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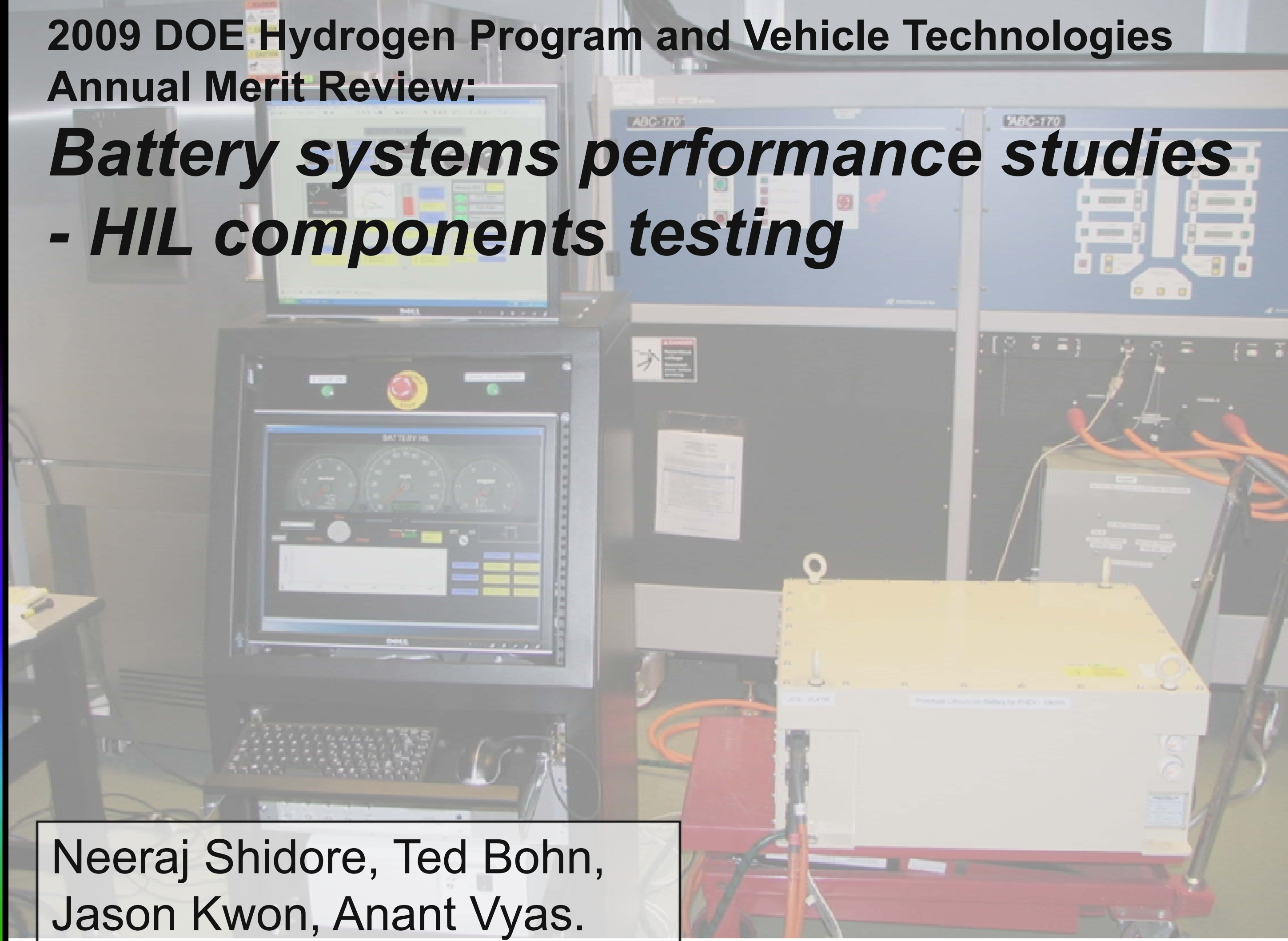
2009 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review:

Battery systems performance studies - HIL components testing



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Argonne National Laboratory

Sponsored by Lee Slezak

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DOE Merit Review

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U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

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Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Project Overview

Timeline
- Project Start Date: FY07.
- Project end date: multi-year effort.

