Do More Batteries Make a Plug-in Better?

Economic and Environmental Analysis of Plug-in Hybrid Electric Vehicles

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PHEV research questions

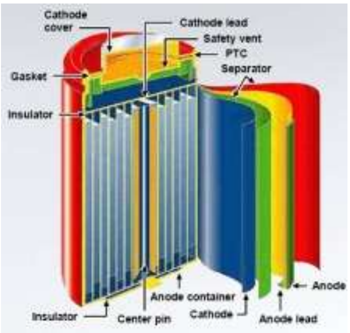
Study #1

1. **How do life cycle PHEV cost and GHGs differ by driver?**
   - Gas mileage claims vary with use
2. **What is the best size for a PHEV battery pack?**
   - Batteries are expensive and heavy
   - More batteries -> more range, but higher cost and lower efficiency

Study #2

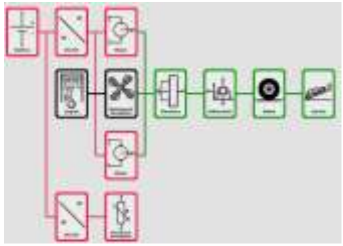
3. **How do batteries degrade, and how should they be best used?**
   - Shallow depth of discharge to protect life?
4. **Which drivers should we target to make the most difference?**

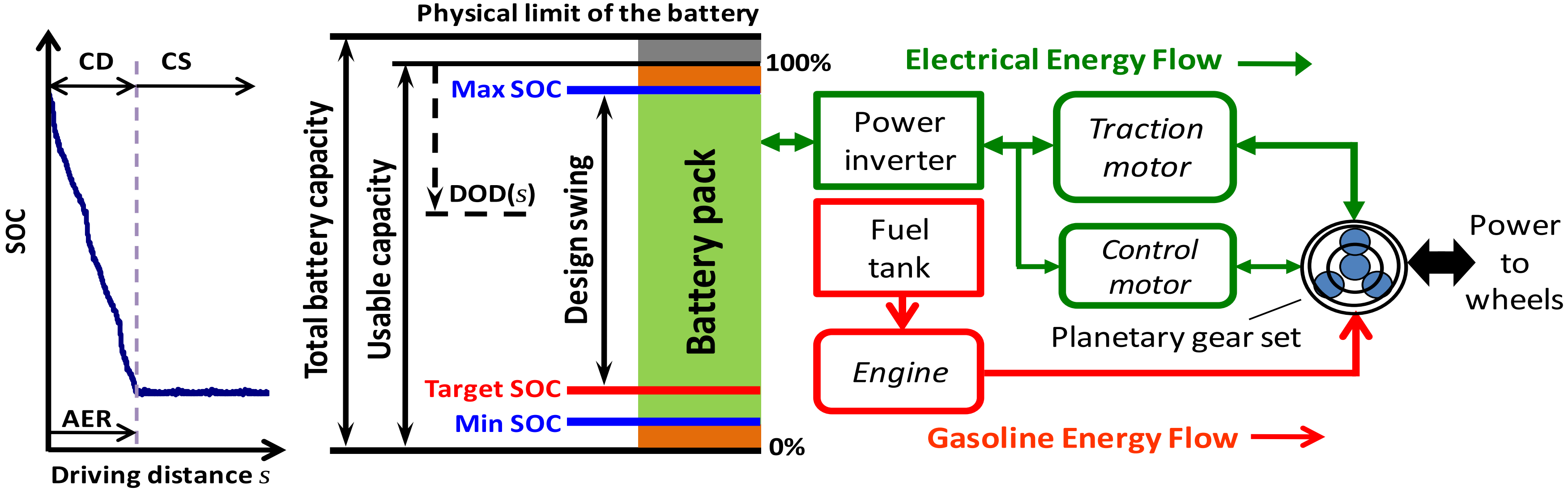
∞ MPG?



Study #1 - Approach

- Use the Powertrain Systems Analysis Toolkit (PSAT) vehicle physics simulator developed by Argonne National Lab
- Start with a model of a Toyota Prius
- Switch from NiMH to Li-ion batteries
- Test the effect of adding batteries





Shiau, C.-S., C. Samaras, R. Hauffe and J.J. Michalek (2009) “Impact of battery weight and charging patterns on the economic and environmental benefits of plug-in hybrid vehicles,” *Energy Policy* v37 p2653-2663.

Assumptions

- **Body:**
  - Prius body, 824kg, 0.26 drag coeff., 2.25m2 frontal area, split powertrain
  - {+0x, **+1x**, +2x} structural weight
- **Engine:**
  - Prius engine (57kW)
- **Motor:**
  - Prius motor (base 52kW scaled to maintain 0-60mph time of 10 seconds)
- **Battery:**
  - Saft li-ion 6Ah, 3.6V
  - {**100**, 140} Wh/kg specific energy
- **Control Strategy:**
  - Extended EV (all electric until target SOC reached)
  - {**50%**, 80%} SOC swing
- **Vehicle Life:**
  - 12 years
  - 150000 miles
  - {**0**, 1} battery replacements per life
- **Cost:**
  - {$1.50, **$3.00**, $6.00} per gal gasoline
  - {$0.06, **$0.11**, $0.30} per kWh electricity
  - $17,600 base vehicle cost
  - {$250, $500, **$1000**} per kWh total battery capacity cost
  - {0%, **5%**, 10%} discount rate
- **Greenhouse Gas Emissions:**
  - 8500 kg CO2-eq. in vehicle manufacturing
  - 120 kg CO2-eq./kWh in battery manufacturing
  - {0.218, **0.730**} kg CO2-eq/kWh electricity consumption
  - 88% charging efficiency
  - 11.34 kg CO2-eq. per gallon gasoline
  - {**$0**, $100} per ton CO_2 tax

Use phase

- PHEVs have lower operation-associated cost, petroleum consumption, and GHG emissions

