ECON 8000/9000 Empirical Energy Econ

Topic 10: Energy Efficiency and Rebound Effect

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March 9, 2026

Outline

- Energy Efficiency and Rebound Effect
- Example 1: Linn (2016) Energy J
- Example 2: Aydin, Kok, & Brounen (2017) RAND J

Energy Efficiency Policies

Goals and examples

Goals of energy efficiency policy: achieve the efficient allocation

- Suppose the total energy consumption is over-allocated due to some market failure (e.g., pollution externality, GHG emission externality, energy efficiency gap, etc.)
  - e.g., kwh of electricity for end-user consumers
  - e.g., gallons of fuels for car drivers
  - e.g., tonnes of coals used for power plants
- Here enter second-best policies and interventions on energy efficiency
  - e.g., fuel economy standard for vehicles, California ZEV policy
  - e.g., fuel tax to incentivize adoption for more fuel-efficient vehicles
  - e.g., building codes for buildings
  - e.g., energy sar labels and fuel economy labels
  - e.g., weatherization for homes
  - e.g., renewable portfolio standard for power plants
  - e.g., investment tax credit for renewables
- EE policies target:
  - adopting a more energy-efficient product
  - adopting a more energy-efficient production technology

Energy Efficiency Policies

Rebound effect: an unintended consequence

Goals of energy efficiency policy: achieve the efficient allocation

- Suppose the total energy consumption is over-allocated due to some market failure (e.g., pollution externality, energy efficiency gap, etc.)
  - e.g., kwh of electricity for end-user consumers
  - e.g., gallons of fuel used by car drivers
  - e.g., tonnes of coal used by power plants
- **EE policies do not target: reducing energy consumption**
- Worse, adopting a more energy-efficient product may incentivize greater energy usage
  - e.g., VMT may be greater if one buys a more fuel-efficient car
  - e.g., use more electricity if one improves the energy efficiency of their homes
- This phenomenon is known as **rebound effect**
  - efficiency gain: potential greater private surplus (CS and PS)
  - efficiency loss: If total energy is previously over-allocated, the existence of the rebound effect would undermine the effectiveness of energy-efficiency policies and interventions

Rebound Effect

Typical questions:

Most common questions:

- Does adopting a more energy-efficient product lead to greater usage (e.g., VMT, kWh)?
- What is the elasticity of energy usage w.r.t. to energy price or energy-efficiency ratings?
- What is/are the mechanism(s) of the rebound effect?
- What is the distributional impact of the rebound effect?

More niche questions:

- In what scenarios do we not observe a rebound effect? Or even the opposite of a rebound effect? What may be potential causes?

Another margin similar to the rebound effect: delayed exit/obsolescence

- e.g., do fuel economy regulations cause people to delay scrapping their vehicles for prolonged periods?
- e.g., do vintage-differentiated regulations (VDRs) for the power sector delay power plant retirements?

Outline

- Energy Efficiency and Rebound Effect ✓
- Example 1: Linn (2016) Energy J
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Linn (2016) Energy Journal

"Rebound effect for passenger vehicles"

Research Question:

- What is the elasticity of vehicle miles travelled (VMT) w.r.t. operating fuel cost (dollar-per-mile)?
- What is the elasticity of VMT w.r.t. fuel price?
- What is the elasticity of VMT w.r.t. fuel economy?

Data

- NHTS 2009 from NHTSA
- Fuel price from ACCRA (city X quarter) and EIA (state X month)

Empirical Strategy

Cross-sectional log-log regression for elasticity

For household h using vehicle i, the author consider Eq (1-2):

$$\ln VMT_{hi} = \delta_0 + \delta_1 \ln dpm_{hi} + \beta \mathbf{X_h} + \varepsilon_{hi} \tag{1}$$

$$\ln VMT_{hi} = \delta_0 + \delta_1 \ln fp_h + \delta_2 \ln m_{hi} + \delta_3 \ln \bar{m}_{h,-i} + f\left(\mathbf{X_h}, \eta_i\right) + \varepsilon_{hi} \tag{2}$$

- Ideally, Eq(1) will estimate elasticity of VMT w.r.t. operating fuel cost
    - $dpm_{hi} = fp_h \cdot \frac{1}{m_{hi}}$: operating fuel cost (dollar-per-mile)
- Consider Eq (2)
    - m_{hi}: fuel economy (mpg)
    - $\bar{m}_{h,-i}$: average fuel economy for other vehicles within the household
    - IVs for m_{hi}: fuel price $\widehat{fp}$ when vehicle was purchased X vehicle vintage
      fuel price $\widehat{fp}$ when vehicle was purchased X demographics
      Note: Fuel price $\widehat{fp} \neq fq$ aka when households were surveyed for their VMT
      Note: This is a bit similar to using cohort-specific gas price in Severen & van Banthem (2022)
    - IVs for $\bar{m}$: similar to the two IVs above
    - Controls: CMSA FE, survey month FE, demographic controls
    - Q1: What's the benefit of running Eq(2) instead of Eq(1)?

Results

Elasticity of VMT wrt MPG: 0.2-0.4 within a household

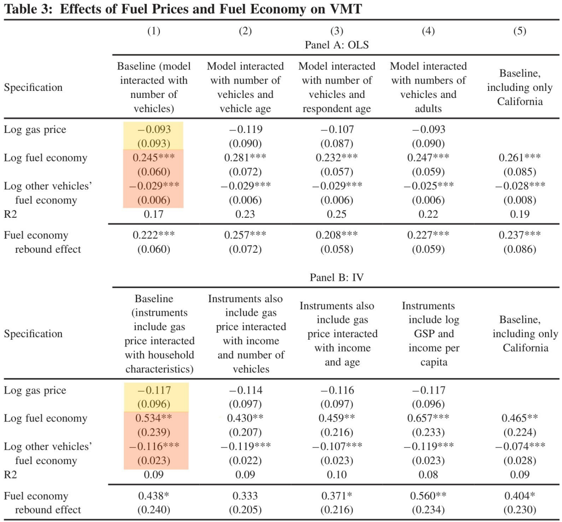


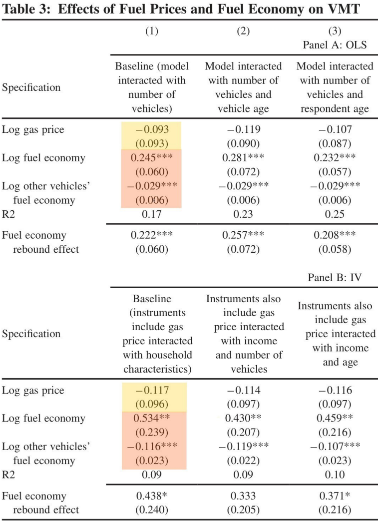
Table 3: Effects of Fuel Prices and Fuel Economy on VMT

	(1)	(2)	(3)	(4)	(5)
			Panel A: OLS		
Specification	Baseline (model interacted with number of vehicles)	Model interacted with number of vehicles and vehicle age	Model interacted with number of vehicles and respondent age	Model interacted with numbers of vehicles and adults	Baseline, including only California
Log gas price	−0.093	−0.119	−0.107	−0.093	
	(0.093)	(0.090)	(0.087)	(0.090)	
Log fuel economy	0.245***	0.281***	0.232***	0.247***	0.261***
	(0.060)	(0.072)	(0.057)	(0.059)	(0.085)
Log other vehicles' fuel economy	−0.029***	−0.029***	−0.029***	−0.025***	−0.028***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.008)
R2	0.17	0.23	0.25	0.22	0.19
Fuel economy rebound effect	0.222***	0.257***	0.208***	0.227***	0.237***
	(0.060)	(0.072)	(0.058)	(0.059)	(0.086)
			Panel B: IV		
Specification	Baseline (instruments include gas price interacted with household characteristics)	Instruments also include gas price interacted with income and number of vehicles	Instruments also include gas price interacted with income and age	Instruments include log GSP and income per capita	Baseline, including only California
Log gas price	−0.117	−0.114	−0.116	−0.117	
	(0.096)	(0.097)	(0.097)	(0.096)	
Log fuel economy	0.534**	0.430**	0.459**	0.657***	0.465**
	(0.239)	(0.207)	(0.216)	(0.233)	(0.224)
Log other vehicles' fuel economy	−0.116***	−0.119***	−0.107***	−0.119***	−0.074***
	(0.023)	(0.022)	(0.023)	(0.023)	(0.028)
R2	0.09	0.09	0.10	0.08	0.09
Fuel economy rebound effect	0.438*	0.333	0.371*	0.560**	0.404*
	(0.240)	(0.205)	(0.216)	(0.234)	(0.230)

- Q2: Why are fuel economy elasticities underestimated in OLS?

