Medium- and Heavy-Duty Electric Drive Vehicle Simulation and Analysis

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Overview

Timeline

Project Start Date: Oct 2009

Project End Date: Oct 2012

Percent Complete: 70%

Budget

Total Project Funding: $740k

DOE: $700k over multiple years

Agency partners: $40k in first year

Industry partners: In-kind support

Funding Received in FY11: $250k

Funding for FY12: $300k

Barriers

- **Risk aversion**
- **Cost**
- **Computational models, design and simulation methodologies**

Partners (NREL = lead)

- **FedEx and UPS** – provided design requirement feedback and access to vehicles for testing and in-use data collection
- **Azure Dynamics and Navistar** – data support for model development and verification
- **Other VT Projects** – used data from lab testing and fleet evaluation to guide modeling and analysis efforts

Relevance for DOE fuel-saving mission

- **Medium- and heavy-duty (MD/HD) vehicles are important vehicle segments**
  - Significant aggregate and per-vehicle petroleum use
  - Commercial operators concerned with total cost of ownership and not simply initial capital cost
  - Increasing knowledge and production volumes in this segment will also benefit other segments
- **Parcel delivery is a particularly good MD candidate for electric drive**
  - Known drive cycles, with significant stop-and-go
  - Fleet vehicles return to base (overnight charging)
  - Operate in densely populated areas
- **Drive cycles important—significantly impact fuel savings**
  - Rate of energy use; charge-depleting/-sustaining (CD/CS) performance

Relevance for addressing barriers (risk aversion, cost and design/simulation methodologies)

- **Reduce uncertainty for OEMs and end users**
  - What are the most promising markets? Best designs for given use profiles? Warranty implications?
  - What options should be considered? Which routes give the best payback? What is the bottom line cost and fuel/CO_2 reduction?
- **Focus on cost (battery = largest driver)**
  - Can specific application achieve payback/justify upfront cost?
  - How long will the battery last? Will payback be better or worse for larger energy storage?
- **Information needed on interaction between vehicle design and application-specific duty cycles**
  - Historic standards for MD/HD segments based only on engine testing

OEM = original equipment manufacturer

Objectives

- **Establish/apply a methodology for comprehensive vehicle evaluation and application-specific design optimization**
  - Detailed component cost estimates
  - Fully capture battery life implications
  - Parametric study of key factors
  - Cost and fuel results for each use case
- **Continue coordination with related DOE tasks for MD/HD laboratory testing and field evaluation**

2011 AMR Feedback

NREL PIX # 18568

NREL PIX # 19821

Milestones and Decision Points

Phase	Date and Deliverable	Status/Decision
1	Sept 2010 – Milestone to DOE (results published at EVS25, Nov 2010)	Completed/Proceed to Phase 2
2	Sept 2011 – Milestone to DOE (results published at EVS26, May 2012)	Completed/Proceed to Phase 3
3	Sept 2012 – Milestone to DOE	Pending

Overall Approach

- **Initial scoping (period 1 – 2011 AMR)**
  - Identify promising MD vocation (parcel delivery)
  - Perform coarse analysis
- **Detailed analysis, driven by test data (period 2 – 2012 AMR)**
  - Refine base model and verify with laboratory testing
  - Detailed field evaluation for actual driving profiles
  - Include battery life modeling in component sizing
  - Sweep large design matrix
- **Complete parcel delivery analysis; Consider HD (period 3)**
  - Identify cost-effectiveness crossover criteria
  - Evaluate additional vehicle design and drive cycle cases
    - E.g., degrees of hybridization and inclusion of grade
  - Plug-in/hybrid electric vehicle (PEV/HEV) vocational analysis for HD
    - Class 8 regional haul, long haul (hybridization for hill climb, acceleration/ deceleration)