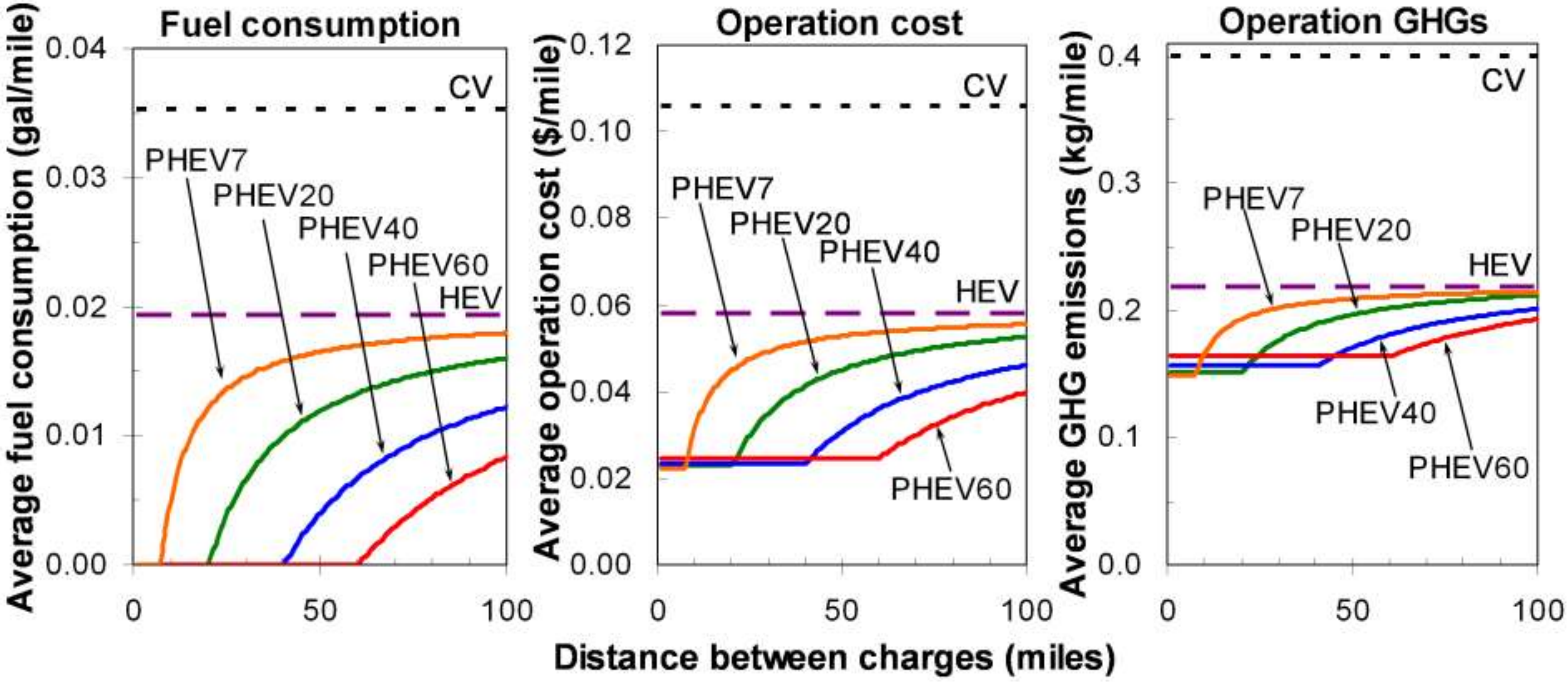
$$d_{\mathrm{CD}} = \begin{cases} d & \text{if } d \le d_{\mathrm{AER}} \\ d_{\mathrm{AER}} & \text{if } d > d_{\mathrm{AER}} \end{cases}$$

$$d_{\mathrm{CS}} = \begin{cases} 0 & \text{if } d \le d_{\mathrm{AER}} \\ d - d_{\mathrm{AER}} & \text{if } d > d_{\mathrm{AER}} \end{cases}$$

$$g = \frac{1}{d}\left(\frac{d_{\mathrm{CS}}}{\eta_{\mathrm{HEV}}}\right)$$

$$c_{\mathrm{OP}} = \frac{1}{d}\left(\frac{d_{\mathrm{CD}}}{\eta_{\mathrm{CD}}}\frac{c_{\mathrm{ELEC}}}{\eta_{\mathrm{C}}} + \frac{d_{\mathrm{CS}}}{\eta_{\mathrm{CS}}}c_{\mathrm{GAS}}\right)$$

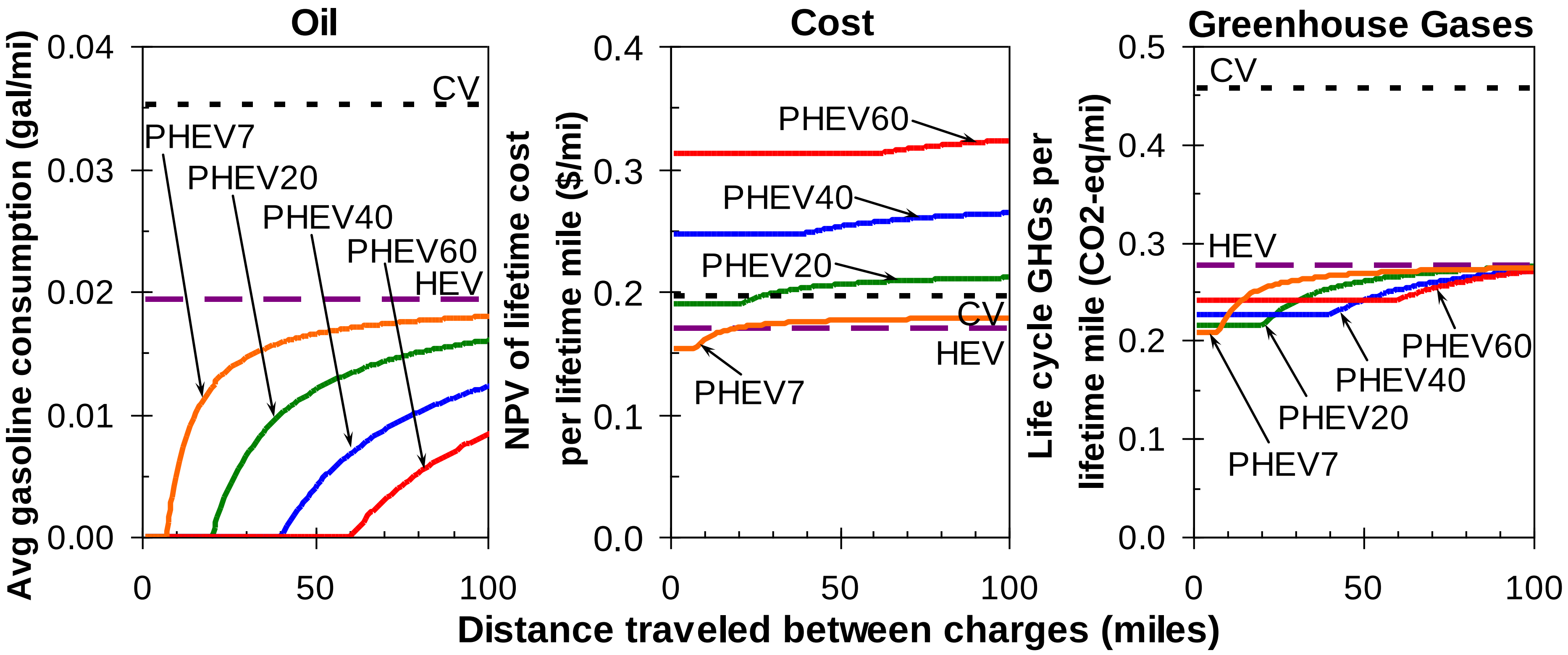
$$\nu_{\mathrm{OP}} = \frac{1}{d}\left(\frac{d_{\mathrm{CD}}}{\eta_{\mathrm{CD}}}\frac{\nu_{\mathrm{ELEC}}}{\eta_{\mathrm{C}}} + \frac{d_{\mathrm{CS}}}{\eta_{\mathrm{CS}}}\nu_{\mathrm{GAS}}\right)$$



