What Electric Ranges Consumers May Choose? –- An Optimization Approach

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Electric range optimization—a relevant concept for product strategy and policy analysis

- Why electric range (ER) optimization?
  - More realistic
- How?
  - Start with “what ER would consumers choose if given full choice flexibility?”
  - Electric range (decision variable); range cost (objective value to be minimized); range anxiety; daily VMT distributions of 36664 drivers
- Key findings (focused on BEV)
  - The near-term most popular BEV range is 66-76 miles
  - The near-term optimal BEV range is ~0.5% of one’s annual VMT
  - Single-range representation creates serious analytical bias against BEV

Why RO?—to accurately evaluating market prospect and social benefit of BEV

- Market competition drives optimal design
  - Optimize = max(value) or min(cost) for consumers
  - But constrained by economies of production scale
- ER affects cost-effectiveness, and thus market penetration and social benefit
  - More BEV range, higher vehicle price, but less range anxiety
  - But how significant?
- To help auto companies design successful BEV products
  - Non-optimal ER → restrain the success potential
- To help policy analysts mitigate analytical bias against BEVs
  - Non-optimal ER → underestimating market appeal and social benefit

Method (applicable for BEV)
minimize range cost (RC in $) wrt electric range (r in miles)

$$\min_{0<r<r_{max}} RC(r) = RC_b(r) + RC_l(r) + RC_e(r)$$

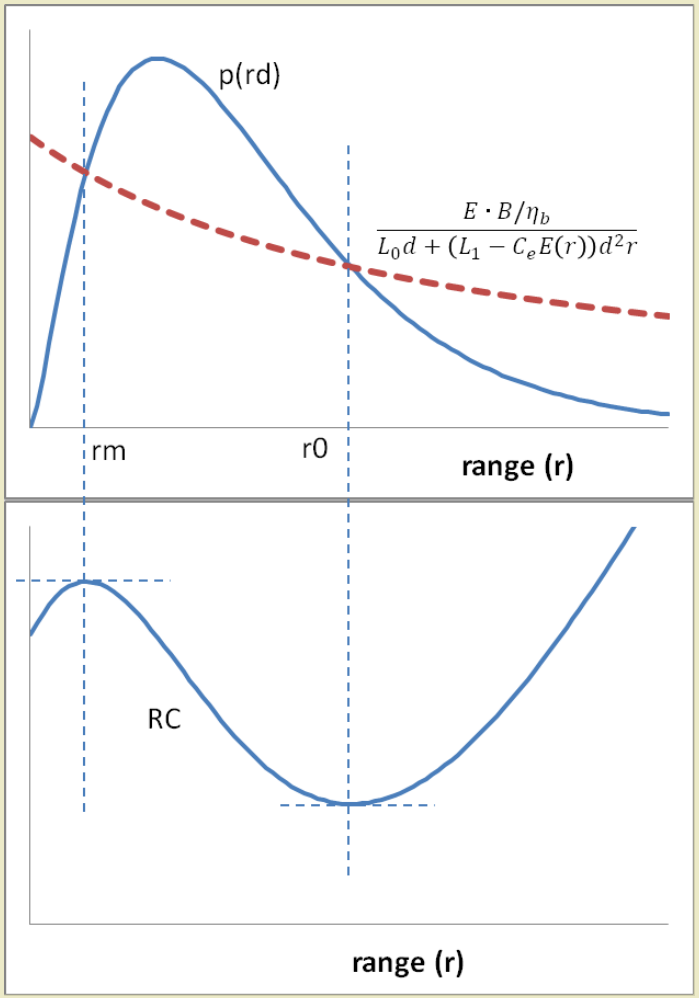
- $RC_b = r \cdot E(r) \cdot B(r)/\eta_b$
  - Battery delivered price (RC_b in $)
  - electric rate (E(r), in kWh/mile)
  - battery utilization (η_b)
  - unit battery price (B(r), in $/kWh)

