Technical Consulting Report

"The Rebound Effect: Fuel Efficiency and Motor Vehicle Travel"

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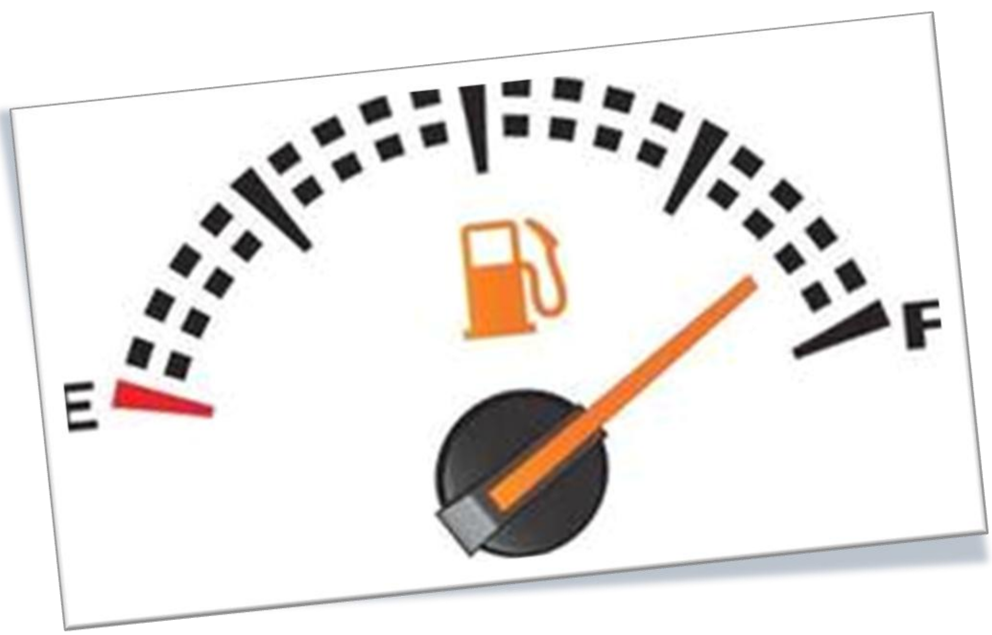

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1. Introduction

The importance of such environmental issue as air pollution is growing over time. Vehicle-fuel efficiency resulting in gasoline-usage decrease is considered as one of possible solutions. Not always that leads to expected pure fuel use reduction. Energy-efficiency measures are typically met with a small but persistent "rebound effect" that manifests itself across various spheres including buying a more fuel-efficient car and traveling more often.

Current studies evidence that efficiency improvements also backfire and lead to producing more vehicle-miles traveled (VMT) overall (so called "Jevons paradox"). As miles-per-gallon ratios improve, owners of more fuel-efficient cars under Corporate Average Fuel Economy (CAFE) standards are driving more as their fuel cost per mile traveled decreases. The rebound effect tends to reduce the effectiveness of energy-efficiency programs in reducing fuel use. Thus, in the increasing interest of adoption of energy saving technology, the attention of environmental policy making entities should be drawn to the existence and magnitude of the rebound effect. Fuel efficiency standards should account for the magnitude of rebound effect in order to decrease greenhouse gas emissions given the policy.

This report aims to define the rebound effect for motor vehicles, explain how to calculate it empirically and estimate it in the U.S. from 1966 to 2001. We choose a model to get unbiased estimate of the rebound effect through adjusting it and allowing the rebound effect vary with income, urbanization, and the fuel cost of driving. As a result we explain the obtained magnitude.

2. Theoretical Analysis

Before working through given data, theoretical analysis is required to explain how to estimate the rebound effect. We use the following variables to express the notation of the rebound effect:

- ✓ E – fuel efficiency (miles/gallon, MPG);
- ✓ VMT or M – vehicle-miles traveled (miles);
- ✓ F – fuel consumption (gallons);
- ✓ PF – fuel price ($/gallon);
- ✓ PM – fuel cost per mile ($/mile).

2.1. Given that fuel consumption (F) can be expressed as a function of E and M:

$$F = f(M, E) = \frac{M}{E} \qquad (1)$$

Intuitively, the needed amount of gallons depends on the automobile fuel economy standards, or how many miles the car runs per 1 gallon of fuel, and the trip length expressed as vehicle-miles travel.

2.2. Fuel cost per mile (PM) – as a function of PF and E, meaning that the amount paid by consumer per mile of travel is the fuel price per gallon divided by miles he/she travels per gallon given the automobile fuel economy standards:

$$PM = f(PF, E) = \frac{PF}{E} \qquad (2)$$

2.3. Further the relationship between the elasticity of F with respect to fuel efficiency ($\varepsilon_{F,E}$) and elasticity of M with respect to the per-mile fuel cost ($\varepsilon_{M,PM}$) is derived:
Given the identity in equation (1), we solve for E:

$$E = f(M, F) = \frac{M}{F} \qquad (3)$$

The elasticity of fuel consumption by definition is given by:

$$\varepsilon_{F,E} = \left(\frac{dF}{dE}\right) * \left(\frac{E}{F}\right) \qquad (4)$$