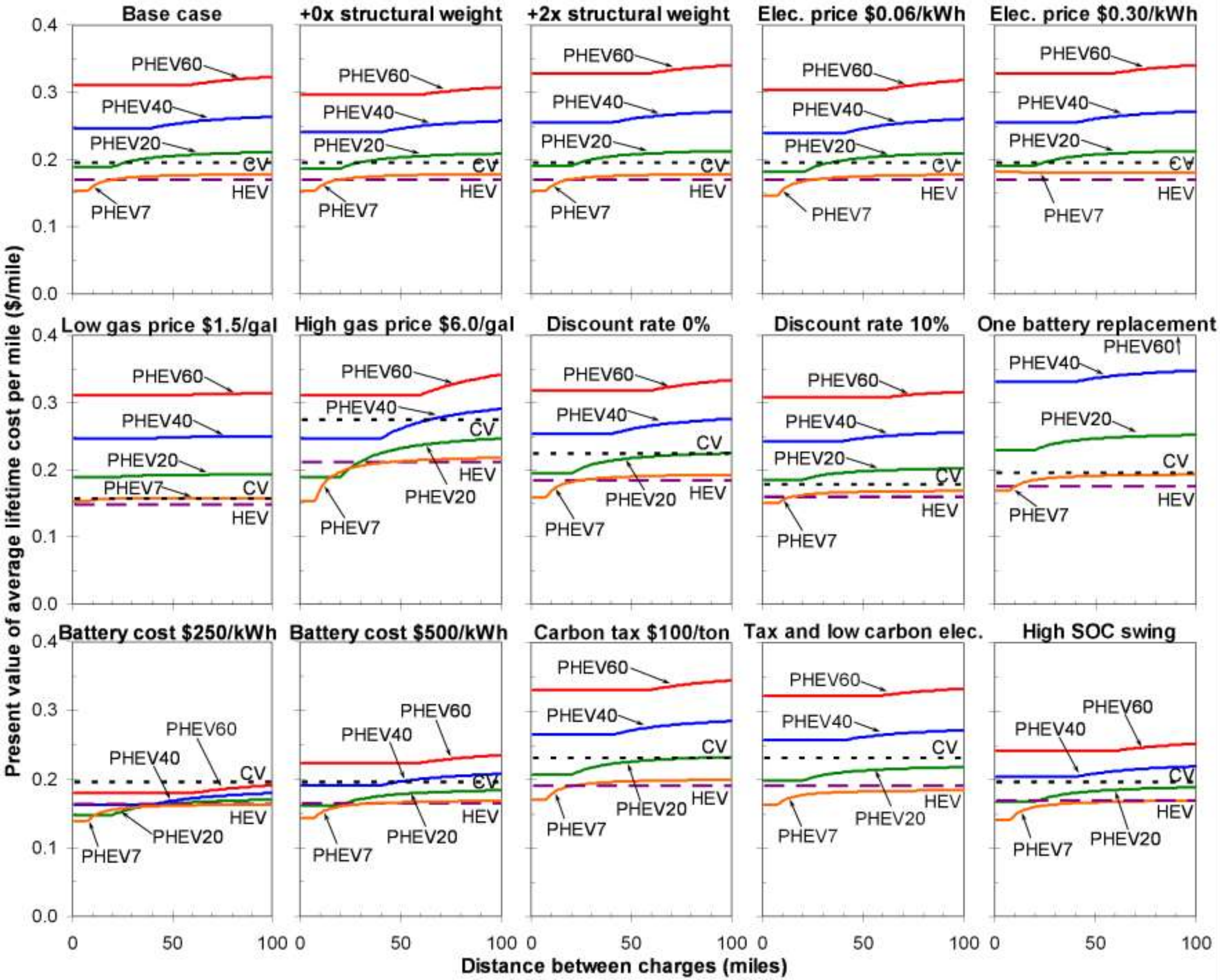
Full life cycle – base case

Production phase + use phase

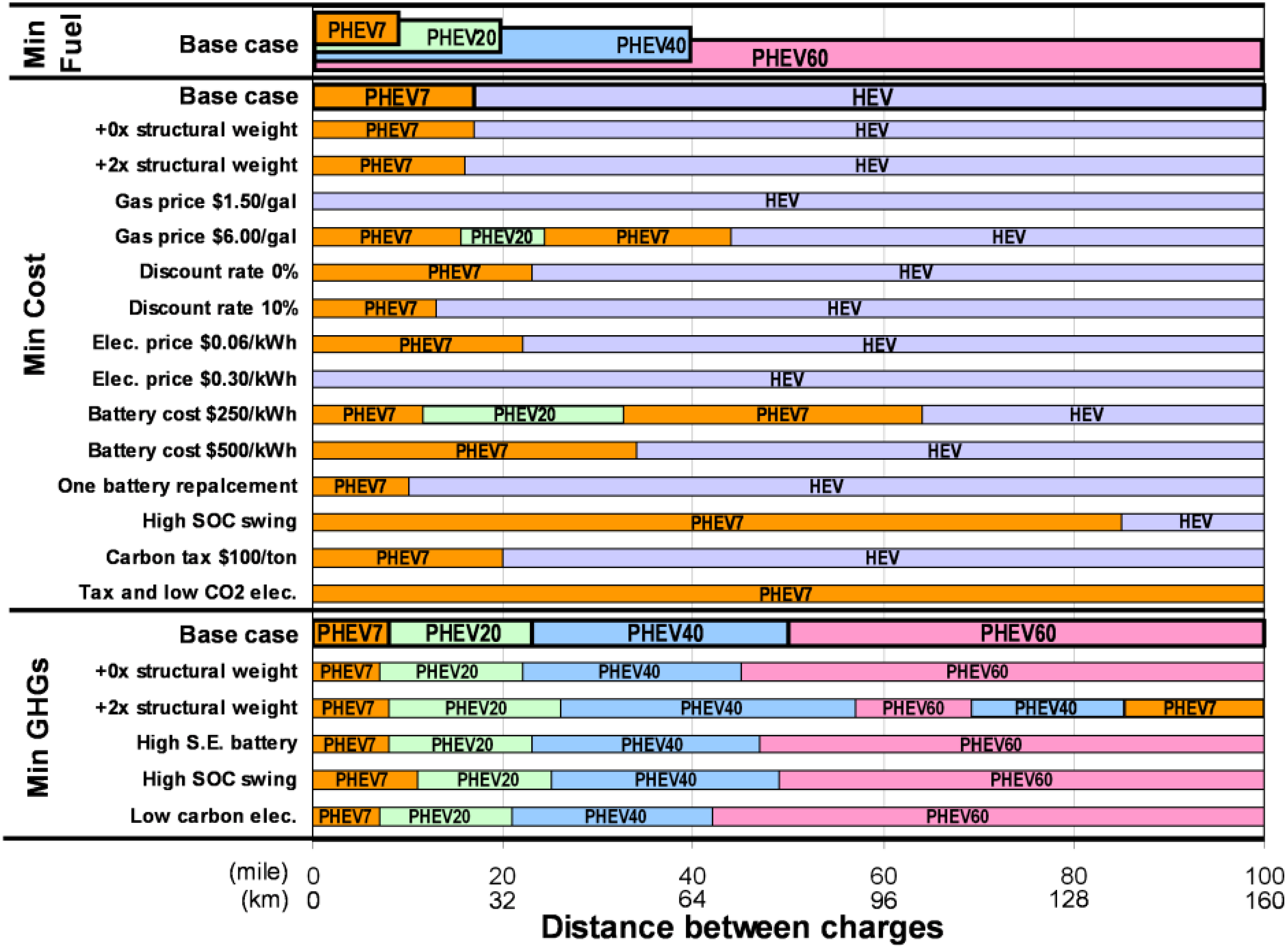
- **Small-capacity PHEVs** are cost-competitive for drivers who *charge frequently*
  - Every ~20 miles or less
- **Large-capacity PHEVs** are not cost-competitive
  - not enough fuel cost savings to make up battery cost



