Are consumers willing to pay for letting the car drive for them? Analyzing response to autonomous navigation

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Technological change in the automotive industry

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2. Automated vehicles

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- Internal combustion engines are highly inefficient
- Tank-to-wheel energy efficiency is about 15%
- Engine loss is 76%
- About 1% of the energy is used to transport the driver

Battery Electric Vehicles

- Battery electric vehicles (BEVs) are propelled by one or more electric motors that are powered by rechargeable EV batteries
- BEVs tank-to-wheel efficiency: $\sim 85\%$
- **Electrification**: pertinent step toward energy sustainability in personal transportation
- BEVs have the potential for being charged using clean energy sources (cf. Zivin et al., NBER 2012)

BEV adoption

- BEVs were (re)introduced into the US market in 2011
- Li-ion batteries (most charge capacity, but high cost per kWh of storage)
- Emerging market with slow consumer shift, despite important operating cost savings (cost equivalent to \$1/gal)
- 2014 PEV sales: rose above the 100,000 level
- 2014 Nissan LEAF: 30,200 deliveries (22,610; <10K)

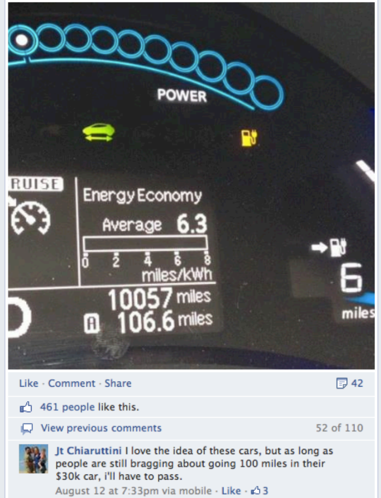
Low emission vehicles and range anxiety

- Range anxiety: important barrier to BEV adoption
- For planning a successful introduction of LEVs in the market it becomes essential to fully understand **consumer valuation of driving range**

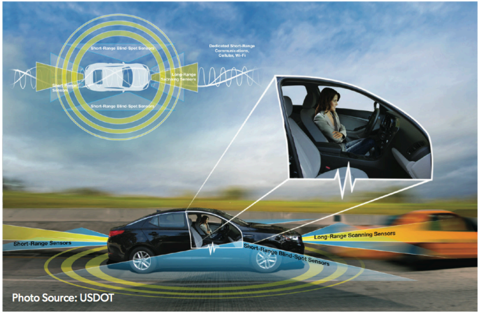
Why is driving range limited?

1. Production cost of batteries is a function of range
2. Added weight is needed to extend range

From the LEAF Facebook page



Automated vehicles: at least some control functions occur without direct input from the driver



Automated vehicles use on-board sensors, cameras, global positioning, and telecommunications to help perform safety-critical driving functions such as steering, acceleration, and/or braking. To ensure full awareness of their surroundings, automated vehicles can leverage connected technology to communicate wirelessly with other vehicles and roadside infrastructure to improve safety, performance, and reliability.

1. **Autonomous**: use vehicle sensors only
2. **Connected**: V2V communication

The Transformative Nature of Automation

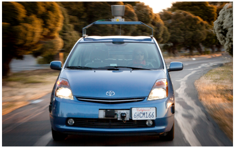
- Transportation Systems Revolution
  1. Safety (crash avoidance)
  2. Efficiency (reduced congestion; energy and env benefits)
  3. Accessibility (improved mobility)

Intelligent Driving

Autonomous parking

What about full automation?

- Google car: 700,000+ miles driven



- Tesla Model S autopilot features (incremental automation)

Choice Modeling: consumer response

- Microeconometric **discrete choice models** of demand (McFadden, AER 2001)
- Probabilistic models of economic choice among a finite group of differentiated products
- Quantitative understanding of the tradeoffs across product characteristics
- Indirect mechanism to determine **willingness to pay**
- Widely used in
  1. Applied economics (health & labor, environment)
  2. Marketing
  3. Political science (voting preferences)
  4. Urban planning
  5. Some fields of civil engineering (transportation analysis)

Transportation analysis

- Researchers, firms, and policy-makers use discrete choice models to
  1. **predict demand for new alternatives** and infrastructure (e.g. a light rail or a new highway)
  2. inform traffic assignment models (route choice)
  3. analyze the market impact of firm decisions (e.g. merger of two airline companies)
  4. set pricing strategies (e.g. congestion pricing, revenue management)
  5. prioritize research and development decisions (e.g. **automotive industry**)
  6. perform cost-benefit analyses of transportation projects (e.g. new bridge or tunnel)
  7. understand car ownership (**vehicle choice**)

