Are There Environmental Benefits from Driving Electric Vehicles? The Importance of Local Factors

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Introduction

- Electric vehicles (EVs) growing in importance
  - 11 models & 130,000 registered cars in July 2014 State Registrations
- Multiple subsidies at time of purchase
  - $7500 Federal subsidy
  - Additional state subsidies (*e.g.*, Colorado $6000)
- Possible justifications for subsidies
  - Environmental benefits relative to gasoline cars
  - Reduce dependance on foreign oil
  - Dynamic efficiency
    - Innovation spillovers
    - Learning by doing
    - Network externalities

Our Study

- We ask: What is the environmental benefit of an electric car?
  - What are the lifetime effects of driving an EV relative to a gasoline car?

What is "Greener"? EV vs. Gasoline Vehicle?

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Our Study

- We ask: What is the environmental benefit of an electric car?
  - What are the lifetime effects of driving an EV relative to a gasoline car?
- Caveats
  - Not focus on full Life Cycle Analysis (LCA)
  - Focus on today's grid
  - Focus on incremental EV penetration
- Key point: Local factors matter
  - Local heterogeneity in benefits (county or state of use)
  - Global *and* local air pollution emissions
  - Uniform vs. differentiated regulation
  - Local jurisdictions (pollution export)

Overview of Methodology

We extend and integrate three components:

- Theoretical discrete choice transportation model
  - *How do subsidies change what type of vehicle people buy?*
- Electricity generation and air pollution
  - *How much air pollution results from charging EVs?*
- Air pollution integrated assessment
  - *What are the health and environmental consequences of driving?*

Theoretical Framework

- Optimal policies
  - Pigovian taxes on both gasoline (t_g) & electric (t_e) miles
  - marginal damages per mile for gasoline vehicle δ_g, $t_g = \delta_g$
  - marginal damages per mile for electric vehicle δ_e, $t_e = \delta_e$
- Second-best policies
  - Subsidize electric miles by "environmental benefit"
  - Subsidy of $\delta_g - \delta_e$ (if electric miles replace gas miles 1:1)
  - Subsidy for electric vehicle purchase based on lifetime miles
    - Lifetime of 150,000 miles for each vehicle type
    - $S = (\delta_g - \delta_e) \bullet 150,000$

Empirical Methods

We determine marginal damages per mile: gasoline δ_{gi} & electricity δ_{ei}

- Five air pollutants: CO_2, SO_2, NO_X, $PM_{2.5}$, and VOCs
- All electric cars for sale in 2014 and close substitute gas cars
- Ford Focus makes *both* a gas model and an electric model

Sales for all EV Types

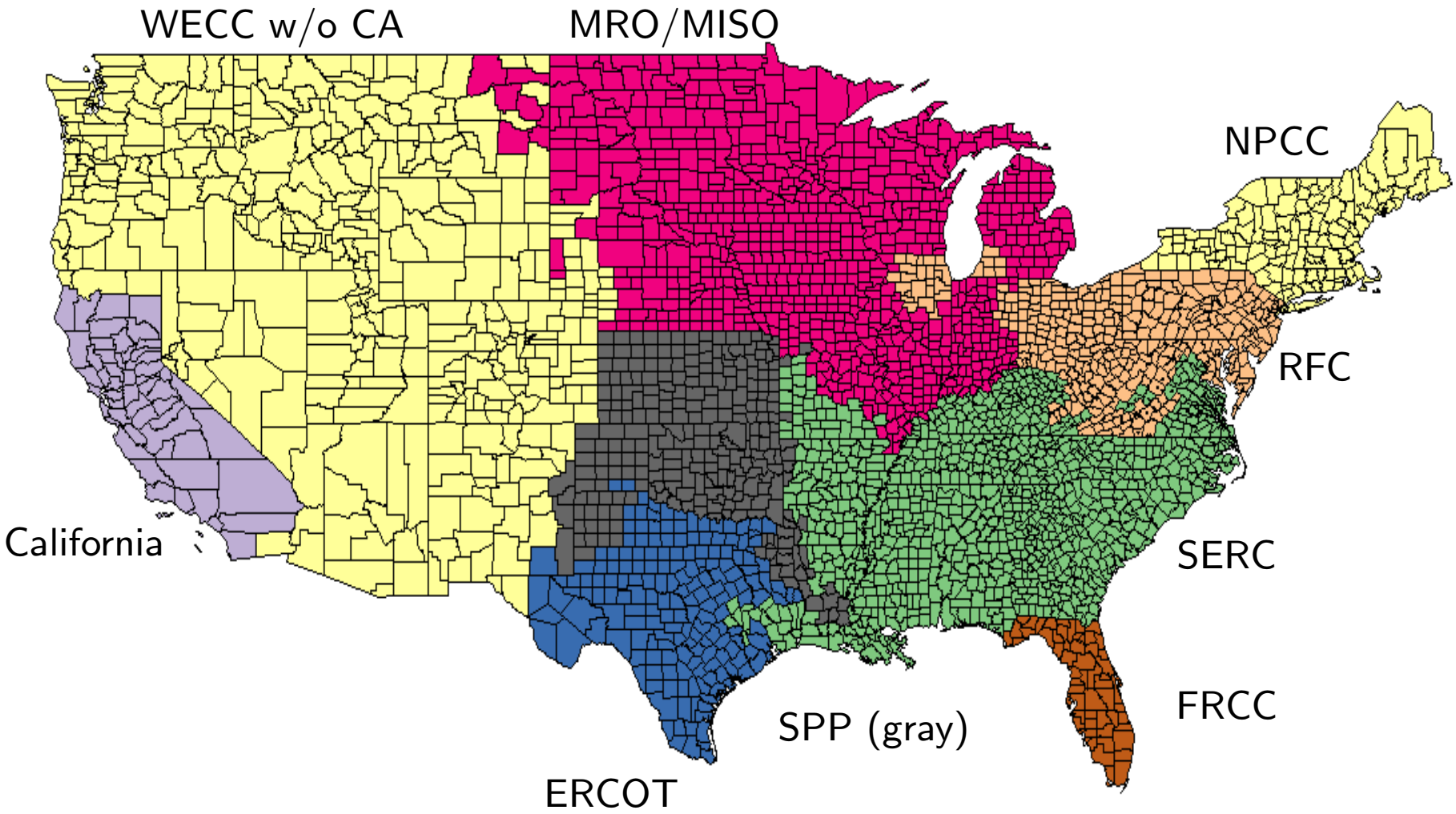
Marginal Damages of Driving

- Product of two factors
- Emissions per mile
  - Gas cars
    - Emissions per mile from GREET and EPA
    - Urban vs. rural adjustment
  - Electric cars
    - kWh per mile from EPA
    - Cold-weather adjustment
    - **Electricity generation and air pollution emissions model**
- Damages from emissions ($ per gram)
  - Global pollutant (CO_2)
    - EPA social cost of carbon ($41/ton)
  - Local pollutants (SO_2, NO_X, $PM_{2.5}$, and VOC)
    - **Air pollution integrated assessment model** (AP2)

