Energy Prices and Electric Vehicle Adoption

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Research questions

1. Does EV demand respond to electricity prices similarly to gasoline prices?
2. To what extent do consumers undervalue operating costs of EVs?
3. What does that imply for optimal tax and subsidy policy?

Conceptual framework

Simple discrete choice between a BEV and ICE

$$U_i^{BEV} = \alpha_i^{BEV} + \sum_{t=0}^{T^{BEV}} \delta^t \gamma_e E[P_{it}^e] \left(\frac{kwh}{mile}\right) VMT_i + \epsilon_i^{BEV} \quad (1)$$

$$U_i^{ICE} = \alpha_i^{ICE} + \sum_{t=0}^{T^{ICE}} \delta^t \gamma_g E[P_{it}^g] \left(\frac{gal}{mile}\right) VMT_i + \epsilon_i^{ICE} \quad (2)$$

- Assumptions:
  - Similar ownership horizons: $T^{BEV} = T^{ICE}$
  - Discount rate (δ) identical
  - $E[P_{it}^e] = P_{i0}^e$, $E[P_{it}^g] = P_{i0}^g$
  - Hold VMT_i constant (i.e., no rebound)

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- Assumptions:
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  - Discount rate (δ) identical
  - $E[P_{it}^e] = P_{i0}^e$, $E[P_{it}^g] = P_{i0}^g$
  - Hold VMT_i constant (i.e., no rebound)
- $\gamma = \gamma_e / \gamma_g$ is the main object of empirical interest
  - Valuation of electricity expenditures relative to gasoline

Conceptual framework

- Under the assumptions above in a logit framework:

$$\hat{\beta}^e = \frac{dPr(BEV)}{dP_0^e} = \gamma_e \frac{kwh}{mile} VMT_i \sum_{t=0}^{T} \delta^t * A$$

$$\hat{\beta}^g = \frac{dPr(BEV)}{dP_0^g} = -\gamma_g \frac{gal}{mile} VMT_i \sum_{t=0}^{T} \delta^t * A$$

where $A = Pr(BEV) * (1 - Pr(BEV))$.

- We can derive an estimate of γ as:

$$\hat{\gamma} = \frac{-\hat{\beta}^e * \frac{miles}{kwh}}{\hat{\beta}^g * \frac{miles}{gal}} \quad (3)$$

We study EV sales in CA from 2014 - 2017

- EV purchase data:
  - EV purchases at transaction-level data with prices, VINs, CBG of owner
  - Aggregate to CBG-level
- Electricity rate panel data:
  - Investor-owned utility (IOU) and municipal utility websites in California
  - RA blood, sweat and tears
- Daily, station-level gasoline prices (from OPIS) aggregated to month-zip level, zips matched to CBGs.
- Other covariates include:
  - 2013 fleet characteristics by CBG, CBG demographics
  - Panel of public charging station density

What is the relevant price faced by consumers?

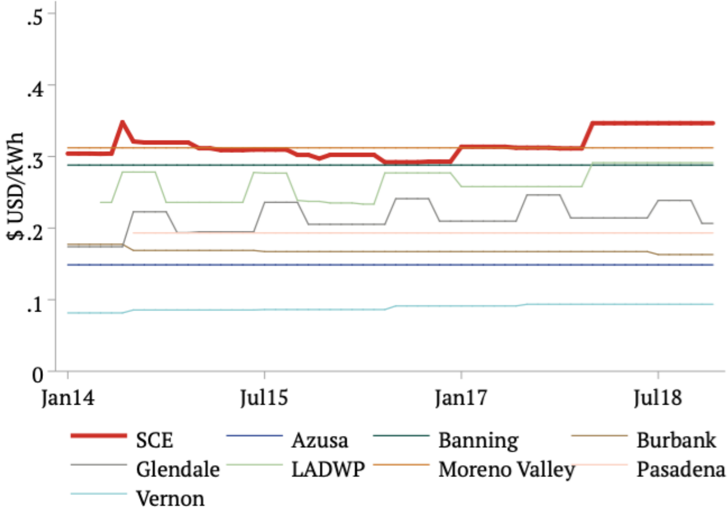
Base case assumption: EV owners are not on lowest electric price tier

