-cat. Exhaust Temp


Coolant Flows

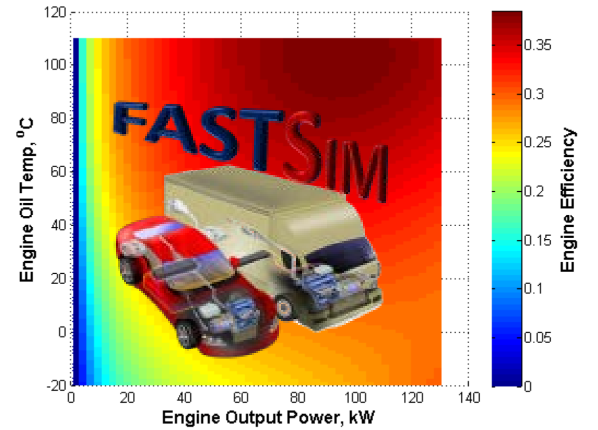

Coolant Temperatures

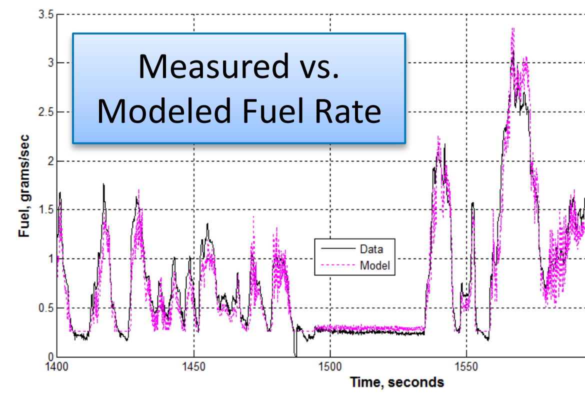

Cabin Temperatures

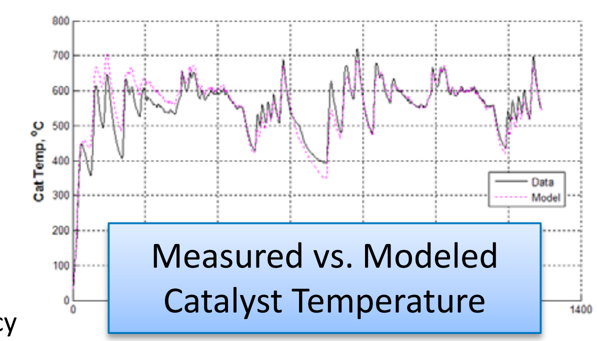
Photos from Forrest Jehlik, ANL

Dynamometer Testing & Model Calibration (Accomplishments)

- **Use dynamometer data to calibrate FASTSim model**
  - Future Automotive Systems Technology Simulator
  - Simplified powertrain model well suited to evaluating on-road fuel economy over large datasets of real-world drive cycles
  - Engine oil viscosity and fuel enrichment estimated using lumped thermal models for engine oil/coolant and exhaust catalyst
  - Mechanical losses modeled relative to power and thermal state
- **Model calculates fuel consumption to within 5.2% on all 16 test conditions with a 2.4% RMS error (RMSE)**
  - Within the range of cycle-to-cycle dynamometer test uncertainty
- **For model validation, EPA 5-cycle testing was conducted at APRF** (FTP, HWFET, US06, SC03, Cold FTP)
- **Simulated mpg within 3.0% on certification cycles**
- **To capture impacts of cabin AC use, a simplified cabin model was calibrated to APRF test data on SC03**
  - AC on = 19.6 mpg / AC off = 26.0 mpg







FTP = Federal Test Procedure
HWFET = Highway Fuel Economy Test
AC = air conditioning
RMS = root mean square
EPA = Environmental Protection Agency

On-Road Testing & Model Validation (Approach)

- **Coordinate with ANL to perform on-road testing**
- **Majority of instrumentation retained from APRF testing**
  - Thermocouples, strain gauges, and CAN message data acquisition reconfigured for mobile collection using IPETRONIK software
- **Additional instrumentation installed to measure fuel flow and vehicle position**

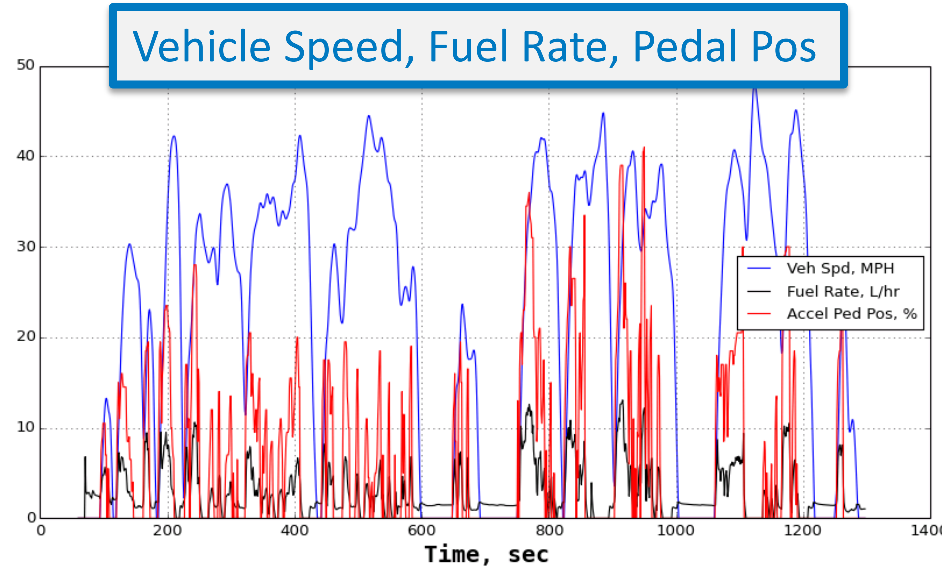
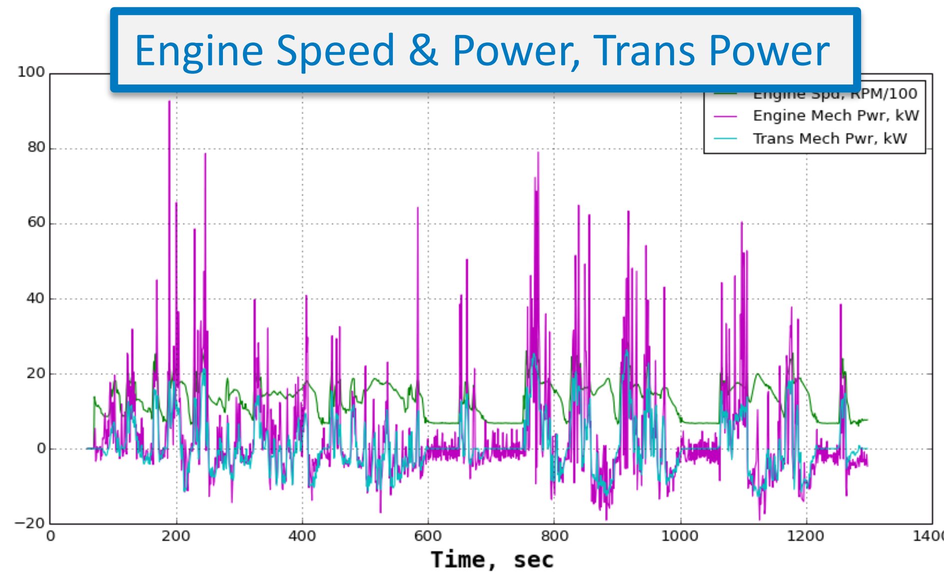


