NREL
NATIONAL RENEWABLE ENERGY LABORATORY

NREL/Industry Range-Extended Electric Vehicle for Package Delivery

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SAE 2017 Range-Extenders for Electric Vehicles Symposium
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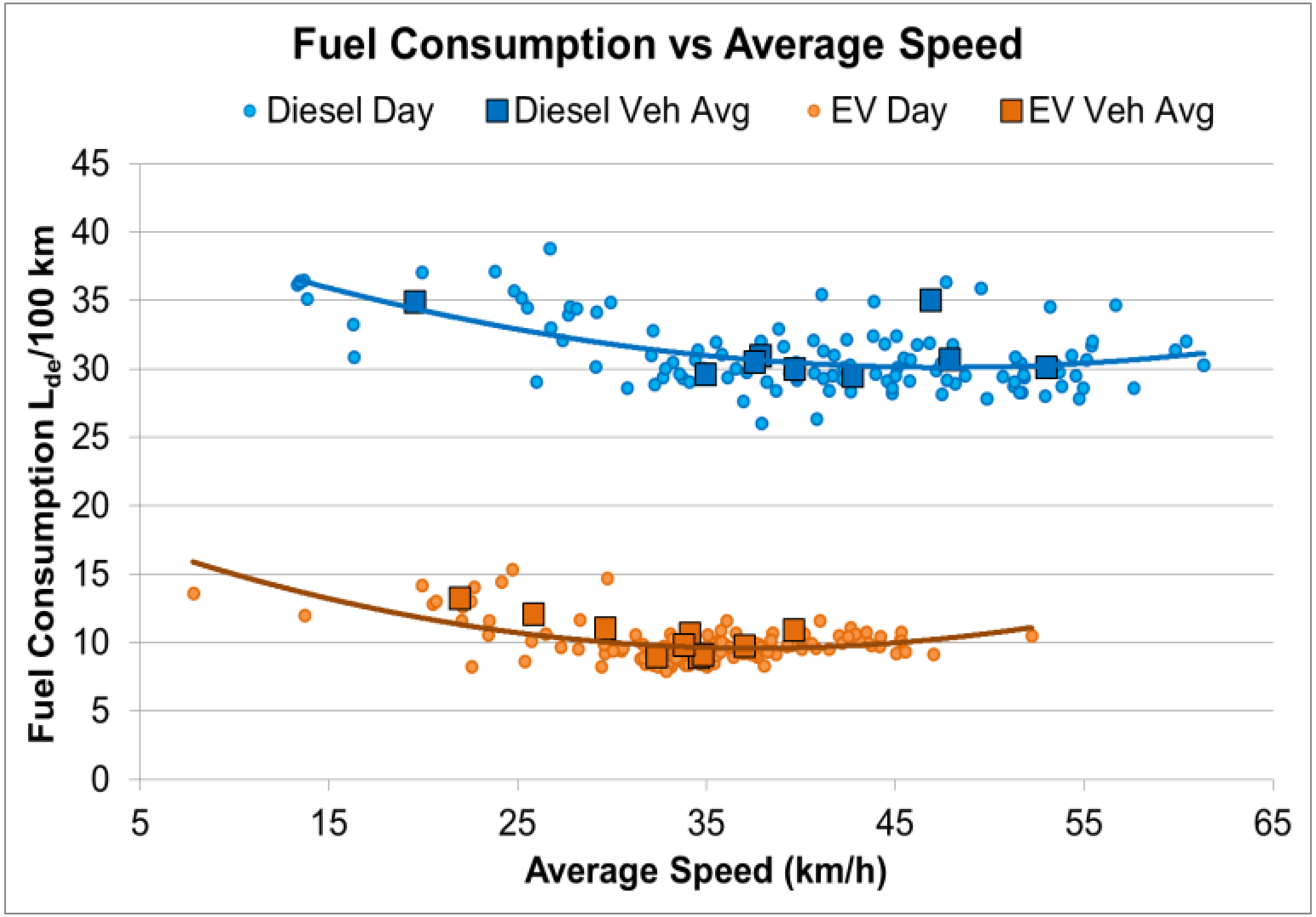
NREL/PR-5400-70558

Approach and Overarching Questions

- Range extenders can be viable technology option for reducing fuel consumption from medium-duty (MD) and heavy-duty (HD) engines
- MD and HD engines have wide variations in use and duty cycle
- How best to identify vocations/duty cycles most suitable for range-extender applications?
- How to optimize powertrain and design requirements?

Benefits of MD/HD Electrification

- Up to 3–4x FE benefit (energy equivalent basis)
- Lower maintenance costs
- Vocation-specific benefits
  - Reduced tailpipe emissions
  - Quiet operation
  - Off-board power
  - Potential for grid services
- U.S. manufacturing and innovation opportunities



MD/HD Electrification: Remaining Challenges

- Low-volume production limits economies of scale
- Energy storage requirements, high cost and range limitations
- Fleet education, unbiased information, and long-term support
- Electric accessories – significant impact on energy consumption
- Centralized fleets may experience significant utility demand charges

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Overview

I. Data collection and analysis approach

II. Parcel delivery range-extender results

NREL Field Data, Evaluation, and Analysis Tools

Data from field evaluations help populate Fleet DNA database

DOE fleet tools (DRIVE, FASTSim, AFLEET, etc.) used to analyze and investigate impacts – data used to validate and improve tools

Published information and data used by fleets, industry, DOE, and other research programs and agencies

Collect Lab and Field Data

Capture, Store, and Analyze

Laboratory Testing

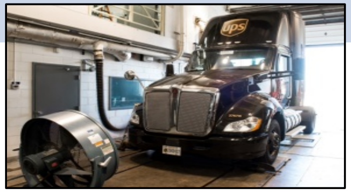
Explore & Optimize

Communicate & Inform

Identify Barriers, New R&D Opportunities, Validate Efforts

Fleet DNA Project

DRIVE Analysis Tool



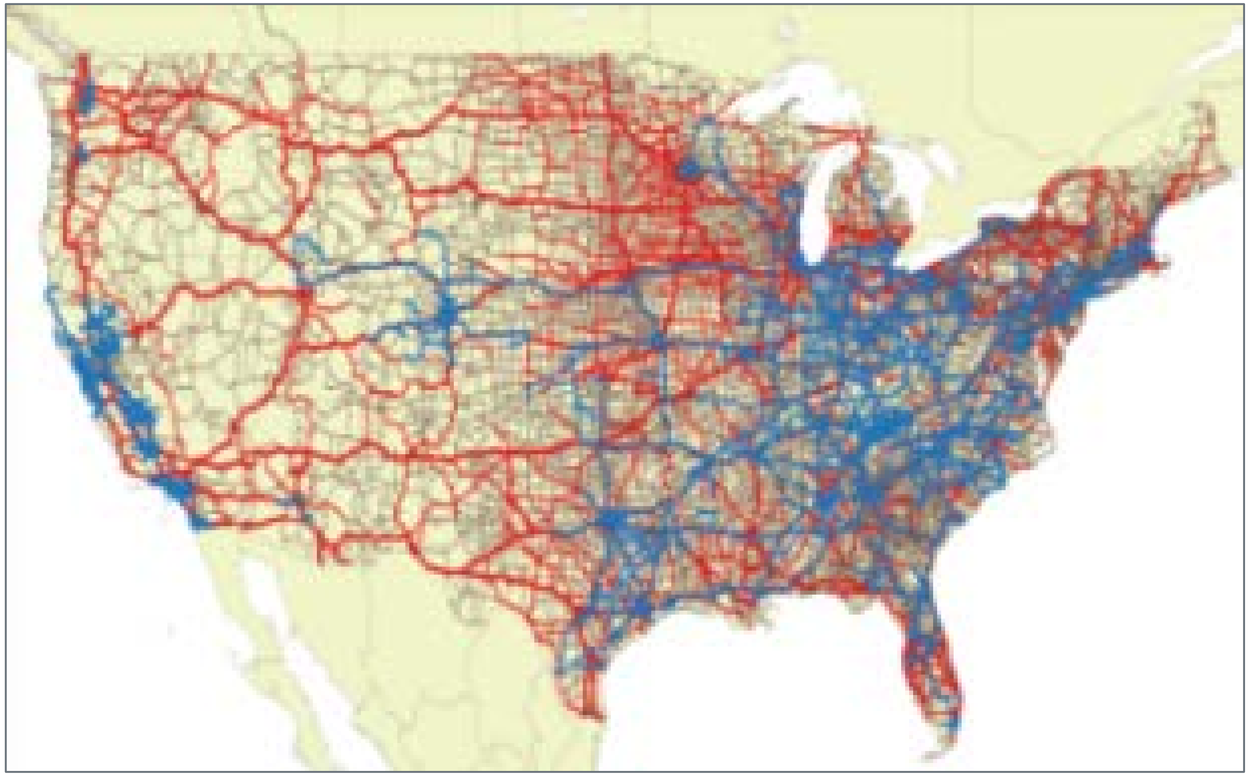
National Clean Fleets Partnership
U.S. Department of Energy

21st Century Truck Partnership

Partnership with Fleets and Technology Providers = Relevant Results & Optimized Solutions for Real-World Applications

Fleet DNA: Clearinghouse of Fleet Vehicle Operating Data

- Repository of broad range of operational data for commercial vehicles across vocations/weight classes
- Features 11.5 million miles of 1-Hz engine CAN, GPS, and component data from 1,700 vocational vehicles operated by fleet partners
- Data processed to produce more than 350 unique duty-cycle metrics characterizing vehicle operating behavior



Freight volumes (red) along major U.S. roadways and Fleet DNA data coverage (blue) along those routes

https://www.nrel.gov/fleetdna

Fleet DNA: Clearinghouse of Fleet Vehicle Operating Data

Fleet DNA Project

	Miles of Data in Database
Local Delivery	3.1M
Line Haul	2.1M
Food/Beverage Delivery	1.8M
Package Delivery	0.8M
Regional Haul	0.5M
Transit Buses	0.24M
Utility	0.12M
Drayage	86k
School Buses	85k
Refuse Pickup	71k

