# Plug-In HEV Vehicle Design Options and Expectations

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*California Air Resources Board*

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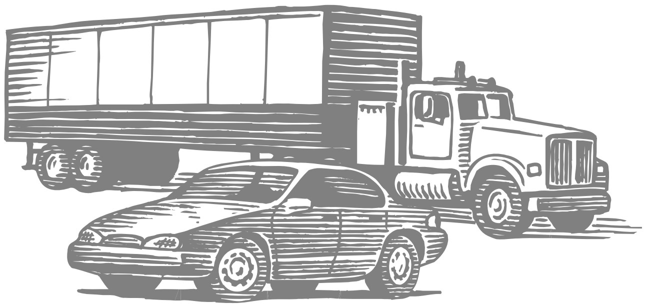


NREL/PR-540-40630

# Key Messages

- There are many ways to design a PHEV …
  - the best design depends on your objective
- PHEVs provide potential for petroleum displacement through fuel flexibility
  - what are the cost and emissions tradeoffs
- PHEV design space has many dimensions
  - simulation being used for detailed exploration
- Simulations using real-world travel data provides early glimpse into in-use operation

# PHEV Stakeholder Objectives

**Consumers**
Affordable
Fun to drive
Functional

**US Gov./DOE**
Reduced petroleum use

**California Gov.**
Reduced air pollution

**Auto Manufacturer**
Sell cars

**Electric Utility**
Sell electricity

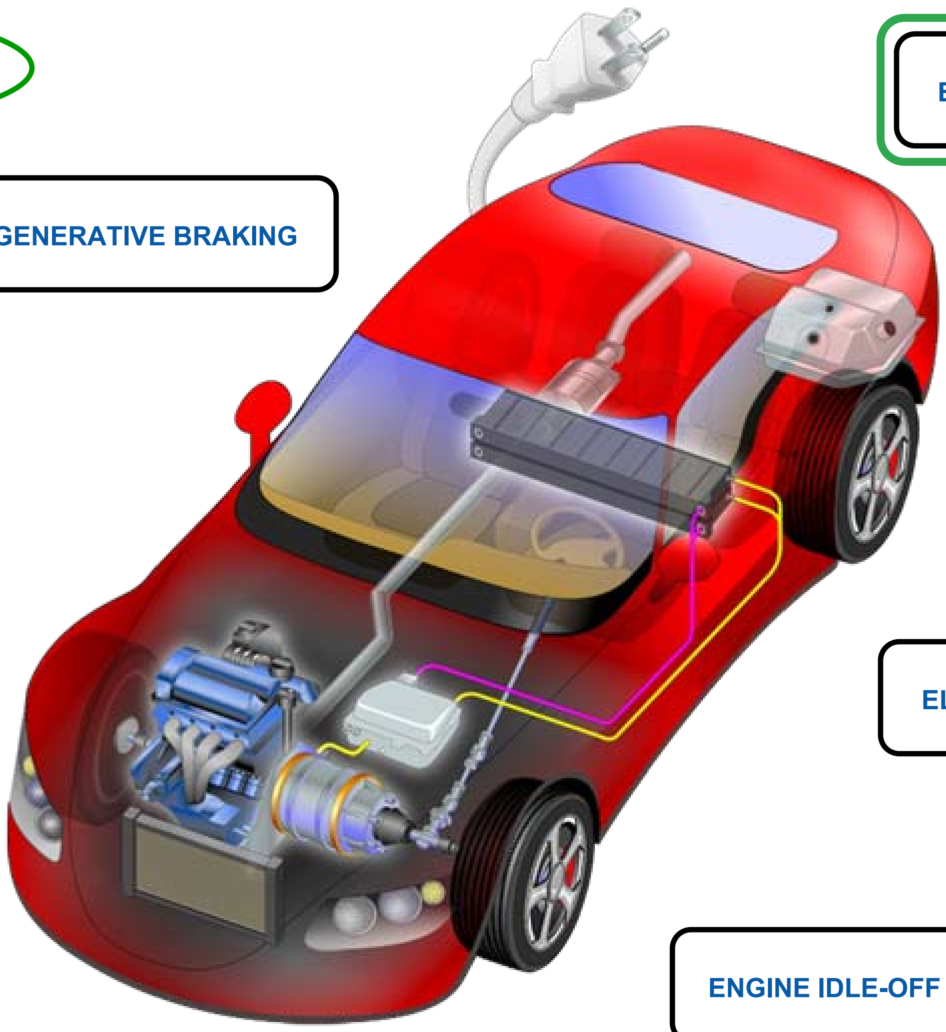
# A Plug-In Hybrid-Electric Vehicle (PHEV)

Fuel Flexibility

PETROLEUM

AND/OR

ELECTRICITY



REGENERATIVE BRAKING

BATTERY RECHARGE

ELECTRIC ACCESSORIES

ADVANCED ENGINE

ENGINE IDLE-OFF

ENGINE DOWNSIZING

# Some PHEV Definitions

**Charge-Depleting (CD) Mode:** An operating mode in which the energy storage SOC may fluctuate but on-average decreases while driving

**Charge-Sustaining (CS) Mode:** An operating mode in which the energy storage SOC may fluctuate but on-average is maintained at a certain level while driving

**All-Electric Range (AER):** After a full recharge, the total miles driven electrically (engine-off) before the engine turns on for the first time.

**Electric Vehicle Miles (EVM):** After a full recharge, the cumulative miles driven electrically (engine-off) before the vehicle reaches charge-sustaining mode.