Implication: Fuel Economy Standard as EE policy

Simulate fuel consumption if all MPG in 2009 survey raised to 2016 standard



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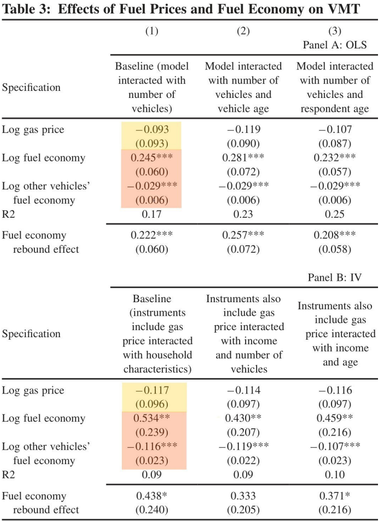
Case 1: no rebound

- Simulate Δfuel consumption (gallon)
- Δfuel economy (mpg)% $= 44\%$
- Δfuel consumpion rate (gpm)% $= 1 - \frac{1}{1.44} = 1 - 0.69 = -31\%$

Implication: Fuel Economy Standard as EE policy

Simulate fuel consumption if all MPG in 2009 survey raised to 2016 standard



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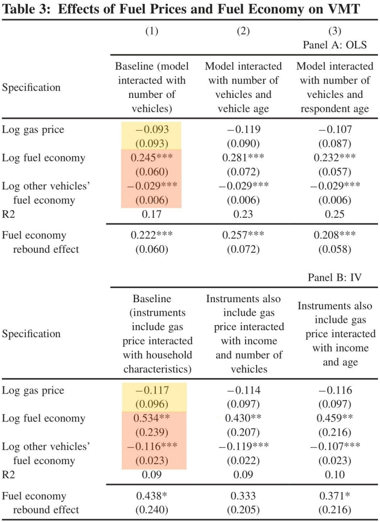
  Δfuel consumption (gallon)% $= \Delta$gpm% $= -31\%$
- Fuel consumption $\downarrow$ 31%

Implication: Fuel Economy Standard as EE policy

Simulate fuel consumption if all MPG in 2009 survey raised to 2016 standard



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Case 2: Baseline rebound results:

- Consider IV result col 1:
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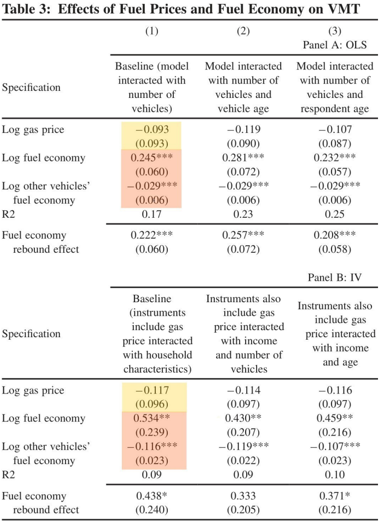

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- ΔVMT $= 0.44 \times 0.438 = 19.3\%$

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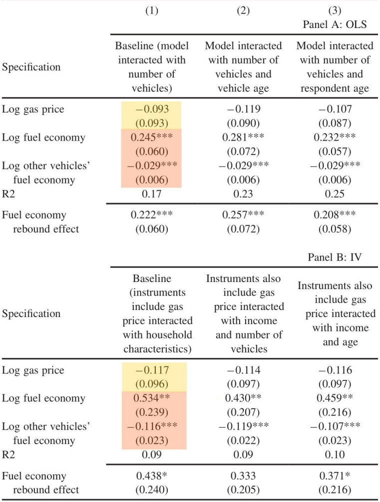

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- If rebound effect's elasticity $= 0.438$
- ΔVMT $= 0.44 \times 0.438 = 19.3\%$
- Δfuel consumption (gallon)% $= 0.69 \times 1.193 - 1 = -18\%$
- Fuel consumption only $\downarrow$ 18%

Implication: Fuel Economy Standard as EE policy

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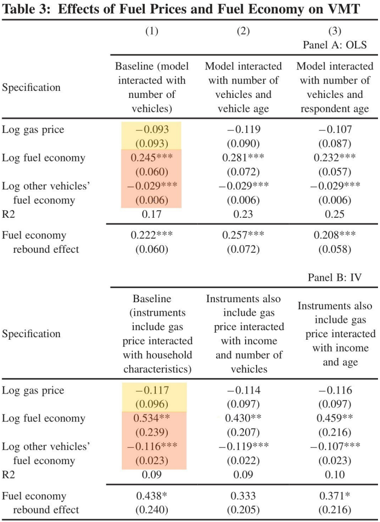

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- Fuel consumption only $\downarrow$ 18%
- Author's calculation: ΔVMT $= 18\%$
- Author's calculation: Δfuel consump. $= -19\%$

Outline

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- Example 1: Linn (2016) Energy J ✓
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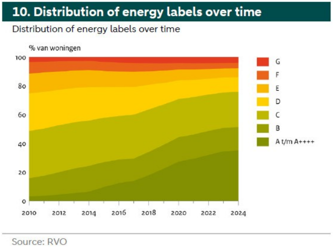
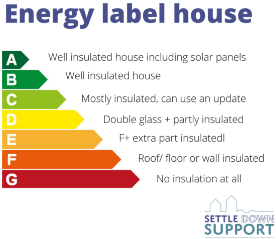
"Energy efficiency & hh behavior: rebound effect in residential sector"

Research Question: How do residents' energy consumption respond to engineer ratings of energy efficiency?

- Context: Energy label in the Netherlands 2008-2011
- All homes are regulated to have energy performance ratings (A++ to G)
- Outcome yvar: natural gas consumption (in m^3)





Label:
Label-A ($EI < 1.06$)
Label-B ($1.05 < EI < 1.31$)
Label-C ($1.30 < EI < 1.61$)
Label-D ($1.60 < EI < 2.01$)
Label-E ($2.00 < EI < 2.41$)
Label-F ($2.40 < EI < 2.91$)
Label-G ($2.90 < EI$)

Aydin, Kok, & Brounen (2017) RAND J

Suggestive evidence of rebound effect

FIGURE 1

PREDICTED VERSUS ACTUAL ANNUAL GAS CONSUMPTION

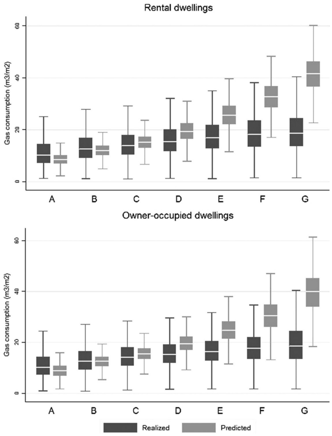
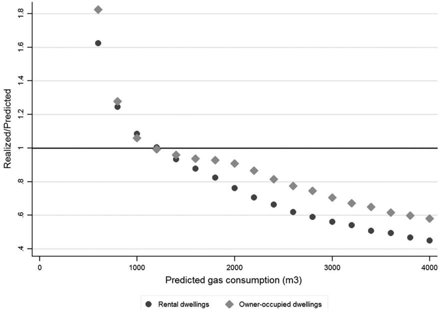