Photo from Eric Wood, NREL

Omniflo® Turbine Flowmeter
(credit: Flow Technology™)

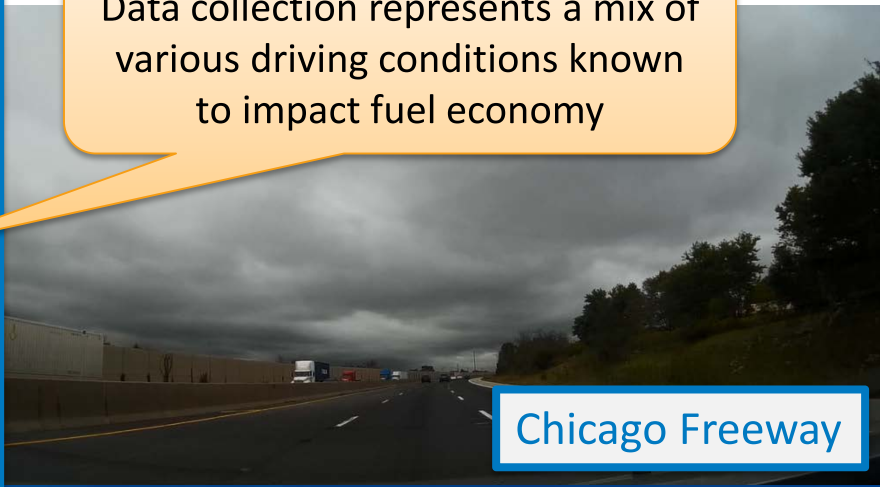


CAN = controller area network

On-Road Testing & Model Validation (Accomplishments)

- **Data collection period: Aug–Sept 2015**
- **Trip count: 85**
- **Total distance: 2,843 miles**
- **Trip avg speeds: 15–75 mph**
  - 36 “highway” trips / 49 “city” trips
  - Delineation* = 40 mph avg trip speed
- **Initial oil temps: 20–100°C (68–212°F)**
  - 32 “hot” start trips / 53 “cold” start trips
  - Delineation* = 80°C initial oil temperature
- **Ambient temps: 17–38°C (63–100°F)**
  - 31 trips with AC on / 54 trips with AC off
- **Significant trip-to-trip elevation & road grade variation**
  - Elevation range: 535–11,100 feet
  - 6 trips with elevation change of ±3,000 feet
  - 8 trips with grade content above >3% RMS
  - Delineation*: trip considered “flat” if start to end elevation change results in an average grade between -0.5% and +0.5%

Data collection represents a mix of various driving conditions known to impact fuel economy



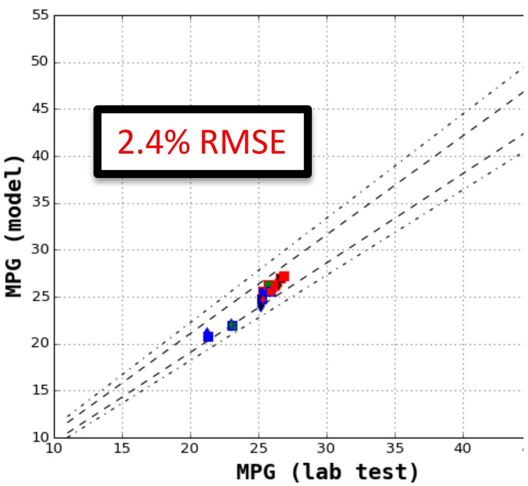
Photos from Eric Wood, NREL

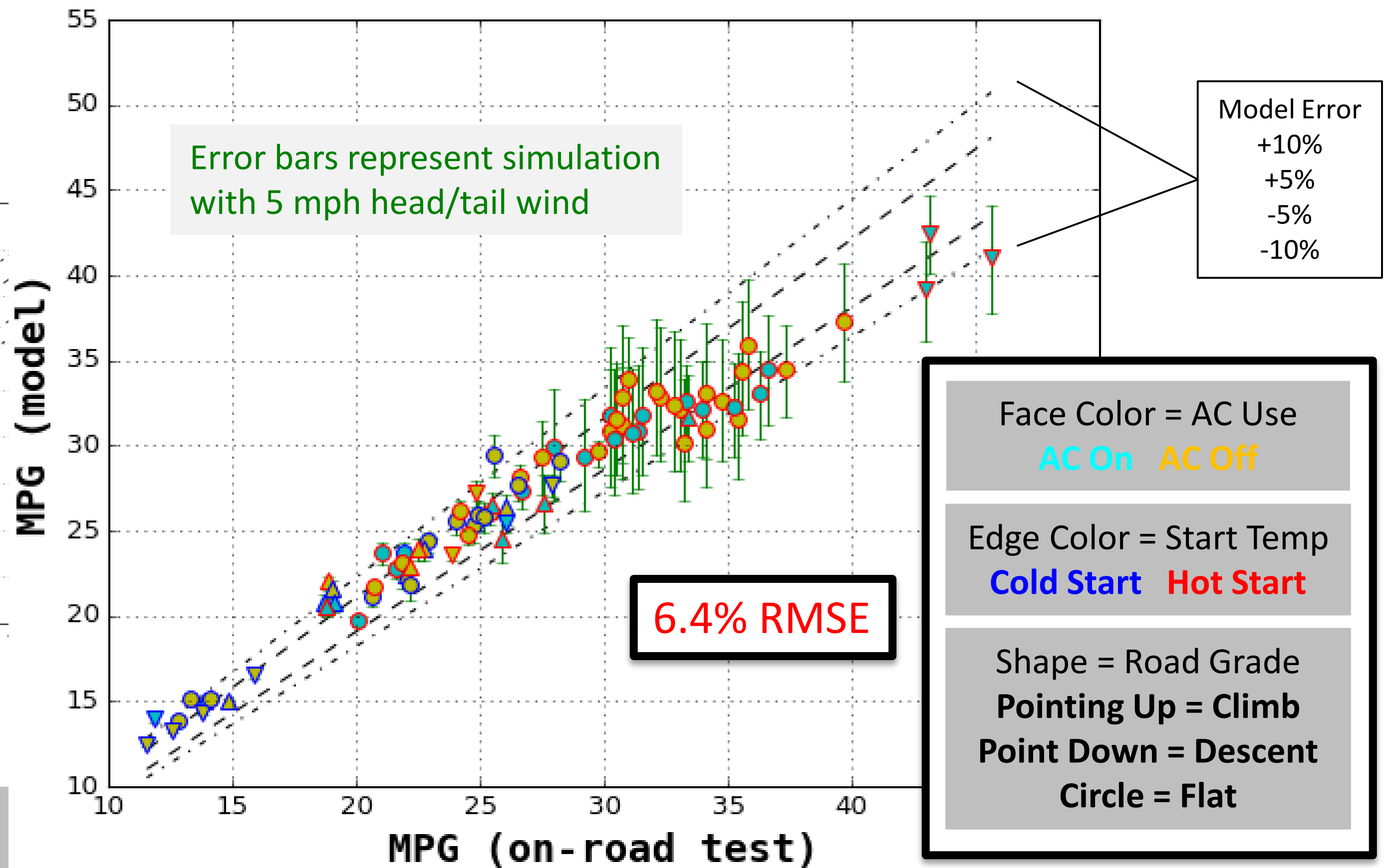
*Delineations used later in this presentation for visualization.
Actual driving speeds, initial component temperatures, and road grades used in the model.