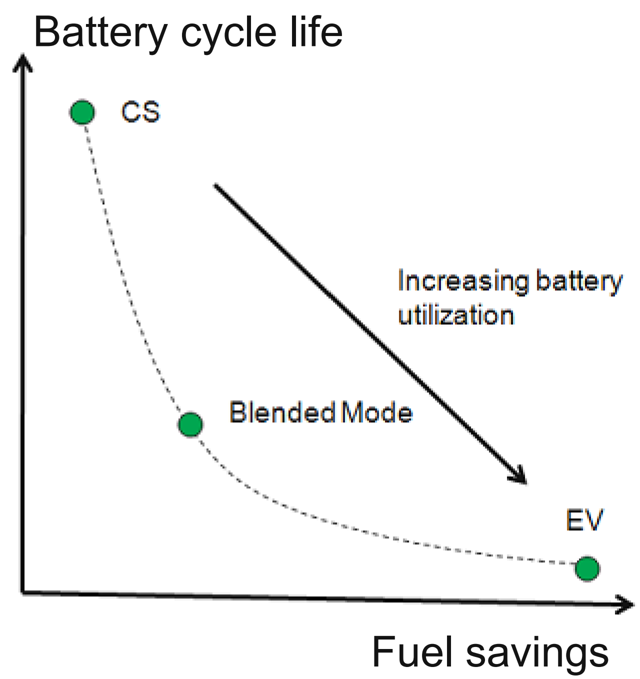
Barriers
- Vehicle Systems approach to analyze PHEV barriers:
  - -Battery cycle life.
  - -PHEV cost issues.

Budget
- FY08: $400k
- FY09: $400k

Partners
- Johnson Controls – SAFT
- System analysis group - ANL

Objectives

- Evaluate the trade-off between battery cycle life and gasoline fuel savings.
- Impact of the above trade-off on cost effectiveness of PHEVs.
- Battery HIL as a tool for other experiments:
  - EV test procedure support.
  - Ultra capacitor – battery combination experiment.