Electricity Generation and Air Pollution Emissions

- Model the U.S. electricity grid
- Nine electricity regions (NERC) are the spatial unit for electricity load shocks due to charging electric car
- Load shock in one region may affect plants in other regions
- Plant-level regressions to estimate effects of change in load in NERC region on emissions
- Time of day when charged matters
- Data from EPA (emissions) and Federal Energy Regulatory Commission (load)

Map of Electricity Load Regions



Plant Level Regressions

$$y_{it} = \sum_{h=1}^{24} \sum_{j=1}^{J(i)} \beta_{ijh} HOUR_h LOAD_{jt} + \sum_{h=1}^{24} \sum_{m=1}^{M} \alpha_{ihm} HOUR_h MONTH_m + \varepsilon_{it},$$

- y_{it}: emissions of plant i and time t
- $J(i)$: number of regions in i's interconnection
- $HOUR_h$: hour of the day h
- $MONTH_m$: month of sample where M is the total number of months.
- $LOAD_{jt}$: electricity consumed in region j at time t.

Emission factors β_{ijh}: marginal change in emissions at plant i from an increase in electricity usage in region j in hour h.

Air pollution integrated assessment model

- AP2 model (Muller 2014)
- Maps emissions $\Rightarrow$ ambient concentrations $\Rightarrow$ damages
- Tailpipe and smokestacks emissions
  - CO_2, SO_2, NO_X, $PM_{2.5}$, and VOCs
- Damages
  - Damages from emissions of CO_2
  - Damages from ambient concentrations of SO_2, O_3, and $PM_{2.5}$
- Both full and native damages
- Counties are spatial unit

AP2 details

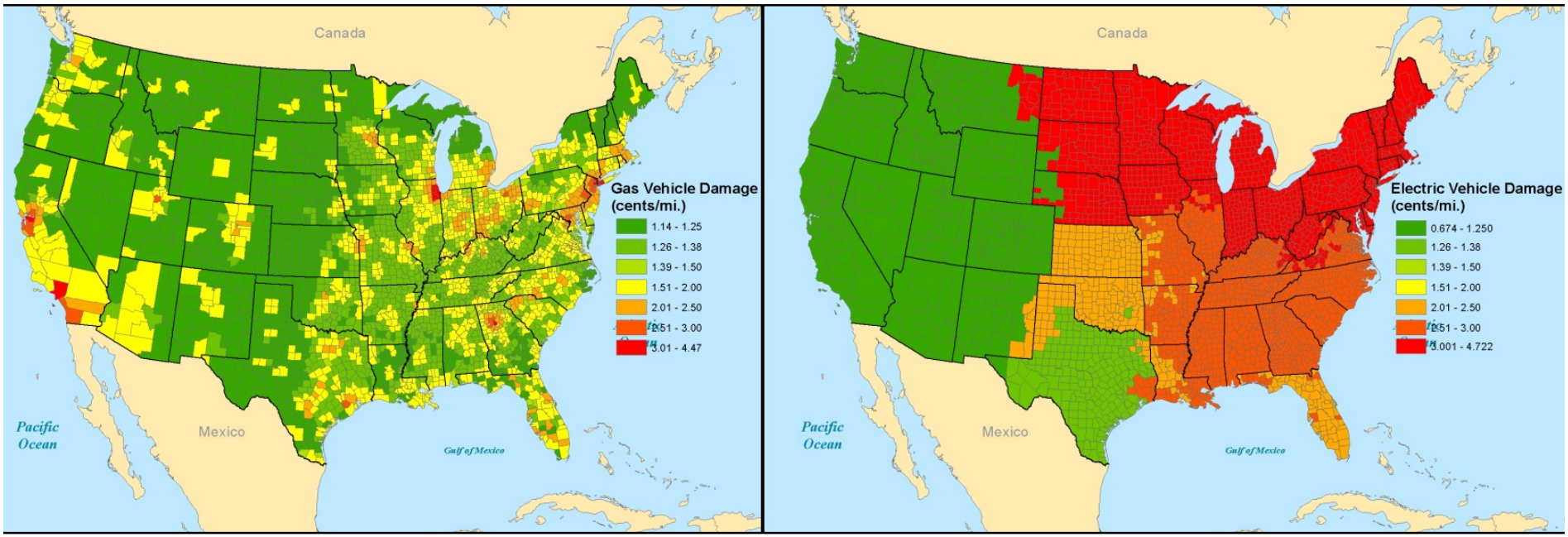
- Chemical and physical processes
  - $PM_{2.5} = f(PM_{2.5}, SO_2, NO_X, VOC)$
  - $SO_2 = f(SO_2)$
  - $O_3 = f(NO_X, VOC)$
- Damages
  - Human health due to $PM_{2.5}$ and O_3 (mortality, VSL)
  - Crop and timber losses due to O_3
  - Building and material degradation due to SO_2
  - Reduced visibility and recreation due to $PM_{2.5}$

Summary of Results

- Considerable heterogeneity in the environmental benefit of EVs
  - Range from $3025 in California to -$4773 in North Dakota
  - On average, -$742 (VMT weighted)
- Electric cars export pollution much more than gas cars
  - At state level, 90% for EVs versus 18% for gasoline cars
- Welfare effects
  - Taxing miles raises welfare relative to purchase subsidies
  - Differentiated regulation can raise welfare
  - Differentiation especially beneficial for milage taxes