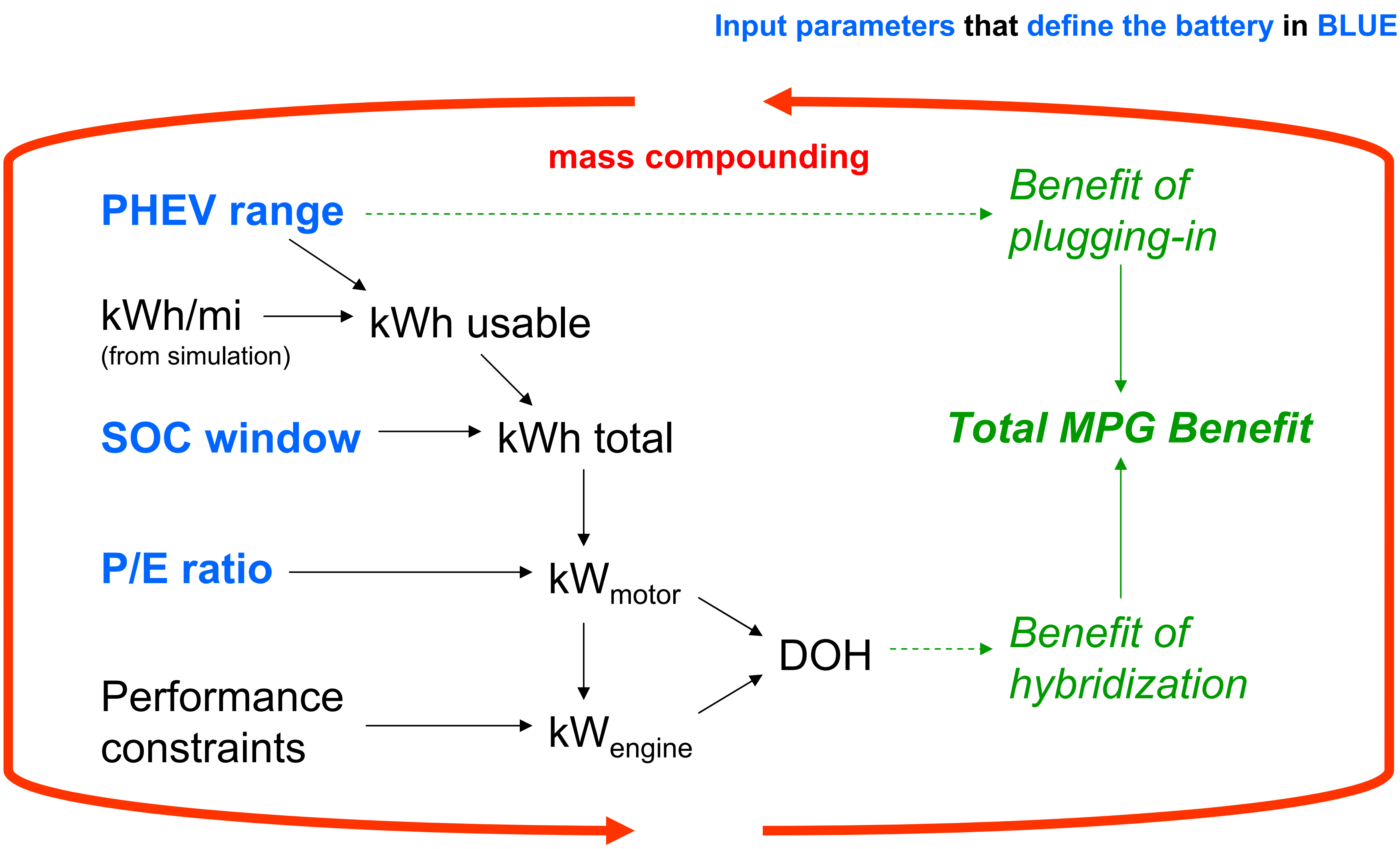
**Charge-Depleting Range (CDR):** After a full recharge, the total miles driven before the vehicle reaches charge-sustaining mode.

**Blended Strategy:** A charge-depleting operating strategy in which the engine is used to supplement battery/motor power.

**PHEV20**: A PHEV with useable energy storage equivalent to 20 miles of driving energy on a reference driving cycle. A PHEV20 can displace petroleum energy equivalent to 20 miles of driving on the reference cycle with off-board electricity.

**NOTE:** PHEV20 does not imply that the vehicle will achieve 20 miles of AER, EVM or CDR on the reference cycle nor any other driving cycle. Operating characteristics also depend on the power ratings of components, the powertrain control strategy and the nature of the driving cycle

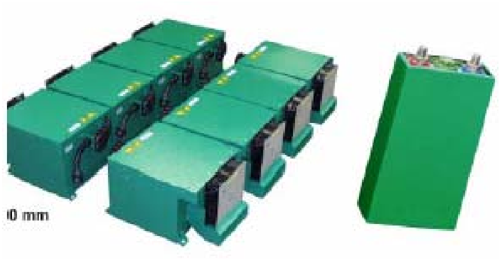
# Battery Definition as Key Input to Simulation



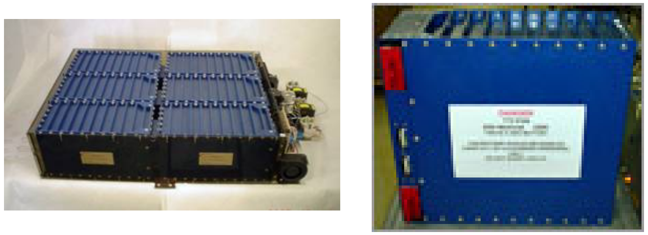

DOH = degree of hybridization

# Batteries in Current PHEVs

NiMH



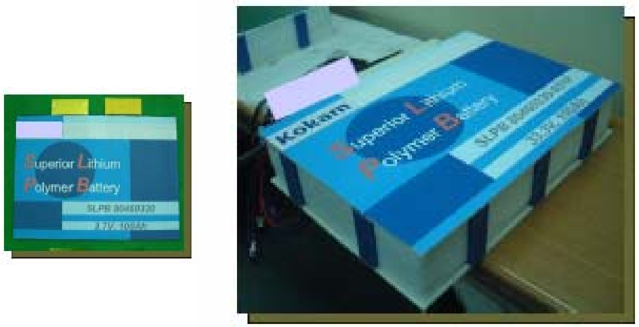

Varta



Electro Energy Inc.

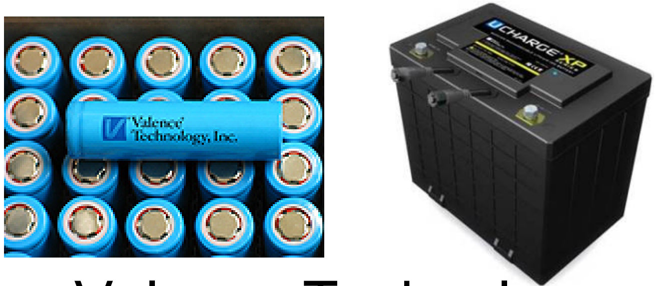
Co/Ni based Li-Ion


Johnson Controls/SAFT




Kokam

Iron phosphate based Li-Ion




Valence Technology


A123 Systems

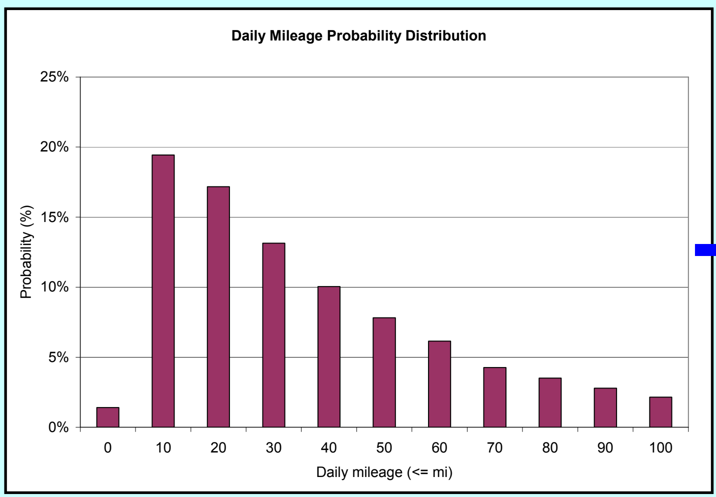
# Battery SOC Design Window

In setting requirements, we must have realistic expectations for battery SOC design window because of the impacts on total battery size and life.