Taking the derivative of F with respect to E, given equation (1), we obtain:

$$\frac{dF}{dE} = -ME^{-2} + E^{-1}\left(\frac{\partial M}{\partial E}\right) \qquad (5)$$

Substitute (5) back into (4):

$$\varepsilon_{F,E} = \left(-ME^{-2} + E^{-1}\left(\frac{\partial M}{\partial E}\right)\right) * \left(\frac{E}{F}\right) \qquad (6)$$

Simplifying (6):

$$\varepsilon_{F,E} = \left(-\frac{M}{E*F}\right) + \left(\frac{\partial M}{F*\partial E}\right) \qquad (7)$$

Substitute (1) and (3) into (7):

$$\varepsilon_{F,E} = -1 + \left(\frac{\partial M}{\partial E}\right)\left(\frac{E}{M}\right) \qquad (8)$$

Multiply second term of right hand side by $\left(\frac{\partial PM}{\partial PM}\right)$ and rearrange that term:

$$\varepsilon_{F,E} = -1 + \left(\left(\frac{\partial M}{\partial \mathrm{PM}}\right)\left(\frac{\partial \mathrm{PM}}{\partial E}\right)\right)\left(\frac{E}{M}\right) \qquad (9)$$

Given PF is constant, derivate with respect to E using equation (2):

$$\varepsilon_{F,E} = -1 + \left(\left(\frac{\partial M}{\partial \mathrm{PM}}\right) * -\left(\frac{\partial \mathrm{PF}}{E^2}\right)\right)\left(\frac{E}{M}\right) \qquad (10)$$

Cross out E, substitute (3) into (10):

$$\varepsilon_{F,E} = -1 - \left(\left(\frac{\partial M}{\partial \mathrm{PM}}\right)\left(\frac{\mathrm{PM}}{M}\right)\right) \qquad (11)$$

Rearrange and the derivation performed above explains the relationship between $\varepsilon_{F,E}$ and $\varepsilon_{M,PM}$ in equation (12):

$$\varepsilon_{F,E} = -1 - \varepsilon_{M,PM} \qquad (12)$$

2.4. That relationship between $\boldsymbol{\varepsilon}_{\mathbf{F,E}}$ and $\boldsymbol{\varepsilon}_{\mathbf{M,PM}}$ says that non-zero value of $\boldsymbol{\varepsilon}_{\boldsymbol{M,PM}}$[1] is the extent of deviation from the proportionality of decrease in fuel consumption with increase in fuel efficiency. It is expressed as a percentage of the forecast reduction in gasoline use that is "lost" due to the sum of consumer and market responses on increase in fuel efficiency. That is exactly what is described in equation (12) as the rebound effect, so we can also write $\boldsymbol{RE} = -\,\boldsymbol{\varepsilon}_{\boldsymbol{M,PM}}$. Thus, $-\boldsymbol{\varepsilon}_{\boldsymbol{M,PM}}$ can be used as definition and measure of the rebound effect and non-zero value of RE then means decreasing VMT given increase in PM. For convenience, replace VMT with VMA (average vehicle miles). Further, we are going to aggregate these and some other factors in a model that simultaneously determines VMA, vehicles, and fuel efficiency.

3. Data

In order to start the analysis, will look through the data we are working with. In this study we use "panel data" from 1966 till 2001 (inclusive) across 50 states and D.C. of the USA[2]. We transform original data into variables for further estimations. Transformations involve log transformation, calculations of per capita values and obtaining real values for monetary variables (1987 base) – definitions of variables are represented in Appendix A. Log transformations make positively skewed distribution more normal[3]. Also, when a change in the dependent variable is related to percentage change in an independent variable, or vice versa, the relationship is better modeled by taking the natural log of either or both variables; that provides elasticity values. Making variables de-meaned is also normalization[4]. As a result, normalized variables are *vma, veh, pm, inc, arm, popa, urb, pf, pv* and *la.* Thus, variables starting with lower case letters are logarithms of the initially described variables. Additionally de-meaned variables are *pm, inc, urb*.

Summary of statistics along with definitions of variables is provided in Table 1 for both logged and unlogged variables (Summary statistics from STATA in Appendix B). The meaning of all variables is explained in the table. In general, the reason why we need so many variables for analysis are the assumptions of what influences the VMT. Intuitively, the most simple and clear assumption is the commonly expected dependence on income (discussed in further sections).