Considerable Heterogeneity in the Environmental Benefits of Electric Vehicles

Map of Marginal Damages of Driving



Summary Statistics of Driving Damages

	Electric Vehicle			Gasoline Vehicle			Environmental Benefit		
Vehicle	mean	min	max	mean	min	max	mean	min	max
Ford Focus	2.50	0.67	4.72	2.00	1.13	4.47	-0.49	-3.53	3.31

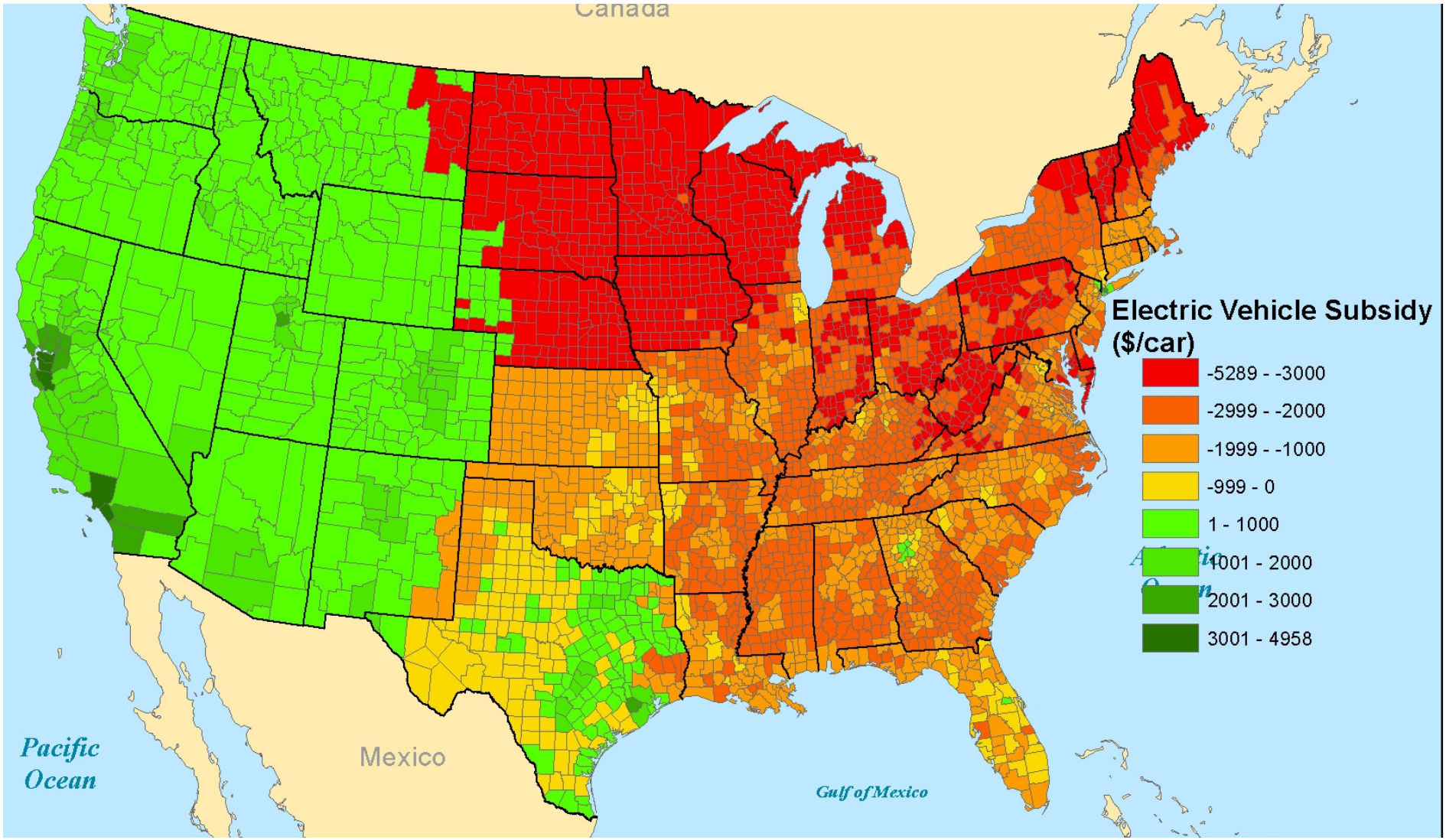
	Environmental Benefit			Global Benefit			Local Benefit		
Vehicle	mean	min	max	mean	min	max	mean	min	max
Ford Focus	-0.49	-3.53	3.31	0.59	-0.16	1.03	-1.08	-3.43	2.28

Notes: Damages and environmental benefits are in cents per mile for 2014 electric vehicles and equivalent 2014 gasoline vehicles across counties. Damages are from power plant emissions or tailpipe emissions of NO_X, VOCs, $PM_{2.5}$, SO_2, and CO_2. Electric vehicles assume the EPRI charging profile. Damages are weighted across counties by VMT.

EV Damages by Time of Day

Additional Damages Slides

Map of Second-Best EV Subsidy (150k miles/car)



Environmental Benefit by Metropolitan Statistical Areas

Metropolitan Statistical Area	Benefits per mile	Damage per Mile Gasoline	Damage per Mile Electricity	Purchase Subsidy
Los Angeles, CA	3.31	3.99	0.69	$4,958
Oakland, CA	2.35	3.04	0.68	$3,531
San Francisco, CA	2.06	2.74	0.68	$3,086
Phoenix, AZ	0.89	1.92	1.03	$1,328
Dallas, TX	0.76	2.05	1.29	$1,144
Houston, TX	0.76	2.16	1.40	$1,140
New York, NY	0.12	3.30	3.17	$184
Tampa, FL	-0.20	2.27	2.47	-$305
Atlanta, GA	-0.21	2.52	2.73	-$314
Chicago, IL	-0.60	3.12	3.72	-$900
Washington, DC	-0.72	2.31	3.03	-$1,077
Fargo, ND	-2.93	1.69	4.61	-$4,388
Grand Forks, ND	-3.00	1.66	4.66	-$4,495
Average	-0.49	2.00	2.50	-$742
Rural	-1.46	1.30	2.77	-$2,193

Notes: The environmental benefit (cents per mile) is the difference in damages between the 2014 gasoline-powered Ford Focus and the 2014 electric Ford Focus. Environmental benefit is weighted by VMT by county within each MSA. Non-urban includes all counties that are not part of an MSA. The vehicle subsidy assumes vehicle is driven 150,000 miles.

