Do More Batteries Make a Plug-in Better?

Economic and Environmental Analysis of Plug-in Hybrid Electric Vehicles

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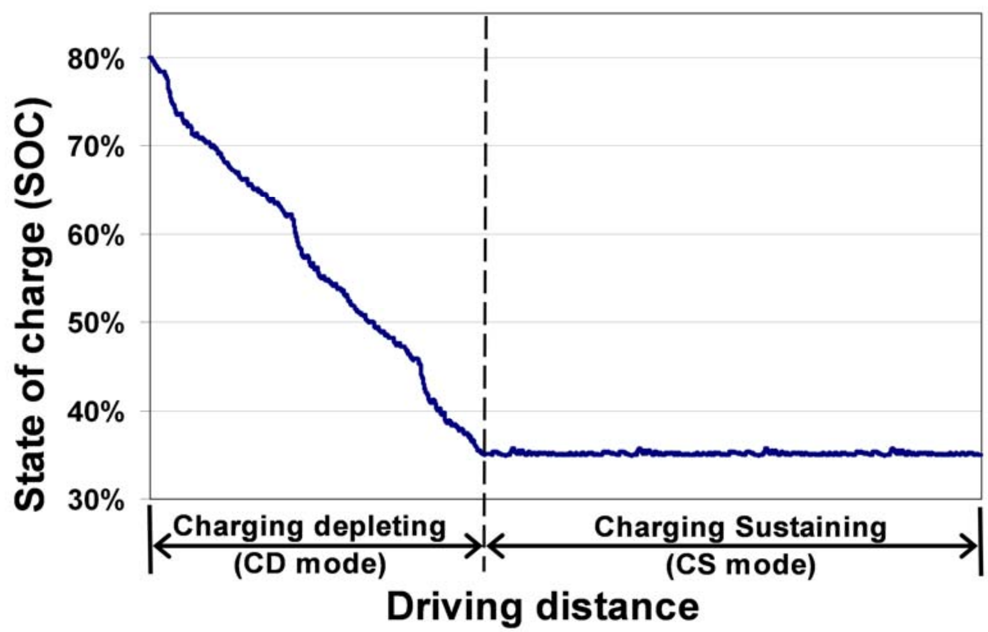
Green design & policy

- **Vehicle design is experiencing major changes**
  - global warming & dependency on foreign oil are increasingly urgent challenges.
- **Government sets transportation energy policy**
  - constraints, penalties, and incentives to influence vehicle design outcomes
  - EISA 2007, Obama/EPA 2009, incentives for alternative fuel vehicles
- **But the effect of policy on design is complicated**
  - engineering tradeoffs, consumer preferences, competition
- **Build quantitative foundation** for understanding and predicting interactions among the decisions of designers, firms, consumers, and government
  - Goal: support informed decision-making

Plug-in hybrid electric vehicles

- Approach to reducing:
  1. Petroleum consumption (*oil independence*)
  2. Greenhouse gas emissions (*global warming*)
  3. Cost (*economy*)
- Plug vehicle in to wall outlet
- Use batteries to store energy and drive partly on electricity from the grid
- More batteries implies
  - Longer all-electric range (AER), but
  - Lower efficiency (more energy per mile)
  - Higher vehicle cost
- **Q:** on balance, is it worthwhile?