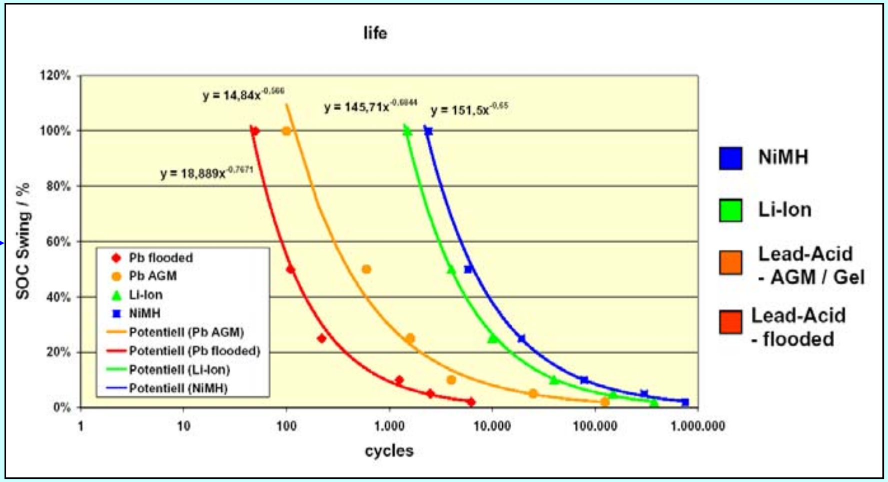
SOC design window is a key factor in battery sizing:

$$kWh_{total} = \frac{kWh_{useable}}{SOC\ window}$$

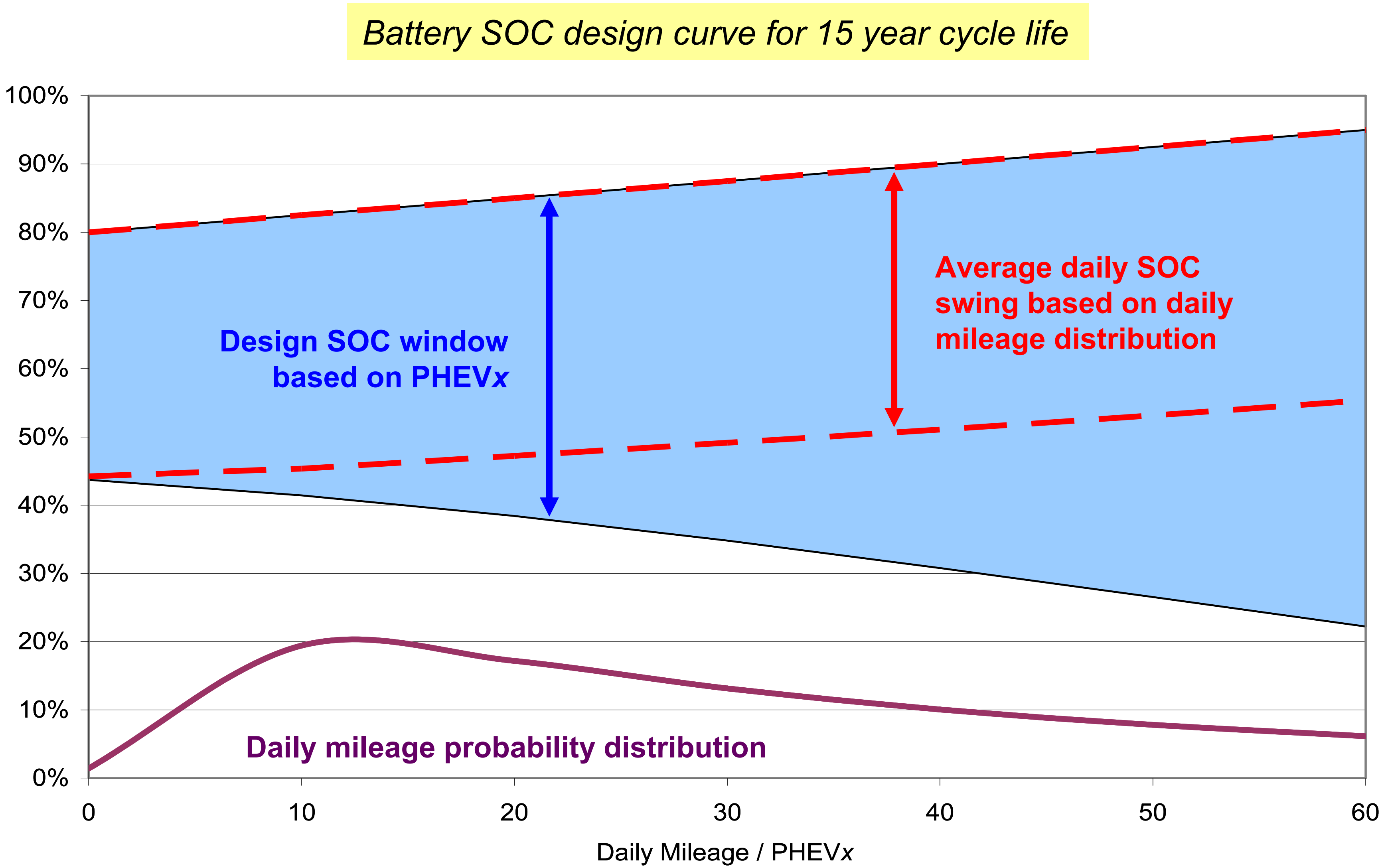
Battery SOC swing is a strong function of driving habits:




Battery cycle life is a strong function of SOC swing:

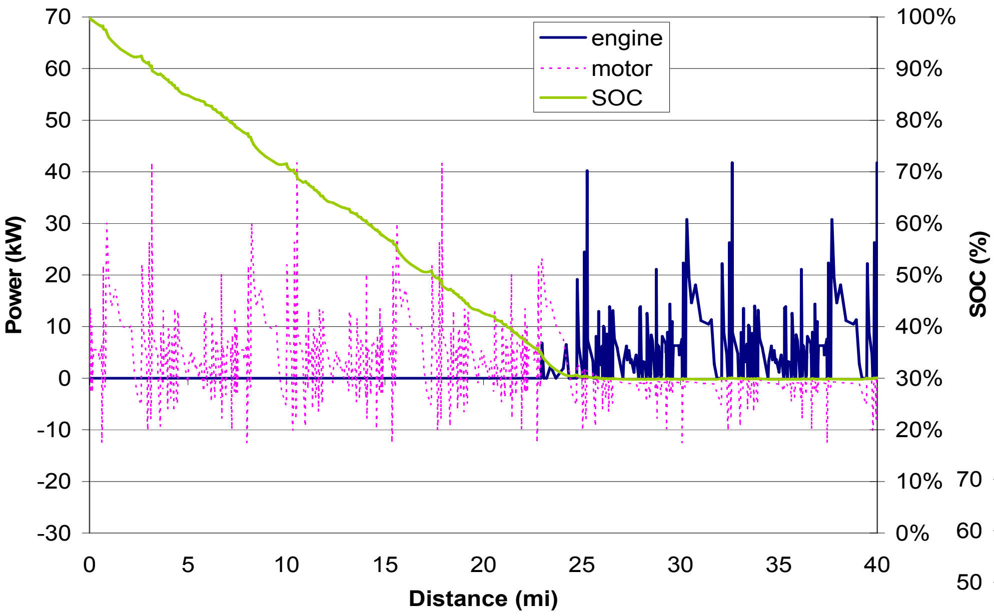


# Battery SOC Design Window



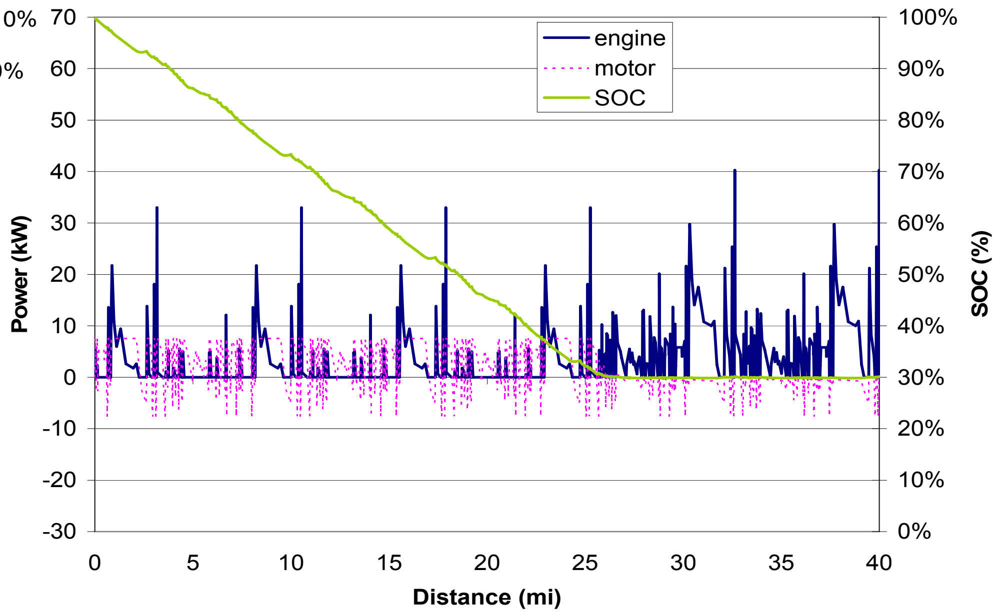
# Operating Strategy Options
## All-Electric or Blended