Random utility maximization

- Theory of individual choice behavior: individuals make choices by maximizing their satisfaction
- Operational model: satisfaction is measured using $U_{ij} = v_{ij}(\mathbf{q}_{ij}, I_i - p_{ij}, \varepsilon_{ij}|\boldsymbol{\theta})$
  - v_{ij} indirect utility of alternative j for individual i
  - $\mathbf{q}_{ij}$ vector of attributes that characterize the alternatives
  - I_i income
  - p_{ij} price of the alternative
  - ε_{ij} taste shocks (unobserved heterogeneity)
  - $\boldsymbol{\theta}$ unknown preference parameters
- Chosen alternative i_j is such that $U_{i_j j} = \max_j U_{ij}$
- Regression with LDV

Modeling adoption of high technology, durable goods

- Barriers to adoption and diffusion
- WTP for new technology affected by attitudes, knowledge, and social network effects
- Asymmetric investment with associated uncertainties and subjective risks

- Energy-efficient technology: willingness to pay for fuel savings (Greene and Hiestand, 2013)

Vehicle choice model

- General model

$$U_{ij} = -\alpha \mathrm{price}_{ij} + \beta_{\mathrm{PVFC}} \mathrm{PVFC}_{ij} + \beta_{\ln range,i} \ln(\mathrm{range}_{ij}) + \mathbf{x}'_{ij}\boldsymbol{\beta}_i + \varepsilon_{ij}$$

$$\mathrm{PVFC}_{ij} = \sum_{t=1}^{L_{ij}} \frac{\mathbb{E}(\mathrm{fc}_{ijt})}{(1+r)^t}$$

1. Endogenous discounting (Hausman, 1979; Greene, 1983; Train, 1985)
2. Exogenous discounting (Allcott and Wozny, 2012)

Endogenous discounting (Hausman, RAND 1979)

- r is treated as an additional parameter
- If L is large enough and appreciation in fuel prices is ignored, then the *capitalized worth* approximation can be used:

$$\boxed{\mathrm{PVFC}_{in} \approx \frac{fc_{ij}}{r}},$$

  where fc_{in} is a uniform equivalent of $\mathbb{E}(fc_{ijt})$
- $\beta_{fc} = \beta_{\mathrm{PVFC}}/r$
- For a rational consumer $(-\alpha = \beta_{\mathrm{PVFC}})$, then

$$\boxed{r = -\frac{\alpha}{\beta_{fc}} = \frac{1}{\mathrm{WTP}_{fc}}},$$

  where WTP_{fc} is the willingness to pay for marginal savings in fuel cost.

Exogenous discounting (Allcott & Wozny, REST 2012)

- Market failures may explain myopic discounting in the sense that $-\alpha \neq \beta_{\mathrm{PVFC}}$
- DCM in WTP-space (A&W, 2012; Newell & Siikamäki, NBER 2013) :

$$\boxed{U_{ij} = -\alpha \left[\mathrm{price}_{ij} + \gamma_{\mathrm{PVFC}} \mathrm{PVFC}_{ij} - \mathbf{x}'_{ij} \boldsymbol{\omega}_x \right] + \varepsilon_{ij}} \, ,$$

  where γ_{PVFC} is the willingness to pay for marginal savings in the present value of lifecycle costs
- If $\gamma_{\mathrm{PVFC}} < 1$, then there is evidence for myopic consumption

WTP for marginal range improvements

Main References	Market	WTP [US$05/mile] Mean est.	Min est.	Max est.
Beggs and Cardell (1980), Beggs et al. (1981)	US (1978)	85	61	132
Calfee (1985)	California (1980)	195	195	195
Bunch et al. (1993)	California (1991)	101	95	106
Brownstone et al. (2000)	California (1993)	99	58	202
Golob et al. (1997)	California (1994)	117	76	202
Topmkins et al. (1998)	US (1995)	64	44	102
Hess et al. (2012)	California (2008)	43	36	49
Hidrue et al. (2011)	US (2009)	58	29	82
Nixon and Saphores (2011)	US (2010)	182	46	317
Train and Hudson (2000), Train and Sonnier (2005)	California (2000)	100	87	131
Daziano (RESEN, 2013)	California (2000)	103	75	171

Table : Willingness to pay estimates for marginal improvements in driving range. (Expanded from Dimitropoulos et al., TRA 2013)

WTP for range improvements cont'd

- Vast literature
- Most consider a constant marginal utility of range
- However, range should exhibit diminishing returns
- Logarithmic transformation of range (Calfee, TRB 1985)
- Marginal rate of substitution of driving range and purchase price:

$$\mathrm{WTP}_{\Delta range} = -\frac{\partial U_{BEV} / \partial \mathrm{range}}{\partial U / \partial \mathrm{price}} = \frac{\beta_{\ln range}}{\alpha} \frac{1}{range}$$

