SAND2014-16807PE

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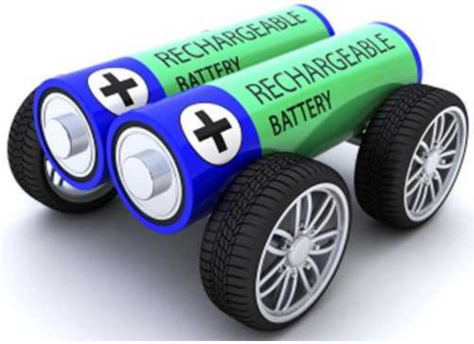

Implications of Modeling Range & Infrastructure Barriers to BEV Adoption

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July 29, 2014

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Two general approaches to modeling the limitations posed by new, alternative fuel vehicle (AFV) powertrains

- New AFV powertrains can have performance limitations (i.e. range) and/or refueling infrastructure limitations that are difficult to capture in a consumer adoption model
- **Penalty approach to modeling these effects:**
  - **Reduced utility**: compare sales rate of similar cars with key attribute differences to tease out value of attribute
  - **Stated preference studies**: consumers estimate how much they would pay for certain vehicle attributes.
  - Calculate **opportunity cost** of frequently refueling a range-limited vehicle
  - Calculate cost of using a **rental substitute** vehicle for long-range trips
- **Threshold perspective:**
  - Consumers will categorically exclude powertrains that are too inconvenient to operate- whether due to limited range, infrastructure, or other feature
  - Uses a **threshold** of **days on inconvenience** tolerated per month or per year.

This study compares BEV market share under the different perspectives of range and infrastructure limitations

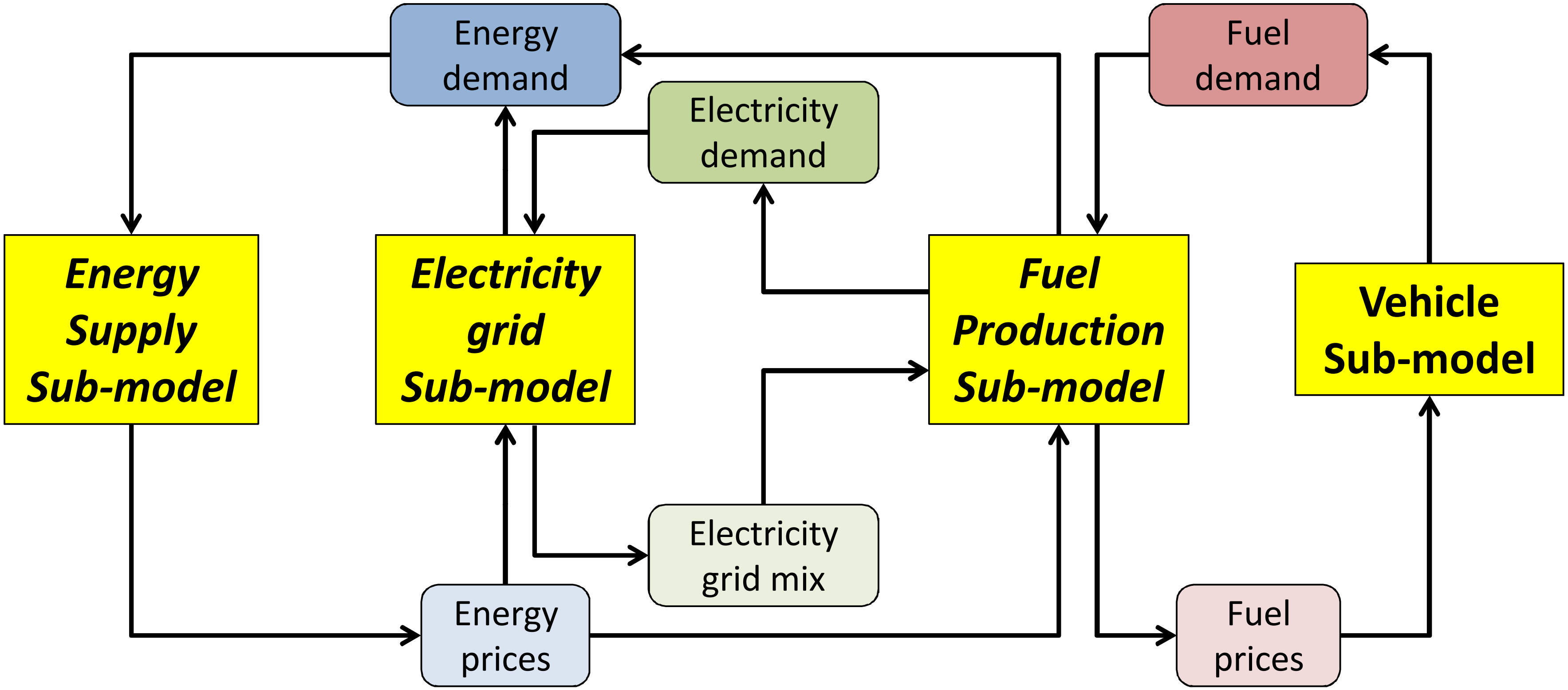
- Actual driving data is acquired to establish daily driving (trip chain) distributions

- Three different approaches to BEV limitation modeling:
  1. A detailed model of cost penalties is implemented as a option in the model
  2. Another model option is the use of hard inconvenience thresholds that excludes powertrains from consideration. A rental car must be used on inconvenienced days.
  3. A third option uses hard inconvenience threshold, but assumes that an alternative vehicle is available (trading cars within a household) for the inconvenienced days.

- A series of single scenario and parametric analyses are performed to examine the breadth of BEV adoption possibilities under the two perspectives

- Analysis assumes that current driving habits are good predictors of future driving habits, even with a completely different powertrain vehicle
  - Some research suggests this might not be true in multi-vehicle households (Kurani et. al 1996), especially in multi-vehicle households. Other researchers also make this assumption.

The analysis was conducted by a model that tracks the feedback between energy supply<-->energy carrier<-->vehicle



The model has many segments to capture the different niches of LDV consumers

Vehicle Stock Segmentation

Powertrain
SI
SI Hybrid
SI PHEV10
SI PHEV40
CI
CI Hybrid
CI PHEV10
CI PHEV40
E85 FFV
E85 FFV Hybrid
E85 FFV PHEV10
E85 FFV PHEV40
BEV75
BEV100
BEV150
BEV225
CNG
CNG Hybrid
CNG Bi-fuel

Housing type
- Single family home without NG
- Single family home with NG
- Other