*All-Electric*




- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

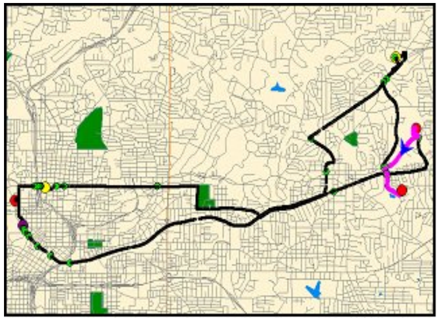
*Blended*

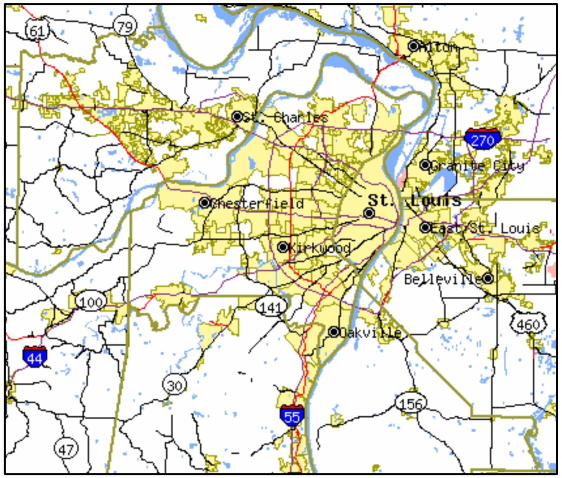


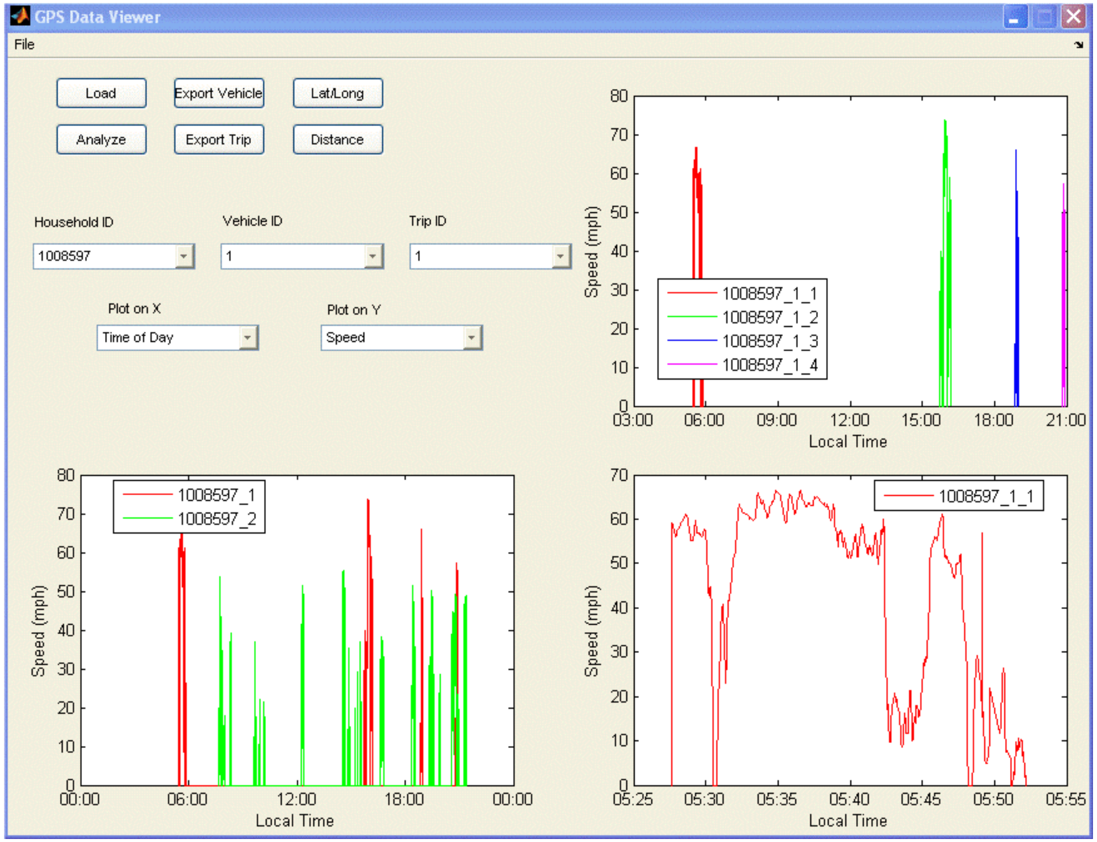

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability

# Real Driving Survey Data

- Provides valuable insight into travel behavior
- GPS augmented surveys supply details needed for vehicle simulation