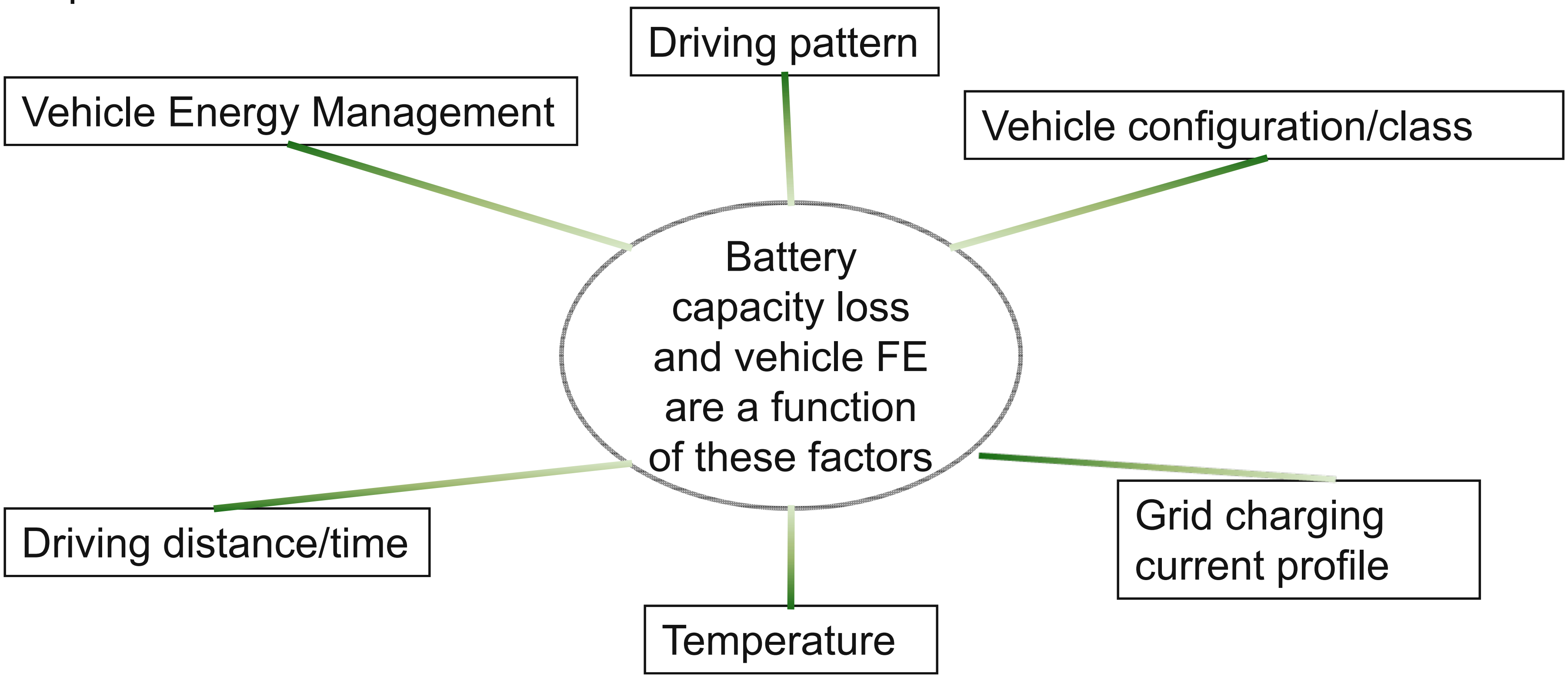


Milestones

- Trade-off between battery cycle life and gasoline fuel consumption for a midsize power split on 20 miles and 40 miles urban driving.
- Cost effectiveness impact for the above.
- Continuing support of other experiments.

Statement of the problem

Several system level factors determine battery utilization in a vehicle, simultaneously; for example:



This experiment will investigate:

1. Trade-off between estimated battery cycle life and gasoline fuel economy for different energy management strategies.
2. Cost effectiveness of different energy management studies when compared to conventional gasoline, charge sustaining hybrid,etc.

Procedure

Fixed vehicle Class, platform: midsize, power split.

Fixed charging profile.

Consecutive urban cycles

Temperature :25 °C