- $RC_e = C_e \cdot E(r) \cdot \int_0^{rd} x \cdot p(x) \cdot dx$
  - electricity cost (RC_e)
  - range extension ratio (d, in 100%)
  - lifetime per-kwh elec cost (C_e in $/kWh)
  - Daily distance probability density (p(x))

- $RC_l = L_0 \cdot \int_{rd}^{X_m} p(x) \cdot dx + L_1 \cdot \int_{rd}^{X_m} x \cdot p(x) \cdot dx$
  - range limitation cost (RC_l in $)
  - maximum daily driving distance (X_m, in miles)
  - lifetime max fixed range limitation cost (L_0 in $)
  - lifetime per-mile range limitation cost (L_1 in $/mile)

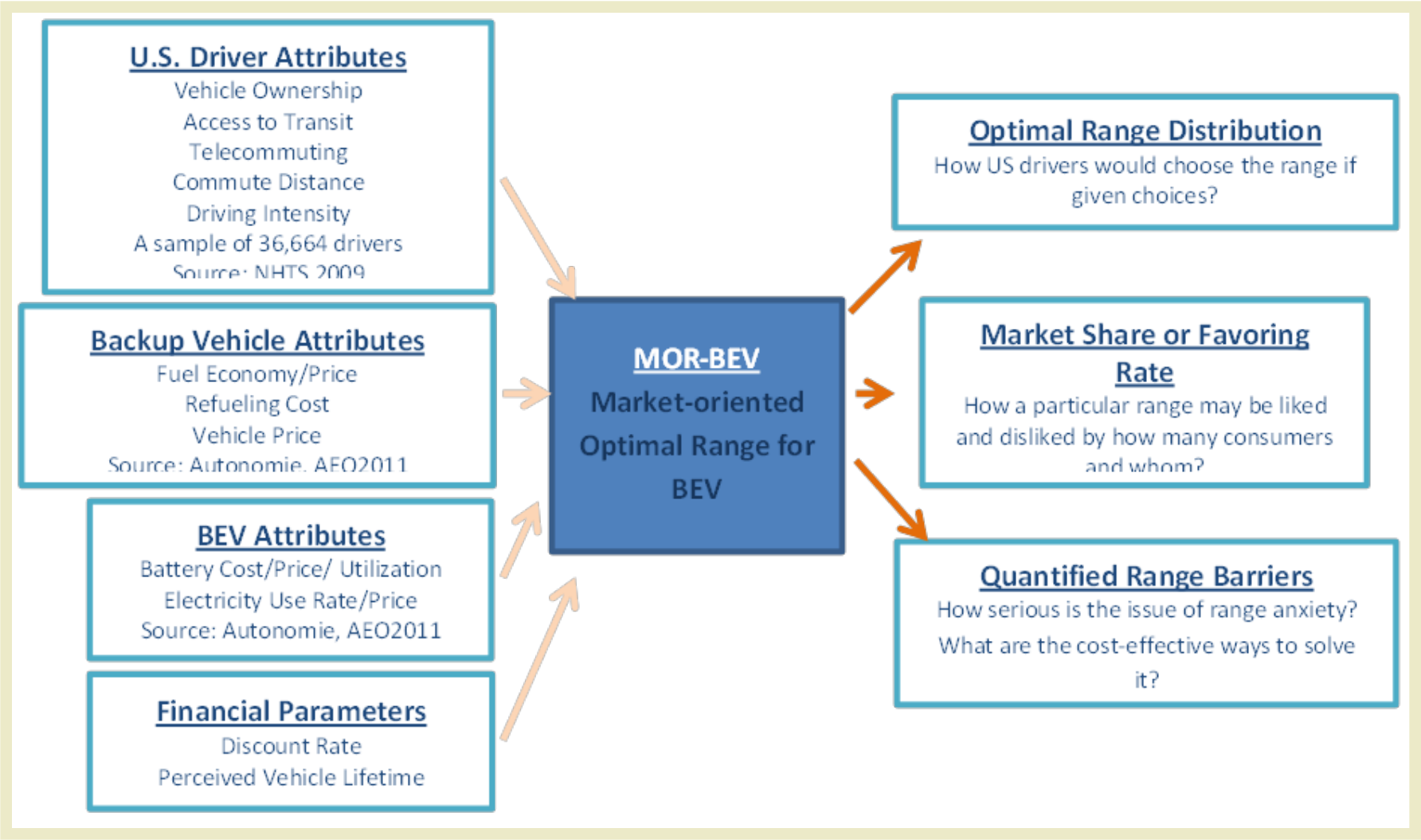
First-order qualitative analysis

$$\frac{\partial RC}{\partial r} \leq 0 \Leftrightarrow p(rd) \geq \frac{E \cdot B/\eta_b}{L_0 d + (L_1 - C_e E(r)) d^2 r}$$



- Consumers would prefer bigger range (r_0 ↑) if:
  - Travel more frequently on long daily distance (p(x) →)
  - Higher vehicle efficiency(E ↓)
  - Lower battery cost (B ↓)
  - Higher discharge ratio (η_b ↑)
  - Lower range extension ratio (d ↓)
  - Higher daily range limitation cost (L_0 ↑)
  - higher per-mile range limitation cost (L_1 ↑)
  - Lower electricity cost (C_e ↓)
  - Lower discounting rate (L_0 ↑, L_1 ↑, C_e ↑)
  - Longer vehicle lifetime rate(L_0 ↑, L_1 ↑, C_e ↑)

Market-oriented Optimal Range for BEV (MOR-BEV) — a tool for studying consumer preferences on BEV range