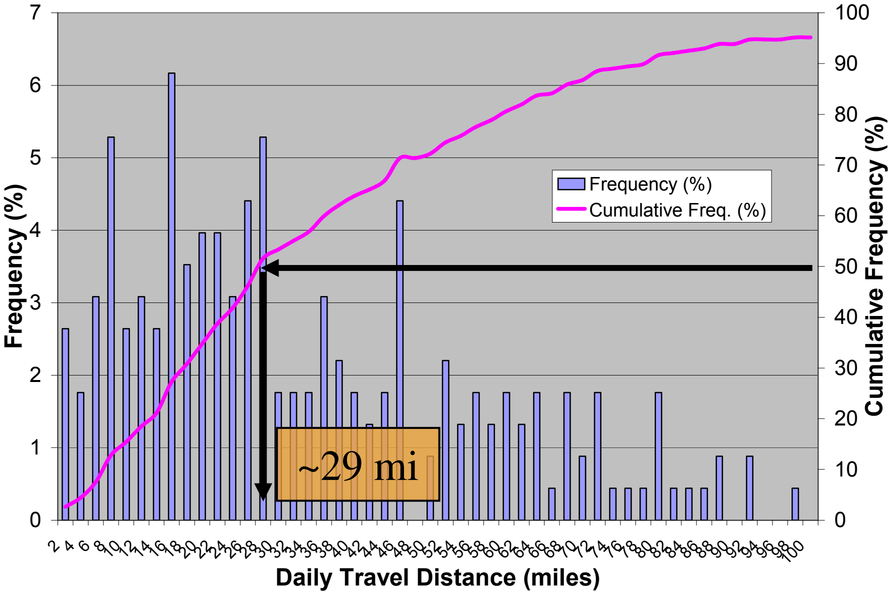


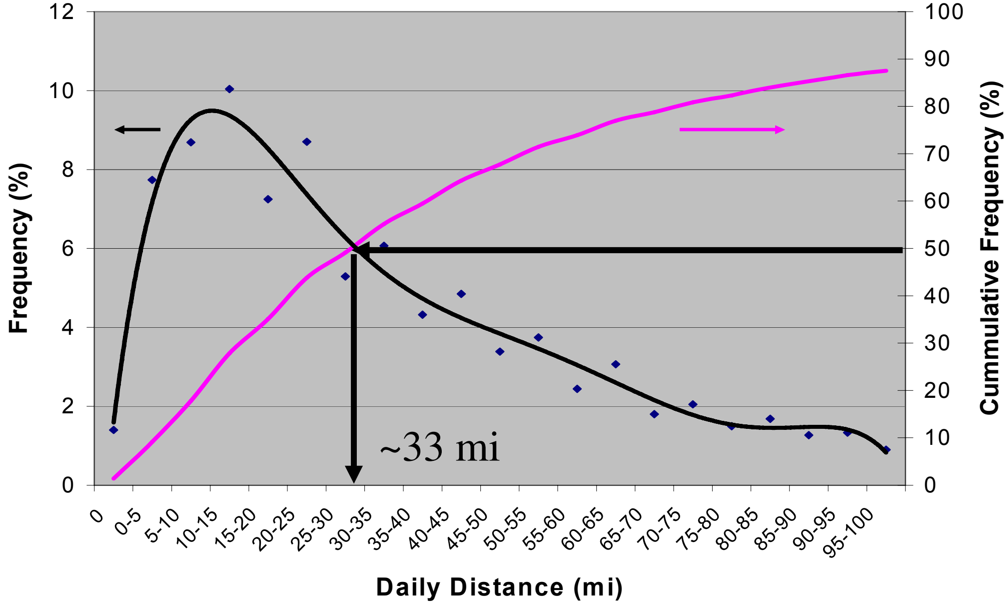
# St. Louis Travel Data Analysis

## Daily Driving Distance Similar to 1995 NPTS Data

### St. Louis HHTS Data



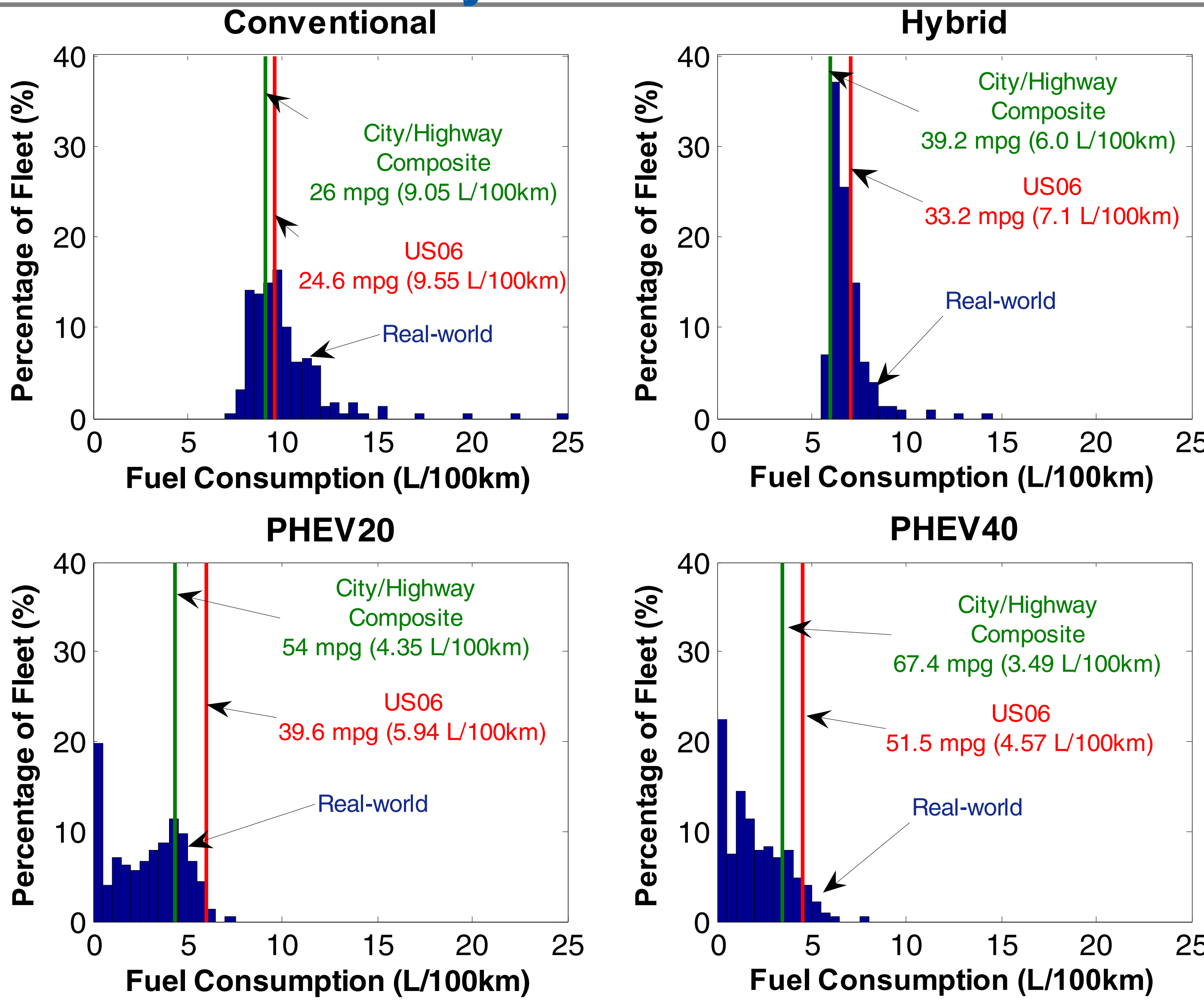

### 1995 NPTS Data




- St. Louis data set includes 227 vehicles from 147 households
- Complete second by second driving profile for one day
- 8650 miles of travel
- St. Louis data set is a small sample of real data
- NPTS data is generated from mileage estimates

# Consumption Distribution

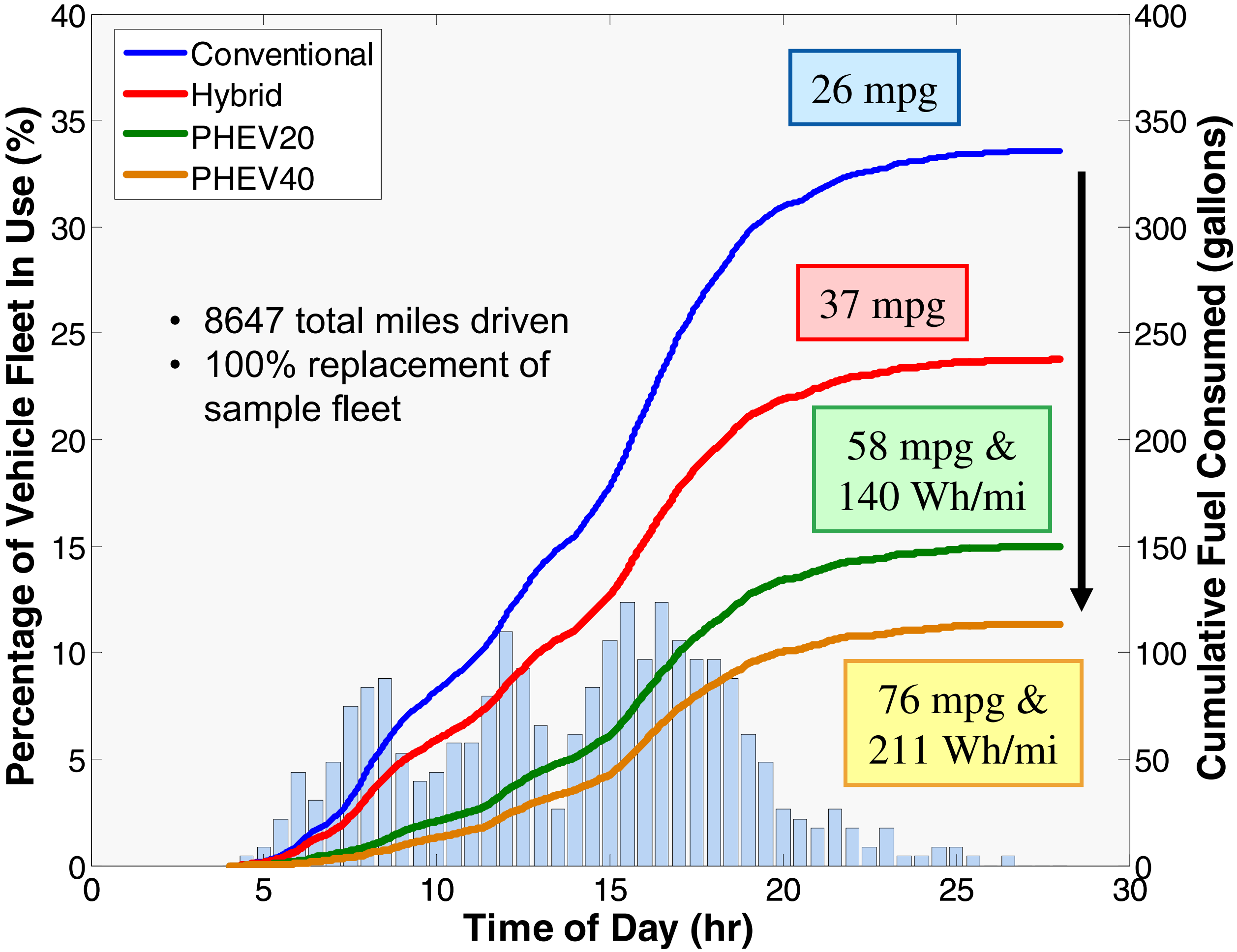
## Many PHEVs Better than Rated Values




“Fleet” results are based on simulations of 227 vehicle driving profiles from St. Louis metropolitan area.