Integrated Approach: Models informed by test data and stakeholder interactions

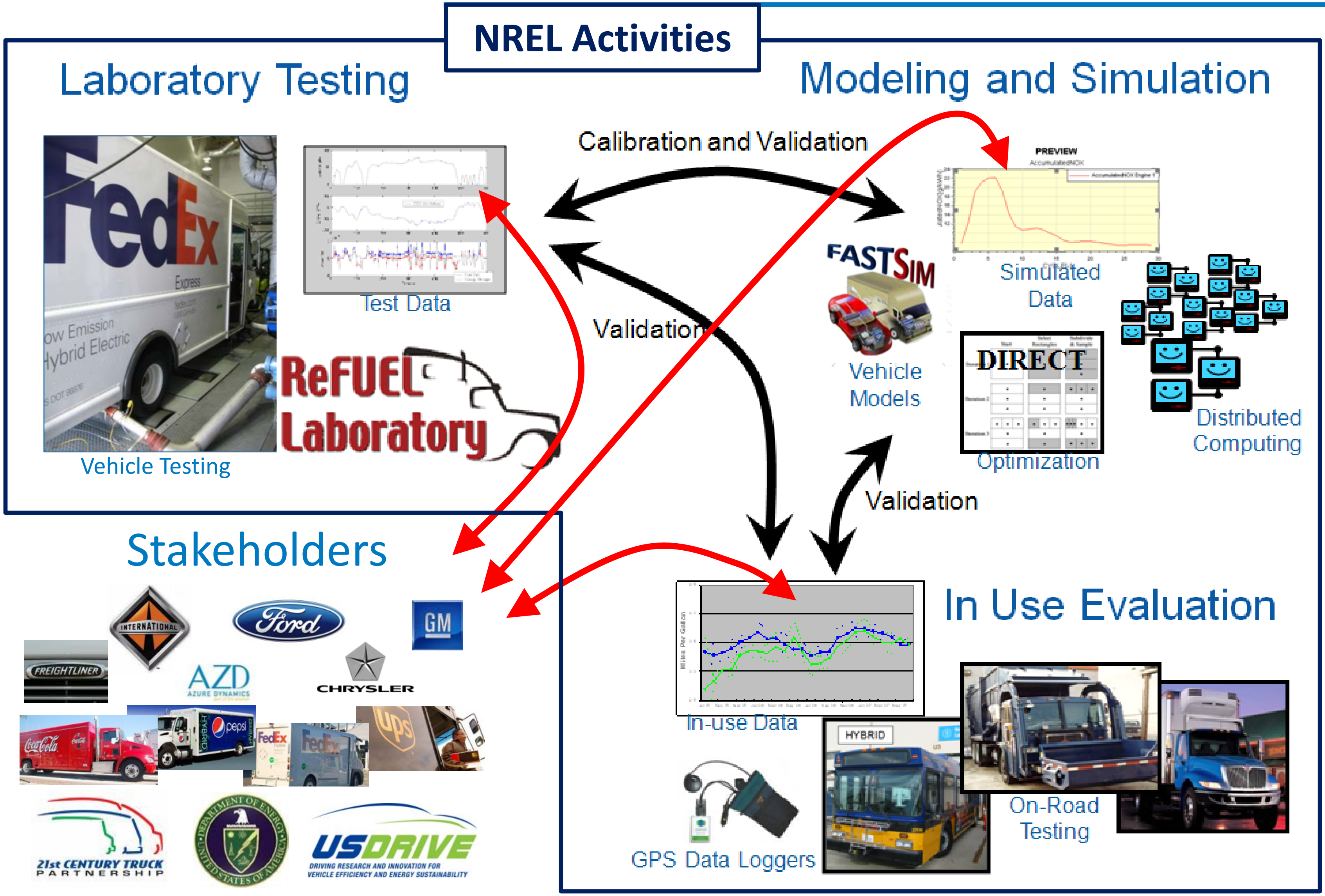


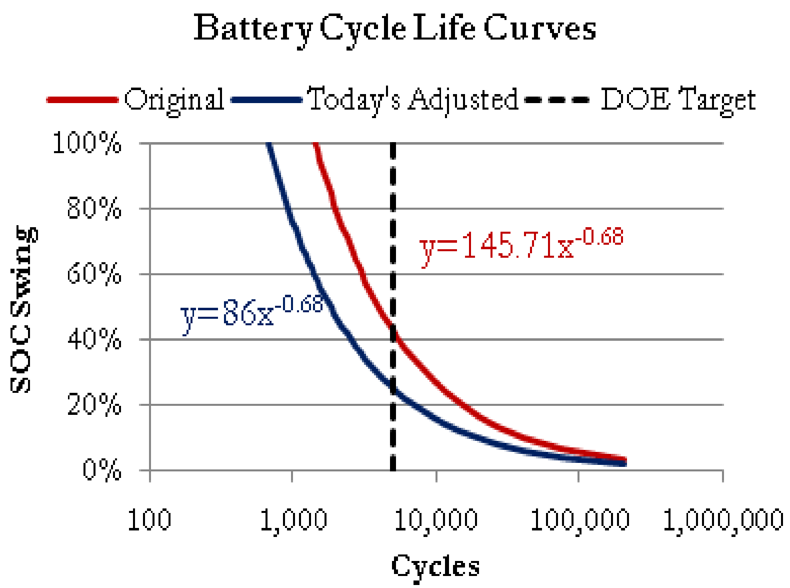
Photo credit: Robb Barnitt, NREL

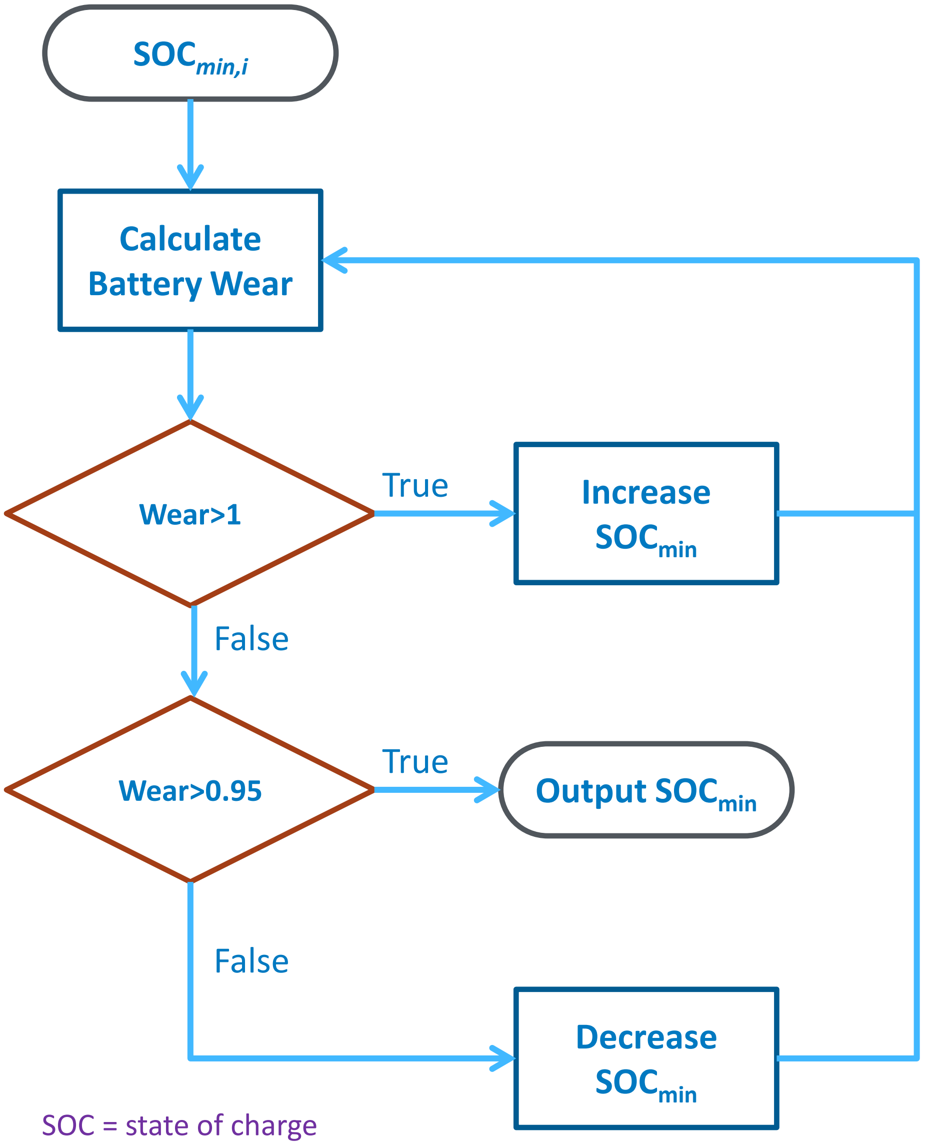
Analysis Approach: Assess interaction between vehicle design and duty profile

- **Vehicle performance sensitive to specific application**
- **Evaluate large design matrix**
- **Select modeling tool to facilitate broad design sweeps (FASTSim)**
  - Power model with short run time
  - Validated performance, fuel economy and cost results
- **Tool also supports other objectives**
  - Includes detailed cost analysis
  - Integrated battery life prediction

Iterative Approach: To correctly size the battery for each design/use profile combination

- **Life estimates adjusted to match published data on production Li batteries**
- **Batteries sized to meet, but not greatly exceed life in intended application**

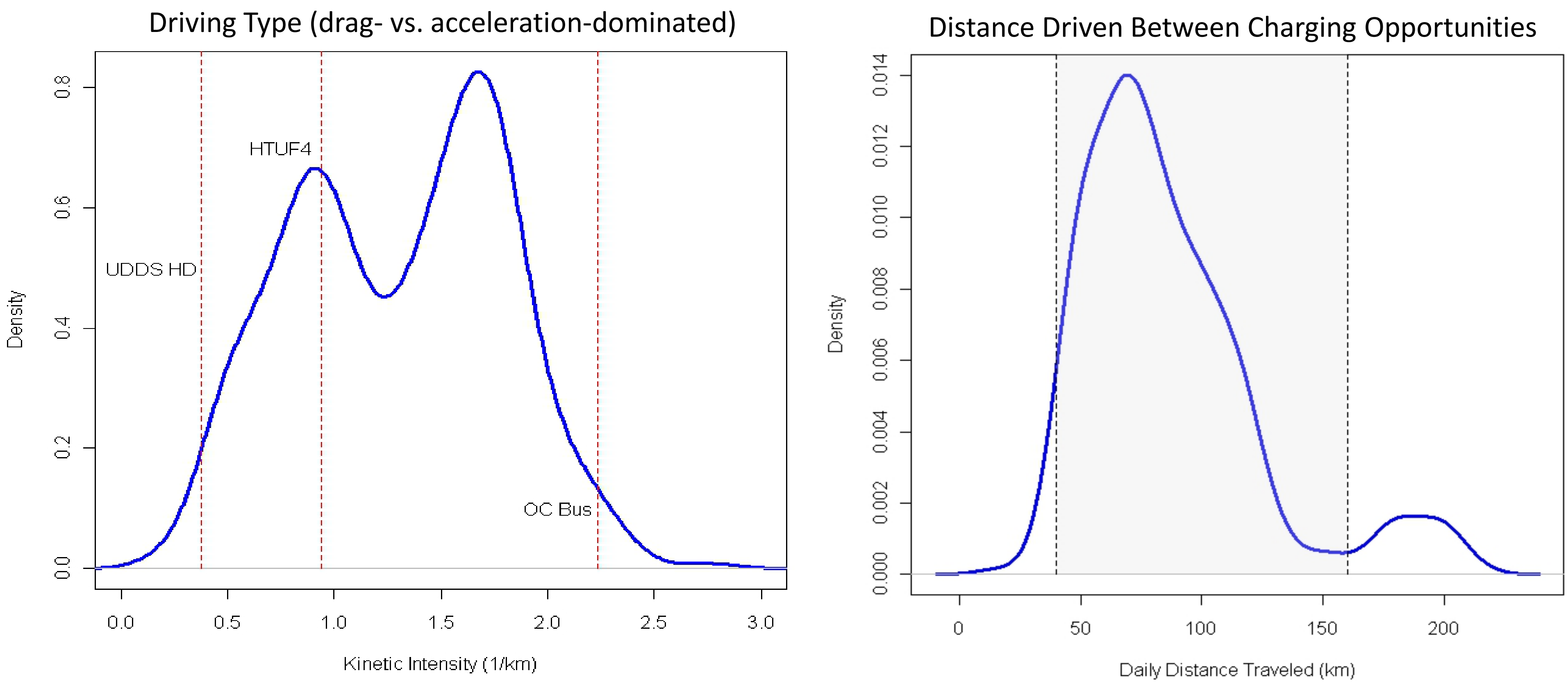




SOC = state of charge

Cycle Selection Approach: Consider distribution of characteristics from in-use data