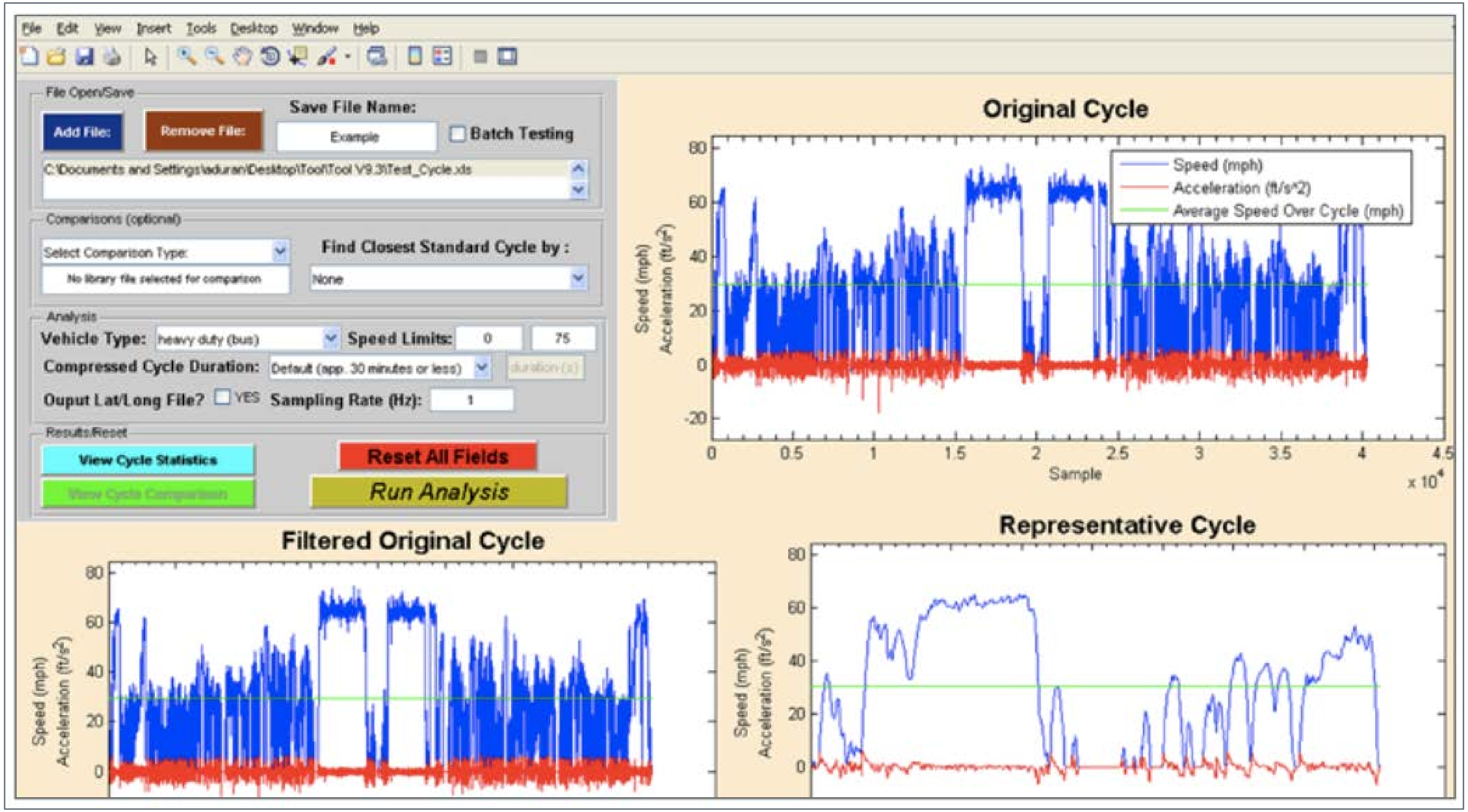
Fleet DNA Statistics

> 10M	Miles of on-road 1Hz GPS and CAN data
2.4M	Miles of HD data through IAG with EPA
250k	Days of driving data
1,740	Vehicles
> 350	Unique statistics for reporting and analysis
5k	Site visitors per year

DRIVE: Representative Drive Cycles from Vehicle Data

DRIVE™ Analysis Tool

- Uses GPS/CAN data to produce statistically representative drive cycles
- 168 unique drive cycle metrics to generate custom representative drive cycles



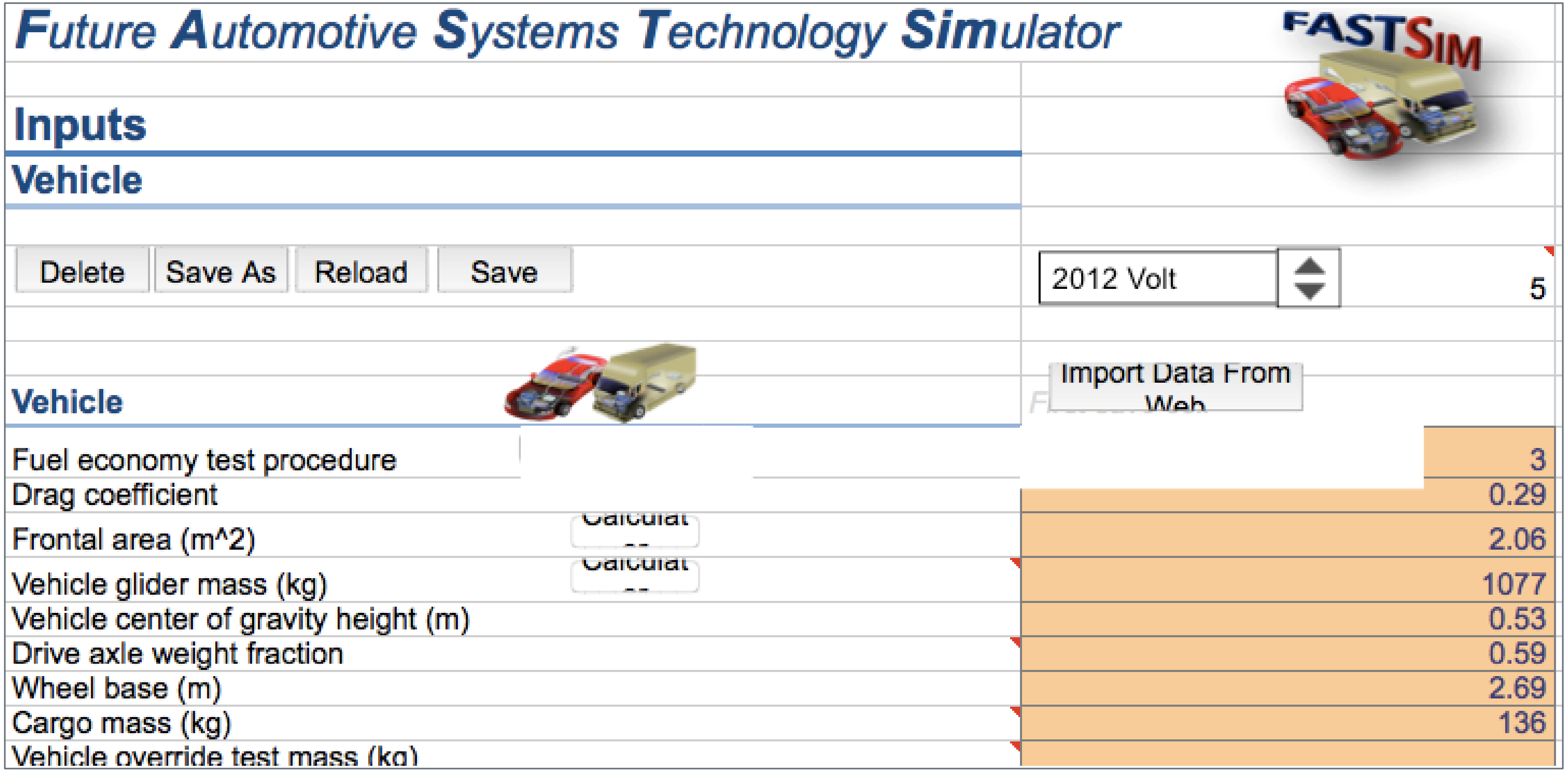
https://www.nrel.gov/transportation/drive.html

FASTSim: Future Automotive Systems Technology Simulator

Used for comparing powertrain technologies and estimating the impact of technology improvements on vehicle efficiency, performance, cost, and battery life

Incorporates:

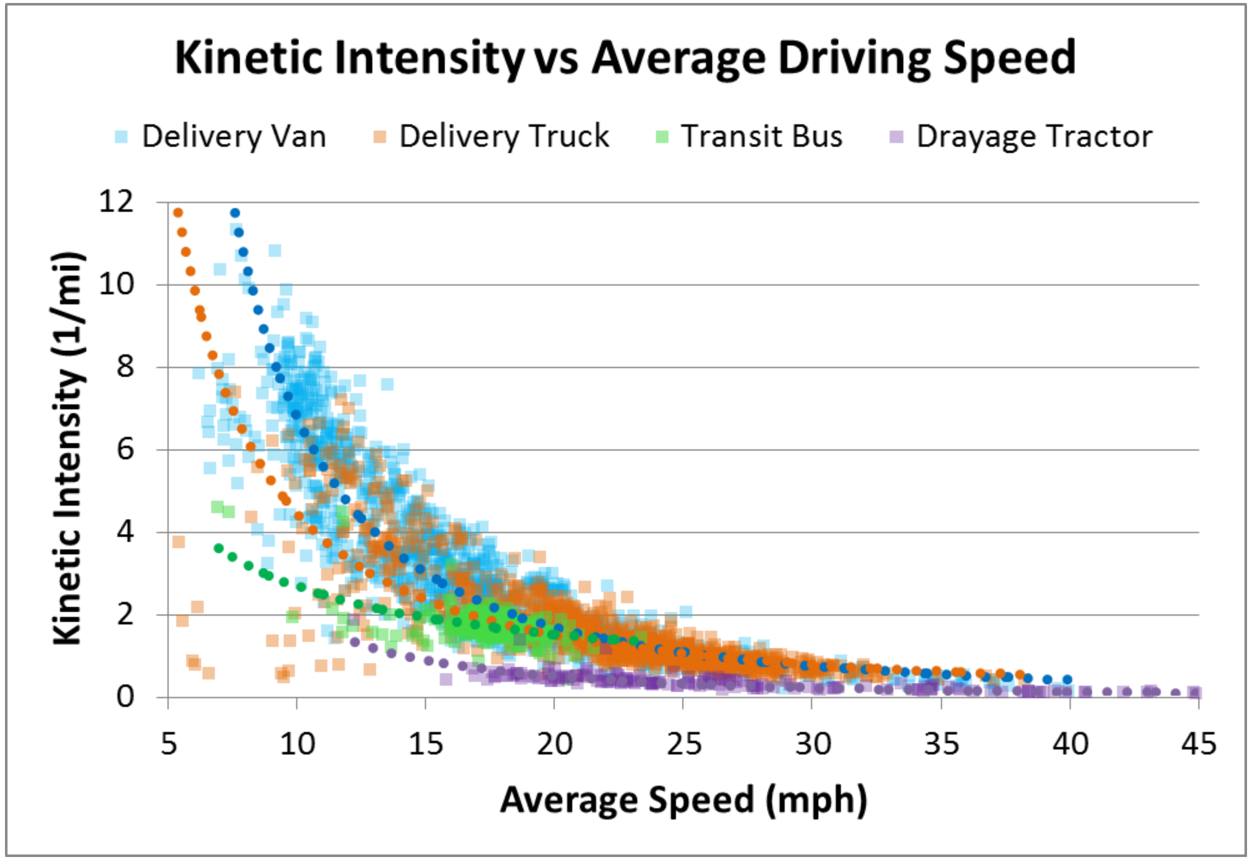
- Speed vs. time simulation
- Powertrain components
- Regenerative braking
- Energy management
- Battery life estimates
- Cost estimates
- Distribution of driving distances