VMT Segmentation

State
48 CONUS +
Washington, DC

Density
Urban
Suburban
Rural

Size
Compact
Midsize
Small SUV
Large SUV
Pickup

Age
0-46 years

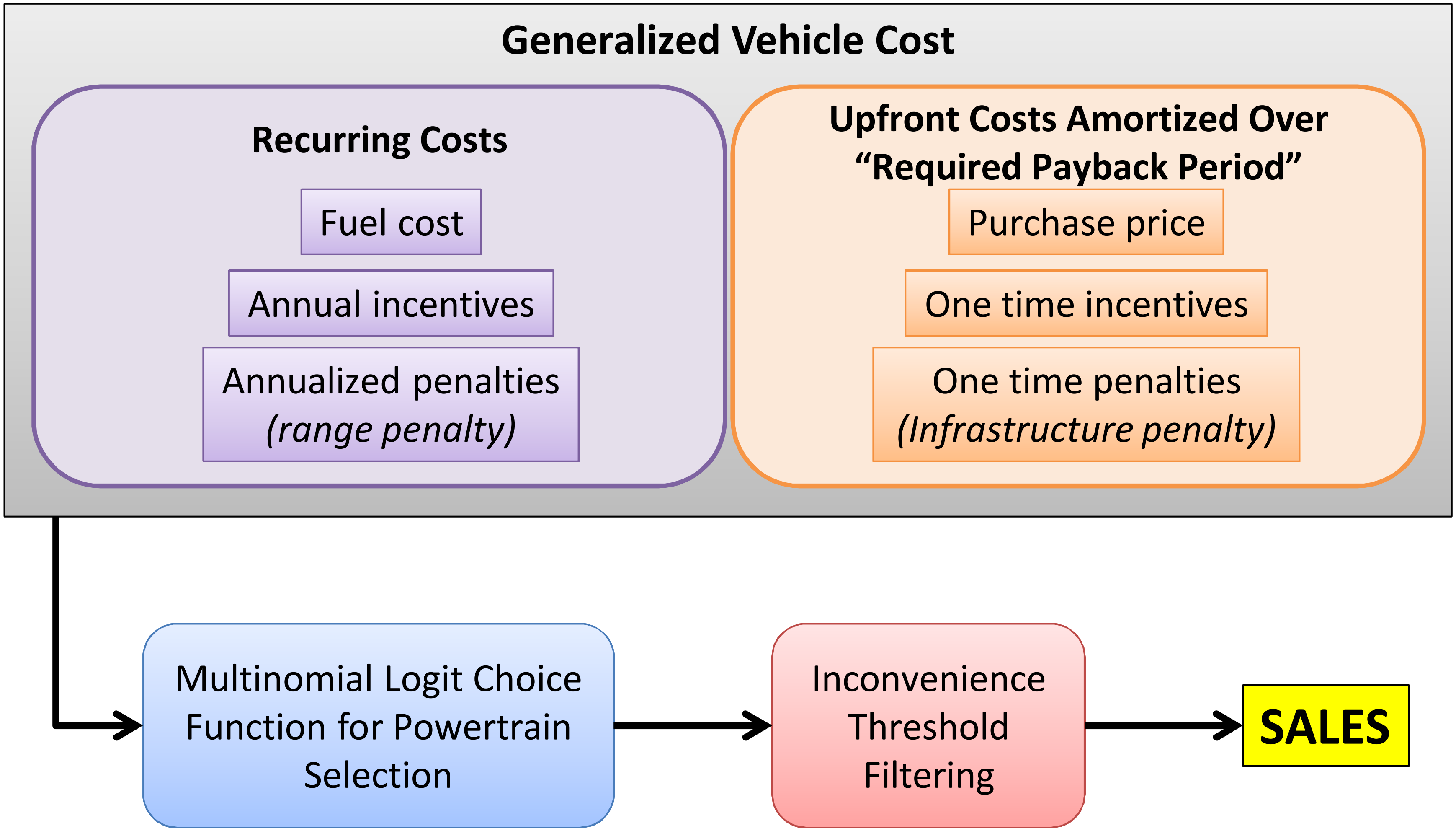
Driver Intensity
High
Medium
Low

Geography
Vehicle
Demographics

Fuels
Gasoline
Diesel
Biodiesel
Ethanol
Electricity
CNG

Energy Sources
Petroleum
Natural Gas
Coal
Biomass
Solar/Wind

A multinomial logit choice function assigns consumer purchase shares based on price sensitivity to a generalized cost



Penalty and inconvenience threshold definitions

Range penalties

- Applied to annual/recurring costs (like fuel)
- Rental car substitution *[applied to both Penalty and Threshold-Rental approaches]*
  - Determine number of days per year inconvenienced by limited range, limited refueling infrastructure vehicle
  - Multiply inconvenienced days by daily cost of a rental car (~$41/day)
- Time spent refueling (Greene) *[applied to Penalty approach only]*
  - Compute total time spent refueling over a year, multiply by dollar value of time
  - Does not penalize time spent wholly or partially refueling/recharging at home

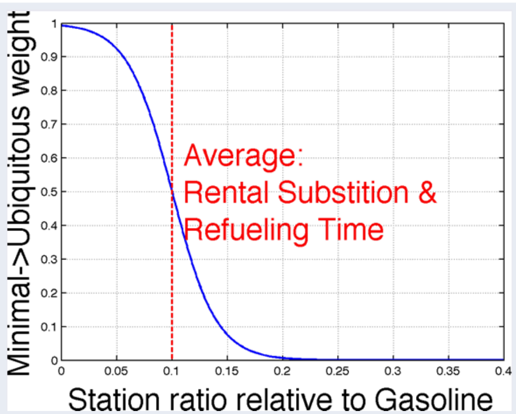
Infrastructure penalty (Greene) *[applied to Penalty approach only]*

- Applied to non-recurring, upfront purchase costs
- Decaying exponential based on refueling station density relative to gasoline
  - Varies with state, population density, powertrain-fuel combination
- Heavily reduced for those that can recharge/refuel at home

Inconvenience Threshold *[applied to Threshold-Rental & Threshold-Household approaches]*

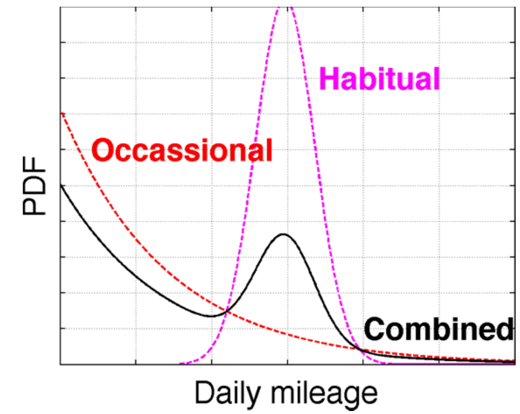
- Default limit of 2 days/inconvenience per month (limit is parameterized)

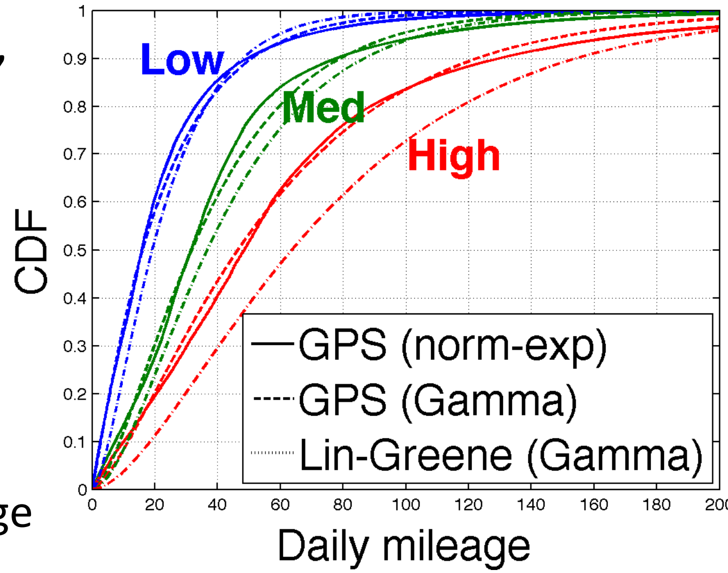
The range penalty added to the generalized purchase price varies with the availability of infrastructure

	Cost Penalties	Inconvenience Threshold
Minimal Infrastructure	1. Infrastructure density penalty (Greene); 2. Rental car substitute for home recharged vehicles on long trips	1. No infrastructure penalty *2. Threshold-Rental only*: Rental car substitute cost for <N days/month inconvenience; Vehicle **EXCLUDED** if it requires rental car substitution >N days/month.
(time, investment) ↓	Logistic blending based on fraction of fueling stations with alternative fuel 	(no change)
Ubiquitous Infrastructure	1. Infrastructure density penalty (Greene); 2. Value of time spent refueling (Greene), not counting home refueling/recharging	No change **Public recharging not considered quick or convenient.**

Actual GPS trip chain data was used to drive the analysis

- Use of GPS trip chain data to assess limitations of vehicle range proposed by Pearre et al (2011)
- Ford researchers fit distributions to GPS recorded driving data of Atlanta, Minneapolis and Puget Sound vehicles, i:
  - $f_i(x) = (w_i/k_i)*\exp[-x/k_i] + (1-w_i)*N(x; \mu_i, \sigma_i)$
- Ensembles of f(x) were binned into High, Medium, Low mileage intensity and then recast as Gamma distributions
  - Ensemble weighting to preserve inconvenience: $g(x)=\Sigma\lambda_i f_i(x)/\Sigma\lambda_i$ (λ_i is fraction of days driving)
- For simplicity, the Gamma distributions were adopted for calculation of:
  - Number of days where driving exceeds vehicle range
  - Fraction of miles electrified by PHEVs
  - Number of public refuels/recharges per year (using VMT too)