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[1] $\varepsilon_{M,PM}$ is defined as the elasticity of miles travelled with respect to cost of fuel per mile;

[2] Source: Small, K.A. and K.V. Dender. 2007. Fuel efficiency and motor vehicle travel: The declining rebound effect. The Energy Journal 28(1): 25-51;

[3] 1) Paper 430-2012 Transforming Variables for Normality and Linearity – When, How, Why and Why Not's Steven M. LaLonde, Rochester Institute of Technology, Rochester, NY;

2) ERIC Clearinghouse on Assessment and Evaluation College Park MD. Normalizing Data Transformations. ERIC Digest. Osborne, Jason W. http://www.ericdigests.org/2003-3/data.htm

[4] Subtracting the sample mean for each variable;

Table 1. Summary statistics and definitions of variables

Variable		Mean	Standard Deviation	Min	Max	Comment
1	2	3	4	5	6	7
VMT/M	Vehicle 000's Miles Traveled	35200000	39300000	830000	311000000	
VMA	Vehicle Miles Traveled / Adult	10929.332	2,537.714	4,747.613	23333.326	
vma	Normalized Vehicle Miles Traveled / Adult	9.272	0.235	8.465	10.058	
VEH	Vehicles per Adult	0.999	0.189	0.458	1.716	
veh	Normalized Vehicles / Adult	-0.020	0.197	-0.781	0.540	
F	Fuel Intensity (gal/mi)	0.061	0.012	0.034	0.092	
PF	Fuel Price Real (cents/gal)	108.922	23.524	60.320	194.907	
PM	Fuel Cost / Mile real (cents/mi)	6.814	2.275	2.782	14.205	
pm	Normalized Fuel Cost per Mile (cents/mile)	0.000	0.349	-0.837	0.793	
INC	Income / Capita Real	14586.850	3,315.928	6,453.909	27266.928	Real personal income per capita at 1987 prices
inc	Normalized Income / Capita	0.000	0.228	-0.790	0.651	
ARM	Adults / Road Mile	57.728	68.274	2.583	490.198	A rough measure of potential congestion
arm	Normalized Adults /Road Mile	3.614	0.935	0.949	6.195	
POPA	Population / Adult	1.418	0.090	1.231	1.736	A measure of family size
popa	Normalized Population /Adult	0.347	0.062	0.208	0.552	
URB	Fraction of Population in Urban Areas	0.713	0.195	0.290	1.000	Fraction of state's population living in metropolitan statistical areas
urb	Normalized Fraction of Population in Urban Areas	0.000	0.195	-0.423	0.287	
RAILPOP	Fraction of Population in Metro Areas Served by Heavy Rail	0.088	0.207	0.000	1.000	Fraction of the state's population living in metropolitan statistical areas with a heavy-rail transit system
D7479	Dummy variable that eq.1 if year is 1974 or 1979*	0.056	0.229	0.000	1.000	* Dummy variables to represent gasoline supply disruptions in 1974 and 1979, when gasoline-price controls were in effect, resulting in queues and sporadic rationing at service stations. Included in order to reduce the extent of autocorrelation in the residuals; ** A time trend measured in years since 1966, intended to capture changes in technology and consumer preferences that we are unable to specify quantitatively.
TREND	Period (years beginning 1966)**	17.500	10.391	0.000	35.000	
pf	Normalized Fuel Price	4.669	0.203	4.100	5.273	
PV	Price of New Vehicles (index)	1.066	0.197	0.777	1.493	
pv	Normalized Price of New Vehicles	0.048	0.178	-0.252	0.401	
LA	Licensed Drives / Adult	0.905	0.083	0.625	1.149	
la	Normalized Licensed Drives / Adult	-0.104	0.094	-0.470	0.139	
cafe	Strictness of CAFÉ (fuel efficiency regulations)	0.103	0.113	0.000	0.349	

Comparing the summary with the results provided by Small and Van Dender (2007), the same data set is obtained except for minor difference in insignificant number of digits. Another difference is that *pf* is normalized in the paper but not for the purpose of this study. That means that its mean is non-zero value here. Other variables are described in further sections.

4. Econometric Models

As given in previous sections, the relationship between $\varepsilon_{F,E}$ and $\varepsilon_{M,PM}$ is expressed in equation (12). Empirically we see that there are more factors influencing the rebound effect. In reality there are at least such factors as the level of person's income, the technical characteristics of his/her car, the matter whether he/she is employed and the distance from home to office that may influence his/her demand for VMT. At the same time these factors might be the case for one period of time but the lifestyle could change in 5 or so years as a result of social changes or personal decisions that are statistically neither easy to estimate nor to take into consideration in a model. Thus, a regression model[5] accounting for number of factors (variables listed in previous sections) over time is required.

Model #1: To begin with, we use a simplified Ordinary Least Squares (OLS) regression model. Hereafter, in the models *i* represents state index and *t* represents the year index.

$$vma_{it}{}^{6} = \beta_0 + \beta_1 pm_{it} + \beta_2 veh_{it} + \beta_3 inc_{it} + \beta_4 arm_{it} + \beta_5 popa_{it} + \beta_6 urb_{it} + \beta_7 RAILPOP_{it} + \beta_8 D7479_{it} + \beta_9 TREND_t + \varepsilon_{it}$$

This formula provides us with elasticity values of vma_{it} for states over time with respect to pm_{it} and other log form independent variables, as well as percentage change in vma_{it} due to unit change in non log explanatory variables (see summary in Table 1) and percentage change in vma_{it} due to impact of dummy variable. Dummy variable $D7479_{it}$ is included for years 1974 and 1979, when gasoline-price controls were in effect. It aims to reduce the extent of autocorrelation in the residuals. $TREND_t$ - is the time trend measured in years since 1966, intended to capture changes in technology and consumer preferences that are difficult to specify quantitatively. As far as vma_{it} and pm_{it} are in log-log form, given their definition in Table 1 the derivative is the elasticity of vma_{it} with respect to pm_{it} corresponds to value of β_1, thus β_1 (see interpretation of the coefficient in Appendix C) provides us with the absolute value of the rebound effect.