- Most IOU rate schedules in CA feature increasing block prices
  - 70-80% of EV owners in PGE territory are on a price tier above $0.27/kwh (see BBRW later this morning)

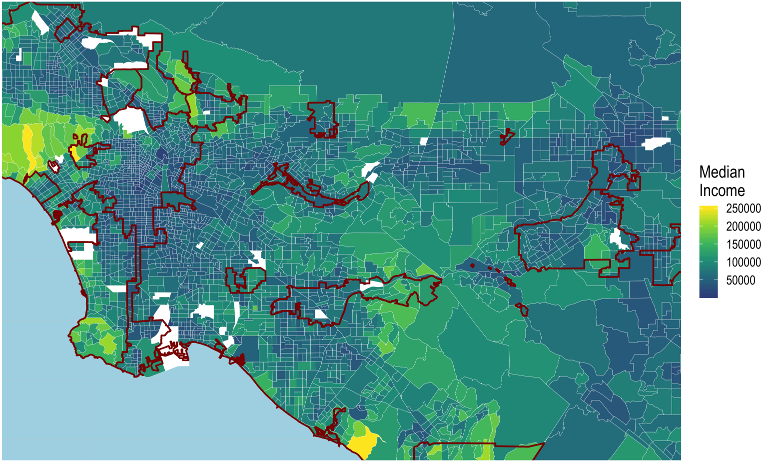
- Alternative rates (e.g., EV TOU rates) are available but not widely used.
  - 50k are on EV rates (TOU) in 2017, 75% of these are in PGE

- Away-from-home charging
  - Household report vast majority of charging at home (Dunkley & Tal 2016, Tal 2017)
  - LCFS credit data
  - Free charging stations may reduce effective price, but price at many public stations are higher than residential rates

Variation in residential rates: LA



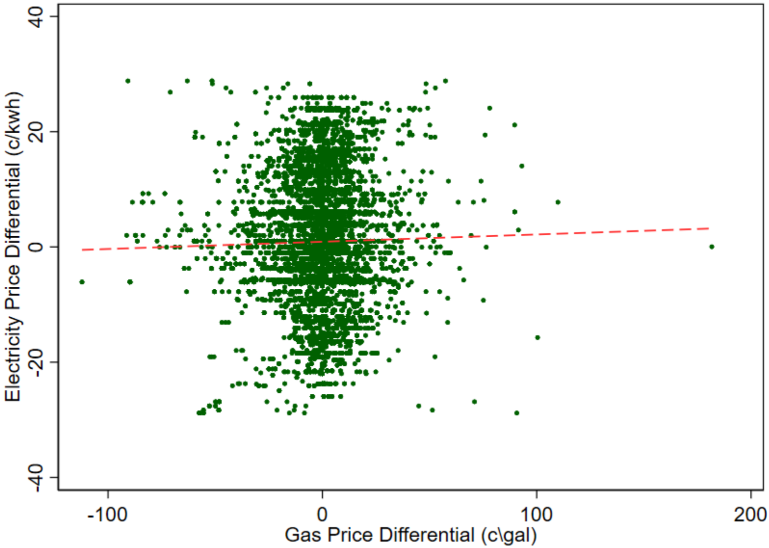
Empirical design: utility boundaries



Empirical sample

- Match each CBG (c) to closest CBG in neighboring service territory (c′)
  - ▸ Pair-matching methodology
- Aggregate transaction data annually
- We examine differences between > 2000 CBG pairs, $i = (c, c')$
  - 4 years (t)

Electricity and gasoline differentials, by CBG pair-yr



Empirical specification

$$\Delta Q_{it}^{BEV} = \beta^e \Delta P_{it}^e + \beta^g \Delta P_{it}^g + \Theta \Delta X_{it} + \nu_{1b} D_c + \nu_{2b} D_{c'} + \epsilon_{it}$$

where:

- ΔQ_{it}^{BEV} denotes BEV sales per 10,000 people
- P^e denotes marginal price of electricity (cents/kwh)
- P^g denotes zip-level gasoline prices ($/gal)
- D_c and $D_{c'}$ are the distances to the service territory boundary
- Errors two-way clustered by origin CBG and destination CBG

For γ calculations (baseline):

- Use Toyota Camry ($\sim$ 30 mpg) and Tesla Model 3 ($\sim$ 4 mpkwh).