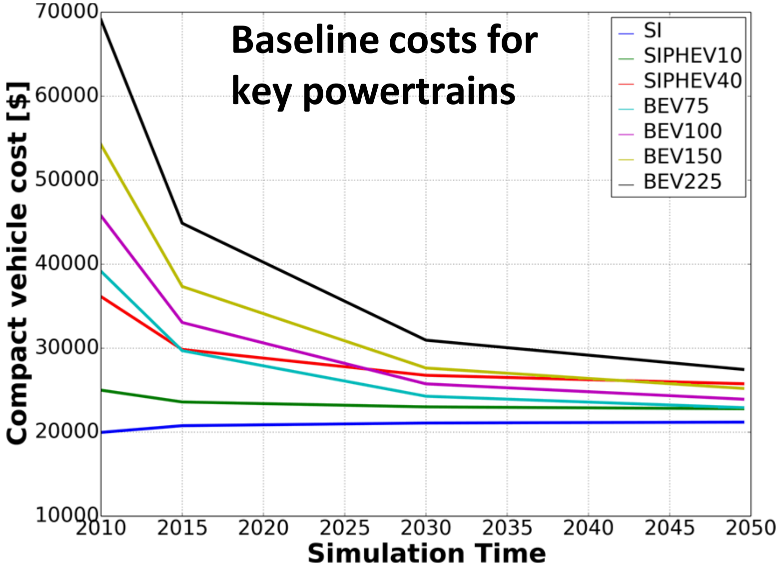


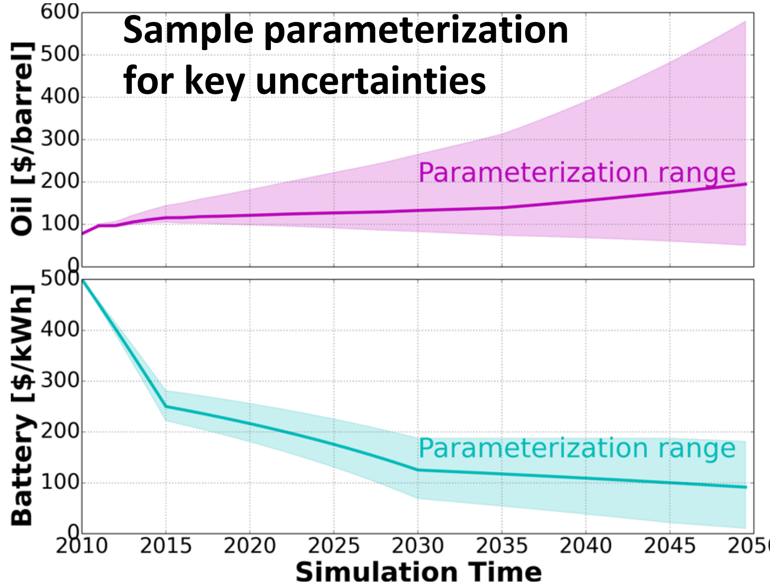


- High intensity drivers still travel less than 20 miles in a day 20% of the time.
- Low intensity drivers go beyond 100 miles in a day a number of times per year.

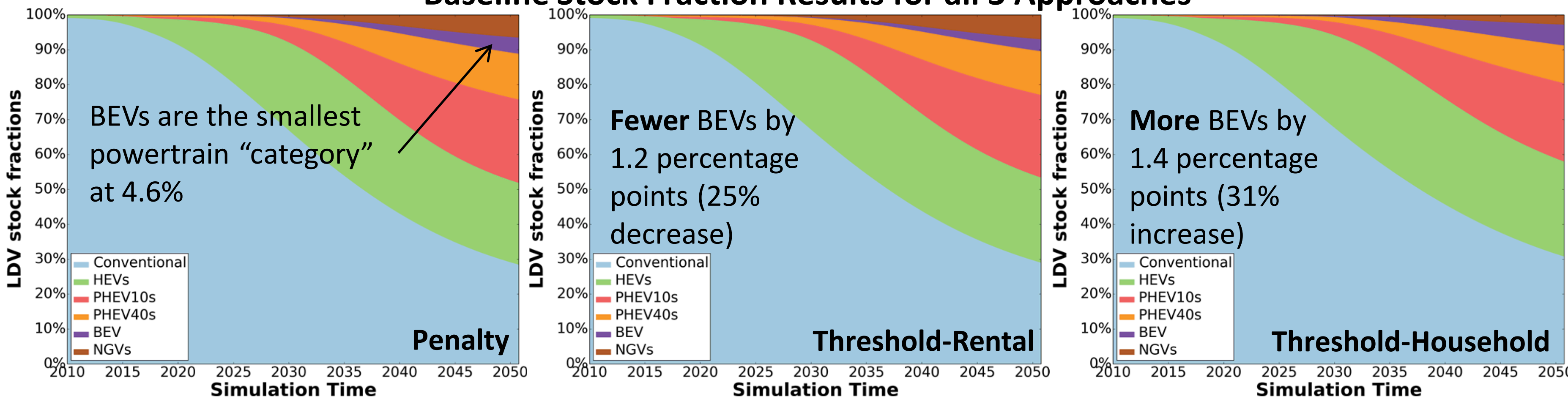
ANALYSIS RESULTS

Baseline model assumptions show up to 5% market share for BEVs, the smallest of all powertrain "categories"



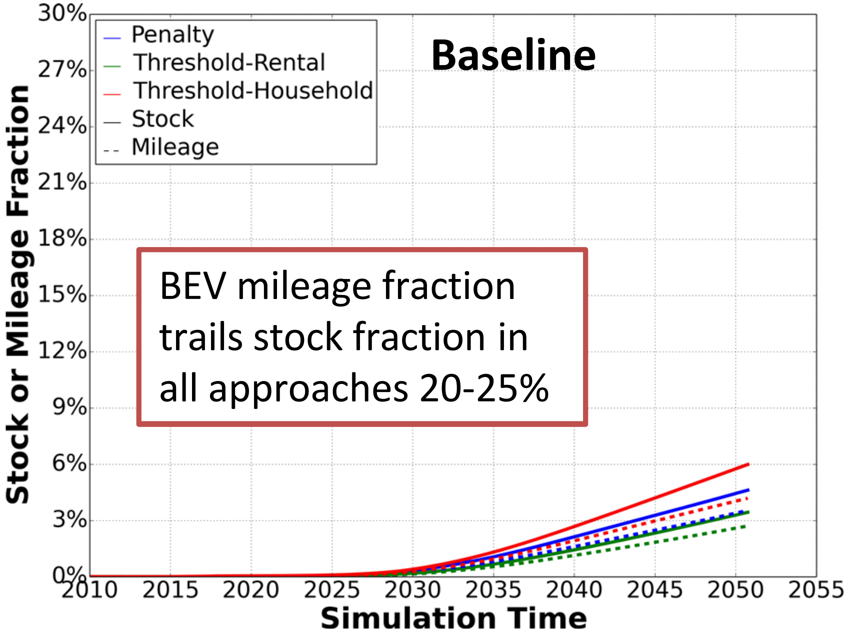


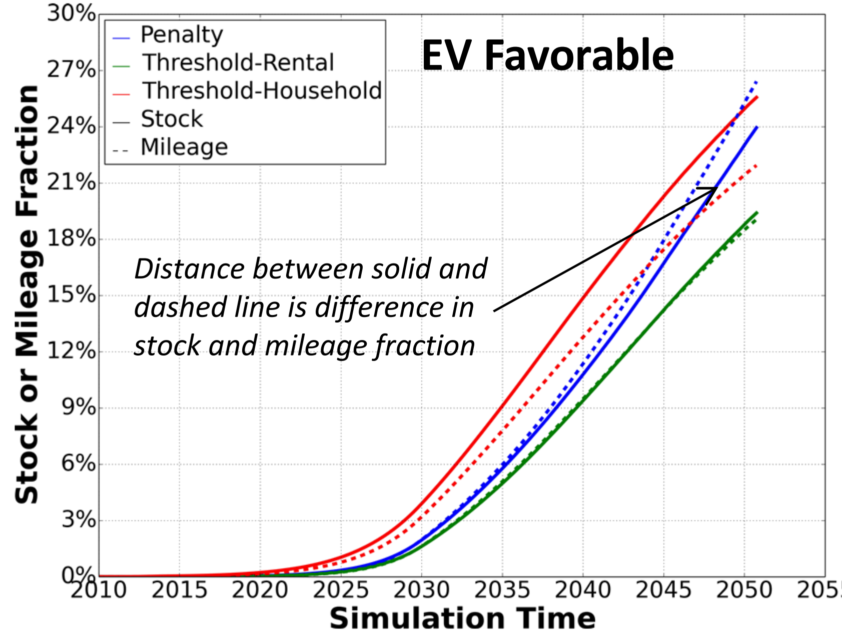
Baseline Stock Fraction Results for all 3 Approaches



Electrified mileage fraction traveled by BEVs trails the stock fraction, even with extremely favorable EV ownership economics

- Fraction of all LDV miles traveled by BEVs trails stock fraction by 20-25% due to:
  - Use of substitute rental or household vehicle for long range trips
  - Likely skewed adoption towards Low and Medium intensity drivers
- In a favorable EV ownership scenario* only the Penalty approach has BEV mileage fraction outpacing the stock fraction
  - Due to the transition of the range penalty from rental substitution to time spent using public fast charging since BEV adoption is more ubiquitous





Favorable EV economics: 1. Cheap batteries (90% lower by 2050) 2. Expensive oil (50% higher by 2050) 3. 9 year payback period