Model #2: At the beginning of this section we also mentioned that some factors are not easy to account for, in other words we assume there is an unobserved state-specific omitted characteristic that enters through error term. The own state characteristic may bias the outcome variable and we need to control for this. It could be a climatic-geographic feature that leads citizens from state to state to buy vehicles with strong engine power and higher clearance to drive in the mountains, thus having greater gas capacity. Others living in a more flat area don't face that problem and afford less gas consuming cars. That is why we focus on another technique of panel data analysis – fixed effect[7] (FE). FE explores the relationship between predictor and outcome variables within state. This is the rationale behind the assumption of the correlation between states' error term and predictor

[5] Describes the statistical relationship between one or more predictor variables and the response variable;

[6] β_0 is the constant term, other β_s are coefficients of explanatory variables to be estimated. They give us the effect of that variable on vma_{it} for states over time; ε_{it} is an error term, assumed to be independent and identically distributed (i.i.d.), with zero mean for all observations (no heteroskedasticity or autocorrelation);

[7] Effect that doesn't vary over time but across states;

variables. FE remove the effect of those time-invariant characteristics so we can assess the net effect of the predictors on the outcome variable.

The FE model looks the next way:

$$vma_{it}{}^{8} = \beta_0 + \beta_1 pm_{it} + \beta_2 veh_{it} + \beta_3 inc_{it} + \beta_4 arm_{it} + \beta_5 popa_{it} + \beta_6 urb_{it} + \beta_7 RAILPOP_{it} + \beta_8 D7479_{it} + \beta_9 TREND_t + \alpha_i + \nu_{it}$$

Interpretation of coefficients is the same as in the previous model. This model says that if the unobserved variable α_i is the one that is not changing with time then any change in the independent variable must be due to influences other than this fixed characteristic.

Model #3: Until now we only mentioned that the rebound effect could also be influenced by other factors, which means that it could be a function of other variables. It could also be the case that there are interaction terms involved, like *inc*, *urb* and *pm* itself. Now the elasticity of *pm* also varies with these variables. Thus, we obtain a new model[9]:

$$vma_{it} = \beta_0 + \beta_{10} pm_{it} + \beta_{11} pm^2{}_{it} + \beta_{12} inc_{it} \cdot pm_{it} + \beta_{13} urb_{it} \cdot pm_{it} + \beta_2 veh_{it} + \beta_3 inc_{it} + \beta_4 arm_{it} + \beta_5 popa_{it} + \beta_6 urb_{it} + \beta_7 RAILPOP_{it} + \beta_8 D7479_{it} + \beta_9 TREND_t + \alpha_i + \nu_{it}$$

What makes that model differ from previous ones is that now it has higher order influence of pm_{it}, interacting variables - inc_{it} and urb_{it} on vma_{it}. Thus the rebound effect β_{10} is a function of these three variables here.

5. Results

Using *Model #1* we run OLS regression. The resulting table is represented in Appendix D along with theoretical interpretation of results. Null hypothesis ($H_0{}^{10}$) of F-stat is rejected given the value of result is less than 0.05.

The estimated magnitude of the rebound effect β_1 is 0.23% (1% increase in fuel cost per mile induces 0.23% decrease in vma_{it}); the sign is negative as expected and is statistically significant at 99%. Its 95% confidence interval is (-0.255,-0.206). An unexpected sign stands for coefficient β_3 (changes in vma_{it} with income change). It is not reasonable. Usually increase in income creates either more reasons to travel for new purposes or not to care about the price of fuel constraint thus buy a car with greater fuel consumption. In addition to that the coefficients β_5 and β_6 for population per adult and population in urban areas respectively are not statistically significant. Obtained results are doubtful and are not consistent with general assumptions on relationship between given

[8] The FE model is one way to control for unobserved individual attributed in panel data. In this model $\varepsilon_{it} = \alpha_i + \nu_{it}$, where α_i is state climatic-geographic features for each state and ν_{it} is assumed to be i.i.d. with zero mean;

[9] Obtained by substitution of $\beta_1 = \beta_{10} + \beta_{11} pm_{it} + \beta_{12} inc_{it} + \beta_{13} urb_{it}$ into β_1 into model #2;

[10] Null hypothesis assumes that beta coefficient of predictor is equal to zero for T-stat and all beta coefficients are equal to zero for F-stat;

variables. This inconsistency could be a result of some unobserved state fixed effect that we didn't account for.

Compared to Model#1, some of these issues are resolved in fixed effect (FE) *Model#2.* The table of results comparison for *Models #1-2* is presented in Appendix E. We notice that after we eliminate these FEs into error term, magnitude of all coefficients changed (most substantially $\beta_{1-4}, \beta_6, \beta_8$). The magnitude of the RE has decreased to 0.166%. It means the previous value was roughly overestimated (39%). The income effect coefficient now has reasonable sign and its magnitude increases significantly up to 0.4%. The coefficients β_5, β_6, do not have expected sign and are still statistically insignificant. The unreferenced variables are still statistically significant.