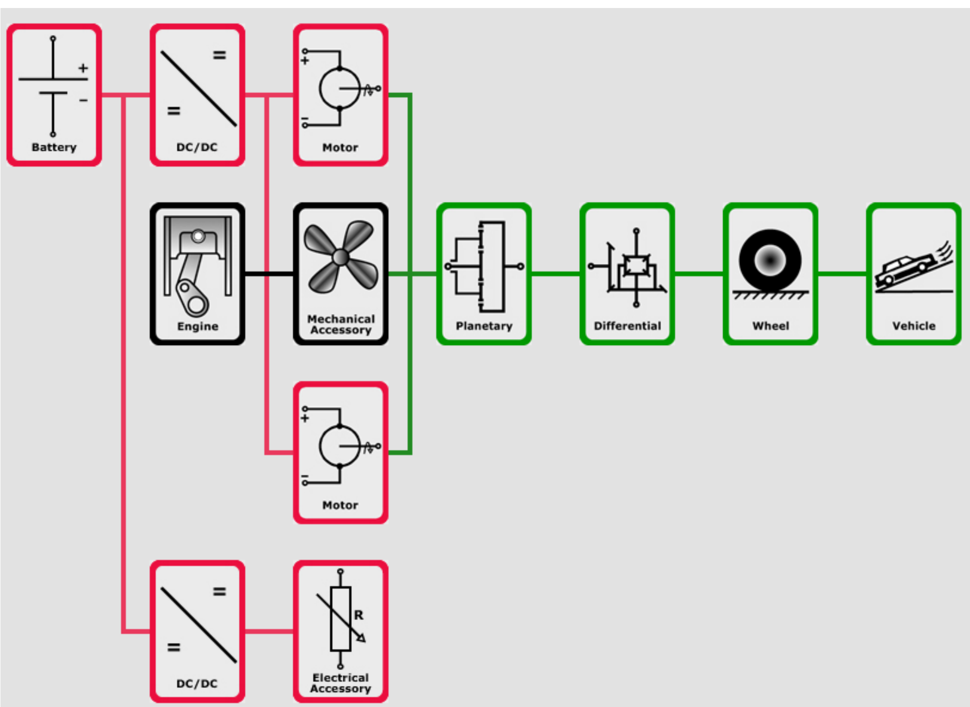
Alternative strategies

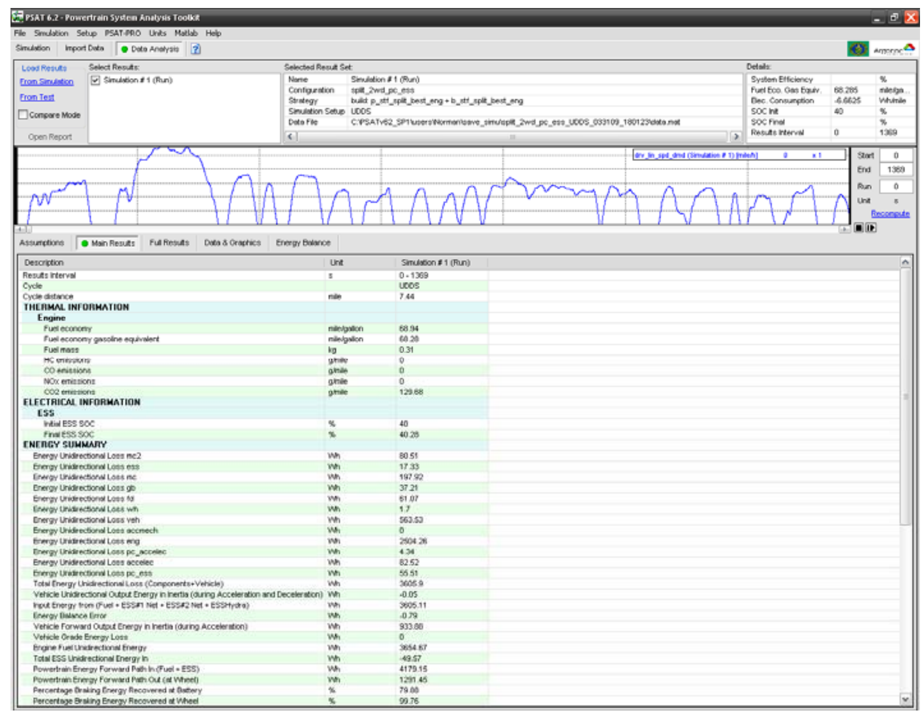
- Chevy Volt
  - PHEV40
  - Series powertrain
- Toyota Prius PHEV
  - PHEV7 - PHEV12
  - Split powertrain

PHEV$x \Rightarrow$ PHEV with x miles of all-electric range (AER)