Different engine management strategy, i.e. engine turn-on at different wheel power levels.

EV

Blended Mode 1

⋮

Blended Mode ‘n’

Step 3 – Test battery in an emulated vehicle for the strategies

Provide SOC, current, temperature, voltage data to SAFT, for the ‘n’ control variations.

1. Trade-off between FE and cycle life.
2. Cost analysis.

Test matrix

- Driving pattern – UDDS cycles repeated until target distance.
- Energy management: Engine turns on at different wheel power thresholds, operates at best efficiency.
- Target distance : 40 miles.

Engine turn on threshold (wheel power)	40 miles
10 kW	
15 kW	
25 kW	
30 kW	
50 kW	

‘

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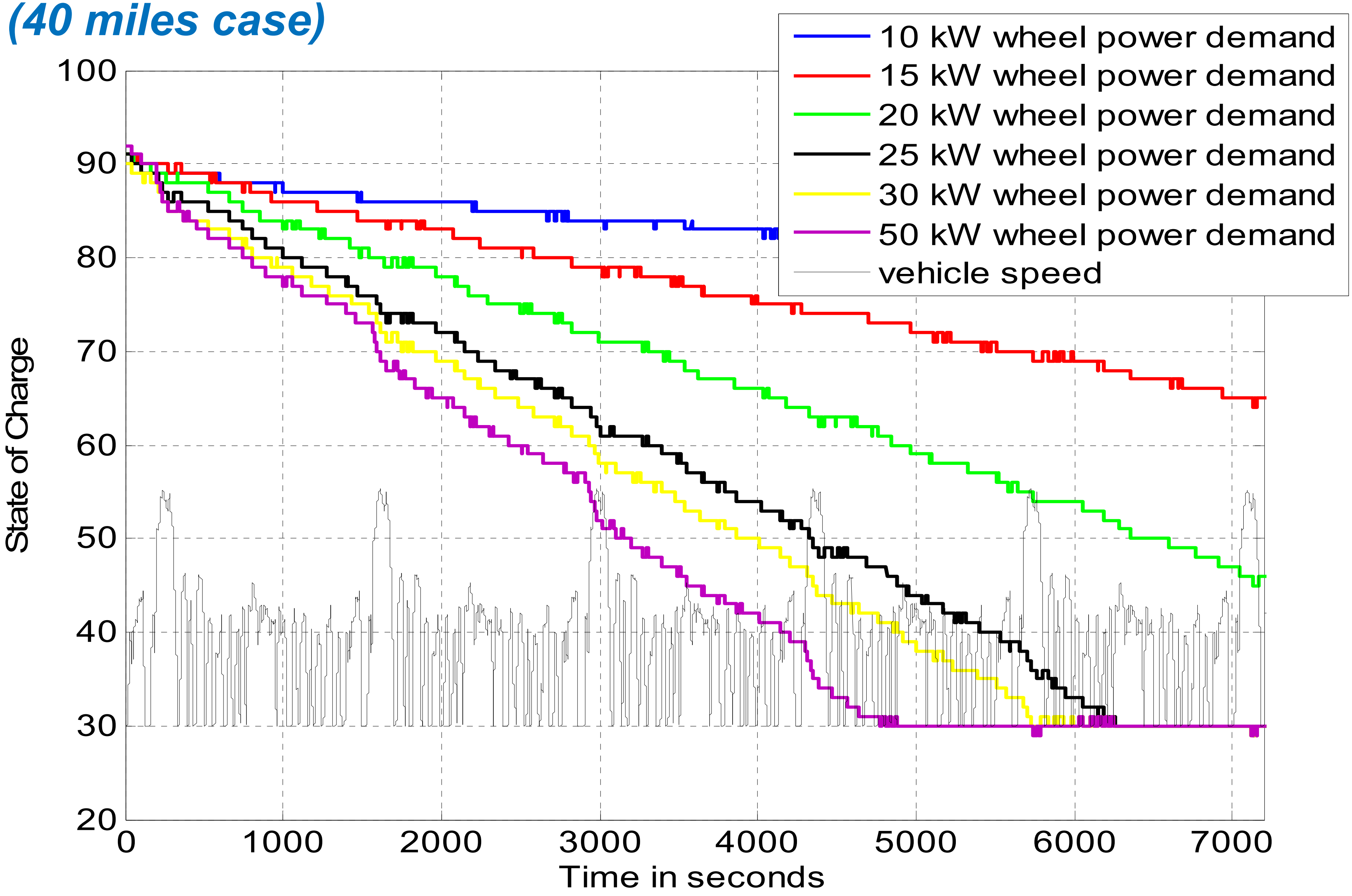
SOC swing for the different energy management strategies (40 miles case)