On-Road Testing & Model Validation (Accomplishments)

- Underscored importance of non-dynamometer effects in estimating real-world fuel economy
- Model trained on limited set of dynamometer cycles performed well over broad range of real-world conditions (weather, grade, elevation, air conditioning use)
- Impact of wind speed on simulated fuel economy is quantified with error bars representing impacts from 5 mph head/tail winds

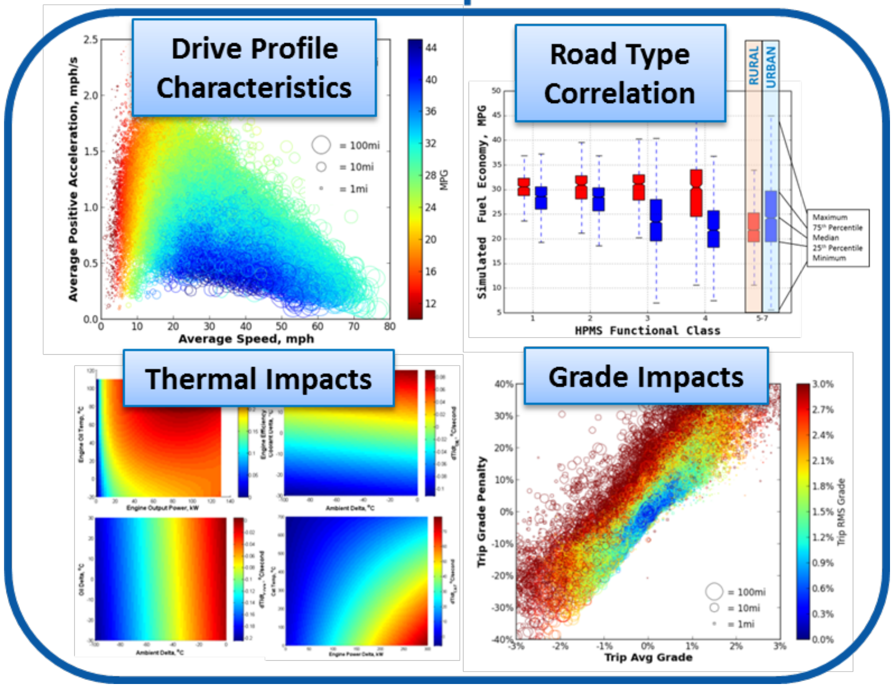
Dyno Results for Reference





Real-World Simulation & Activity-Based Weighting (Approach)

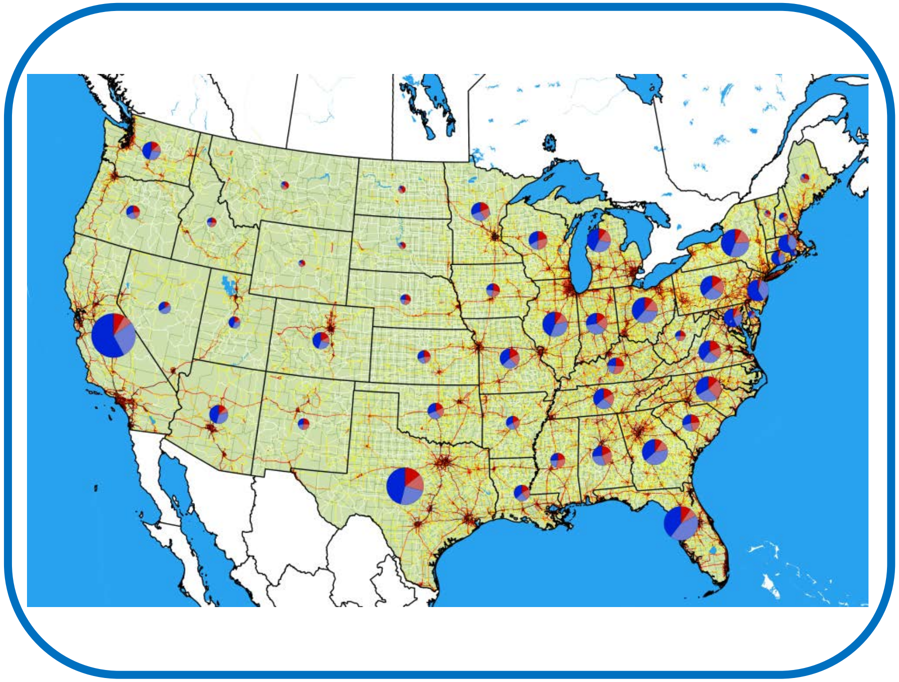
Fuel Consumption *Rates*



Use testing/modeling to determine a given vehicle's fuel economy over a range of driving conditions

- Drive profile, road grade, ambient conditions, etc.
- Use large real-world driving database to correlate drive profile characteristics with road type/traffic conditions

Vehicle Miles Traveled *Volumes*



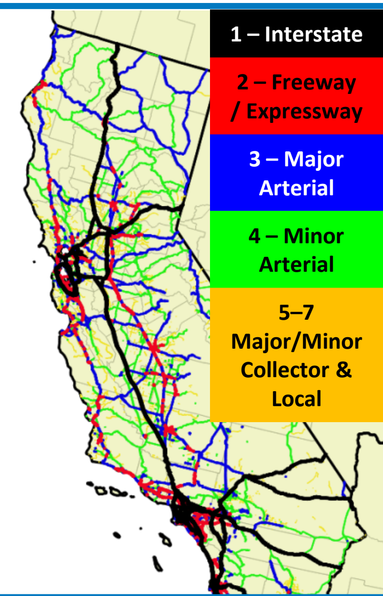
Combine national datasets on driving volumes by road type, climate conditions, road grades, etc.