Border discontinuity results

	(1)	(2)	(3)	(4)
Δ Marg. Price (cents/kwh)	-0.025	-0.12***	-0.15***	-0.080
	(0.063)	(0.045)	(0.051)	(0.10)
Δ Gas Price (cpg)	0.15***	0.10**	0.071*	0.072*
	(0.055)	(0.047)	(0.040)	(0.041)
Δ Population (000s)		-0.81***	-0.76***	-0.76***
		(0.25)	(0.25)	(0.25)
Δ Pop Density (000s ppl/sqm)		-0.29***	-0.17***	-0.18***
		(0.046)	(0.040)	(0.042)
Δ Income ($000)		0.16***	0.074***	0.074***
		(0.018)	(0.017)	(0.017)
Δ Mean Fuel Econ (mpg, 2013)			1.99***	2.00***
			(0.72)	(0.72)
Δ Hybrid Fleet Share (2013)			-11.5	-10.7
			(27.3)	(26.9)
Δ Luxury Fleet Share (2013)			123.2***	123.8***
			(18.1)	(18.3)
Δ MUD HH share (2013)			-2.28*	-2.25*
			(1.19)	(1.20)
Include PG&E	Y	Y	Y	N
Implied γ	.022	.155	.284	.148
	(.055)	(.101)	(.185)	(.182)
Observations	8595	8163	8135	8135
R-Squared	0.088	0.24	0.30	0.30

▸ Panel Results ▸ Per-mile specification ▸ Residualized Bin-Scatter Plot ▸ Falsifications

Interpretation of magnitudes

How do electricity prices affect EV purchase decisions?

- Mean annual BEV sales per 10,000 population = 11.3
- Electricity prices:
  - An increase of 10 cents/kWh translates to a $\sim$ 13% reduction.
  - A one standard deviation increase ($\sim$ 6 cents/kwh) $\rightarrow$ 8% reduction.
- Gasoline prices:
  - An increase of 10 cents/gal translates to a $\sim$ 6% increase.
  - A one standard deviation increase $\sim$ 50 cents/gal $\rightarrow$ 30% increase.
    - ★ CA prices fell roughly $1.10/gal from Nov.19 - Apr.20

▸ Alternative Samples

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▸ Alternative Samples

Could γ be plausibly driven by assumptions?

- Choice of alternative vehicle:
  - Using a Toyota Prius ($\sim$ 52 mpg) $\rightarrow \hat{\gamma} = 0.16$
  - Using a Toyota Corolla ($\sim$ 35 mpg) $\rightarrow \hat{\gamma} = 0.24$
    - Consistent with Xing, Leard & Li (2019), Muehlegger & Rapson (2020)
  - 8.5 mpg vehicles $\rightarrow \hat{\gamma} = 0.99$
    - Lower mpg than a Ford F150 4WD
- Other possibilities:
  - Four-fold reduction in eVMT?
  - Expectations of dramatic reduction in electricity prices?

Optimal subsidies

We adapt Allcott, Mullainathan and Taubinsky (2013)

- First-best subsidy: social planner observes VMT_i and sets

$$\begin{aligned} S^*(V\bar{M}T_i) &= V\bar{M}T_i[\phi_g - \tau_g - (\phi_e - \tau_e)] \\ &+[1-\gamma]V\bar{M}T_i(c_g + \tau_g - (c_e + \tau_e))] \end{aligned}$$

- First term addresses unpriced externalities.
  - $\phi - \tau =$ externality $-$ tax
- Second term captures foregone savings a consumer ignores when choosing a vehicle.
  - $c + \tau =$ consumer price per mile, weighted by $[1 - \gamma]$