As for *Model #3,* results are different from simple OLS model for the reasons that we account for state fixed effect, β_1 is no longer held constant. The table of the three models results' comparison is represented in Appendix E. The sign of coefficients β_5, β_6 has now become reasonable and their values are statistically significant at 99% confidence level. Instead β_7, β_8 are no longer statistically significant. The absolute value of the rebound effect in that model is denoted by β_{10} and is equal to 0.17%. The equation for β_1 now is:

$$\beta_1 = -0.17 + 0.13\, pm_{it} + 0.35\, inc_{it} + 0.03\, urb_{it}$$

Among three variables, the only coefficient that is not statistically significant is *urb* (β_{13}). Comparing given magnitudes, the coefficient of *inc* (β_{12}) has the greatest value. This means that income has a dominant influence on the rebound effect making consumers almost indifferent to fuel prices. Given the rebound effect is negative by definition, 1% increase in income leads to 0.0035% decrease in β_1. Similarly 1% increase in *pm* (β_{11}) causes 0.0013% decrease in β_1. Given relationship between the rebound effect and fuel efficiency in equation (12), it means that CAFE standards incorporated in $\varepsilon_{F,E}$ is more effective at high income and prices levels.

Summaries of the rebound effect over the whole sample as well as across states and time are

Variable	Obs	Mean	Std. Dev.	Min	Max
rebound	**1836**	**-.1702133**	**.0831993**	**-.3819439**	**.0882224**

represented below.

Variable	Obs	Mean	Std. Dev.	Min	Max
rebound_a_yr	**36**	**-.1702133**	**.0525168**	**-.2413779**	**-.0493691**

Table 2. Average value of the rebound effect across whole sample

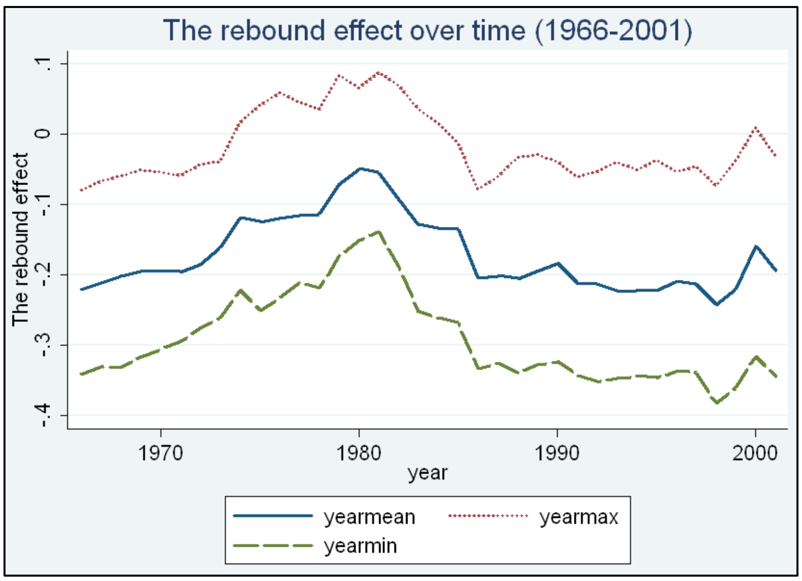
Variable	Obs	Mean	Std. Dev.	Min	Max
rebound_a_~e	**51**	**-.1702133**	**.0605998**	**-.2890511**	**-.0467663**

Table 3. Average value of the rebound effect across time

Table 4. Average value of the rebound effect across states

The value of the rebound effect from Model#3 (-0.17) is close to the Model#2 value (-0.166), but different from Model#1 value (-0.23), which turned out to be biased. The summary of the rebound effect by year and by state is presented in the Appendix F-1-2. We notice that the rebound effect varies from state to state. It might be the lifestyle matter or the case that the state with flat terrain has smaller rebound effect compared to mountainous terrain. It is also small for more economically developed states. The reasons for this could be that wealthier states have strict green house gas emissions policies or better public transportation, hence drive less. We also represent the rebound effect changing over time graphically.

Figure 1. The rebound effect over time



Its dynamics could be caused by some historical fuel market shocks and is consistent with price charts for the same period of time. The lowest level of the rebound effect was around 1980s, most likely as a result of fuel price increase during Iraq-Iran war[11]. In 1998 where we see the highest level of the rebound effect that could be characterized by low fuel price.

[11] http://zfacts.com/gas-price-history-graph

6. Conclusion

Energy efficiency standards such as CAFÉ do not always lead to pure consumption economy effect, consequently pollution reduction for the reason of the rebound effect. On the average, it reduces the effectiveness of energy efficiency policies by 0.17 points.

To correctly estimate the rebound effect, the estimation should account for time-invariant characteristics and such interacting variables as income and price of fuel per mile. The higher the value of these variables the more effective are the pollution reduction policies.

The analysis suggests that the rebound effect does matter in environmental policy questions. Therefore, it should be taken into account both on the technological and policy levels of energy efficiency decision-making. Thus environmentally conscious states should not only motivate energy-efficient technological innovations and policy, but also should promote economic development. On the country level, federal policies should also account for specifics of each state due to the varying rebound effect across states. This means that policies would better achieve their goal if lowered to state level.

