Impact of Driving Behavior on PHEV Fuel Consumption for Different Powertrain, Component Sizes and Control

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Aymeric Rousseau (PI)

Argonne National Laboratory

Sponsored by Lee Slezak

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U.S. Department of Energy

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Project Overview

Timeline

- Start – September 2009
- End – September 2010
- 90% Complete

Barriers

- Evaluate fuel displacement potential in real world driving conditions

Budget

- FY09 - $200K
- FY10 - $250K

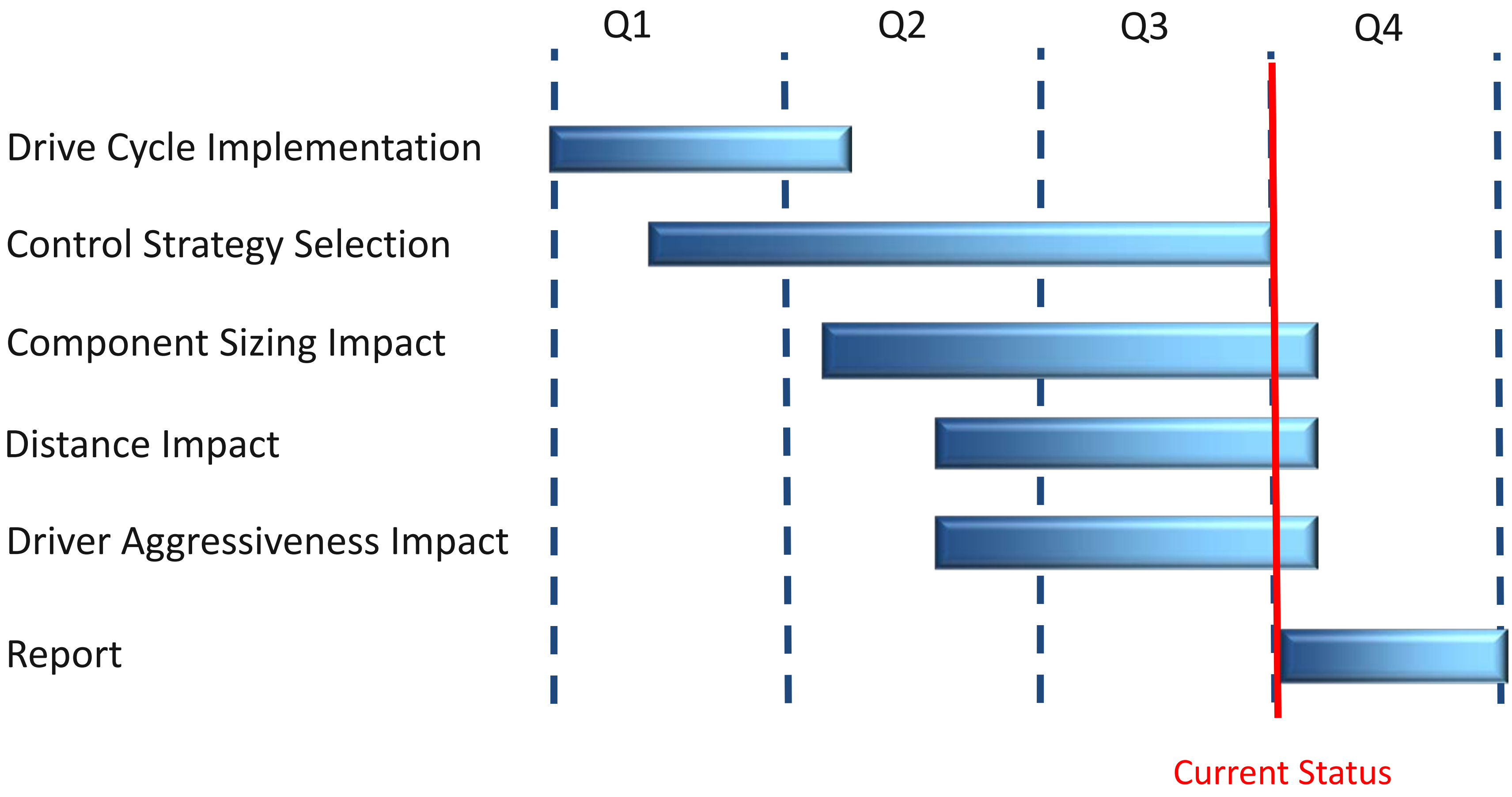
Partners

- U.S. EPA
- City of Chicago
- University of California Davis
- MathWorks

Objectives

- Define the best control strategy philosophy for different battery characteristics
- Select the most appropriate set of control parameters to maximize fuel efficiency while maintaining acceptable drive quality and maximizing battery life
- Define the most appropriate battery energy/power to maximize fuel displacement
- Assess the impact of driving distance and driver aggressiveness on fuel displacement

Milestones



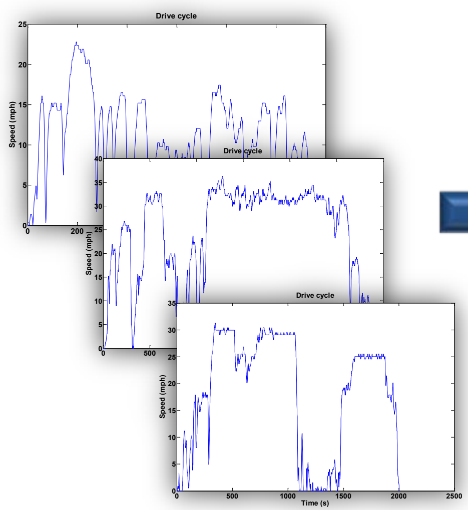
Q1
Q2
Q3
Q4
Drive Cycle Implementation
Control Strategy Selection
Component Sizing Impact
Distance Impact
Driver Aggressiveness Impact
Report
Current Status

Approach

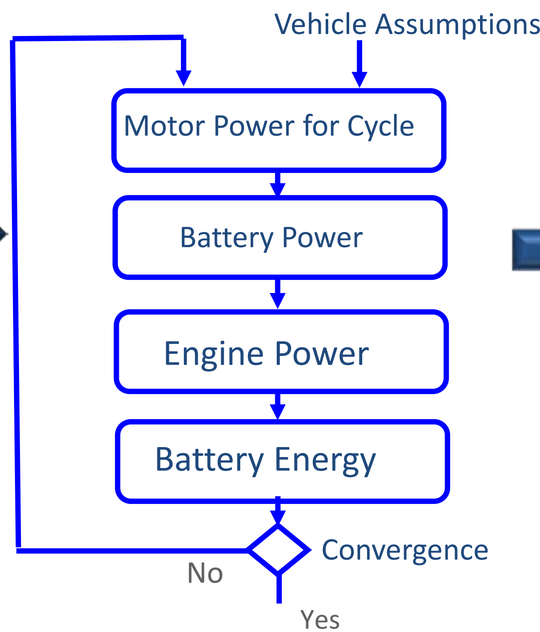
Real World Drive Cycles

Automated Sizing

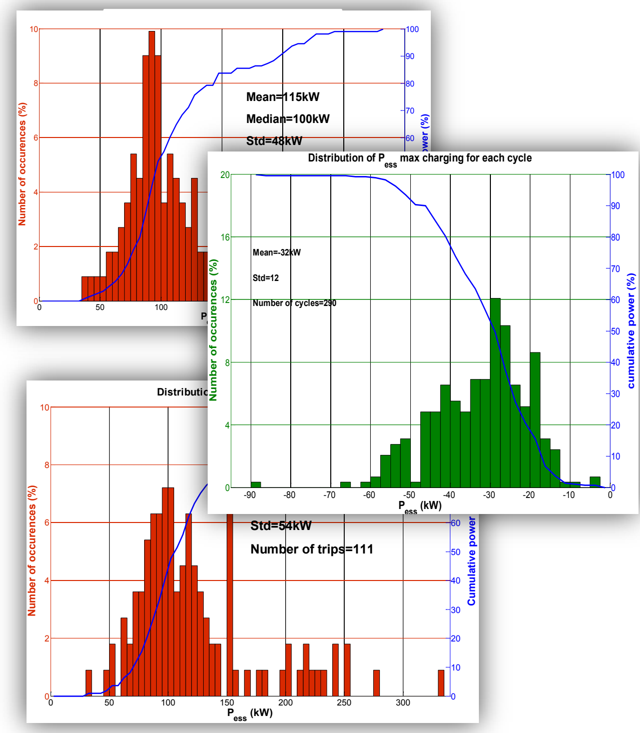
Analysis (Distribution)