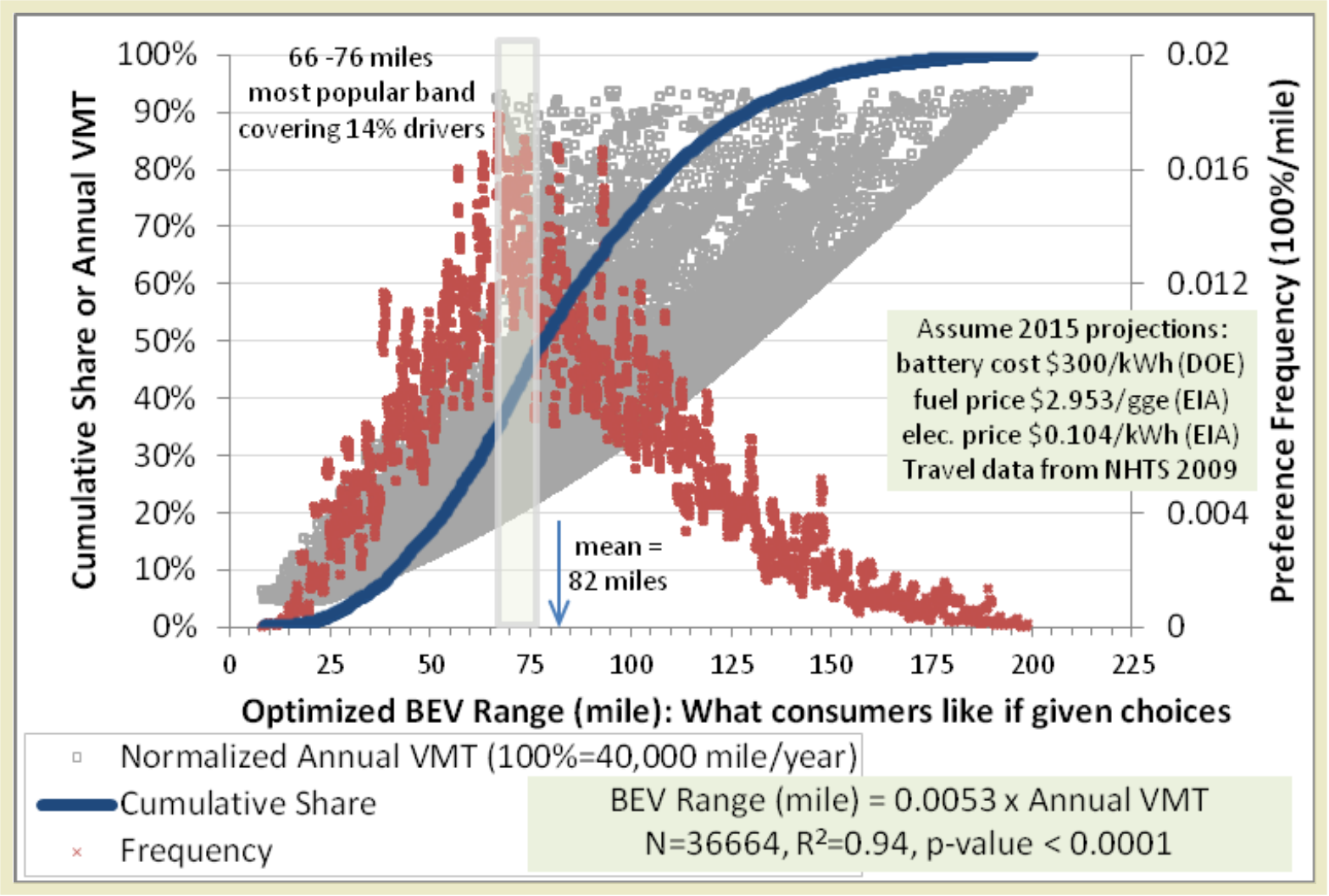


Data and baseline key assumptions in MOR-BEV

- Driver Attributes
  - Sample: 36,664 new vehicle driver records from NHTS 2009
  - Each characterized by a unique Gamma distribution of daily VMT
  - Daily range limitation cost 15~50 $/day, depending on household vehicle flexibility
- Vehicle Attributes