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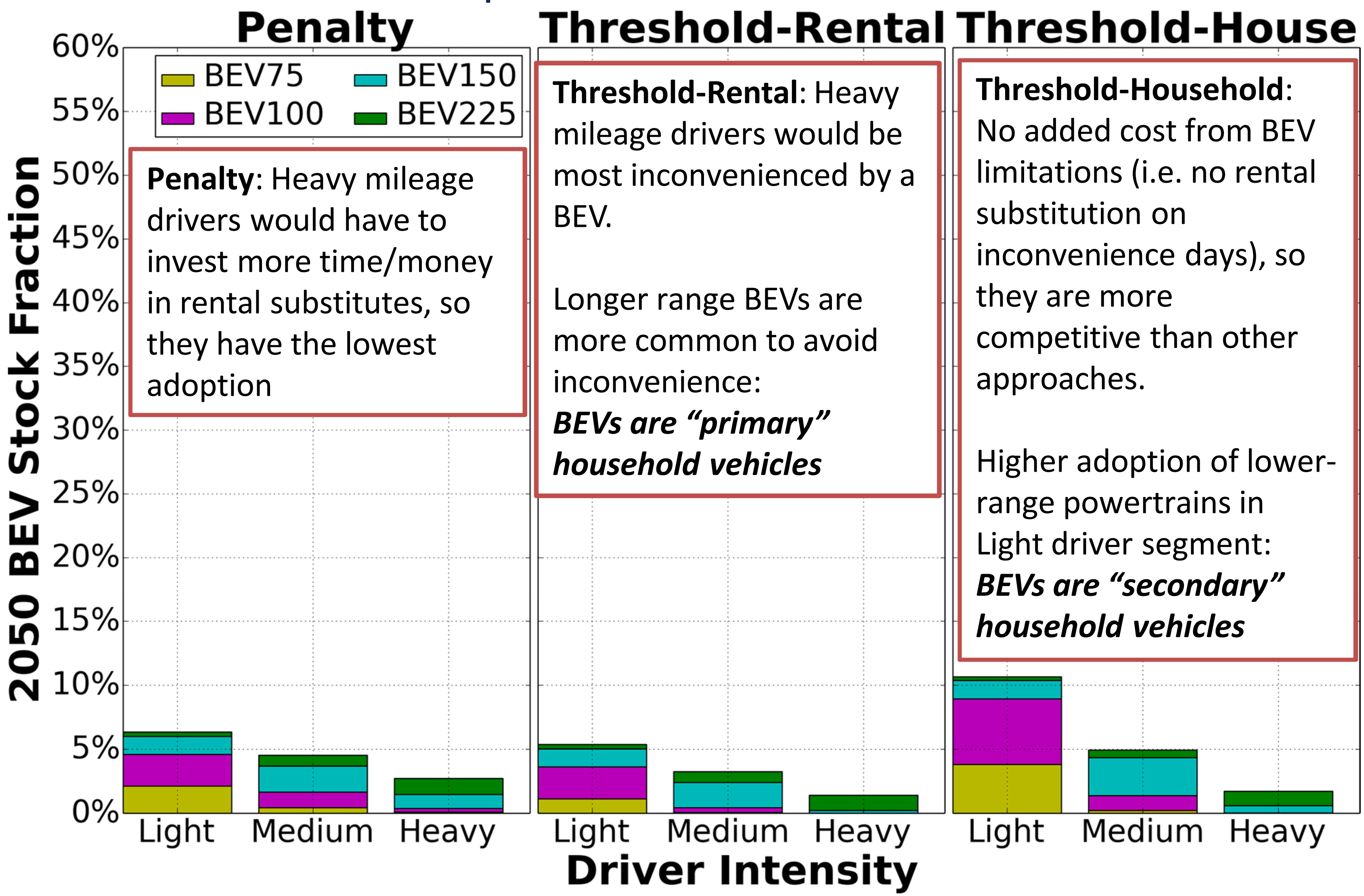
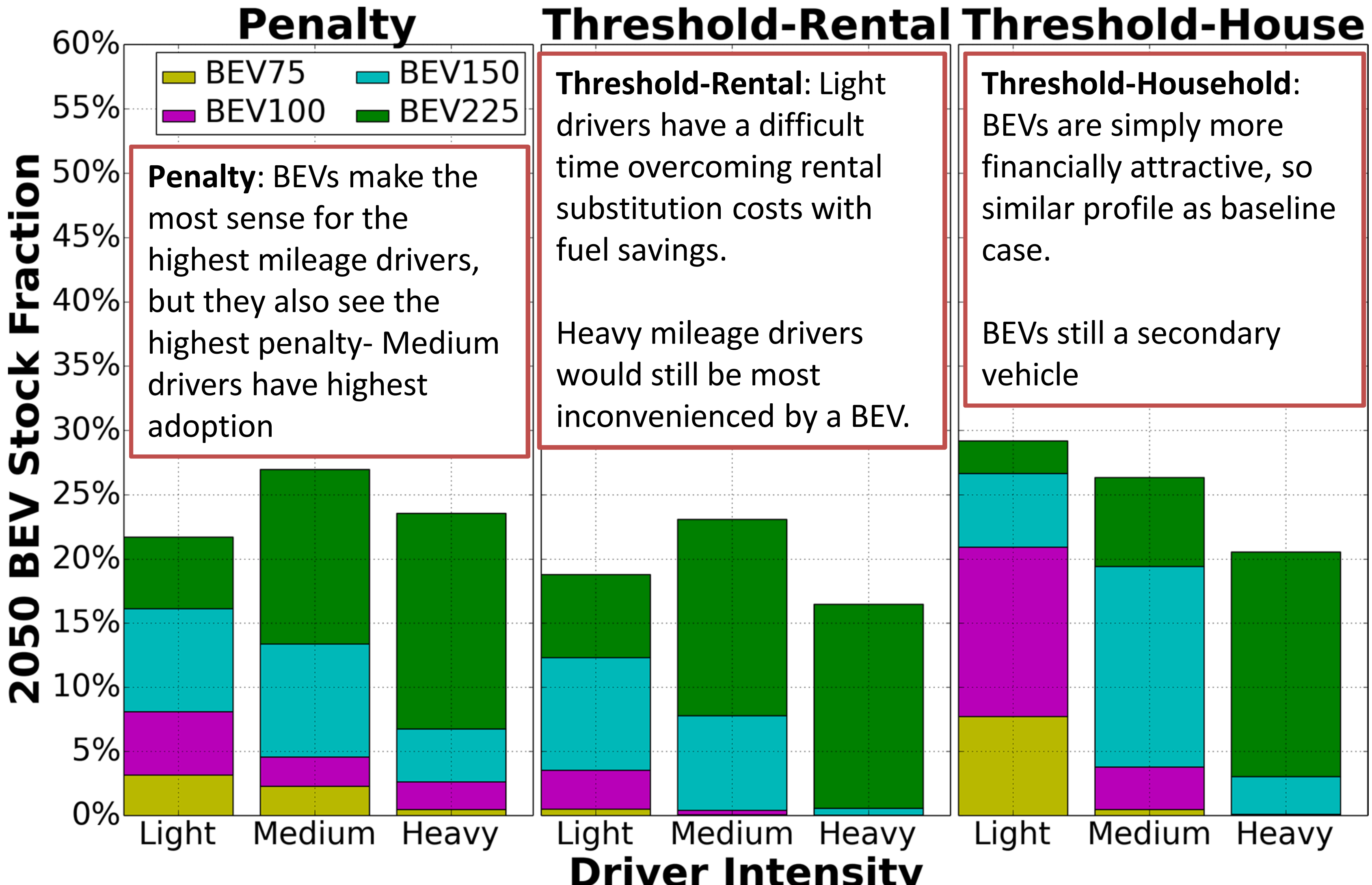
Can investigate which types of drivers buy which types of BEVs under baseline assumptions