Sensitivity analysis – life cycle cost



Best Vehicle Choice



Study #1 - Take Away

- For urban drivers who charge frequently, PHEVs with small battery packs can save money, gasoline, and GHGs
  - Opportunity to jump-start a market-driven sustainable adoption of PHEV technology
- For infrequent charging, PHEVs with large battery packs save gas and GHGs, but HEVs have lower lifetime cost
  - Incentives could shift who pays
- Implications
  - Battery cost is critical
  - Incentives should not ignore low-capacity PHEVs
    - Obama's target of 1 mil. PHEVs on the road by 2015
  - Charging infrastructure

PHEV research questions

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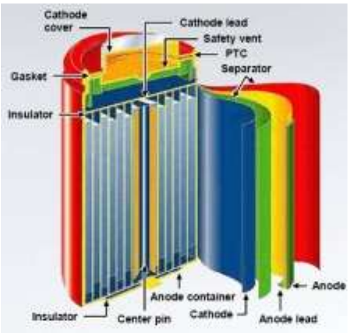


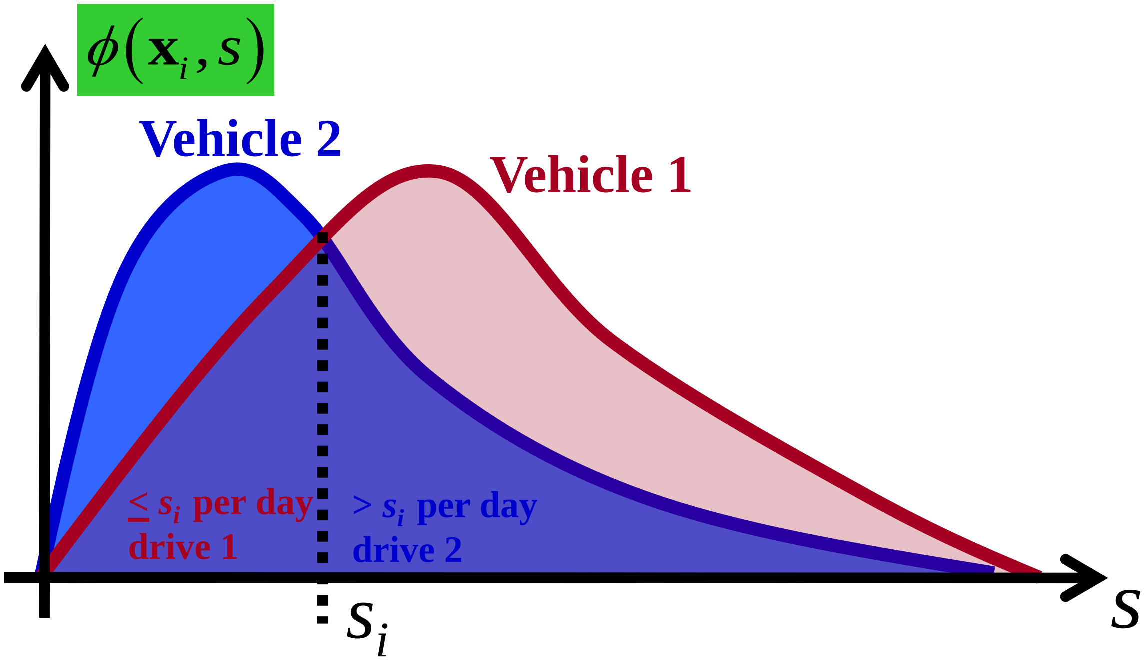
Study #2 – Approach

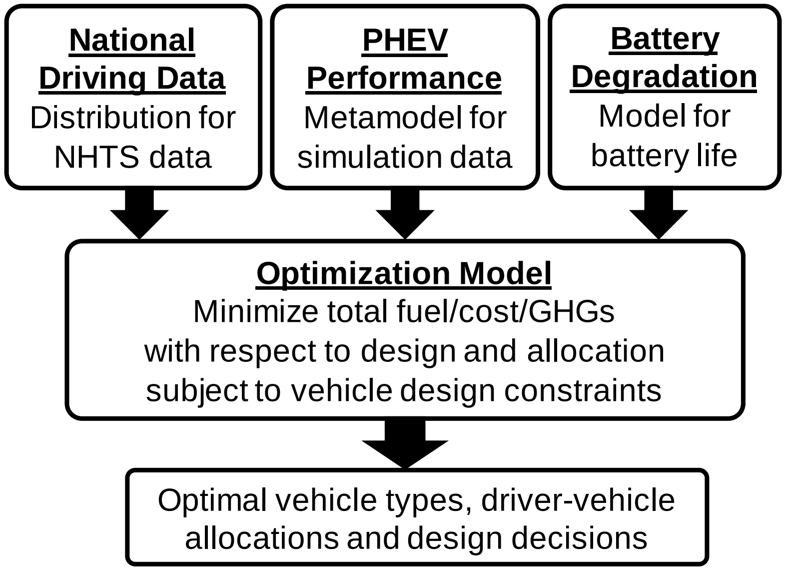
- Optimal design and allocation of vehicles to drivers on the basis of daily distance traveled

Avg. {cost | GHG | oil} per day for vehicle x driven *s* miles/day

Distribution of miles driven per day

$$\underset{\substack{\mathbf{x}_i\ \forall i\in\{1,\ldots,n\}\\ s_i\ \forall i\in\{1,\ldots,n-1\}}}{\text{minimize}}\ \sum_{i=0}^{n-1}\left(\int_{s_i}^{s_{i+1}} \underbrace{f_{\mathrm{O}}\left(\mathbf{x}_i, s\right) f_{\mathrm{S}}\left(s\right)}_{\phi\left(\mathbf{x}_i, s\right)} ds\right)$$