FIGURE 3

ACTUAL/PREDICTED ANNUAL GAS CONSUMPTION



Empirical Strategy

A log-log regression for elasticity

For household *i* year *t*, they estimate:

$$\ln G^a_{it} = \beta_0 + \beta_1 \ln G^p_{it} + \sum_j \beta_j \mathbf{Z_{ijt}} + \alpha_i + \varepsilon_{it}$$

- G^a: actual energy consumption
- G^p: predicted energy consumption on the label based on: e.g., home size, insulation, window
- **Z**: hh characteristics that affect energy consumption: e.g., hh size, income, owner/rental, location, year
- Rebound effect (in elasticity) $\tau = 1 - \beta_1$
- IV for G^p: year of construction
  - Idea: the year of construction implicitly has info on (i) vintage of the home and (ii) home-building technology when the home was constructed

Main Results

Homeowners vs renters

TABLE 4 **Instrumental Variable Estimations**

	τ=0.41 (1)	τ=0.27 (2)
	Rental	Owner-Occupied
Log (predicted annual gas consumption)	0.587^{***}	0.733^{***}
	[0.012]	[0.016]
Number of household members	0.093^{***}	0.105^{***}
	[0.004]	[0.009]
Number of household members^2	-0.010^{***}	-0.011^{***}
	[0.001]	[0.001]
Number of children (Age $<$ 18)	-0.004^{***}	0.001
	[0.001]	[0.003]
Number of elderly (Age $>$ 64)	0.034^{***}	0.043^{***}
	[0.002]	[0.004]
Number of females in household	0.037^{***}	0.015^{***}
	[0.001]	[0.002]
All household members are working (1=yes)	-0.056^{***}	-0.038^{***}
	[0.002]	[0.004]
Log (household annual income)	0.052^{***}	0.051^{***}
	[0.002]	[0.006]
Receiving rent subsidy (1=yes)	-0.034^{***}	
	[0.002]	
Province dummy	Yes	Yes
Year dummy	Yes	Yes
Constant	2.276^{***}	1.208^{***}
	[0.078]	[0.130]
R^2	0.239	0.375
R^2 (First-stage regression)	0.225	0.256
First-stage F-statistic on the excluded IVs	34123	1191
Number of observations	1,664,113	87,282
Number of dwellings	519,512	43,498

Distributional Effects

What are the implications on equity and efficiency?

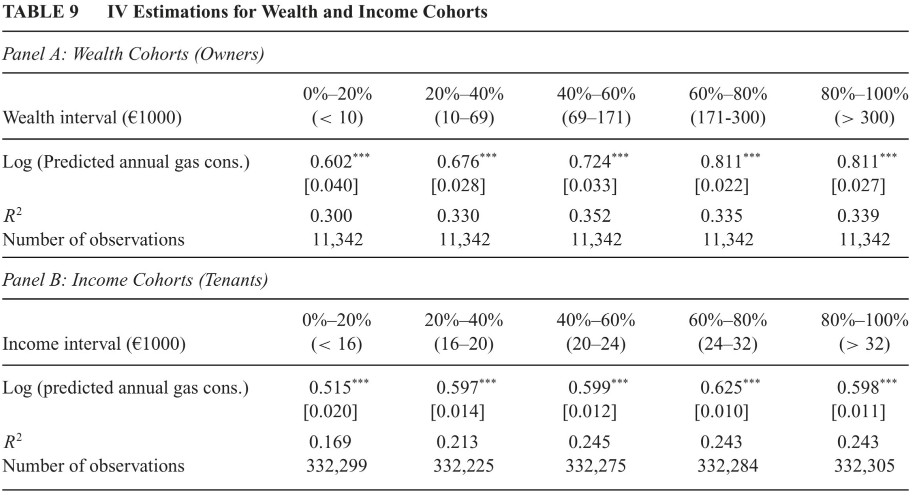


TABLE 9 IV Estimations for Wealth and Income Cohorts

Panel A: Wealth Cohorts (Owners)

Wealth interval (€1000)	0%–20% (< 10)	20%–40% (10–69)	40%–60% (69–171)	60%–80% (171-300)	80%–100% (> 300)
Log (Predicted annual gas cons.)	0.602***	0.676***	0.724***	0.811***	0.811***
	[0.040]	[0.028]	[0.033]	[0.022]	[0.027]
R^2	0.300	0.330	0.352	0.335	0.339
Number of observations	11,342	11,342	11,342	11,342	11,342

Panel B: Income Cohorts (Tenants)

Income interval (€1000)	0%–20% (< 16)	20%–40% (16–20)	40%–60% (20–24)	60%–80% (24–32)	80%–100% (> 32)
Log (predicted annual gas cons.)	0.515***	0.597***	0.599***	0.625***	0.598***
	[0.020]	[0.014]	[0.012]	[0.010]	[0.011]
R^2	0.169	0.213	0.245	0.243	0.243
Number of observations	332,299	332,225	332,275	332,284	332,305

Outline

- Energy Efficiency and Rebound Effect ✓
- Example 1: Linn (2016) Energy J ✓
- Example 2: Aydin, Kok, & Brounen (2017) RAND J ✓
- Example 3: West, Hoekstra, Meer, & Puller (2017) JPubE

West, Hoekstra, Meer, Puller (2016) JPubE

VM(not)T: Fuel economy requirement, vehicle characteristics, & hh driving

Research Question:

- What is the rebound effect from an exogenous shock on fuel economy requirement driven by the Cash for Clunker (CfC) program?
- How should we think of the rebound effect, considering the tradeoff between fuel economy v. other attributes?

West et al. (2016) JPubE: VM(not)T

Innovations

Innovation 1:

- Unless in the scenario of a natural experiment in energy efficiency (e.g., AKB (2017)), most studies on the rebound effect rely on variation in fuel price (e.g., some specs in Linn (2016))
- For that reason:
  It is difficult to estimate the rebound effect $\varepsilon_{\text{usage,energy efficiency}}$ such as $\varepsilon_{\text{vmt,mpg}}$
  Most studies settle to estimate $\varepsilon_{\text{usage,operating energy cost}}$ such as $\varepsilon_{\text{vmt,dpm}}$
- And because exogenous variation comes from energy price, the rebound effect of $\varepsilon_{\text{vmt,dpm}}$ means something else...
- This study uses eligibility to generate exogenous variation in fuel economy (*mpg*) and an RD estimator

West et al. (2016) JPubE: VM(not)T

Innovations

Innovation 1:

- Unless in the scenario of a natural experiment in energy efficiency (e.g., AKB (2017)), most studies on the rebound effect rely on variation in fuel price (e.g., some specs in Linn (2016))
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- And because exogenous variation comes from energy price, the rebound effect of $\varepsilon_{\text{vmt,dpm}}$ means something else...
- This study uses eligibility to generate exogenous variation in fuel economy (*mpg*) and an RD estimator

Innovation 2:

- This study considers the tradeoffs between fuel economy v. other attributes
- Q1: Why does this matter?
- Recall, OLS in Linn (2016) may be biased and the author uses an IV in the baseline?
- To explain the tradeoff, I will briefly cover Knittel (2012) "Automobiles on Steroids" AER