https://www.nrel.gov/transportation/fastsim.html

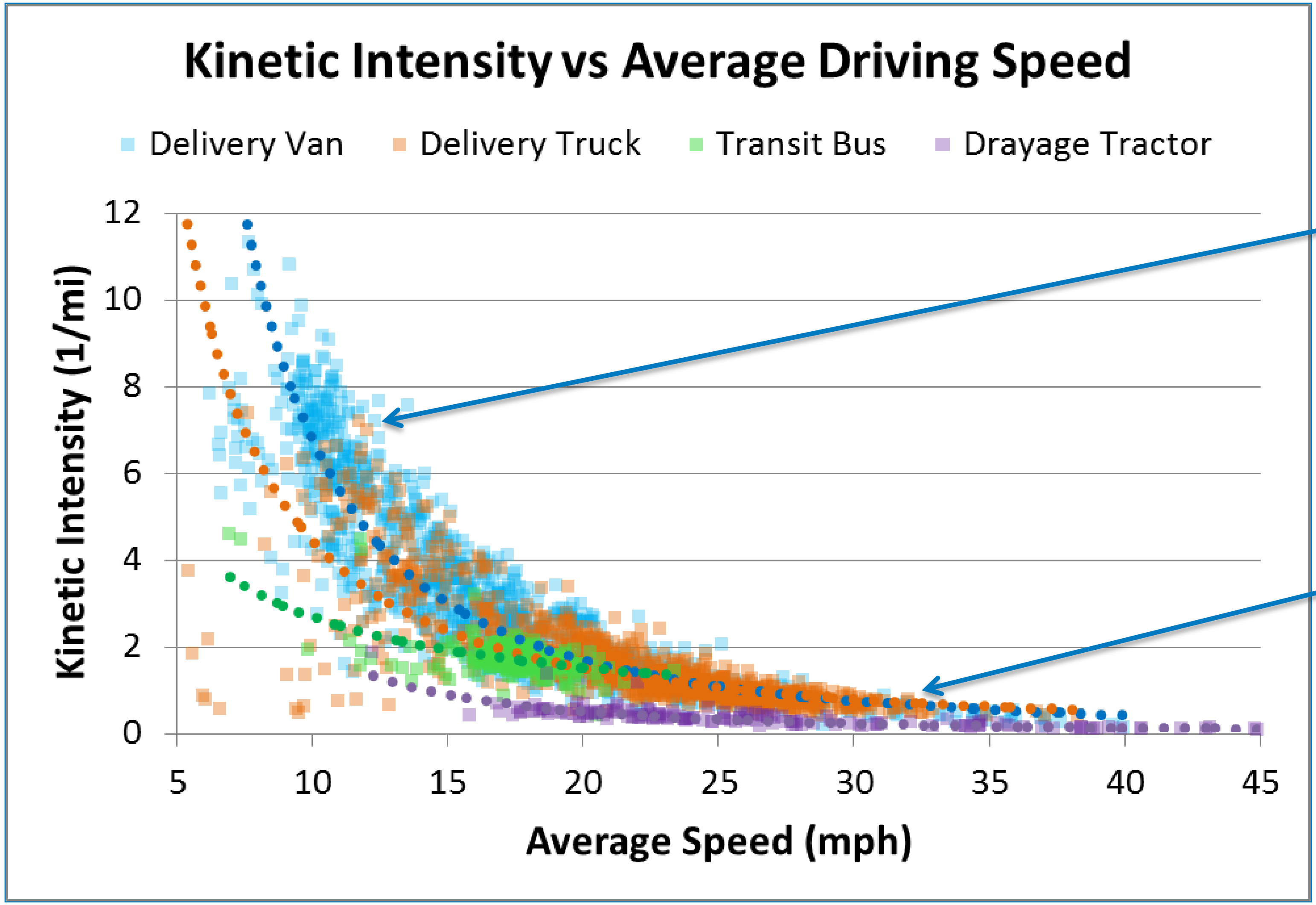
An Aside on Kinetic Intensity

- Kinetic intensity (KI) characterizes relative driving aggressiveness
  - Ratio of characteristic acceleration and aerodynamic speed, where
  - Characteristic acceleration: Reflects inertial work to accelerate and/or raise the vehicle per unit mass per unit distance over the cycle
  - Aerodynamic speed: Ratio of overall average cubic speed to average speed

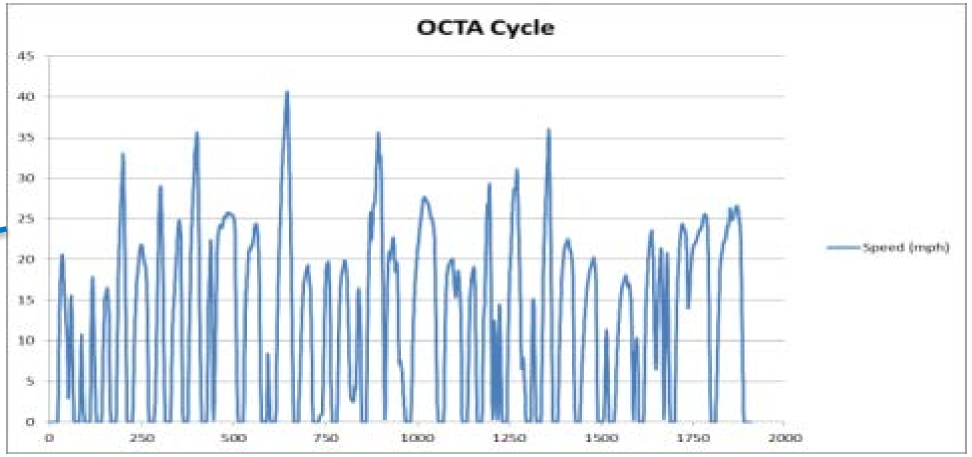


See SAE 2007-01-0302 for derivation

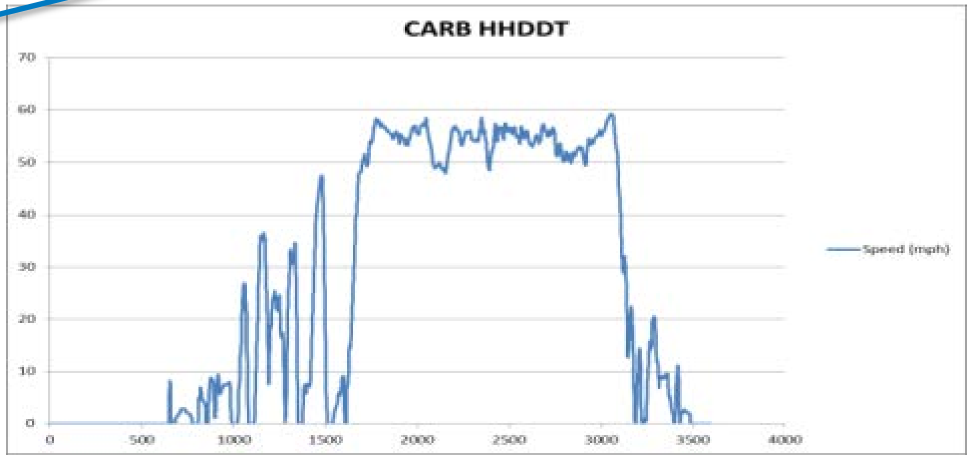
An Aside on Kinetic Intensity



High KI Low Speed Cycle



Low KI High Speed Cycle



Drive Cycle Development Process – Parcel Delivery Example

Step 1

- Leverage Fleet DNA's parcel delivery data for representative drive/duty cycle characteristics
- Identify suitable standard drive cycles to model

Step 2

- Perform trip-level clustering analysis to identify distinct operating modes and driving patterns

Step 3

- Create custom representative drive cycles from real-world data

Step 4

- Develop validated FASTSim vehicle model for system component sizing and system performance modeling over various drive cycles

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Provider	Class	City	Miles	Number Days	Number of vehicles
FedEx	5	Los Angeles	12,657.79	279	21
UPS	6	Baltimore	7,591.46	275	15
UPS	4	Minneapolis	11,895.30	241	13
UPS	4	Minneapolis	19,381.11	364	11
UPS	6	Houston	7,179.90	114	6
UPS	6	Los Angeles	16,138.91	324	15
		Total	74,844.47	1,597	81

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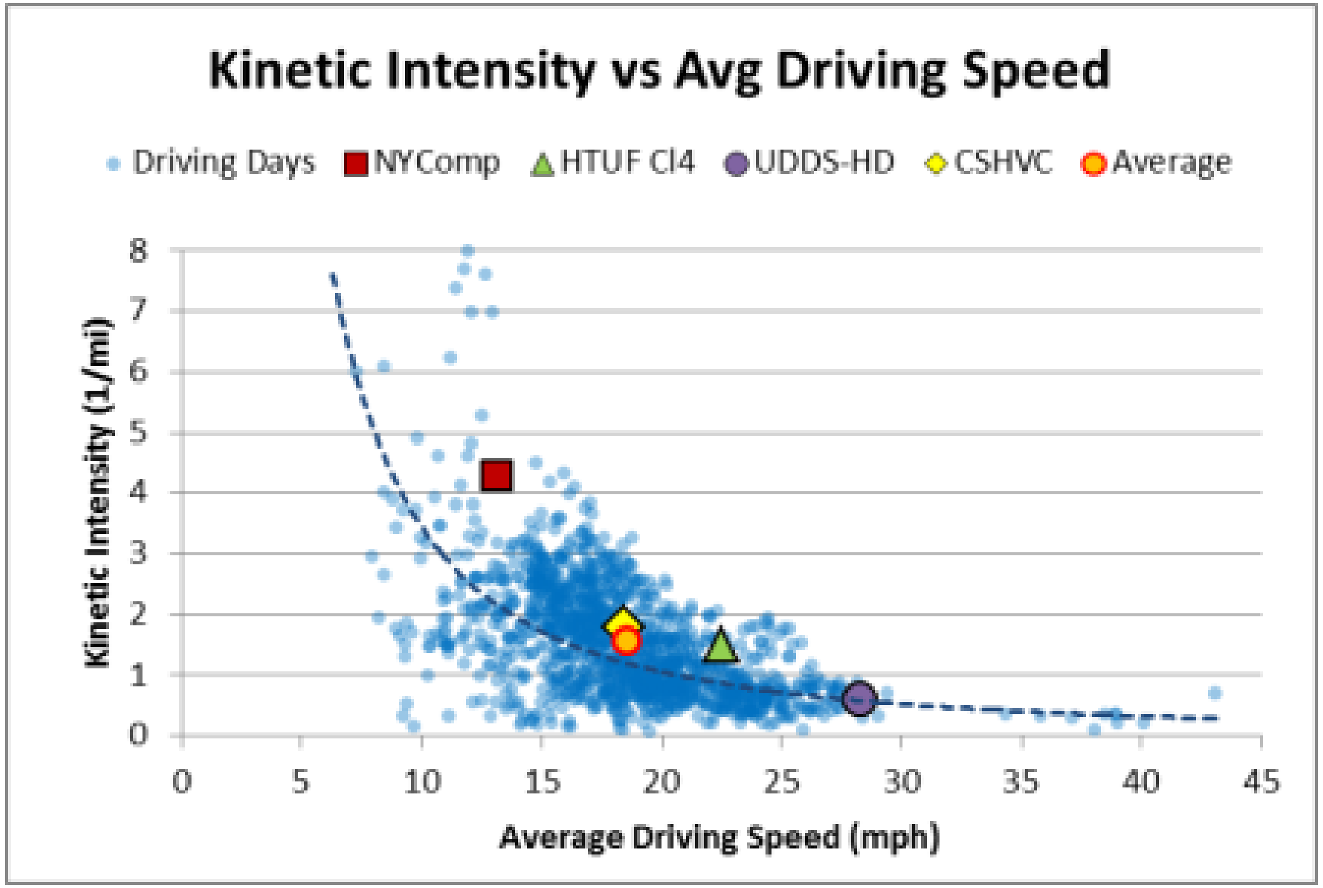