National Driving Data
Distribution for NHTS data

PHEV Performance
Metamodel for simulation data

Battery Degradation
Model for battery life

Optimization Model
Minimize total fuel/cost/GHGs
with respect to design and allocation
subject to vehicle design constraints

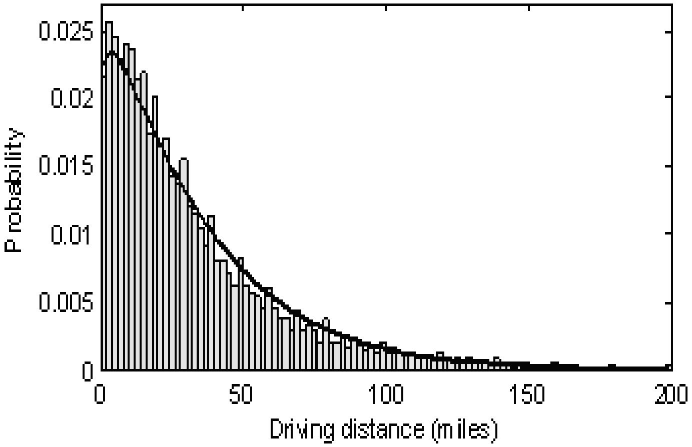
Optimal vehicle types, driver-vehicle allocations and design decisions

Shiau, C.-S., N. Kaushal, S. Peterson and J.J. Michalek (2010) "Optimal Plug-in Hybrid Electric Vehicle Design and Allocation for Minimum Net Cost, Petroleum Consumption and Greenhouse Gas Emissions," in review, *ASME Journal of Mechanical Design*.

Model

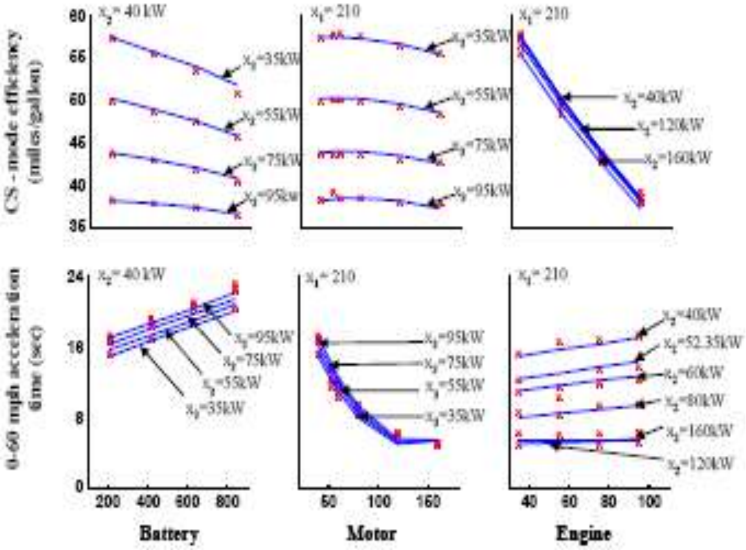
Driver behavior

- 2001 National Household Transportation Survey (NHTS)
- Interviewed 70,000 households across US
- Fit Weibull distribution
- Assumptions (to be relaxed)
  - One charge per day
  - No within-driver variance
  - UDDS representative driving style



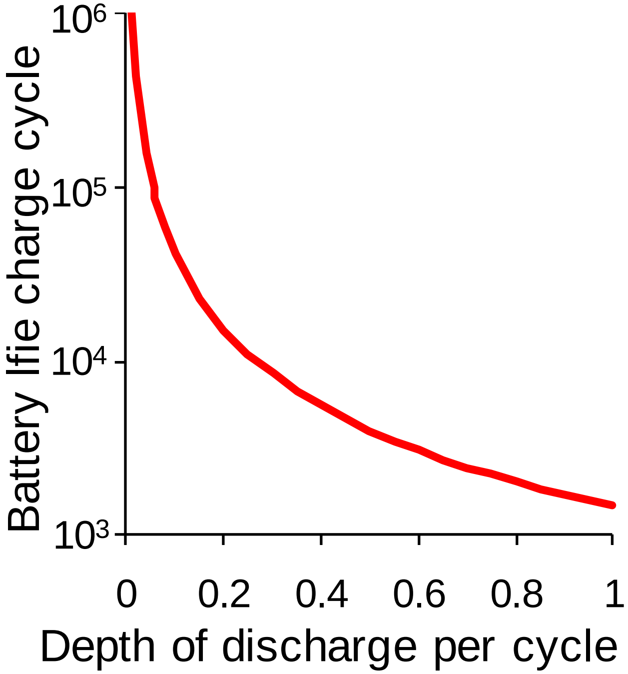
Vehicle physics

- PSAT simulation
- Metamodel fit
- Variables: engine size, motor size, battery size, battery swing
- Assumptions (to be relaxed)
  - All-electric control strategy



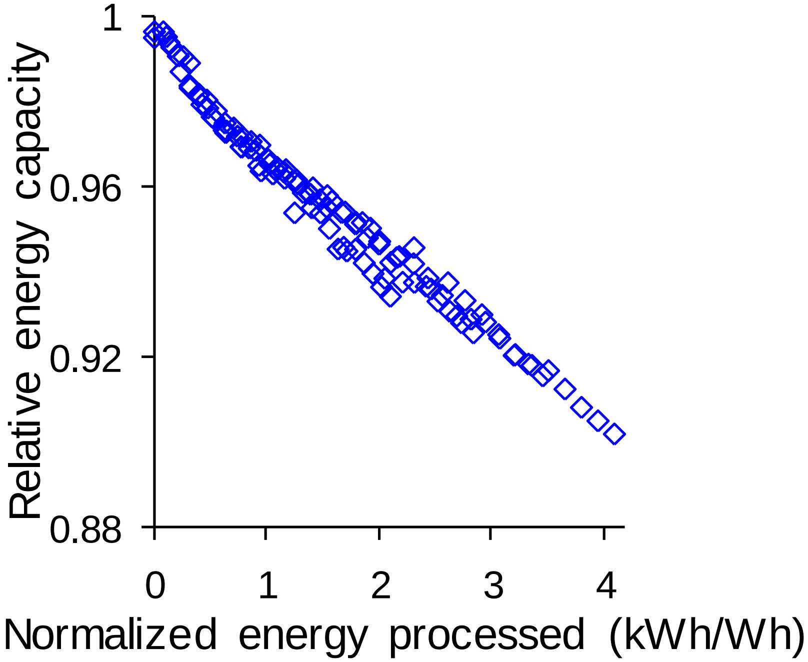
Battery degradation

- Rosenkrantz model:
  - Varta laptop cells
  - Constant C-rate charge discharge
  - Capacity fade faster at deeper DoD



(a)

- Peterson model:
  - A123 $LiFePO_4$ cells
  - Test discharge cycle representative of driving
  - Capacity fade linear with Ah-processed



(b)