7. References

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Appendix A: Definitions of variables

Expressed in given table are definitions of variables that are created by means of STATA software. See Appendix G for used commands to create variables.

Variables	Definition
VMT	$vmt\_state * 1000000$
VMA	$VMT/adult\_pop$
vma	$ln(VMA)$
VEH	$(no\_auto + no\_truck)/adult\_pop$
veh	$ln(VEH)$
F	fuel intensity (note: this is the inverse of efficiency)
PF	$(gas\_price + state\_gas\_tax + fed\_gas\_tax)/(cpi\_87/100)$
PM	$PF * F$
pm	$ln(PM) - mean(ln(PM))$
INC	$(state\_income/(cpi\_87/100))/state\_population$
inc	$ln(INC) - mean(ln(INC))$
ARM	$adult\_pop/road\_mileage$
arm	$ln(ARM)$
POPA	$state\_population/adult\_pop$
popa	$ln(POPA)$
URB	fraction of pop in urban area
urb	$URB - mean(URB)$
RAILPOP	Fraction of urban pop with heavy rail access
D7479	dummy variable= 1 if $year = 1974$ or $year = 1979$
TREND	$year - 1966$
pf	$ln(PF)$
PV	$new\_car\_price/100$
pv	$ln(PV)$
LA	$lic\_driver/adult\_pop$
la	$ln(LA)$
cafe	CAFE strictness

Appendix B: Summary statistics table

Variable	Obs	Mean	Std. Dev.	Min	Max
VMT	1836	3.52e+10	3.93e+10	8.30e+08	3.11e+11
VMA	1836	10929.332	2,537.714	4,747.613	23333.326
vma	1836	9.272	0.235	8.465	10.058
VEH	1836	0.999	0.189	0.458	1.716
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arm	1836	3.614	0.935	0.949	6.195
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popa	1836	0.347	0.062	0.208	0.552
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urb	1836	0.000	0.195	-0.423	0.287
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D7479	1836	0.056	0.229	0.000	1.000
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PV	1836	1.066	0.197	0.777	1.493
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la	1836	-0.104	0.094	-0.470	0.139
cafe	1836	0.103	0.113	0.000	0.349

Appendix C: Interpretation of the coefficient

β_1 is the coefficient for pm_{it} according to the model. Because vma_{it} and pm_{it} are in log-log form, given their definition in Table 1, relationship in equation (12), β_1 is the elasticity of vma_{it} with respect to pm_{it} and denotes the absolute value of the rebound effect:

$$\beta_1 = \left(\frac{\partial vma_{it}}{\partial pm_{it}}\right) = -\varepsilon_{M,PM}$$

Appendix D: Regression Model #1 analysis results

```
. reg vma pm veh inc arm popa urb RAILPOP D7479 TREND
```

Source	SS	df	MS
Model	83.4273507	9	9.26970563
Residual	17.7061602	1826	.009696692
Total	101.133511	1835	.05511363

Number of obs =	1836
F(9, 1826) =	955.97
Prob > F =	0.0000
R-squared =	0.8249
Adj R-squared =	0.8241
Root MSE =	.09847

vma	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
pm	-.2301315	.012462	-18.47	0.000	-.2545727	-.2056903
veh	.5797463	.0213403	27.17	0.000	.5378923	.6216004
inc	-.1527639	.0192735	-7.93	0.000	-.1905643	-.1149636
arm	-.0222661	.0055999	-3.98	0.000	-.0332489	-.0112833
popa	.1066056	.075276	1.42	0.157	-.0410305	.2542417
urb	-.0243707	.0199983	-1.22	0.223	-.0635926	.0148511
RAILPOP	-.0460049	.0141874	-3.24	0.001	-.0738302	-.0181796
D7479	.0417092	.0105033	3.97	0.000	.0211095	.0623088
TREND	.0072272	.000657	11.00	0.000	.0059386	.0085158
_cons	9.202452	.0427698	215.16	0.000	9.118569	9.286335

1. Strongly balanced refers to the fact that all states have data for all years. We could run the analysis even if one state didn't have data for one year but that would lead us to study unbalanced data.

2. The p-value for each term tests the null hypothesis that the beta coefficient is equal to zero, thus the variable has no effect on predictor variable vma_{it}. A low p-value (< 0.05) indicates that we can reject the null hypothesis. In other words, a predictor that has a low p-value is likely to be a meaningful addition to the model because changes in the predictor's value are related to changes in the response variable. Conversely, a larger (insignificant) p-value suggests that changes in the predictor are not associated with changes in the response.