  - Backup vehicle, gasoline 27.5mpg, refueling hassle cost $3/trip, equivalent to $160/year, gasoline price $3/gallon
  - BEV: $450/kWh (price), 340 Wh/mile (charged), constant for now
  - 10% charging loss, 80% capacity utilization
  - 100% range extension ratio (no extension)
- Financial
  - discount rate 7%/year, 5-year analytical vehicle lifetime

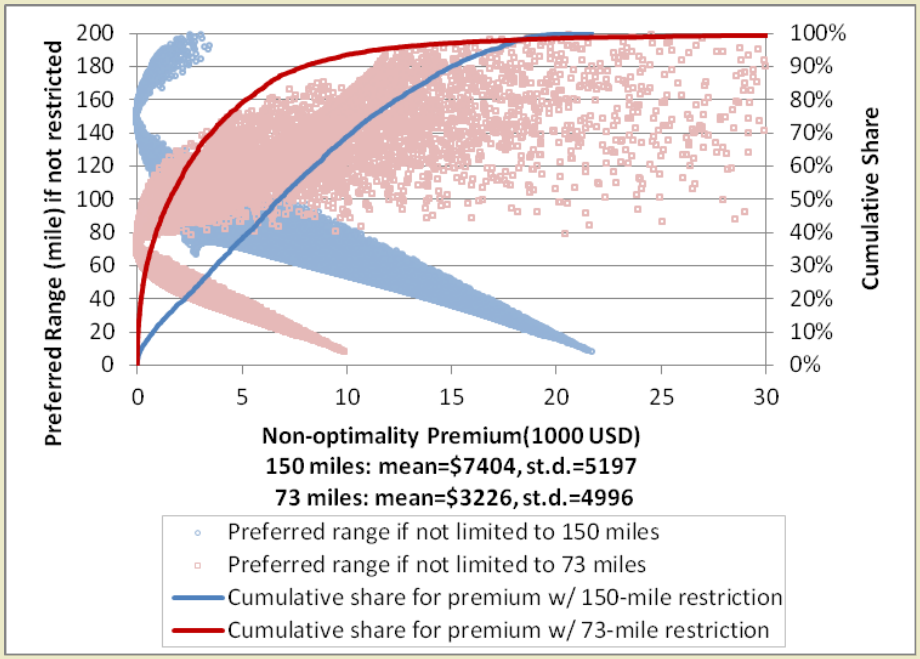
Base case (near term) observations:

1. All ORs <200 miles; 70%<100 miles
2. OR = ~ 0.5% x annual distance
3. Most popular band 66-76 miles, covering 14% sampled consumers



A non-optimized range, if assumed in market simulation models or technology comparisons, could introduce significant bias against the BEV technology

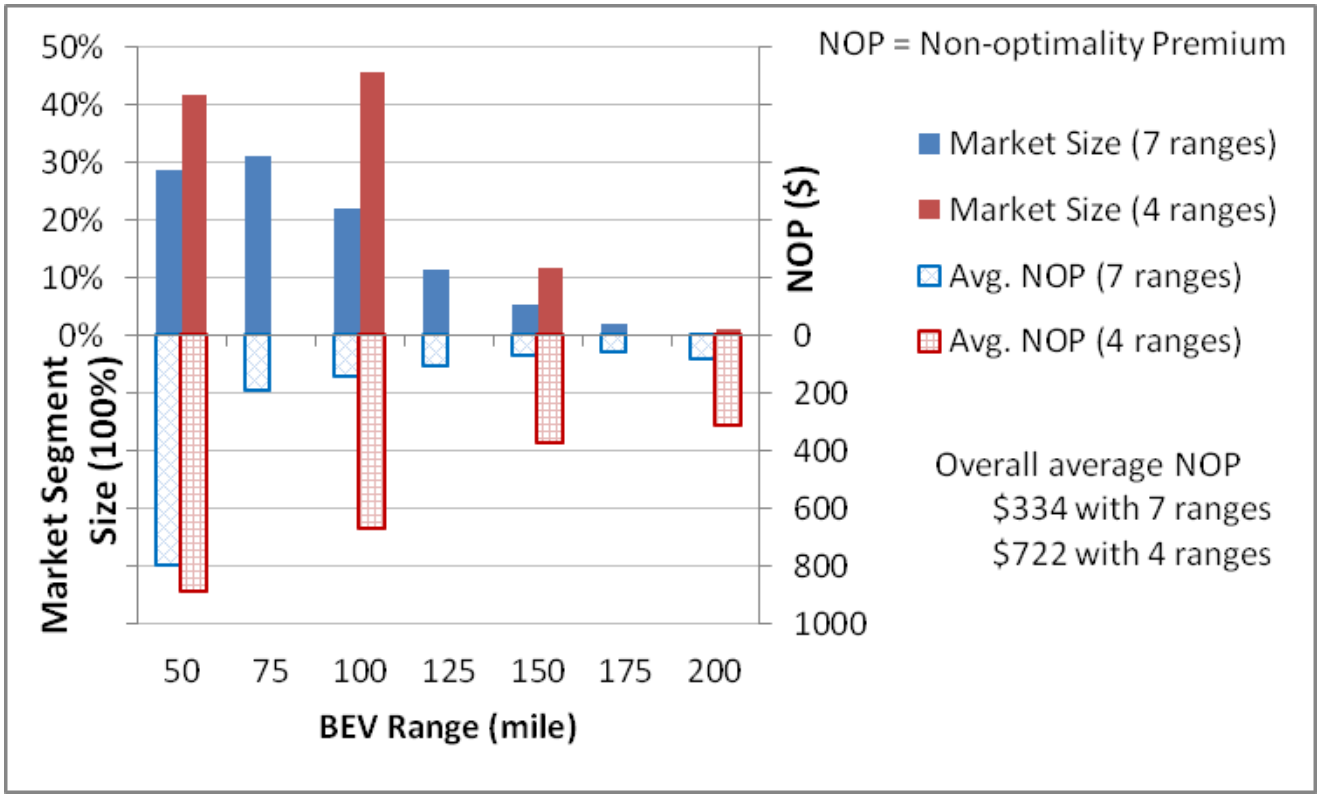
Distribution of non-optimality premium among U.S. drivers if only 73-mi or 150-mi is represented in analysis



- Measurement of analytical bias against BEV
  - measured by non-optimality premium = the extra range cost due to choosing a non-optimal range
- The average bias if BEVs are represented with a single range
  - $7404 for 150-mile
  - $3226 for 73-mile