MINLP Formulation

- Nonconvex MINLP | global optimization using BARON

$$\underset{\substack{\mathbf{x}_{il},t_{il},z_{ij},y_{ik},q_{io}\\ \forall i\in\{1,\ldots,n\},\ \forall l,j,k,o\in\{1,2,3\};\\ s_i\forall i\in\{1,\ldots,n-1\}}}{\text{minimize}} \quad \sum_{i=0}^{n-1}\sum_{l=1}^{3}\sum_{j=1}^{3}\sum_{k=1}^{3}\sum_{o=1}^{3} t_{il}z_{ij}y_{ik}q_{io}F_{ijko}\left(\mathbf{x}_{il},s_i,s_{i+1}\right)$$

$$\text{subject to } \mathbf{x}_l^{\text{LB}} \le \mathbf{x}_{il} \le \mathbf{x}_l^{\text{UB}};\ t_{\text{CD}} \le 11;\ t_{\text{CS}} \le 11;\ u_{\text{CS}} \ge 32\%;$$

$$\sum\nolimits_{l=1}^{3} t_{il} = 1; \quad \sum\nolimits_{j=1}^{3} z_{ij} = 1; \quad \sum\nolimits_{k=1}^{3} y_{ik} = 1; \quad \sum\nolimits_{o=1}^{3} q_{io} = 1; \qquad s_{i-1} \le s_i;$$

$$\left(z_{i1}\right)\left(s_{\text{AER}} - s_i\right) \le 0; \qquad \left(z_{i2}\right)\left(s_i - s_{\text{AER}}\right) \le 0;$$

$$\left(z_{i2}\right)\left(s_{\text{AER}} - s_{i+1}\right) \le 0; \qquad \left(z_{i3}\right)\left(s_{i+1} - s_{\text{AER}}\right) \le 0;$$

$$\left(q_{i1}\right)\left(s_{\text{BAT}}^{\infty} - s_{\text{LIFE}}\right) \le 0; \qquad \left(q_{i2}\right)\left(s_{\text{BAT}}^{0} - s_{\text{LIFE}}\right) \le 0;$$

$$\left(q_{i2}\right)\left(s_{\text{LIFE}} - s_{\text{BAT}}^{\infty}\right) \le 0; \qquad \left(q_{i3}\right)\left(s_{\text{LIFE}} - s_{\text{BAT}}^{0}\right) \le 0;$$

$$\left(q_{i2}\right)\left(y_{i1}\right)\left(s_{\text{T}} - s_i\right) \le 0; \qquad \left(q_{i2}\right)\left(y_{i2}\right)\left(s_i - s_{\text{T}}\right) \le 0;$$

$$\left(q_{i2}\right)\left(y_{i2}\right)\left(s_{\text{T}} - s_{i+1}\right) \le 0; \qquad \left(q_{i2}\right)\left(y_{i3}\right)\left(s_{i+1} - s_{\text{T}}\right) \le 0;$$

$$t_{il}, z_{ij}, y_{ik}, q_{io} \in \{0,1\}; \quad s_i \in R; \quad \mathbf{x}_{il} \in R^{p_l};\ \forall i \in \{1,\ldots,n\}, \forall l,j,k,o \in \{1,2,3\}$$

$$\text{where } s_0 = 0;\ s_n = \infty;\ s_{\text{AER}} = 10^3 t_{i3}\kappa x_3 x_4 \eta_{\text{E}};\ s_{\text{BAT}}^{0} = \frac{10^6 x_3 \kappa r_{\text{EOL}}}{\alpha_{\text{DRV}}\mu_{\text{CD}} + \alpha_{\text{CHG}}\eta_{\text{E}}^{-1}};$$

$$s_{\text{BAT}}^{\infty} = \frac{10^6 x_3 \kappa r_{\text{EOL}}}{\alpha_{\text{DRV}}\mu_{\text{CS}}};\ s_{\text{T}} = \frac{s_{\text{LIFE}} s_{\text{AER}}\left(\alpha_{\text{DRV}}\left(\mu_{\text{CD}} - \mu_{\text{CS}}\right) + \alpha_{\text{CHG}}\eta_{\text{E}}^{-1}\right)}{10^6 \kappa x_3 r_{\text{EOL}} - \alpha_{\text{DRV}}\mu_{\text{CS}} s_{\text{LIFE}}}$$

$$\eta_{\text{E}i} = \sum\nolimits_l t_{il} f_{1l}\left(\mathbf{x}_{il}\right);\ \eta_{\text{G}i} = \sum\nolimits_l t_{il} f_{2l}\left(\mathbf{x}_{il}\right);\ t_{\text{CD}i} = \sum\nolimits_l t_{il} f_{3l}\left(\mathbf{x}_{il}\right);\ t_{\text{CS}i} = \sum\nolimits_l t_{il} f_{4l}\left(\mathbf{x}_{il}\right);$$

$$\mu_{\text{CD}i} = \sum\nolimits_l t_{il} f_{5l}\left(\mathbf{x}_{il}\right);\ \mu_{\text{CS}i} = \sum\nolimits_l t_{il} f_{6l}\left(\mathbf{x}_{il}\right);\ u_{\text{CS}i} = \sum\nolimits_l t_{il} f_{7l}\left(\mathbf{x}_{il}\right);$$

$$F_{ijko}\left(\mathbf{x}_{il}, s_i, s_{i+1}\right) = \int_{s_i}^{s_{i+1}} f_{\text{O}}\left(\mathbf{x}_i, s\right) f_{\text{S}}\left(s\right) ds$$

Results

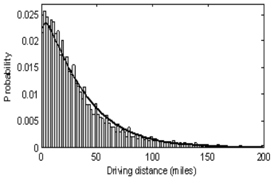
- Base case

Optimization Objective			**Minimum Petroleum**	**Minimum GHGs**		**Minimum Cost**	
Optimal Vehicle Set	**CV**	**HEV**	**PHEV**	**PHEV**	**PHEV**	**PHEV**	**HEV**
Allocation to drivers (miles/day)	0-200	0-200	0-200	0-32	32-200	0-53	53-200
AER (miles)	–	–	87	29	46	35	–
Engine power (kW)	126	57	47	44	48	45.8	57
Motor power (kW)	–	52	90	71	72	70.2	52
Number of battery cells	–	168	1000[†]	314	503	383	168
Battery design swing	–	–	0.8[†]	0.8[†]	0.8[†]	0.8	–
Battery capacity (kWh)	–	1.3	21.6	6.8	10.9	8.3	1.3
CD-mode efficiency (miles/kWh)	–	–	5.04	5.33	5.26	5.31	–
CS-mode efficiency (mpg)	29.5	60.1	58.0	60.5	59.6	60.2	60.1
CD-mode 0-60mph time (sec)	–	–	11.0	11.0	11.0	11.0	–
CS-mode 0-60mph time (sec)	11.0	11.0	8.3	9.8	8.9	9.0	11.0
Final SOC after US06 cycles	–	–	0.32	0.32	0.32	0.32	–
Petroleum (gallon per person-day)	1.153	0.566	**0.041**	0.148		0.326	
GHGs (kg CO_2-eq per person-day)	15.0	8.41	8.19	**5.65**		8.05	
Cost ($ per person-day)	7.0	5.39	6.69	7.86		**5.34**	
Reduction with respect to CV only	–	–	−96%	−62%		−24%	