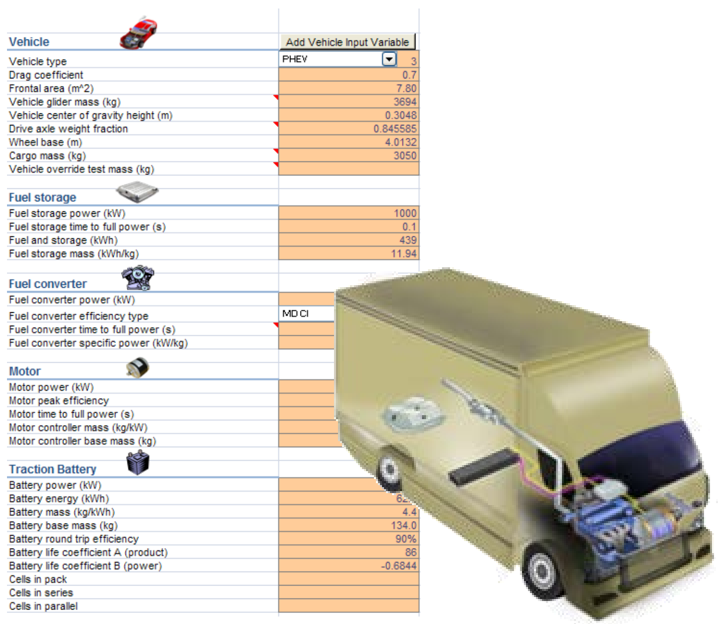
334 parcel delivery daily driving profiles

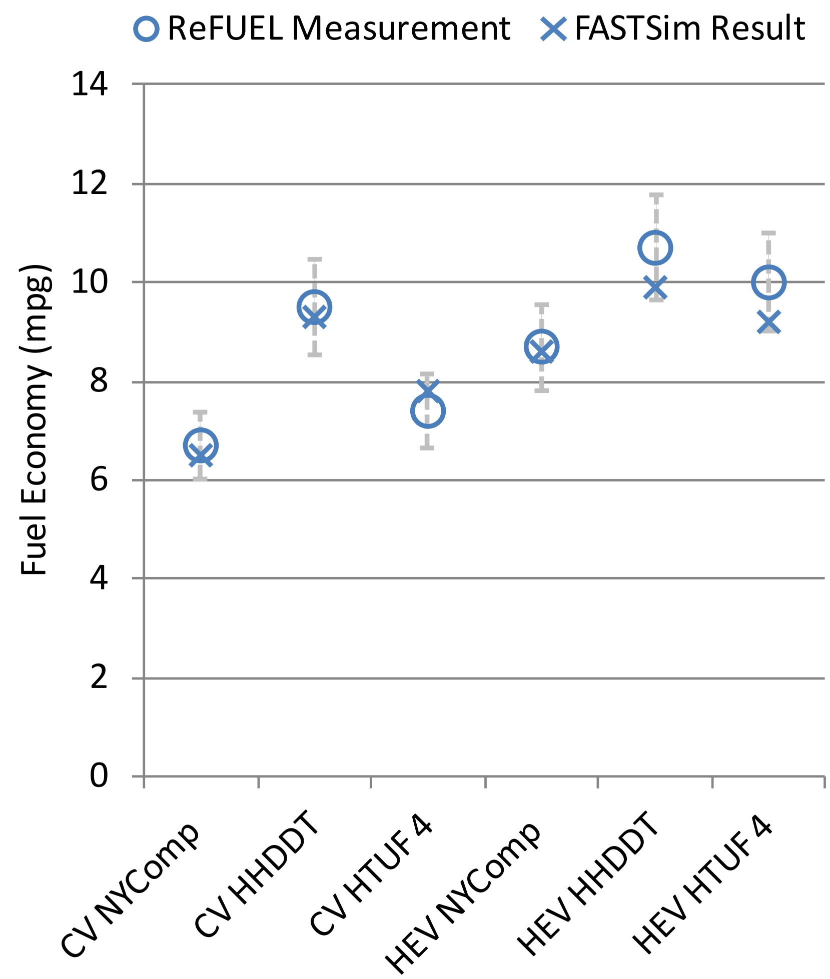


Kinetic Intensity (KI) – Derives from the vehicle road load equation and has been shown to correlate with hybridization benefit

Accomplishments: Created detailed vehicle models and verified baseline simulations to lab testing results

- **Models created**
  - Conventional diesel baseline
  - Diesel hybrid for PHEV basis
- **Simulated results within uncertainty of laboratory measurements**





Accomplishments: Simulated design matrix with hundreds of scenario combinations

Design Matrix for PHEVs

Drive cycles	UDDS HD, HTUF 4, OC Bus
Daily distance traveled	40, 80, 120, 160 km
Additional battery capacity	10, 20, 40, 60 kWh
Range of electric motor power	30 – 70 kW
Battery sizing/use strategies	Single battery to last life of vehicle vs. one or more battery replacements

Cost Matrix Assumptions

Scenario	Battery Cost	Fuel Cost		Electricity Cost
		Gas	Diesel	
Current	$700/kWh	$0.81/L ($3.08/gal)	$0.85/L ($3.23/gal)	$0.11/kWh
Future	$100/kWh	$1.29/L ($4.90/gal)	$1.37/L ($5.19/gal)	$0.11/kWh

Reference Key	
(green)	USABC/DOE
(tan)	EIA

UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

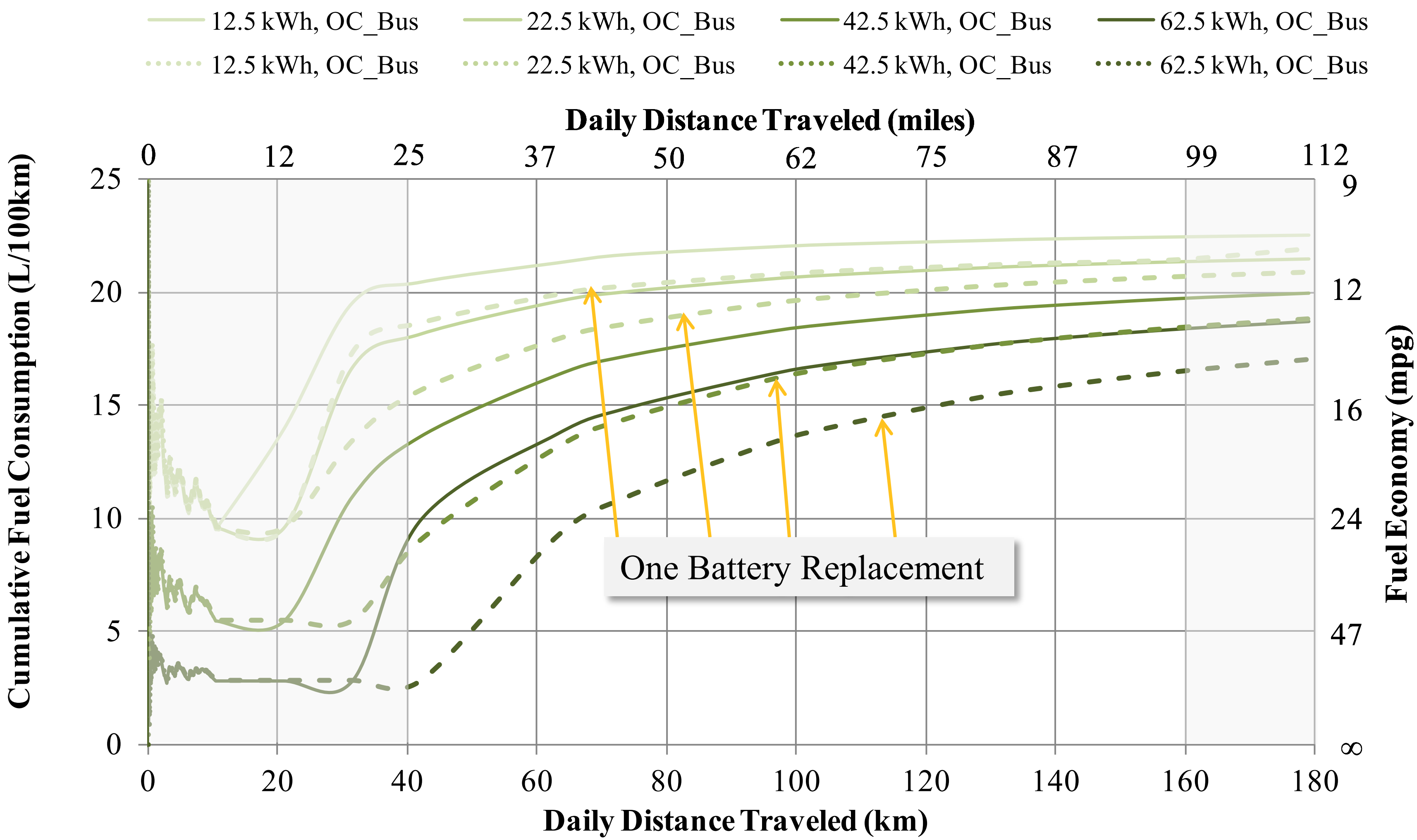
Additional assumptions and references listed in appendix