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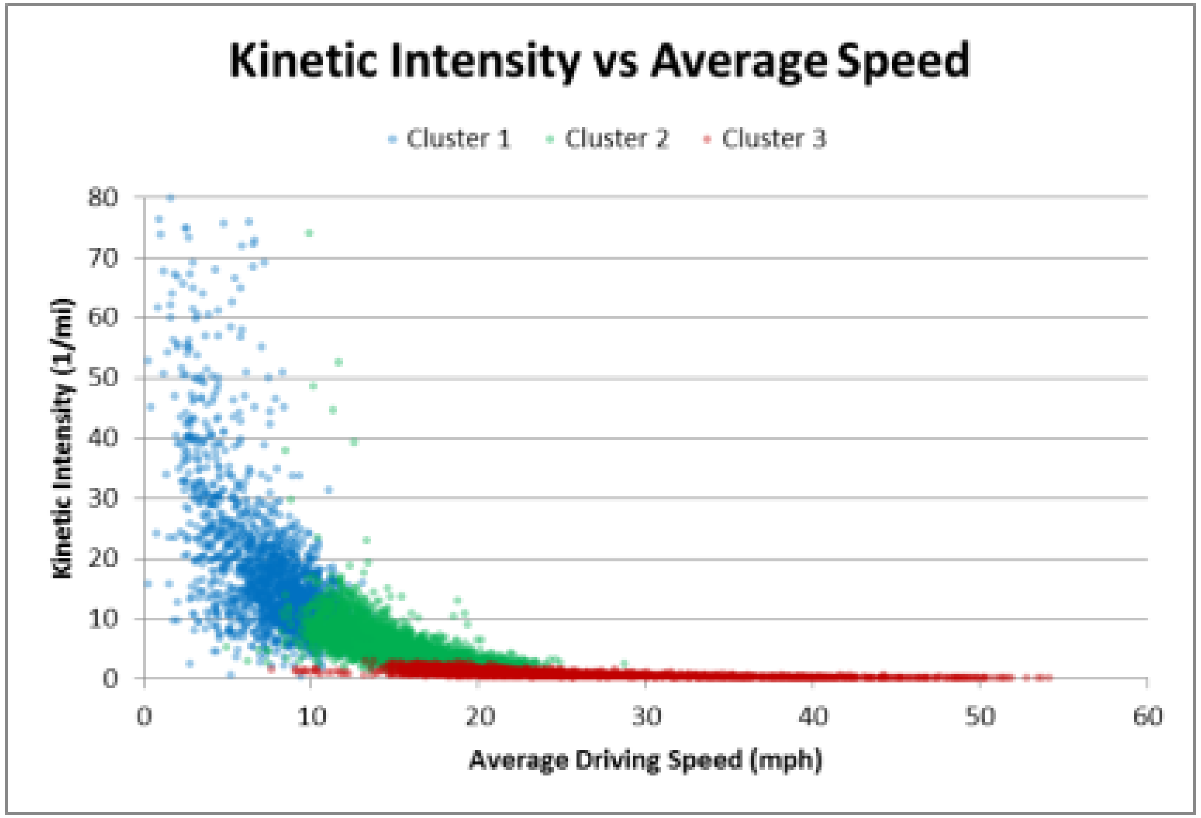
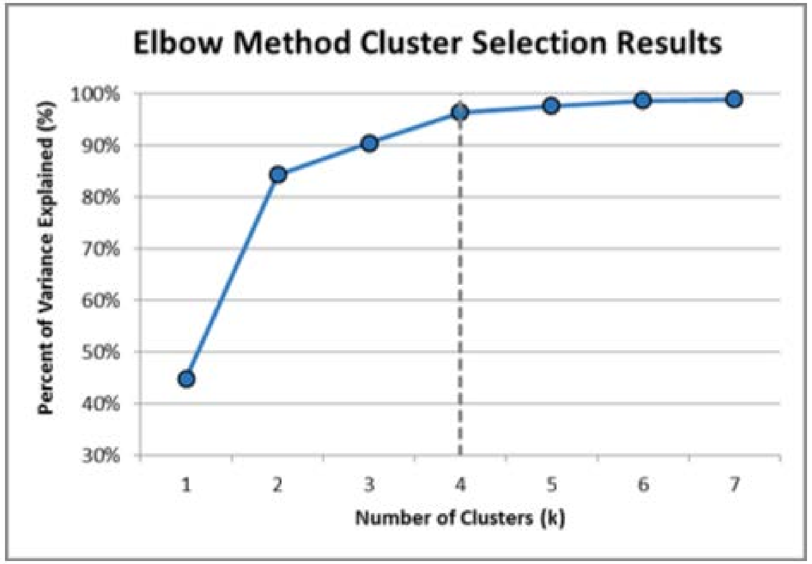


Drive Cycle Development Process – Parcel Delivery Example

Clustering Analysis

1. Trip-level metrics selected to define kinematic driving behavior
2. Clustering metrics scaled using the z-score scaling method
3. Identify number of clusters using both mean shift and elbow method
4. Use k-medoid clustering algorithm

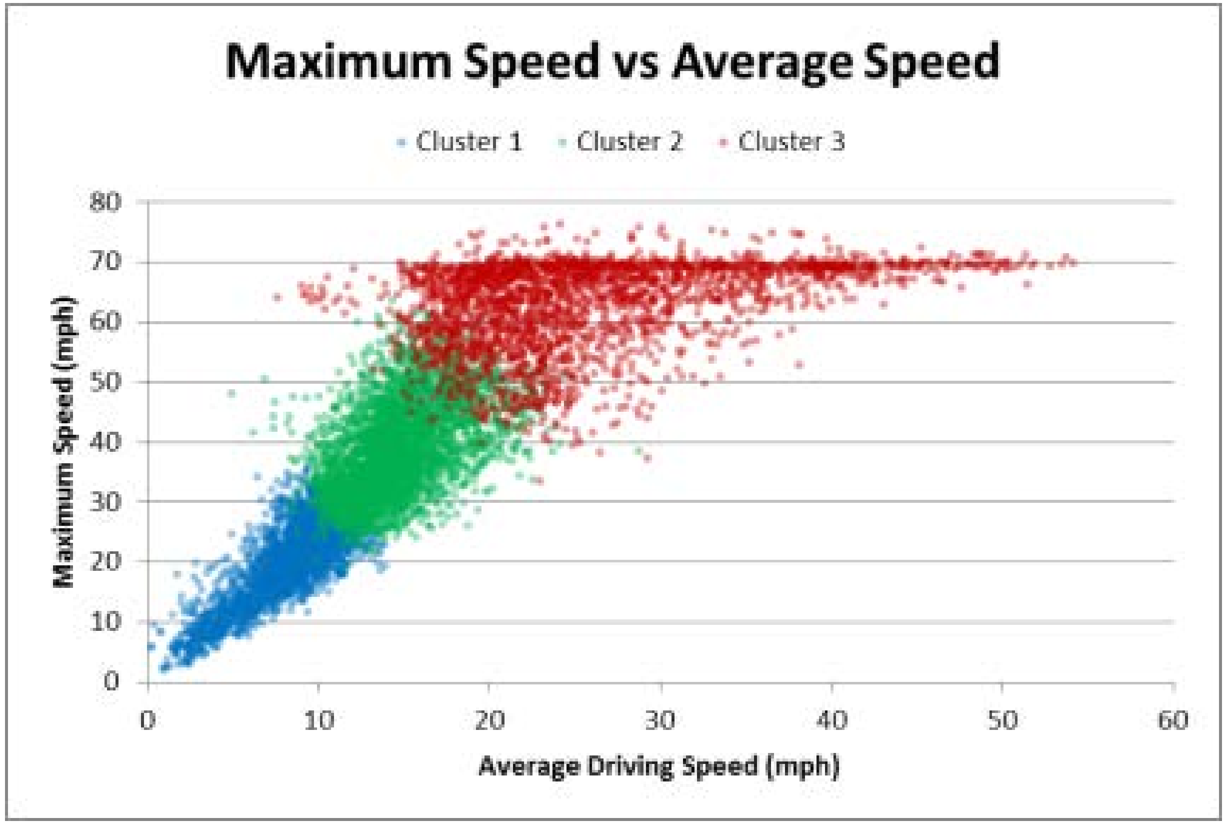


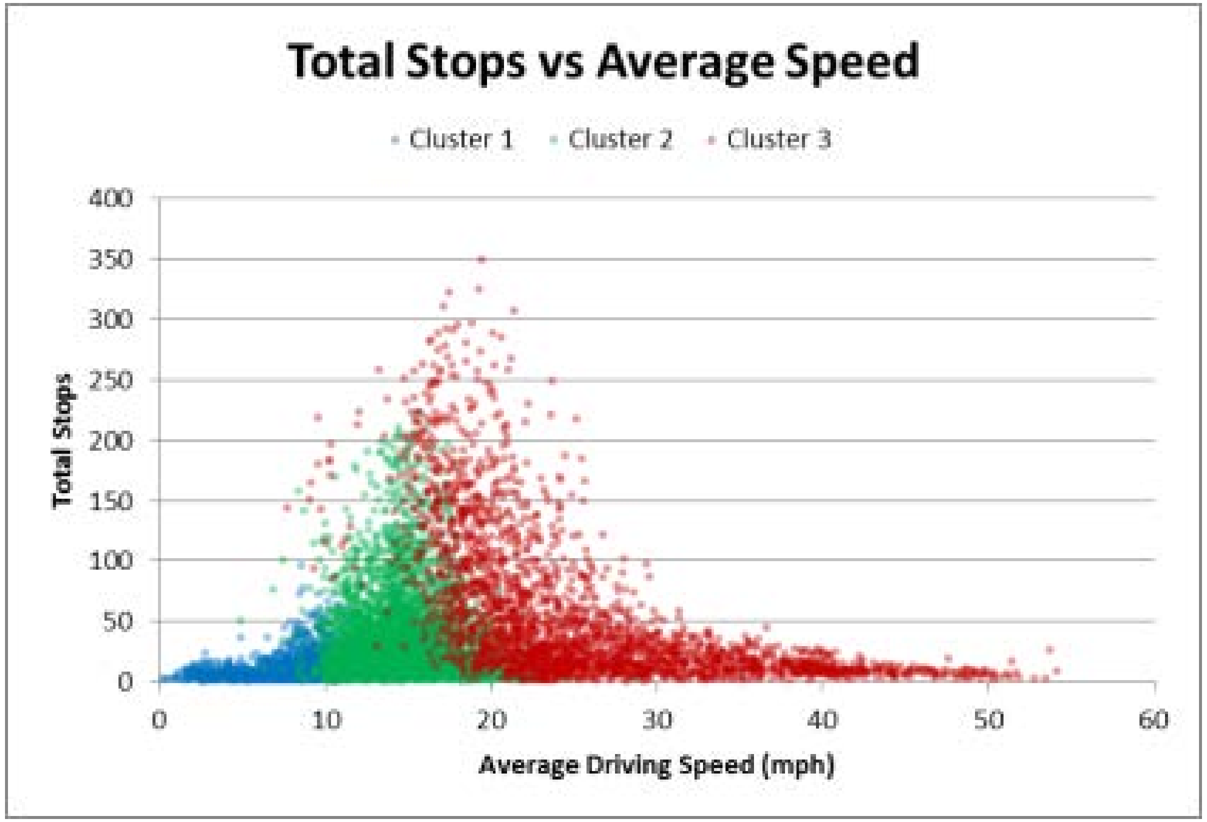
Clustering Metrics

- Aerodynamic speed
- Average driving speed
- Characteristic acceleration
- Kinetic intensity
- Maximum speed
- Stops per mile
- Total average speed
- Total distance
- Total stops

$$F\ (x) = minimize \sum_{i=1}^{n} \sum_{j=1}^{n} d(i,j) z_{ij}$$

Drive Cycle Development Process – Parcel Delivery Example





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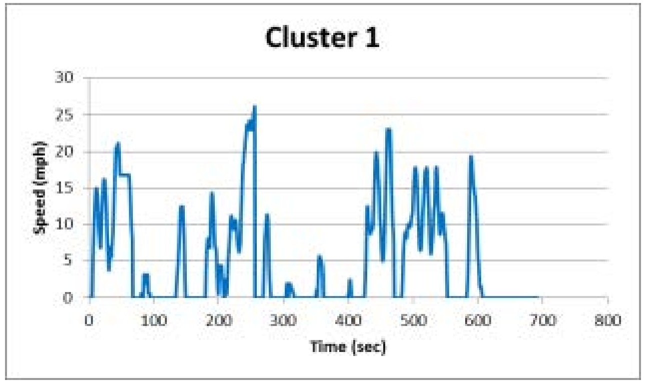
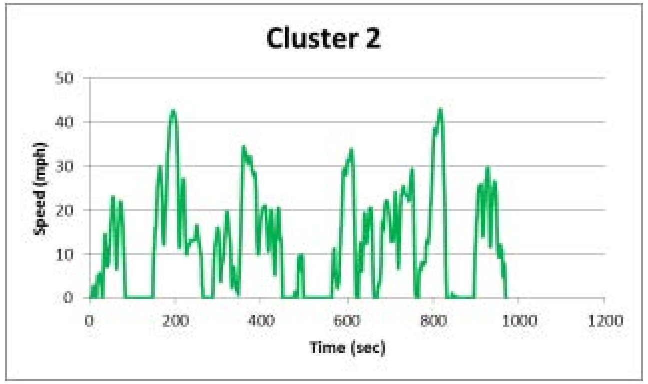