Battery utilization data for the test matrix

Test ID	Test description	RMS current	Temperature rise**	Initial SOC	Delta SOC*
812003	40 miles UDDS, engine turn on at 10 kW	19 A	3.78	90	11%
902004	40 miles UDDS, engine turn on at 15 kW	23.9 A	4.71	91	26%
902006	40 miles UDDS , engine turn on at 20 KW	30 A	4.6	90	45%
812005	40 miles UDDS, engine turn on at 25 kW	36A	4.8	91	60%
902005	40 miles UDDS, engine turn on at 30 kW	35.6 A	4.8	90	60%
812007	40 miles UDDS, engine turn on at 50 kW	38.7 A	4.7	92	62%

* Initial SOC -Final SOC;

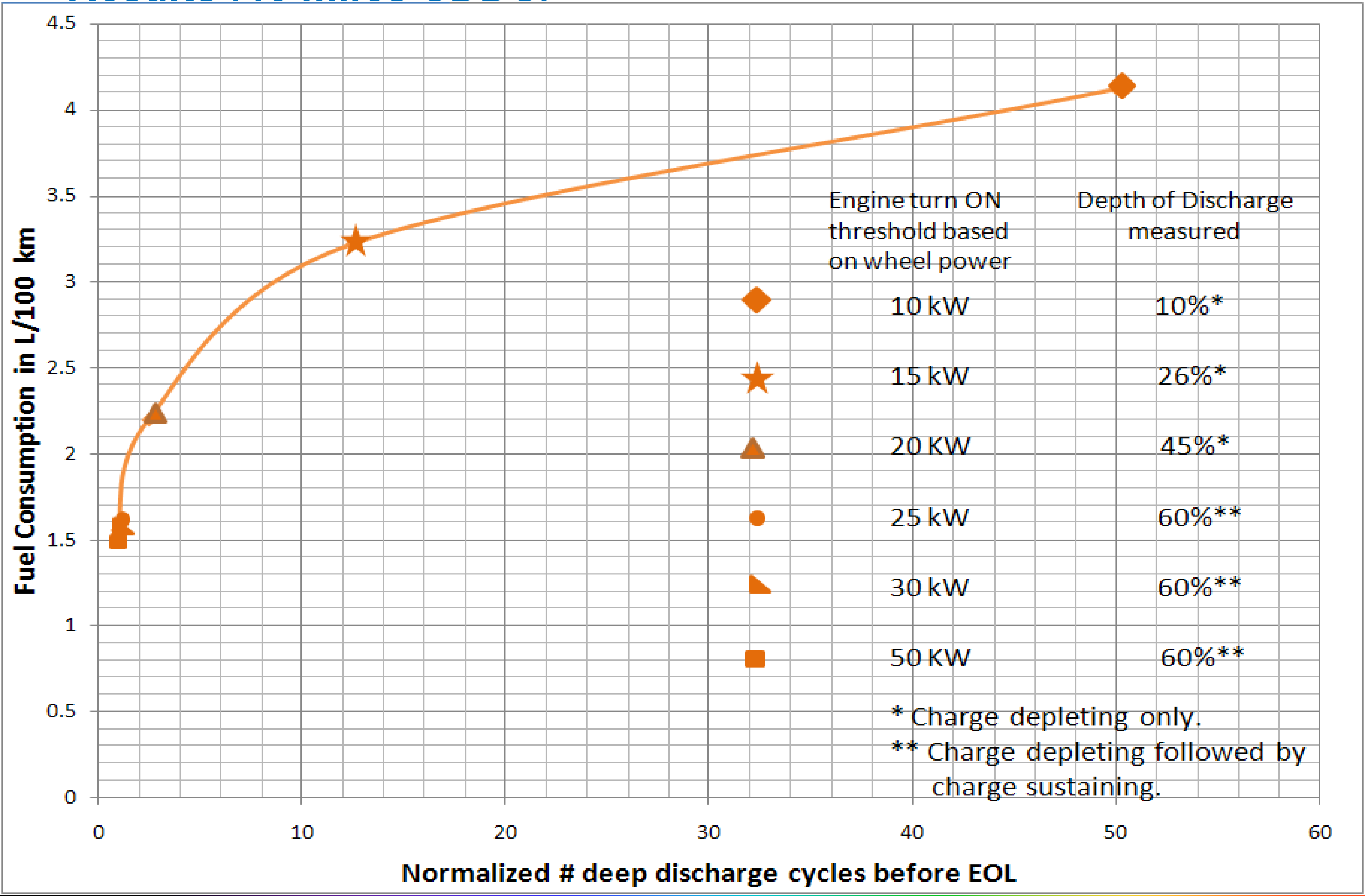
** Mean temperature rise – Initial temperature.