[†] Variable limited by model boundary

Results

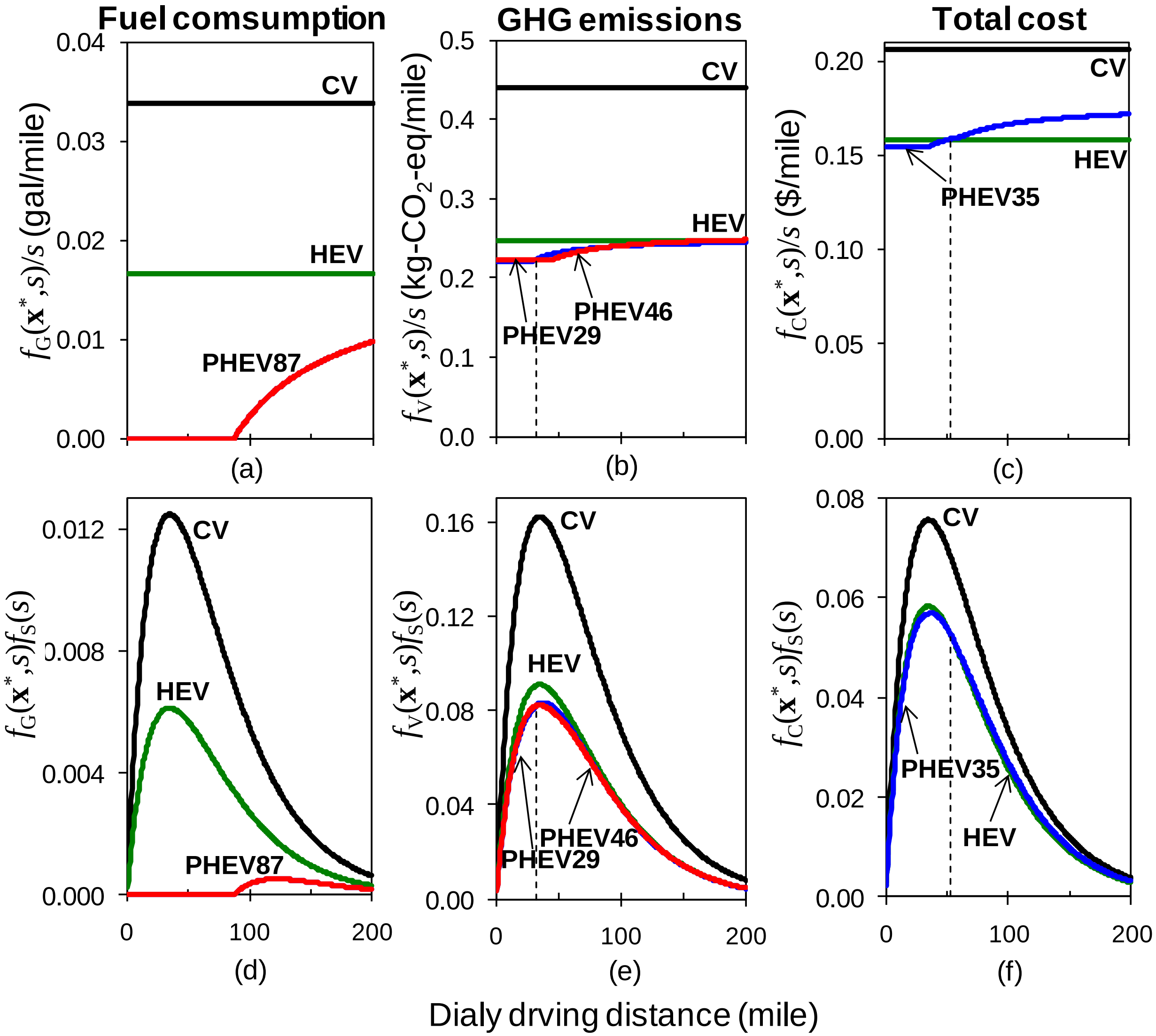
- Largest number of drivers near 0 miles/day
- Largest impact per driver near 200 miles/day
- Largest net cost and GHGs for ~30-50 mile/day driver category



