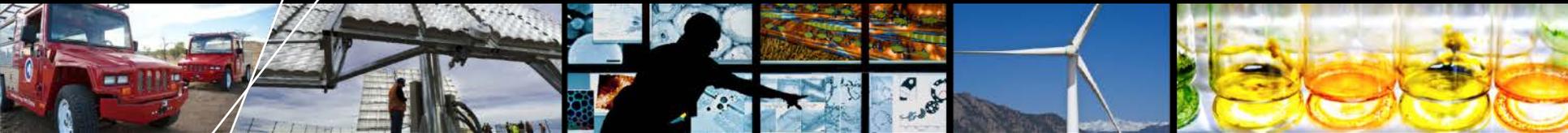




Connectivity-Enhanced Route Selection and Adaptive Control for the Chevrolet Volt



2013 SAE Energy Management Symposium: *Connectivity Trends*

October 22, 2013

Dearborn Heights, Michigan

Cooperative Research and Development Agreement (CRADA)
between the National Renewable Energy Laboratory (NREL)
and General Motors (GM)

Eric Wood, NREL (presenting)

Jeffrey Gonder, NREL

Sai Rajagopalan, GM

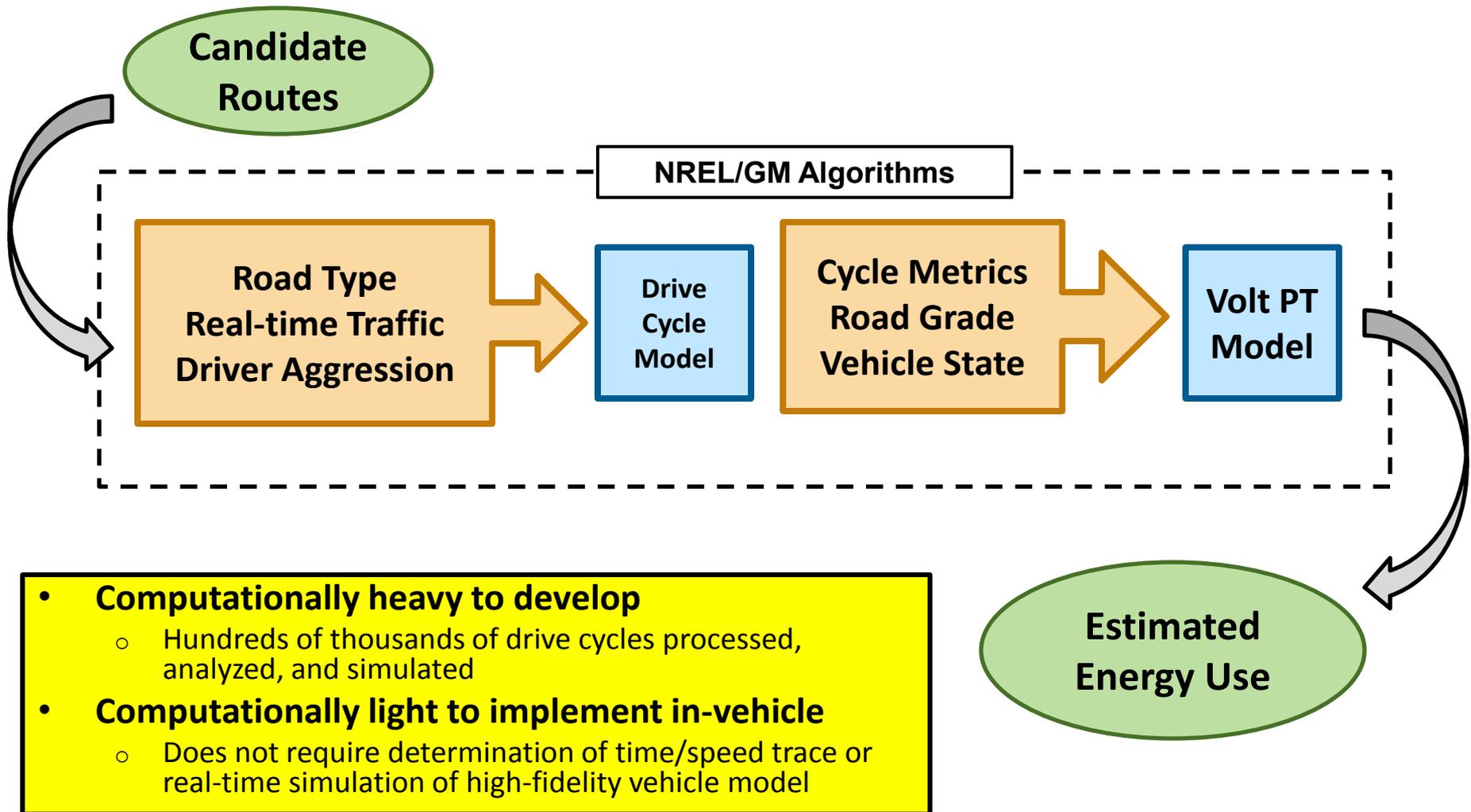
NREL IG 18563



Project Scope

- **Intelligent transportation systems (ITS) offer the potential for efficiency improvement without requiring additional powertrain hardware**
- **These improvements are most relevant to dual fuel powertrains, which have the capability to intelligently sequence energy sources and optimize hybrid control strategies**
- **This analysis uses the Chevy Volt as a platform to develop/investigate green routing and route-connected control techniques**

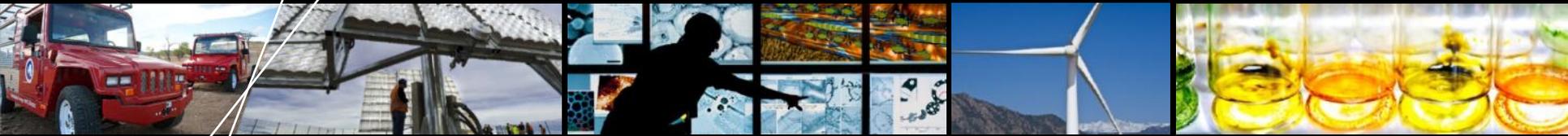
Proposed Methodology



Outline

- **Route-Connected Energy Prediction**
 - Drive Cycle Prediction
 - Energy Estimation Model
- **Model Applications**
 - TSDC + Google Directions API
 - Green Routing
 - Control Mode Scheduling

TSDC – Transportation Secure Data Center
API – Application Programming Interface



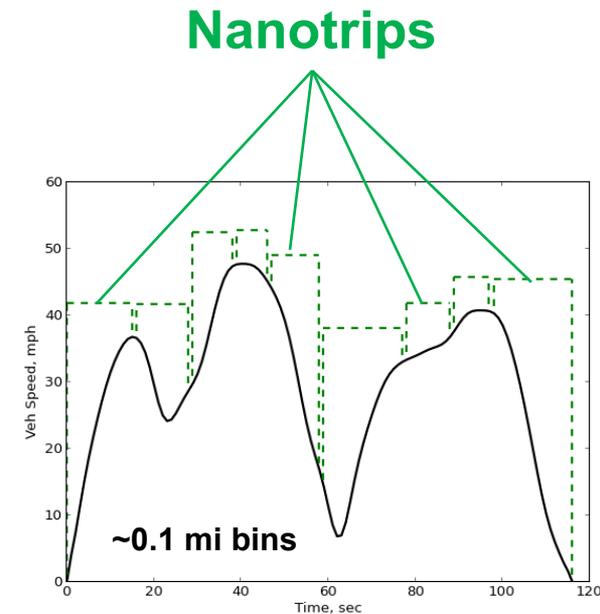
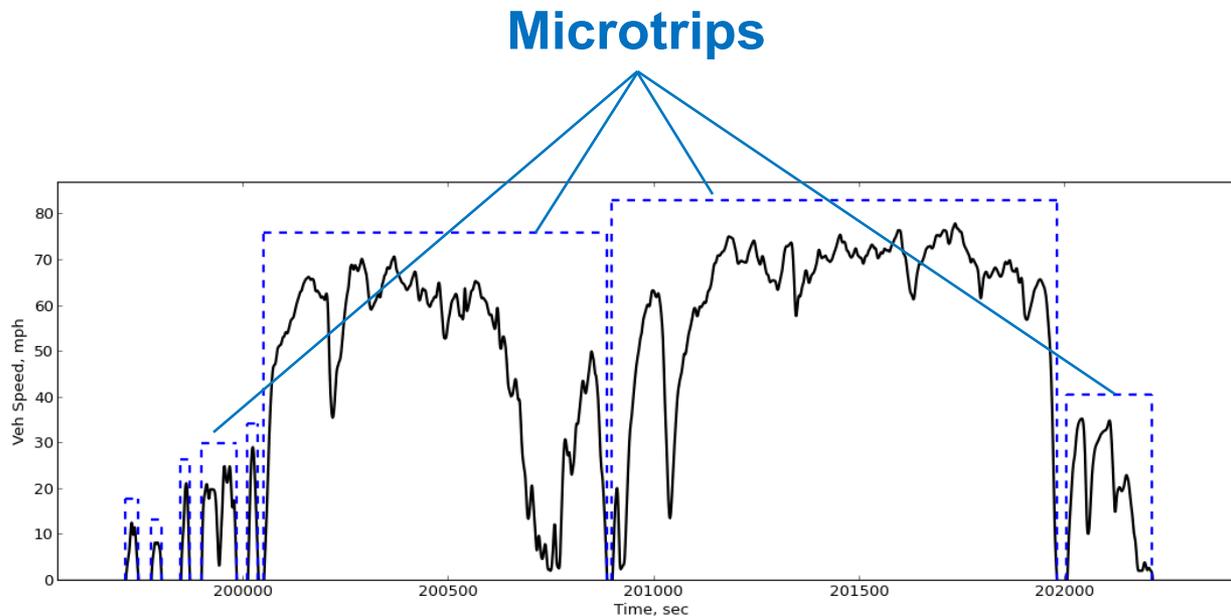
Drive Cycle Prediction

Drive Cycle Prediction

- Use historical speed data from TSDC to determine how road type affects driving style
- To facilitate application across various models, data are binned into equivalent micro-/nanotrips (as shown below)
 - Nanotrip bins sized to sufficiently track battery state of charge

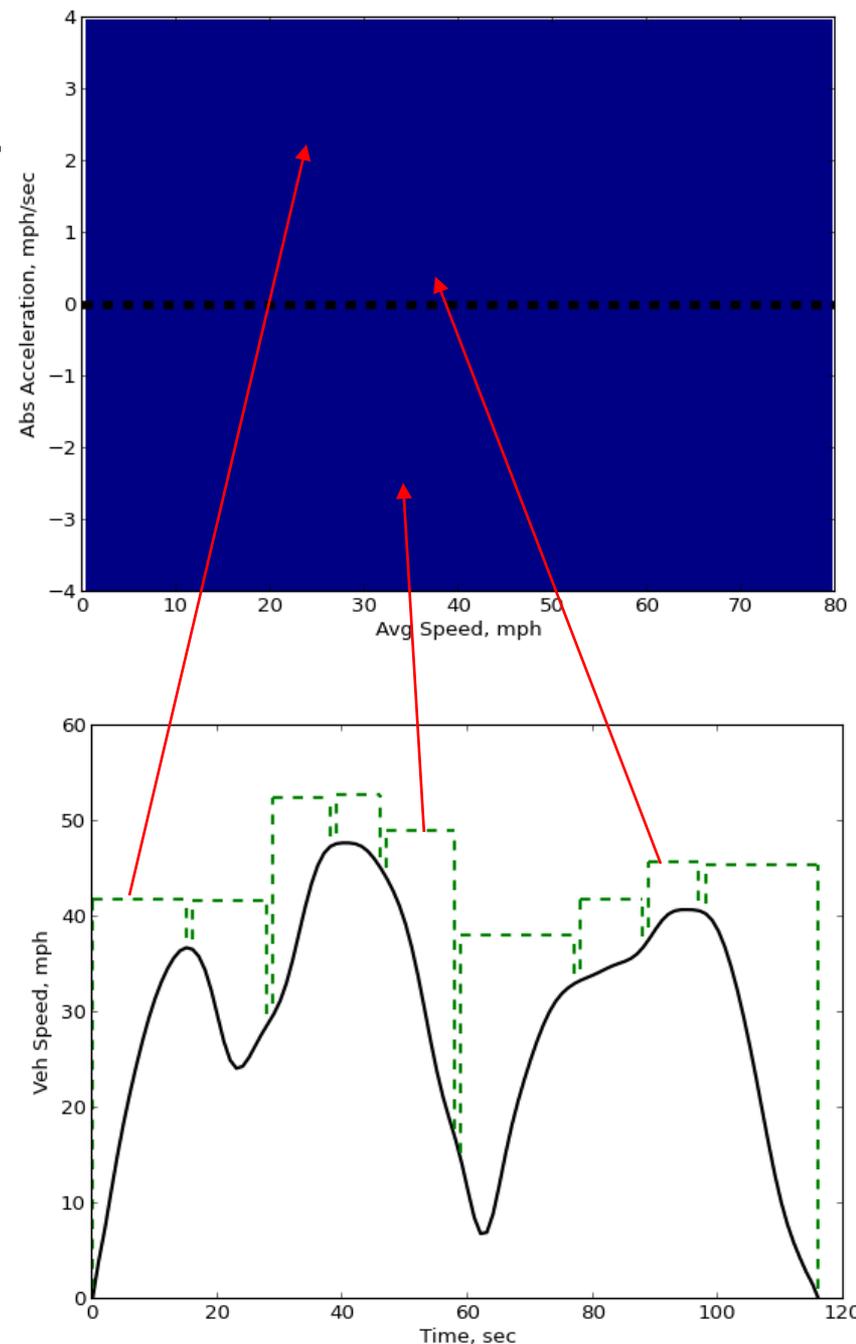


Transportation
Secure Data Center



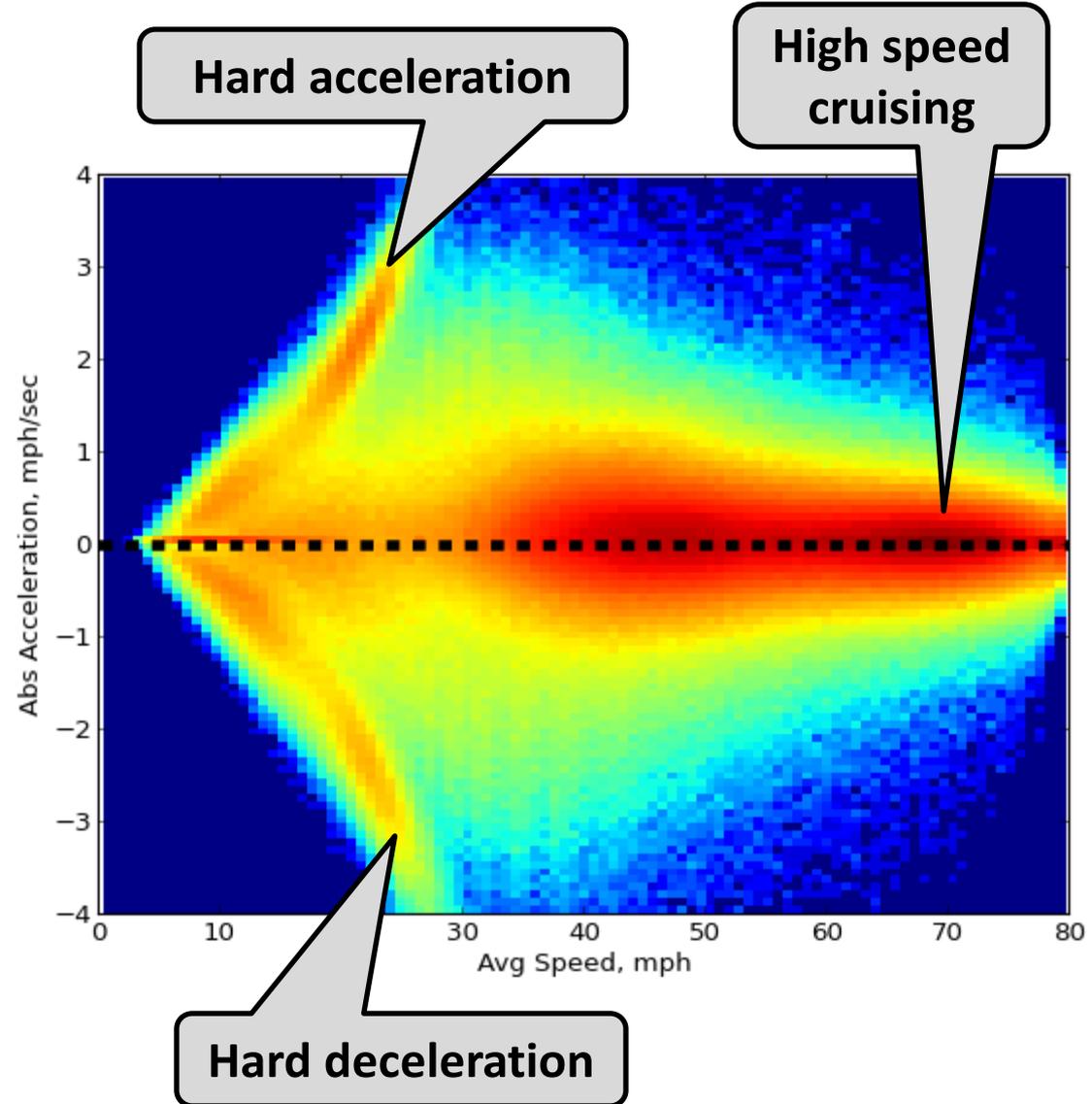
Drive Cycle Prediction

- Define 2D space with average vehicle speed and acceleration
- Loop through large dataset of real-world speed data to populate density plots of this space