Results (40 miles UDDS)

Engine ON threshold wheel power (kW)	Fuel consumption * (L/100 km)	Depth of discharge swing	Estimated battery cycle life (# Deep discharge cycles).	Normalized # deep discharge cycles
10	4.12	11%	x*50	50
15	3.22	26%	x*12.5	12.5
20	2.2	45%	x*2.5	2.5
25	1.56	~60%	x	1
30	1.4	~60%	x	1
50	1.5	~60%	x	1

* Warm engine assumed through out the study; impact of cold engine start is neglected

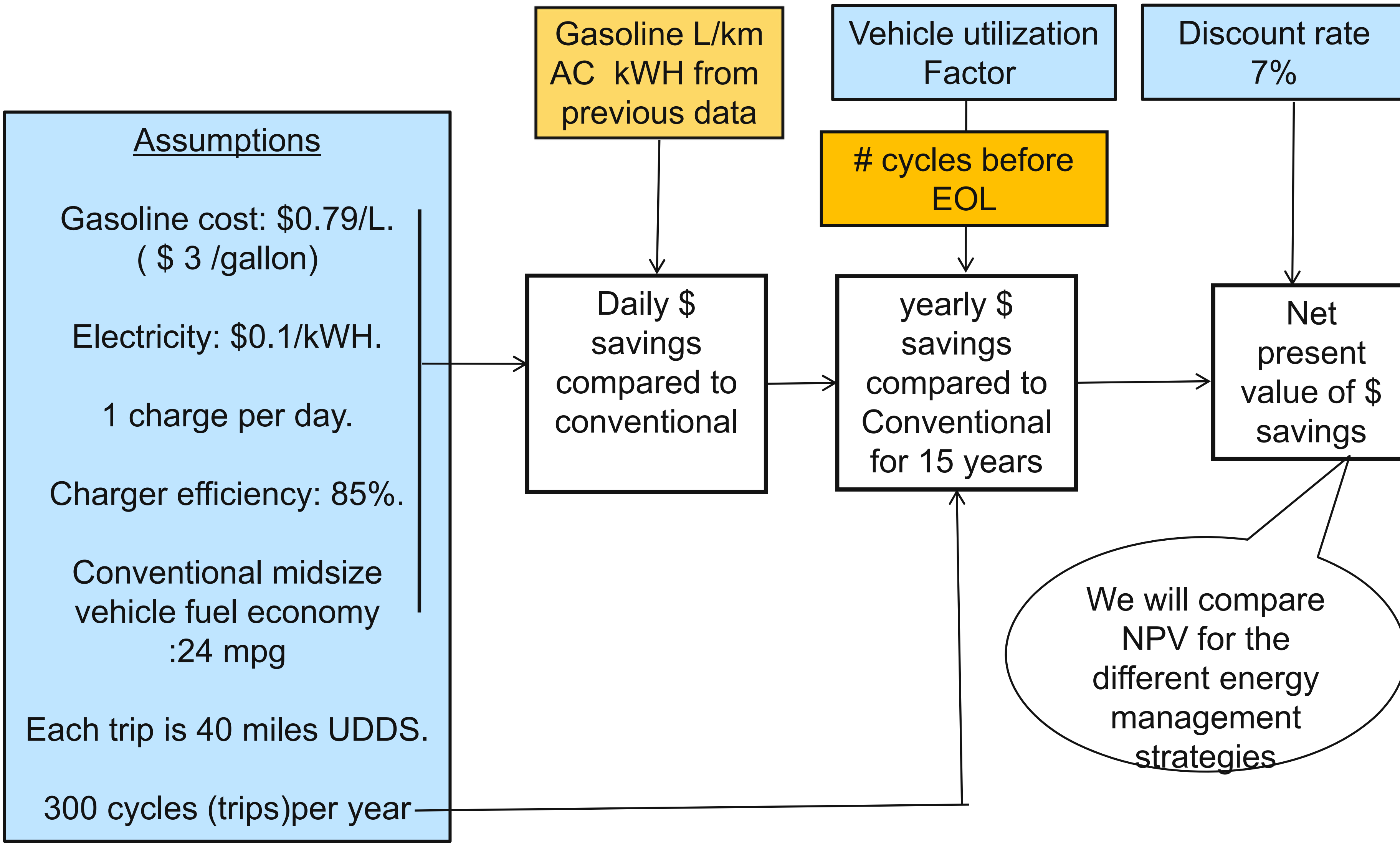
Results (40 miles UDDS)