- Vehicle service life
- Battery cost
- Motor and controller cost
- Markup factor
- Discount rate
- Charger efficiency

DOE, current battery cost: www1.eere.energy.gov/vehiclesandfuels/pdfs/merit_review_2011/plenary/vtpn07_howell_ft_2011_o.pdf
USABC/DOE, future battery cost: www.uscar.org/guest/view_team.php?teams_id=11

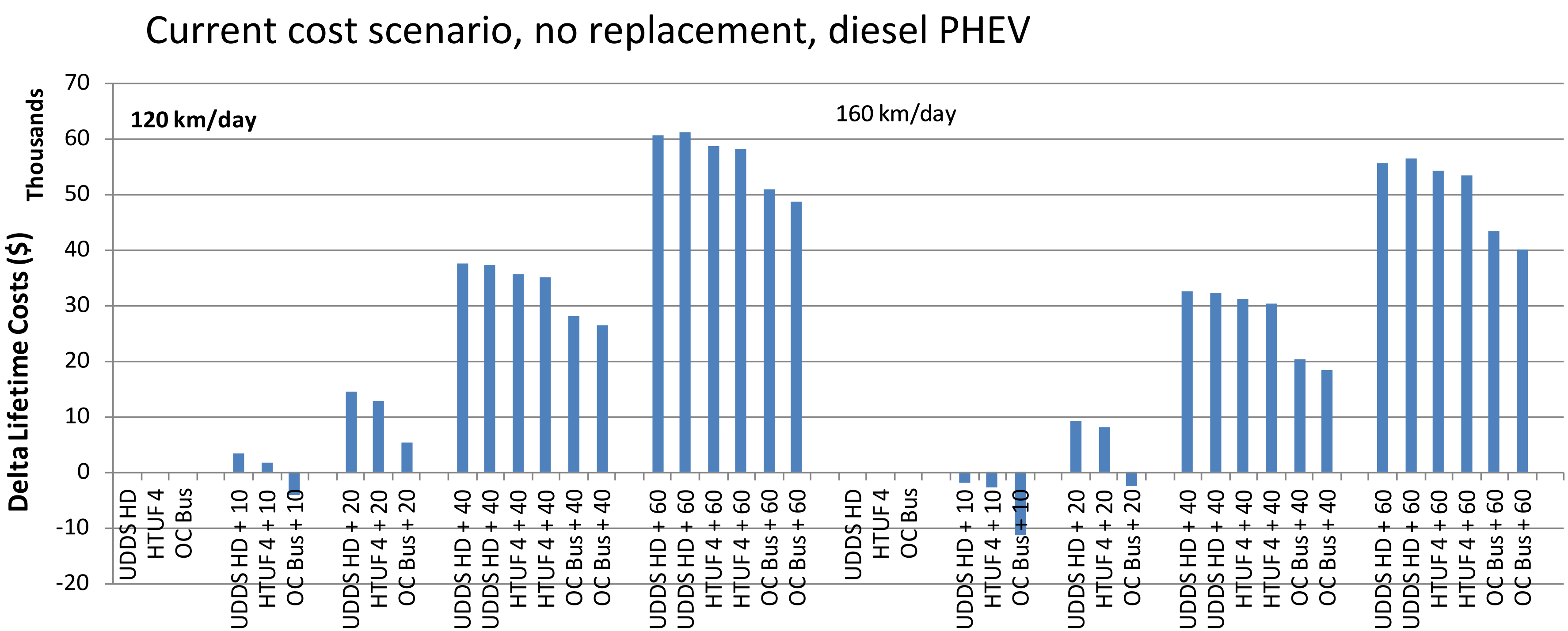
Accomplishments: Understanding influence of attribute combinations on fuel economy

- E.g.: CD/CS performance, battery/motor size, replacement strategy



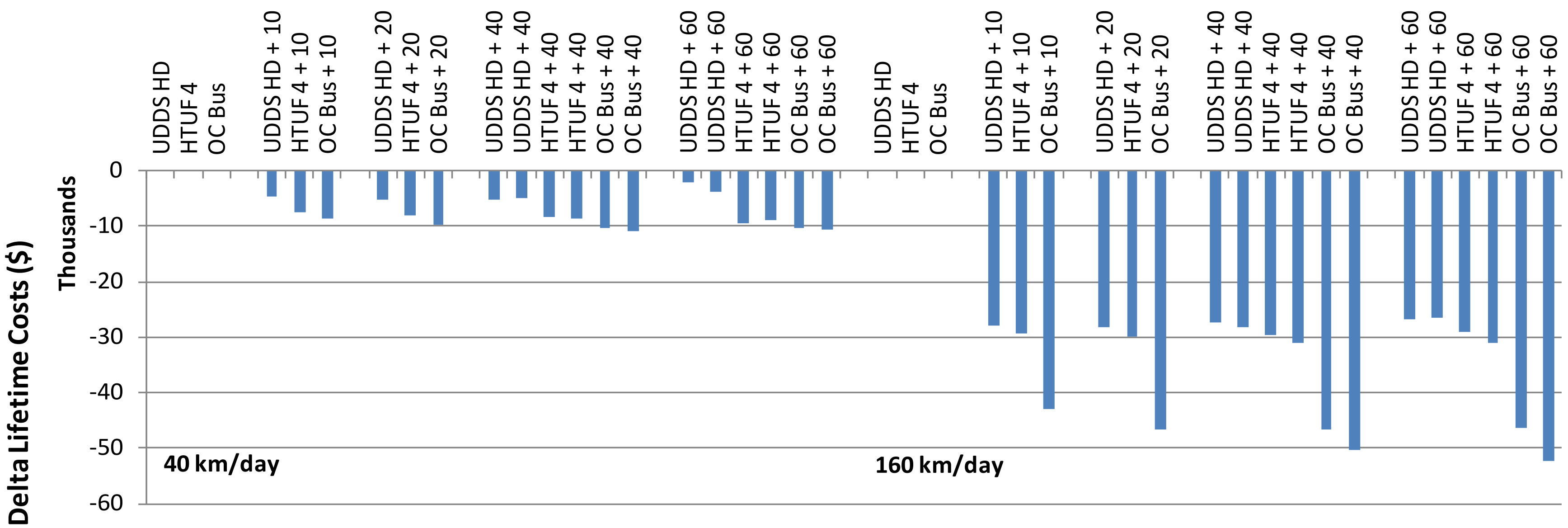
Cost Analysis Accomplishments: Few scenarios pay back under current day cost assumptions