- WTP is not just a parameter ratio but also a nonlinear function of the range level

Data: discrete choice experiment

- Web survey about vehicle preferences (including ULEVs), automation awareness & attitudes
- Data collected in September-October 2014
- Population: Americans that have a driver's license
- 1,260 respondents answered 8 experimental choice situations
- Choice among 4 vehicle alternatives (labeled)
- $10{,}000^{+}$ choices

The sample

Table : Sample Demographic Statistics

Variable	Mean	(S.D.)
Household size	2.717	(1.32)
Age of respondent	47.565	(13.55)
Number of children	1.41	(1.36)
Household Income (2014 $'s)	61,226	(42,135)
Years respondent has held license	25.409	(9.98)
Number of household members with license	1.914	(0.74)
Number of vehicles held by household	1.592	(0.79)
Respondent daily one-way commute (miles)	13.903	(12.72)

The sample cont'd

Respondent characteristics	Percentage
Male	50.49
Married	54.49
Widowed	2.94
Divorced	13.70
Single	21.45
Living with partner	7.42
White	85.24
Black	8.32
Hispanic	7.18
Asian	2.934
High school diploma	98.613
Some college experience	76.84
Bachelors degree	38.25
Masters or professional degree	12.40
Full time ($\geq$ 30 hours per week) job	66.40
Part time job	8.64
Homemaker	7.83
Student	0.90
Retired	10.44
Unemployed but actively looking for work	5.79
Household income $\leq$ \$30, 000	22.43
Household income $>$ \$30, 000 and $\leq$ \$60, 000	34.01
Household income $>$ \$60, 000 and $\leq$ \$90, 000	23.82
Household income $>$ \$90, 000	19.74

Notes: The white, black, Hispanic and Asian percentages sum to more than 100 percent because some of the respondents have multicultural backgrounds.

DCE: experimental design

- D-efficient design, 16 choice situations, 2 blocks, some customization
- Similar to how info is presented in **fueleconomy.gov** (Monroney stickers)
- Alternatives: HEV, PHEV, BEV, GAS
- Attributes:
  1. Cost to drive 100 miles
  2. Purchase price
  3. Driving range (electric/gasoline)
  4. Refueling time (electric/gas)
  5. Driverless package: some automation (crash avoidance), full automation (Google car)

DCE - sample 1

	Hybrid Vehicle Gasoline HEV	Plug-in Hybrid Electric Gasoline-Electricity PHEV	Electric Vehicle BEV	Gasoline Vehicle GAS
Cost to Drive 100 Miles	$7.00	$6.50	$4.00	$15.20
Price	$25,000	$29,000	$26,000	$20,000
Driving Range	590 miles Gasoline	40 miles / 520 miles Gasoline Only	80 miles Electricity	495 miles Gasoline
Refueling Time	5 minutes	2 hours (electricity) / 5 minutes (gas)	1.5 hours	5 minutes
Driverless Package	Some Automation	No Automation	Full Automation	No Automation

DCE - sample 2

	Hybrid Vehicle HEV Gasoline	Plug-in Hybrid Electric PHEV Gasoline-Electricity	Electric Vehicle BEV	Gasoline Vehicle GAS
Cost to Drive 100 Miles	$8.80	$5.50	$3.20	$15.20
Price	$25,000	$37,000	$26,000	$20,000
Driving Range	590 miles Gasoline	15 miles / 520 miles Gasoline Only	150 miles Electricity	550 miles Gasoline
Refueling Time	5 minutes	2 hours / 5 minutes (electricity) (gas)	8 hours	5 minutes
Driverless Package	Some Automation	Full Automation	No Automation	No Automation

Models and robustness checks

1. Conditional logit with deterministic consumer heterogeneity (sociodem: additive and interactions)
2. Parametric random parameter logit (mixed logit with normally dist. param, MXL)
3. Semi-parametric random parameter logit (mixed mixed logit, M-MXL): heterogeneity distributions are a mixture of normals

1. Endogenous discounting
2. Exogenous discounting (5%, 6%, experimental discount rate)
3. Models with and without income effects
4. Panel structure

Stylized facts: subjective discounting

- Subjective discount rate estimate: **29.91%**
- Evidence of the **energy paradox** (Jaffe & Stavins, RESEN 1994)
  - Average interest rate for used vehicles loans estimated at 6.9%
  - Average interest rate reported by dealerships to JD power is 8.9%
  - Interest rate of the opportunity cost of vehicles paid in cash: 5.8%