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



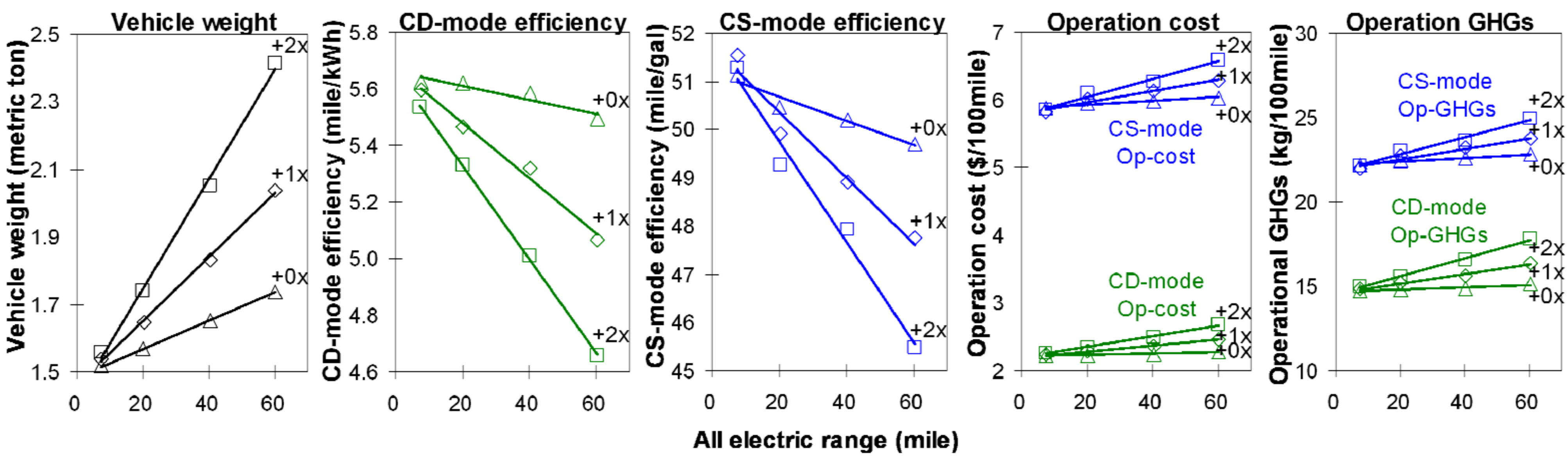


Assumptions

- **Body:** Prius body, 824kg, 0.26 drag coeff., 2.25m^2 frontal area
- **Engine:** Prius engine (57kW)
- **Motor:** Prius motor (52kW) scaled to maintain 0-60mph time of 10 seconds
- **Battery:** Saft li-ion 6Ah, 3.6V, 100Wh/kg
- **Control Strategy:** Extended EV (all electric until target SOC reached)
- **Base case:**
  - Cost:
    - $3.00/gal gasoline
    - $0.11/kWh electricity
    - $17,600 base vehicle cost + $1000/kWh total battery capacity cost
  - GHGs:
    - 8500 kg CO2-eq. in vehicle manufacturing
    - 120 kg CO2-eq./kWh in battery manufacturing
    - 0.730 kg CO2-eq/kWh electricity consumption (+88% charging efficiency)
    - 11.34 kg CO_2-eq. per gallon gasoline
  - Life:
    - 12 years
    - 150000 miles

Effect of additional batteries

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



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.