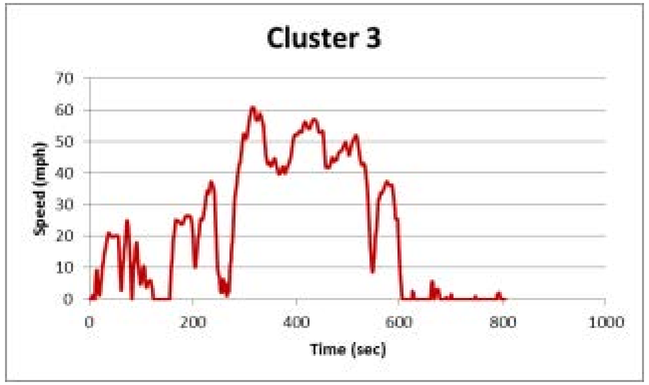
Cluster 1

Slow moving, short trips with frequent stops



Cluster 2

Medium speed driving activity



Cluster 3

Higher speed driving activity with fewer stops

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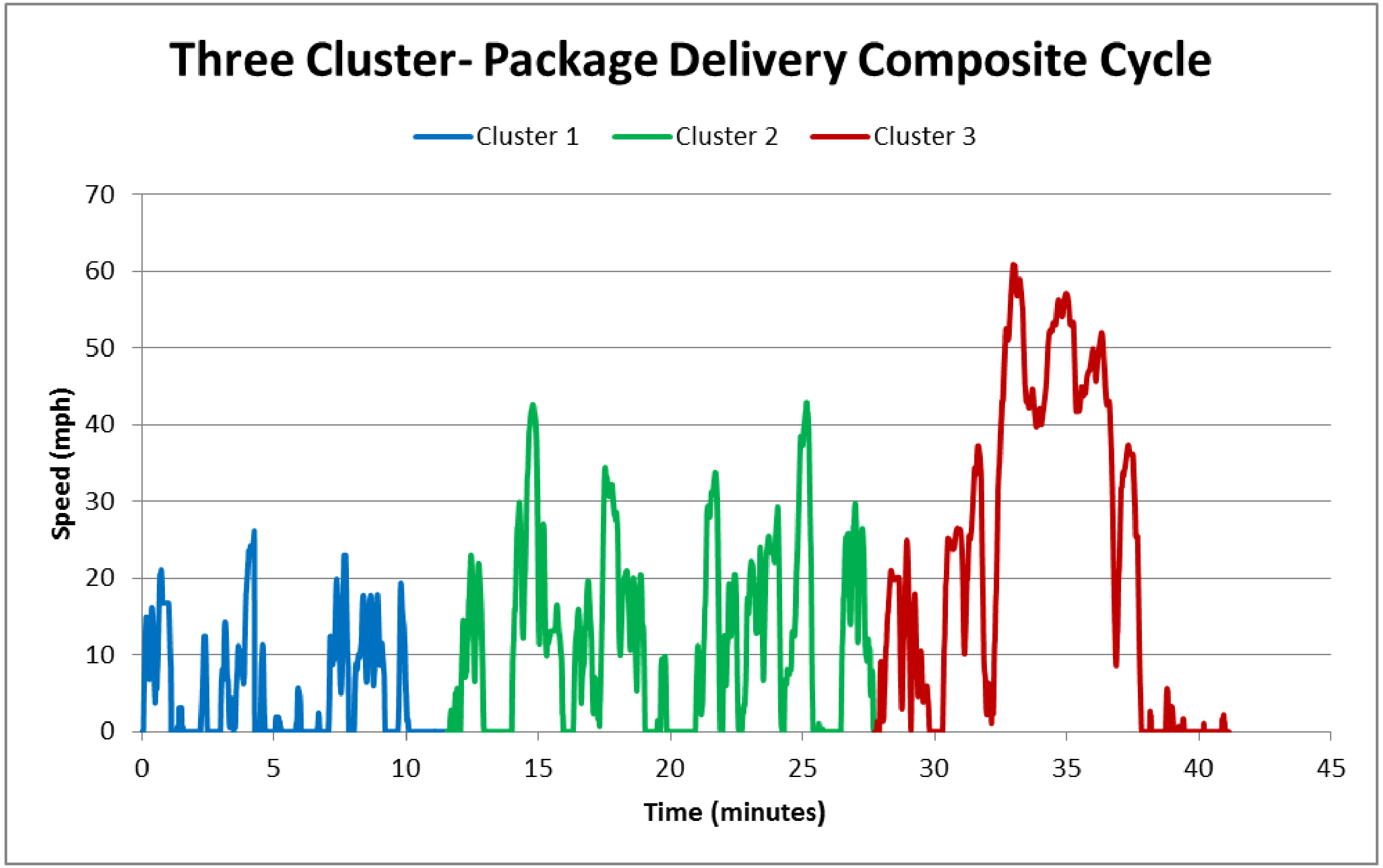
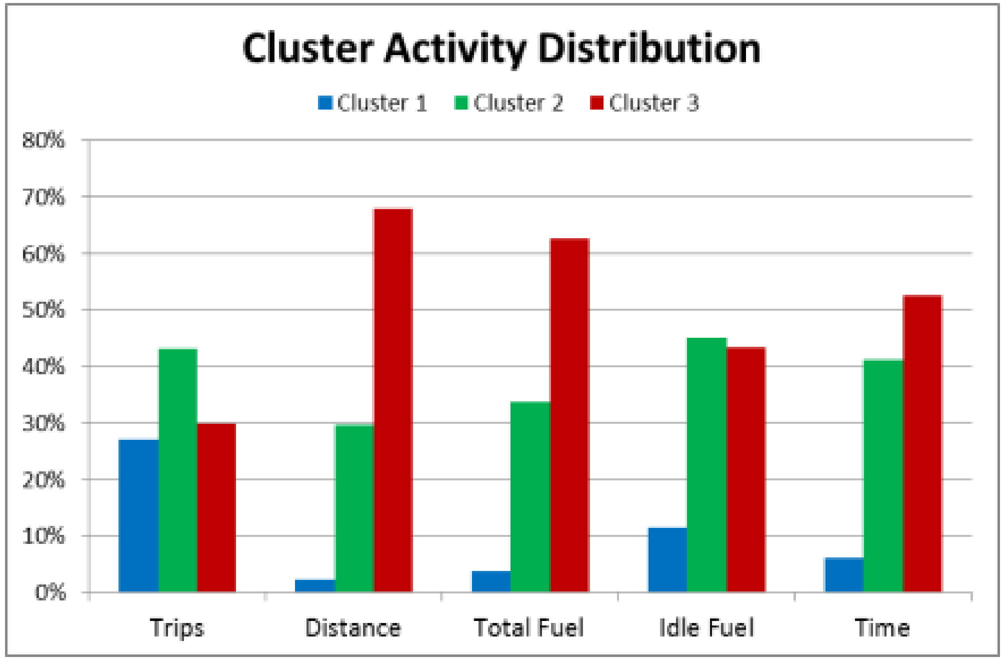


Weighting Factors



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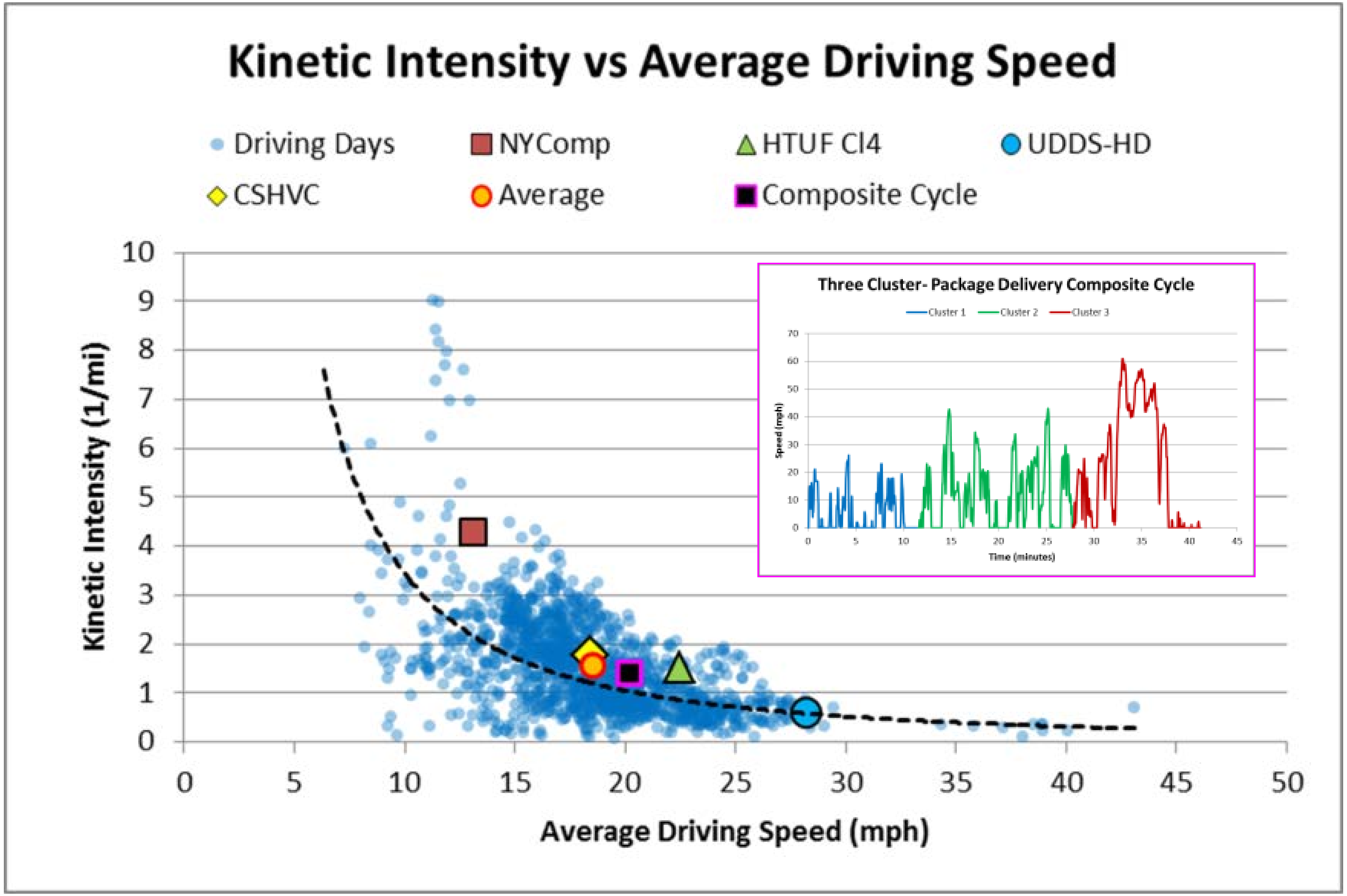