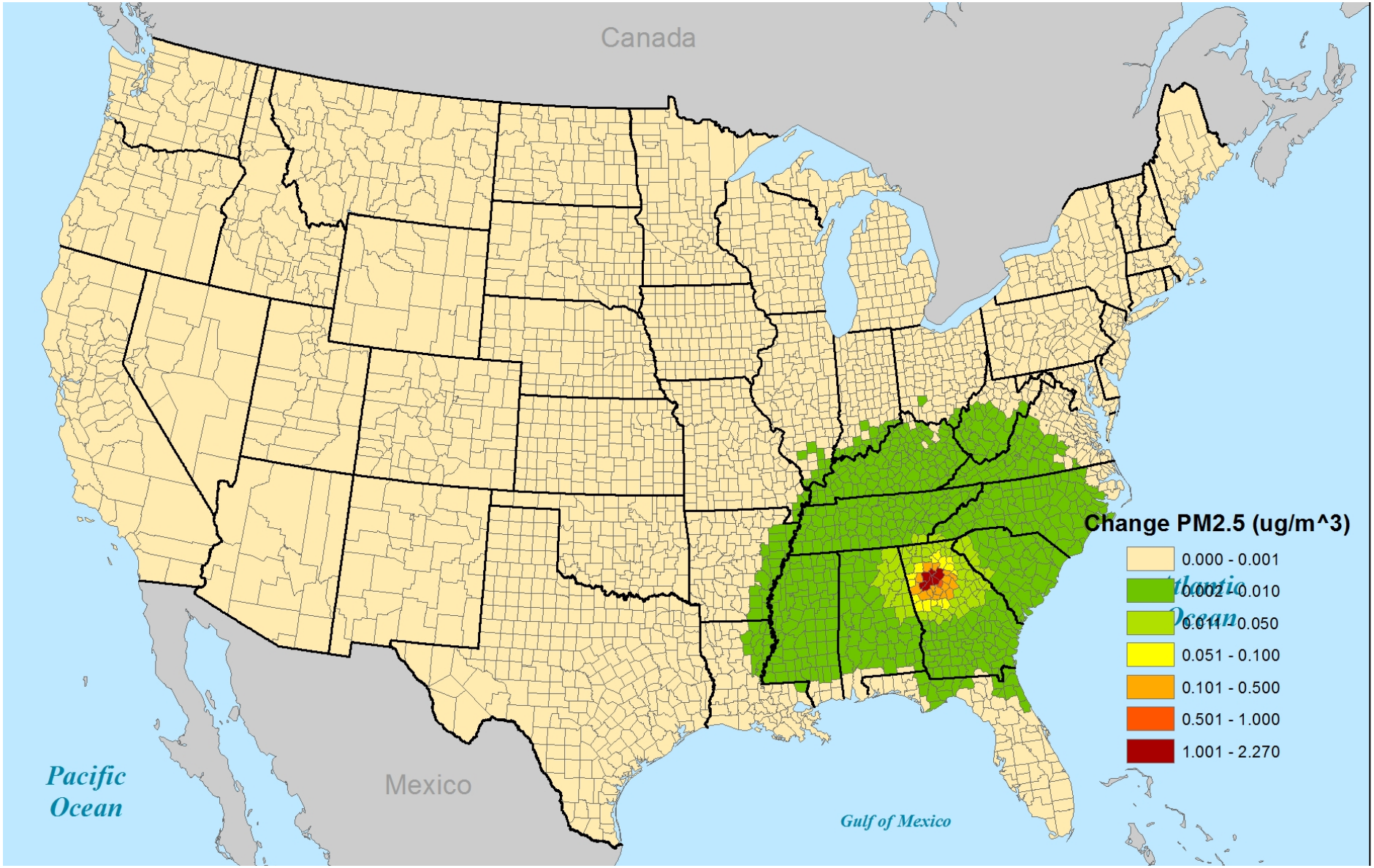
Benefits by State

Second-Best Uniform Subsidy

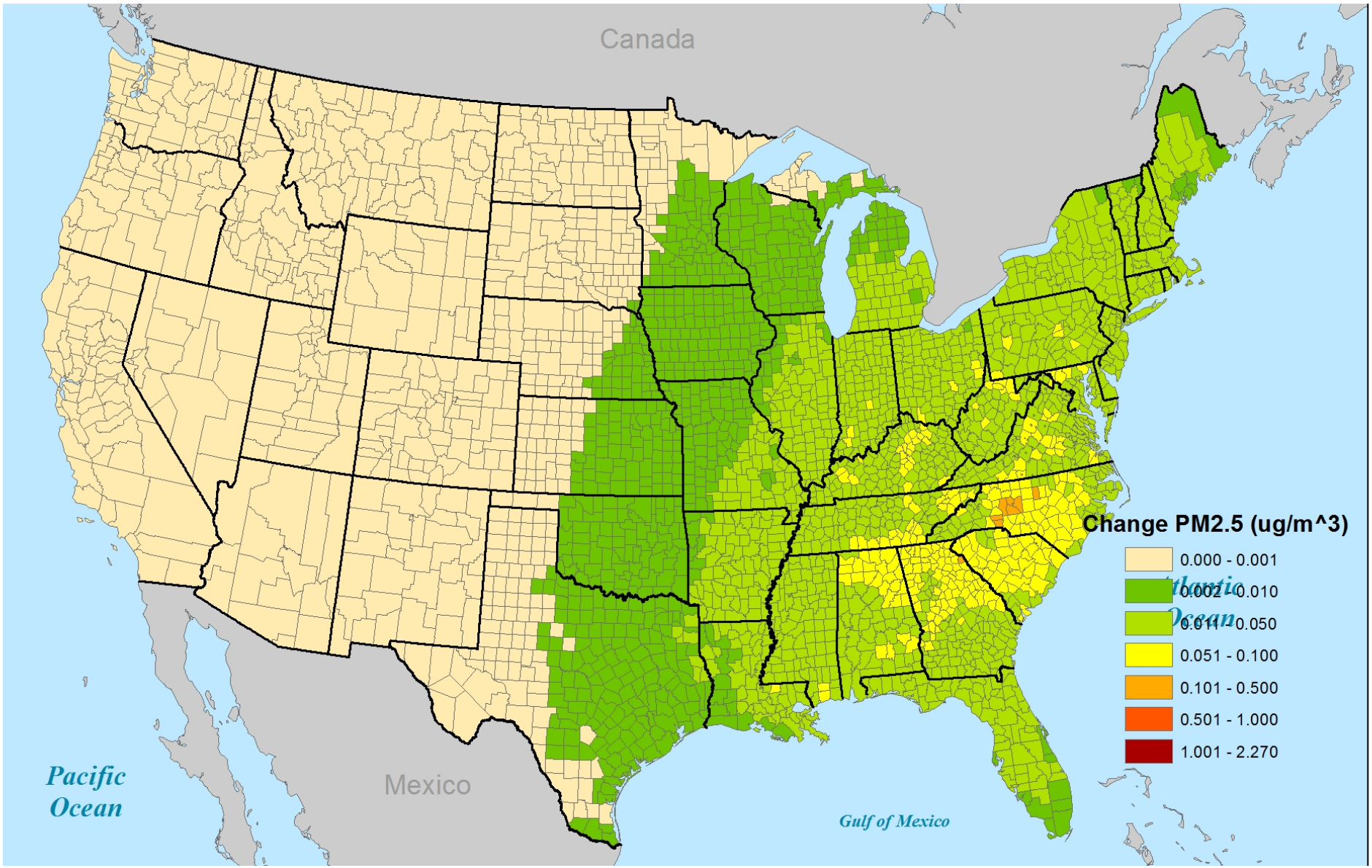
- Second-best uniform subsidy is negative (-$742)
- Considering only CO_2 emissions, subsidy is positive ($885)
- Electric cars are better for carbon emissions, but worse when we include local pollution