Observations (40 miles case)

- A slight increase in fuel consumption, could lead to a very large increase in battery cycle life.
- $\frac{\Delta \, Cycle\, life}{\Delta \, Fuel\, Consumption}$ is highly nonlinear ; shallower the depth of discharge, more is the gain in cycle life per unit increase in fuel consumption.
- Battery cycle life is a strong function of depth of discharge, within a certain temperature rise window.
- Any energy management strategy which results in C.S. operation would result in more or less the same battery life. In that case, energy management development should be focused on fuel economy improvement.
- Based on desired battery cycle life, a depth of discharge window and in turn an engine threshold can be coarsely chosen.

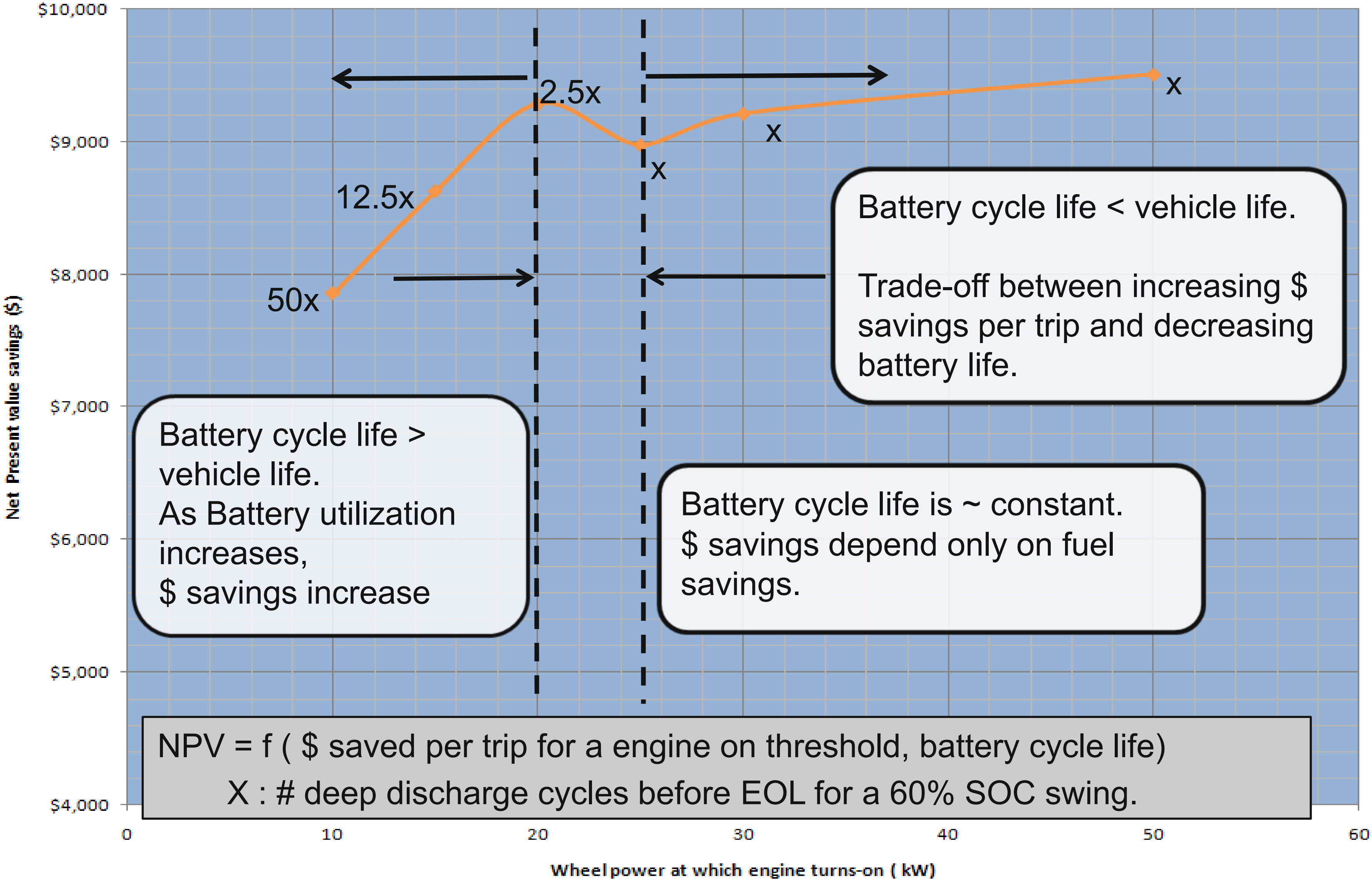
Net Present Value (NPV) of PHEV savings* as compared to a conventional gasoline vehicle [1] -