Drive Cycle Prediction

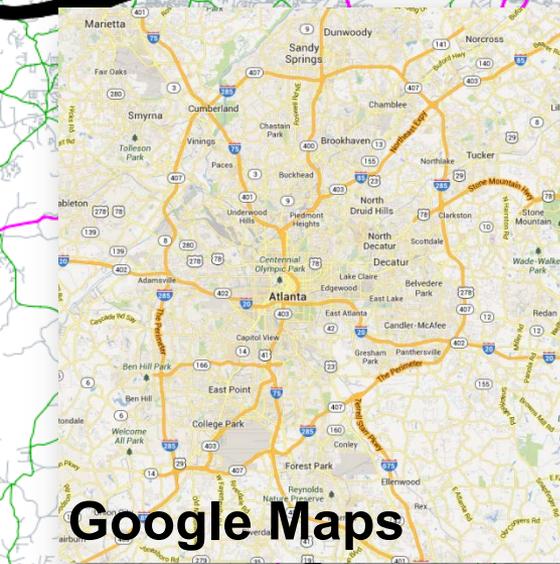
- Employ GPS data from Atlanta Regional Commission Travel Survey
 - 1,601 unique vehicles
 - 290,000 miles and 8,270 hours of driving data
- On a per-distance basis, the heaviest concentration of data exists at high-speed cruising conditions from 40-75 mph



Drive Cycle Prediction

- Functional Class 1**
- Functional Class 2**
- Functional Class 3**
- Functional Class 4**
- Functional Class 5**

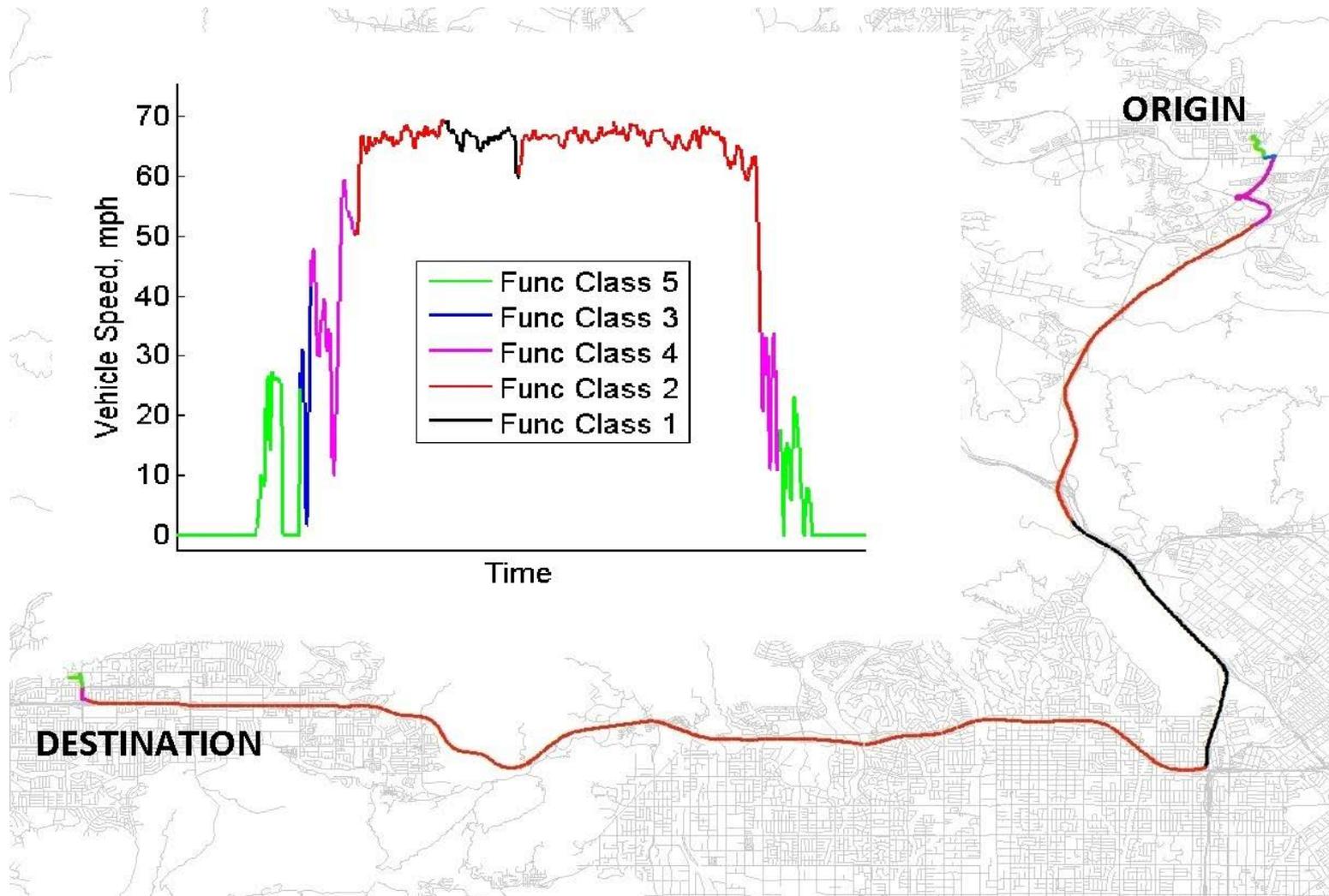
TSDC GPS data are map-matched to road network to determine roads used during each leg of trip



Google Maps

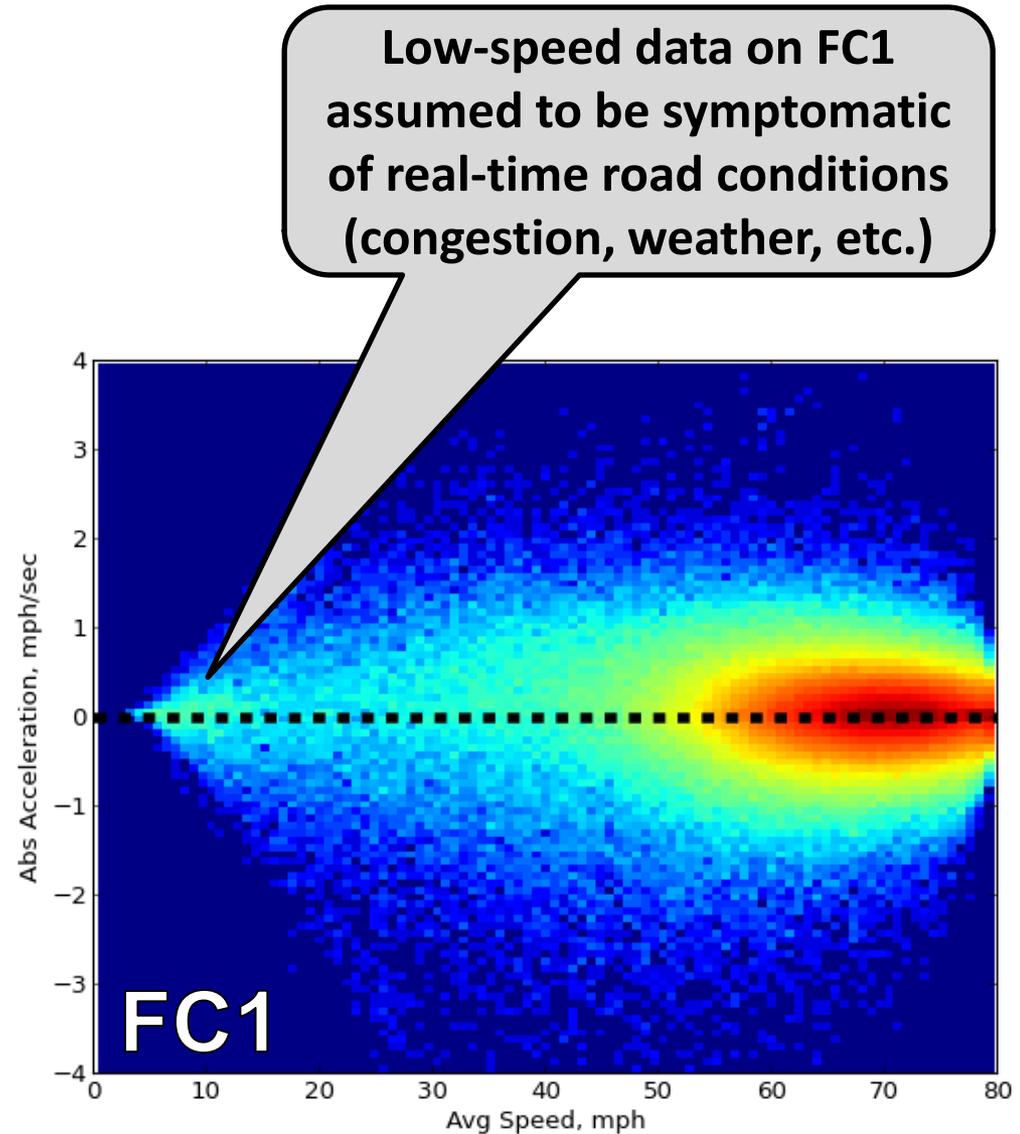
**NAVTEQ/Nokia/HERE
road layers**

Drive Cycle Prediction



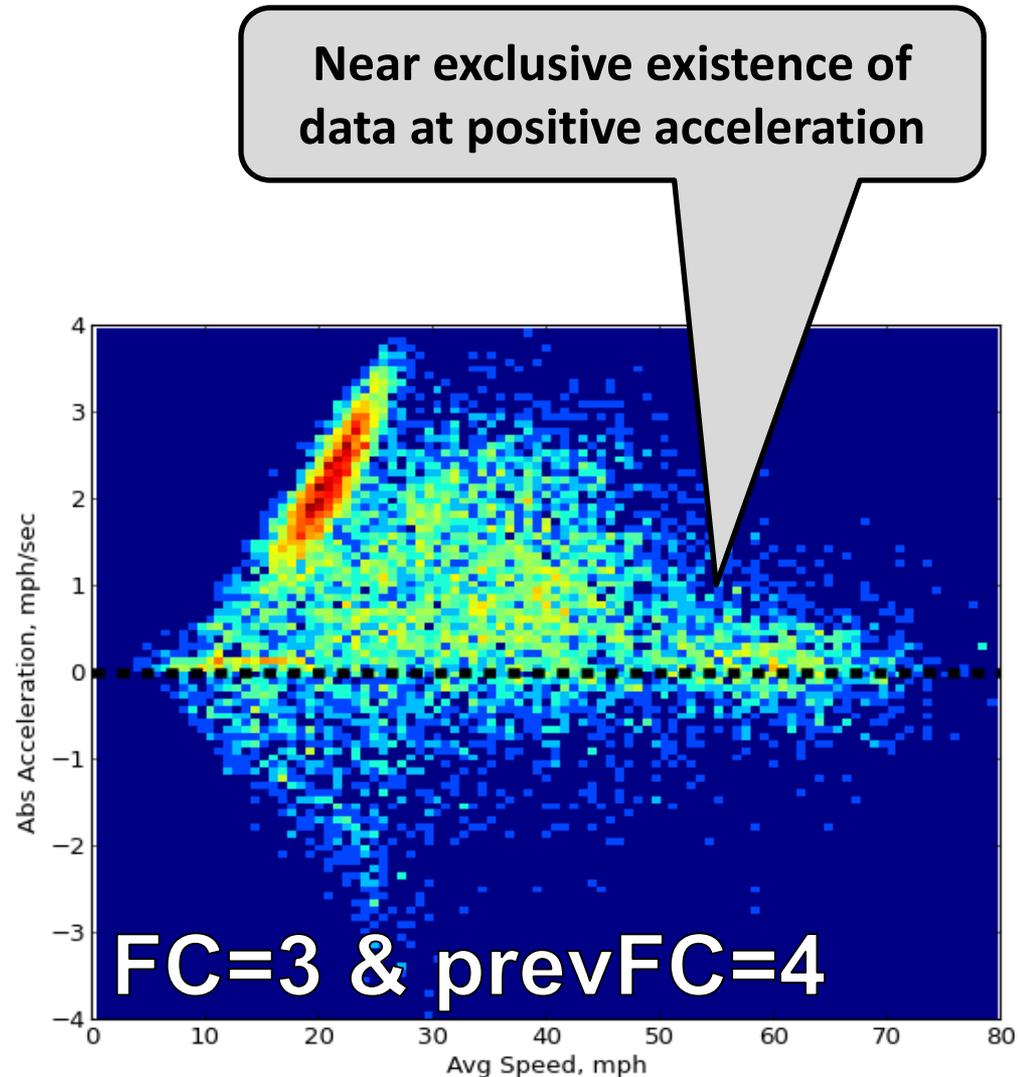
Drive Cycle Prediction

- Isolate data to only look at travel on Functional Class 1 roads
- Data consist mainly of high speed-cruising
- Access to real-time traffic data would further bolster predictions in a production environment