Knittel (2012) AER

Technology improvement + attribute tradeoffs (mpg v. performance): Observations

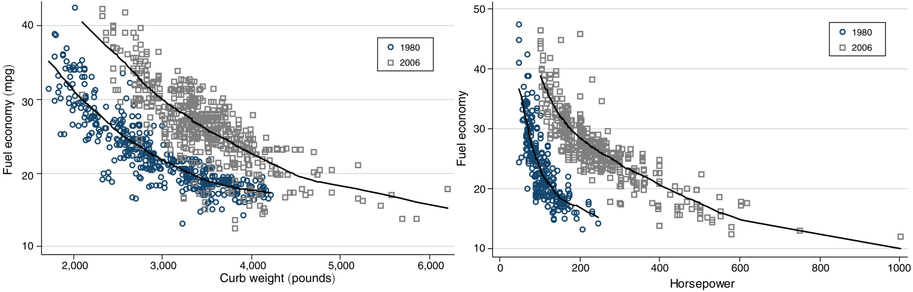


Figure 3. Fuel Economy versus Weight, 1980 and 2006, Passenger Cars

Figure 4. Fuel Economy versus Horsepower, 1980 and 2006, Passenger Cars

- For vehicles with the same weight, their fuel economy improved from 1980 to 2006
- For vehicles with the same horsepower, their fuel economy improved from 1980 to 2006
- For vehicles within the same model year (roughly the same technological frontier), there is a negative tradeoff between fuel economy and other desirable attributes (informally called performance)

Knittel (2012) AER

Technology improvement + attribute tradeoffs (mpg v. performance): Estimation

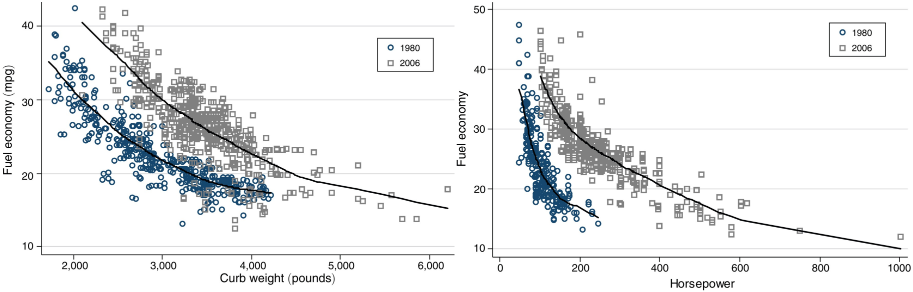


FIGURE 3. FUEL ECONOMY VERSUS WEIGHT, 1980 AND 2006, PASSENGER CARS

FIGURE 4. FUEL ECONOMY VERSUS HORSEPOWER, 1980 AND 2006, PASSENGER CARS

- If we consider marginal cost $mc_{it} = c(mpg_{it}, weight_{it}, horsepower_{it}, torque_{it}, \mathbf{X}_{it}, t)$ takes a Cobb-Douglas form, we can estimate a trans-log regression
- Regression: $\ln mpg_{it} = T_t + \beta_1 \ln w_{it} + \beta_2 \ln hp_{it} + \beta_3 \ln tq_{it} + \mathbf{X}_{it}\gamma + \varepsilon_{it}$
- Year FE measures the market-level frontier (technological improvement over time)
- The βs will measure the tradeoff ratio (% to %)

Knittel (2012) AER

Technology improvement + attribute tradeoffs: Estimation

Left: Tradeoffs $\hat{\beta}$s
(negative relations)

Right: Frontier as in $\hat{T}_t$
(improvements over time)

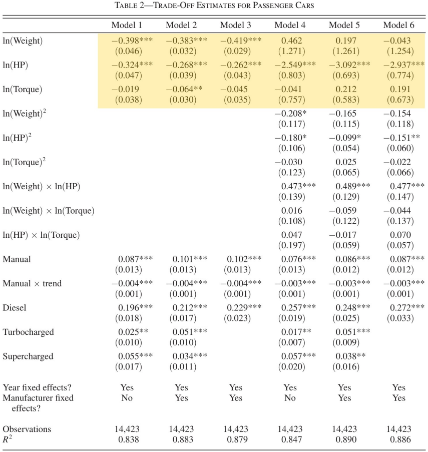


TABLE 2—TRADE-OFF ESTIMATES FOR PASSENGER CARS

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ln(Weight)	−0.398***	−0.383***	−0.419***	0.462	0.197	−0.043
	(0.046)	(0.032)	(0.029)	(1.271)	(1.261)	(1.254)
ln(HP)	−0.324***	−0.268***	−0.262***	−2.549***	−3.092***	−2.937***
	(0.047)	(0.039)	(0.043)	(0.803)	(0.693)	(0.774)
ln(Torque)	−0.019	−0.064**	−0.045	−0.041	0.212	0.191
	(0.038)	(0.030)	(0.035)	(0.757)	(0.583)	(0.673)
ln(Weight)^2				−0.208*	−0.165	−0.154
				(0.117)	(0.115)	(0.118)
ln(HP)^2				−0.180*	−0.099*	−0.151**
				(0.106)	(0.054)	(0.060)
ln(Torque)^2				−0.030	0.025	−0.022
				(0.123)	(0.065)	(0.066)
ln(Weight) × ln(HP)				0.473***	0.489***	0.477***
				(0.139)	(0.129)	(0.147)
ln(Weight) × ln(Torque)				0.016	−0.059	−0.044
				(0.108)	(0.122)	(0.137)
ln(HP) × ln(Torque)				0.047	−0.017	0.070
				(0.197)	(0.059)	(0.057)
Manual	0.087***	0.101***	0.102***	0.076***	0.086***	0.087***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.012)	(0.012)
Manual × trend	−0.004***	−0.004***	−0.004***	−0.003***	−0.003***	−0.003***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Diesel	0.196***	0.212***	0.229***	0.257***	0.248***	0.272***
	(0.018)	(0.017)	(0.023)	(0.019)	(0.025)	(0.033)
Turbocharged	0.025**	0.051***		0.017**	0.051***	
	(0.010)	(0.010)		(0.007)	(0.009)	
Supercharged	0.055***	0.034***		0.057***	0.038**	
	(0.017)	(0.011)		(0.020)	(0.016)	
Year fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer fixed effects?	No	Yes	Yes	No	Yes	Yes
Observations	14,423	14,423	14,423	14,423	14,423	14,423
R^2	0.838	0.883	0.879	0.847	0.890	0.886

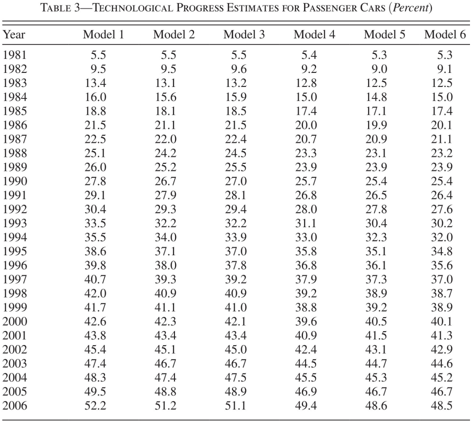


TABLE 3—TECHNOLOGICAL PROGRESS ESTIMATES FOR PASSENGER CARS (*Percent*)