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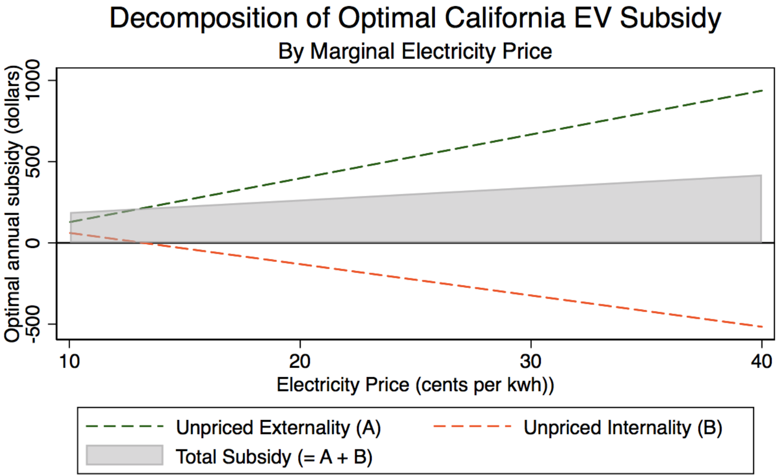
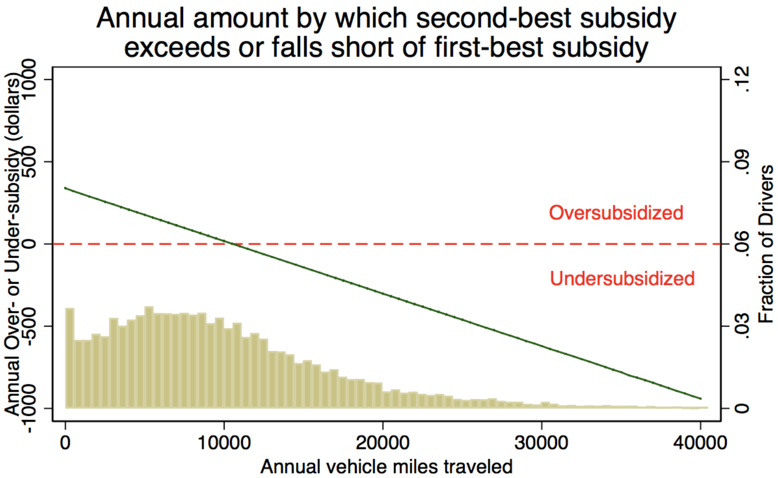
Optimal first-best subsidies



Assumptions:
VMT = 10793, Gamma = .286, BEV fuel efficiency = 4 mpkwh
ICE fuel efficiency = 30mpg, Damages per mile for EVs and ICEs taken from HMMY (2016)
MPC (3.6 cpkwh) of Electricity from BB(2019), Implied assumed EPA electricity price = 13.2 cpm

Optimal second-best subsidies



Assumptions:
Marginal Electricity Price = 30.1 cpkwh, BEV fuel efficiency = 4 mpkwh
Damages per mile for EVs and ICEs taken from HMMY (2016)
MPC (3.6 cpkwh) of Electricity from BB(2019), Implied assumed EPA electricity price = 13.2 cpm

Conclusion

- We compare the response to electricity and gasoline prices, and find buyers undervalue electricity *relative* to gasoline prices.
- RD implies a four-fold difference in the response to gasoline relative to electricity prices.
  - Panel FE models imply a slightly larger difference (not reported today)
- Undervaluation implies a potentially significant role for subsidies (or alternative approaches) to address consumer mis-optimization.
  - Subsidy calculations suggest "internalities" and "externalities" of similar magnitude
  - Second-best subsidy excessively promotes to low-VMT households and under-promotes high-VMT households, all else equal.

Next steps

- Direct evidence of marginal electricity price for EV buyers in SCE and SDGE
  - Data in hand (see BBRW)
- Secure more direct evidence of home vs away charging
  - LCFS, commercial charging data
- Test robustness of gasoline price result
  - Relying on time-series variation in panel specifications
  - Spatial station-level averages in gasoline prices within concentric distance rings

Thank You

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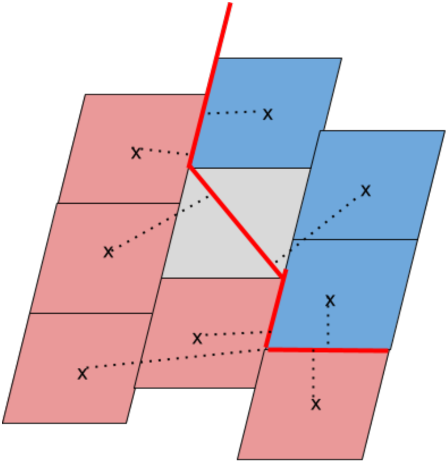
Appendix