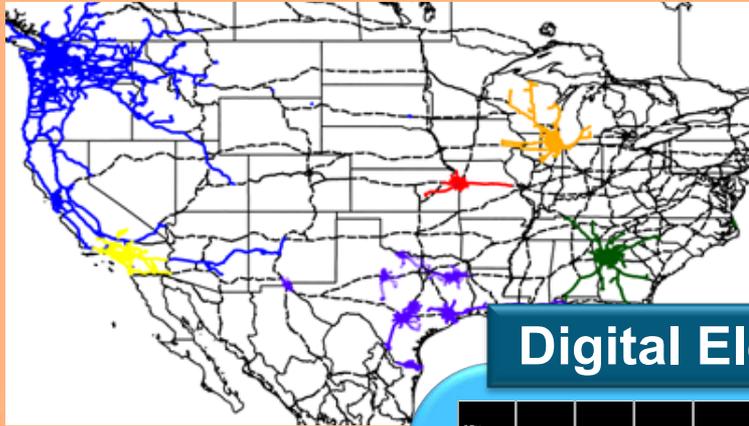
Drive Cycle Prediction

- Now bin data by **Functional Class AND** previous Functional Class
- Note concentration of data around hard acceleration when transitioning to higher speed/capacity roadway
- Combination of current state with previous state significantly strengthens drive cycle prediction methods



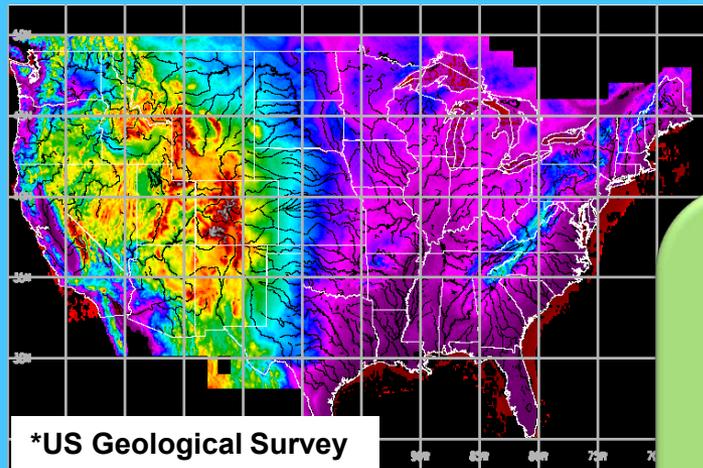
Appending Elevation Data

Telemetry Data

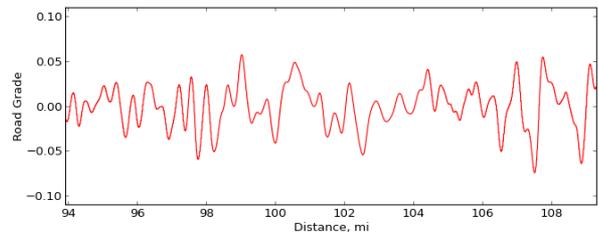
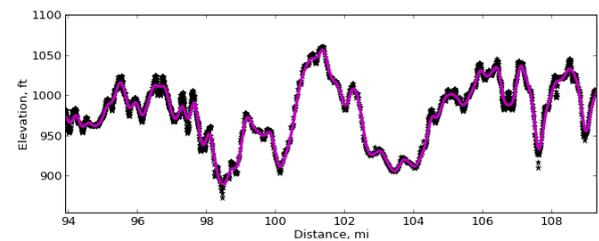


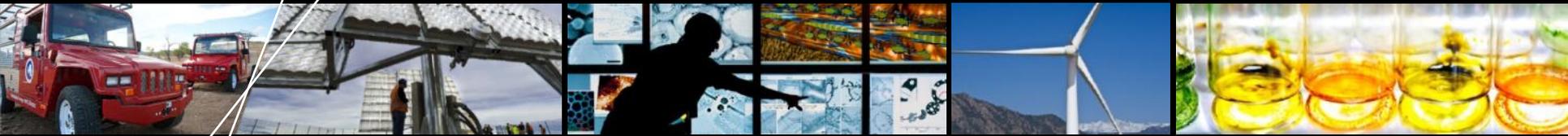
- Elevation data are appended to each route to improve energy predictions
- Leverage USGS* Digital Elevation Model
- Raw elevations are filtered and smoothed to eliminate errant points and reduce noise in grade calculations

Digital Elevation Model



Smooth & Filter Data

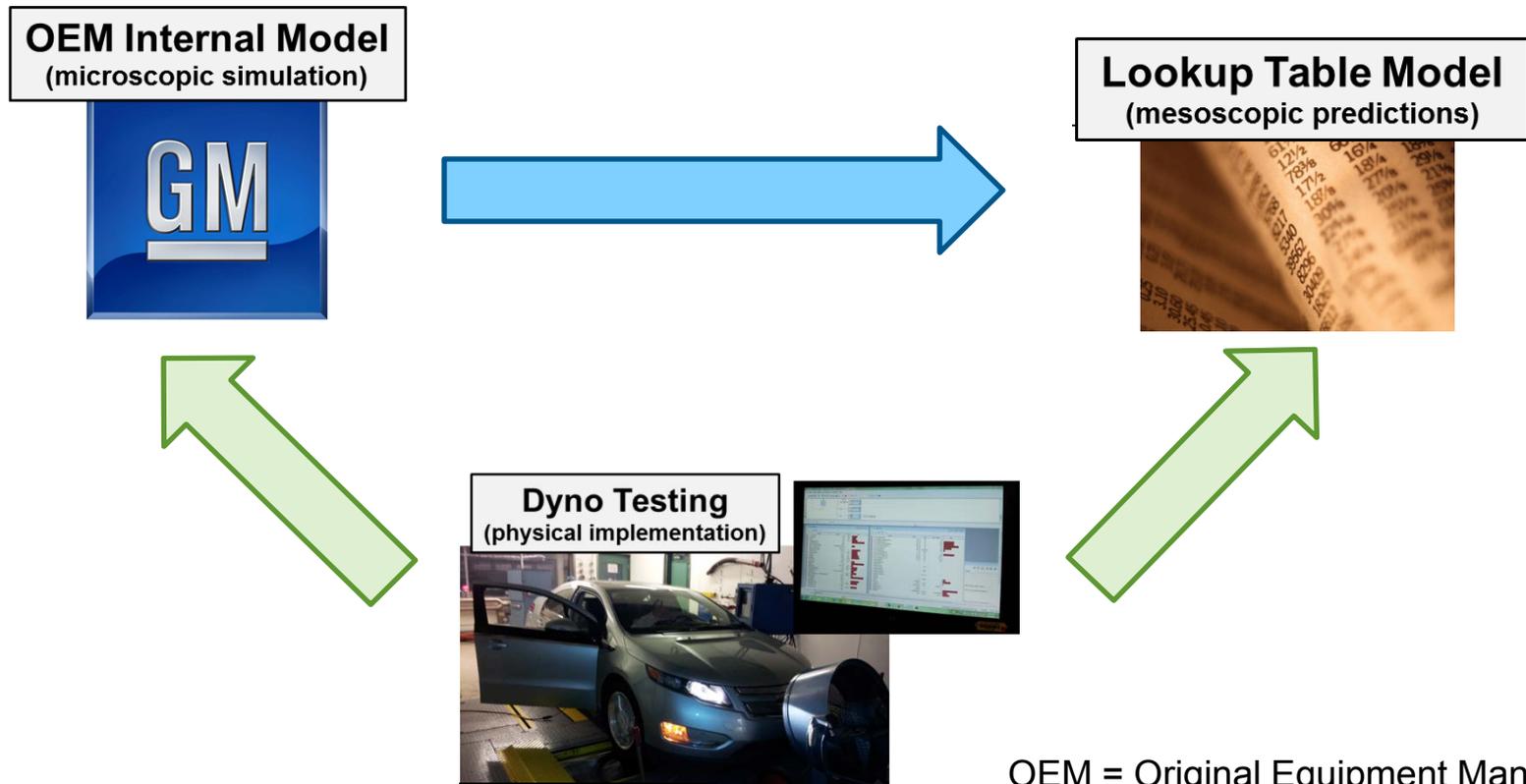




Energy Estimation Model

Modeling Environments

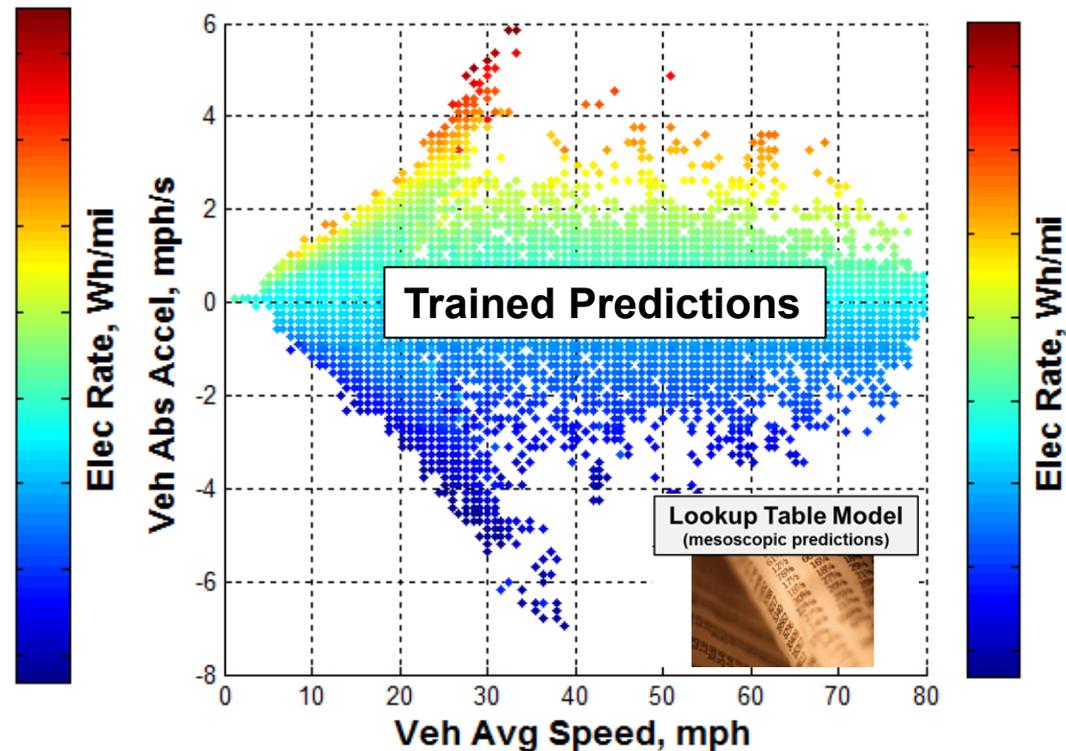
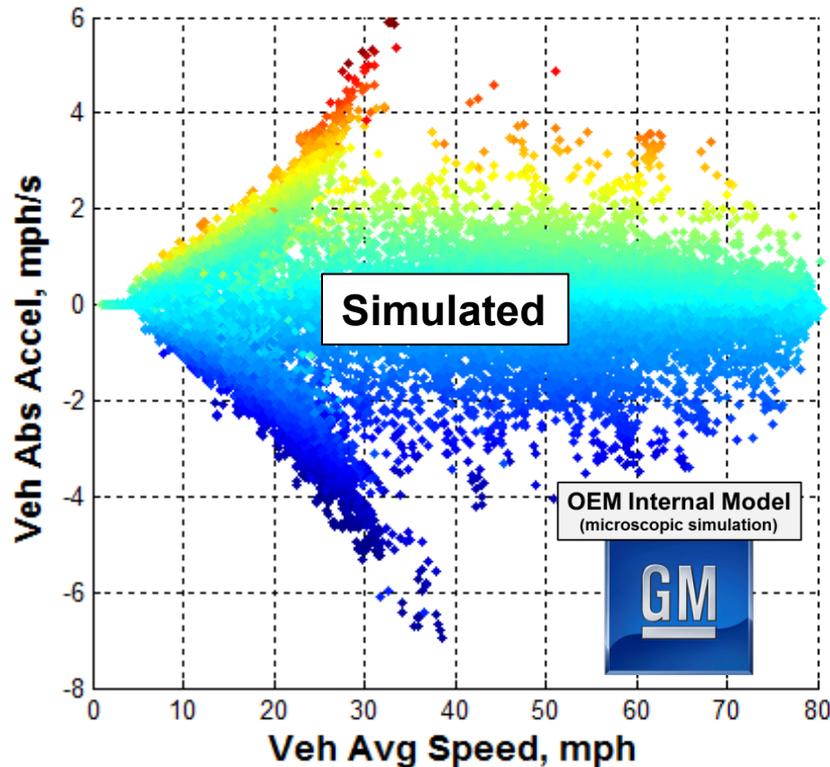
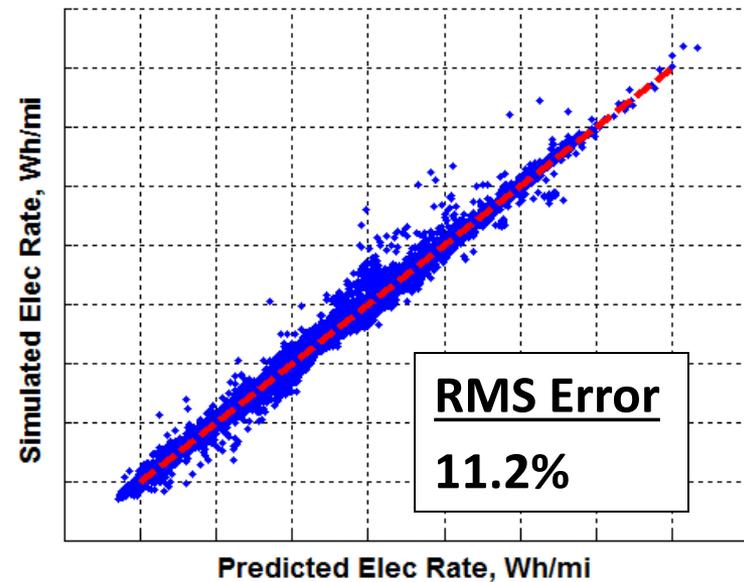
- Use GM internal model of Volt to train lookup tables for electric and fuel depletion rates (relative to speed, acceleration, grade, and SOC)
- Spot check both models against test data collected from Volt during dynamometer testing