Year	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
1981	5.5	5.5	5.5	5.4	5.3	5.3
1982	9.5	9.5	9.6	9.2	9.0	9.1
1983	13.4	13.1	13.2	12.8	12.5	12.5
1984	16.0	15.6	15.9	15.0	14.8	15.0
1985	18.8	18.1	18.5	17.4	17.1	17.4
1986	21.5	21.1	21.5	20.0	19.9	20.1
1987	22.5	22.0	22.4	20.7	20.9	21.1
1988	25.1	24.2	24.5	23.3	23.1	23.2
1989	26.0	25.2	25.5	23.9	23.9	23.9
1990	27.8	26.7	27.0	25.7	25.4	25.4
1991	29.1	27.9	28.1	26.8	26.5	26.4
1992	30.4	29.3	29.4	28.0	27.8	27.6
1993	33.5	32.2	32.2	31.1	30.4	30.2
1994	35.5	34.0	33.9	33.0	32.3	32.0
1995	38.6	37.1	37.0	35.8	35.1	34.8
1996	39.8	38.0	37.8	36.8	36.1	35.6
1997	40.7	39.3	39.2	37.9	37.3	37.0
1998	42.0	40.9	40.9	39.2	38.9	38.7
1999	41.7	41.1	41.0	38.8	39.2	38.9
2000	42.6	42.3	42.1	39.6	40.5	40.1
2001	43.8	43.4	43.4	40.9	41.5	41.3
2002	45.4	45.1	45.0	42.4	43.1	42.9
2003	47.4	46.7	46.7	44.5	44.7	44.6
2004	48.3	47.4	47.5	45.5	45.3	45.2
2005	49.5	48.8	48.9	46.9	46.7	46.7
2006	52.2	51.2	51.1	49.4	48.6	48.5

Knittel (2012) AER

Technology improvement + attribute tradeoffs: Estimation

Left: Tradeoffs $\hat{\beta}$s
(negative relations)

Right: Frontier as in $\hat{T}_t$
(improvements over time)

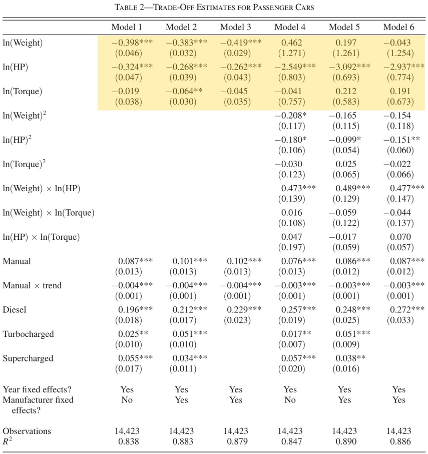


Table 2—Trade-Off Estimates for Passenger Cars

	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
ln(Weight)	−0.398*** (0.046)	−0.383*** (0.032)	−0.419*** (0.029)	0.462 (1.271)	0.197 (1.261)	−0.043 (1.254)
ln(HP)	−0.324*** (0.047)	−0.268*** (0.039)	−0.262*** (0.043)	−2.549*** (0.803)	−3.092*** (0.693)	−2.937*** (0.774)
ln(Torque)	−0.019 (0.038)	−0.064** (0.030)	−0.045 (0.035)	−0.041 (0.757)	0.212 (0.583)	0.191 (0.673)
$\ln(\text{Weight})^2$				−0.208* (0.117)	−0.165 (0.115)	−0.154 (0.118)
$\ln(\text{HP})^2$				−0.180* (0.106)	−0.099* (0.054)	−0.151** (0.060)
$\ln(\text{Torque})^2$				−0.030 (0.123)	0.025 (0.065)	−0.022 (0.066)
ln(Weight) × ln(HP)				0.473*** (0.139)	0.489*** (0.129)	0.477*** (0.147)
ln(Weight) × ln(Torque)				0.016 (0.108)	−0.059 (0.122)	−0.044 (0.137)
ln(HP) × ln(Torque)				0.047 (0.197)	−0.017 (0.059)	0.070 (0.057)
Manual	0.087*** (0.013)	0.101*** (0.013)	0.102*** (0.013)	0.076*** (0.013)	0.086*** (0.012)	0.087*** (0.012)
Manual × trend	−0.004*** (0.001)	−0.004*** (0.001)	−0.004*** (0.001)	−0.003*** (0.001)	−0.003*** (0.001)	−0.003*** (0.001)
Diesel	0.196*** (0.018)	0.212*** (0.017)	0.229*** (0.023)	0.257*** (0.019)	0.248*** (0.025)	0.272*** (0.033)
Turbocharged	0.025** (0.010)	0.051*** (0.010)		0.017** (0.007)	0.051*** (0.009)	
Supercharged	0.055*** (0.017)	0.034*** (0.011)		0.057*** (0.020)	0.038** (0.016)	
Year fixed effects?	Yes	Yes	Yes	Yes	Yes	Yes
Manufacturer fixed effects?	No	Yes	Yes	No	Yes	Yes
Observations	14,423	14,423	14,423	14,423	14,423	14,423
R^2	0.838	0.883	0.879	0.847	0.890	0.886

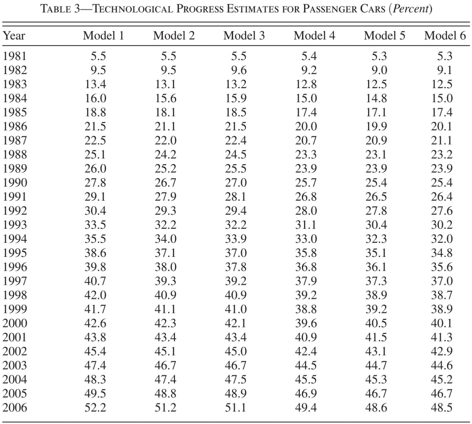


Table 3—Technological Progress Estimates for Passenger Cars (*Percent*)

Year	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
1981	5.5	5.5	5.5	5.4	5.3	5.3
1982	9.5	9.5	9.6	9.2	9.0	9.1
1983	13.4	13.1	13.2	12.8	12.5	12.5
1984	16.0	15.6	15.9	15.0	14.8	15.0
1985	18.8	18.1	18.5	17.4	17.1	17.4
1986	21.5	21.1	21.5	20.0	19.9	20.1
1987	22.5	22.0	22.4	20.7	20.9	21.1
1988	25.1	24.2	24.5	23.3	23.1	23.2
1989	26.0	25.2	25.5	23.9	23.9	23.9
1990	27.8	26.7	27.0	25.7	25.4	25.4
1991	29.1	27.9	28.1	26.8	26.5	26.4
1992	30.4	29.3	29.4	28.0	27.8	27.6
1993	33.5	32.2	32.2	31.1	30.4	30.2
1994	35.5	34.0	33.9	33.0	32.3	32.0
1995	38.6	37.1	37.0	35.8	35.1	34.8
1996	39.8	38.0	37.8	36.8	36.1	35.6
1997	40.7	39.3	39.2	37.9	37.3	37.0
1998	42.0	40.9	40.9	39.2	38.9	38.7
1999	41.7	41.1	41.0	38.8	39.2	38.9
2000	42.6	42.3	42.1	39.6	40.5	40.1
2001	43.8	43.4	43.4	40.9	41.5	41.3
2002	45.4	45.1	45.0	42.4	43.1	42.9
2003	47.4	46.7	46.7	44.5	44.7	44.6
2004	48.3	47.4	47.5	45.5	45.3	45.2
2005	49.5	48.8	48.9	46.9	46.7	46.7
2006	52.2	51.2	51.1	49.4	48.6	48.5

- Later people estimate product-specific frontier using product-by-model year FE (see Klier & Linn (2016) JPubE)

West et al. (2016) JPubE: VM(not)T

Express the elasticity of total fuel use (gallon) to energy efficiency (mpg)

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity }(+)} + \underbrace{\frac{1}{gallon}\cdot\frac{\partial VMT}{\partial X}\cdot\frac{\partial X}{\partial mpg}}_{\text{attribute tradeoffs (-)}} \qquad (1)$$

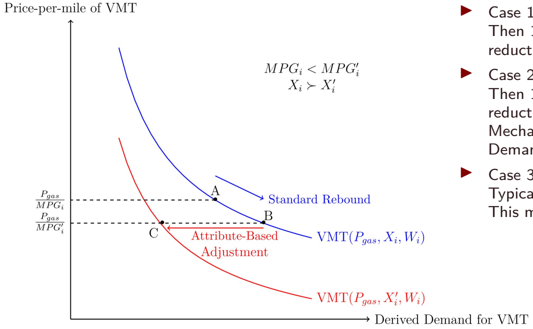


Fig. 1. Illustration of two components of policy-induced improvement in fuel economy.