Appendix E: Models #1-3 regression results and comparison

Model #2 regression results:

```
. xtreg vma pm veh inc arm popa urb RAILPOP D7479 TREND, fe

Fixed-effects (within) regression               Number of obs      =      1836
Group variable: id                              Number of groups   =        51

R-sq:  within  = 0.8955                         Obs per group: min =        36
       between = 0.1897                                        avg =      36.0
       overall = 0.5570                                        max =        36

                                                F(9,1776)          =   1691.32
corr(u_i, Xb)  = -0.0087                        Prob > F           =    0.0000

------------------------------------------------------------------------------
         vma |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          pm |  -.1662821   .0080003   -20.78   0.000    -.1819731   -.1505911
         veh |   .2569884   .0209681    12.26   0.000     .2158637    .2981132
         inc |    .401629   .0244874    16.40   0.000     .3536018    .4496562
         arm |  -.0579252   .0111761    -5.18   0.000    -.0798449   -.0360056
        popa |  -.1272982   .0757926    -1.68   0.093    -.2759504     .021354
         urb |   .1438621   .0960269     1.50   0.134    -.0444755    .3321997
     RAILPOP |  -.0430473   .0145531    -2.96   0.003    -.0715903   -.0145044
       D7479 |   .0143666   .0060378     2.38   0.017     .0025247    .0262085
       TREND |   .0020035   .0005747     3.49   0.001     .0008763    .0031307
       _cons |   9.498745   .0532432   178.40   0.000     9.394319    9.603171
-------------+----------------------------------------------------------------
     sigma_u |  .14777285
     sigma_e |   .0556544
         rho |   .8757767   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(50, 1776) =    86.38             Prob > F = 0.0000
```

Model #3 regression results:

```
. xtreg vma pm pm2 inc_pm urb_pm veh inc arm popa urb RAILPOP D7479 TREND, fe

Fixed-effects (within) regression               Number of obs      =      1836
Group variable: id                              Number of groups   =        51

R-sq:  within  = 0.9064                         Obs per group: min =        36
       between = 0.5118                                        avg =      36.0
       overall = 0.7122                                        max =        36

                                                F(12,1773)         =   1431.02
corr(u_i, Xb)  = -0.1241                        Prob > F           =    0.0000

------------------------------------------------------------------------------
         vma |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
          pm |  -.1702134   .0079807   -21.33   0.000     -.185866   -.1545609
         pm2 |   .1286945   .0144678     8.90   0.000     .1003188    .1570702
      inc_pm |   .3467404   .0314941    11.01   0.000      .284971    .4085098
      urb_pm |   .0261891    .024652     1.06   0.288     -.022161    .0745392
         veh |   .2506962    .019999    12.54   0.000     .2114722    .2899202
         inc |   .3965954   .0244004    16.25   0.000     .3487388    .4444521
         arm |  -.0608016   .0107159    -5.67   0.000    -.0818187   -.0397845
        popa |   .3144881    .084132     3.74   0.000     .1494798    .4794964
         urb |  -.3921175   .1019939    -3.84   0.000    -.5921585   -.1920765
     RAILPOP |  -.0003053   .0142761    -0.02   0.983     -.028305    .0276945
       D7479 |   .0054448   .0057666     0.94   0.345    -.0058652    .0167549
       TREND |   .0042583   .0006413     6.64   0.000     .0030005     .005516
       _cons |   9.312383    .053706   173.40   0.000     9.207049    9.417716
-------------+----------------------------------------------------------------
     sigma_u |  .11681398
     sigma_e |  .05271645
         rho |  .83080036   (fraction of variance due to u_i)
------------------------------------------------------------------------------
F test that all u_i=0:     F(50, 1773) =    88.38             Prob > F = 0.0000
```

Models #1-3 regression results comparison:

	Ordinary L~s	State-Leve~t	A Variable~h
	b/se/t	b/se/t	b/se/t
pm	-0.230***	-0.166***	-0.170***
	(0.01)	(0.01)	(0.01)
	-18.467***	-20.784***	-21.328***
veh	0.580***	0.257***	0.251***
	(0.02)	(0.02)	(0.02)
	27.167***	12.256***	12.535***
inc	-0.153***	0.402***	0.397***
	(0.02)	(0.02)	(0.02)
	-7.926***	16.401***	16.254***
arm	-0.022***	-0.058***	-0.061***
	(0.01)	(0.01)	(0.01)
	-3.976***	-5.183***	-5.674***
popa	0.107	-0.127	0.314***
	(0.08)	(0.08)	(0.08)
	1.416	-1.680	3.738***
urb	-0.024	0.144	-0.392***
	(0.02)	(0.10)	(0.10)
	-1.219	1.498	-3.845***
RAILPOP	-0.046**	-0.043**	-0.000
	(0.01)	(0.01)	(0.01)
	-3.243**	-2.958**	-0.021
D7479	0.042***	0.014*	0.005
	(0.01)	(0.01)	(0.01)
	3.971***	2.379*	0.944
TREND	0.007***	0.002***	0.004***
	(0.00)	(0.00)	(0.00)
	11.000***	3.486***	6.640***
pm2			0.129***
			(0.01)
			8.895***
inc_pm			0.347***
			(0.03)
			11.010***
urb_pm			0.026
			(0.02)
			1.062
constant	9.202***	9.499***	9.312***
	(0.04)	(0.05)	(0.05)
	215.162***	178.403***	173.396***
R-sqr	0.825	0.896	0.906
dfres	1826	1776	1773
BIC	-3236.2	-5382.4	-5562.1