>110 Trips
One day in
Kansas City

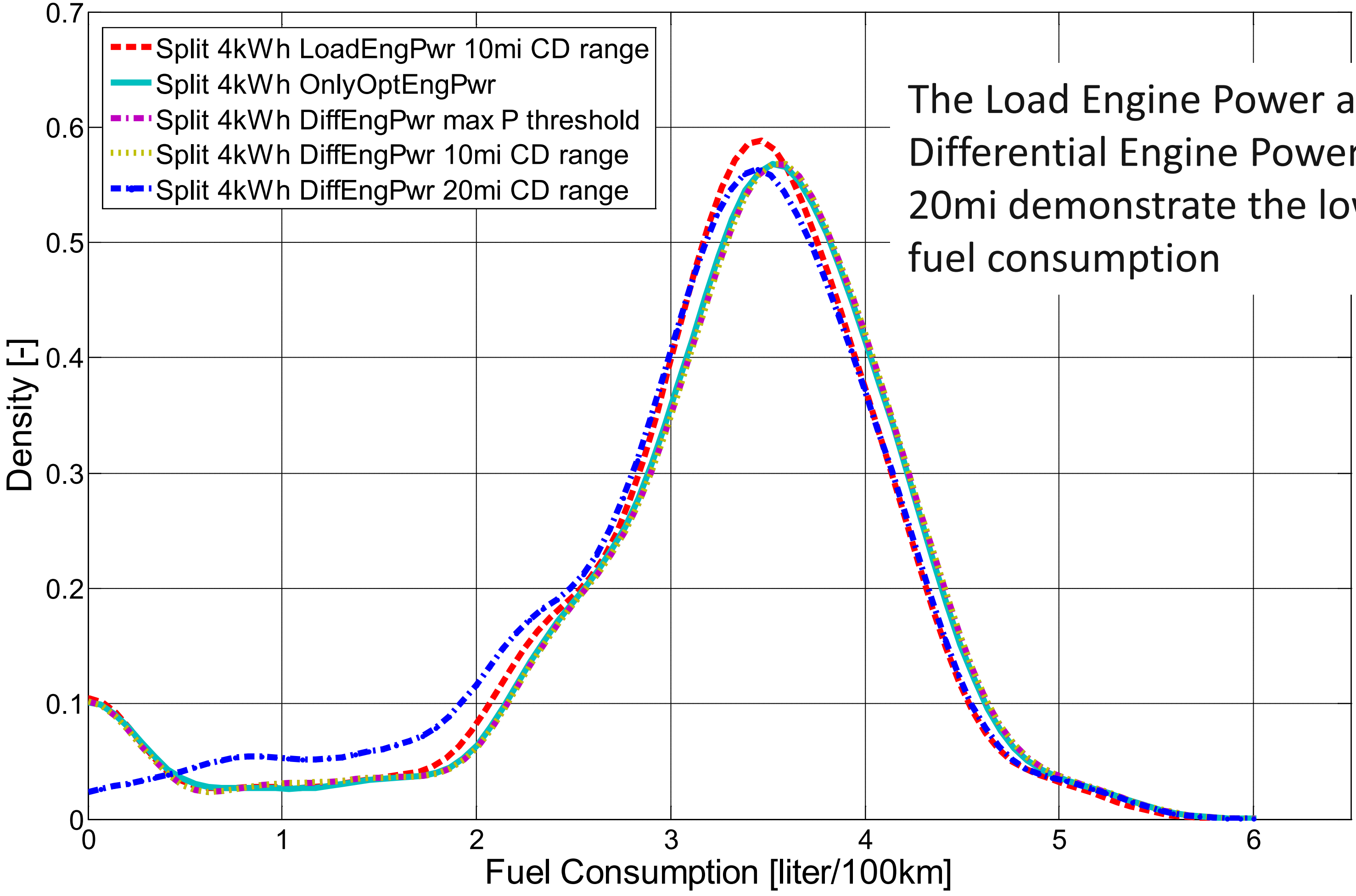


Midsize Vehicle



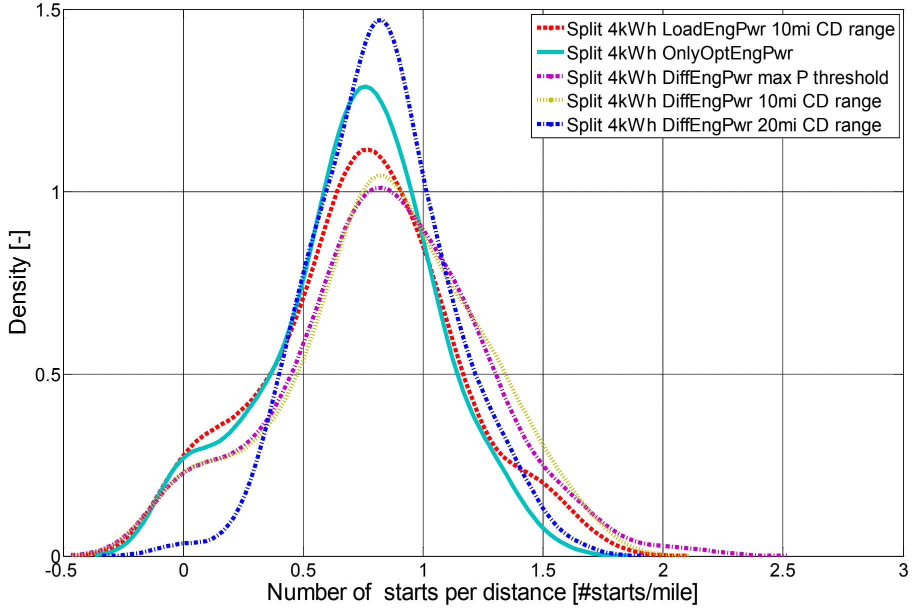
Technical Accomplishments
Selection of Control Strategies - Fuel Consumption

Example of Power Split HEV with 4kWh Total Energy



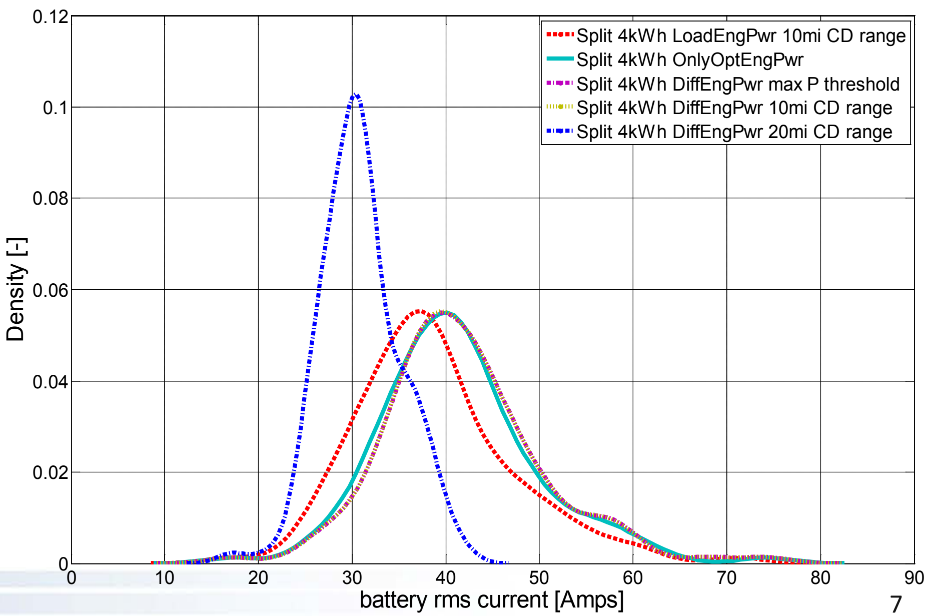
The Load Engine Power and Differential Engine Power 20mi demonstrate the lowest fuel consumption

Technical Accomplishments
Selection of Control Strategies – Drive Quality, Battery Life



Several controls provide low number of engine starts, including the Optimum Engine Power and the Differential Engine Power