- **Consider lifetime cost impact from drive cycle type, battery/motor size, driving distance, etc.**



Cost Analysis Accomplishments: Significant PHEV payback under optimistic future cost scenario

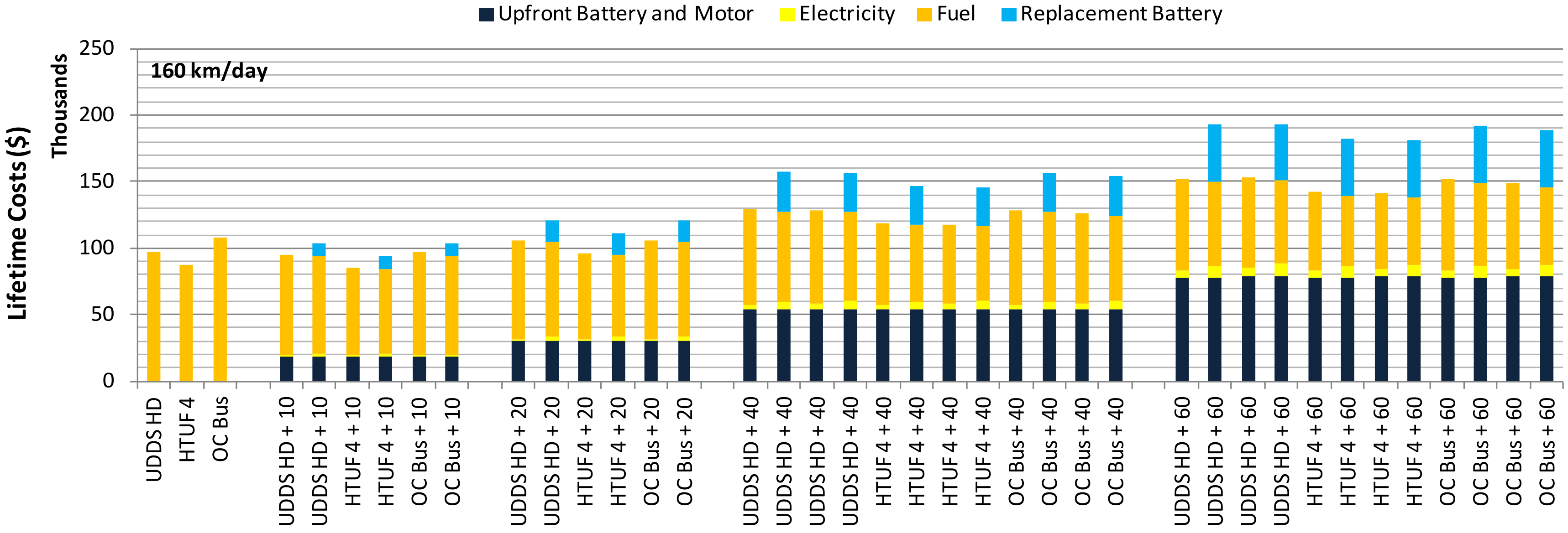
- **Assumes lower battery and higher fuel prices**
- **Payback increases with battery size and driving distance**



Future cost scenario, no replacement, diesel PHEV

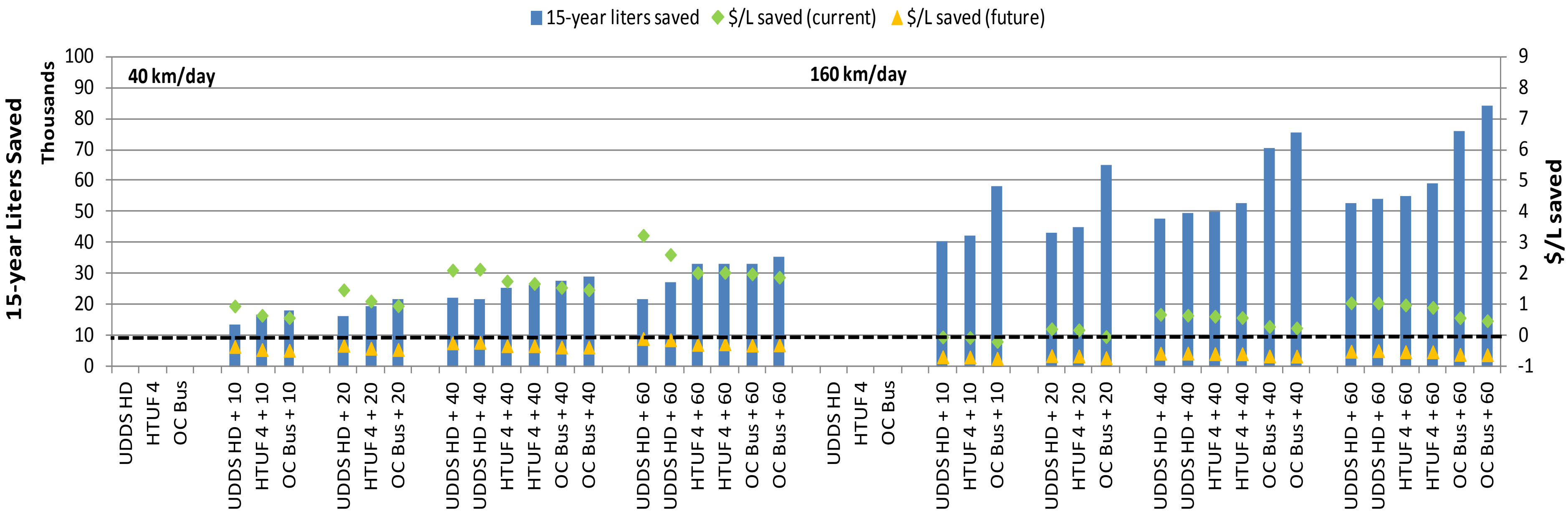
Accomplishment: Cost breakdown analysis highlights battery as the cost driver

- **Replacement cases use a little less fuel, but cost more**



Current cost scenario, with and without replacement. Results only show the fuel and incremental vehicle price above the price of the conventional baseline vehicle.