- Proportionally weight fuel rates by the amount of driving across the country and a typical meteorological year (TMY)
- Calculate aggregated national-level fuel economy

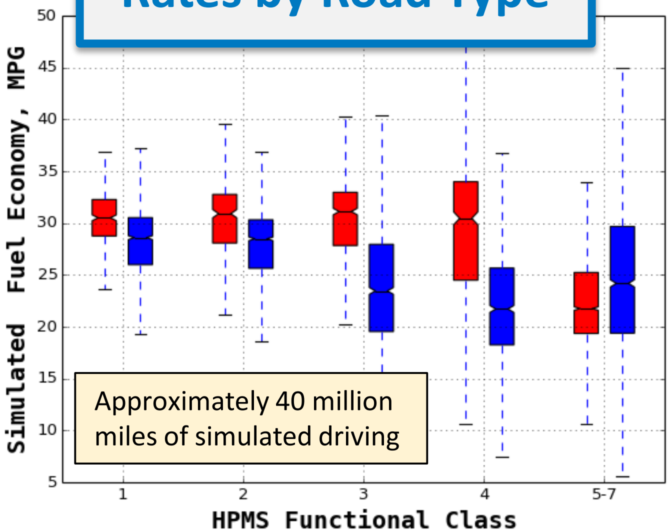
Repeat process with and without a given off-cycle technology enabled to calculate its national-level benefit

Real-World Simulation & Activity-Based Weighting (Accomplishments)

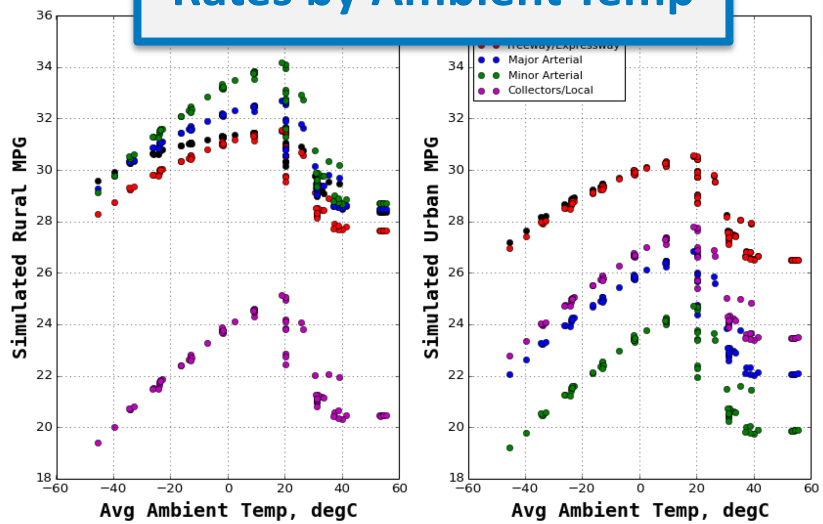
- **"Mapped" operational space of light-duty vehicles by running model over a large set of real-world cycles (approx. 40 million miles simulated driving)**
- **Aggregated simulation results by FHWA road type designations and range of superimposed ambient temperatures**
- **Results show reduced fuel economy on lower speed/capacity roads**
  - Distinct urban/rural trends likely a result of congestion and frequency of signalized intersections
- **Results show increasing fuel economy from -40°C to +20°C (reduced viscous losses and enrichment), then decreasing due to cabin air conditioning load**