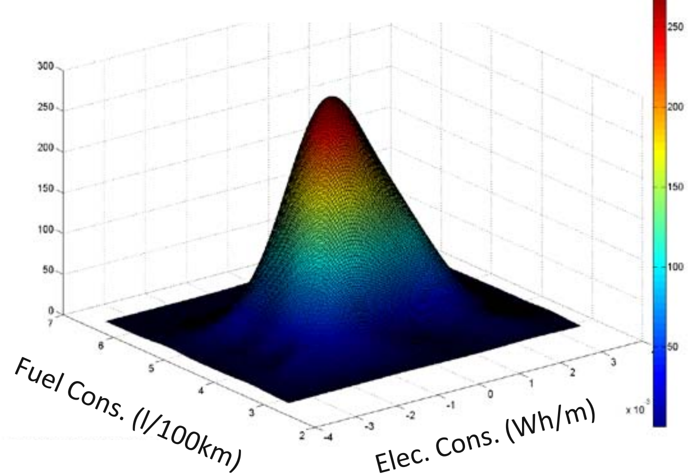
The Differential Engine Power tuned for 20 miles AER on the UDDS clearly provides lower battery RMS current



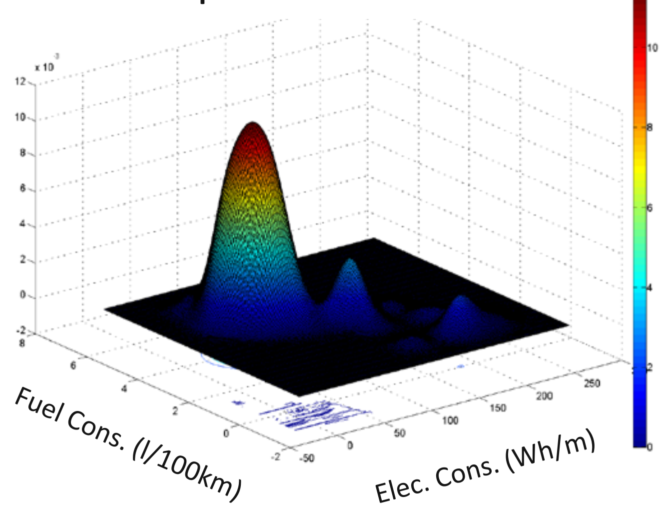
Technical Accomplishments

Component Sizing Has Clear Impact on Fuel and Electrical Consumption Patterns

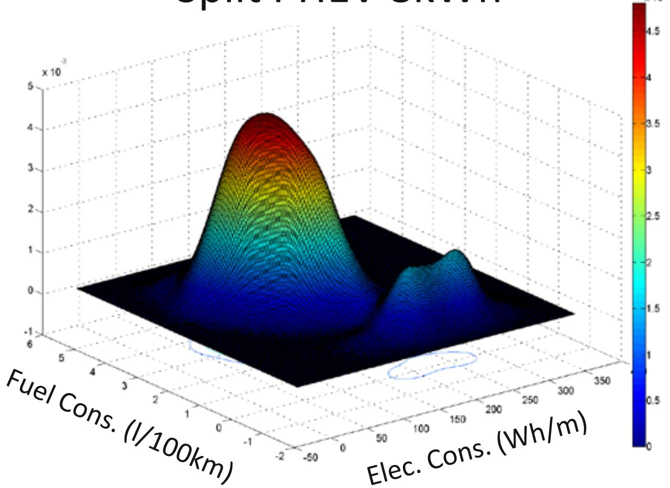
HEV



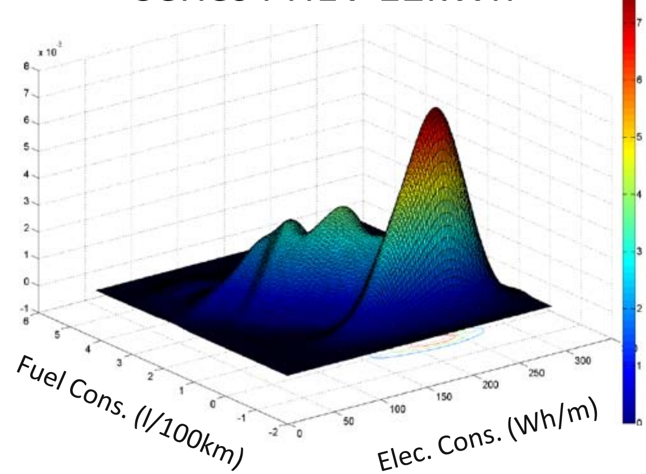
Split PHEV 4kWh



Split PHEV 8kWh

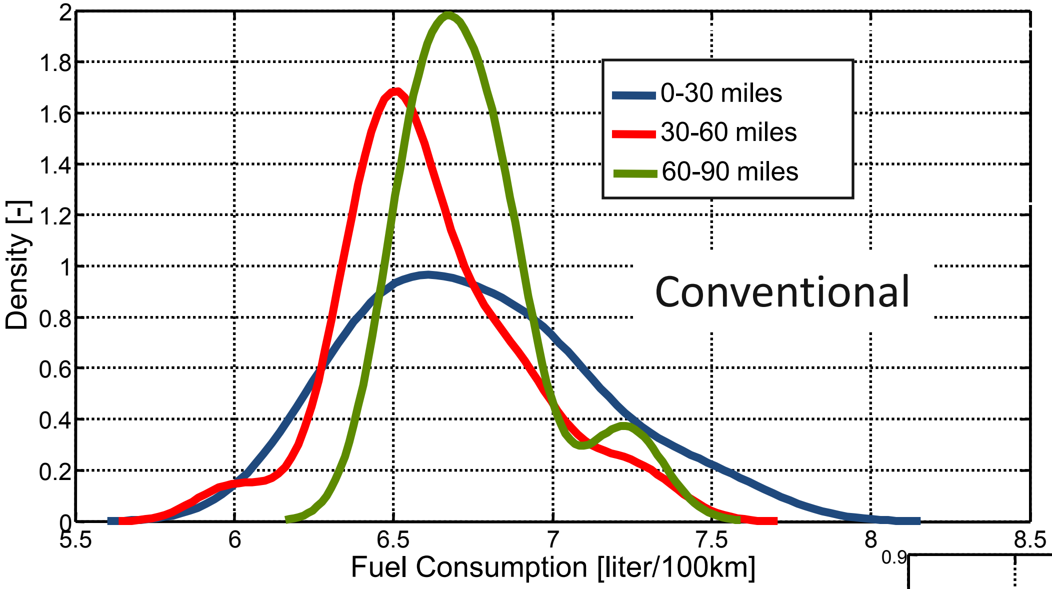


Series PHEV 12kWh

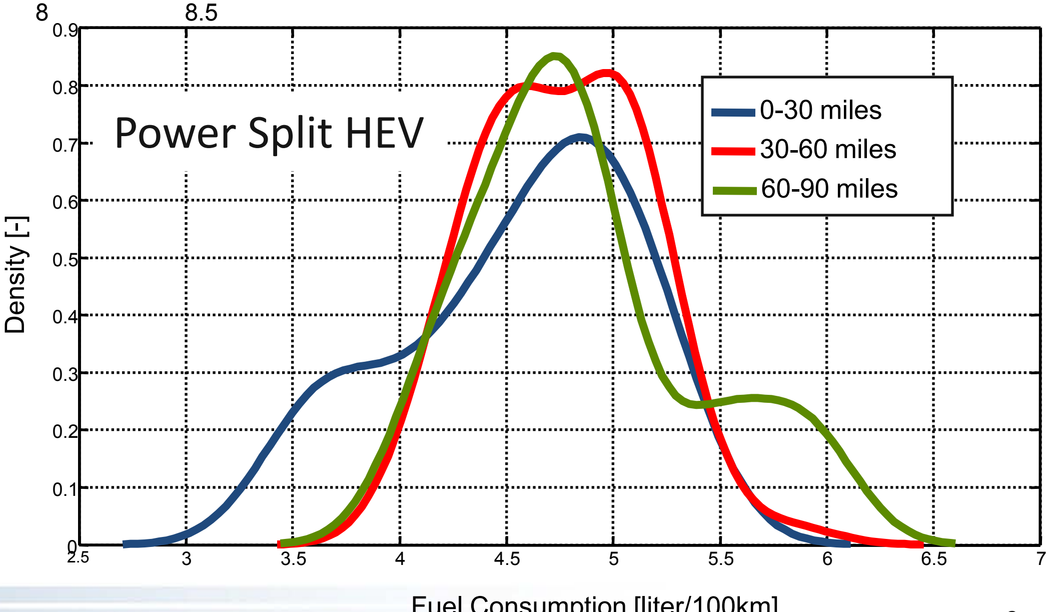


Technical Accomplishments

Impact of Distance on Fuel Consumption Displacement



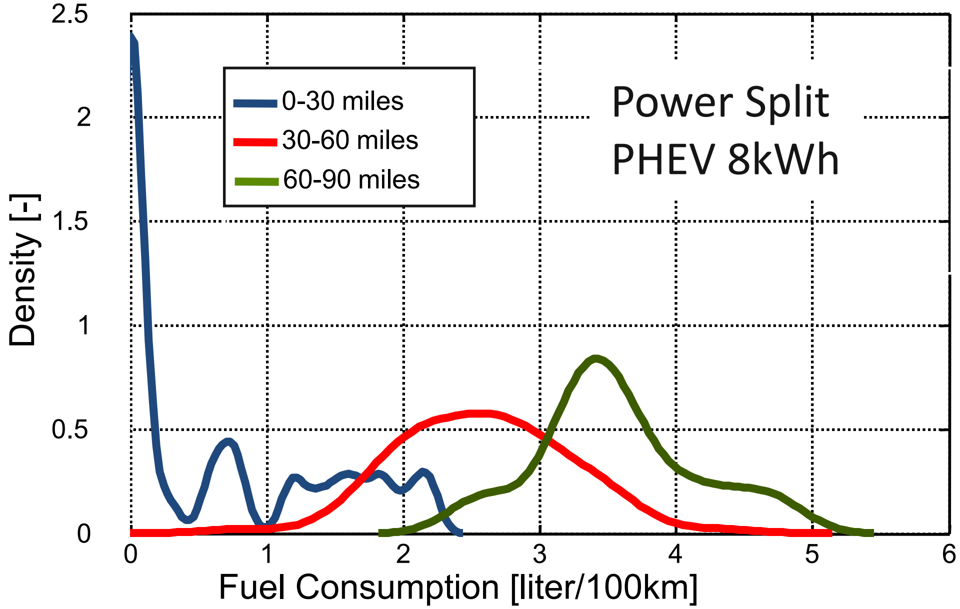
- The driving distance has a small influence on the conventional (STD from 0.2 to 0.35).