OEM = Original Equipment Manufacturer

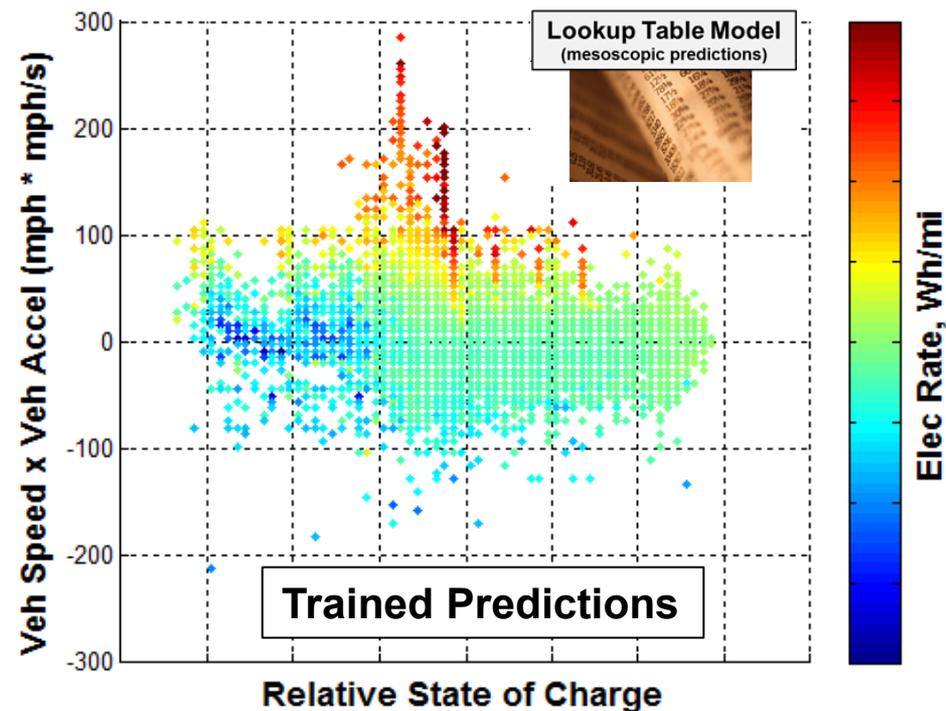
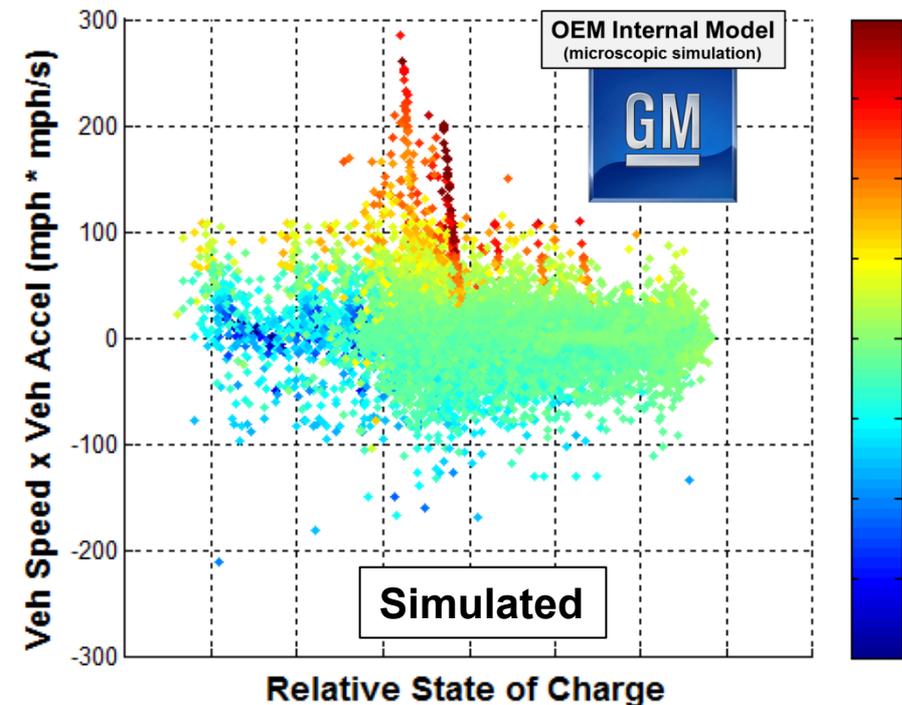
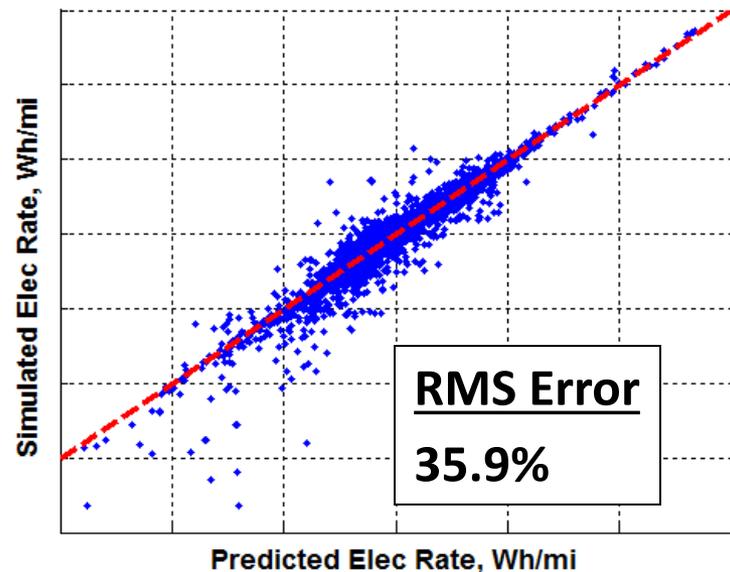
All-Electric Operation

- OEM model simulations are aggregated by nanotrip and scattered versus speed/accel
- Digital lookup table is then built using data from OEM model
- Lookup table is exercised over original data to demonstrate degree of fit



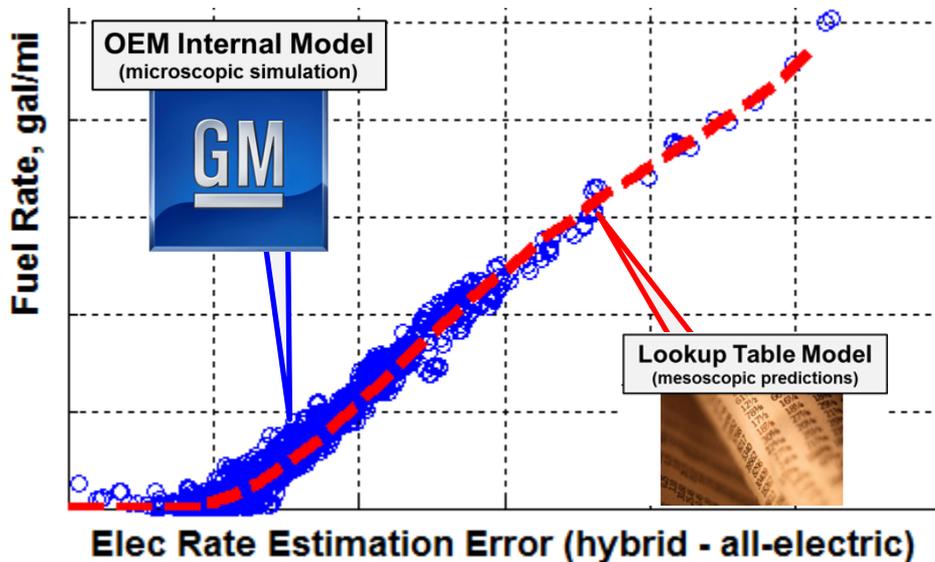
Hybrid Operation

- OEM model simulations are aggregated by nanotrip and scattered versus speed/accel/SOC
- Digital lookup table is then built using data from OEM model
- Lookup table is exercised over original data to demonstrate degree of fit

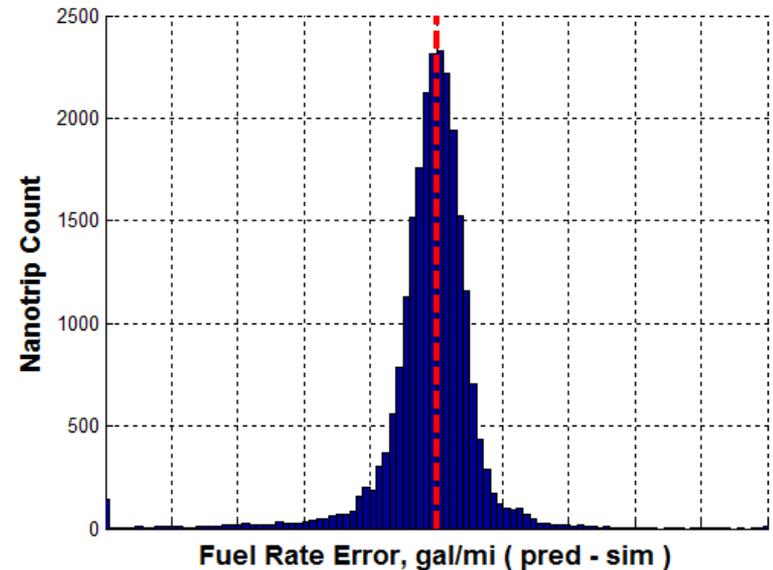
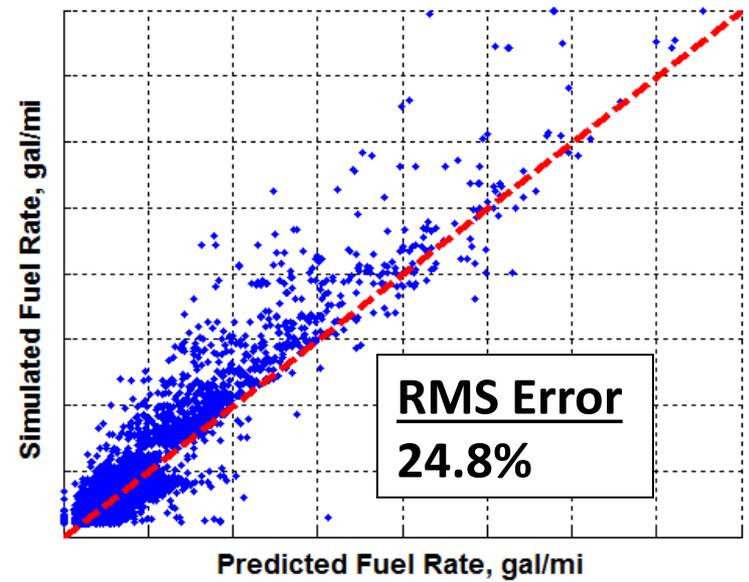


Hybrid Operation

- OEM model simulations are aggregated by nanotrip and scattered versus electric rate prediction error
- Best fit polynomial is then calculated using data from OEM model
- Lookup table is exercised over original data to demonstrate degree of fit

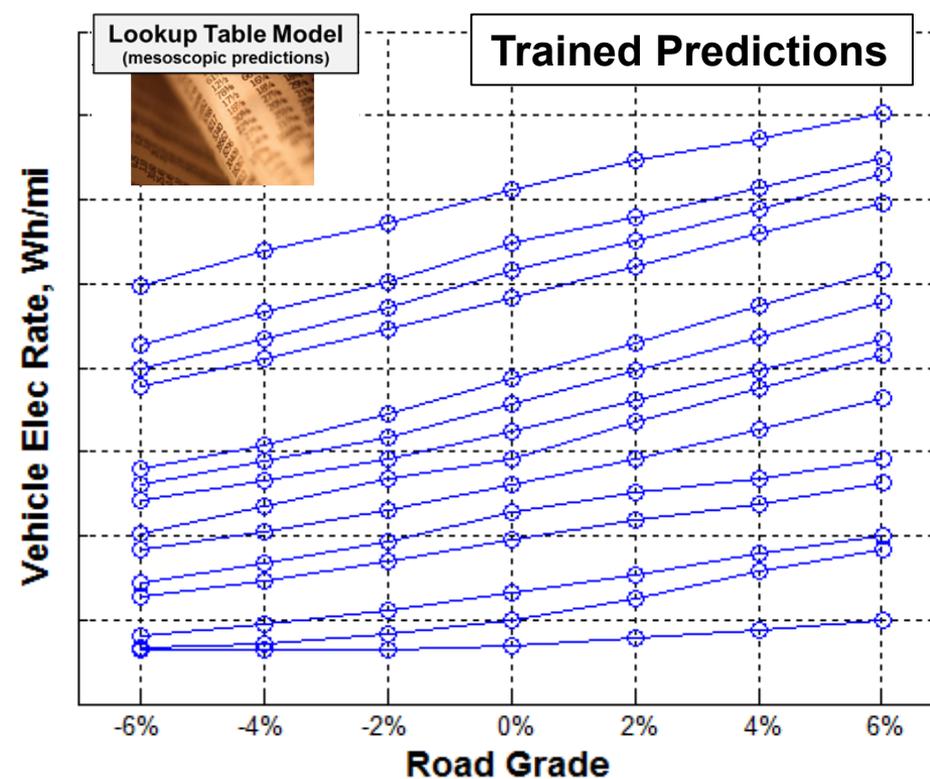
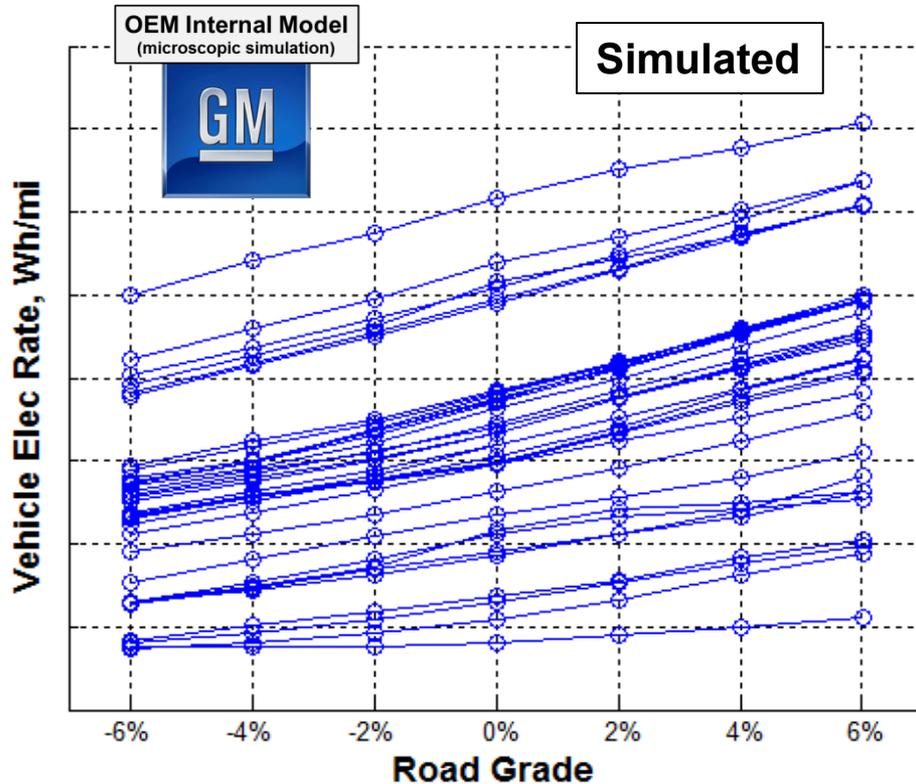
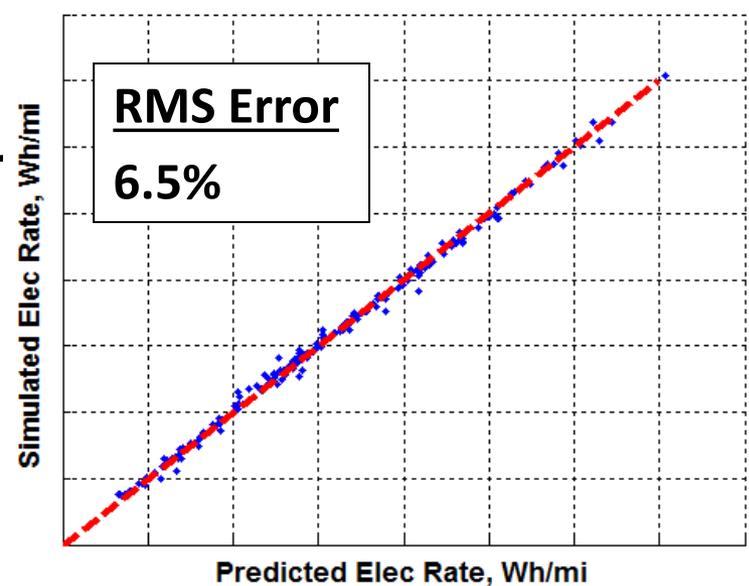


X-axis represents difference in electric rates predicted by hybrid and all-electric lookup tables