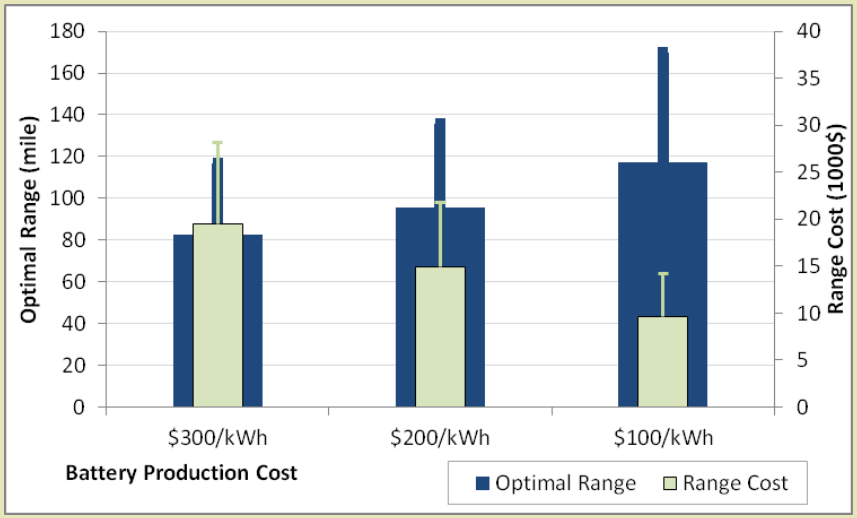
Diverse representation of BEVs with just a couple of ranges would significantly reduce analysis bias

- Full and continuous representation of ranges is unrealistic and unnecessary
  - Scale of production
- A few discrete ranges seem sufficient and necessary
  - Avg. bias = $3226/veh if 73-mile only
  - $722/veh if 4 ranges, a 78% ↓ in bias
  - $334/veh if 7 ranges, a 90% ↓ in bias

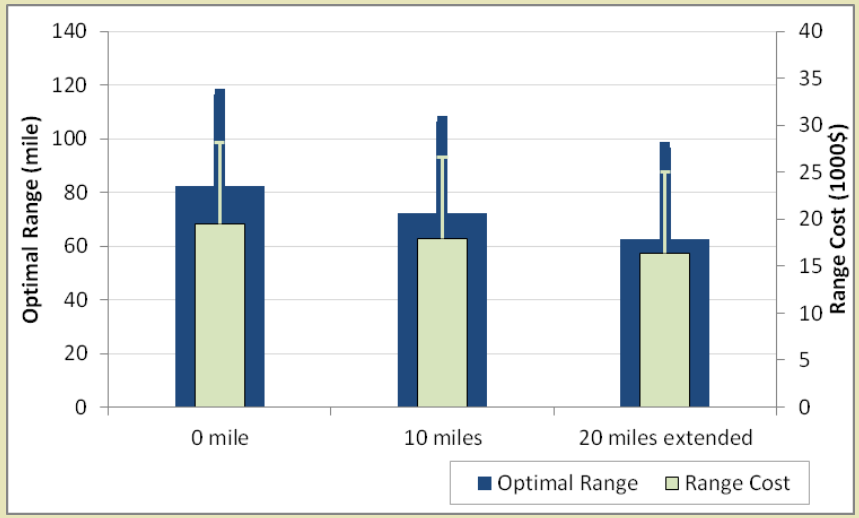


Consumers would prefer bigger ranges if battery cost reduces or if they charge less frequently.