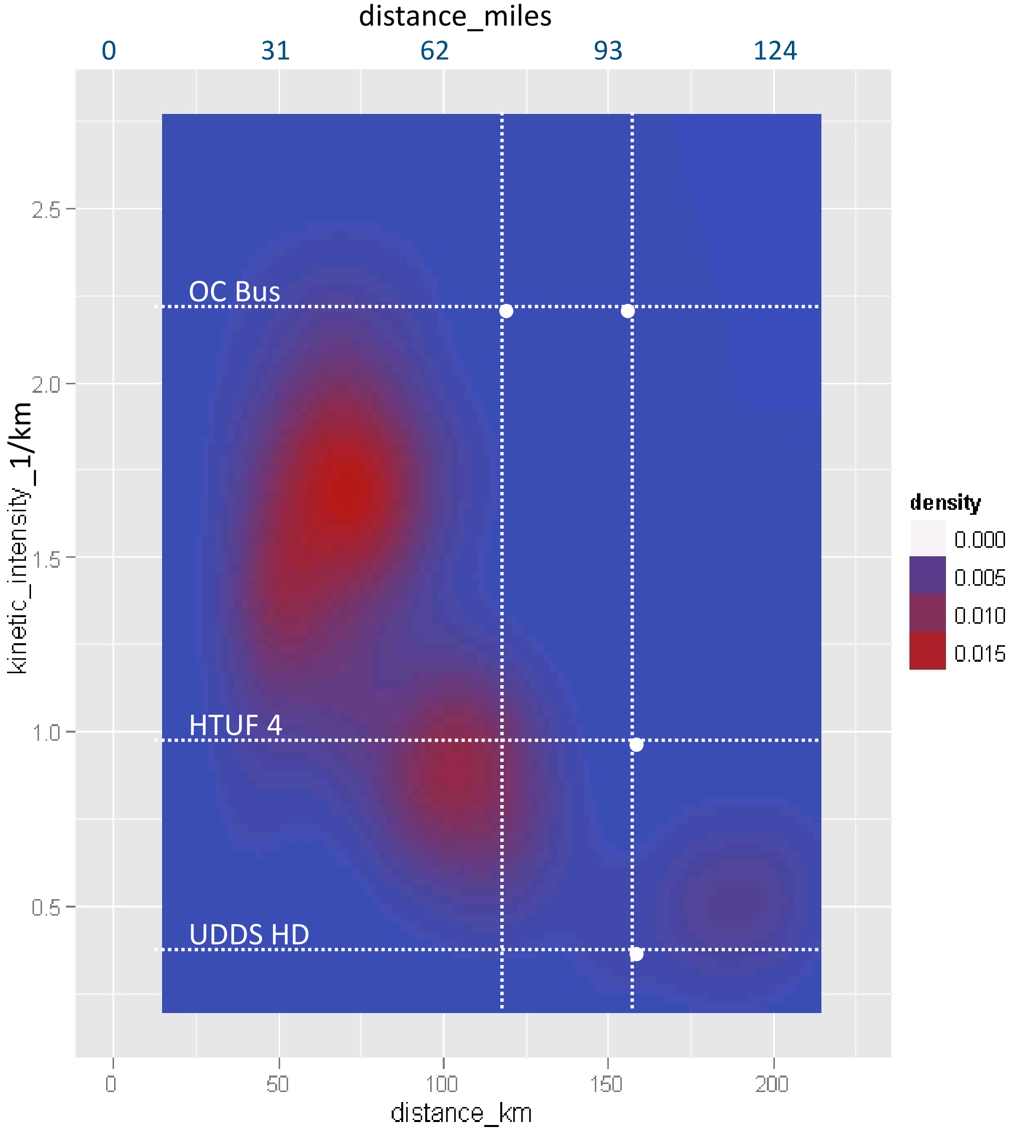
Accomplishment: Fuel Savings and Cost-Effectiveness Analysis



- **Scenarios with negative $/L saved pay back with no incentives**
  - Requires future cost scenario, or…
  - Combination of low range PHEV, high KI cycle and long daily distance, but…

Accomplishment: Multi-factor analysis of in-use data

- **High KI cycles tend to have shorter daily distance**
- **Payback under current cost scenario requires different driving pattern**
  - Longer distance at high KI for small battery PHEV
- **Future work to examine other potential payback scenarios**



Collaboration and Coordination

Industry Partners

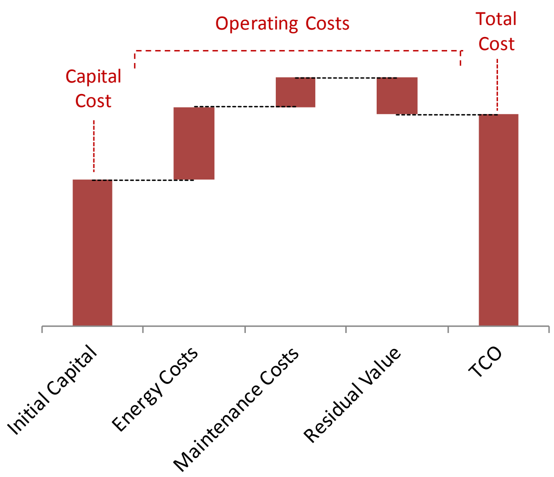
- **FedEx and UPS**
  - Supplied vehicles, drive cycle data and MD vehicle design criteria
- **Azure Dynamics**
  - Supported lab testing and modeling
- **Navistar**
  - Providing HD vehicle and performance data

Collaboration within VTP

- **Renewable Fuels and Lubricants (ReFUEL) Laboratory**
  - Performed chassis dynamometer testing for baseline model verification
- **Advanced Vehicle Testing Activity**
  - Collected field drive cycles for use in analyses
- **Oak Ridge National Laboratory**
  - Providing class 8 long-haul drive cycles for HD analysis

Proposed Future Work

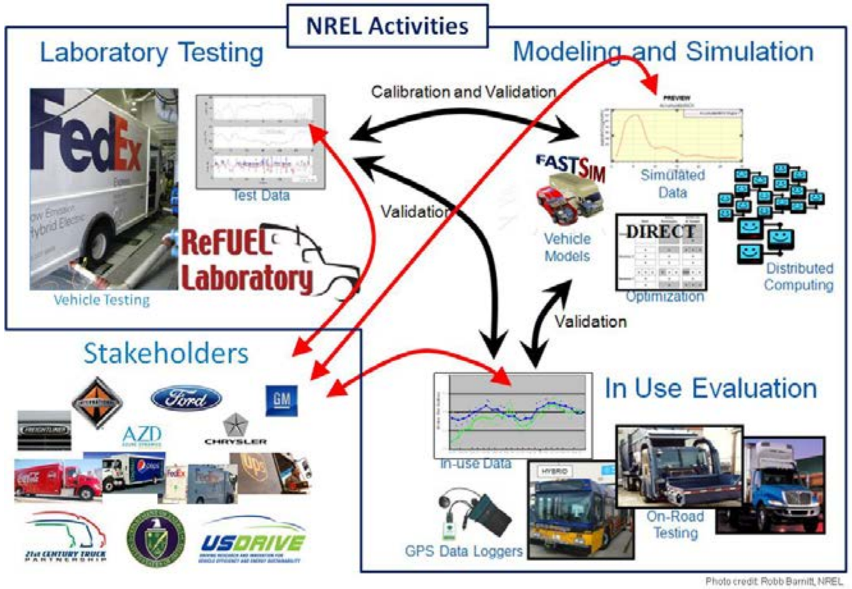
- **Perform enhanced cost analysis**
  - Where is the payback crossover point?
  - Factor in maintenance, service intervals
  - Decreased cost battery replacement
- **Consider further design scenarios**
  - Additional engine sizes/degrees of hybridization
  - PHEV vs. HEV or EV
  - Opportunity charging or battery swapping
- **Analyze additional cycle factors**
  - Such as incorporating grade
- **Investigate HD hybridization/electrification**
  - Regional delivery/short-haul
  - Long-haul



NREL PIX # 13288

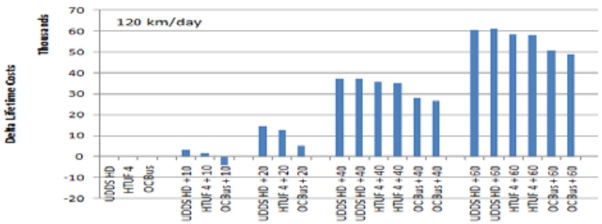
Summary – 1

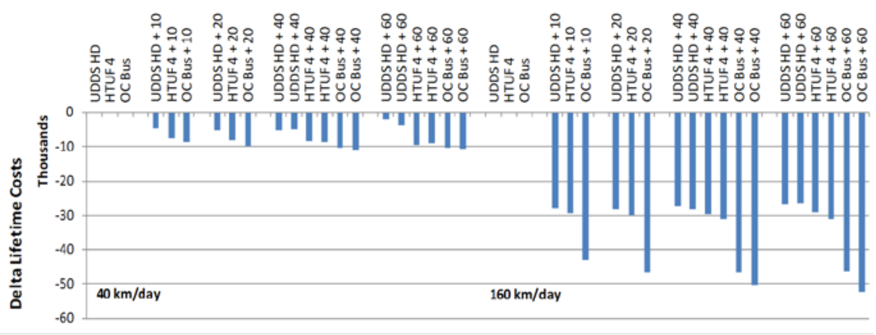
- MD and HD are important segments for research on fuel saving technologies such as vehicle electrification
- Actual fuel savings are sensitive to the specific application
- This project leverages NREL expertise in MD/HD modeling and simulation, laboratory testing and field evaluation to assess vehicle performance in real-world use conditions