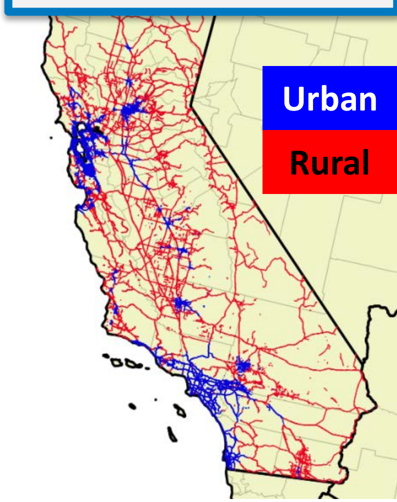
Rates by Road Type



Rates by Ambient Temp

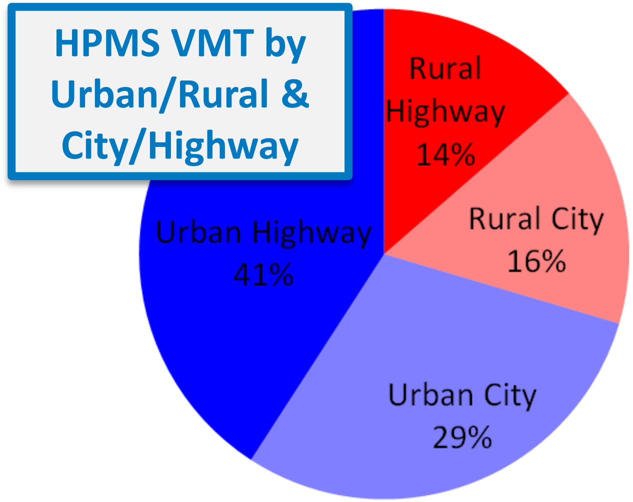


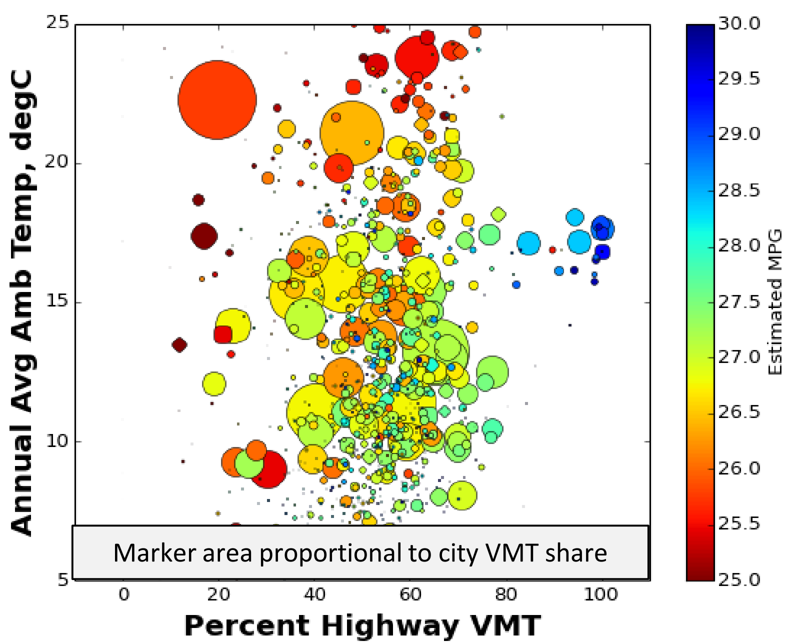
CA FHWA classifications

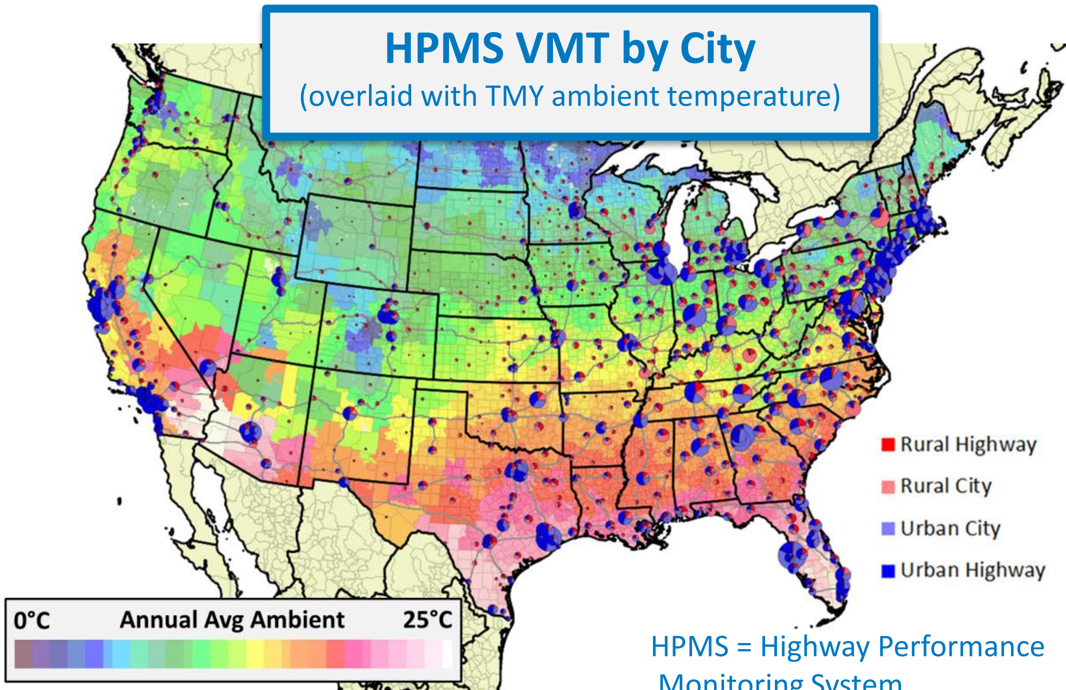


Real-World Simulation & Activity-Based Weighting (Accomplishments)

- **Weighted simulation rates using FHWA data on VMT by road segment and typical climate conditions**
- **Visualized city-level mpg estimates using percent of VMT on highways and annual average ambient temperature**
  - Highest performing mpg cities feature high percent of VMT on highways in moderate climate
- **Distance weighting the city-level mpg estimates yields a national-level average (27.0 mpg for the modeled Fusion)**







Real-World Simulation & Activity-Based Weighting (Accomplishments)

- **Estimates for hypothetical accessory load reduction technology**
  - 10% reduction over all driving conditions (such as improved alternator efficiency)
- **Small savings, but not substantially different from standard cycle approaches**

Calculation Approach	Baseline MPG	Tech-enabled MPG	g CO_2/mi benefit	Percent benefit
EPA 2-cycle	30.9	31.1	1.8	0.6%
EPA 5-cycle	24.0	24.2	1.7	0.5%
Real-world estimate	27.0	27.1	1.6	0.5%

- **Estimates for hypothetical thermal retention technology (e.g., encapsulation)**
  - Doubles time constant on engine oil cool-down following key-off
- **Significant difference between real-world and standard cycle simulations**
  - Improved engine warm-up AND heat retention captured by real-world method

Calculation Approach	Baseline MPG	Tech-enabled MPG	g CO_2/mi benefit	Percent benefit
EPA 2-cycle	30.9	31.0	1.3	0.4%
EPA 5-cycle	24.0	24.2	2.3	0.6%
Real-world estimate	27.0	27.4	5.3	1.6%

Response to Previous Year Reviewers' Comments

Two critical comment themes were distilled from reviews of the FY15 effort on "Analyzing Real-World Light Duty Vehicle Efficiency Benefits":

1. **Sufficiency of simplified models to assess advanced vehicle technologies**

   On-road testing in the past year has helped to address this comment, and further relevant testing efforts are planned (per the future work slides). While simplified models can bring uncertainty considerations, accuracy relative to chassis dynamometer testing (2.4% RMSE) and on-road testing (6.4% RMSE) suggests that the largest source of uncertainly in this project is associated with real-world vehicle use conditions.

   Specifically, on-road testing revealed real-world fuel consumption rates to vary by up to 123% (11-46 MPG) relative to drive cycle, thermal state, and environmental conditions. Establishing appropriate weighting factors to properly account for a wide array of usage conditions is the most critical source of uncertainly in this project.

2. **Limited industry involvement and testing-based A/B evaluations**

   This research has been heavily focused on methodology development and incorporation of the necessary national datasets to quantify impacts of real-world drive cycles, spatially resolved vehicle activity, typical meteorological conditions, and roadway elevation/grade—only a handful of hypothetical A/B technology scenarios have been explored to date. In addition to the increased interaction with USCAR OEMs over the past year, emphasis going forward will transition to DOE- and privately-funded, testing-based evaluations (as discussed on the collaboration and future work slides).

Collaboration and Coordination with Other Institutions

- **ANL – APRF**
  - Lead on chassis dyno testing; support for on-road testing and data acquisition
- **OEMs/labs via VSATT and "Vehicle Usage Parameter" Work Group**
  - Updates and input/feedback at "deep dive" project reviews and regular conference calls/meetings; dataset identification
- **US DOT, US Geological Survey (with NREL filtering), TMY3**
  - Data sources for travel, speeds, volumes, grade, temperature, solar radiation…
- **New multi-lab efforts (with ANL, NREL and Idaho National Laboratory) targeting specific off-cycle technologies**
  - Efforts will leverage/test the developed methodology (e.g., testing and analysis to estimate off-cycle benefits of active transmission warm-up)
- **EPA**
  - Positive response to initial presentations; keeping in touch (particularly for on-going testing + analysis for specific off-cycle technologies)
- **Case studies planned on specific OEM technologies**
  - Details not yet publicly shareable

Remaining Challenges and Future Work

Challenges/Barriers

- **Comprehensively accounting for real-world variables and uncertainties**
- **Full approach application to relevant technologies and further validation across critical dimensions**

Corresponding Future Work Plan

- **Further improve model fidelity**
  - Integrate models for thermally sensitive transmission and wheel set efficiency
  - Coordinate with NREL's A/C team to incorporate thermal comfort modeling along with cabin HVAC load
- **Analyze and account for regional drive cycle variability**
- **Embed national-level data on traffic congestion**
  - Isolate impacts on simulated fuel economy
- **A/B technology comparisons – demonstrate and validate approach with specific technologies**
  - Multi-lab effort on transmission active heating
  - (OEM-specific approach application)
  - Confirm modeled A/B comparisons agree with A/B test data over multiple conditions