- With reduced battery cost, consumers would buy more range and bear less range cost.
- Bigger ranges chosen mean more social benefits to be realized
- Increasing marginal impact of battery cost reduction on optimal range



- Range extension
  - Improved charging availability, more user-friendly chargers, and behavior adaptation
- Improved charging infrastructure motivates less range
  - The social benefit per vehicle does not change
  - But fleet-wide social benefits can increase due to lower range cost and higher market penetration



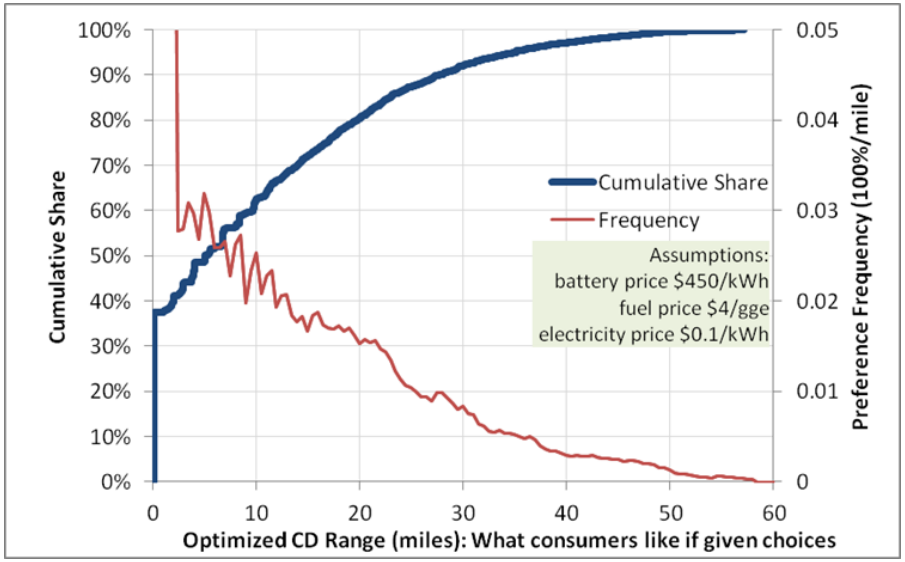
Conclusion: range optimization is important for product design and policy analysis of BEVs

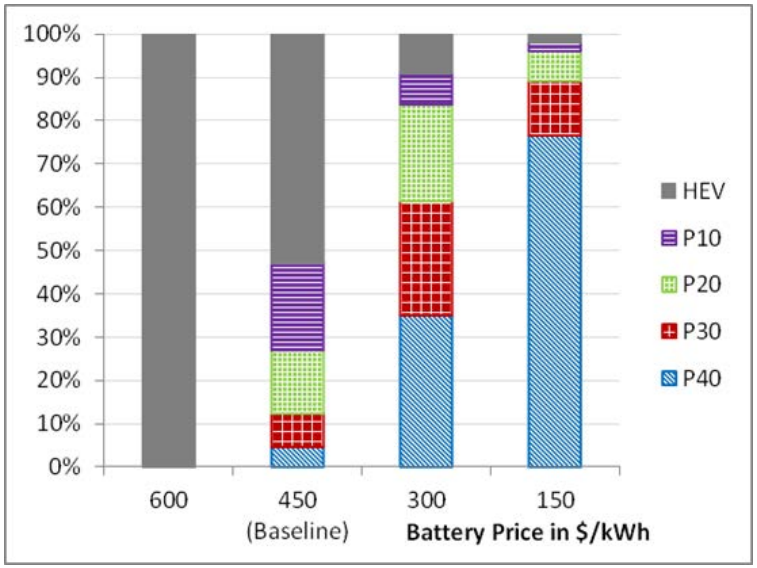
- Assuming market competition, optimal design is more realistic, so is the resulting assessments of technology, market, and social benefits.
- BEV range is optimized by minimizing range-related costs. Optimization is conducted for each of 36664 sampled drivers by considering daily VMT variation and rang anxiety (measured by range limitation cost).
- Key empirical findings
  - The near-term most popular BEV range is 66-76 miles
  - Single-range representation creates significant bias against BEV
  - Multiple-range representation can effectively reduce analytical bias.
  - The near-term optimal BEV range is ~0.5% of one's annual VMT
  - Battery cost reduction or lack of infrastructure support leads to preferences for less range.

PHEV electric range optimization

-- to be presented at SAE World Congress, April 2012 in Detroit

- Optimal electric range of PHEV is found to be about **two-thirds** of one's mode, i.e. most frequent daily driving distance





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