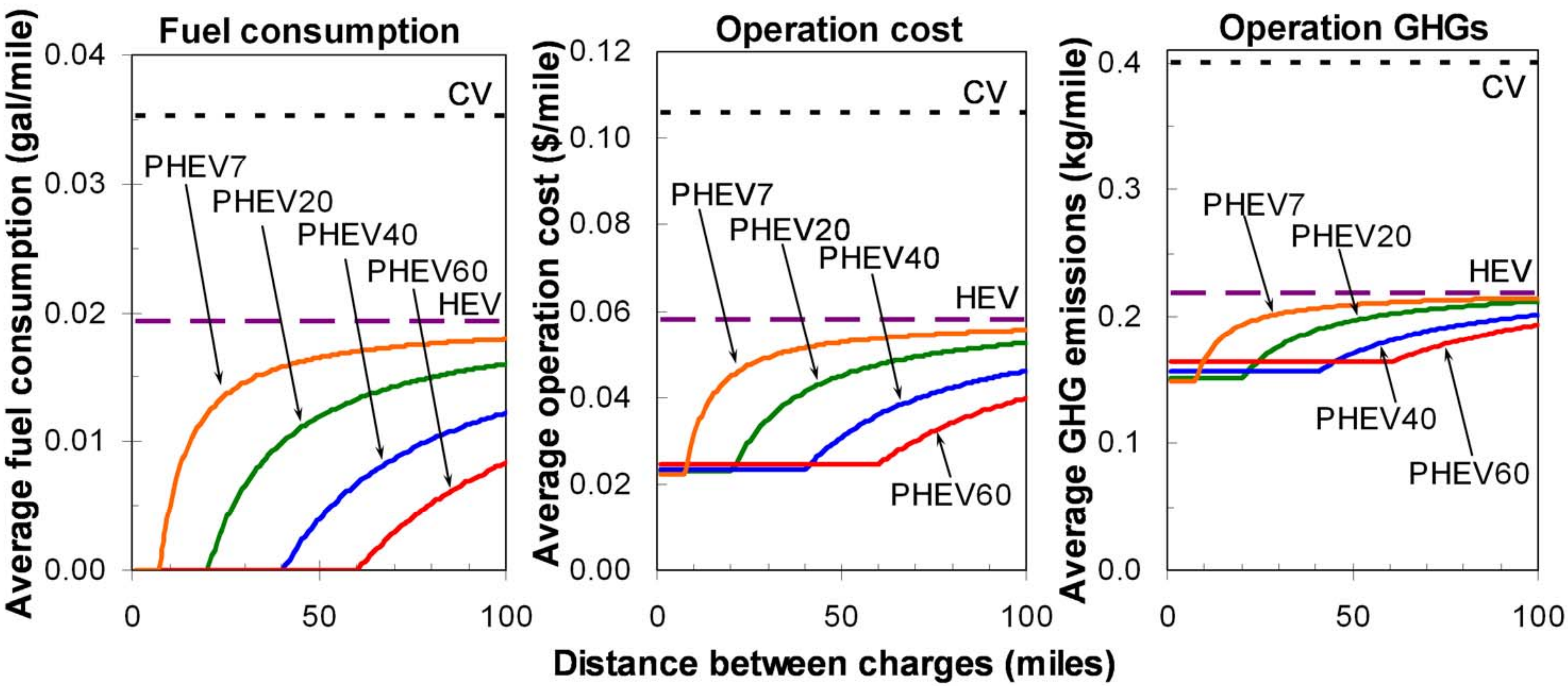
Use phase

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

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

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

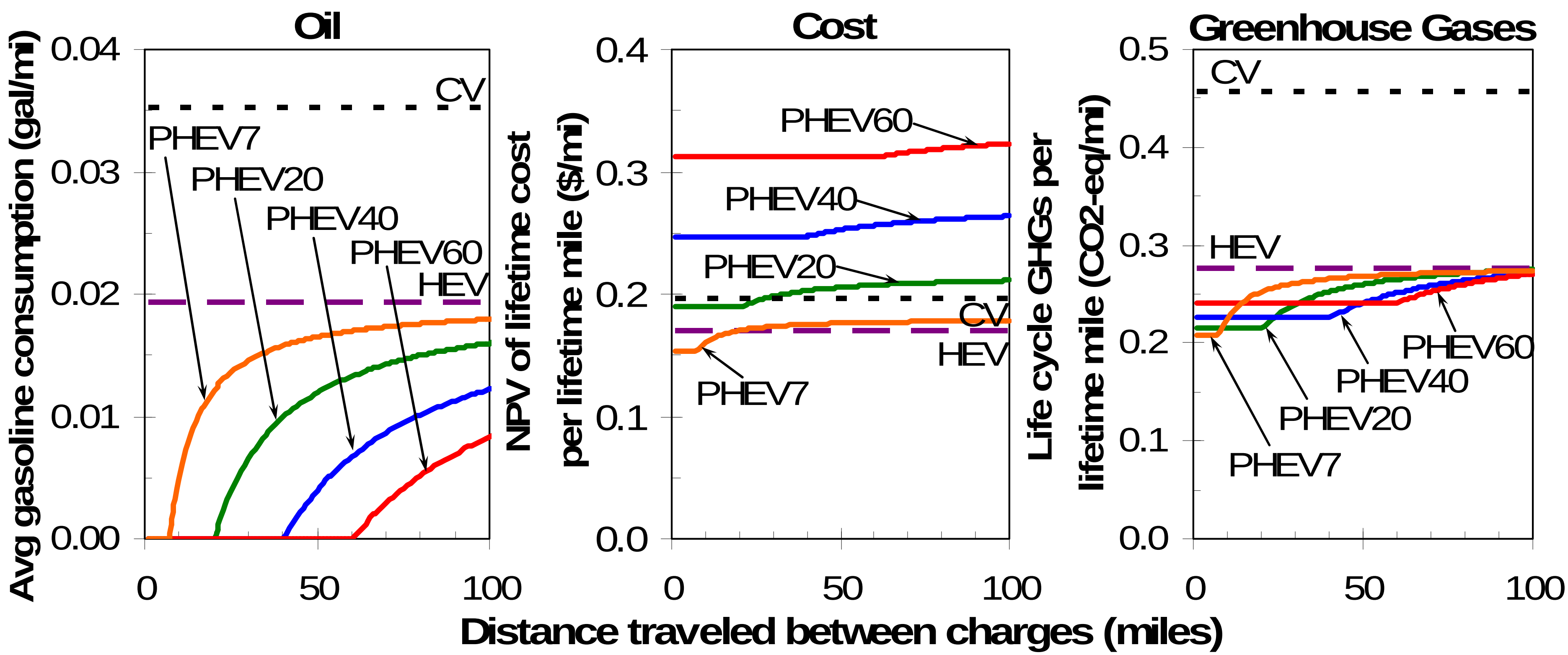
$$g = \frac{1}{d}\left(\frac{d_{CS}}{\eta_{HEV}}\right) \qquad c_{OP} = \frac{1}{d}\left(\frac{d_{CD}}{\eta_{CD}}\frac{c_{ELEC}}{\eta_{C}} + \frac{d_{CS}}{\eta_{CS}}c_{GAS}\right) \qquad v_{OP} = \frac{1}{d}\left(\frac{d_{CD}}{\eta_{CD}}\frac{v_{ELEC}}{\eta_{C}} + \frac{d_{CS}}{\eta_{CS}}v_{GAS}\right)$$