Summary – 2

- **Assessment swept a large design space**
  - Using tool that captures details of cost and battery life estimation
- **Results with present-day cost assumptions show few PHEV scenarios pay back, but many scenarios pay back under future projections of low battery and high fuel prices**
- **On-going/future work**
  - Refine cost analysis
  - Analyze additional scenarios
  - Consider HD applications
  - Educate fleets about findings

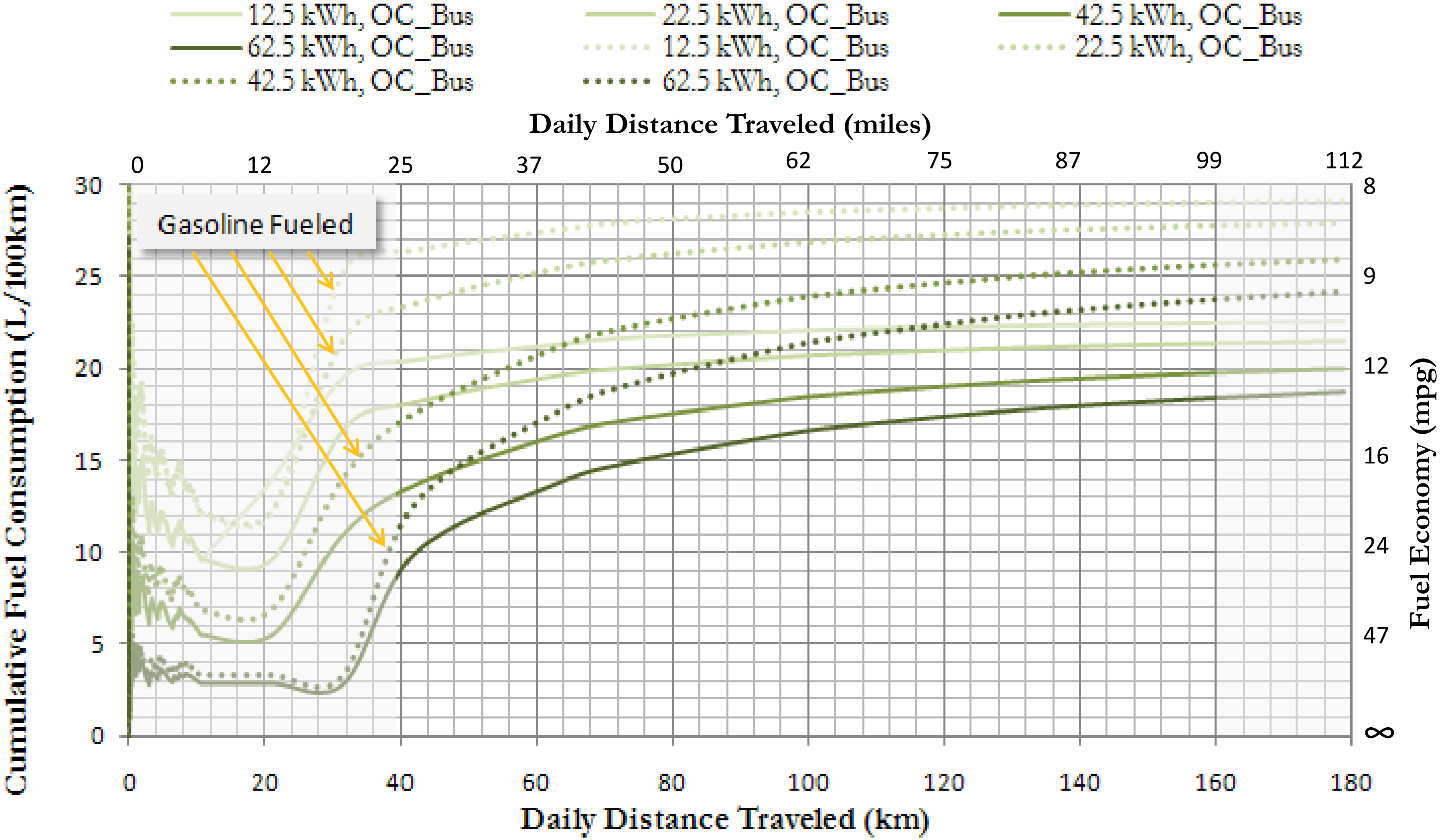




Technical Back-Up Slides

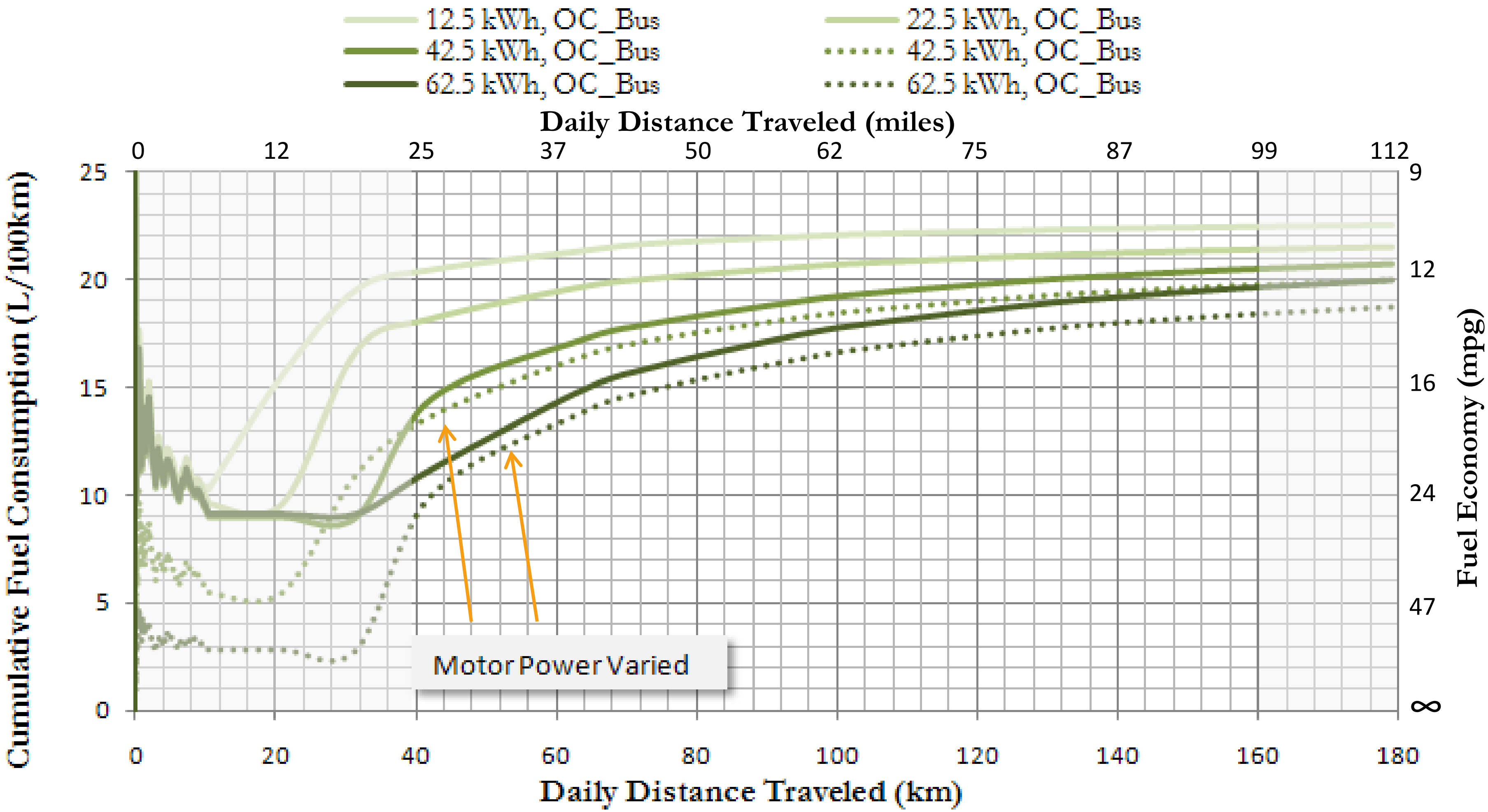
Results: Cumulative Fuel Consumption

Effect of gasoline vs. diesel PHEV



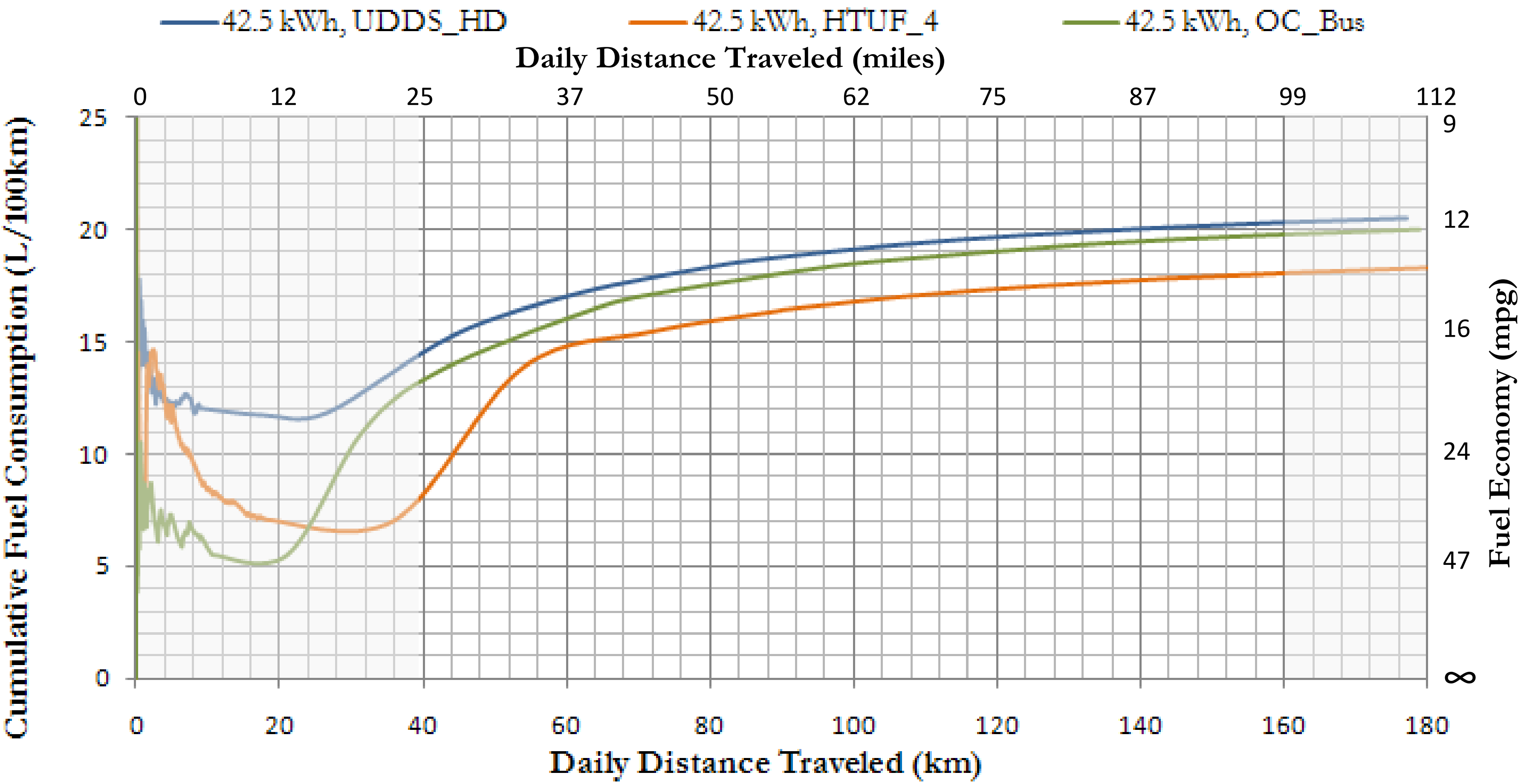