Empirical design: utility boundaries & CBGs



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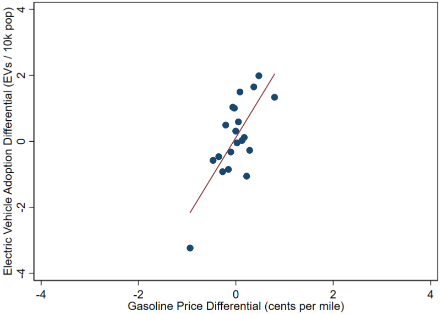
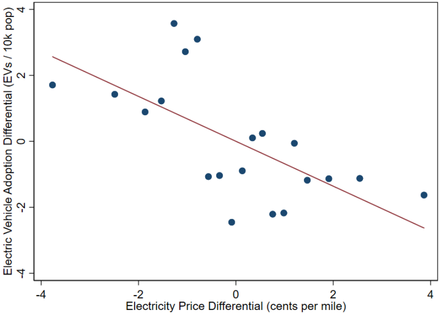
EV adoption, gas and electricity prices per mile

- Binned scatter plots: Residualized EV sales, Gas price and Electricity prices.





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Border discontinuity results

	(1)	(2)	(3)	(4)
Δ Marg. Price (cents/mile)	-0.10	-0.48***	-0.60***	-0.32
	(0.25)	(0.18)	(0.21)	(0.40)
Δ Gas Price (cents/mile)	4.62***	3.07**	2.12*	2.17*
	(1.66)	(1.42)	(1.19)	(1.22)
Δ Population (000s)		-0.81***	-0.76***	-0.76***
		(0.25)	(0.25)	(0.25)
Δ Pop Density (000s ppl/sqm)		-0.29***	-0.17***	-0.18***
		(0.046)	(0.040)	(0.042)
Δ Income ($000)		0.16***	0.074***	0.074***
		(0.018)	(0.017)	(0.017)
Δ Mean Fuel Econ (mpg, 2013)			1.99***	2.00***
			(0.72)	(0.72)
Δ Hybrid Fleet Share (2013)			-11.5	-10.7
			(27.3)	(26.9)
Δ Luxury Fleet Share (2013)			123.2***	123.8***
			(18.1)	(18.3)
Δ MUD HH share (2013)			-2.28*	-2.25*
			(1.19)	(1.20)
p-value, $H0 : \beta^g = \beta^e$	.005	.012	.024	.071
Implied γ	.022	.155	.284	.148
	(.055)	(.101)	(.185)	(.182)

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Panel results

	Monthly Sales Per Cap		Annual Sales Per Cap	
	(1)	(2)	(3)	(4)
Marg. Price (cents/kwh)	0.0036***	-0.0035**	0.032***	-0.063***
	(0.00084)	(0.0014)	(0.010)	(0.021)
Gas Price (cpg)	-0.00062***	0.0027***	-0.016***	0.11***
	(0.000079)	(0.00062)	(0.0012)	(0.011)
Time FE		X		X
CBG FE		X		X
Implied γ		.172		.074
		(.078)		(.026)
Observations	962999	960587	81032	80766
R-Squared	0.00013	0.14	0.0012	0.59