* Fuel cost savings, calculations do not involve vehicle or battery cost at all.

[1] Anant Vyas, Dan Santini, Michael Duoba, Mark Alexander, *'Plug-in Hybrid Electric Vehicles: How Does One Determine Their Potential for Reducing U.S. Oil Dependence?'* presented at EVS-23, Anaheim , California, December 2-5, 2007.

NPV savings* of the PHEV versus a conventional gasoline vehicle, for different energy management strategies- using data from previous slides.

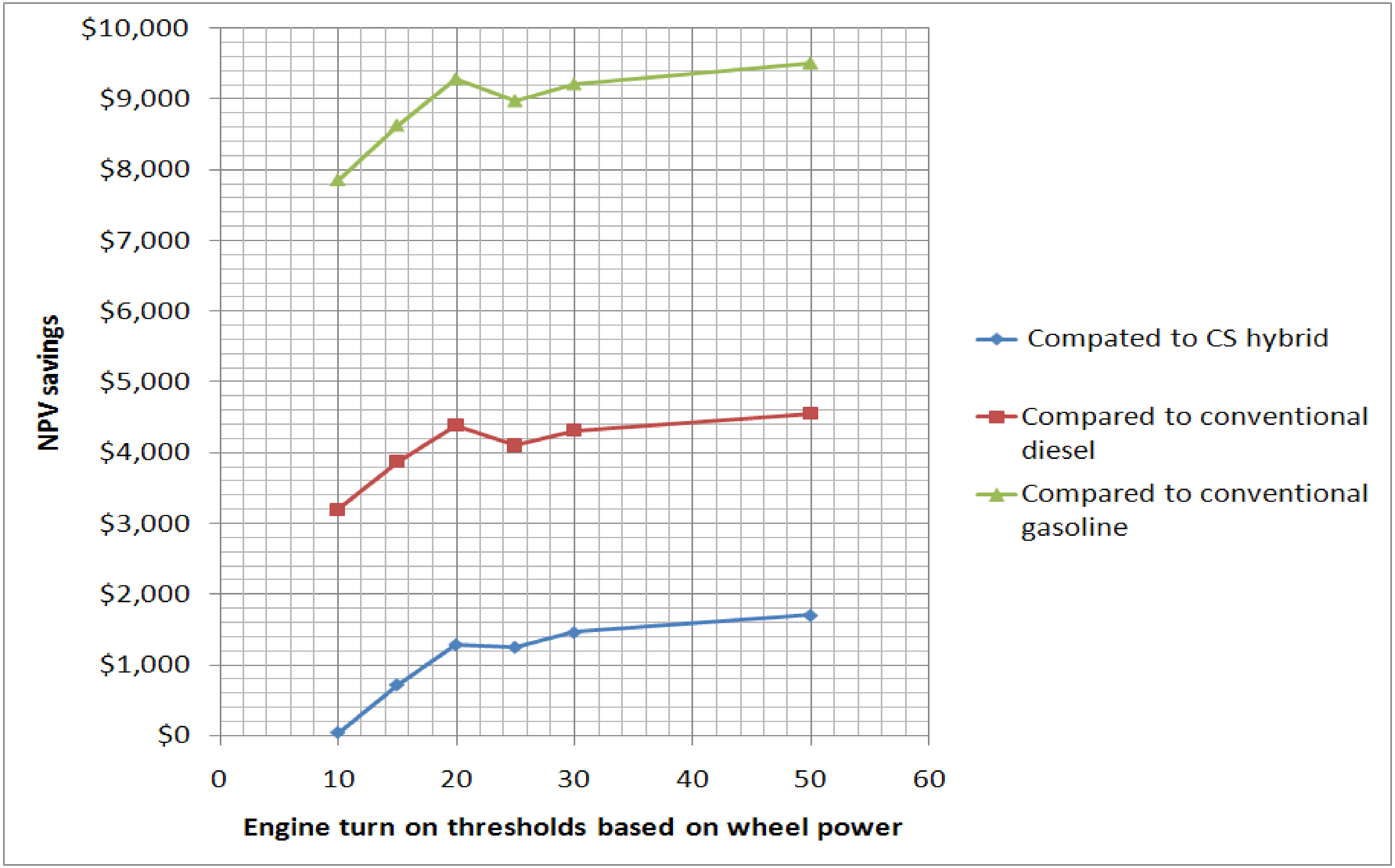


* Fuel cost savings, calculations do not involve vehicle or battery cost at all.

Additional comments for previous slide

- Highest NPV savings are not necessarily at maximum EV utilization of the battery.
- Total NPV $ savings for higher engine turn-on thresholds (25, 30 and 50 kW) will be concentrated in the initial years of the vehicle, while for the lower engine turn-on thresholds (10,15 and 20 kW) will be spread over the life of the vehicle – no need for battery replacement.
- Lower the value of ‘x’ , deeper and wider the trade-off region.
- Ideal engine turn-on threshold would lie somewhere in the threshold region, such that battery cycle life = vehicle life.
- ZEV credits push towards EV operation of the vehicle.

Net Present Value (NPV) of PHEV Savings as compared to a CS hybrid, conventional diesel and conventional gasoline.*



* Fuel cost savings, calculations do not involve vehicle or battery cost at all.

Continued work for this study

- Trade-off analysis and NPV calculations for the 20 miles case (impact of distance on trade-off between battery cycle life and fuel consumption).

- Repeat analysis for real world drive cycle data from EPA and INL.

EV test procedure: Abbreviated range determination compared to Full J1634

	Shortcut Test # 1	J1634 Test # 1	Shortcut Test # 2	J1634 Test # 2	Shortcut Test # 3	J1634 Test # 3
Range (mi)	123.4	127.31	124.48	122.17	124.48	122.18
Discharge Wh/mile	161.709	165.9	161.51	166.55	161.49	166.86

Full J1634 test: vehicle goes through sets of 2 consecutive UDDS (with 10 min soak in between each set). Initially battery at full capacity, test stops when battery completely discharged.

Short-cut: Run only a part of the full J1634 test, use calculations to predict result of full test.

EV test procedure: Charge consumption method compared to Full J1634

	Shortcut Test # 1	**J1634 Test # 1**	**Shortcut Test # 2**	**J1634 Test # 2**
Charge Consumption (AC Wh/mi)	197.7	194.4	193.6	193.4

Future Work – BHIL supporting other studies

- Autonomie HIL testing and implementation.
- EV Test procedure – J1634.
- Active power distribution between batteries and ultra capacitors.

Future work

PHEV battery issues from a vehicle perspective

Cold temperature performance

- Impact of cold temperature on battery performance and AER
- Compare vehicle energy management strategies for PHEV battery temperature rise in CD mode at cold temperatures, and its impact on engine warm –up time and efficiency.*

Battery life

- Trade-off between Battery cycle life and fuel economy
- New battery and end of life battery: impact of decrease in capacity and power, on vehicle performance, electric range, fuel economy by comparing BHIL results of a new and EOL battery.

Cost

- Net present value savings based on the trade-off between cycle life and fuel economy

Legend:
- Grey box: Previous, current work.
- Green box: Future work.

* See additional slides for details

Summary

- A slight increase in fuel consumption, could lead to a very large increase in battery cycle life.

- $\frac{\Delta\ Cycle\ life}{\Delta\ Fuel\ Consumption}$ is highly nonlinear ; shallower the depth of discharge, more is the gain in cycle life per unit increase in fuel consumption.

- High fuel cost savings can be obtained by optimum blended mode operation, without sacrificing battery life.

- In spite of the above, achieving higher and higher AT PZEV credits will push towards
  more and more electric operation.