Electric Vehicles Export Local Pollutants Much More than Gasoline Internal Combustion Engine (ICE) Vehicles

Change in $PM_{2.5}$: Drive 1000 ICE Focus in Fulton County



Change in $PM_{2.5}$: Drive 1000 EV Focus in SERC Region



Native Damages (cents/mile) and Export Shares

Vehicle	Damages	mean	med	std. dev.	min	max
Electric	All	2.50	2.74	1.11	0.67	4.72
	Non-GHG	1.62	1.86	0.95	0.16	3.50
	State	0.15	0.16	0.07	0.04	0.33
	Export %	91%	91%			91%
	County	0.02	0.02	0.01	0.00	0.06
	Export %	99%	99%			98%
Gasoline	All	2.00	1.91	0.60	1.13	4.47
	Non-GHG	0.54	0.37	0.53	0.01	2.92
	State	0.44	0.27	0.51	0.00	2.76
	Export %	18%	27%			5%
	County	0.23	0.11	0.38	0.00	2.03
	Export %	57%	71%			30%

Notes: "All" reports damages from all pollutants at all receptors. "Non-GHG" reports damages from local pollutants (*i.e.*, excluding CO_2) at all receptors. "State" ("County") reports damages from local pollutants from receptors within the same state (county) as the source. "State Export %" ("County Export %") reports the share of non-GHG damages which occur at receptors outside the state (county).

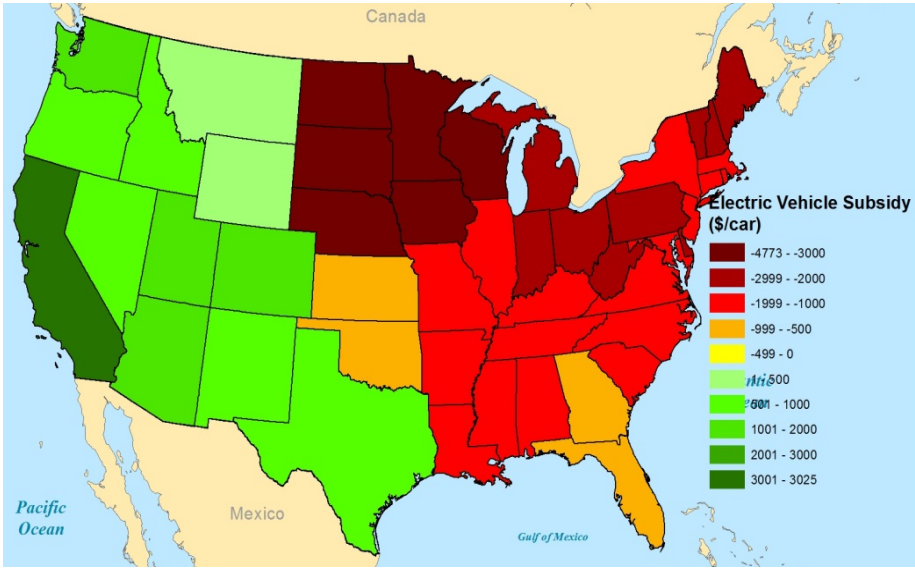
Native Benefits

Vehicle	Damages	mean	med	std. dev.	min	max
Environmental	All	-0.49	-0.81	1.34	-3.53	3.31
Benefit	Non-GHG	-1.08	-1.44	1.14	-3.43	2.28
	State	0.29	0.12	0.51	-0.32	2.46
	County	0.21	0.09	0.37	-0.06	2.00