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

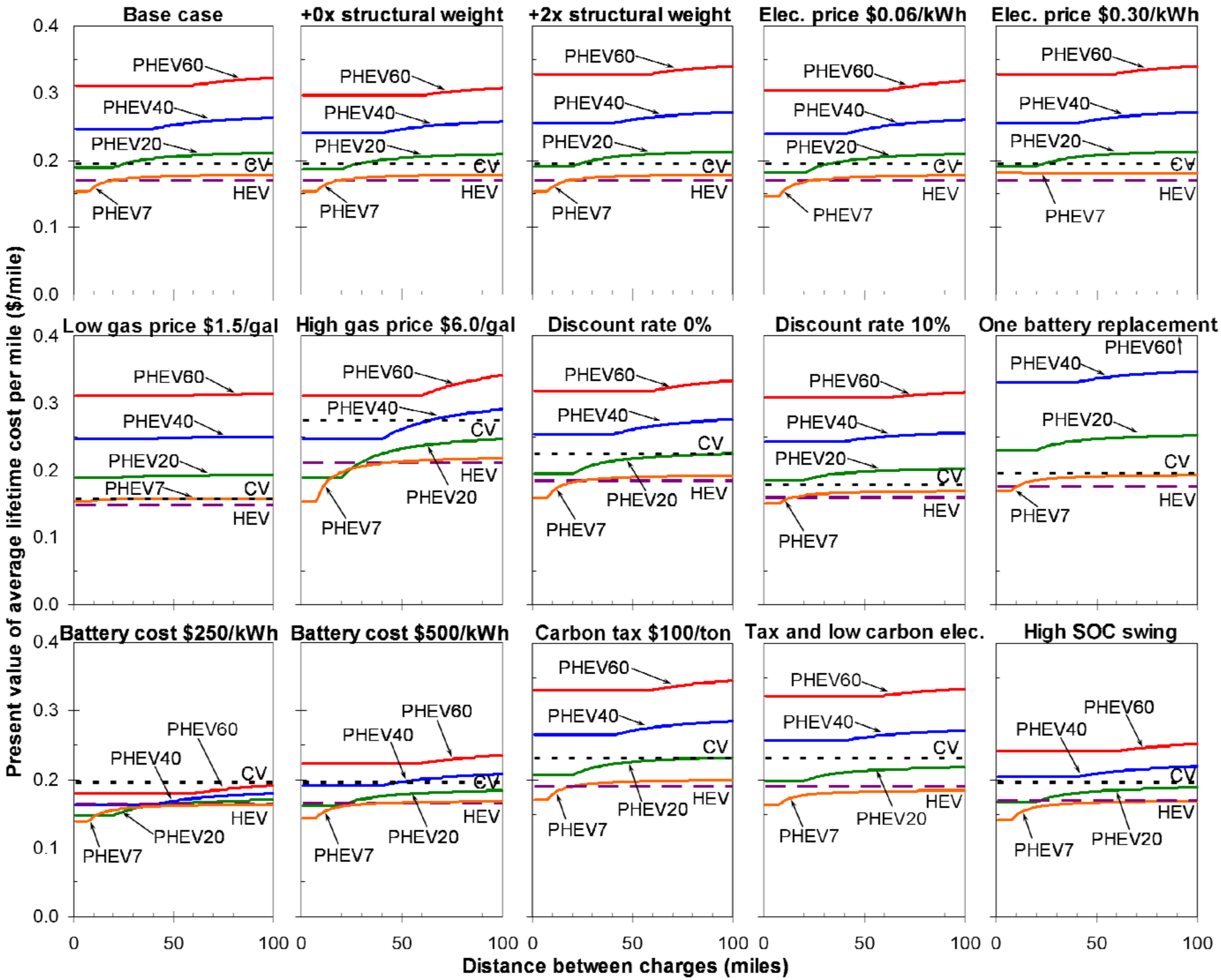


Sensitivity analysis

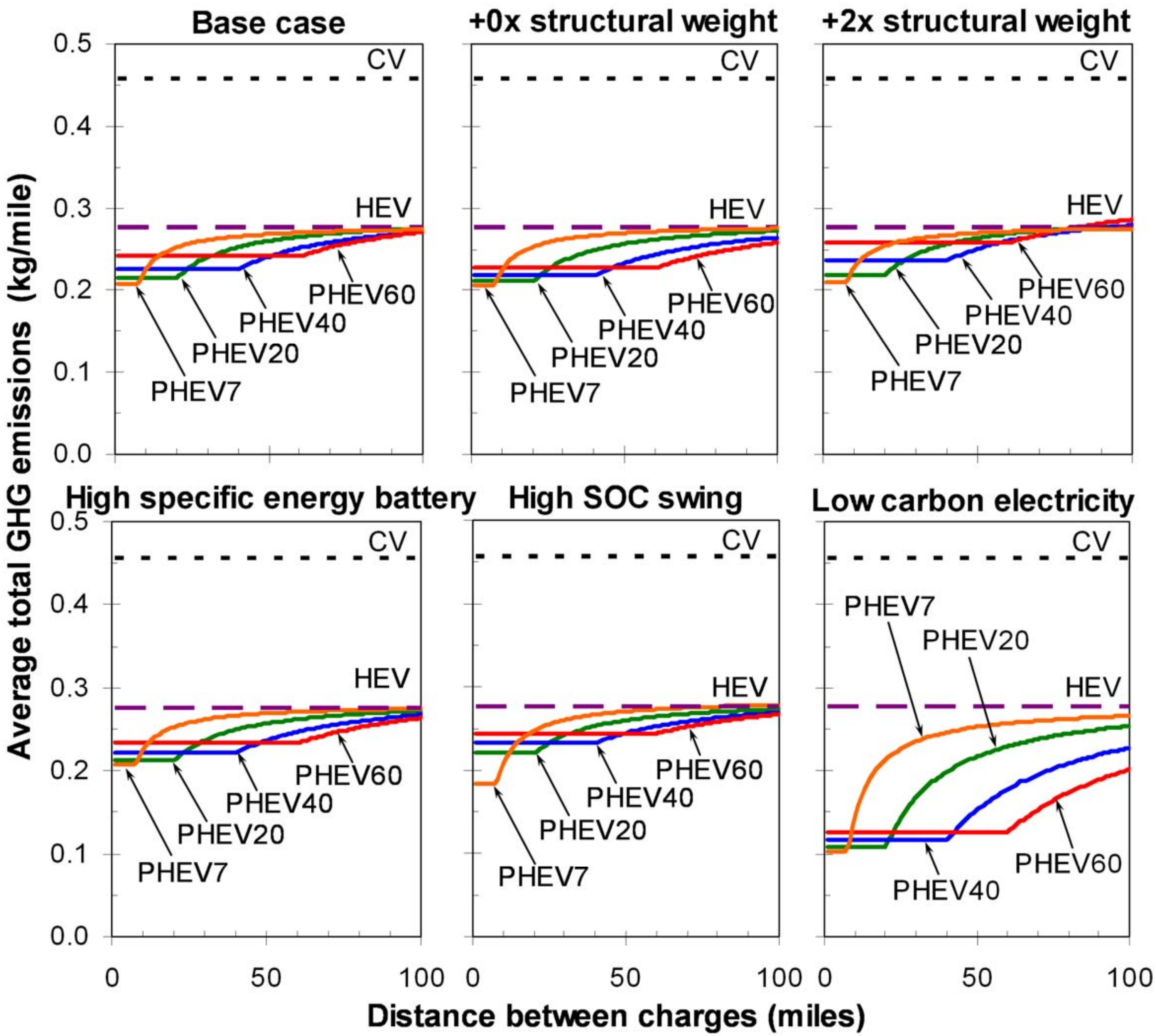
- Uncertainty in major parameters

Sensitivity analysis parameter	Unit	Low level	Base level	High level
Structural weight	–	+0 ×	+1 ×	+2 ×
Discount rate	%	0	5	10
Gas price	$/gal	1.5	3	6
Battery SOC swing	%	–	50	80
Battery specific energy	Wh/kg	–	100	140
Battery replacement frequency over life	–	–	0	1
Electricity price	$/kWh	0.06	0.11	0.30