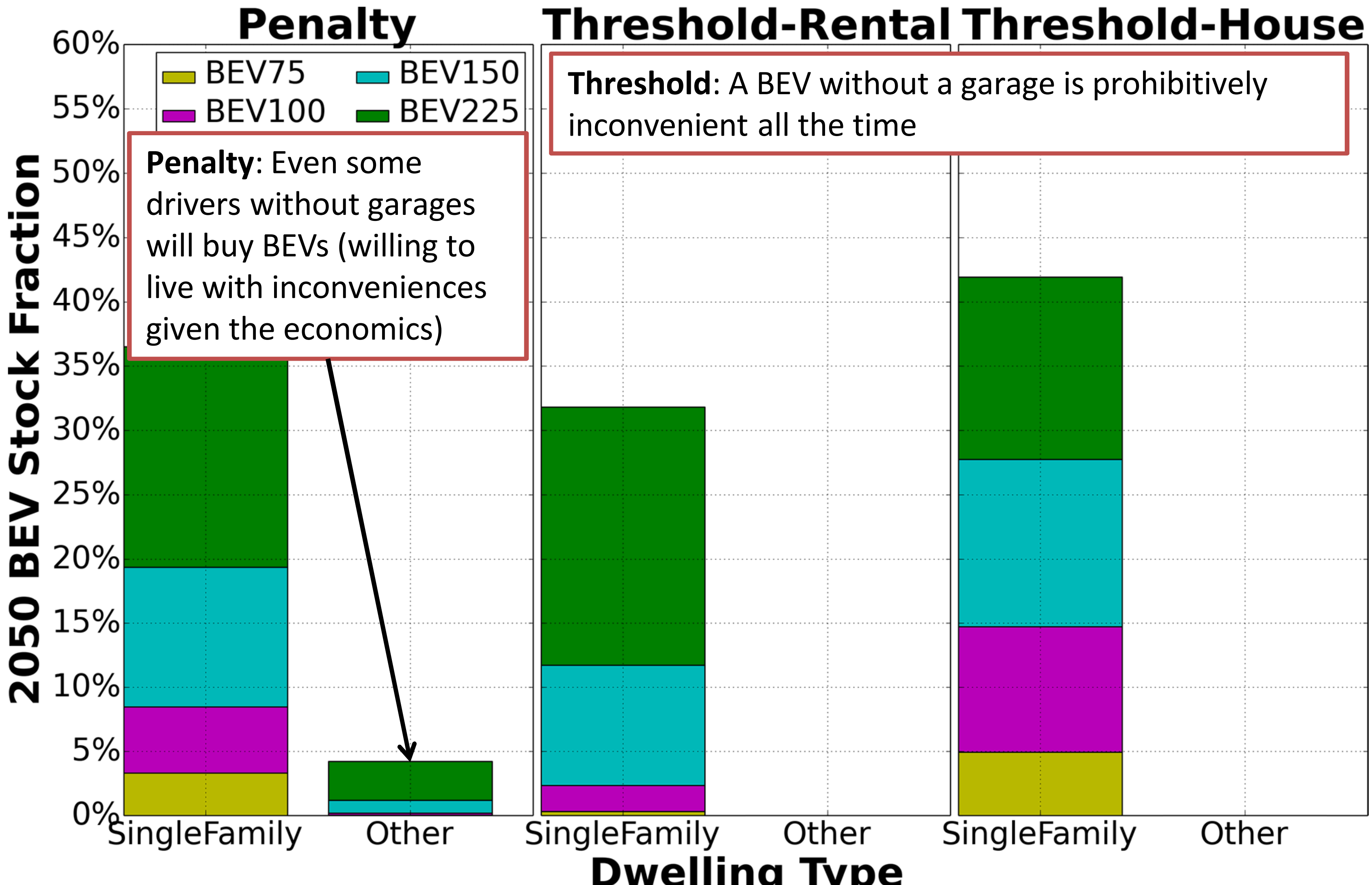
BEVs generally suffer both from being **expensive vehicles** in their own right and the **additional range/infrastructure limitations** imposed upon them in a choice model.

Under favorable EV economics, can see some different consumer choice dynamics at play compared to the baseline



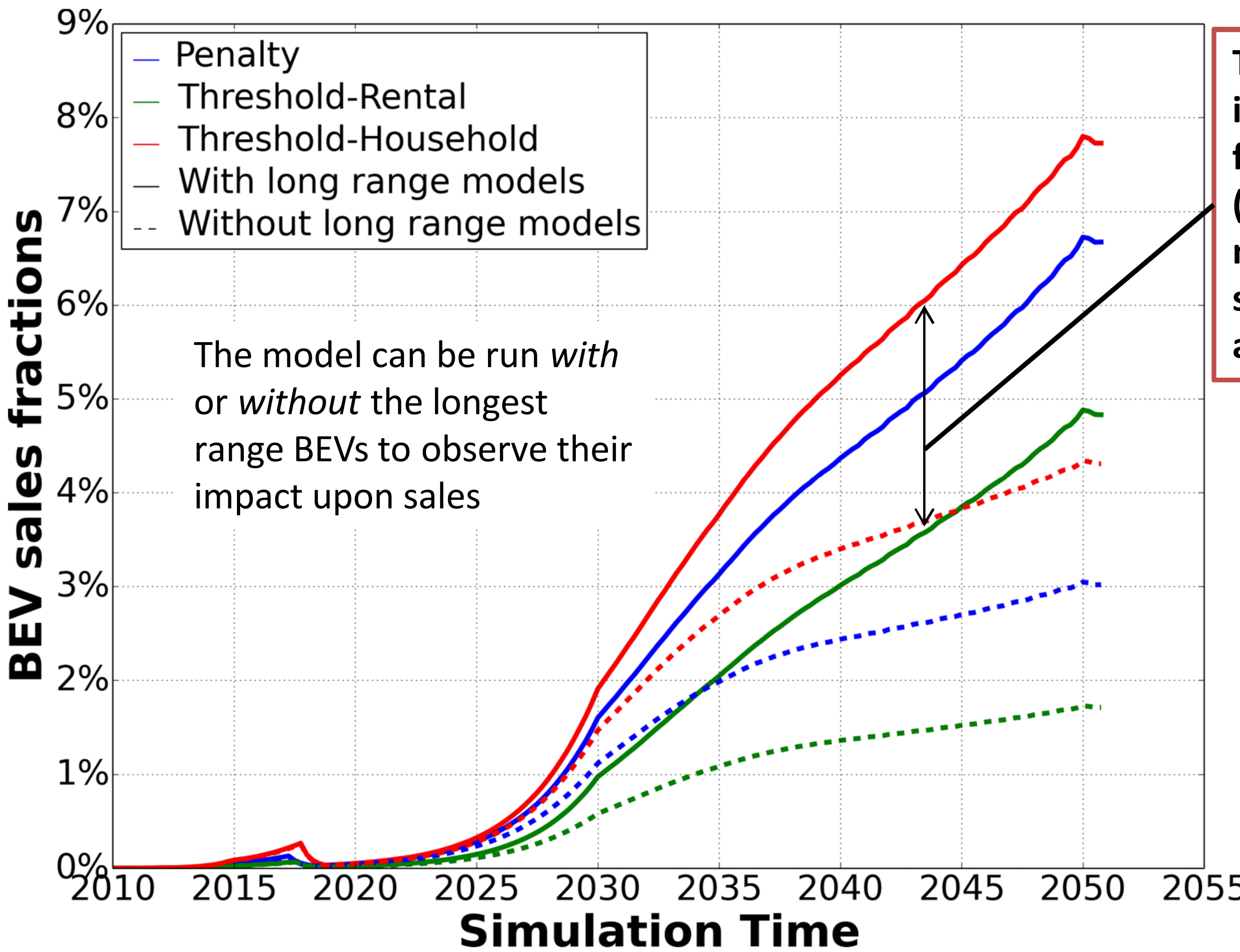
**Favorable EV economics*: 1. Cheap batteries (90% lower) 2. Expensive oil (50% higher) 3. 9 year payback period 4. No CNG vehicles

Under favorable EV economics, the Penalty approach can lead to some ostensibly nonsensical results



**Favorable EV economics*: 1. Cheap batteries (90% lower) 2. Expensive oil (50% higher) 3. 9 year payback period 4. No CNG vehicles

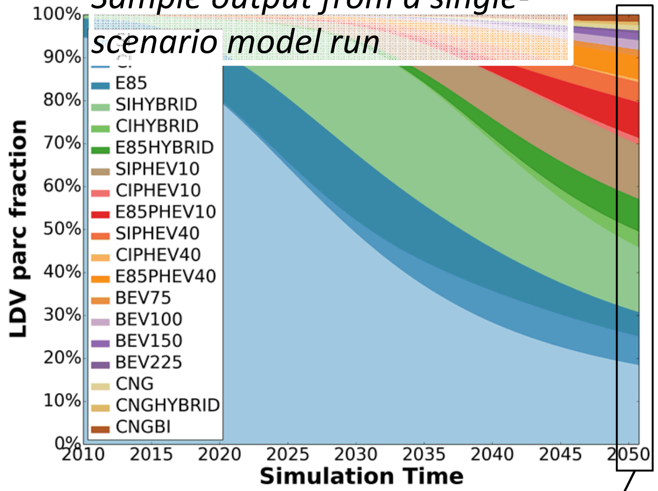
The longest range BEVs are critical to overcoming barriers and increasing BEV market share (the “Tesla” impact)



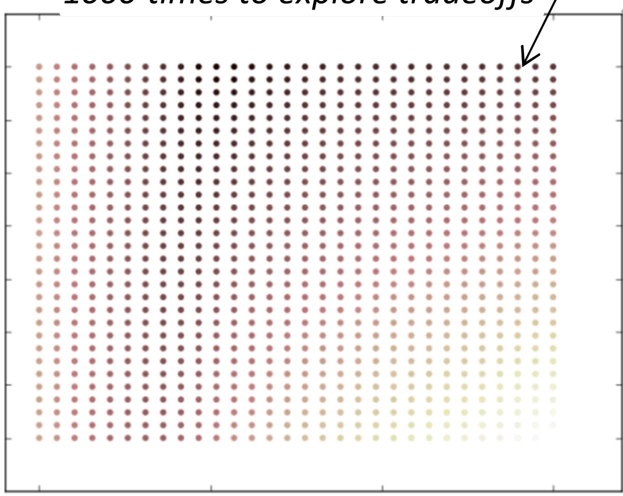
The 150mi and 225mi BEVs in the mix are responsible for 40-60% of BEV sales (and 40-50% of BEV mileage which is not shown) in all modeling approaches