- Case 1: No rebound effect, no tradeoff:
  Then 10% improvement in fuel economy will imply 10% reduction in fuel consumption
- Case 2: 10% rebound effect, no tradeoff:
  Then 10% improvement in fuel economy will imply 9% reduction in fuel consumption
  Mechanism:
  Demand curve of VMT to dpm is downward sloping
- Case 3: Some tradeoff.
  Typically $dX/dmpg < 0$ and $dVMT/dX > 0$.
  This may cancel out the rebound effect!

West et al. (2016) JPubE: VM(not)T

Derive $E_{gallon,mpg}$ as in Eq (1)

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{\frac{1}{gallon}\cdot\frac{\partial VMT}{\partial X}\cdot\frac{\partial X}{\partial mpg}}_{\text{attribute tradeoffs (-)}} \tag{1}$$

- Total fuel consumption: $gallon = VMT \cdot gpm \equiv VMT \cdot \frac{1}{mpg}$
- Demand of VMT: $VMT = f(dpm, X, W)$

  where X is attribute such as horsepower, $dpm = \frac{fp}{mpg}$, W is exogenous demographics
- Total fuel consumption: $gallon = VMT(dpm, X, W) \cdot \frac{1}{mpg}$

$$\begin{aligned}
\frac{\partial gallon}{\partial mpg} &= \left[\frac{\partial VMT}{\partial dpm}\frac{\partial dpm}{\partial mpg} + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\right]\cdot\frac{1}{mpg} + VMT\cdot\left(-\frac{1}{mpg^2}\right)\\
&= \left[\frac{\partial VMT}{\partial dpm}\left(-\frac{fp}{mpg^2}\right) + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\right]\cdot\frac{1}{mpg} + VMT\cdot\left(-\frac{1}{mpg^2}\right)\\
\frac{\partial gallon}{\partial mpg}\frac{mpg}{gallon} &= -\frac{\partial VMT}{\partial dpm}\cdot\frac{fp}{mpg^2\cdot gallon} + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\cdot\frac{1}{gallon} - VMT\cdot\frac{gallon}{mpg}\\
&= -\frac{\partial VMT}{\partial dpm}\cdot\frac{fp}{mpg}\cdot\frac{1}{mpg\cdot gallon} + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\cdot\frac{1}{gallon} - VMT\cdot\frac{1}{VMT}\\
&= -\frac{\partial VMT}{\partial dpm}\cdot\frac{dpm}{VMT} + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\cdot\frac{1}{gallon} - VMT\cdot\frac{1}{VMT}\\
E_{gallon,mpg} &= -E_{vmt,dpm} + \frac{\partial VMT}{\partial X}\frac{\partial X}{\partial mpg}\cdot\frac{1}{gallon} - 1
\end{aligned}$$

West et al. (2016) JPubE: VM(not)T

Derive $E_{gallon,mpg}$ as in Eq (1): Further derivations...

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{\frac{1}{gallon} \cdot \frac{\partial VMT}{\partial X} \cdot \frac{\partial X}{\partial mpg}}_{\text{attribute tradeoffs (-)}} \tag{1}$$

Note that the 3rd tradeoff term can be further simplified:

$$\begin{aligned}
\frac{1}{gallon} \cdot \frac{\partial VMT}{\partial X} \cdot \frac{\partial X}{\partial mpg} &= \frac{mpg}{VMT} \cdot \frac{\partial VMT}{\partial X} \cdot \frac{\partial X}{\partial mpg} \\
&= \frac{mpg}{VMT} \cdot \frac{X}{X} \cdot \frac{\partial VMT}{\partial X} \cdot \frac{\partial X}{\partial mpg} \\
&= \frac{X}{VMT} \cdot \frac{mpg}{X} \cdot \frac{\partial VMT}{\partial X} \cdot \frac{\partial X}{\partial mpg} \\
&= \left[\frac{\partial VMT}{\partial X} \cdot \frac{X}{VMT}\right] \cdot \left[\frac{\partial X}{\partial mpg} \cdot \frac{mpg}{X}\right] = E_{vmt,x} \cdot E_{x,mpg}
\end{aligned}$$

We can further write Eq (1) as:

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{E_{vmt,x} \cdot E_{x,mpg}}_{\text{attribute tradeoffs (-)}} \tag{1'}$$

- If either or both elasticities $E_{vmt,x}$ and $E_{x,mpg}$ are sizable
- The attribute tradeoff terms may be sizable enough to cancel out the direct rebound elasticity
- Note: Tradeoff elasticities $E_{x,mpg}$ are the reverse of the βs estimated in Knittel (2012) AER

Express Elasticity $E_{gallon,mpg}$

Piecing everything together

Re-write West et al. (2016) Eq (1) into Eq (1') below:

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{E_{vmt,x} \cdot E_{x,mpg}}_{\text{attribute tradeoffs (-)}} \qquad (1')$$

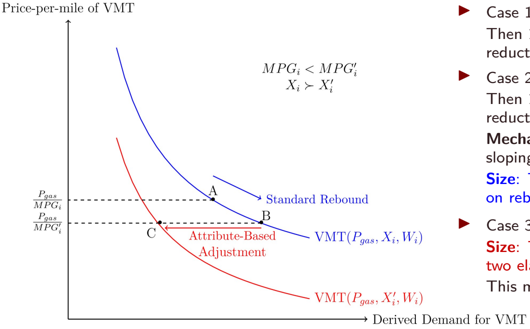


Fig. 1. Illustration of two components of policy-induced improvement in fuel economy.

- Case 1: No rebound effect, no tradeoff:
  Then 10% improvement in fuel economy will imply 10% reduction in fuel consumption
- Case 2: 10% rebound effect, no tradeoff:
  Then 10% improvement in fuel economy will imply 9% reduction in fuel consumption
  Mechanism: Demand curve of VMT to dpm is downward sloping
  Size: The horizontal movement $\Delta VMT\%$ from A to B depends on rebound elasticity $E_{vmt,dpm}$
- Case 3: Tradeoff between *mpg* and performance X
  Size: The horizontal shift $\Delta VMT\%$ from B to C depends on two elasticities $E_{vmt,x}$ and $E_{x,mpg}$
  This may cancel out the rebound effect!

Implications on Energy Efficiency Policies

1. Price-based policy vs. Energy efficiency standard

Re-write West et al. (2016) Eq (1) into Eq (1') below:

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{E_{vmt,x} \cdot E_{x,mpg}}_{\text{attribute tradeoffs (-)}} \tag{1'}$$

Consider two types of energy efficiency policies targeting \$-per-mile: $dpm \equiv \frac{fp}{mpg}$

Evaluate their effectiveness as corrective policies:

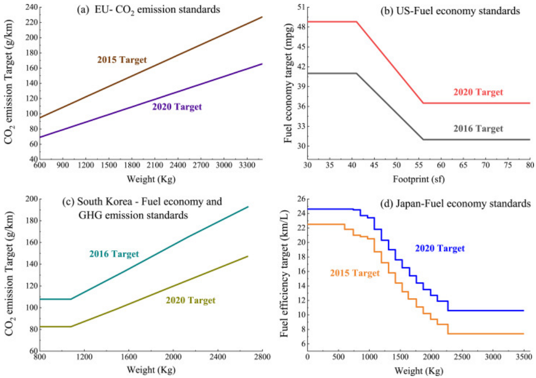
- Case 1: Fuel tax: Only rebound channel
- Case 2: Fuel economy standard: Both rebound + attribute tradeoff channels
- This is one of a rare mechanisms that fuel economy standard (a second-best approxy) can be more effective in correcting energy consumption than a first-best instrument (aka a price directly on energy consumption such as a fuel tax)
- Still, effectiveness $\neq$ efficiency
  As efficiency needs to account for private welfare as well. There can be surplus reduction for foregone improvements in performance