Total battery capacity cost	$/kWh	{250,500}	1000	–
CO_2 lifecycle emissions in electricity	kg/kWh	0.218	0.730	–
Carbon tax	$/ton	–	0	100

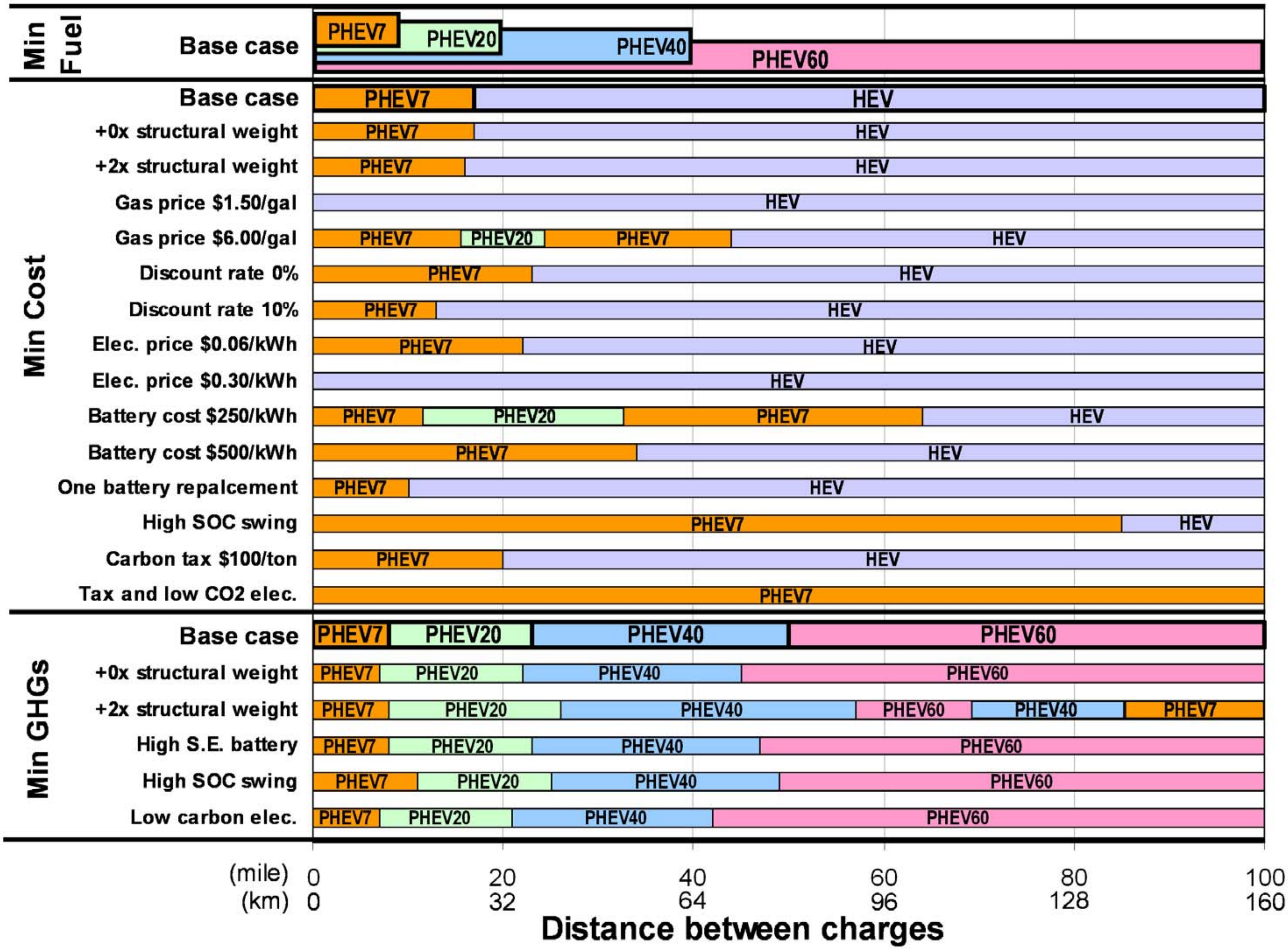
Sensitivity analysis – life cycle cost



Sensitivity analysis – life cycle GHGs



Best vehicle choice for each objective



Study summary

- **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
    - Obama's target of 1 mil. PHEVs on the road by 2015
    - Charging infrastructure