Average per mile

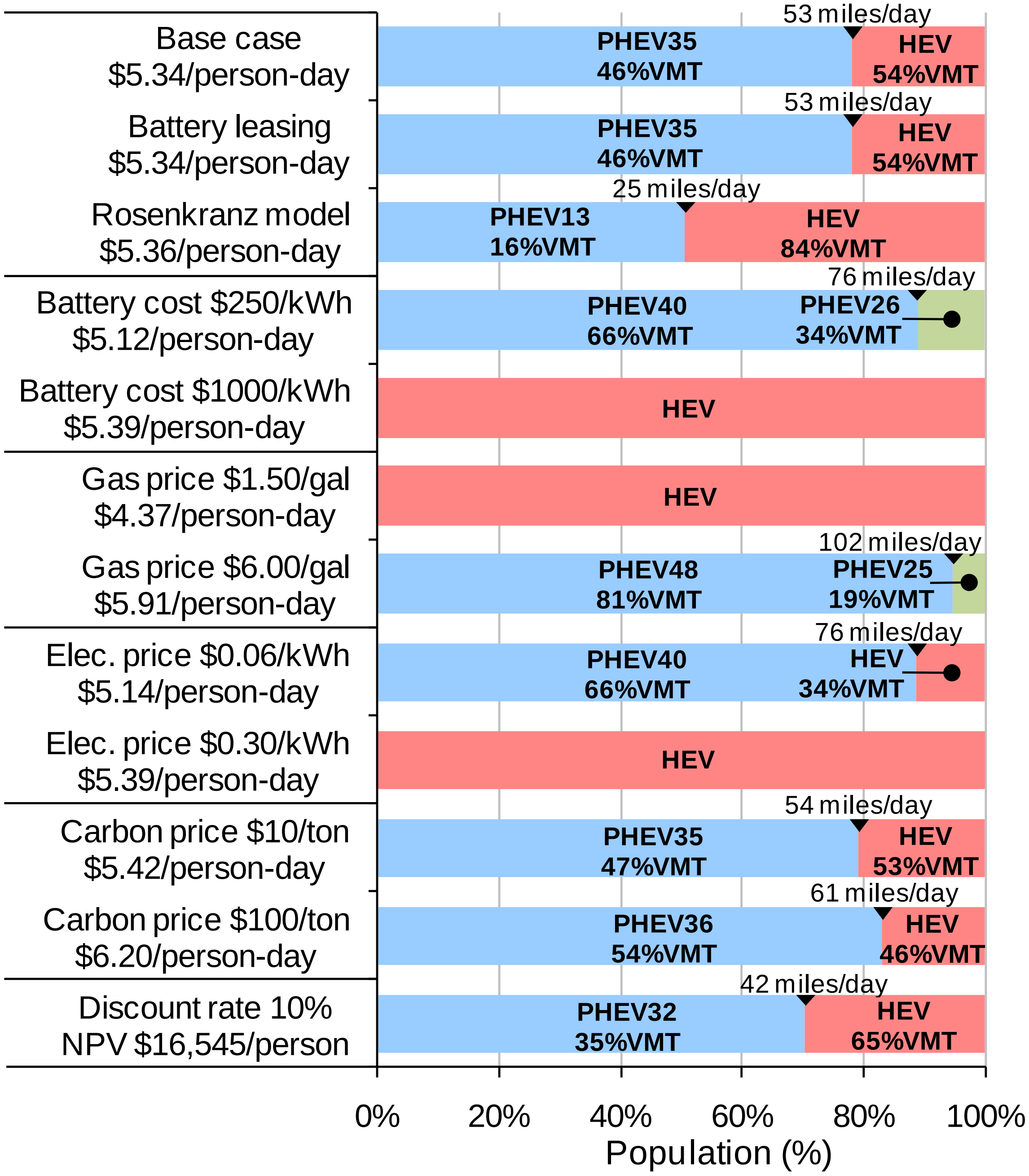
Population-weighted average per day

(*integral is per person per day*)



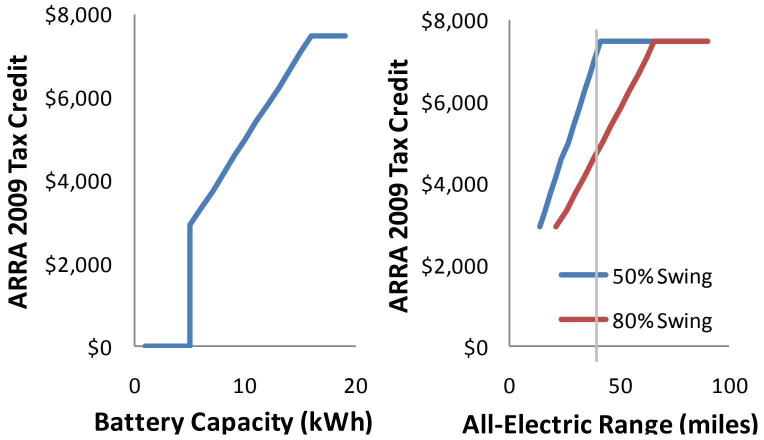
Sensitivity analysis – minimum cost

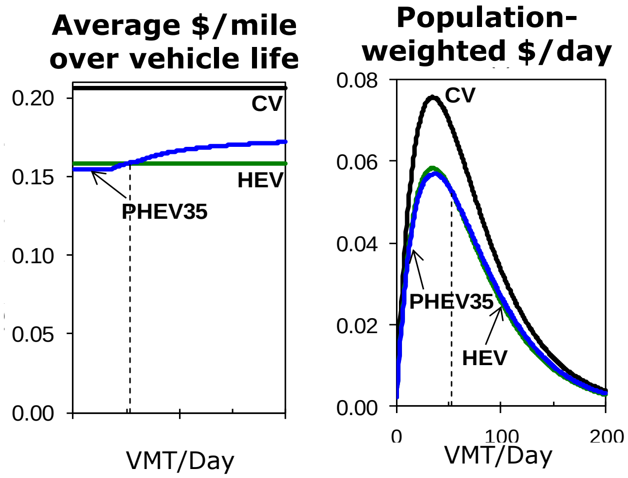
- Base case:
  - $400/kWh Li-ion
  - $600/kWh NiMH
  - Peterson degradation
  - $3.30/gal gasoline
  - $0.11/kWh electricity
  - $0/ton CO_2
  - 0% discount rate
- PHEVs are part of the least-cost solution:
  - Above $3/gal gas, or
  - Below $0.14/kWh electricity, or
  - Below 23% discount rate, or
  - Below $465/kWh batteries

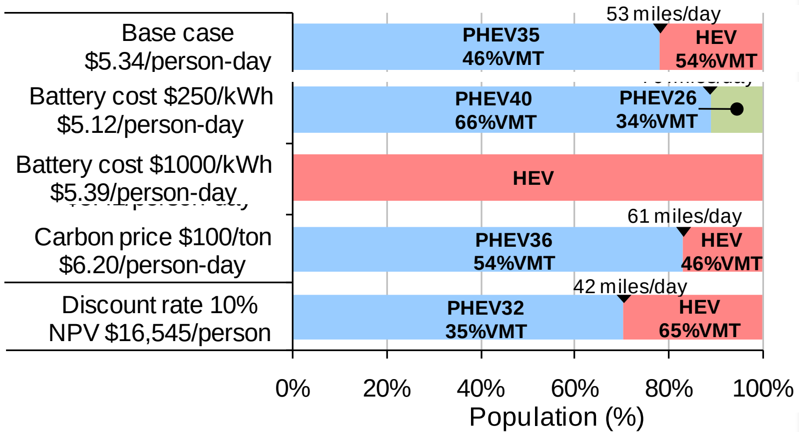


Take Away

- **Battery swing**
  - Peterson battery degradation implies maximum swing is best for minimum cost and GHGs
  - Battery incentives should be for AER, not kWh
- **Which drivers to target?**
  - Drivers who charge frequently have the most to gain from low capacity PHEVs –most likely adopters?
  - Group that makes the most net impact (cost and GHGs) are those who drive 30-50 miles/day
  - Accounting for replacement, batteries below \$450/kWh range to be part of the least-cost solution
- **Carbon price**
  - Even high CO_2 allowance prices have marginal effect on PHEV competitiveness (avg. US grid) => global warming not a good rationale for the switch?
  - Battery cost matters most. Large swing helps.







Research Direction

1. **Cost of Mitigation:** Minimize cost per unit of GHG reduced (under constraints)
2. **Driver Variance:** Assess impact of day to day variance in driving distances for each driver. Variation in driving style (drive cycle)
3. **Battery Thermal Management:** Battery HVAC systems
4. **Location:** Assess marginal and locational grid effects on CO_2 and cost for PHEVs vs. alternatives – which part of the country should drive them?
    - Temperature, terrain, grid, charging infrastructure, driving cycles and styles
5. **Infrastructure:** Assess technical, economic and environmental implications of battery charging and swapping stations
6. **Consumer Preferences:** Willingness to pay for PHEV attributes
7. **On Road:** Hymotion Prius sensored for road testing and data logging

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  - Dr. Constantine Samaras (RAND)
  - Ching-Shin Norman Shiau (CMU Mechanical Engineering)
  - Nikhil Kaushal (CMU Mechanical Engineering)
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Questions & Discussion

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Effect of additional batteries

- PHEV7 ⇒ PHEV40 implies
  - +300kg additional weight
  - +5% more energy required per mile (gasoline or electricity)