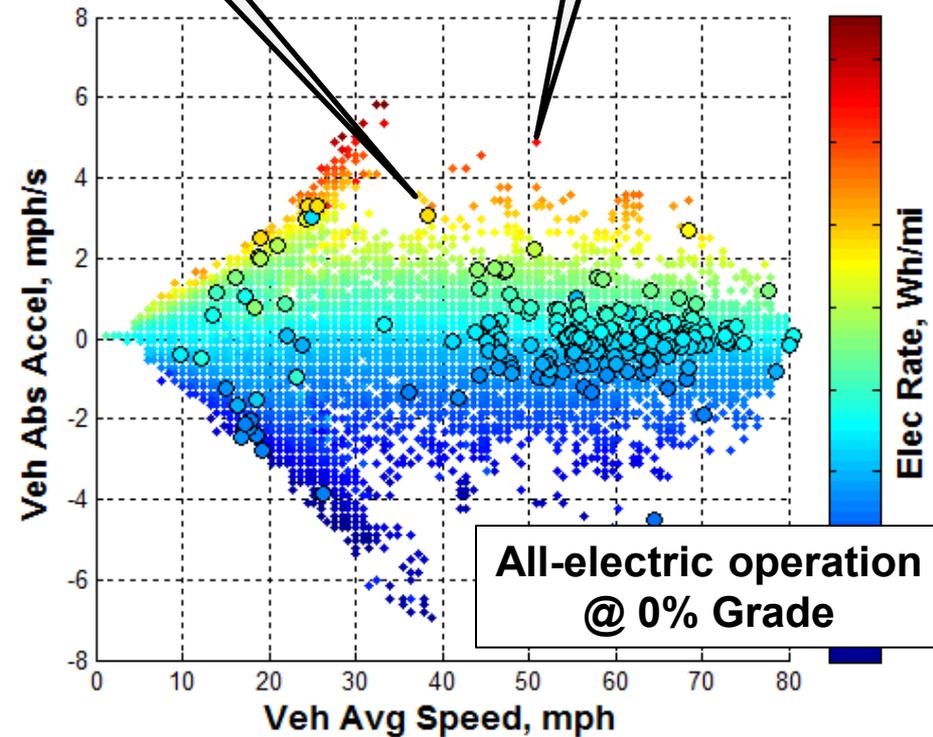
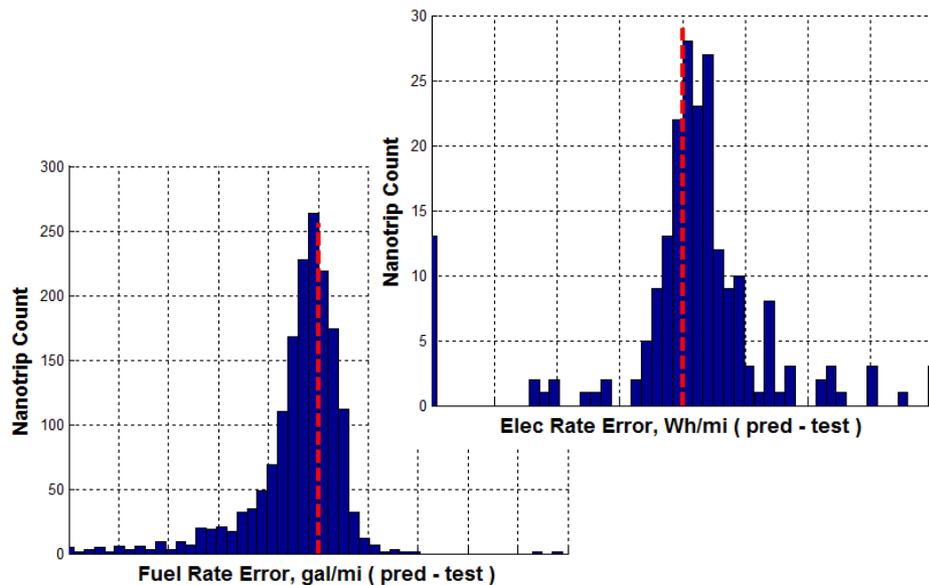
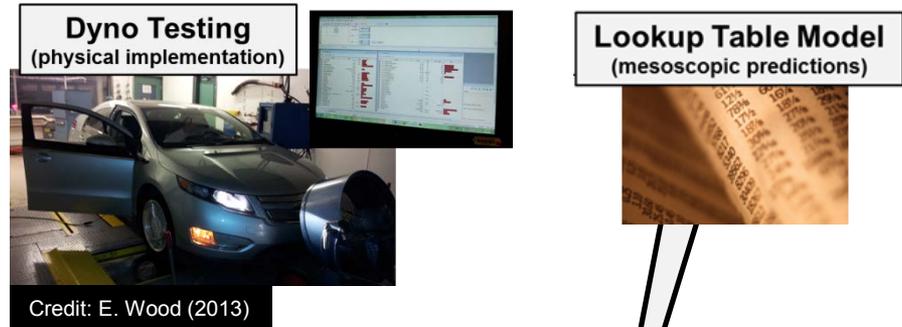
Electric Rate at Grade

- OEM model simulations are aggregated by speed/accel and scattered versus road grade
- Digital lookup table is then built using data from OEM model
- Lookup table is exercised over original data to demonstrate degree of fit



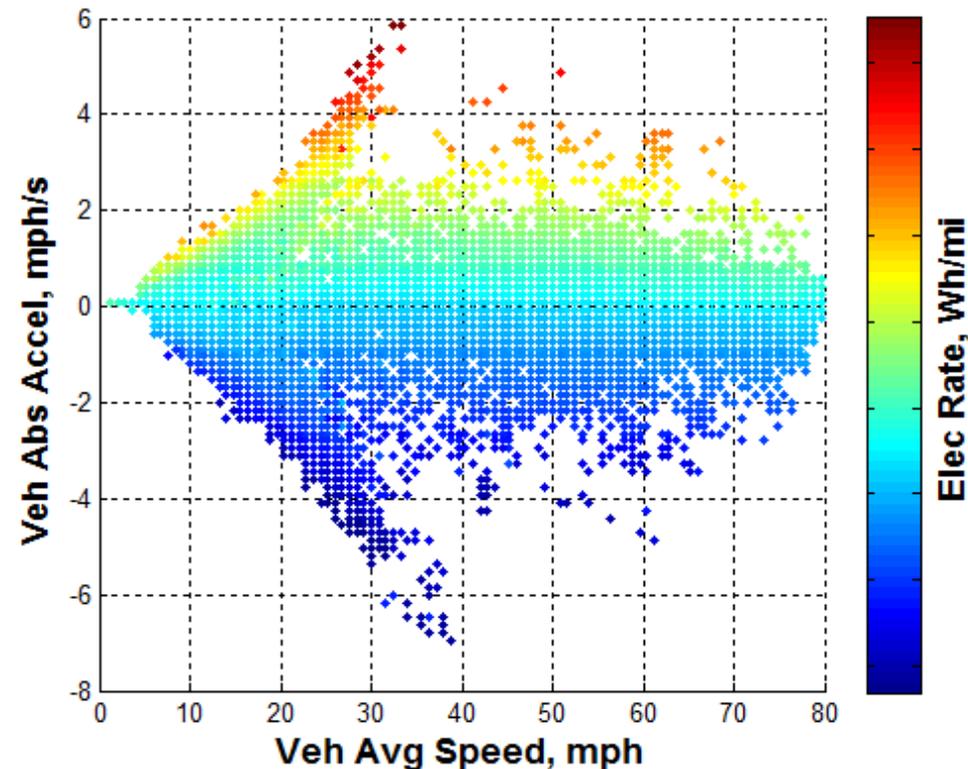
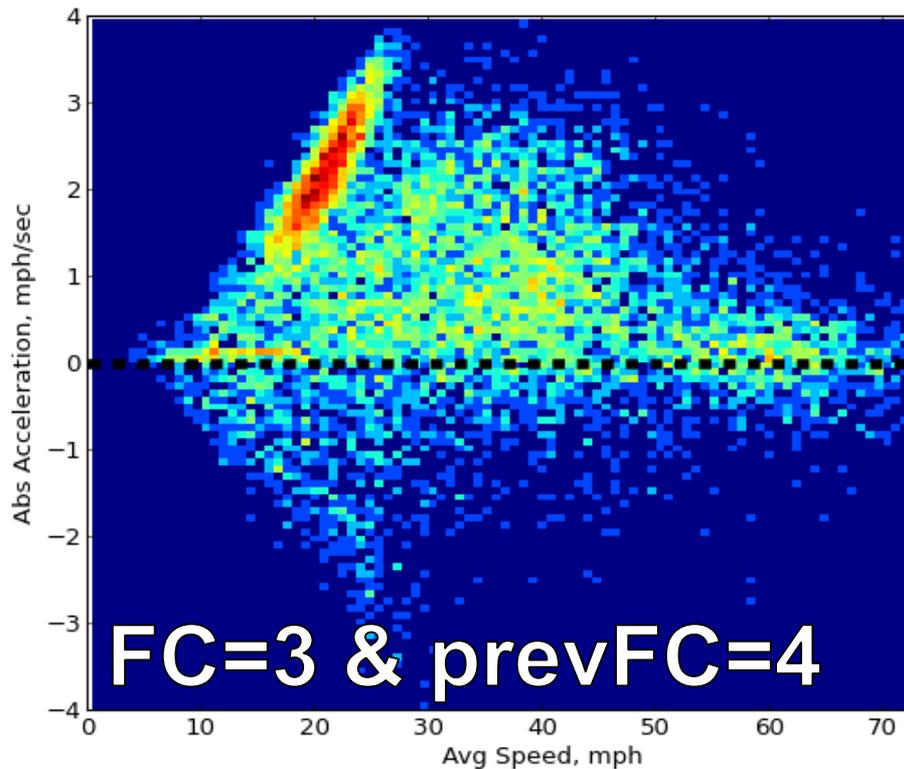
Validation to Test Data

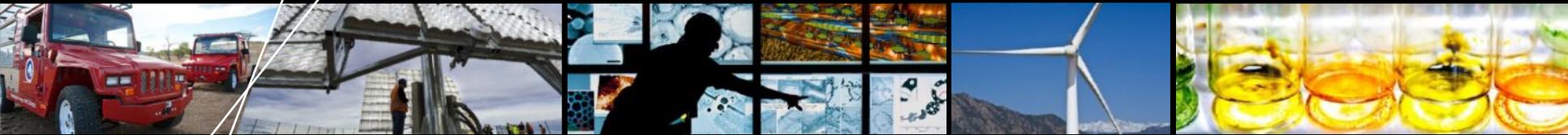
- Small amount of testing was conducted to spot check modeled values with respect to speed, accel, SOC, and road grade



Putting Everything Together...

- Drive cycle and vehicle maps can be overlaid to calculate weighted average rate for any combination of road type and vehicle state

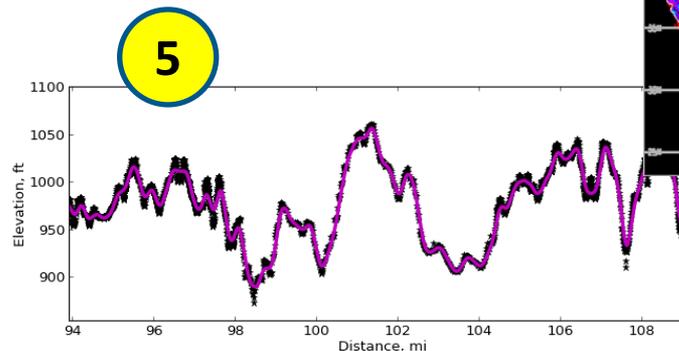
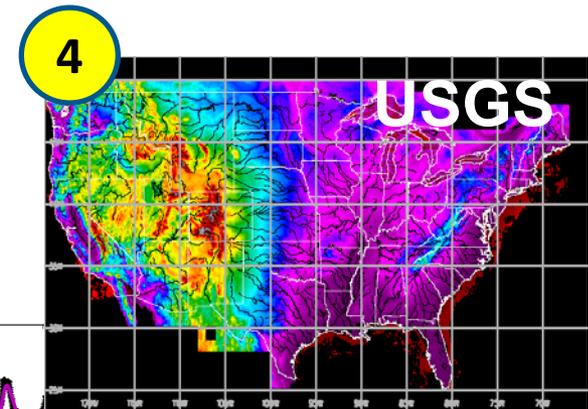
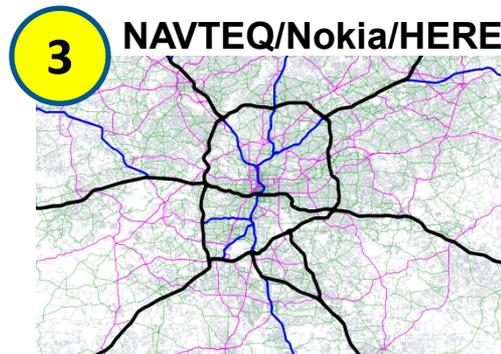
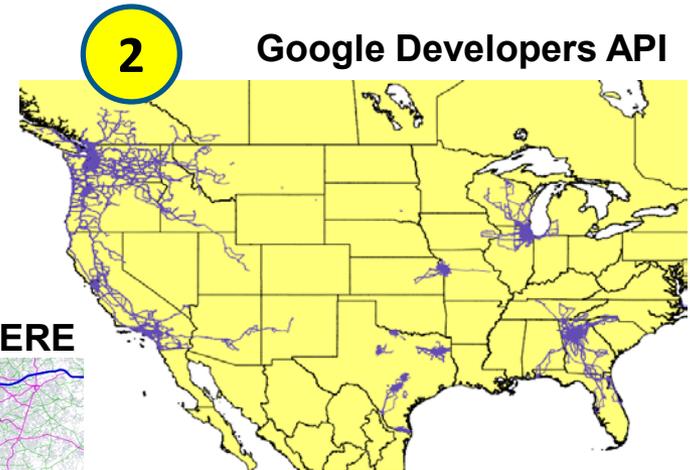