Research direction

1. **Battery Degradation:** Integrate battery degradation studies and battery HVAC systems
2. **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
3. **Consumer Preferences:** Willingness to pay for PHEV attributes
4. **Infrastructure:** Assess technical, economic and environmental implications of battery charging and swapping stations

Sneak peek: optimization study

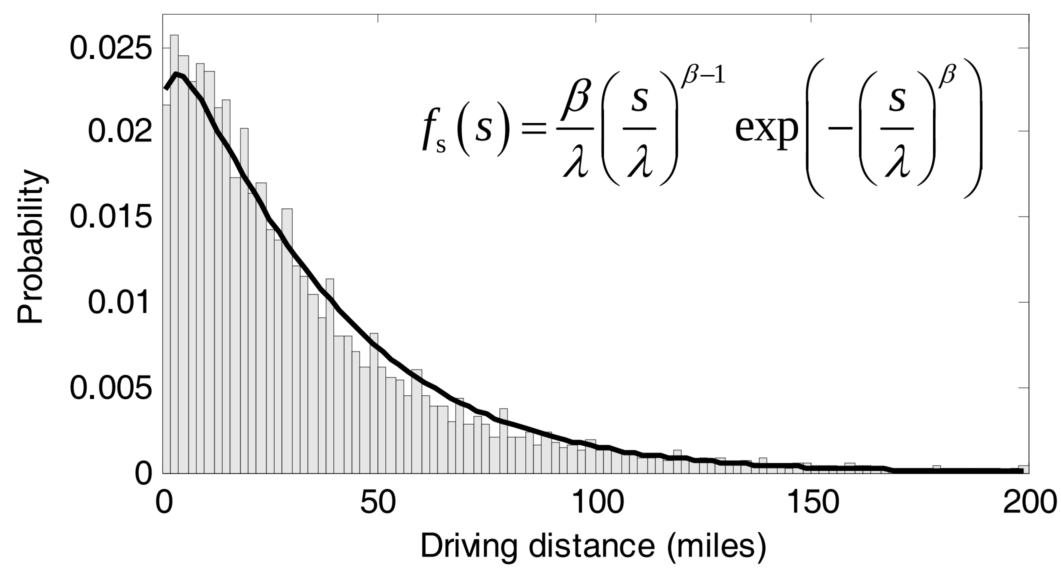
- PHEV implications depend on charging patterns
  - What is the optimal vehicle design and allocation combination for each objective?
- Approach
  - Use NHTS data for distribution of driving patterns
  - Assume: drivers travel the same distance every day and charge once per day (at night)
  - Determine vehicle design parameters (motor, engine, battery size) and allocation of vehicles to drivers to minimize net…
    1. cost
    2. GHGs
    3. oil consumption

$$\underset{\substack{\mathbf{x}_i\ \forall i \in \{1,\ldots,n\} \\ s_i\ \forall i \in \{1,\ldots,n-1\}}}{\text{minimize}} \sum_{i=0}^{n-1} \left(\int_{s_i}^{s_{i+1}} \tilde{s} f\left(\mathbf{x}_i, \tilde{s}\right) f_s\left(\tilde{s}\right) d\tilde{s} \right)$$

$$\text{subject to } \mathbf{g}\left(\mathbf{x}_i\right) \leq \mathbf{0};\ \forall i \in \{1,\ldots,n\}$$

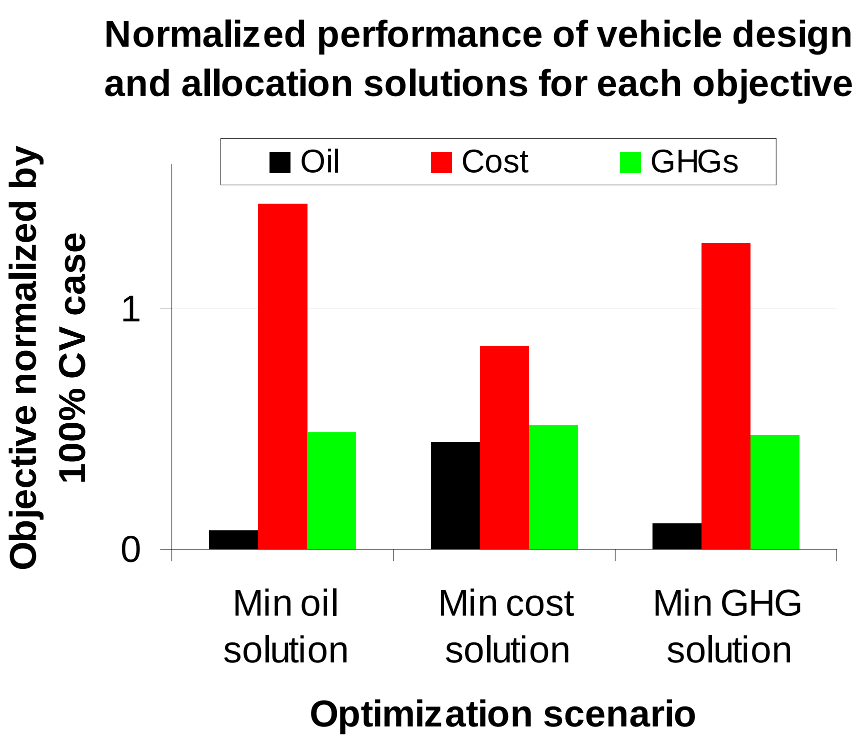
$$0 \leq s_i \leq s_{\max};\ \forall i \in \{1,\ldots,n-1\}$$