# PHEVs Reduce Fuel Consumption By >50% On Real-World Driving Cycles

227 vehicles from St. Louis each modeled as a conventional, hybrid and PHEV

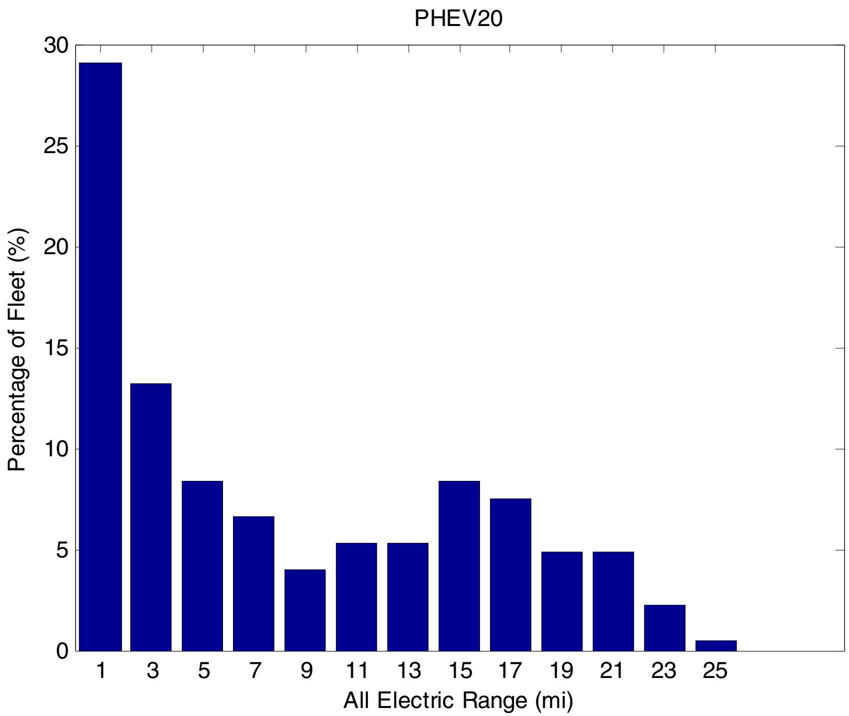


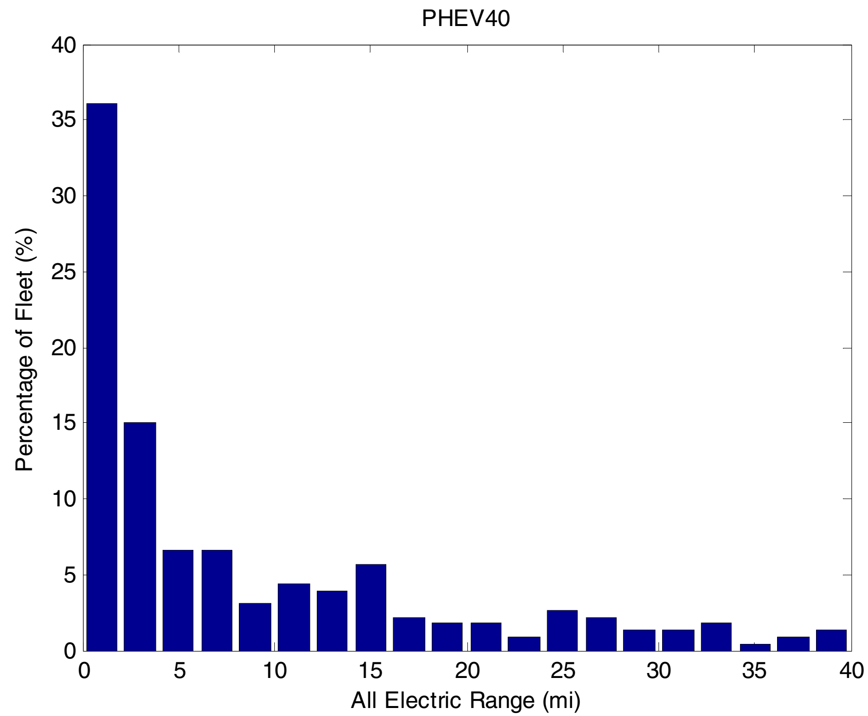

| | Average Daily Costs | | |
|---|---|---|---|
| | Gas. | Elec. | ¢/mi |
| CV | $3.45 | --- | 9.1 |
| HEV | $2.48 | --- | 6.5 |
| PHEV20 | $1.58 | $0.48 | 5.4 |
| PHEV40 | $1.21 | $0.72 | 5.1 |

Assumes $2.41/gal and 9¢/kWh

PHEVs:
>40% reduction in energy costs
>$500 annual savings

# Simulated In-Use All-Electric Range Distribution




- Vehicles were designed to operate all electrically on UDDS
- Power demands of real profiles exceed UDDS peak power within the first few miles