Results: Cumulative Fuel Consumption

Effect of increasing motor power to match battery power



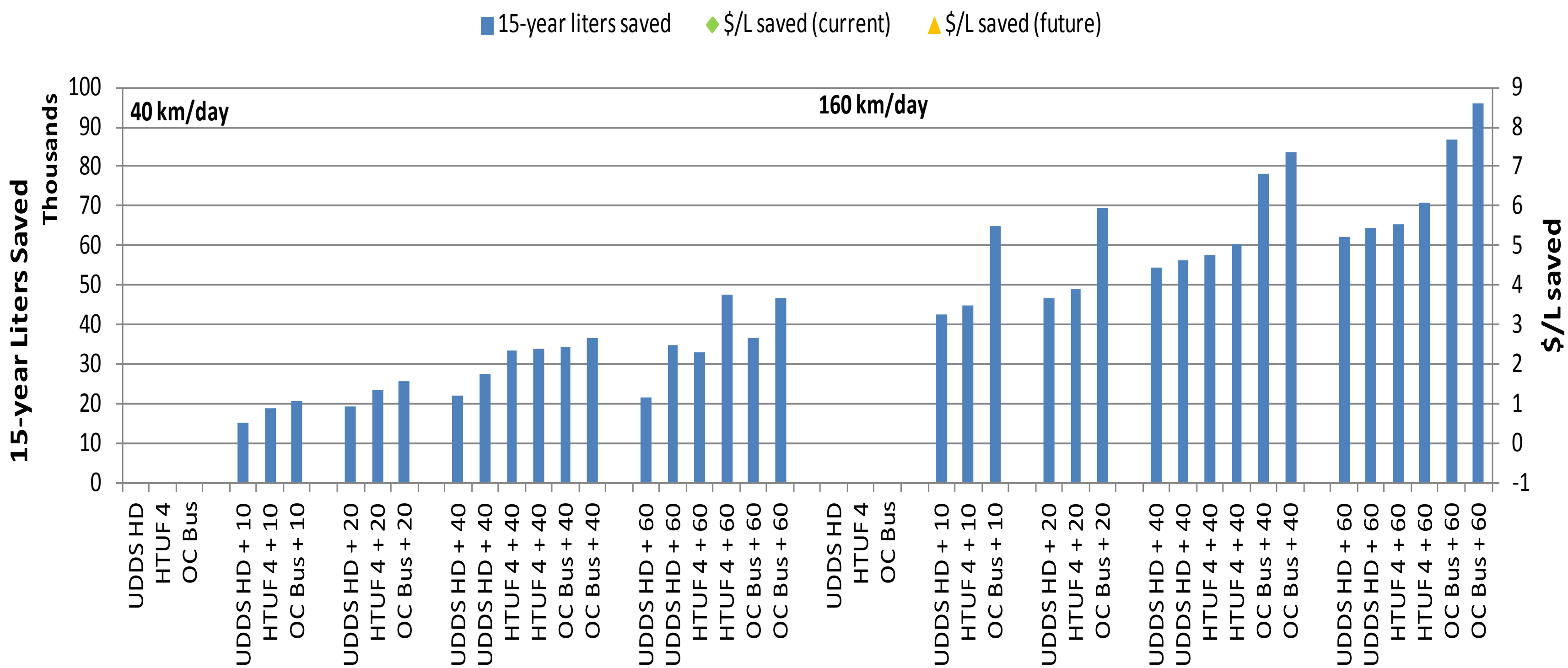
Results: Cumulative Fuel Consumption

Effect of drive cycle/kinetic intensity



Results: Cost Effectiveness

With battery replacement



Replacing the battery displaces more fuel but pays less per liter.

References and Additional Assumptions

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Additional Analysis Assumptions

Vehicle life (years)	15
Battery cost	\$22/kW × (kW) + scenario \$/kWh * (kWh) + \$680
Motor and controller cost	\$21.7/kW + \$425
Markup factor	1.75
Discount rate	8%
Charger efficiency	0.9