TSDC + Google Directions API

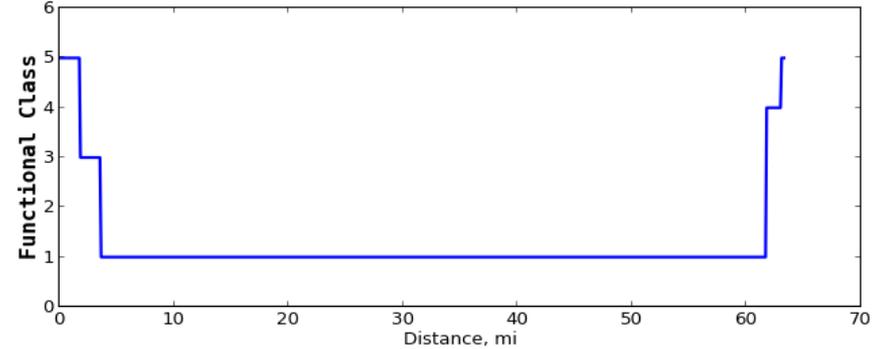
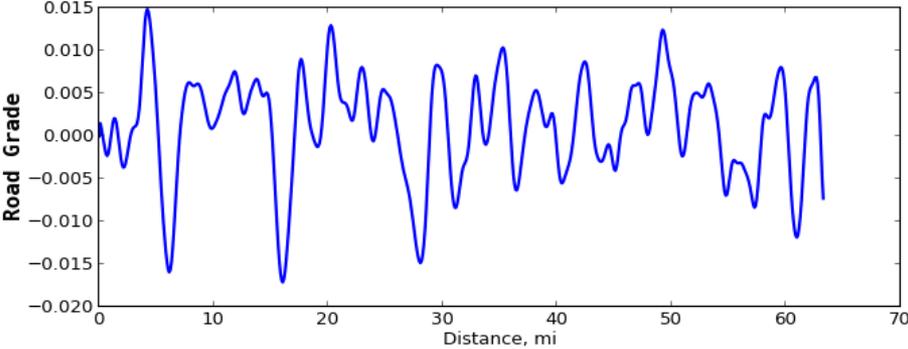
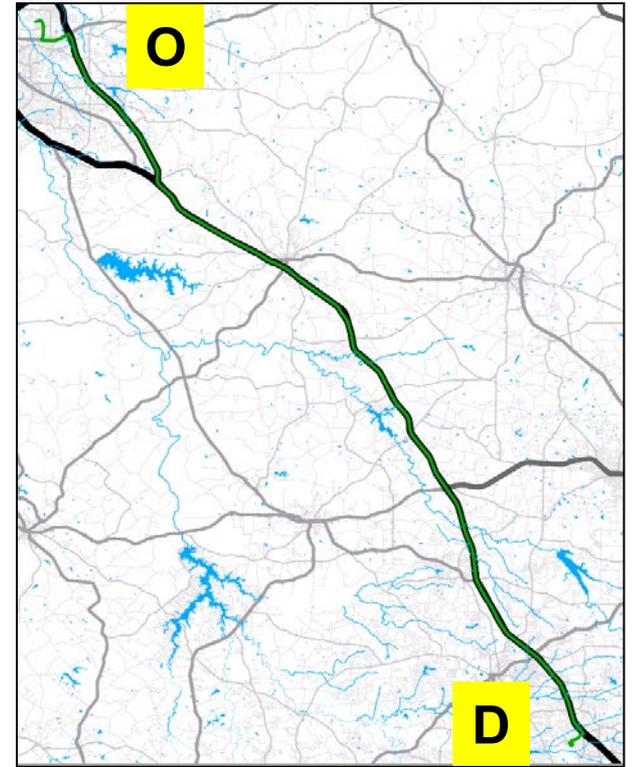
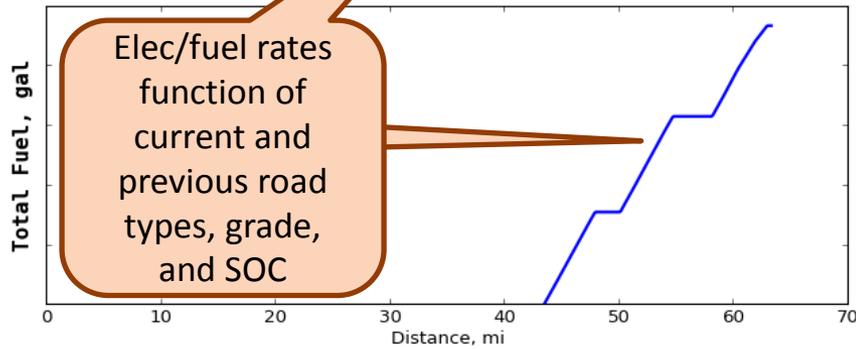
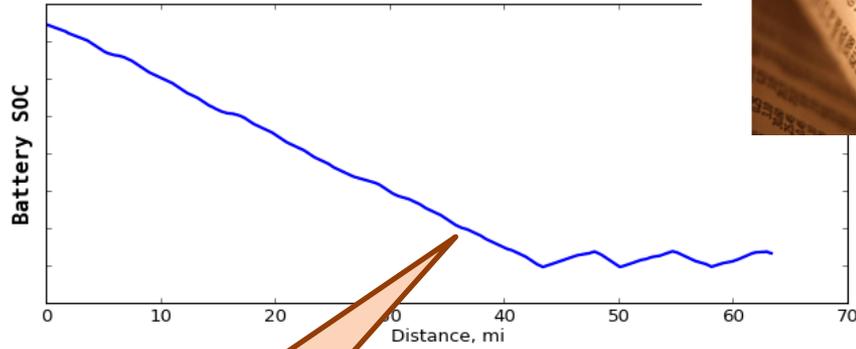
Model Evaluation: Setting the table

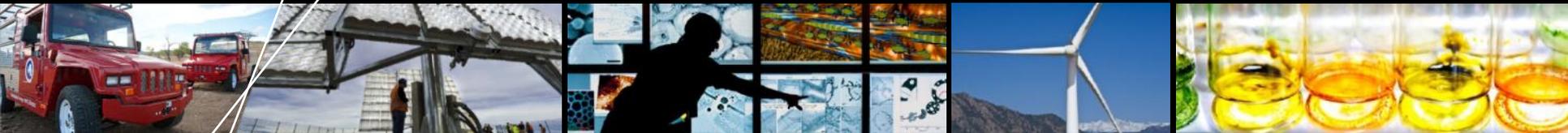
1. Extract real-world origin/destination (O/D) pairs from NREL's TSDC
2. Feed O/D pairs through Google Directions API returning multiple routes for each O/D pair
3. Map match routes to Navteq streets layer to determine functional class and speed category
4. Append elevation to each route using the USGS digital elevation model
5. Filter and smooth elevation profiles to remove anomalous road grades



Model Evaluation: Example

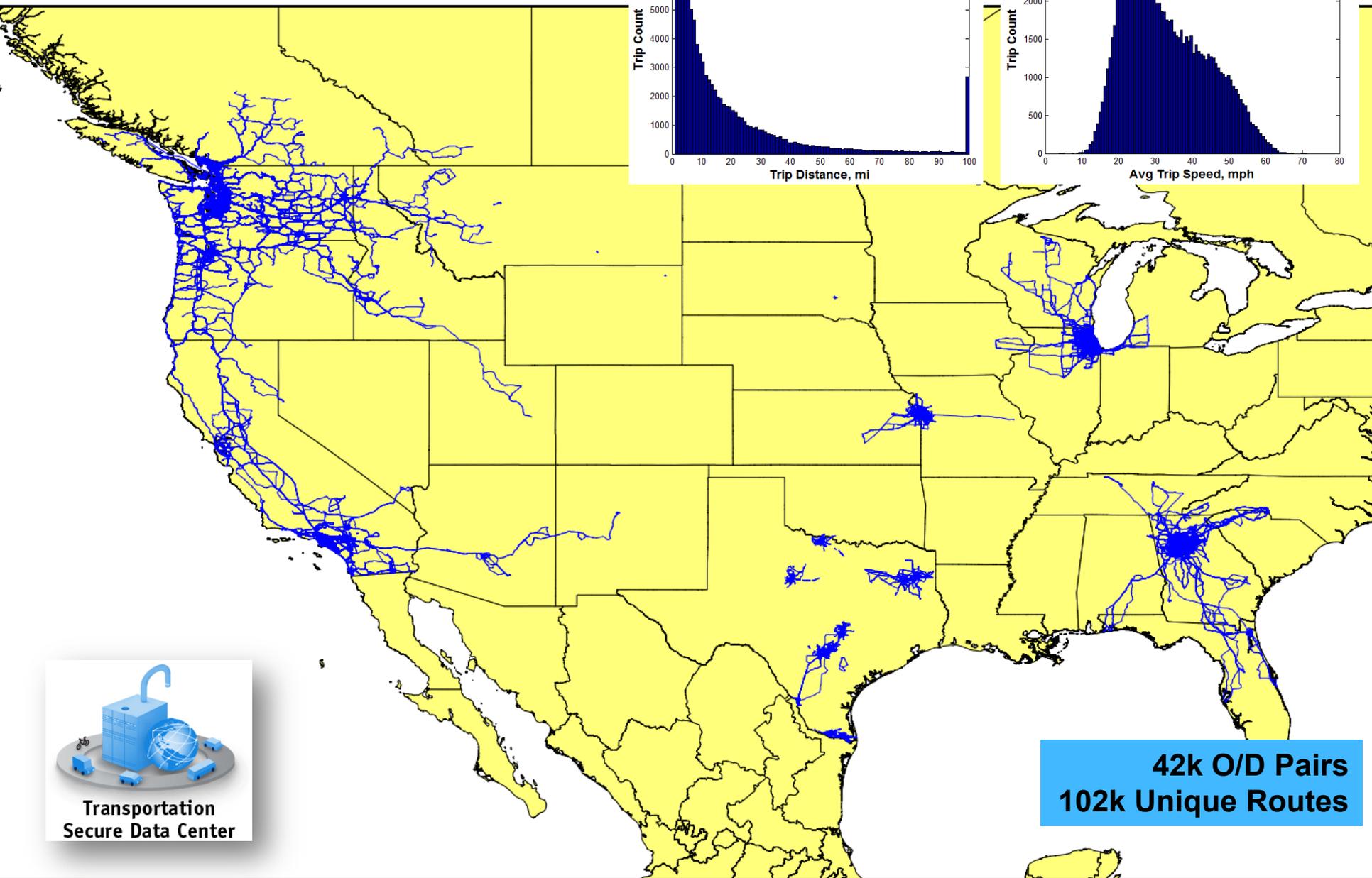
Lookup Table Model
(mesoscopic predictions)





Green Routing

Google Directions



42k O/D Pairs
102k Unique Routes

Route Summary

***Consider the route with the shortest estimated travel time to be the default.**

- **One Option**

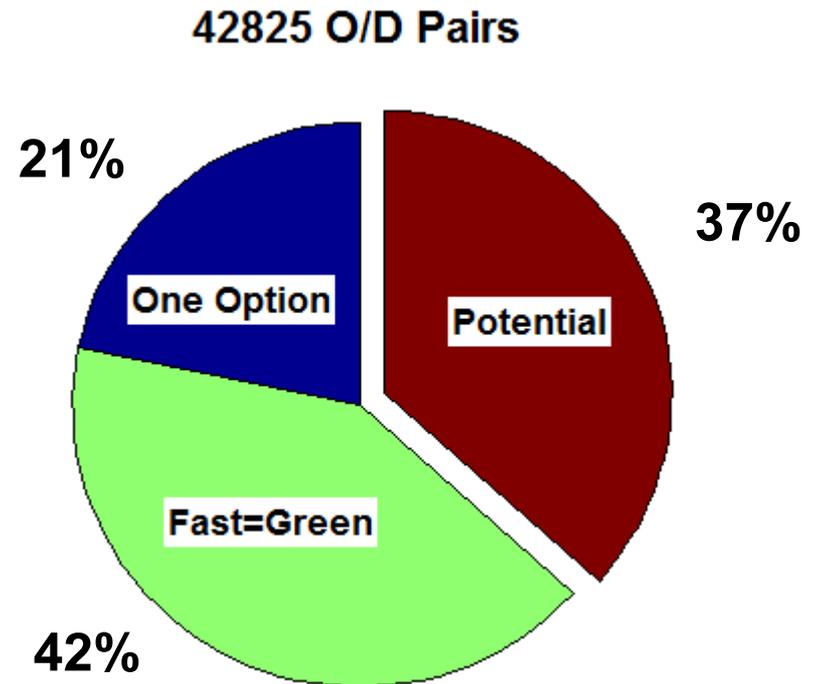
- Directions API only provided one route for 21% of O/D pairs

- **Fast = Green**

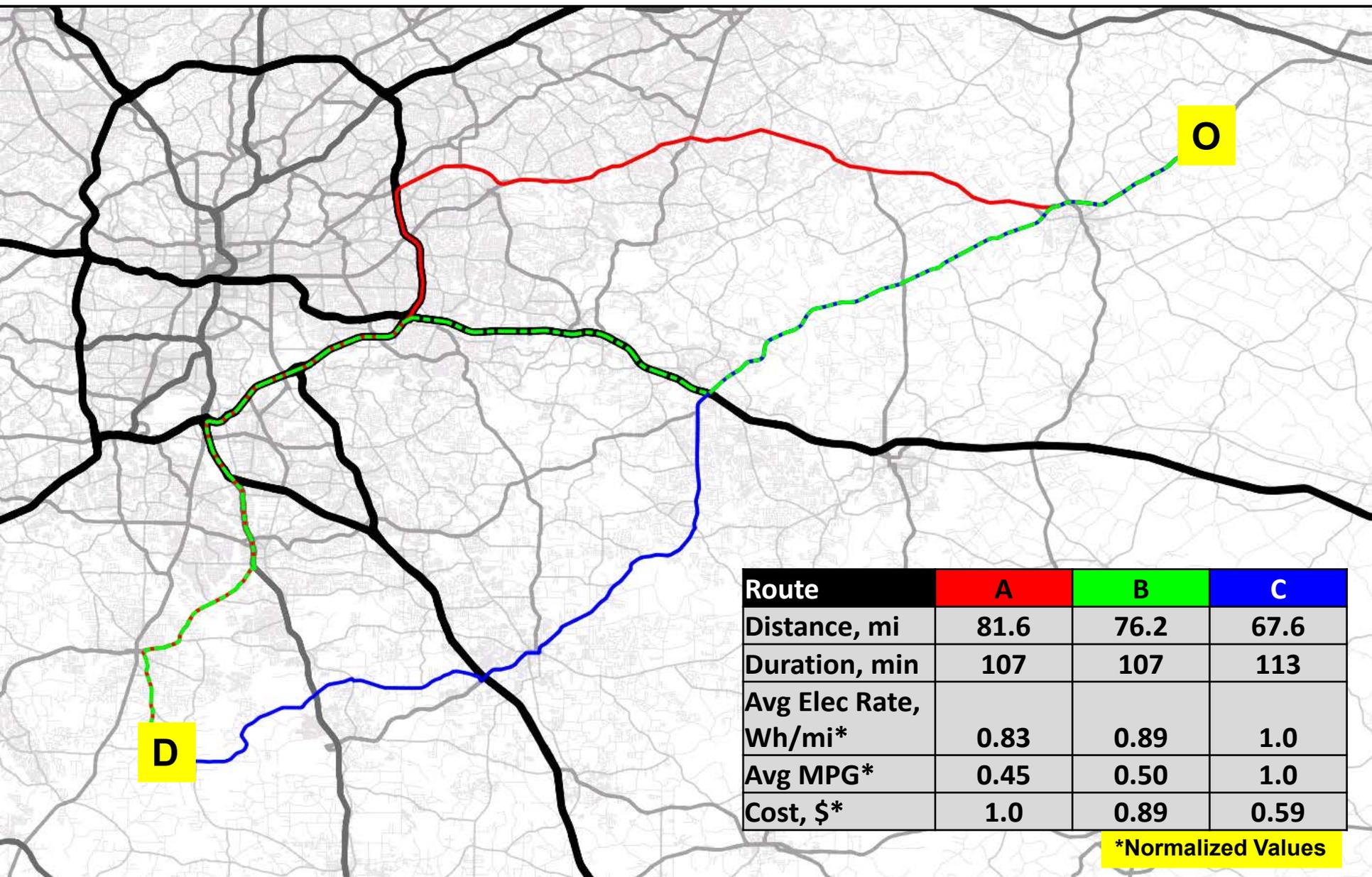
- The route with the estimated shortest travel time also required the least amount of estimated energy to complete for 42% of O/D pairs