- The impact increases slightly for the HEV (STD from 0.38 to 0.55)



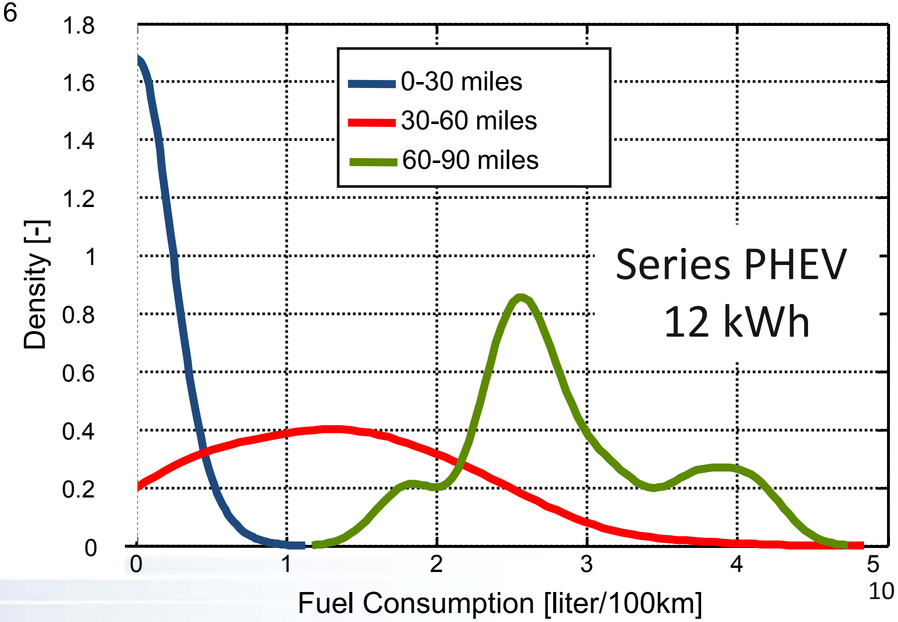
STD = standard deviation

Technical Accomplishments

Impact of Distance on Fuel Consumption Displacement



- The driving distance impact increases with the available electrical energy (STD from 0.6 to 0.7 for the 8kWh and 0.1 to 0.8 for the 12kWh)



STD = standard deviation

Technical Accomplishments
Impact of Distance on Fuel Consumption Displacement

Percentage of Fuel Saved as a Function of Distance

TO CONVENTIONAL

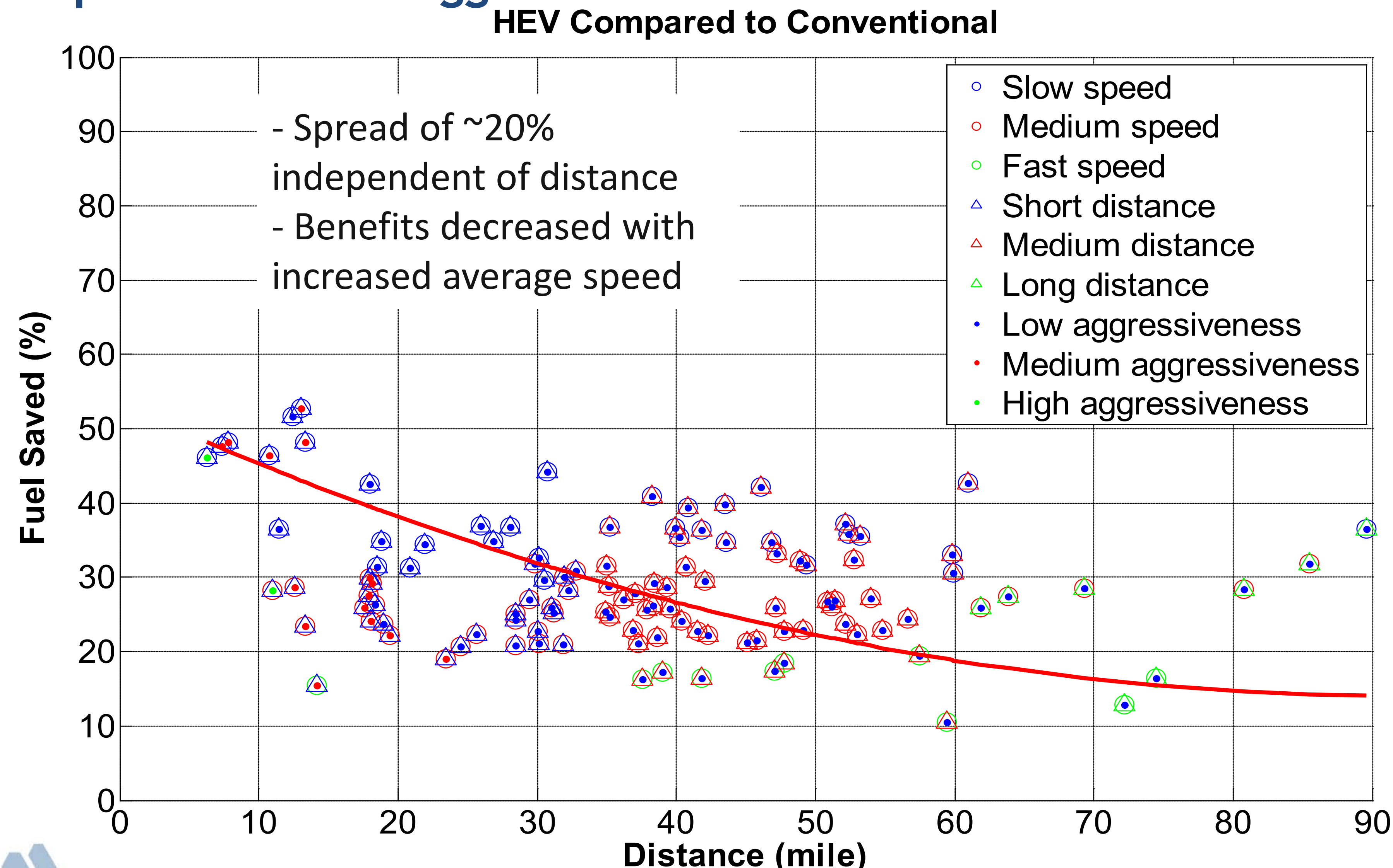
Vehicle	0-30 miles	30-60 miles	60-90miles
Conventional	0.0%	0.0%	0.0%
HEV	2.7%	2.6%	-0.2%
Split 4kWh	19.7%	25.8%	6.1%
Split 8kWh	27.6%	40.4%	12.8%
Series 12kWh	21.1%	42.2%	21.1%
Series 16kWh	9.7%	33.7%	24.0%