Implications on Energy Efficiency Policies

2. Modern attribute-based standard

There is a case when attribute adjustment exacerbates the direct rebound

$$E_{gallon,mpg} = -1 + \underbrace{-E_{vmt,dpm}}_{\text{direct rebound elasticity } (+)} + \underbrace{E_{vmt,x} \cdot E_{x,mpg}}_{\text{attribute bunching } (+)} \tag{1'}$$



- Since 2010s-ish, most standards became attribute-based
- E.g., a lower MPG requirement for larger vehicle
- On the margin near a threshold, carmakers have incentive to increase (not decrease) weight
- This is known as a weight or footprint-bunching loophole
- In this case, on those margins, the EE policy would further undermine the effectiveness of EE policy

West et al. (2017)

Cash for Clunkers (CfC) in 2009

CARS
car allowance rebate system

- Official name: Car Allowance Rebate System (CARS),
  Establish by: Consumer Assistance to Recycle and Save (CARS) Act of 2009
- Program: July 2009 - August 2009
- A large scrappage incentive program packaged into a stimulus program for the Auto industry
- Rebate: \$3500 to \$4500 cash
- Eligibility:

  Clunkers: (i) mpg $\leq$ 18, (ii) vintage $\leq$ 25 years

  New car: (i) mpg $\geq$ 22, (ii) price \$45k

Empirical Strategy: A RD Design

Goal: Study Eq (1’): $E_{gallon,mpg} = -1 + (-E_{vmt,dpm}) + E_{vmt,x} \cdot E_{x,mpg}$

For each household i, authors estimate Eq (2) in cross-sectional data:

$$\begin{aligned} Y_i = \beta_0 &+ \beta_1 \cdot f(\text{distance-to-cutoff}_i) \cdot \mathbf{1}\{eligible_i = 1\} \\ &+ \beta_2 \cdot f(\text{distance-to-cutoff}_i) \cdot \mathbf{1}\{eligible_i = 0\} \\ &+ \beta_3 \cdot \mathbf{1}\{eligible_i = 1\} + \varepsilon_i \end{aligned} \tag{2}$$

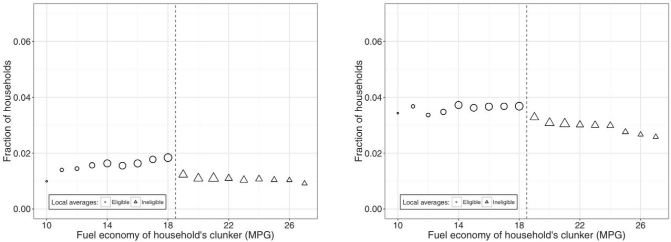
- Outcome Y_i:
  - To study $\Delta mpg\%$: New car mpg
  - To study $E_{vmt,dpm}$ and $E_{vmt,x}$: VMT
  - To study $E_{x,mpg}$: Curb weight, performance (hp/weight), MRSP
  - Other vars: $\mathbf{1}\{\text{Buy a new vehicle}\}$
- Running variable: MPG of the clunkers
  - Key identification: no manipulation in mpg of the clunkers’ eligibility
- β_3: key parameters of interest
- β_1 and β_2: allow for RKD and other slopes & curvatures
- Key data effort:
  - Eligibility indicator: linking all vehicles for a household using the Texas DMV vehicle registration
  - VMT: vehicle smog test odometer readings
  - MPG and attributes: EPA MPG ratings and VIN-decoder

Results

1. Prob{Buy a new vehicle} and baseline time window

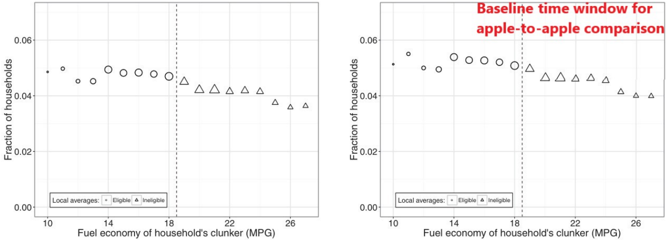
(a) July 2009 - August 2009 (Cash for Clunkers)

(b) July 2009 - January 2010 (7 months)



(e) July 2009 - April 2010 (10 months)

(f) July 2009 - May 2010 (11 months)

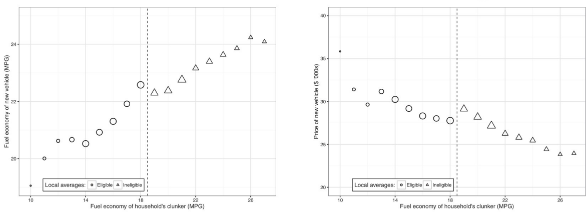


Baseline time window for apple-to-apple comparison

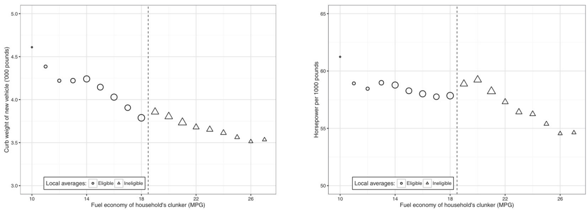
Fig. 2. Cumulative fraction of households purchasing any new vehicle by time period.

Results

2. Effect of CfC on New Vehicles: MPG (↑) vs other attributes ↓


(a) Fuel economy (MPG)

(b) Book value (manufacturer suggested retail price)


(c) Safety/comfort (curb weight)

(d) Performance (horsepower per pound)

Note: 11 month time window July 2009 - May 2010.

Fig. 3. Reduced-form: Selected vehicle attributes of new vehicle purchases.

- **Fuel economy (MPG)**: We observe $\Delta mpg\% > 0$ on the margin
- **Performance X**: We observe $\Delta X\% < 0$ on the margin Consistent with $E_{x,mpg} < 0$

Results

2. Effect of CfC on New Vehicles: MPG (↑) vs other attributes ↓

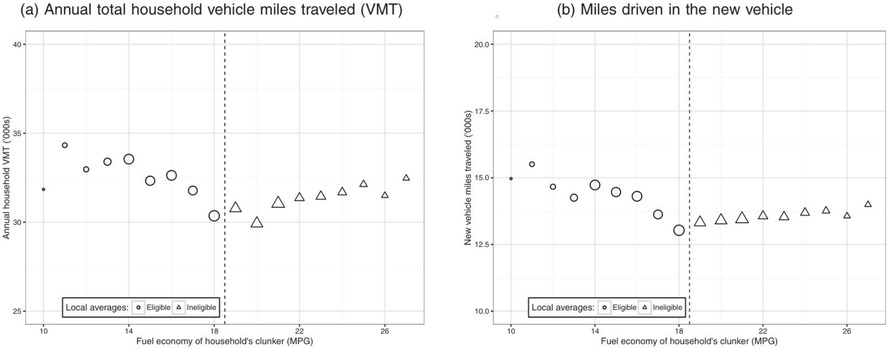
Table 3
Reduced-form estimated discontinuities for new vehicle purchase characteristics.