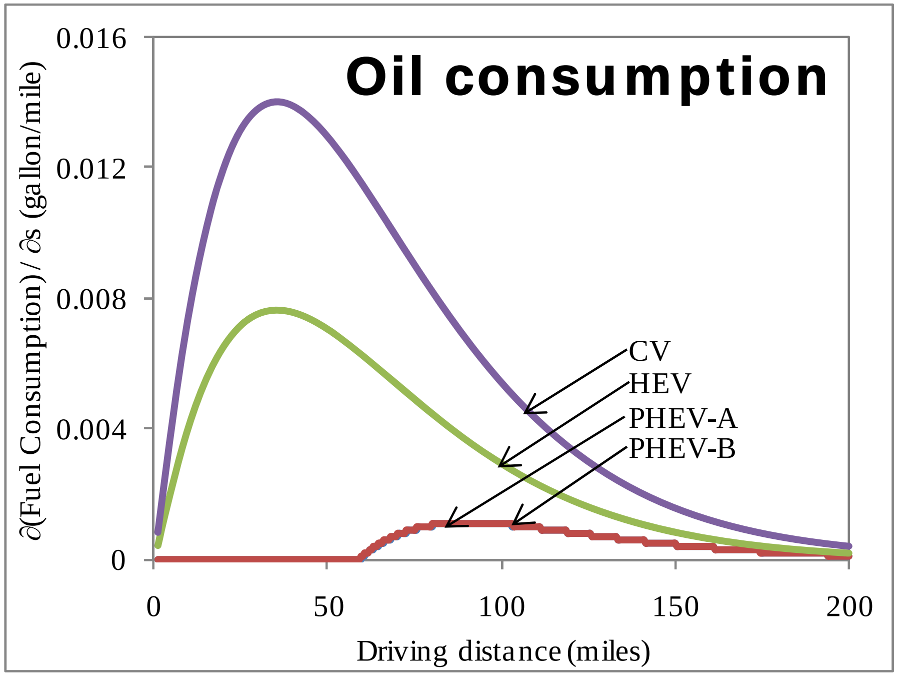
$$\text{where } s_0 = 0;\ s_n = s_{\max}$$

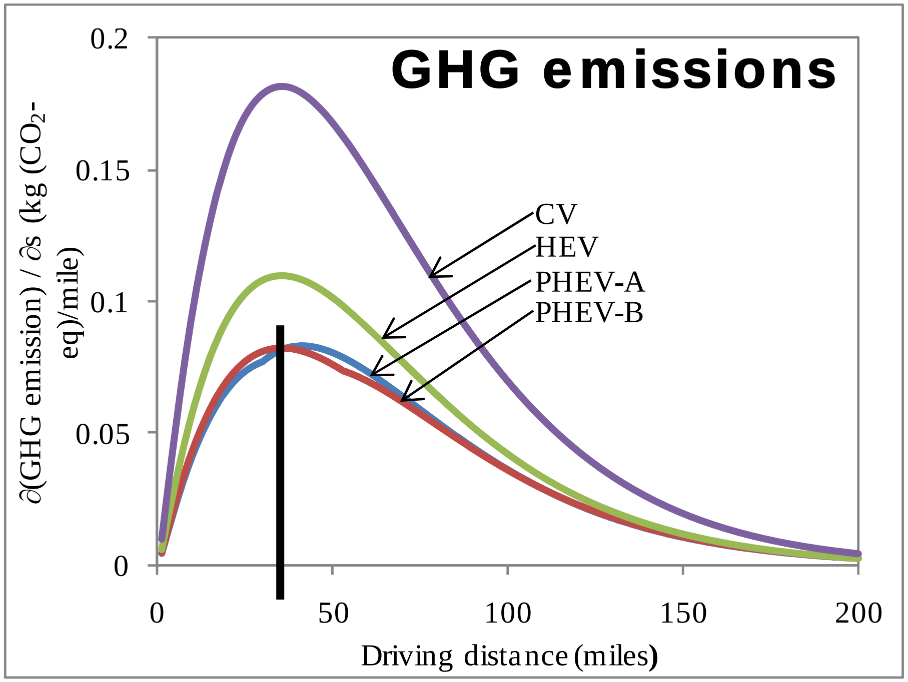


Preliminary results - base case

- Majority of savings is for shifting vehicle type
  - Good allocation is second order
- Targeting oil or GHGs only will cost more
- Targeting lifetime cost reduction may be good for oil and GHGs
- Sensitivity analysis in progress







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Questions & Discussion