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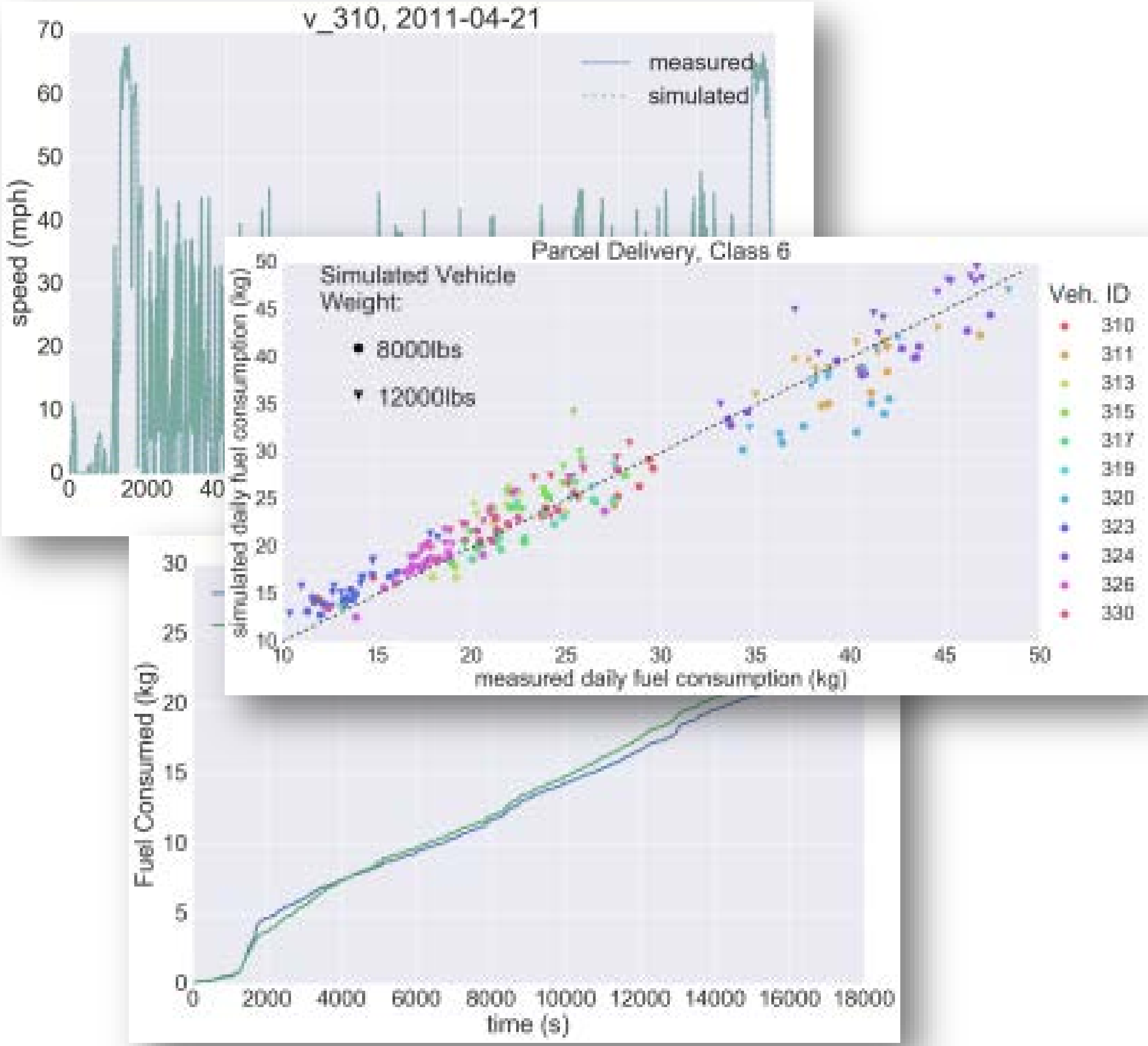
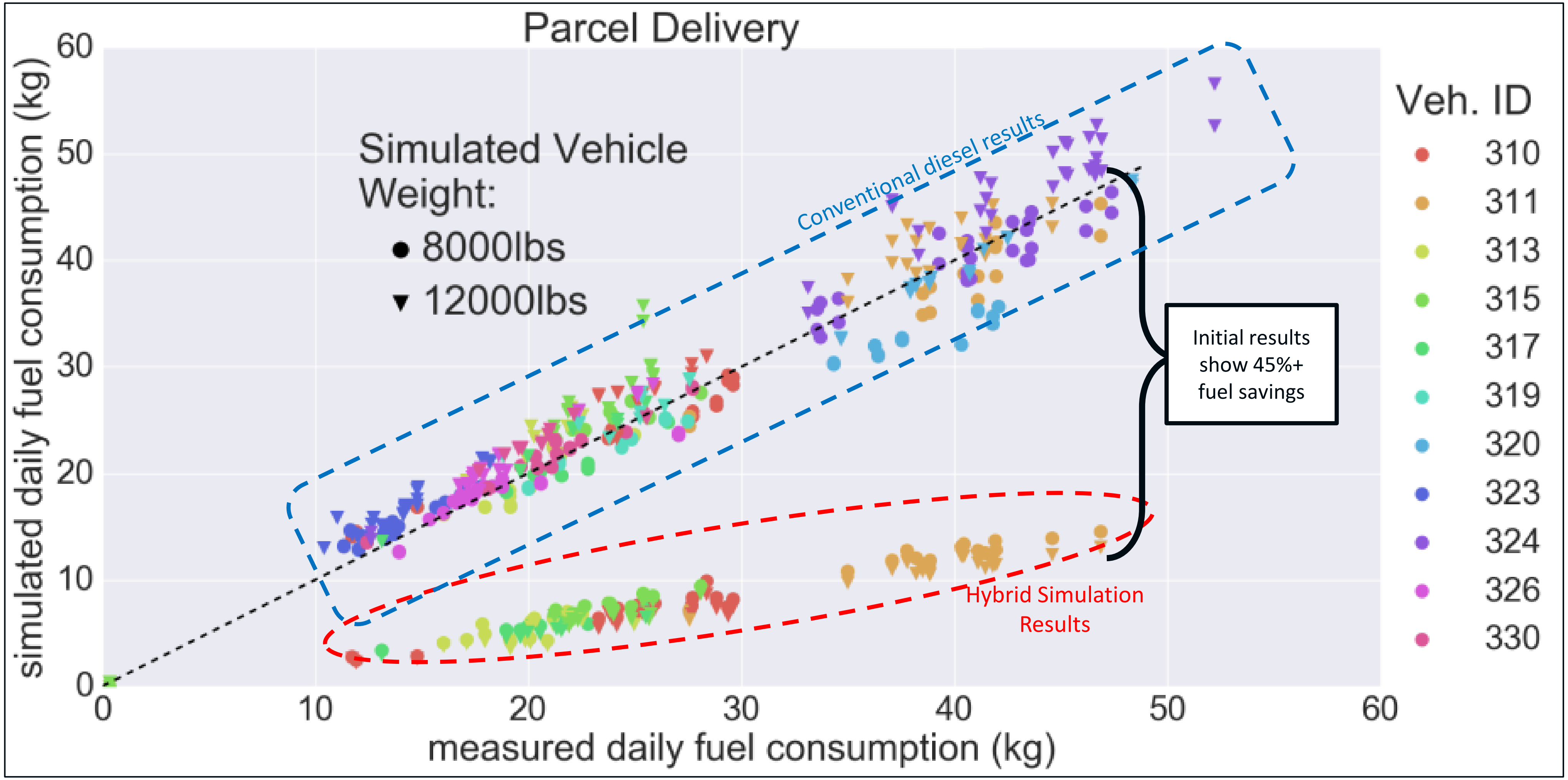


FASTSim Vehicle Modeling – Initial Results

- Conventional and initial hybrid vehicle model run over 231 days at two different vehicle weights
- Conventional diesel model results correlate to observed field data



Cummins FOA Project

Electric Truck with Range-Extending Engine (ETREE)

Team

- Cummins (lead), PACCAR, NREL, Argonne National Laboratory, Ohio State University

Objectives

- Develop, demonstrate, validate Class 6 vehicle with performance/range equivalent to conventional vehicle
- Use electricity to reduce fuel consumption by at least 50% over wide range of real-world drive cycles
- Evaluate performance in fleet service

Vehicle Features

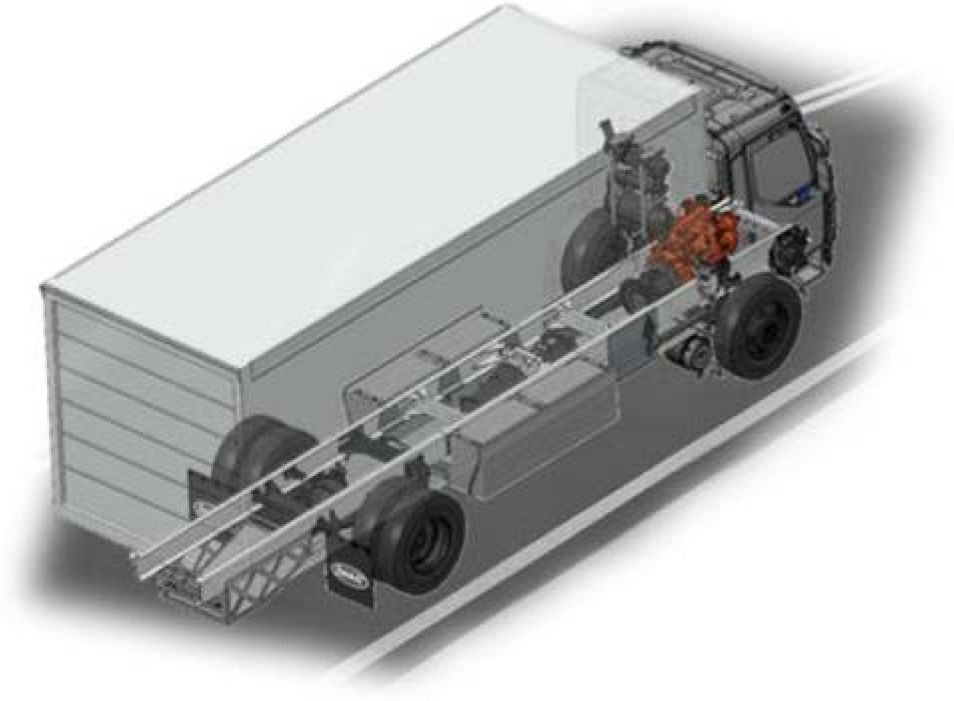
- Series hybrid architecture
- 112 kWh battery
- 155 kW ISB 4.5 diesel engine
- 160 kW motor, 130 kW generator

Kenworth K270

Figure credit: Cummins 2017 Annual Merit Review presentation
https://energy.gov/sites/prod/files/2017/06/f34/gi189_kresse_2017_o.pdf

Need: Expanded Drive Cycle Development

- Developing hybrid system controls technology focused on battery state-of-charge trajectory management and vehicle integration
  - Electrified accessories and thermal management systems
- EV design optimization requires a "workday" drive cycle due to limited energy density and state-of-charge impact on continuous power
- Also need grade and key-on information