- **Potential**

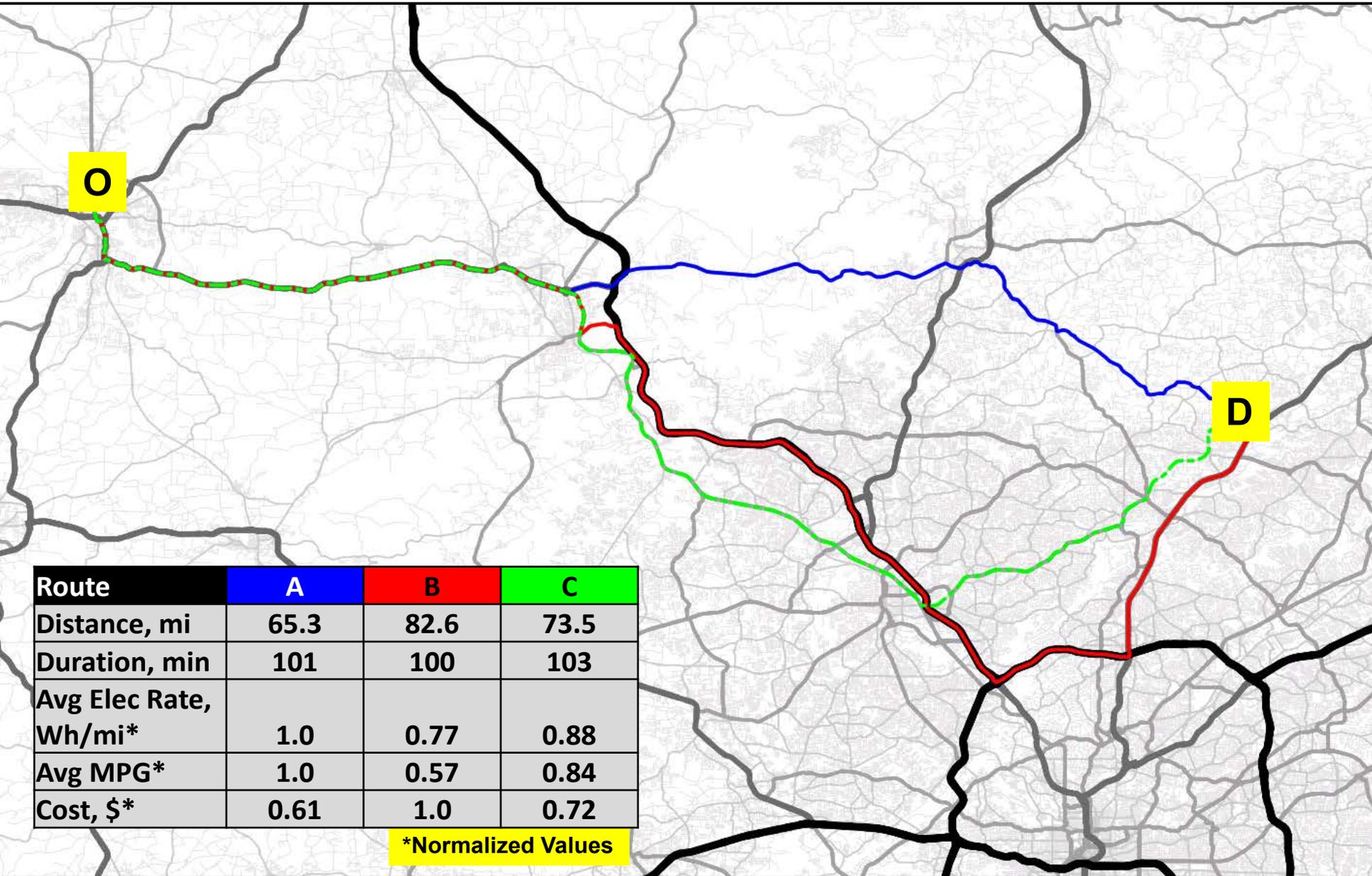
- The remaining 37% of O/D pairs offer the potential for a green routing algorithm to inform an energy saving route selection



Green Routing Example

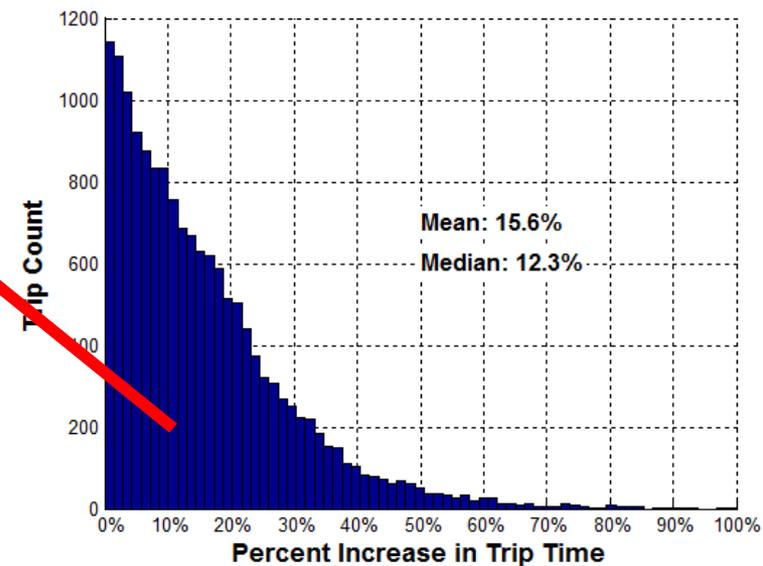
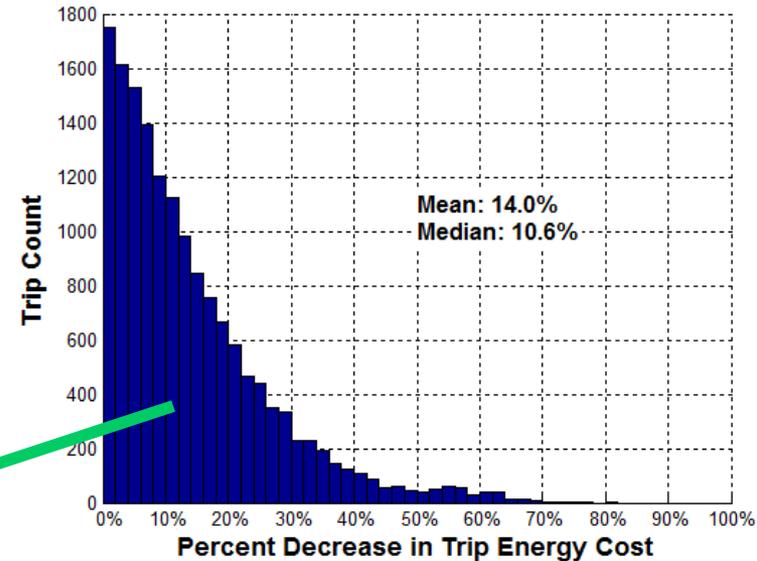


Green Routing Example



Will people select the green route?

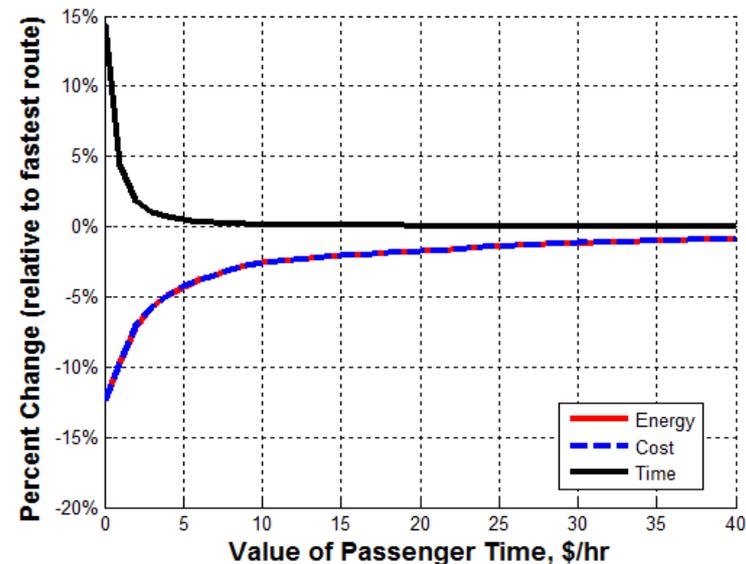
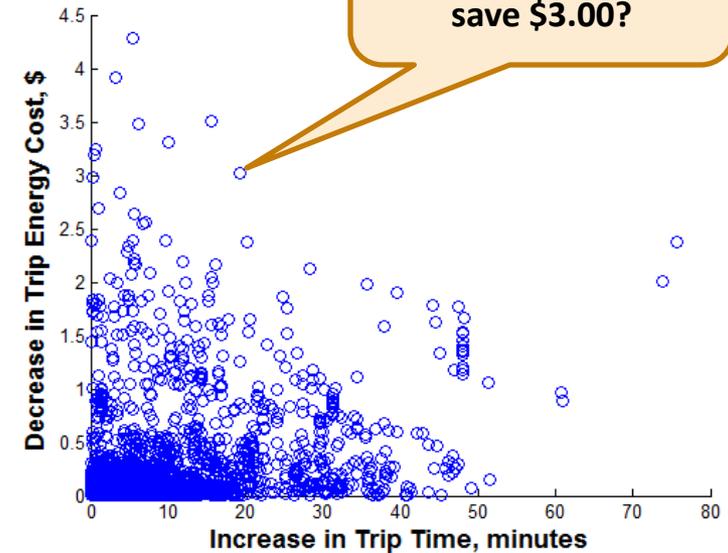
- On aggregate the benefits of green routing appear to be significant
- However, in order for green routes to be selected in practice, the **incentive of energy savings** must be weighed against **disincentive of longer travel times**

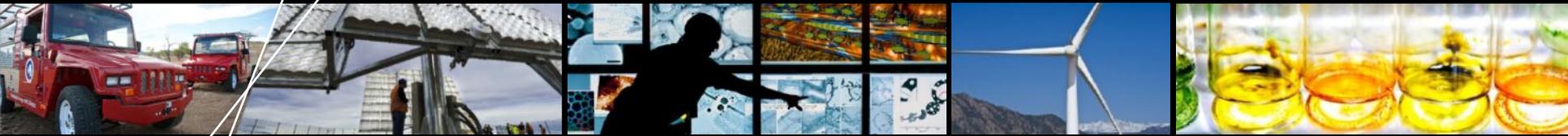


Value of Time Considerations

- Energy savings is plotted against increase in travel time (selecting green route over shortest duration)
- This 2D space is swept versus value of passenger time (\$/hr) to show cumulative effects of green routing given a return on investment threshold
 - **Ex1:** If passenger has no value of time, cost/energy could be decreased by 12.3% and travel time increased by 14.4%
 - **Ex2:** If passenger values time at \$35/hr, cost/energy could be decreased by 1.0% and travel time increased by 0.0%

*The data only consider the 37% of O/D pairs previously identified as having green routing potential.





Control Mode Scheduling

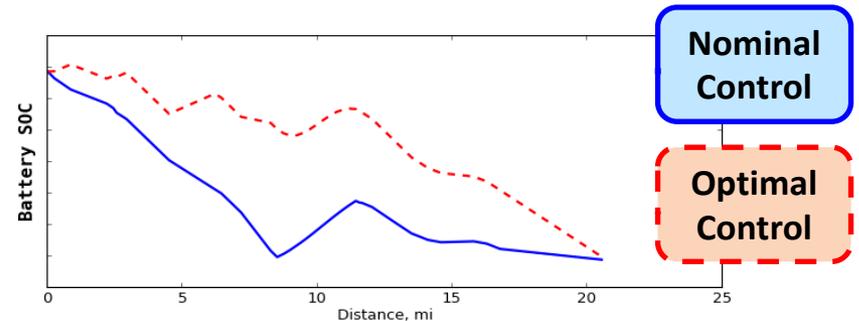
Mode Scheduling: Methodology

1. Evaluate route twice, assuming:

- Vehicle operates with no knowledge of route (nominal schedule)
- Vehicle operates exclusively in AE mode across all links (optimized schedule)

2. Substitute hybrid links into the optimized schedule until:

$$SOC_{final,opt} \geq SOC_{final,nom}$$



3. Order substitutions such that the following cost/benefit ratio is minimized:

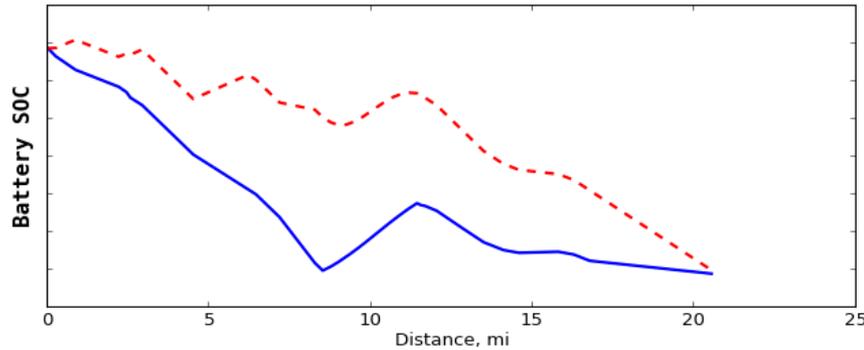
$$\frac{Cost}{Benefit} = \frac{Fuel_{hybrid\ mode}}{Elec_{AE\ mode} - Elec_{hybrid\ mode}}$$

Decrease battery depletion rate while minimizing fuel use (battery depletion defined as positive electric rate)

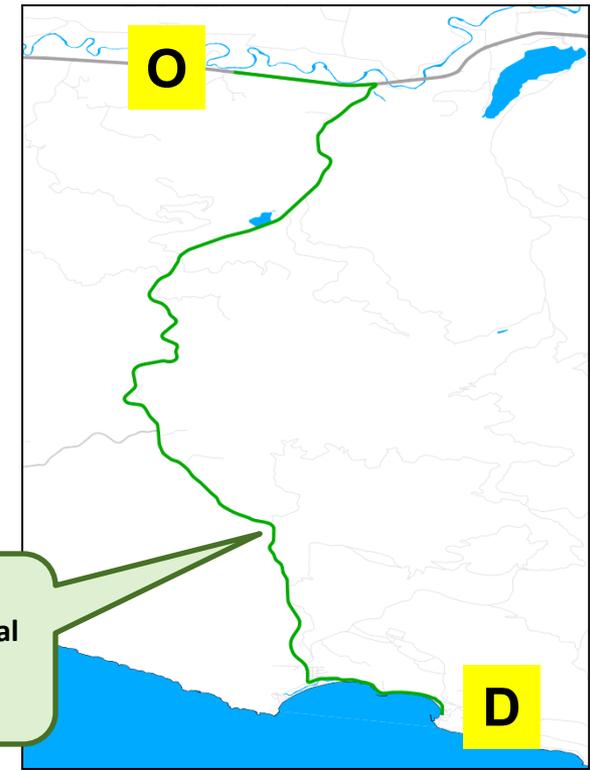
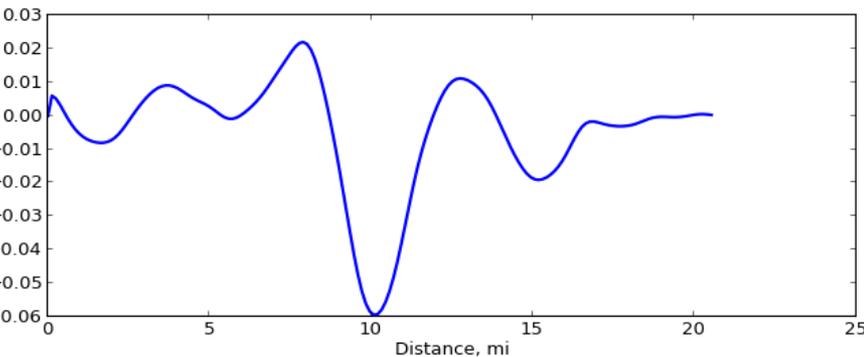
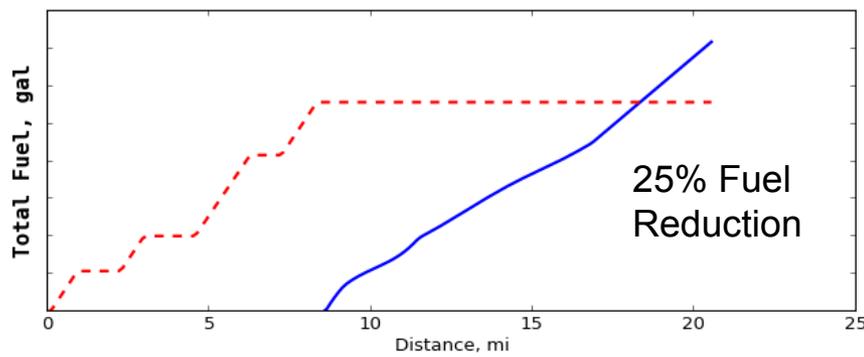
*AE = All-Electric