TO HEV

Vehicle	0-30 miles	30-60 miles	60-90miles
Conventional	-2.7%	-2.6%	0.2%
HEV	0.0%	0.0%	0.0%
Split 4kWh	25.5%	34.1%	8.6%
Split 8kWh	37.6%	55.5%	17.9%
Series 12kWh	29.2%	58.6%	29.4%
Series 16kWh	13.4%	46.8%	33.4%

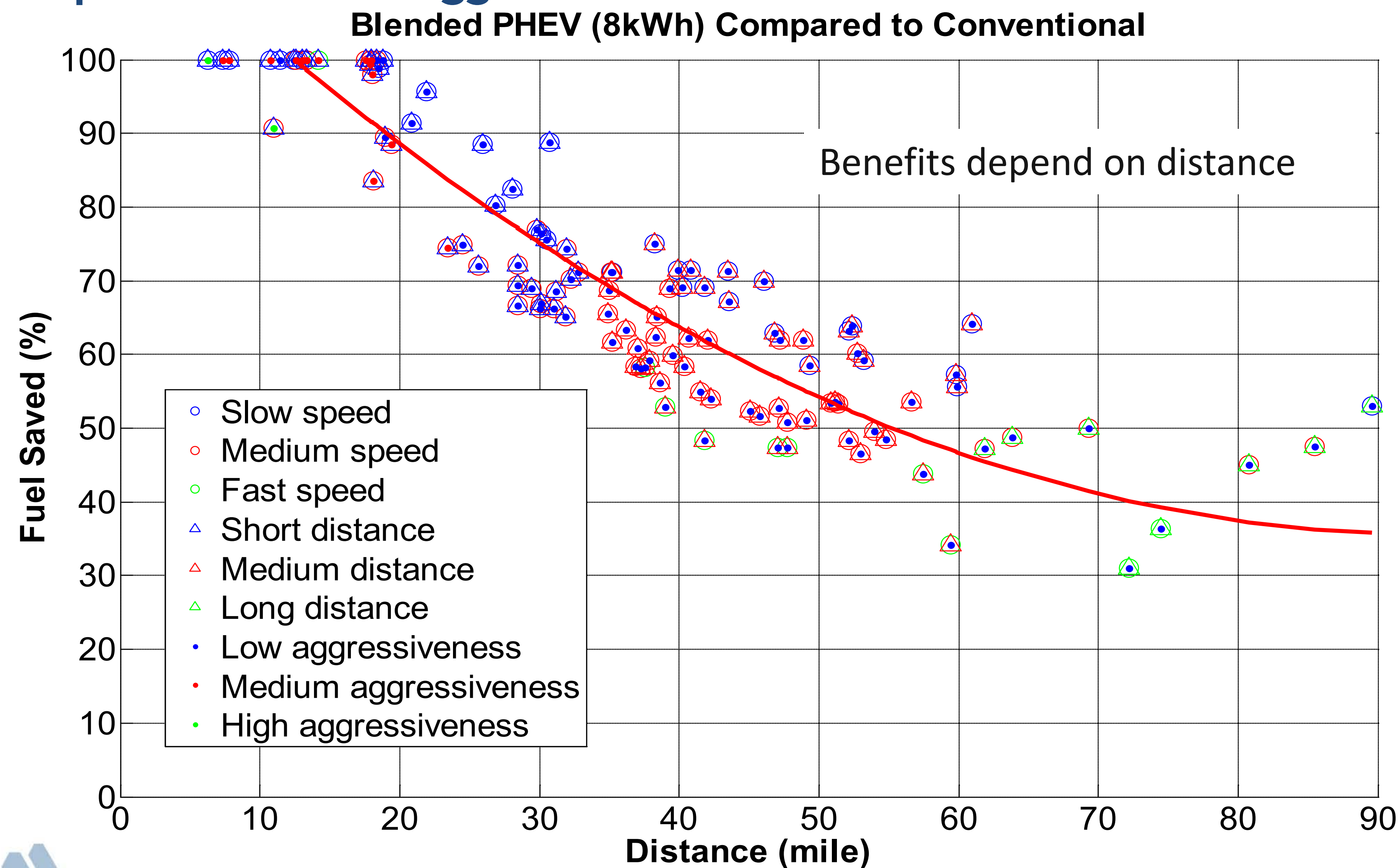
Technical Accomplishments

Impact of Driver Aggressiveness



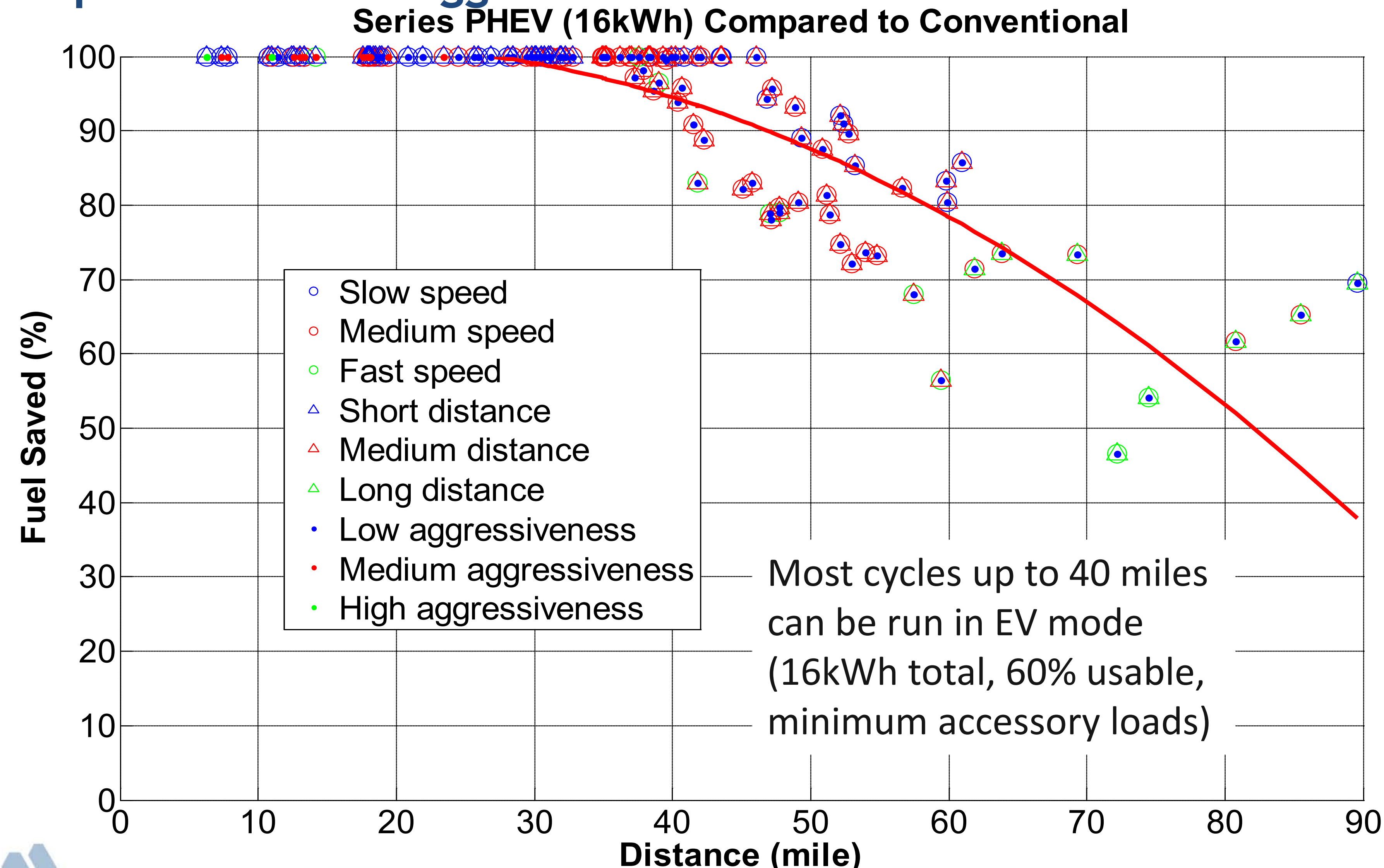
Technical Accomplishments

Impact of Driver Aggressiveness



Technical Accomplishments

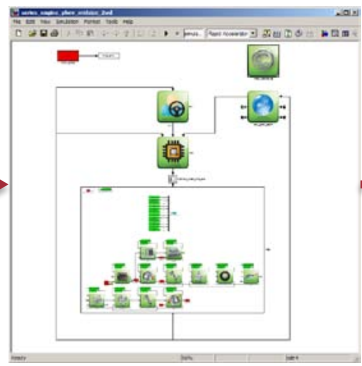
Impact of Driver Aggressiveness



Technical Accomplishments

Battery Size Selection to Maximize Net Present Value

Process



PHEV Model in Autonomie

Fuel Consumption on Real-World Drive-Cycles

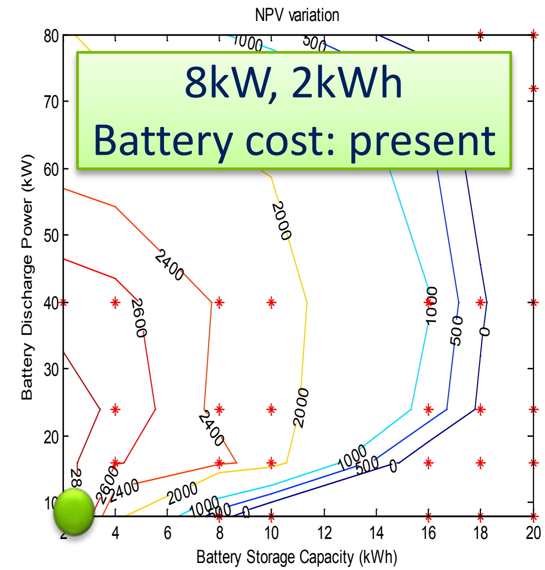
Financial Calculations

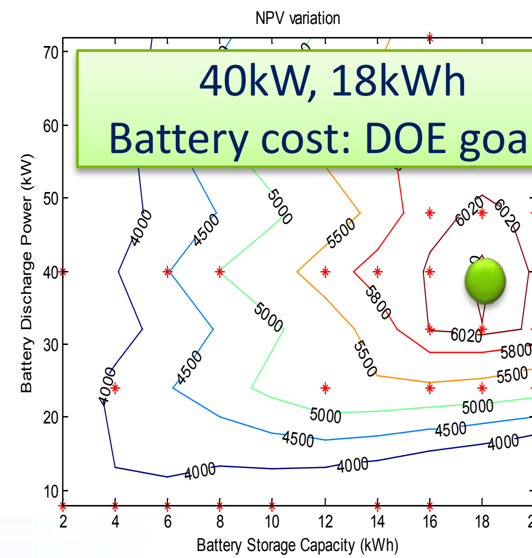
Net Present Value (NPV) of investment & future savings ($)

Numerical Optimizer

IC Engine-On Threshold
IC Engine-Off Threshold
Battery Storage Capacity
Battery Max Discharge Power

Results

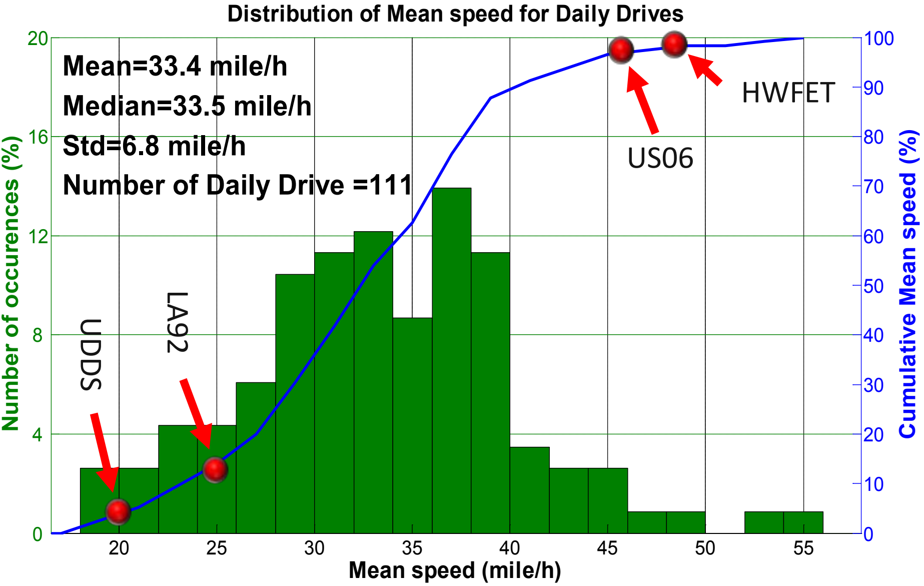