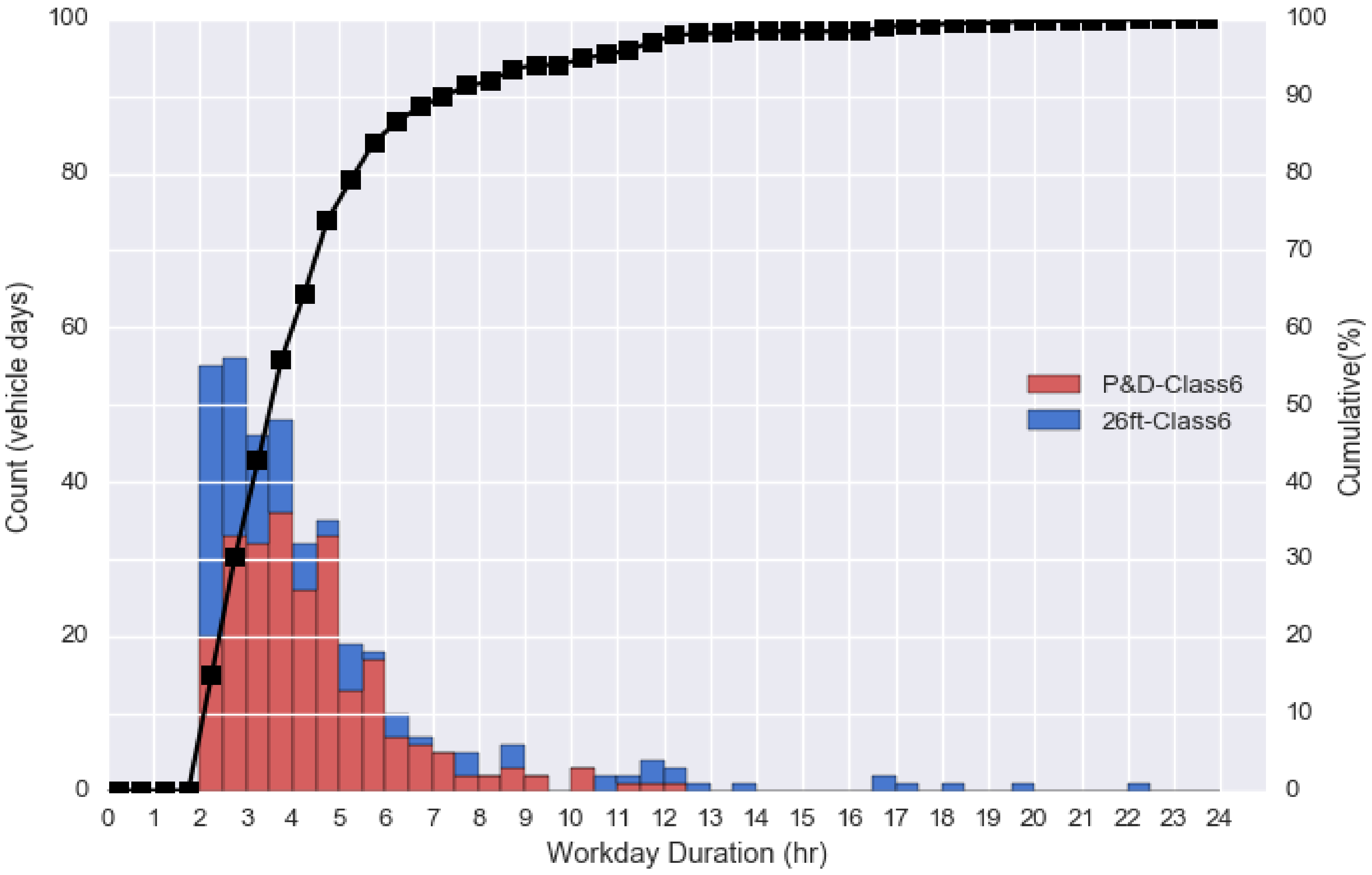
K270/PB220 ETREE

Figure credit: Cummins 2017 Annual Merit Review presentation
https://energy.gov/sites/prod/files/2017/06/f34/gi189_kresse_2017_o.pdf

Work Day Drive Cycle Development: Class 6 P&D

78,000	Days of operation data
260	Vehicles
2.5M	Miles of real-world data analyzed

- Median operating day duration ~ 4 hours
- 95% days operate 8 hours or less



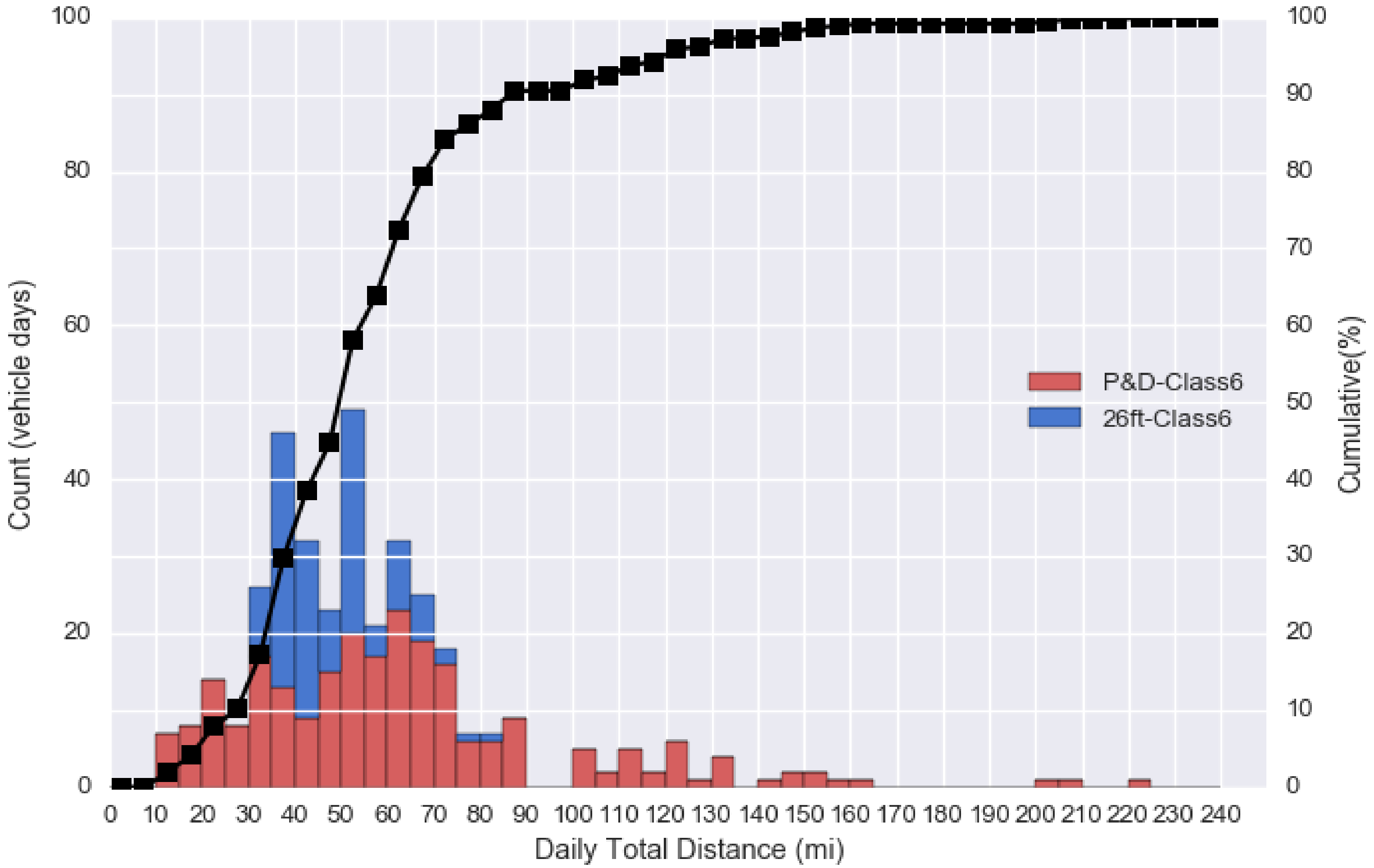
Work Day Drive Cycle Development: Class 6 P&D

78,000 Days of operation data

260 Vehicles

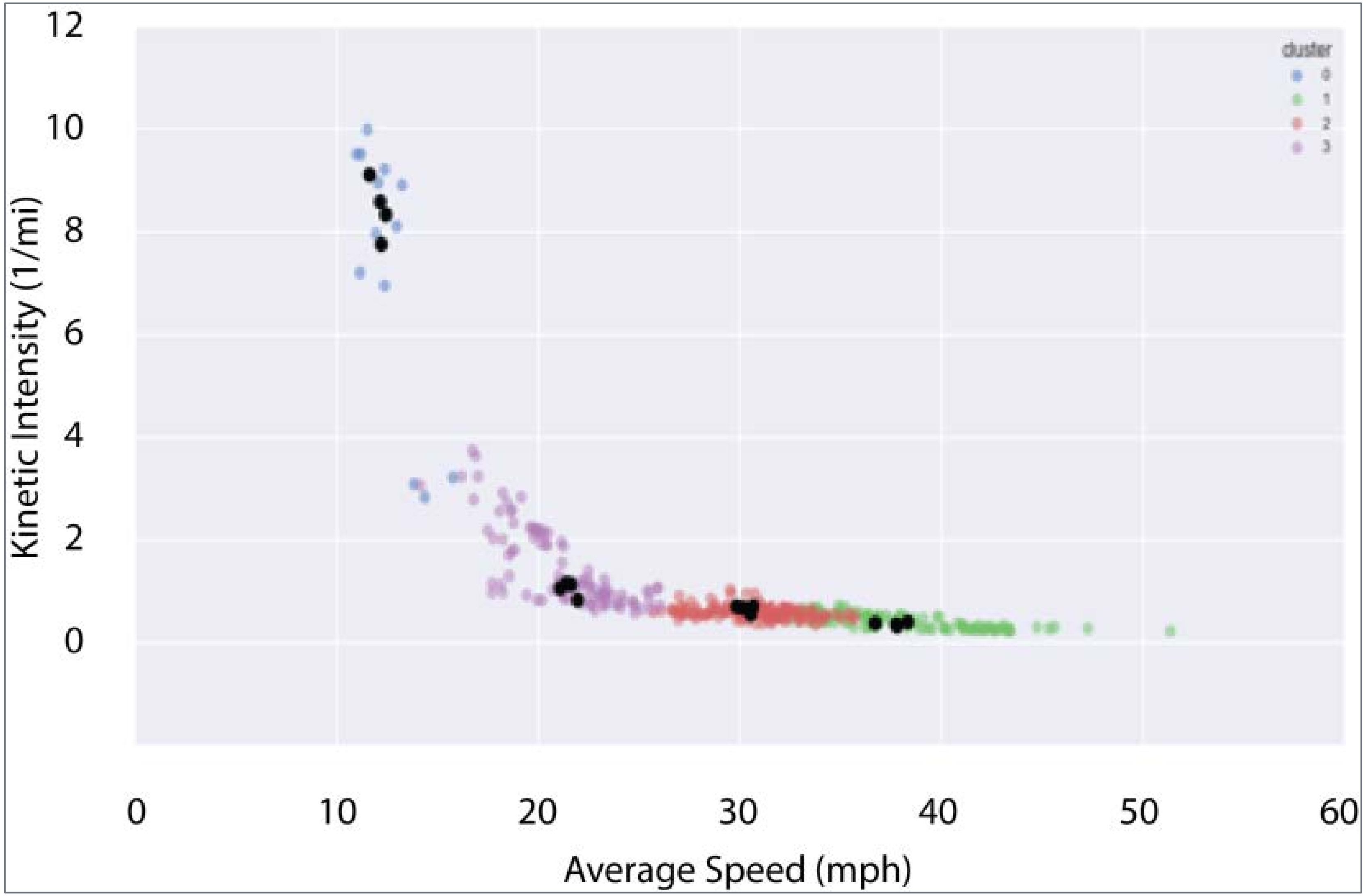
2.5M Miles of real-world data analyzed

- Median daily VMT ~ 55 miles
- 90th percentile: 80 miles
- 95th percentile: 100 miles