Summary

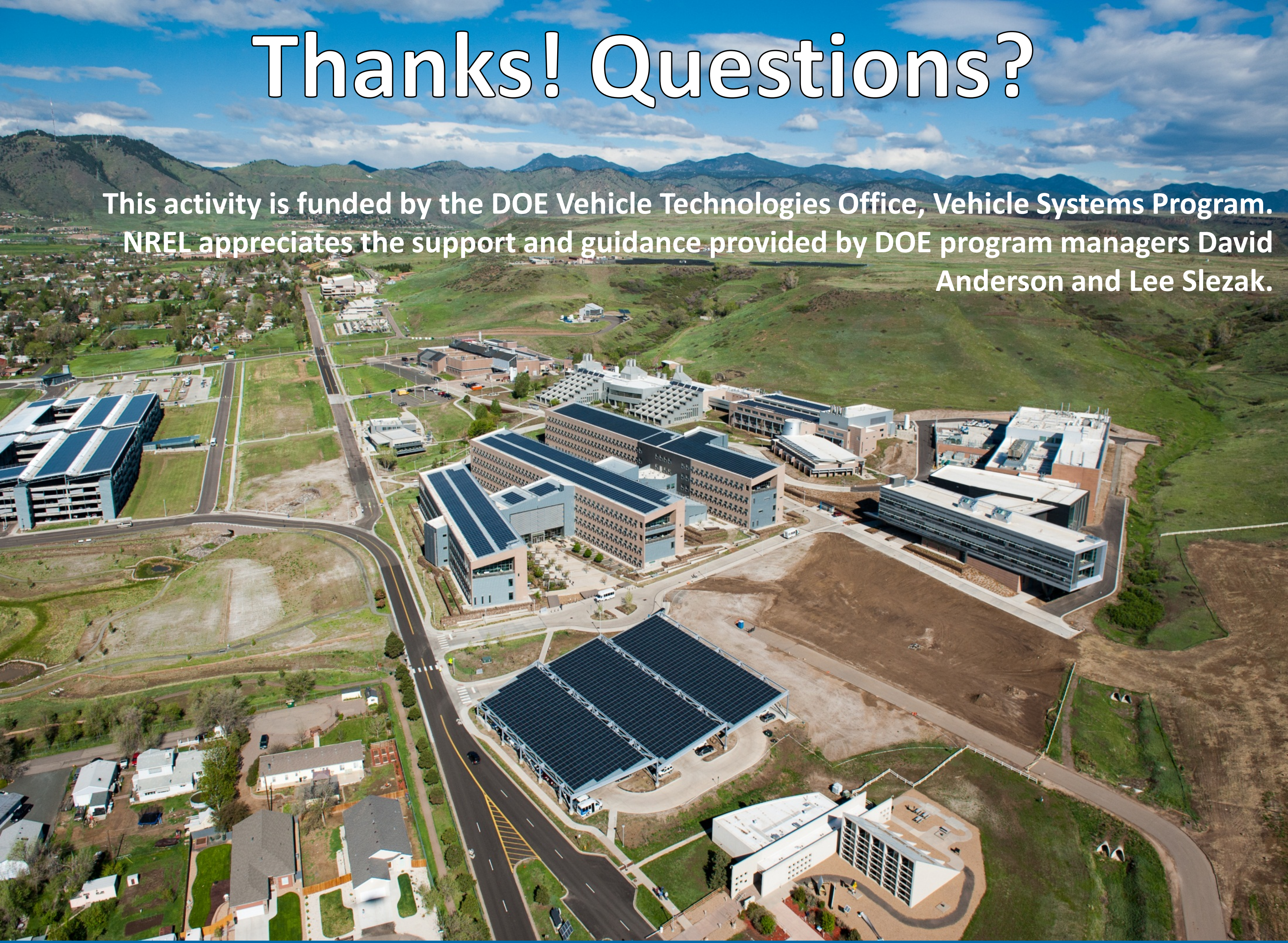
- Off-cycle technologies represent an important pathway to achieve real-world fuel savings (and through which OEMs can potentially receive credit toward CAFE compliance)
- DOE national labs such as NREL are well positioned to provide objective input on these technologies using large national datasets in conjunction with OEM- and technology-specific testing

- This project demonstrates an approach that combines vehicle testing (dynamometer and on-road) with powertrain modeling and simulation over large, representative datasets to quantify real-world fuel economy
- The approach can be applied to specific off-cycle technologies (engine encapsulation, start/stop, connected vehicle, etc.) in A/B comparisons to support calculation of realistic real-world impacts

- Future work will focus on testing-based A/B technology comparisons that demonstrate the significance of this approach

Thanks! Questions?

This activity is funded by the DOE Vehicle Technologies Office, Vehicle Systems Program. NREL appreciates the support and guidance provided by DOE program managers David Anderson and Lee Slezak.



Technical Back-Up Slides

NREL Transportation Data Center Efforts

Secure Access, Expert Analysis, and Validation to Support Decision-Making

Alternative Fuels Data Center (AFDC): *Public clearinghouse of information on the full range of advanced vehicles and fuels*

National Fuel Cell Technology Evaluation Center (NFCTEC): *Industry data and reports on hydrogen fuel cell technology status, progress, and challenges*

Transportation Secure Data Center (TSDC): *Detailed individual travel data, including GPS profiles*

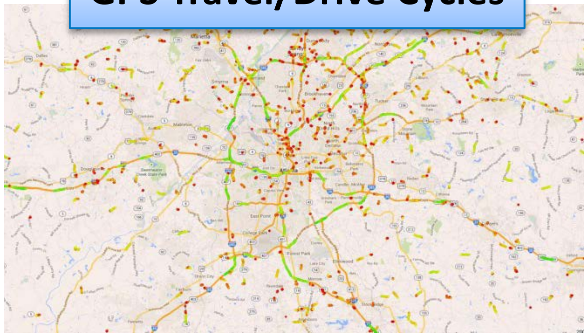
Fleet DNA Data Collection: *Medium- and heavy-duty drive-cycle and powertrain data from advanced commercial fleets*

FleetDASH: *Business intelligence to manage federal fleet petroleum/alternative fuel consumption*

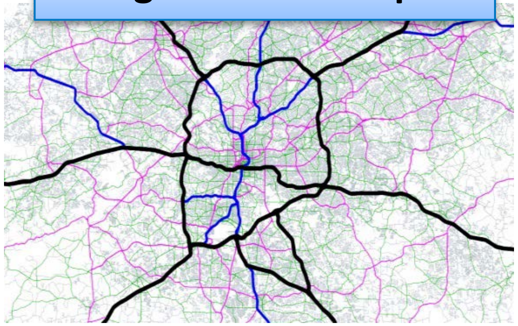
Features	AFDC	NFCTEC	TSDC	Fleet DNA	Fleet DASH
Securely Archived Sensitive Data		Y	Y	Y	Y
Publicly Available Cleansed Composite Data	Y	Y	Y	Y	
Quality Control Processing	Y	Y	Y	Y	Y
Spatial Mapping/GIS Analysis	Y	Y	Y	Y	Y
Custom Reports		Y		Y	Y
Controlled Access via Application Process			Y		
Detailed GPS Drive-Cycle Analysis			Y	Y	