# Fuel Economy and All-Electric Range Comparison

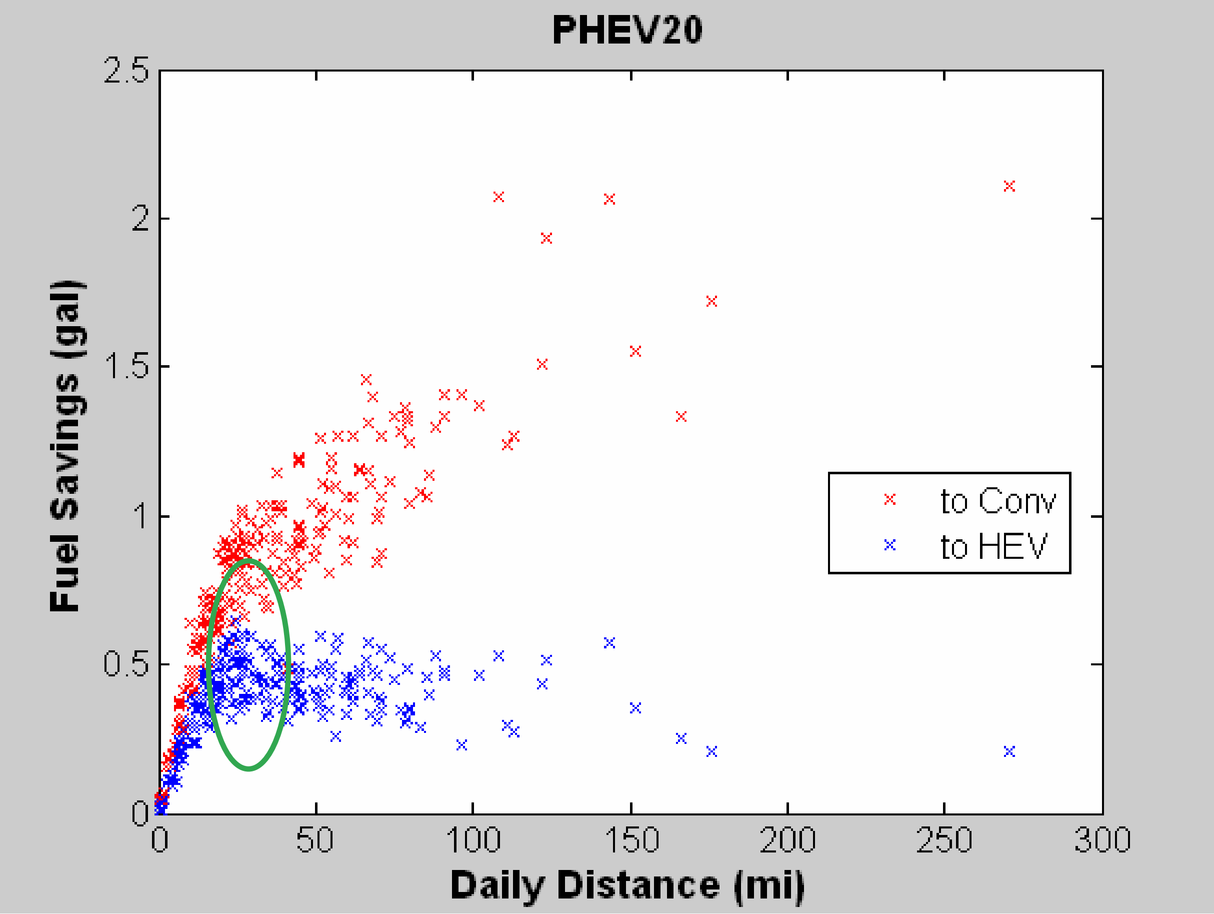
- Significant difference between rated (EPA drive cycles) and real-world median values for PHEVs
  - Consumers likely to observe fuel economy higher than rated value in daily driving
  - Vehicles designed with all-electric range likely to operate in a blended mode to meet driver demands

| | *Fuel Economy (mpg) ** | | *All Electric Range (mi)* | |
|---|---|---|---|---|
| | **Rated** | **Median** | **Rated** | **Median** |
| **Conventional** | 26 | 24.4 | n/a | n/a |
| **HEV** | 39.2 | 35.8 | n/a | n/a |
| **PHEV20** | 54 | 70.2 | 22.3 | 5.6 |
| **PHEV40** | 67.4 | 133.6 | 35.8 | 3.8 |

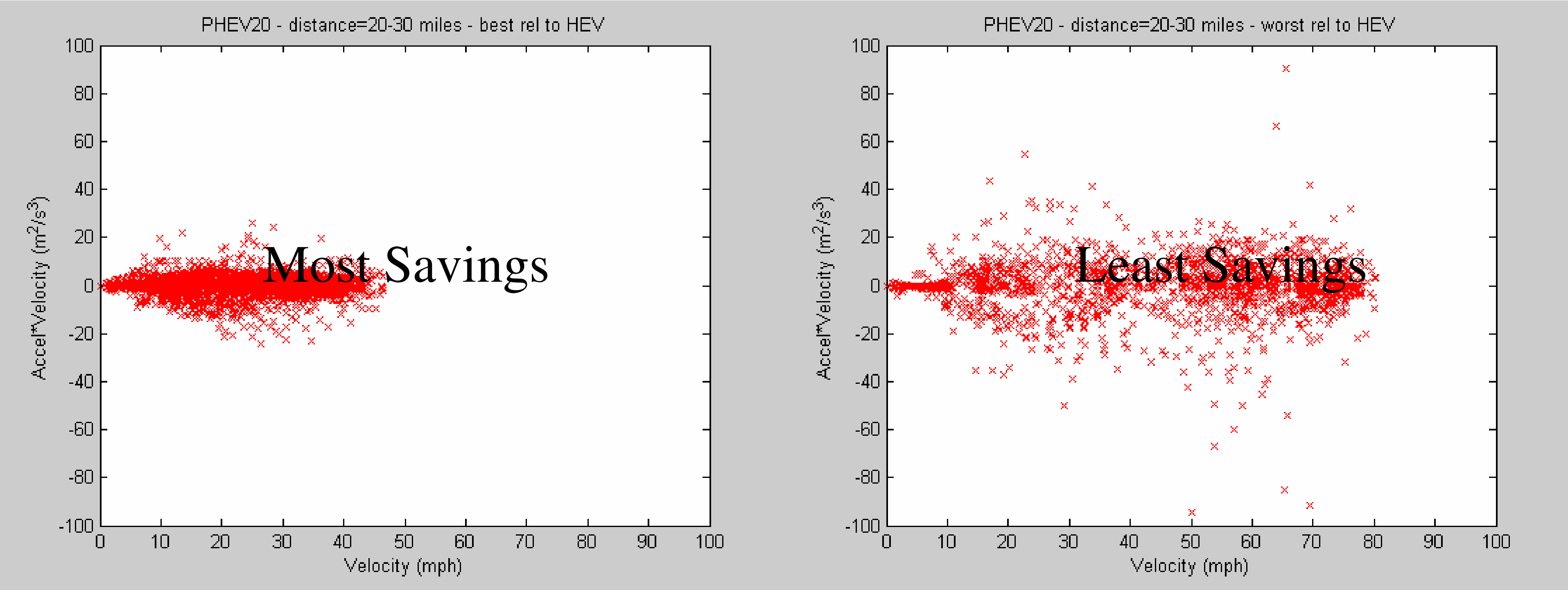
** Fuel economy values do not include electrical energy consumption

# PHEV20 Savings Relative to Conventional and HEV

- Savings relative to conventional are almost entirely distance dependent
- Savings relative to HEV are distance dependent up to PHEV distance then constant



# Deep Dive into Real-World PHEV Simulations




*Insights:*

The PHEV20s that saved the most fuel relative to an HEV travel ~25 miles with speeds under 60 mph and light accelerations

The PHEV20s that saved the least fuel relative to the HEV in the 20-30 mile range had periods of 60+ mph highway driving and the accelerations were significantly more aggressive

# Summary and Conclusions

- PHEVs provide petroleum displacement through fuel flexibility
- Design needs to consider a spectrum of stakeholder objectives
- Analysis of real-world travel behavior provides perspective on design challenges
  - — Vehicles designed as all-electric likely to operate as blended
  - — What's emissions impact of real-world blended operation
- In-use petroleum displacement not tied to all-electric range
  - — Consider *energy equivalent* all-electric range
- PHEV benefit is strongly related to distance and aggressiveness of real-world usage