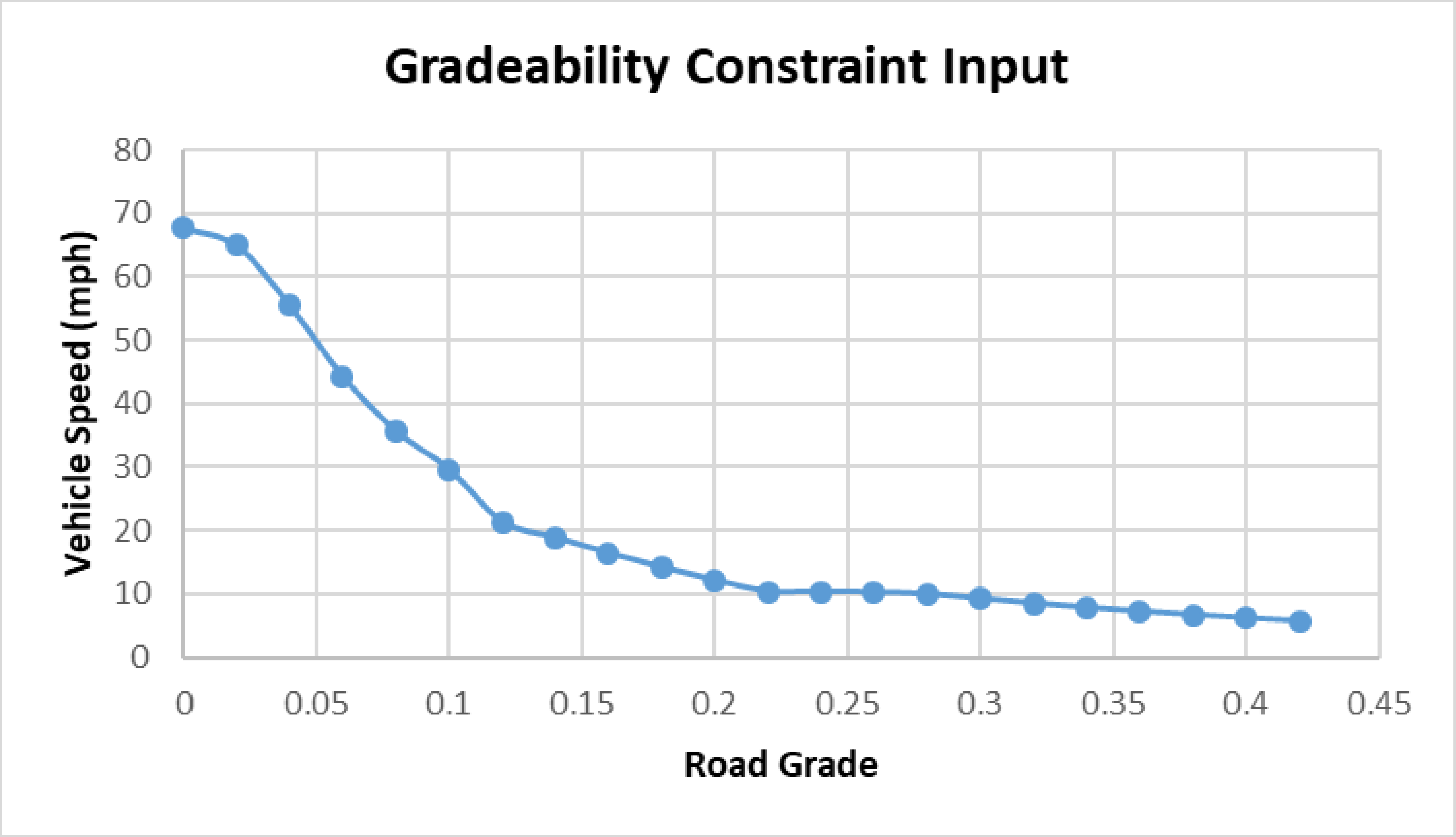


Results consistent with other data (VIUS, CalHEAT, etc.)

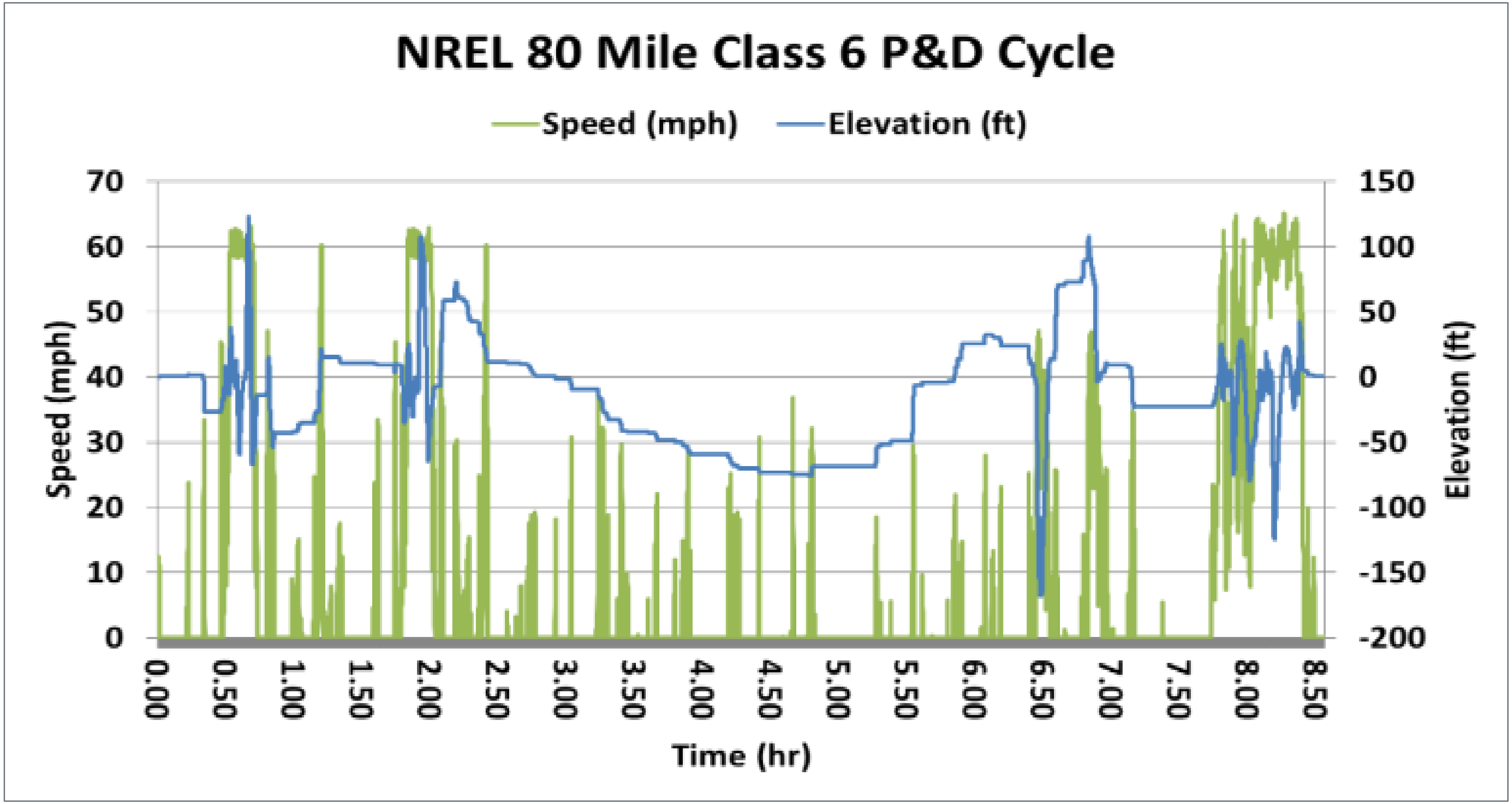
80- and 100-Mile Cycles



Road Grade/Vehicle Speed Constraints



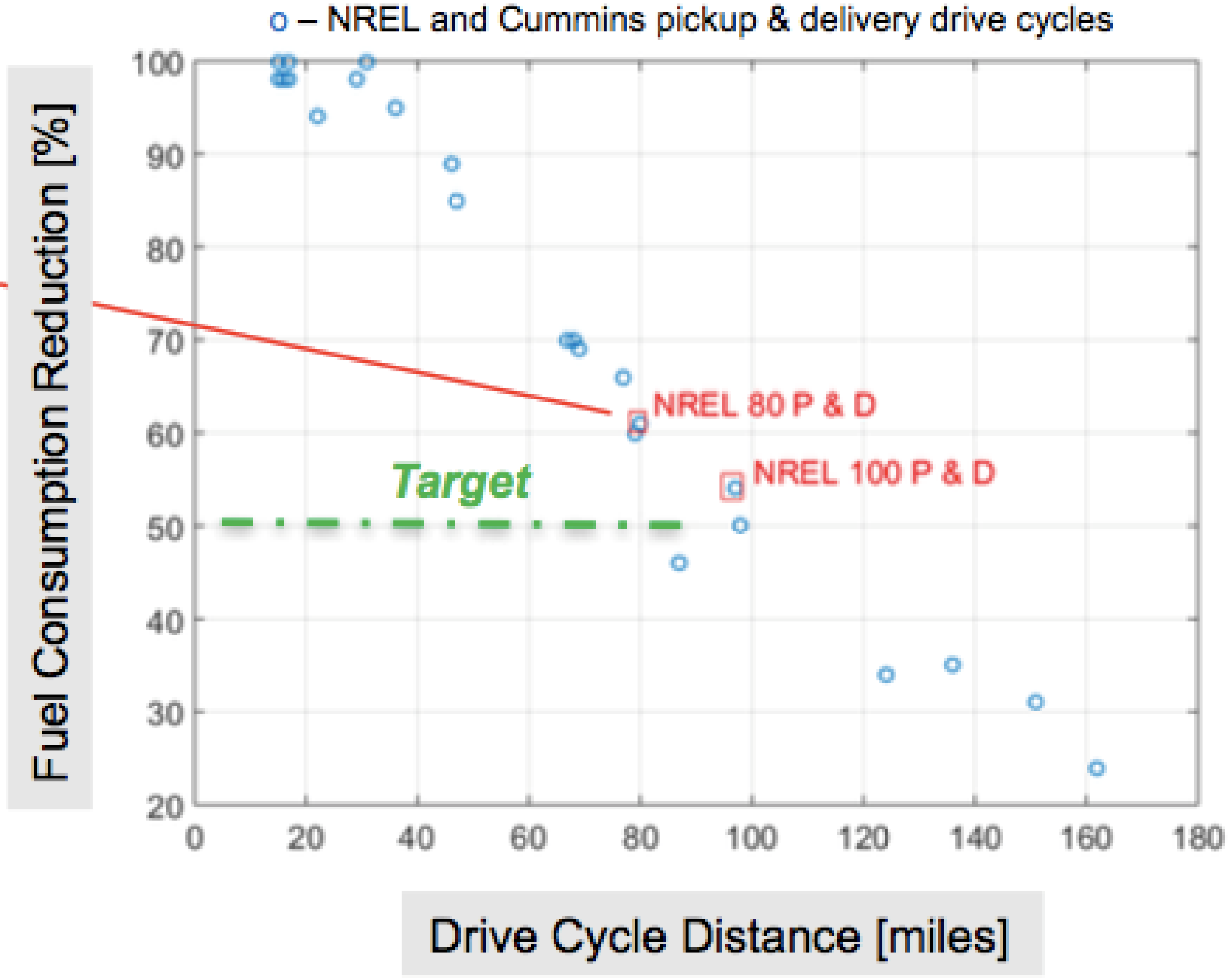
Final Drive Cycle with Elevation



Next Steps

System development, vehicle integration, and vehicle demonstration underway

Predicted fuel consumption for target cycle (NREL 80) is well within objective.



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Conclusions

- Range extenders can be viable technology option for reducing fuel consumption from MD and HD engines by ~50% or more
  - Need to maximize e-miles to minimize payback period
- MD and HD engines have wide variations in use and duty cycle; real-world data and sophisticated analysis can:
  - Identify vocations/duty cycles best suited for range-extender applications
  - Help guide powertrain optimization and design requirements
- We have only just begun to make use of all the data (and computational power) available — talk to us!

Thank you!

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Steven Boyd, Lee Slezak, and
David Anderson

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