Integration with Other Large Datasets

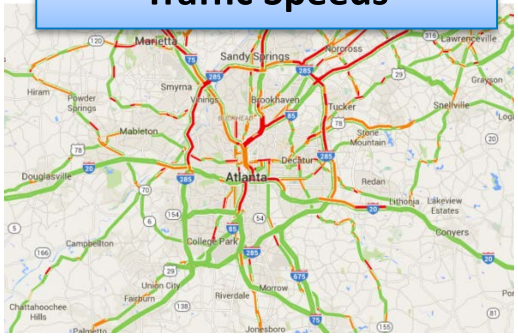
GPS Travel/Drive Cycles



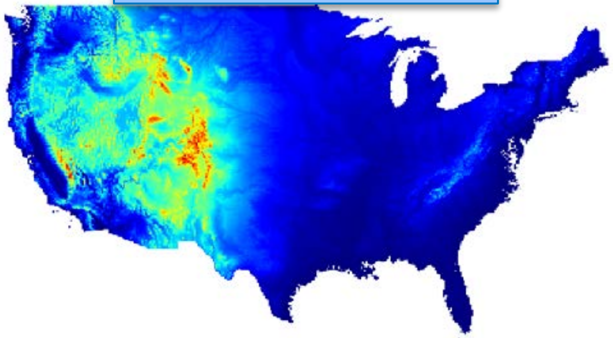
Digital Street Maps



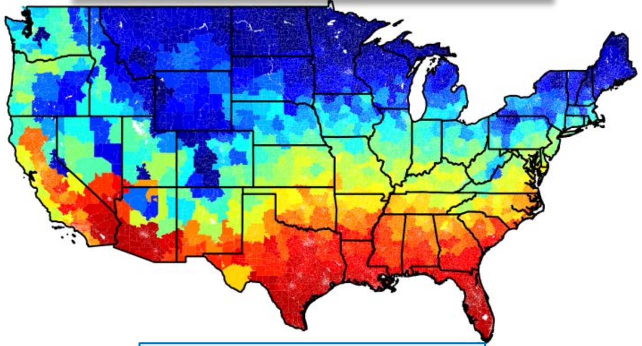
Traffic Speeds



Elevation / Grade

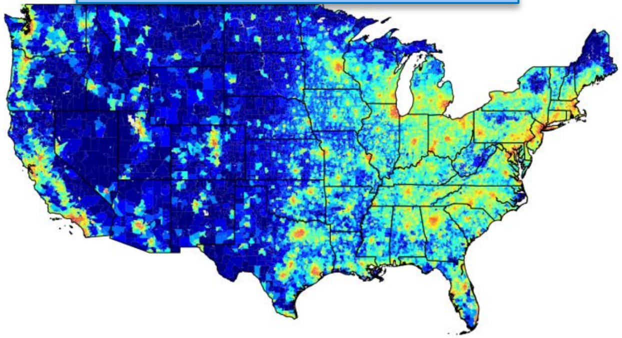


Ambient Temperature

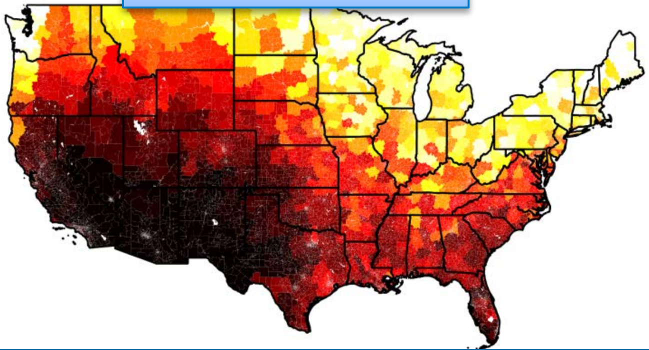


Freight Volumes

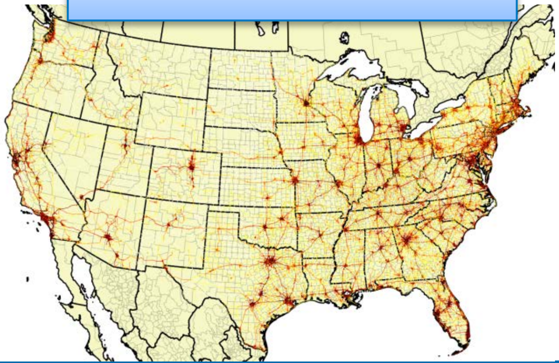
Vehicle Registrations



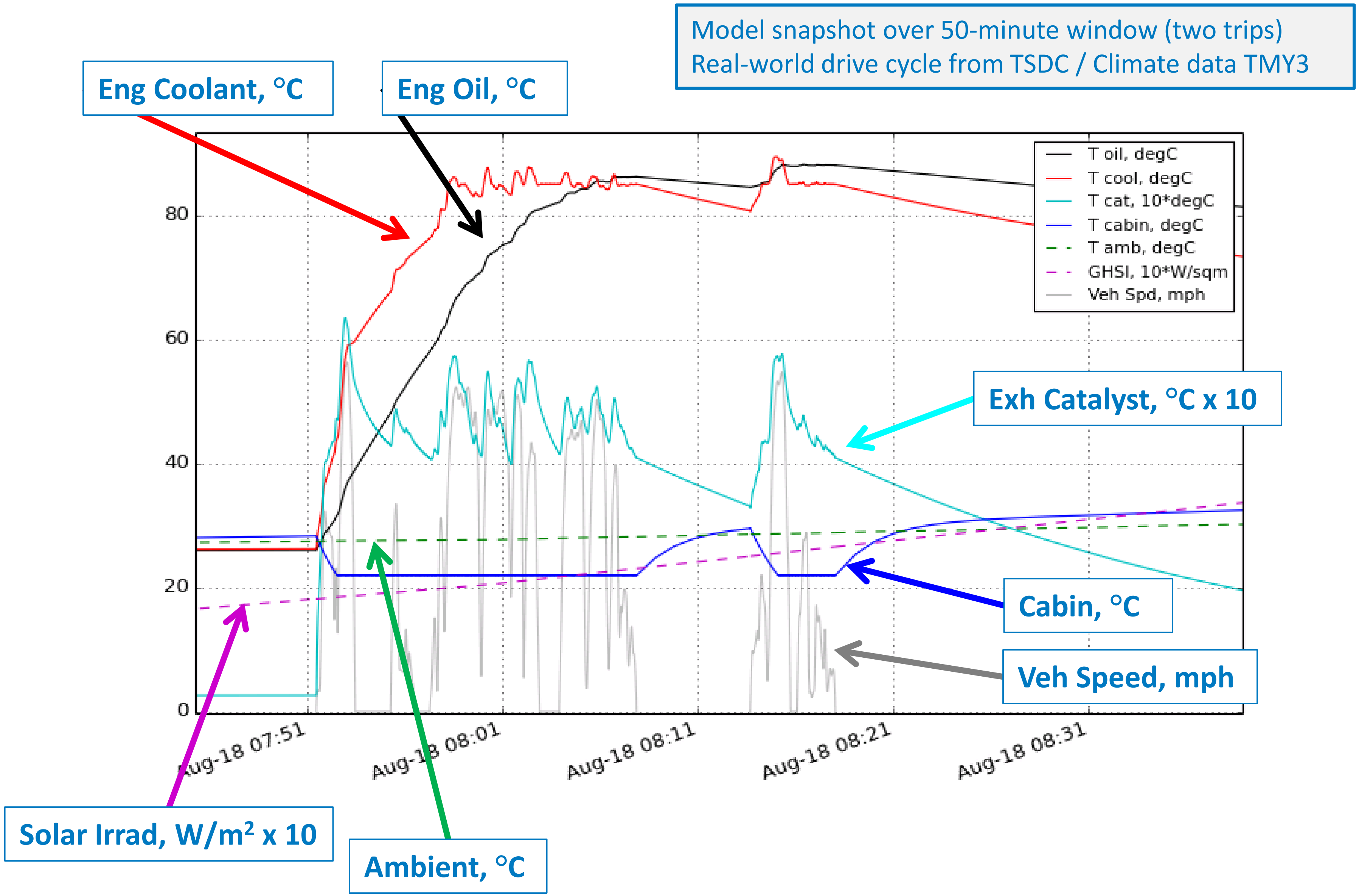
Solar Intensity



Overall Road Volumes



Model Snapshot: 50 Minutes



Example Calculations

- **Jan 1st in Chicago, IL**
  - Avg Ambient Temp = 5.2°C
  - Avg Solar Irradiation = 31 W/m^2

"Rates" @ 5.2°C and 31 W/m^2

From real-world simulations of model calibrated to dynamometer data and validated to on-road data

	Rural	Urban
Interstate	31.4	30.3
Freeway	31.3	30.3
Major Arterial	32.5	26.4
Minor Arterial	33.8	24.1
Collector/Local	24.5	27.3

"Volumes" @ Chicago, IL

Annual average VMT estimates from disaggregated HPMS tables (millions of miles)

	Rural	Urban
Interstate	103	8,196
Freeway	-	124
Major Arterial	70	4,663
Minor Arterial	59	3,910
Collector/Local	107	4,607

Distance-Weighted Average

27.5 MPG

Example Calculations

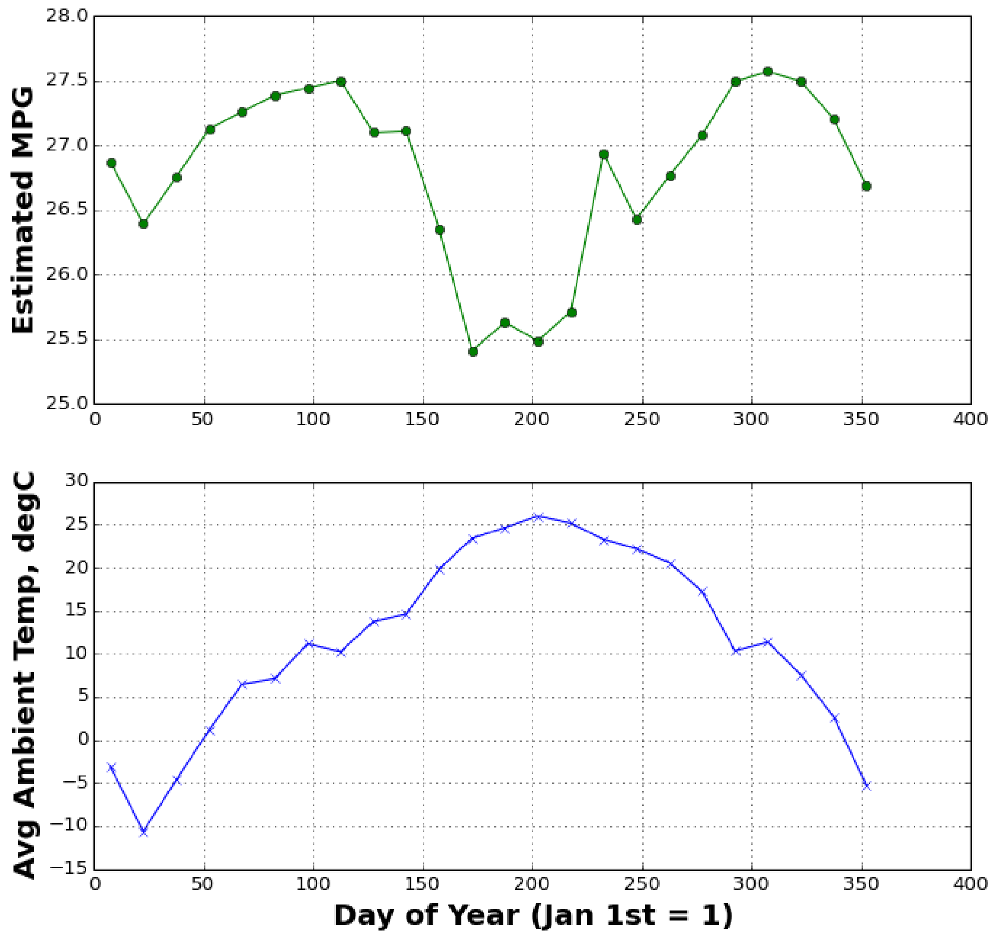
Extend Chicago calculations to all 365 days of the year

Plot results in 15-day increments

Note correlations with ambient temperature

Highest MPG values achieved at moderate ambient temperatures

Lowest MPG values achieved at ambient temperature extremes



Additional Details on Off-Cycle Technologies and Connection to CAFE

Mercedes-Benz successfully petitioned EPA for off-cycle credits on MY2012–16 vehicles (Sept 2014)

Received off-cycle credit for high-efficiency lighting, ventilated seats, glazing technology, engine start/stop

Off-cycle pathway provided additional incentive for Mercedes-Benz to **significantly increase commercialization** of this fuel-efficient technology

Mercedes-Benz has increased planning for start/stop systems from 1.5% in 2012 to 90+% in 2016

"Encouraging the deployment of the full range of [off-cycle] technologies is one of the primary reasons for the MY2012–2016 and MY2017–2025 regulations, and these regulations are the single-most powerful tool the administration has employed to mitigate global warming." (from Union of Concerned Scientists Comment on Mercedes-Benz Application)

Lack of established, defensible processes for calculating "off-table" off-cycle benefits has resulted in few successful application examples to date.