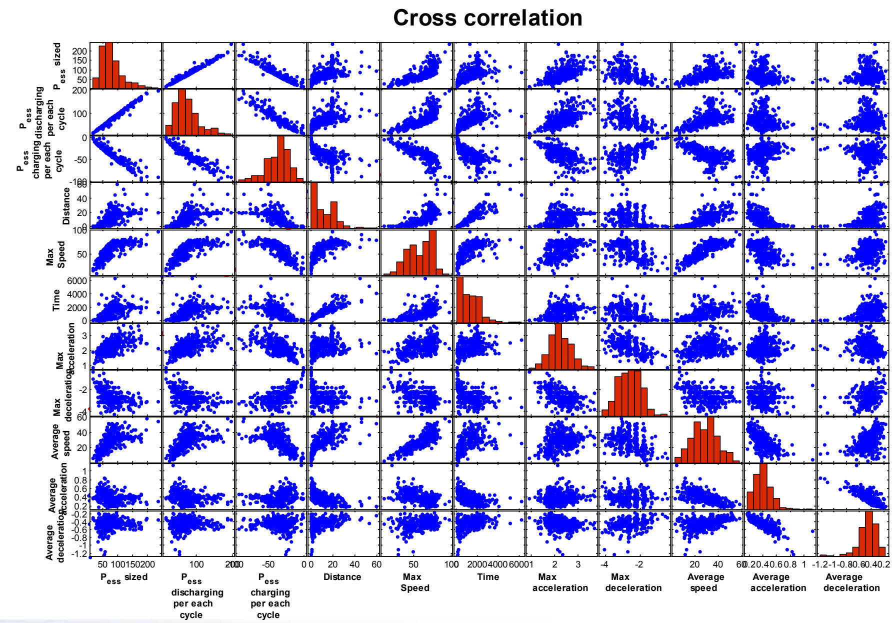
Study performed in partnership with MathWorks

Collaborations

- U.S.EPA, City of Chicago, University of Davis (through INL) provided real world drive cycles
- Implementation of optimization algorithm with the MathWorks



Cycle characteristics compared to standard ones



Cross correlation used to understand relations between key parameters (speed, acceleration, deceleration…)

Future Activities

- Study impact of set of Real World Drive Cycle used on fuel displacement -> How much of the results can be generalized?
- Develop and test vehicle level control strategies with trip recognition.
- Understand comparison with standard drive cycles for conventional, HEVs and PHEVs (J1711)
- Perform MonteCarlo analysis on the assumptions and control options to provide an uncertainty value.
- Use the existing process (i.e., run simulations, automated post-processing…) to assess fuel displacement potential for Medium and Heavy duty applications.