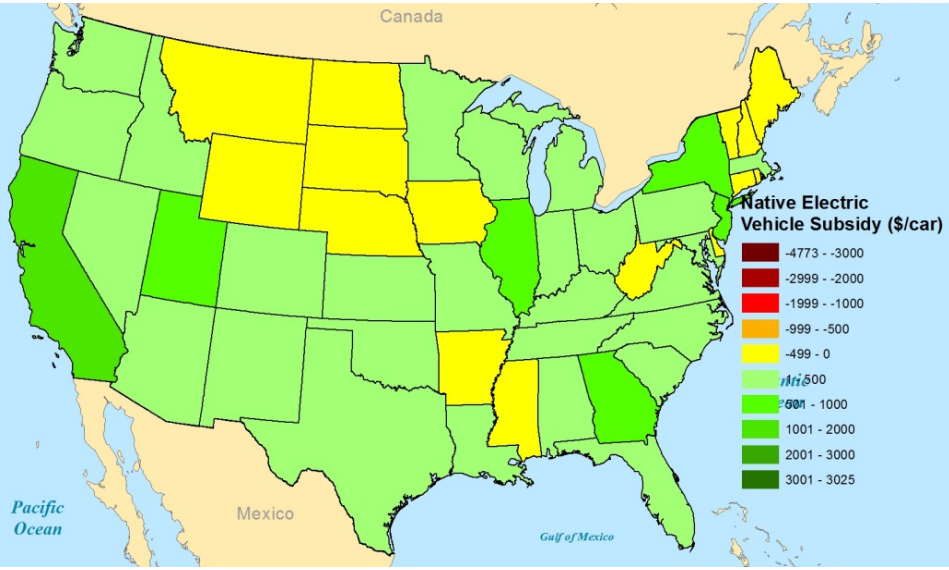
- In sum, states export 18% of gasoline damages vs. 91% for electric

"Optimal" State EV Subsidy (Full vs. Native Damages)

Full Damages



Native Damages



- When you buy an electric car, you generally make the air in *your* state cleaner (33/48 states better off)
- When you buy an electric car, you generally make *society* worse off due to dirtier air overall (only 12/48 states better off)

State EV policies

- Eight states offered purchase subsidies in 2014
  - California ($2500), Colorado ($6000), Georgia ($5000), Illinois ($4000), Maryland ($3000), Mass. ($2500), Texas ($2500) & Utah ($1500)
- Other policies such as carpool benefits, parking benefits, reduced electricity prices
- State policies more highly correlated with subsidy based on native damages than subsidy based on full damages

Welfare loss of various policies

Policy Level	Subsidy	Tax g and e	Tax g only
County Specific	1996	0	192
State Specific	2000	90	281
Uniform Federal	2024	163	336
County (native)	2022	1158	
State (native)	2026	1234	
Federal (native)	2028	911	
Actual Uniform Federal	2765		
Zero Subsidy	2027		

Notes: Welfare loss in millions \$/year.

Calibration Additional Welfare Slides

Sensitivity Analysis

- "Carbon cost": social cost of carbon of \$51 or \$31
- "No temperature adjustment": no range degradation at low temperatures
- "Flat charging profile": EV charging occurs equally in all hours (vs. EPRI)
- "Average MPG": average MPG for gasoline vehicles instead of using the city MPG in urban counties and the highway MPG in non-urban counties
- "Double gasoline emissions rates" doubles the local pollutants' emissions rates
- "\$2 Million VSL" assumes the VSL is \$2 million instead of the baseline \$6 million
- "PM dose response" assumes the higher $PM_{2.5}$ adult-mortality dose-response from Roman *et al.* (2008)
- **"Future grid & vehicle"** assumes
  - all coal-fired power plants are replaced by clean natural gas plants which are dispatched identically, and
  - the gasoline vehicle is a Toyota Prius

Sensitivity Analysis: County-level subsidies for purchase

	mean	minimum	maximum
Baseline	-742	-5295	4965
Average MPG	-945	-4950	4530
No temp adjustment	-525	-4110	4980
Future grid & cars	960	-750	4215

- Retiring coal plants results in positive EV benefits in most counties

Additional Sensitivity Slides

Interaction with other regulations

- CAFE standards
  - Assume that the current standard binds
  - Electric car sale allows another consumer to purchase a low mpg car instead of a high mpg car
  - Additional cost to society ($1439 per EV purchase)
- NO_X and SO_2 permit markets
  - Permit prices are very low right now, reflecting transactions costs
  - If permit markets do not bind, then EV local externalities
  - What if bind?
    - General equilibrium effects like other inputs
    - However permit price may change, causing wealth transfers

Conclusions

- Large geographic variation in environmental benefits of electric cars
- Local discretion in regulation?
  - Problem of pollution export
  - Federal policy but can it differentiate by location?
- Environmental benefits *alone* do not justify $7500 subsidy
- Pigovian taxes! But no, subsidy on purchase
- Unintended consequences. E.g., CAFE

Appendix Slides

Registered Electric Vehicles

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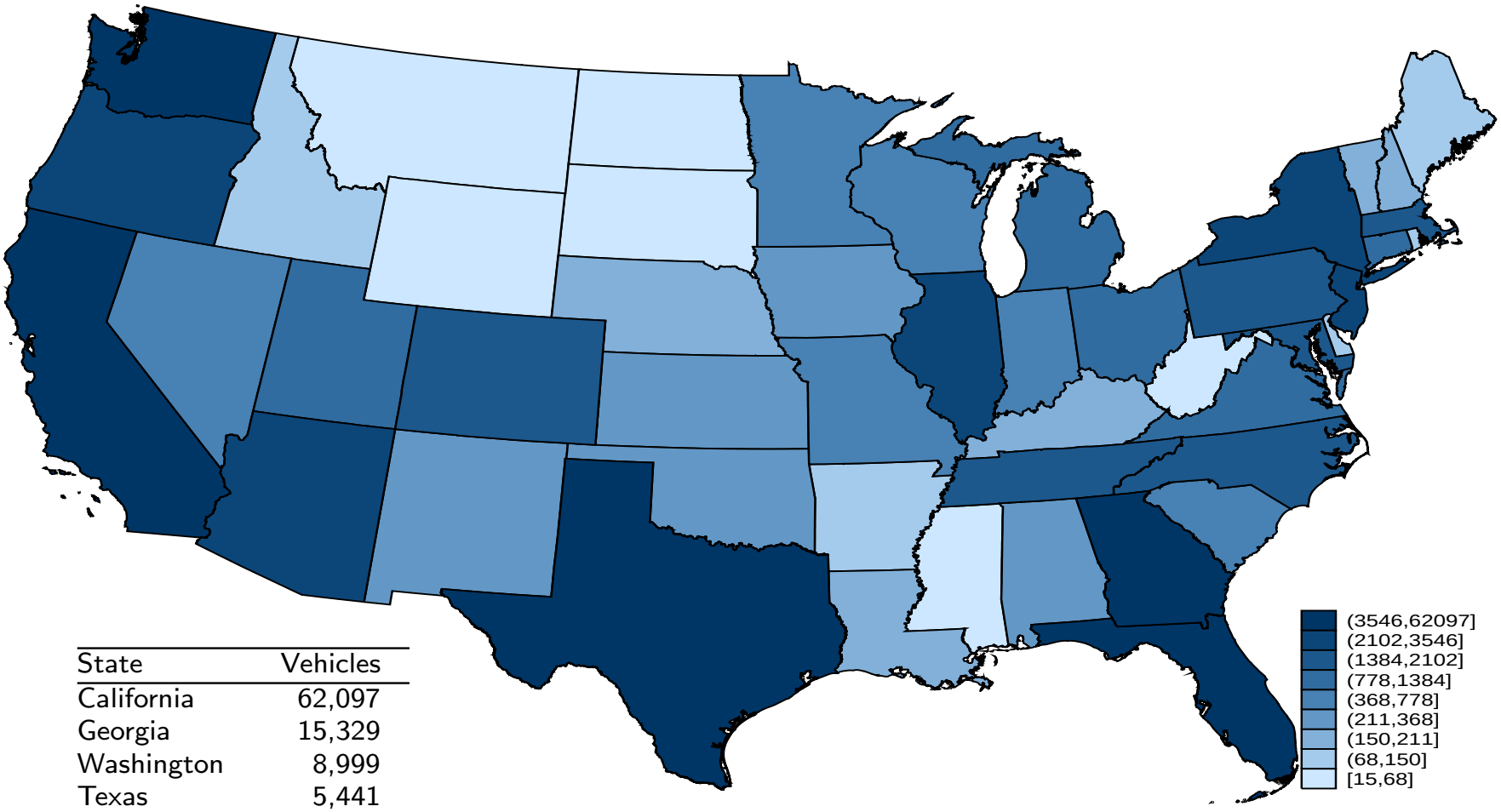