	Estimated discontinuity					
	(1)	(2)	(3)	(4)	(5)	(6)
Fuel economy (MPG)	0.7937^{***}	0.7198^{***}	0.7569^{***}	0.7734^{***}	0.6579^{***}	0.6716^{***}
	(0.1038)	(0.1221)	(0.0751)	(0.0853)	(0.1136)	(0.1131)
MSRP (dollars)	$-1,917^{***}$	$-1,796^{***}$	$-2,162^{***}$	$-2,000^{***}$	$-1,956^{***}$	$-1,660^{***}$
	(193)	(227)	(139)	(159)	(221)	(213)
Curb weight (lbs.)	-175.82^{***}	-160.38^{***}	-159.57^{***}	-162.30^{***}	-153.22^{***}	-150.46^{***}
	(16.45)	(19.02)	(11.70)	(13.10)	(17.22)	(17.11)
Footprint (ft^2)	-1.6031^{***}	-1.0035^{***}	-1.4073^{***}	-1.2881^{***}	-1.0037^{***}	-1.0961^{***}
	(0.2533)	(0.2929)	(0.1801)	(0.1995)	(0.2591)	(0.2579)
Size (ft^3)	-20.630^{***}	-15.411^{***}	-17.481^{***}	-17.393^{***}	-13.819^{***}	-15.111^{***}
	(3.104)	(3.589)	(2.207)	(2.451)	(3.199)	(3.180)
Horsepower	-13.659^{***}	-11.941^{***}	-15.380^{***}	-14.586^{***}	-11.565^{***}	-10.740^{***}
	(1.346)	(1.576)	(0.969)	(1.101)	(1.470)	(1.451)
Horsepower/1000 lbs.	-1.0616^{***}	-0.7720^{***}	-1.8197^{***}	-1.5291^{***}	-0.7944^{***}	-0.6219^{**}
	(0.2279)	(0.2699)	(0.1660)	(0.1910)	(0.2590)	(0.2564)
Engine displacement (L)	-0.1802^{***}	-0.1525^{***}	-0.1971^{***}	-0.1871^{***}	-0.1473^{***}	-0.1459^{***}
	(0.0222)	(0.0257)	(0.0158)	(0.0178)	(0.0234)	(0.0233)
6+ cylinders	-0.0930^{***}	-0.0832^{***}	-0.1054^{***}	-0.0995^{***}	-0.0835^{***}	-0.0795^{***}
	(0.0086)	(0.0102)	(0.0063)	(0.0072)	(0.0095)	(0.0094)
4WD or AWD	-0.0475^{***}	-0.0504^{***}	-0.0279^{***}	-0.0382^{***}	-0.0400^{***}	-0.0424^{***}
	(0.0081)	(0.0094)	(0.0058)	(0.0065)	(0.0085)	(0.0085)
Bandwidth	5 MPG	4 MPG	4 MPG	3 MPG	2 MPG	2 MPG
Polynomial	Quadratic	Quadratic	Linear	Linear	Linear	Linear
Controls	No	No	No	No	No	Yes
Observations	126,147	103,671	103,671	83,628	53,417	53,417

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$ Each coefficient represents a separate regression of the dependent variable (in rows) on an indicator for CARS eligibility, which yields an estimate of β_3 in Eq. (2). Columns vary the bandwidth and included control terms. Standard errors are reported in parentheses.

Results

2. Effect of CfC on VMT (↓)


(a) Annual total household vehicle miles traveled (VMT)

(b) Miles driven in the new vehicle

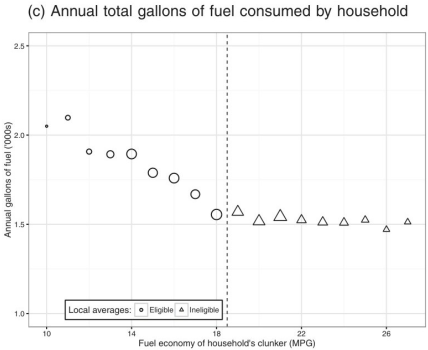
Fig. 4. Reduced-form: driving outcomes for households with new vehicle purchases.

Consider Eq(1'): $E_{gallon,mpg} = -1 + (-E_{vmt,dpm}) + E_{vmt,x} \cdot E_{x,mpg}$

- Directly effect ($\frac{dVMT}{dmpg}$) is slightly weaker than indirect effect ($\frac{dVMT}{dX} \cdot \frac{dX}{dmpg}$)
- Net effect: Barely eligible HH drive a bit less than barely ineligible HH

Results

3. Effect of CfC on total fuel consumption (↓)



(c) Annual total gallons of fuel consumed by household

Note: 11 month time window July 2009 - May 2010.

Fig. 4. Reduced-form: driving outcomes for households with new vehicle purchases.

Consider Eq(1'): $E_{gallon,mpg} = -1 + (-E_{vmt,dpm}) + E_{vmt,x} \cdot E_{x,mpg}$

- Directly effect $(-E_{vmt,dpm})$ is slightly weaker than indirect effect $(E_{vmt,x} \cdot E_{x,mpg})$
- Net effect: Barely eligible HH consume a bit less fuel than barely ineligible HH

Results + Discuss Mechanisms

2-3. Effect of CfC on VMT (↓) and total fuel consumption (↓)

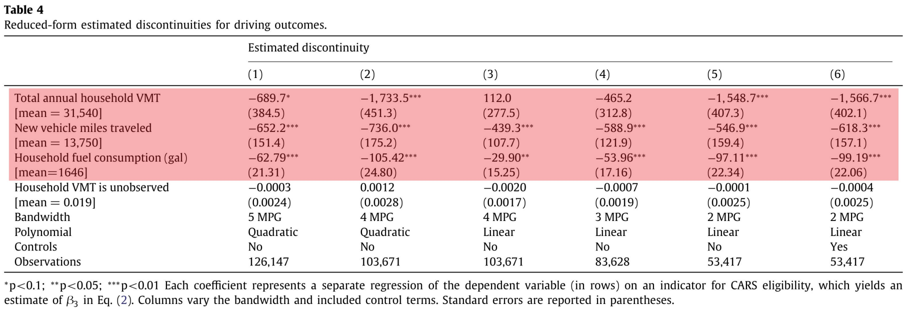


Table 4

Reduced-form estimated discontinuities for driving outcomes.

	Estimated discontinuity					
	(1)	(2)	(3)	(4)	(5)	(6)
Total annual household VMT	-689.7^{*}	$-1,733.5^{***}$	112.0	−465.2	$-1,548.7^{***}$	$-1,566.7^{***}$
[mean = 31,540]	(384.5)	(451.3)	(277.5)	(312.8)	(407.3)	(402.1)
New vehicle miles traveled	-652.2^{***}	-736.0^{***}	-439.3^{***}	-588.9^{***}	-546.9^{***}	-618.3^{***}
[mean = 13,750]	(151.4)	(175.2)	(107.7)	(121.9)	(159.4)	(157.1)
Household fuel consumption (gal)	-62.79^{***}	-105.42^{***}	-29.90^{**}	-53.96^{***}	-97.11^{***}	-99.19^{***}
[mean=1646]	(21.31)	(24.80)	(15.25)	(17.16)	(22.34)	(22.06)
Household VMT is unobserved	−0.0003	0.0012	−0.0020	−0.0007	−0.0001	−0.0004
[mean = 0.019]	(0.0024)	(0.0028)	(0.0017)	(0.0019)	(0.0025)	(0.0025)
Bandwidth	5 MPG	4 MPG	4 MPG	3 MPG	2 MPG	2 MPG
Polynomial	Quadratic	Quadratic	Linear	Linear	Linear	Linear
Controls	No	No	No	No	No	Yes
Observations	126,147	103,671	103,671	83,628	53,417	53,417

$^{*}p<0.1$; $^{**}p<0.05$; $^{***}p<0.01$ Each coefficient represents a separate regression of the dependent variable (in rows) on an indicator for CARS eligibility, which yields an estimate of β_3 in Eq. (2). Columns vary the bandwidth and included control terms. Standard errors are reported in parentheses.

Discuss: $E_{gallon,mpg} = -1 + (-E_{vmt,dpm}) + E_{vmt,x} \cdot E_{x,mpg}$

- Why do we observe a reserve rebound?
- Is this because $E_{x,mpg}$ is really sizable? Or is it because $E_{vmt,x}$ is very sizable? Or both?
- Those are questions for future work