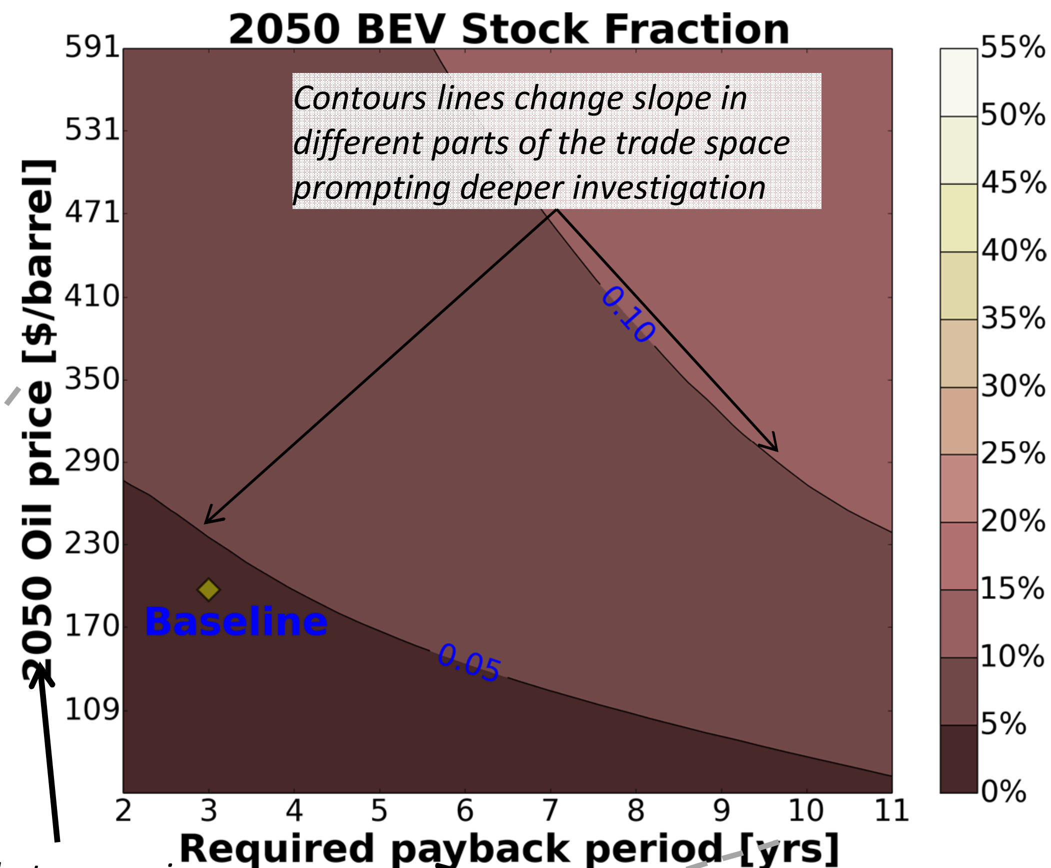
Example results: Parametric studies focus on one, two, and all parameter variations to explore the trade space

Sample output from a single-scenario model run



Parameter space is sampled 1000 times to explore tradeoffs





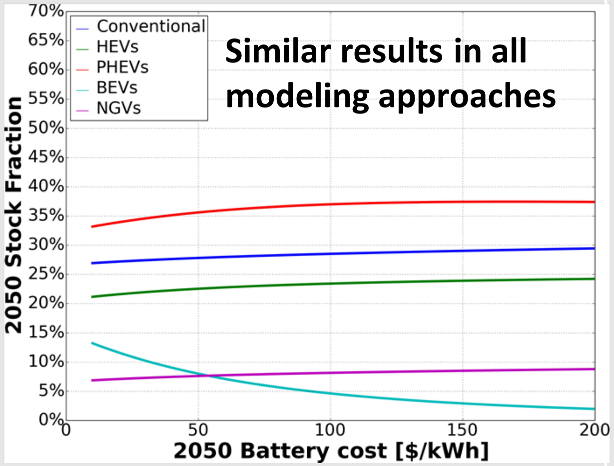
Contours lines change slope in different parts of the trade space prompting deeper investigation

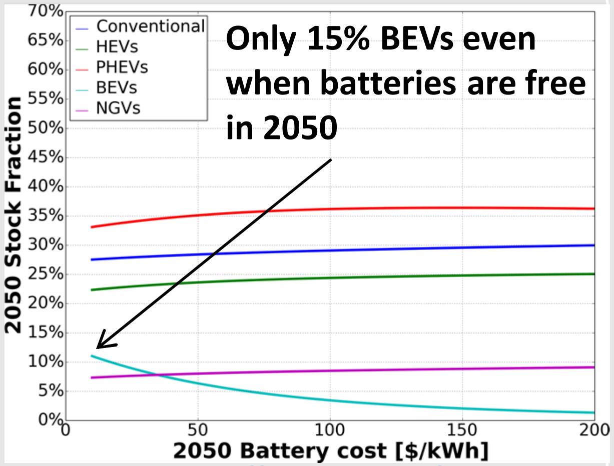
Tradeoff between price uncertainty and market incentives

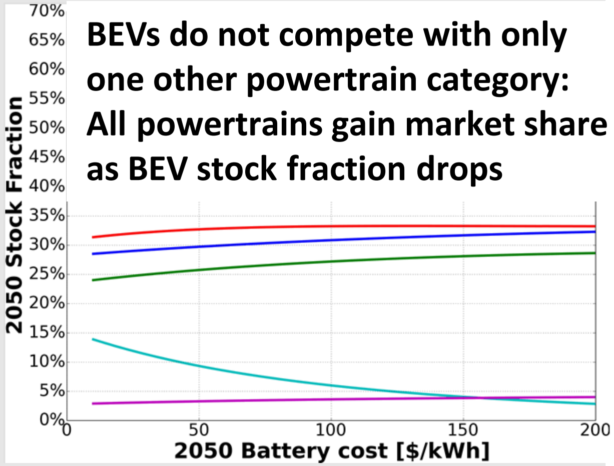
Contour features reveal trade-space insights

Baseline model assumptions show up to 5% market share for BEVs, the smallest of all powertrain “categories”

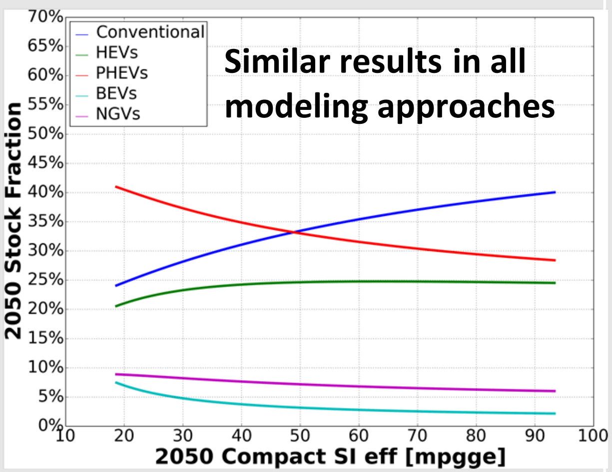
Penalty	Threshold-Rental	Threshold-Household