Quant.	Fixed param. logit	Parametric rand. param. logit	Semiparam. rand. param. logit	Parametric rand. param. logit**	Semiparam. rand. param. logit**
			$WTP_{\Delta range}$(80 miles, LEAF under normal conditions)		
Mean	93.1	73.3	75.2	129.6	68.7
2.5%	65.1	53.4	59.0	-1.0	4.6
25%	83.3	66.2	67.8	75.8	44.4
50%	93.0	73.6	74.3	112.0	64.4
75%	102.8	80.3	81.1	160.1	87.8
97.5%	121.8	92.4	95.1	368.1	162.0
			$WTP_{\Delta range}$(100 miles, LEAF under ideal conditions)		
Mean	75.1	60.1	62.8	106.3	56.4
2.5%	53.4	43.8	48.3	-0.8	3.7
25%	68.3	54.3	55.6	62.1	36.5
50%	76.2	60.4	61.0	91.8	52.8
75%	84.3	65.9	66.9	131.3	72.0
97.5%	99.9	75.7	78.0	301.8	132.8
			$WTP_{\Delta range}$(150 miles, Tesla S with a 40kWh electric battery)		
Mean	50.5	40.4	42.2	71.4	37.9
2.5%	35.9	29.5	32.5	-0.5	2.5
25%	45.9	36.5	37.4	41.8	24.5
50%	51.3	40.6	41.0	61.7	35.5
75%	56.7	44.3	45.0	88.3	48.4
97.5%	67.1	50.9	52.4	202.9	89.3

Table : Mean and selected quantiles of the posterior distribution of willingness to pay for different levels of range

Stylized facts: WTP for range improvements

- Mean WTP for an additional mile of driving range at 80 miles: $75
- Mean WTP for an additional mile of driving range at 100 miles: $63
- Robustness check: meta-analysis mean estimates of 66-75 $/mile (Dimitropoulos et al., TRA 2013)

- Mean WTP for an additional mile of driving range at 20 miles: $300

Individual WTP

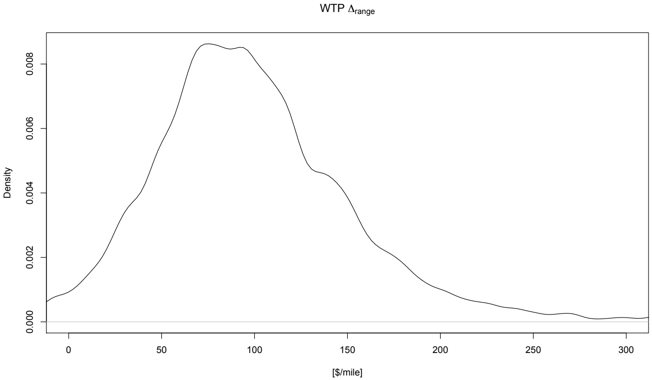


Figure : Nonparametric estimate of the posterior density of WTP for driving range improvements of a randomly selected individual (evaluated at 80 miles).

What about the MC?

- Given the current lower bound of the cost of lithium-ion batteries ($\sim$ 400 [\$/kWh])...
- at 100 miles the marginal cost of producing batteries with an additional mile of range is 160 \$/mile
- All of the population $\mathrm{WTP}_{\Delta range}$ point estimates at 100 miles are well below that MC

Stylized facts: WTP for automation and quick charging

- Mean WTP for entry-level automated features: \$3,100
- Mean WTP for full automation: \$4,450
- Robustness check: Tesla's Tech Package with Autopilot costs \$4,250

- Mean WTP for reducing charging time in an hour: \$700

Stylized facts: consumer segments

- Young people more likely to choose PHEVs
- Current owners of hybrids more likely to buy advanced technologies
- People living in apartment buildings less likely to choose BEVs and PHEVs
- People in the American South opt for conventional technologies
- Conservatives less likely to choose HEVs and PHEVs, much less BEVs
- Males more likely to choose BEVs, less likely to choose HEVs

In sum...

Slow transition to new propulsion technologies

- Evidence of an energy paradox in the valuation of future savings
- The compensating variation of range improvements is much lower than the cost of producing that improvement

Adoption of autonomous navigation looks promising

- Even at this early stage, WTP for autonomous navigation is relatively high
  - KPMG 2012 Study: 20% of respondents were willing to pay up to $3,000
- Desirability for safety features

Next steps

- Bayes estimators of consumer heterogeneity
  1. Semiparametric M-MXL requires number of normal components of the mixture
  2. Finite mixture with Dirichlet priors
  3. Dirichlet process (no need for setting the number of components)
- Bayes estimates of WTP
  - WTP: problems of parameter ratio inference (weak identification)
  - Individual WTP estimates
  - Construction of CIs of the individual estimates

Thank you!