Mode Scheduling: Example

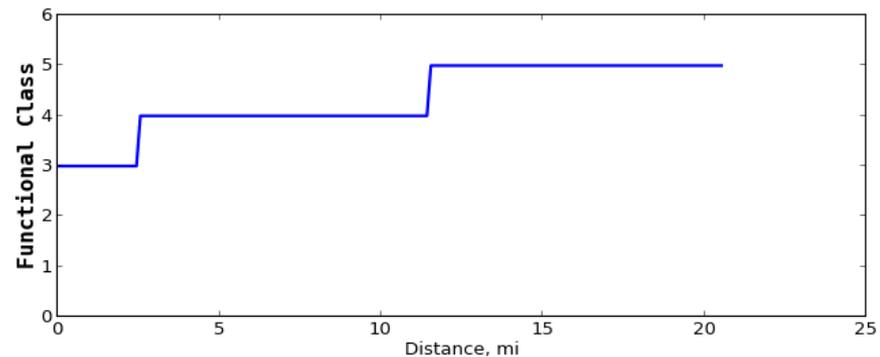
Utilize engine at highway speeds



Nominal Control
Optimal Control

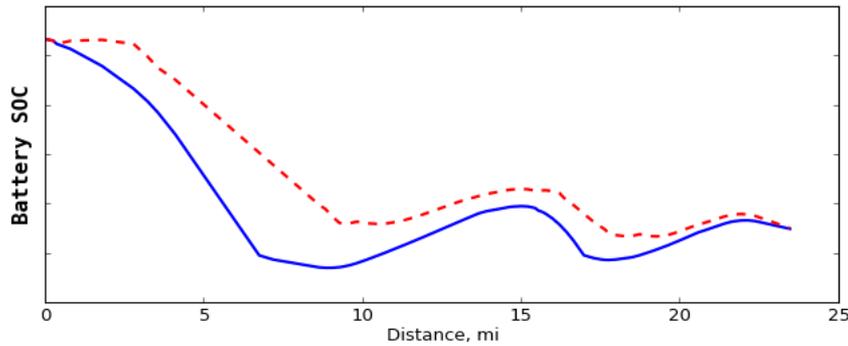


Transition from highway to residential speeds upon approaching coast



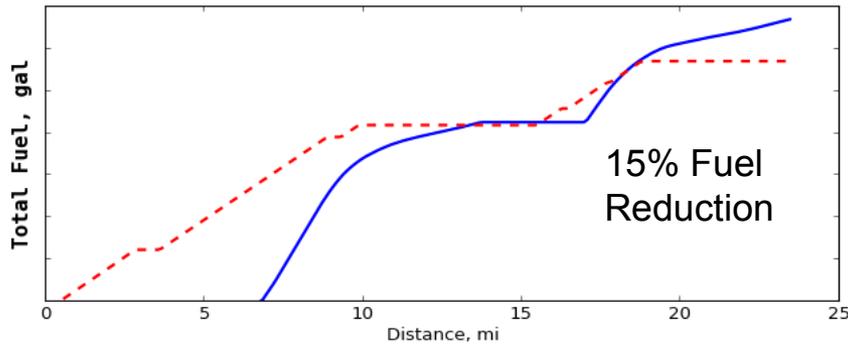
Mode Scheduling: Example

Anticipate hill climbs

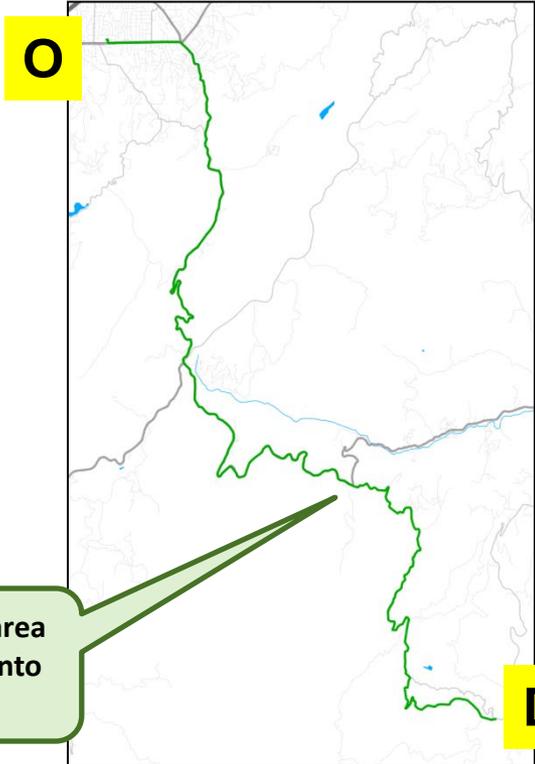
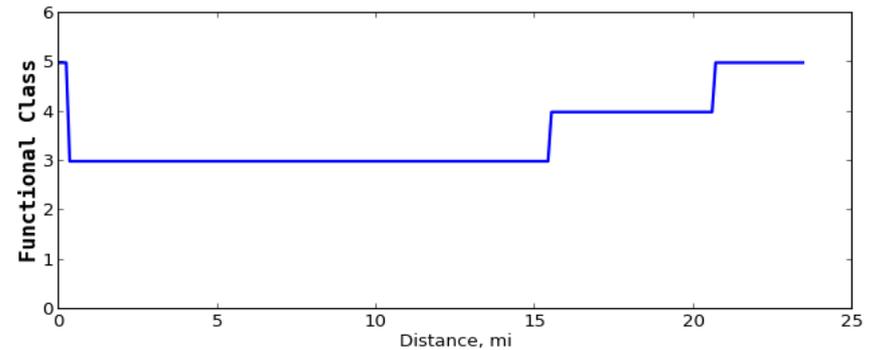
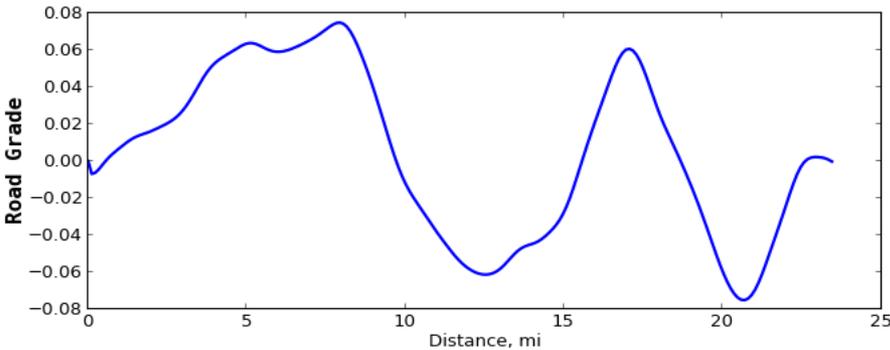


Nominal Control

Optimal Control

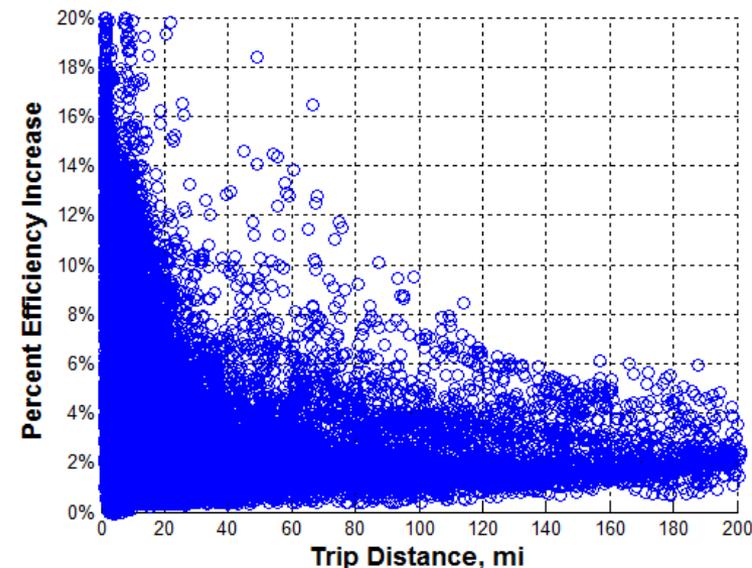
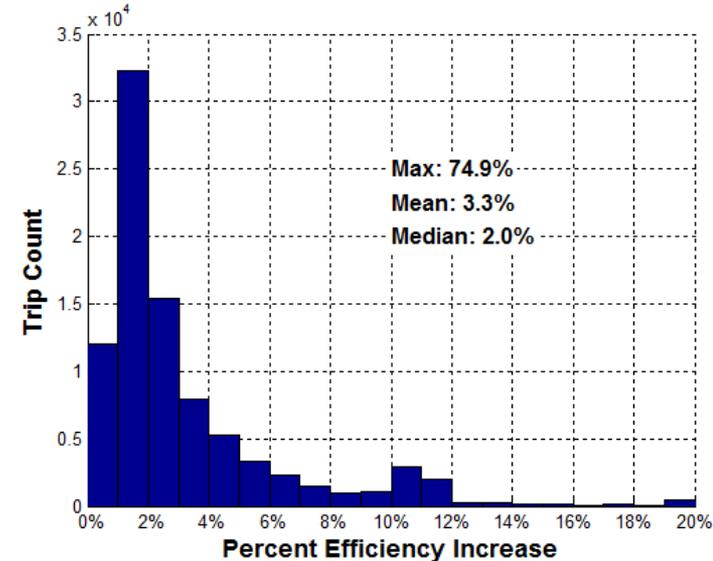


15% Fuel Reduction



Mode Scheduling: Aggregate Results

- Across 100k+ trips, intelligent mode scheduling increased efficiency by an average of 3.3%
- Short distance trips exhibited the greatest potential for mode scheduling
- Further gains could be achieved by making route-connected information available to low-level hybrid control algorithms



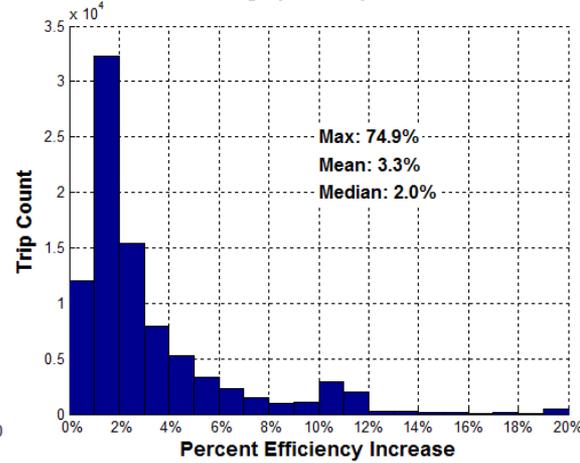
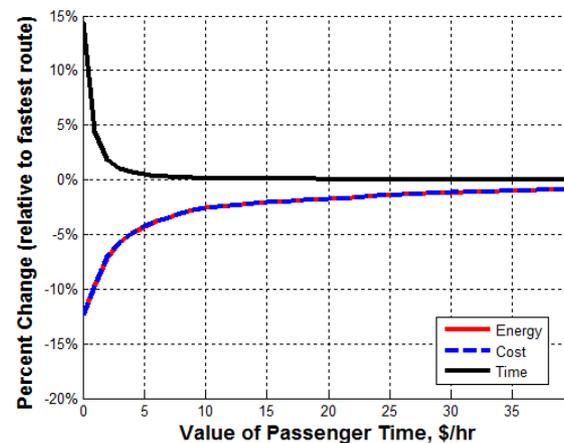
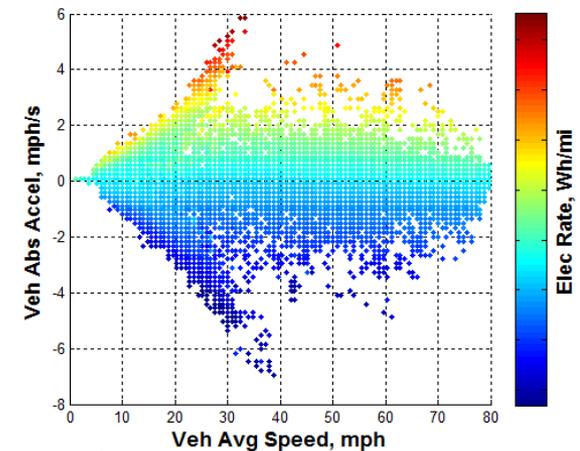
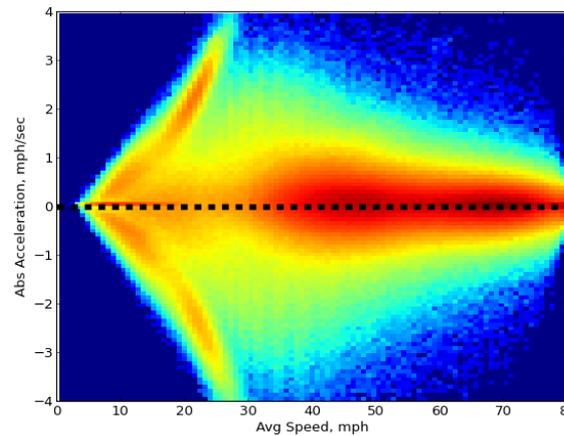
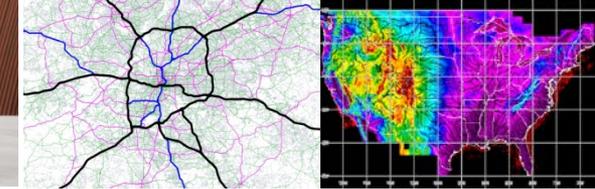
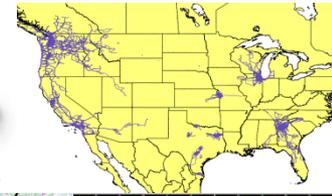
Summary

NREL IG 18563

- Demonstrated ability to model vehicle speed/accel profiles relative to road type
- Constructed high-level powertrain model employing cycle metrics and vehicle state as inputs
- Applied model using real-world distribution of O/D pairs, demonstrating:
 - Aggregate energy savings of up to 4.6% for green routing (relative to passenger value of time)
 - Average energy savings of 3.3% for mode scheduling



Transportation Secure Data Center



Thanks! Questions?



NAVTEQ/Nokia/HERE Road Attributes

- **Speed Category (1-8)**

1. Greater than 80 mph
2. 65-80 mph
3. 55-64 mph
4. 41-54 mph
5. 31-40 mph
6. 21-30 mph
7. 6-20 mph
8. Less than 6 mph

- **Functional Class (1-5)**

1. Roads with very few, if any speed changes, typically controlled access, and provide high volume, maximum speed movement between and through major metropolitan areas.
2. Roads with very few, if any speed changes, and provide high volume, high speed traffic movement. Typically used to channel traffic to (and from) Level 1 roads.
3. Roads which interconnect Level 2 roads and provide a high volume of traffic movement at a lower level of mobility than Level 2 roads.
4. Roads that provide for a high volume of traffic movement at moderate speeds between neighborhoods.
5. All other roads.