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Alternative Samples

	(1) Full Sample	(2) CBG dist < 5km	(3) Excl. PGE CBGs	(4) Pairwise Best Matches	(5) No Duplicate Pairs
Δ Marg. Price (cents/kwh)	-0.15***	-0.21***	-0.19***	-0.034	-0.16***
	(0.051)	(0.076)	(0.071)	(0.15)	(0.053)
Δ Gas Price (cpg)	0.071*	0.075	0.11**	0.064	0.078*
	(0.040)	(0.057)	(0.046)	(0.12)	(0.040)
Δ Population (000s)	-0.76***	-1.92***	-1.10***	-0.96	-0.74***
	(0.25)	(0.43)	(0.35)	(0.79)	(0.25)
Δ Pop Density (000s ppl/sqm)	-0.17***	-0.12***	-0.17***	-0.15	-0.17***
	(0.040)	(0.037)	(0.040)	(0.096)	(0.043)
Δ Income ($000)	0.074***	0.088***	0.069***	0.13**	0.068***
	(0.017)	(0.022)	(0.023)	(0.060)	(0.017)
Δ Mean Fuel Econ (mpg, 2013)	1.99***	2.19***	1.78**	2.30	2.17***
	(0.72)	(0.82)	(0.78)	(1.88)	(0.70)
Δ Hybrid Fleet Share (2013)	-11.5	-20.1	-29.0	-50.7	-12.2
	(27.3)	(33.8)	(32.2)	(92.3)	(25.5)
Δ Luxury Fleet Share (2013)	123.2***	143.1***	119.6***	164.5**	123.7***
	(18.1)	(22.7)	(20.1)	(65.5)	(17.2)
Δ MUD HH share (2013)	-2.28*	-1.43	-1.87	3.99	-2.91**
	(1.19)	(1.37)	(1.41)	(4.01)	(1.20)
Implied γ	.284	.37	.237	.071	.271
	(.185)	(.317)	(.128)	(.349)	(.165)
Observations	8135	5111	5663	578	7551
R-Squared	0.30	0.30	0.28	0.38	0.31

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Falsification tests

No significant effects at municipal, not-IOU boundaries

	(1) Income	(2) Population	(3) Pop. Density
CBG	0.627	0.991	0.879
	(0.772)	(0.898)	(0.915)
Municipality	0.398	-2.006	1.103
	(0.977)	(1.846)	(1.052)
Observations	5,030	5,202	5,202

Notes:

- Each observation is a CBG pair along municipal borders within IOUs that are not also IOU borders
- Controls: CBG differences in income, population, population density, gas price, fuel economy, and fleet shares of hybrids, luxury vehicles and MUD household counts.
- Observations are ordered within a pair wrt column header variable, by CBG and Municipality respectively.

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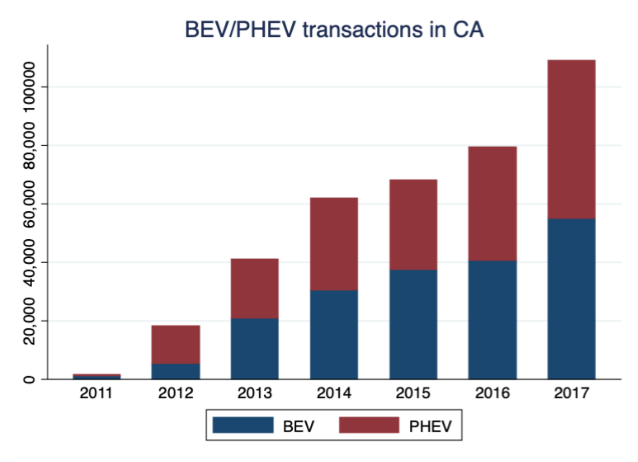
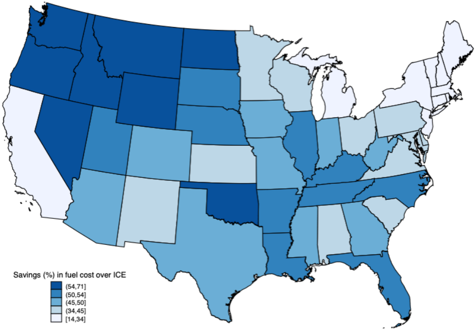
EV Sales in California

Figure: **Annual EV Sales**



Operational costs vary substantially across states

Figure: Percent savings of Leaf vs. Versa



- Locations vary with respect to the operational savings of an EV.
  - Lowest EV savings in MA = $106 per 12k miles (14%)
  - Highest EV savings in WA = $625 per 12k miles (71%)
  - California = $326 per 12k miles (34%)

Other characteristics of the CBG

Table: **Summary statistics**

	mean	sd	min	max	sd_b	sd_w
Population	362.256	114.5832	58	1223	113.9965	0
Population/sq mile	491.9567	651.9797	.2111294	6924.443	646.9094	0
Base tier rate	.1719072	.0167451	.09524	.22267	.0154613	.0072556
Highest tier rate	.3486361	.0501632	.1147535	.42364	.0464579	.0207648
Highest tier usage amount	1391.851	1061.716	20	4788	617.7833	859.3586
N	314795					
n	13590					