State	Vehicles
California	62,097
Georgia	15,329
Washington	8,999
Texas	5,441
Florida	4,765
Oregon	3,546
Illinois	3,073
New York	2,442
New Jersey	2,284
Arizona	2,133

Types of Electric Cars

Electric Car Model	Registered Number of Cars	Equivalent Gasoline Car Model
Chevy Spark EV	1,899	Chevy Spark
Honda Fit EV	1,055	Honda Fit
Fiat 500e	8,555	Fiat 500
Nissan Leaf	69,860	Toyota Prius
Mitsubishi i-Miev	1,721	Chevy Spark
Smart Fortwo EV	4,077	Smart Fortwo
Ford Focus EV	4,436	Ford Focus
Tesla S (60/85 kWh)	38,235	BMW 740/750
Toyota Rav4 EV	2,456	Toyota Rav4
BYD e6	n/a	Toyota Rav4

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Mean Damages by Electricity Region (cents per mile)

	Damages in cents per mile								
Region	EPRI	Flat	Hr 1-4	Hr 5-8	Hr 9-12	Hr 13-16	Hr 17-20	Hr 21-24	VMT (pct)
California	0.69	0.75	0.65	0.78	0.78	0.84	0.82	0.64	12%
WECC w/o CA	1.03	0.92	1.18	0.98	0.84	0.76	0.73	0.99	10%
ERCOT	1.28	1.21	1.50	1.41	1.10	1.07	1.05	1.16	8%
FRCC	2.48	2.14	3.21	2.36	2.25	1.39	1.53	2.11	7%
SERC	2.75	2.68	2.76	2.26	2.73	2.97	2.64	2.72	24%
SPP	2.24	2.74	2.07	4.91	2.30	2.89	2.39	1.89	4%
NPCC	3.11	2.75	4.19	3.75	1.61	2.12	2.49	2.35	9%
RFC	3.65	3.56	3.44	3.39	3.85	3.07	3.44	4.17	22%
MRO	4.39	3.61	5.77	4.01	3.11	2.63	2.37	3.78	5%
Total	2.50	2.38	2.69	2.49	2.30	2.18	2.18	2.44	100%

Notes: 2014 Ford Focus electric vehicle for different charging profiles Back to Damages Slides

Summary Statistics

	Electric Vehicle			Gasoline Vehicle			Environmental Benefit		
Vehicle	mean	min	max	mean	min	max	mean	min	max
Chevy Spark	2.20	0.59	4.17	1.81	1.05	4.42	-0.39	-3.05	3.20
Honda Fit	2.22	0.60	4.20	2.07	1.24	4.96	-0.15	-2.88	3.73
Fiat 500e	2.26	0.61	4.27	1.87	1.03	4.75	-0.39	-3.17	3.45
Nissan Leaf	2.30	0.62	4.35	1.31	0.81	3.60	-1.00	-3.44	2.29
Mitsubishi i-Miev	2.34	0.63	4.41	1.81	1.05	4.42	-0.53	-3.30	3.17
Smart fortwo	2.45	0.66	4.63	1.78	1.08	4.61	-0.67	-3.48	3.24
Ford Focus	2.50	0.67	4.72	2.00	1.13	4.47	-0.49	-3.53	3.31
Tesla S (60 kWh)	2.72	0.73	5.15	2.64	1.41	5.68	-0.09	-3.65	4.48
Tesla S (85 kWh)	2.96	0.80	5.59	2.89	1.63	5.96	-0.07	-3.87	4.77
Toyota Rav4	3.45	0.93	6.52	2.25	1.32	5.18	-1.21	-5.11	3.66
BYD e6	4.20	1.13	7.94	2.25	1.32	5.18	-1.96	-6.52	3.45

Notes: Damages and environmental benefits are in cents per mile for 2014 electric vehicles and equivalent 2014 gasoline vehicles across counties. Damages are from power plant emissions or tailpipe emissions of NO_X, VOCs, $PM_{2.5}$, SO_2, and CO_2. Electric vehicles assume the EPRI charging profile. Damages are weighted across counties by VMT.