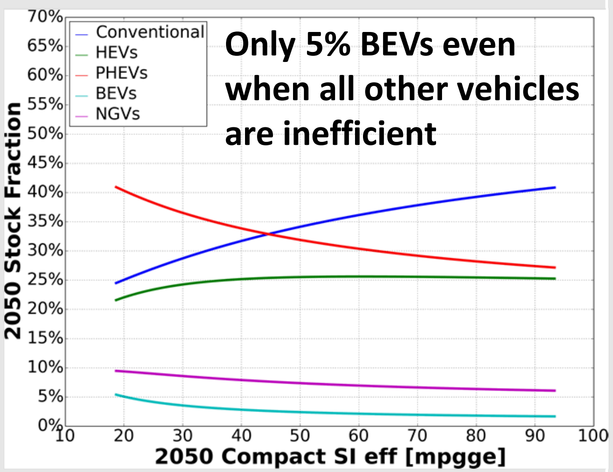


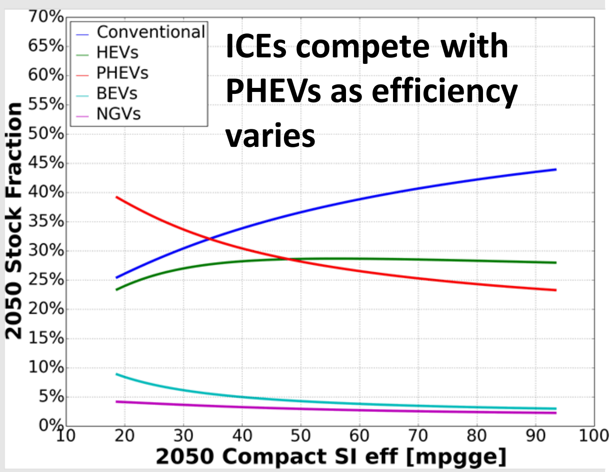




Parametrically varying battery cost



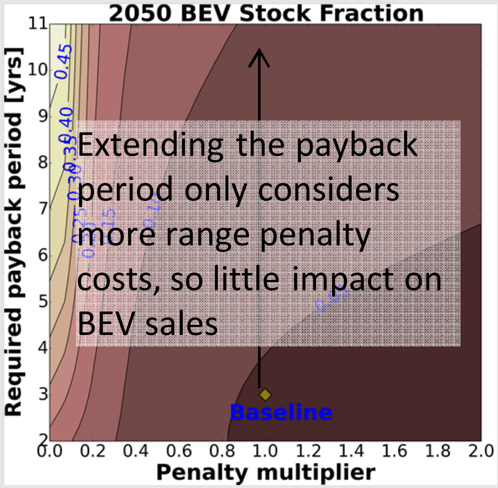


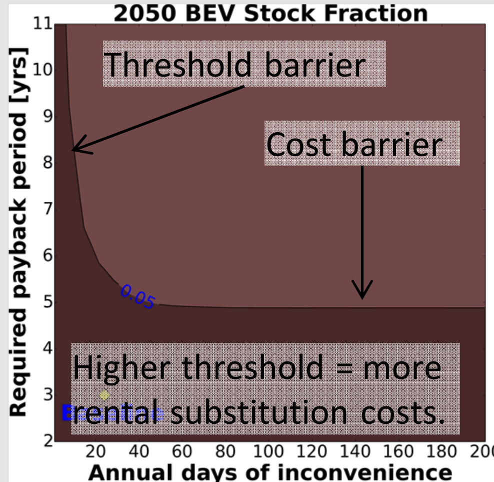


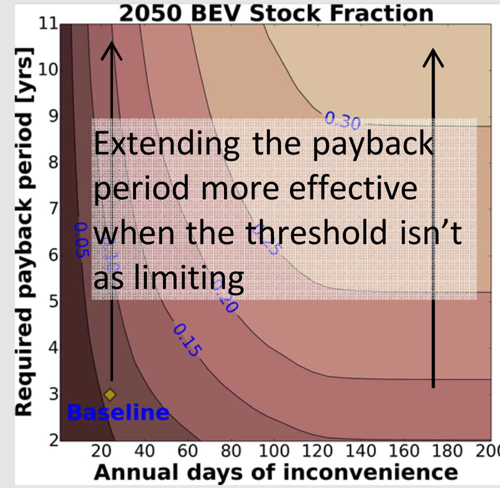
Parametrically varying ICE efficiency performance

Alleviating the non-cost barriers can significantly increase BEV adoption, but BEV mileage fraction can stagnate

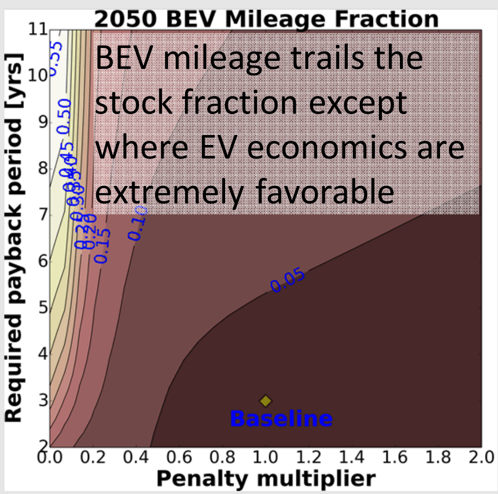
Penalty	Threshold-Rental	Threshold-Household

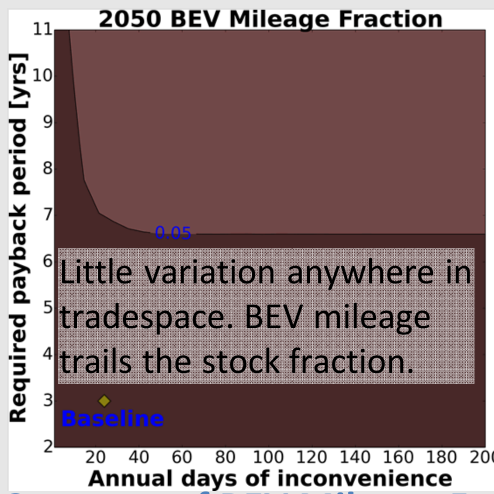


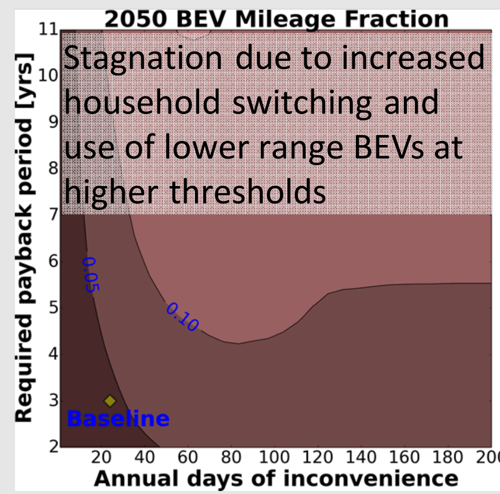




Contours of BEV Stock Fraction



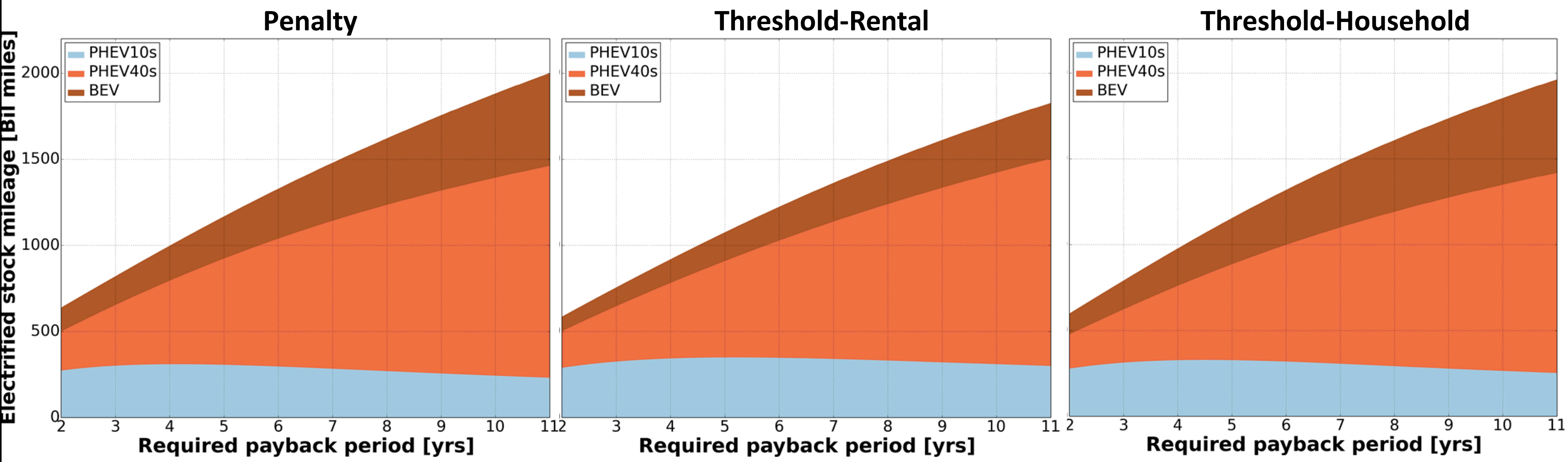




Contours of BEV Mileage Fraction

Most electrified mileage is contributed by PHEVs, not BEVs

- Increasing payback period through incentives or informational campaigns does not impact BEV sales much (see previous slide) due to the non-cost barriers, but it can significantly increase PHEV sales
- PHEVs contribute more electrified mileage than BEVs
- If electrifying miles traveled by US LDVs is a goal, then incentivizing PHEVs might be more effective than incentivizing BEVs