Summary

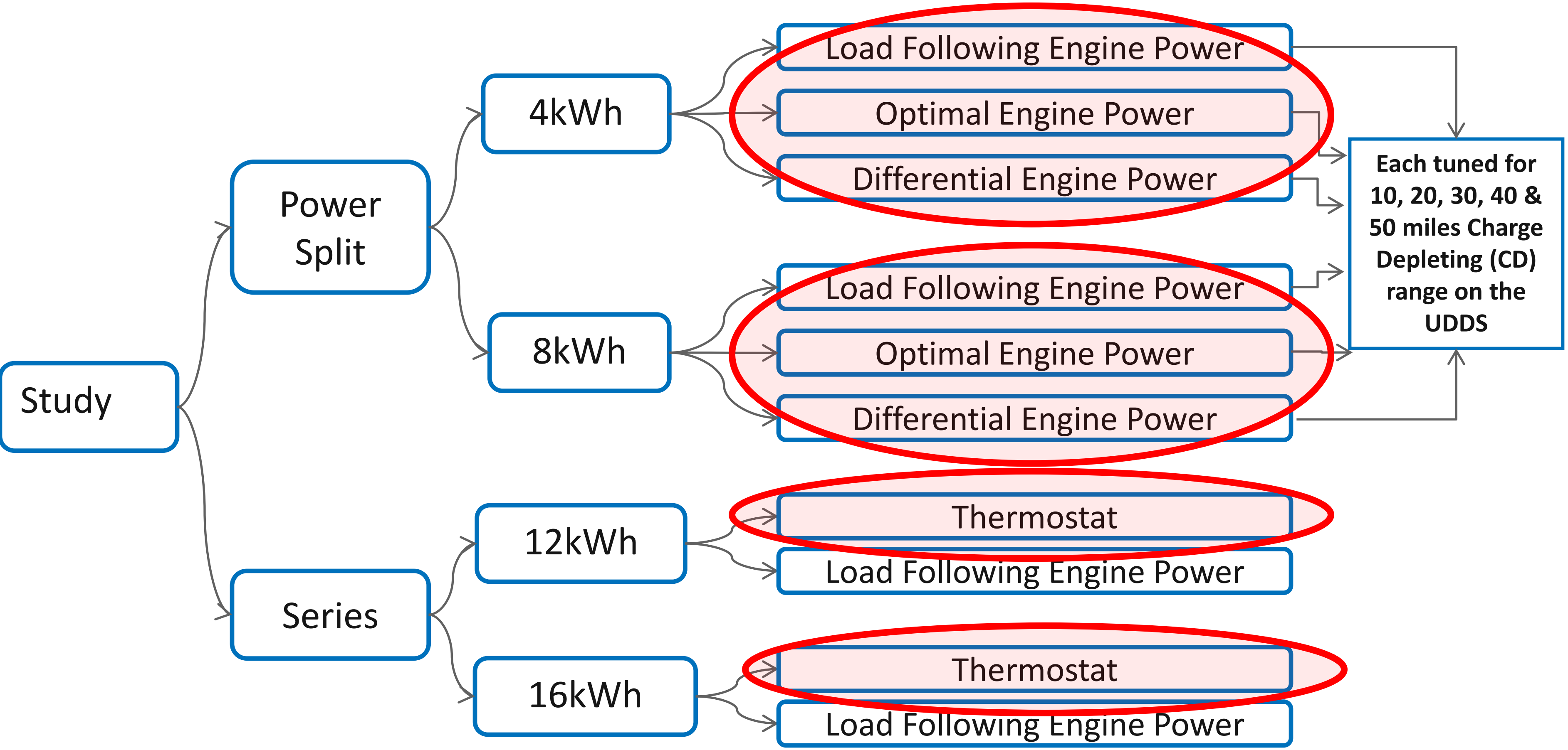
- Real World Drive Cycles (RWDC) were used to assess to fuel consumption potential of different vehicles (powertrain, component sizing, vehicle control)
- Different vehicle control philosophies and tuning parameters were selected based on fuel efficiency, drive quality and battery RMS current.
- The impact of driving distance and driver aggressiveness was also evaluated.
- Future studies will focus on determining how much these results can be generalized using different set of RWDC as well as compare the results with standard test procedure.

Additional Slides

List of Publications

- Vijayagopal, R., Kwon, J., Rousseau, A., P. Maloney (MathWorks), “Maximizing Net Present Value of a Series PHEV by Optimizing Battery Size and Control”, SAE 2010-01-0037, SAE Convergence, Detroit, November 2010
- Karbowski, K, Freiherr von Pechmann, S. Pagerit, J. Kwon, A. Rousseau, “Fair Comparison of Powertrain Configurations for Plug-In Hybrid Operation using Global Optimization”, SAE paper 2009-01-1383, SAE World Congress, Detroit, April 2009
- M. Fellah, G. Singh, A. Rousseau, S. Pagerit, “Impact of Real-World Drive Cycles on PHEV Battery Requirements”, SAE paper 2006-01-0377, SAE World Congress, Detroit, April 2009
- A.Moawad, G. Singh, S. Hagspiel, M. Fellah, A. Rousseau, “Real World Drive Cycles on PHEV Fuel Efficiency and Cost for Different Powertrain and Battery Characteristics”, EVS24, Norway, May 2009 , **WEVA Journal, ISSN 2032-6653**
- G. Faron, S. Pagerit, A. Rousseau, “Evaluation of PHEVs Fuel Efficiency and Cost Using MonteCarlo Analysis “,EVS24, Norway, May 2009 , **WEVA Journal, ISSN 2032-6653**

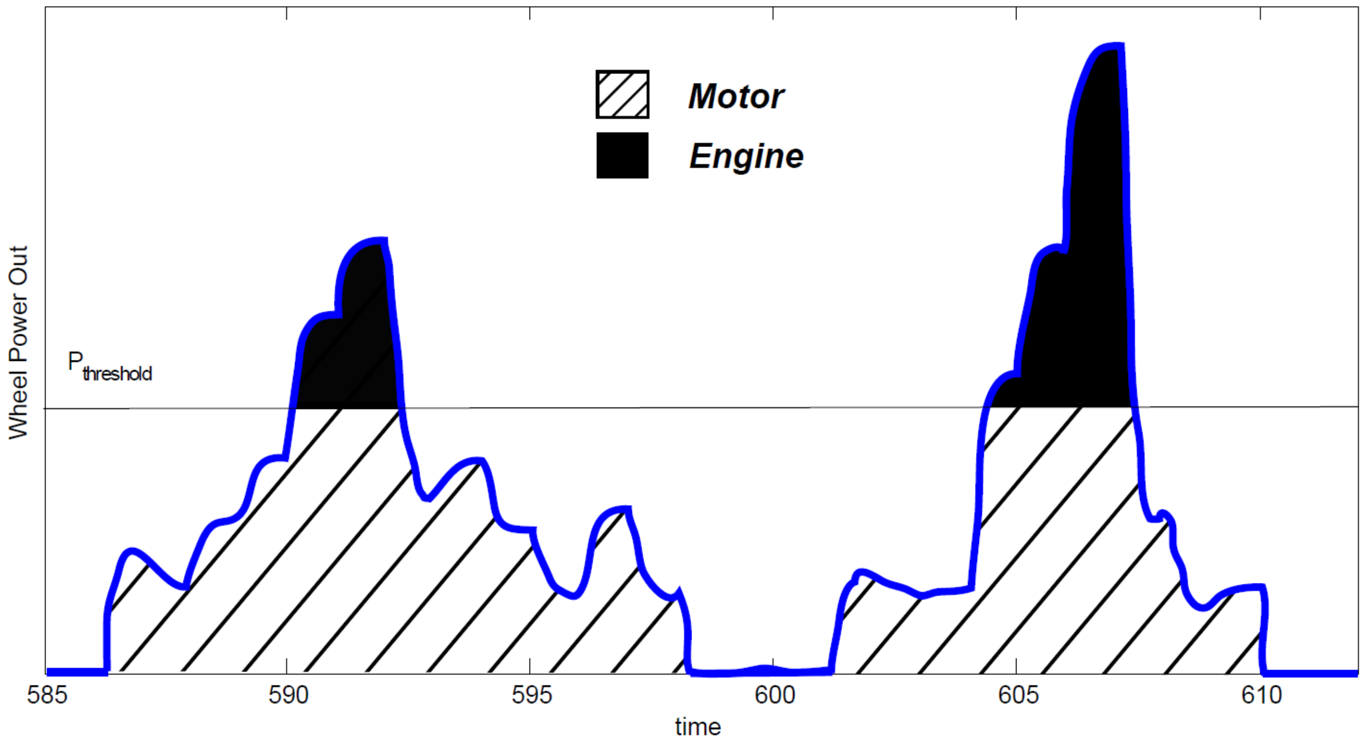
Approach - Control Strategies Considered