Decomposition of Benefits

	Environmental Benefit			Global Env. Benefit			Local Env. Benefit		
Vehicle	mean	min	max	mean	min	max	mean	min	max
Chevy Spark	-0.39	-3.05	3.20	0.47	-0.09	0.84	-0.87	-3.01	2.37
Honda Fit	-0.15	-2.88	3.73	0.66	0.09	1.03	-0.81	-3.02	2.71
Fiat 500e	-0.39	-3.17	3.45	0.45	-0.15	0.83	-0.84	-3.08	2.63
Nissan Leaf	-1.00	-3.44	2.29	-0.01	-0.36	0.35	-0.98	-3.16	1.99
Mitsubishi i-Miev	-0.53	-3.30	3.17	0.42	-0.16	0.82	-0.95	-3.20	2.36
Smart fortwo	-0.67	-3.48	3.24	0.30	-0.19	0.68	-0.97	-3.34	2.57
Ford Focus	-0.49	-3.53	3.31	0.59	-0.16	1.03	-1.08	-3.43	2.28
Tesla S (60 kWh)	-0.09	-3.65	4.48	1.02	0.00	1.56	-1.11	-3.72	2.93
Tesla S (85 kWh)	-0.07	-3.87	4.77	1.18	0.10	1.76	-1.25	-4.04	3.02
Toyota Rav4	-1.21	-5.11	3.66	0.39	-0.46	0.96	-1.59	-4.73	2.71
BYD e6	-1.96	-6.52	3.45	0.12	-0.85	0.81	-2.08	-5.78	2.66

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Environmental Benefit by State

State	Environmental benefit per mile	VMT (pct)	Damage per mile (gasoline)	Damage per mile (electric)	Purchase Subsidy
Highest Benefit States					
California	2.02	12%	2.71	0.69	$3,025
Utah	0.88	1%	1.92	1.04	$1,320
Colorado	0.75	2%	1.78	1.03	$1,123
Washington	0.74	1%	1.76	1.02	$1,108
Arizona	0.73	2%	1.75	1.02	$1,093
Lowest Benefit States					
South Dakota	-2.52	0%	1.40	3.92	-$3,787
Minnesota	-2.57	1%	1.57	4.14	-$3,856
Nebraska	-2.63	2%	1.85	4.48	-$3,951
Iowa	-2.75	1%	1.49	4.24	-$4,118
North Dakota	-3.18	0%	1.39	4.58	-$4,773

Environmental Benefit by State (cont.)

State	Environmental benefit per mile	VMT (pct)	Damage per mile (gasoline)	Damage per mile (electric)	Purchase Subsidy
Other High VMT States					
Texas	0.52	9%	1.90	1.38	$784
Florida	-0.55	7%	1.94	2.49	-$829
Georgia	-0.64	4%	2.10	2.74	-$955
New York	-0.75	5%	2.35	3.10	-$1,122
New Jersey	-0.91	3%	2.70	3.61	-$1,367
Virginia	-1.02	4%	1.87	2.89	-$1,532
Ohio	-1.62	5%	2.02	3.65	-$2,437
Pennsylvania	-1.65	3%	2.00	3.64	-$2,472
Indiana	-1.70	3%	1.96	3.65	-$2,543
Michigan	-1.81	3%	1.93	3.75	-$2,720

Calibration for Welfare Analysis

- Calibrate the theory model
- Price of gas miles ($0.11), price of electric miles ($0.04)
- Price of gas car ($35,170), price of electric car ($16,810)
- Constant elasticity f and h (elasticity for miles -0.5)
- Percent of sales due to subsidy (50%, Li *et al.* 2015)
- Determine H and μ

Back to Welfare

Deadweight Losses of Differentiated VMT Taxes

	Gas and Electric Tax			Gas Tax Only			Electric Tax Only		
	BAU EV Share			BAU EV Share			BAU EV Share		
	1%	5%	10%	1%	5%	10%	1%	5%	10%
County policies	0	0	0	192	863	1543	1958	1994	2042
State policies	90	102	118	281	962	1688	1960	2005	2064
Federal policy	163	273	415	336	1004	1830	1983	2121	2303
County (Native)	1158	1445	1808						
State (Native)	1234	1531	1906						
Federal (Native)	911	1034	1194						

Notes: Deadweight loss in millions of dollars per year is based on 15 million annual vehicle sales normalized to the emissions profile of the Ford Focus. The BAU EV Share is the proportion of electric vehicles sold if there were no subsidy. This share is determined by the assumed value for μ (10735.3, 16753.7, 22451.1) which is proportional to the standard deviation of the unobserved relative preference shock. Federal taxes in the joint tax case are 2.0 cents per mile on gasoline miles and 2.5 cents per mile on electric miles.

Deadweight Losses of Differentiated Electric Vehicle Purchase Subsidies

	BAU EV Share		
	1%	5%	10%
County policies	1996	2182	2411
State policies	2000	2205	2458
Federal policy (-$742 subsidy)	2024	2324	2703
County policies (native damages)	2022	2315	2686
State policies (native damages)	2026	2333	2723
Federal policy (native damages, -$1553 subsidy)	2028	2344	2744
Current Federal Policy ($7500 subsidy)	2765	6009	10015
BAU Federal Policy (Zero subsidy)	2027	2343	2742

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Sensitivity Analysis: Damages

	Electric Vehicle			Gasoline Vehicle			Environmental Benefit		
	mean	min	max	mean	min	max	mean	min	max
Baseline	2.50	0.67	4.72	2.00	1.13	4.47	-0.49	-3.53	3.31
Carbon cost									
SCC=$51	2.71	0.80	5.02	2.36	1.41	4.84	-0.35	-3.55	3.56
SCC=$31	2.28	0.55	4.42	1.65	0.86	4.09	-0.64	-3.50	3.06
No temperature adjustment	2.35	0.67	3.90	2.00	1.13	4.47	-0.35	-2.74	3.32
Flat charging profile	2.38	0.74	3.88	2.00	1.13	4.47	-0.38	-2.69	3.24
Average MPG	2.50	0.67	4.72	1.87	1.36	4.23	-0.63	-3.30	3.02
Double gasoline emissions rates	2.50	0.67	4.72	2.54	1.15	7.38	0.04	-3.48	5.75
$2 Million VSL	1.57	0.71	2.64	1.68	1.13	2.69	0.12	-1.49	1.78
PM dose response	3.59	1.25	6.89	2.31	1.14	6.10	-1.28	-5.65	4.05
Future grid & vehicle	0.66	0.37	1.39	1.31	0.81	3.60	0.64	-0.50	2.81

Notes: Damages in cents per mile for 2014 electric and gasoline Ford Focus.

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