Key observations

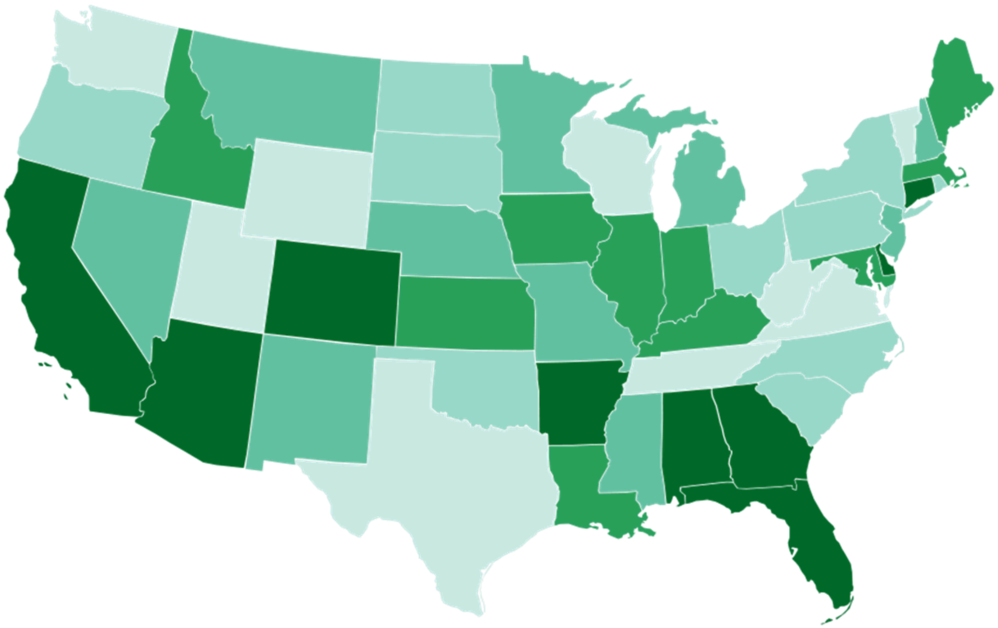
- Under baseline assumptions, BEV powertrains are only expected to be ~5% of the LDV vehicle stock in 2050, regardless of penalty/threshold perspective
  - Under some extreme parameter values, the Penalty approach can yield unrealistic results (i.e. consumers in apartment buildings buying BEVs)
- Longer range BEVs may play role as *primary* household vehicle while shorter range BEVs are *secondary* household vehicles.
- The policy levers that could be applied to promote BEVs would be different for the different perspectives
  - Penalty: Financial incentives and public infrastructure investment are most effective
  - Threshold: Incentives help, but have to introduce longer range BEVs (like the Tesla)
- Technology investment to reduce battery costs are not enough- investments must address the non-cost barriers to BEV adoption
  - Allowing for household-switching of vehicles to avoid BEV limitations can have a significant impact on expected adoption rates
  - Introducing 200-300 mile range BEVs doubles sales projections
  - Extended range BEV technology (BEVx) is projected to be successful by this analysis
- BEV mileage fraction consistently trailed stock fraction in all results.
  - Replacing a gasoline vehicle with a BEV does not reduce GHGs as much as one might think

PARKING LOT

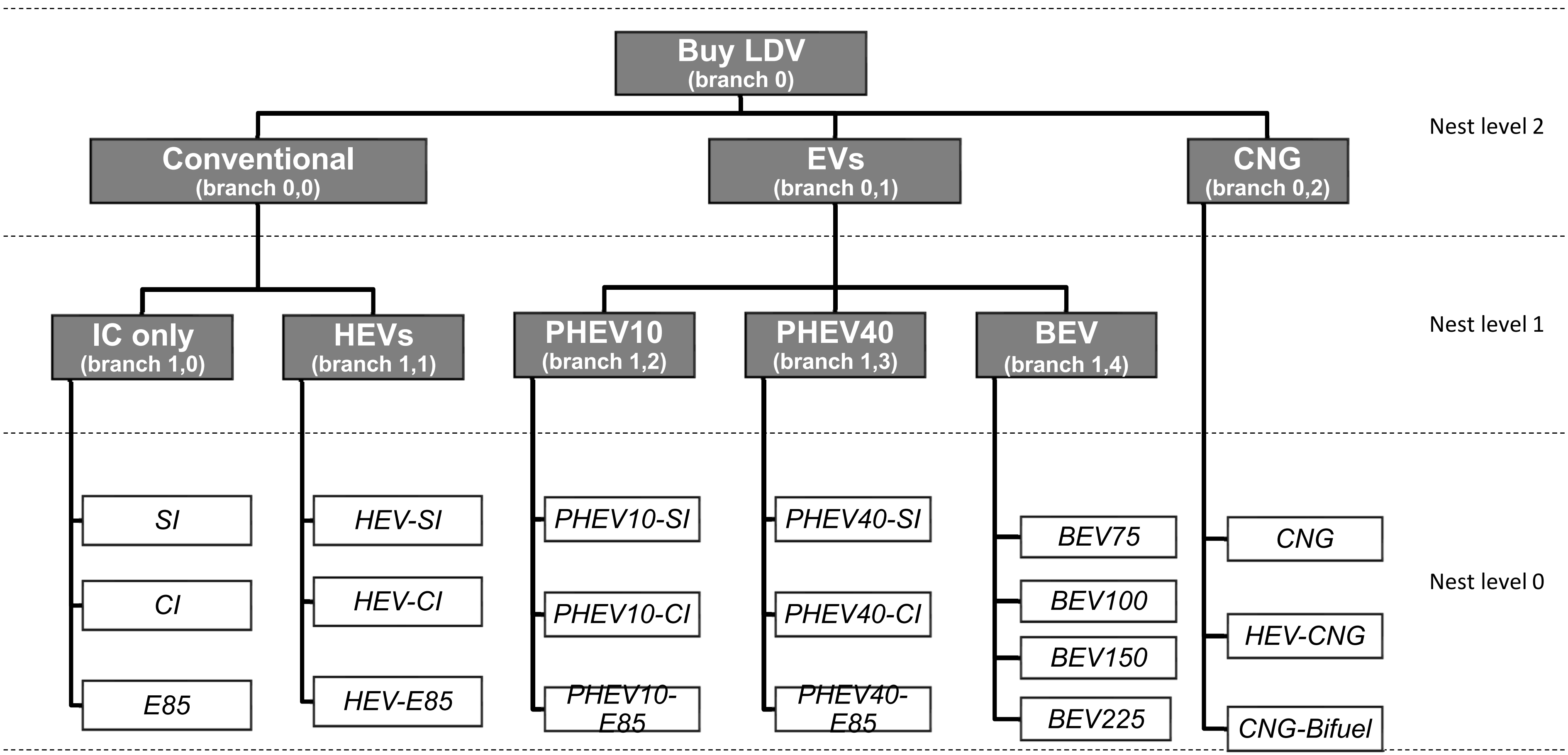
Energy supplies, fuels, and vehicle mixes vary by state

State-level Variations

- Vehicles
  - Numbers, sizes, drive-train mixes
- Driver demographics
  - VMT intensity, urban-suburban-rural divisions, single-family home rates
- Fuels
  - Costs, electricity mix, taxes & fees, alternative fuel infrastructure
- Energy supply curves (as appropriate)
  - Biomass, natural gas
- Policy
  - Consumer subsidies and incentives



New BEV powertrains are nested together in the choice model



Model inputs are taken from published sources when possible; assumptions are listed for review

Energy sources

- Oil: Global price from EIA Annual Energy Outlook (2012)
- Coal: National price from EIA Annual Energy Outlook (2012)
- NG: Regional price from EIA Annual Energy Outlook (2012)
  - Also use differential prices for industrial, power, and residential uses
- Biomass: State supply curves from ORNL's Billion Ton Study
  - Price corrected to match current feedstock markets

Fuel conversion and distribution

- Conversion costs and GHG emissions derived from ANL GREET model
- RFS grain mandate is satisfied first, then cellulosic (but not enforced)
  - Gasohol blendstock allowed to rise from E10 to E15
- Ethanol can be transported from one region to another for cost or supply balance
- Electricity grid
  - State-based electricity mix, allowed to evolve according to population growth and energy costs
  - Intermittent and "always-on" sources assumed to supply base load first
  - Vehicles assumed to be supplied by marginal mix

Model inputs are taken from published sources when possible; assumptions are listed for review

Vehicle model

- Consumers do not change vehicle class (size)
- VMT varies by model segmentation, but does not change over time
- LDV stock growth rate is the same as population growth rate (per capita vehicles is constant)
- Consumers have baseline 3 year payback period with no discounting
- Vehicle efficiency, cost, and battery capacity taken from ANL *Autonomie* model analysis
- CAFE requirements are satisfied
- Consumer choice model is nested, multinomial logit type, like MA3T and NEMS
  - Sale shares depend on amortized consumer *utility cost* = vehicle purchase price – subsidies + fuel operating costs + penalties (range and fuel availability)
- Bi-fuel vehicles (E85 FFVs, diesel vehicles, and CNG bi-fuel vehicle) dynamically choose fuel use rate breakdown using:

(Probability of visiting a station with CNG) * (Willing-to-pay price premium)

Changes as new pumps are added in response to vehicle sales

Responds to market conditions (price sensitivity is parameterized)