All these options were simulated on the RWDCs (source EPA 2005 Kansas City Cycles – 110 trips)

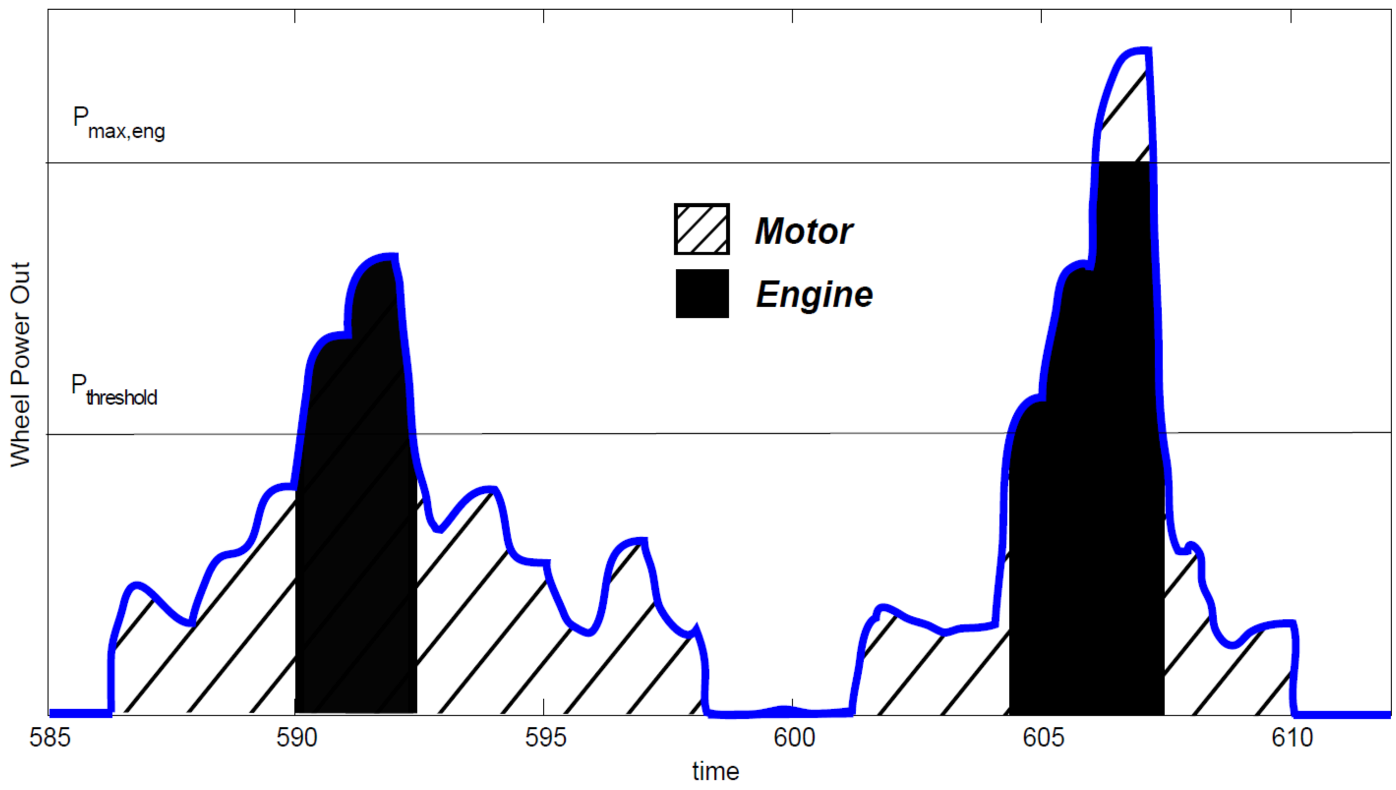
Differential Engine Power Strategy

- The engine is started when **wheel power demand** exceeds a certain threshold.
- It then provides the **difference** between the wheel power demand and the power threshold.



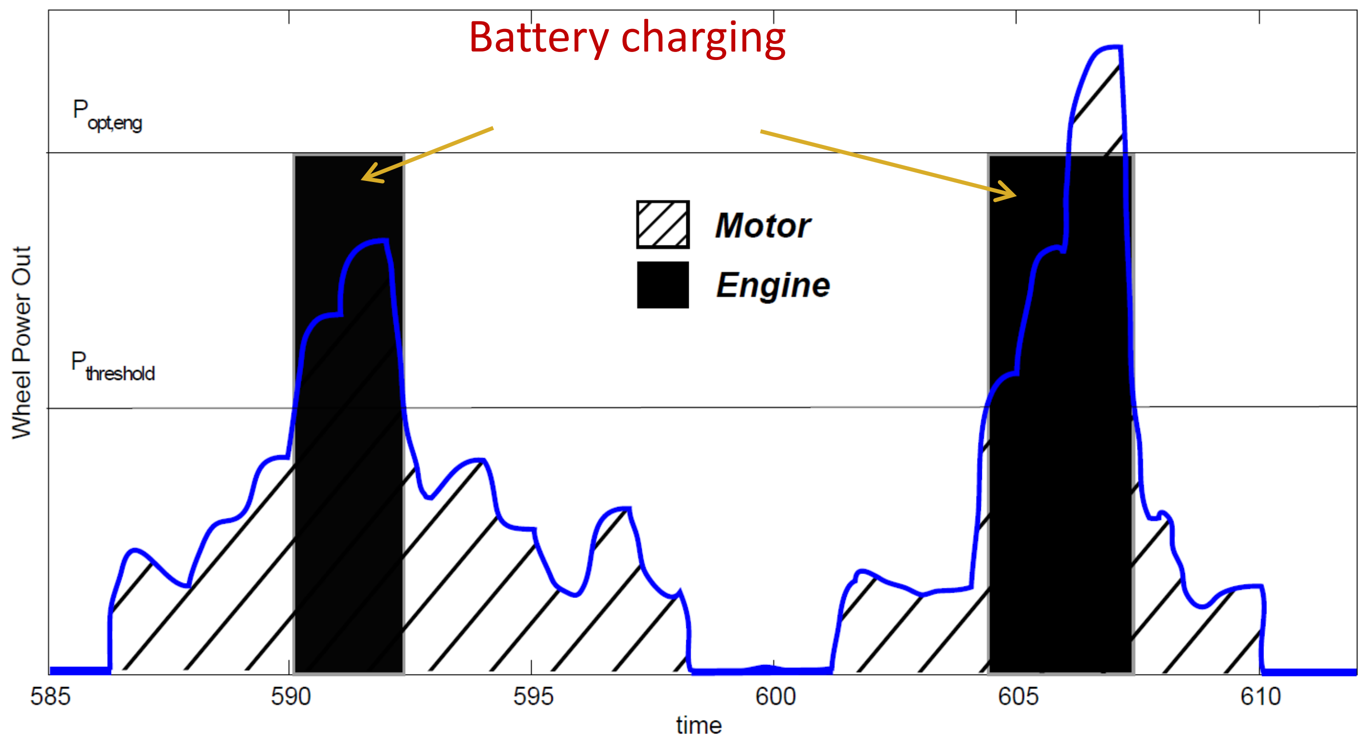
Load Following Strategy

- The engine is started when **wheel power demand** exceeds a certain threshold.
- It then provides the **full wheel power**, i.e. it is load following



Constant Optimal Engine Strategy

- The engine is started when **wheel power demand** exceeds a certain threshold.
- Engine then operates at its **optimal power**.
- If engine power exceeds wheel power demand, the battery is charged.



Thresholds Definition for Slides 12, 13, 14

- Distance (miles)
  - short 0 to 32,
  - medium 32 to 61,
  - long 61 to 90
- Speed (mph):
  - low 0-31,
  - medium 31 to 42,
  - high 42 to 55
- Aggressiveness (W/mile):
  - low 0 to 407,
  - medium 407 to 714,
  - high 714 to 1066