* p<0.05, ** p<0.01, *** p<0.001

Appendix F-1: Summary of the rebound effect by each year

30.	1966	-.2196822	-.3411312	-.0790096
62.	1967	-.2098839	-.3301935	-.0660828
144.	1968	-.2009672	-.3309192	-.0591326
204.	1969	-.193831	-.3154795	-.0505095
253.	1970	-.1945162	-.3050928	-.0536206
284.	1971	-.1950161	-.2943422	-.0583478
336.	1972	-.1848795	-.2752314	-.0426342
365.	1973	-.1613601	-.2612177	-.0384528
437.	1974	-.1183525	-.2210447	.017102
467.	1975	-.1248888	-.2498286	.0413676
548.	1976	-.1181674	-.2319278	.0591358
603.	1977	-.1143598	-.2107643	.0458816
617.	1978	-.112788	-.2188908	.0357406
673.	1979	-.0709045	-.172795	.0839781
761.	1980	-.0493691	-.1504354	.0663166

785.	1981	-.0540104	-.1377471	.0882224
857.	1982	-.0920899	-.1889832	.0694279
909.	1983	-.1286296	-.252086	.0356986
931.	1984	-.1333412	-.2607353	.0159111
984.	1985	-.1356444	-.2683529	-.0123966
1065.	1986	-.2033057	-.3328701	-.0778344
1074.	1987	-.2007578	-.3252831	-.060282
1128.	1988	-.2056258	-.3384833	-.0326082
1202.	1989	-.1940463	-.3266346	-.0287505
1231.	1990	-.1836841	-.3231619	-.0389447
1292.	1991	-.2112969	-.3422583	-.0604301
1338.	1992	-.2135911	-.3513148	-.0528374
1391.	1993	-.2226495	-.3461612	-.0392703
1469.	1994	-.2212509	-.3432928	-.0503672
1496.	1995	-.2219724	-.3455449	-.0367511
1551.	1996	-.2096557	-.3365785	-.0526623
1588.	1997	-.2130233	-.3384078	-.0456809
1681.	1998	-.2413779	-.3819439	-.0730419
1702.	1999	-.219757	-.3592894	-.0368605
1735.	2000	-.1583314	-.315166	.0094642
1800.	2001	-.1946707	-.3439374	-.0305618

Appendix F-2: Summary of the rebound effect by each state

	state	statemean	statemax	statemin
28.	Alabama	-.2516756	-.1166797	-.3344621
71.	Alaska	-.0506986	.0882224	-.1448113
86.	Arizona	-.1862949	-.0298633	-.2614515
115.	Arkansas	-.25014	-.1230938	-.3396029
160.	California	-.1062407	.0528987	-.1977348
185.	Colorado	-.1339775	-.0291012	-.2005527
232.	Connecticut	-.0486899	.0565424	-.1332798
261.	Delaware	-.1143023	-.0119319	-.2038067
315.	Dist. of Col.	-.0467663	.017102	-.1146403
336.	Florida	-.1704694	-.0437376	-.2432733
392.	Georgia	-.2218667	-.0976901	-.307136
420.	Hawaii	-.1001754	-.0106067	-.1779694
467.	Idaho	-.223708	-.0991118	-.3008585
479.	Illinois	-.1047319	.0127661	-.1912654
536.	Indiana	-.1943157	-.0537976	-.2862521
560.	Iowa	-.1666216	-.0248921	-.2609223
598.	Kansas	-.1759179	-.0414079	-.2673914
642.	Kentucky	-.2443009	-.1076251	-.3092119
674.	Louisiana	-.202466	-.0085478	-.2839732
690.	Maine	-.2082856	-.1031216	-.2744468
749.	Maryland	-.095913	.011518	-.1816938
789.	Massachusetts	-.0915734	-.0059111	-.1611243
804.	Michigan	-.1465926	-.0162524	-.2300432
838.	Minnesota	-.1411581	-.0325788	-.196253
871.	Mississippi	-.2890511	-.1335947	-.3819439
914.	Missouri	-.176381	-.0523864	-.2803052
967.	Montana	-.2165057	-.0870477	-.3006174
1002.	Nebraska	-.1773444	-.0589963	-.2674325
1013.	Nevada	-.0766192	.0663166	-.1589924
1061.	New Hampshire	-.1415817	-.0492495	-.2384752

	state	statemean	statemax	statemin
1091.	New Jersey	-.0806571	.0046128	-.1641493
1127.	New Mexico	-.2543772	-.111444	-.3559431
1180.	New York	-.0845418	.026005	-.1865281
1213.	North Carolina	-.2115523	-.0995651	-.2801664
1240.	North Dakota	-.2125176	-.0670858	-.3309192
1274.	Ohio	-.1540974	-.0443851	-.2315968
1313.	Oklahoma	-.2375201	-.0647115	-.3617037
1364.	Oregon	-.1696628	-.0305219	-.2337546
1391.	Pennsylvania	-.1551801	-.0410095	-.2263731
1407.	Rhode Island	-.1440764	-.0453955	-.2205173
1474.	South Carolina	-.2516782	-.113955	-.3184086
1510.	South Dakota	-.2264402	-.1002283	-.3142428
1519.	Tennessee	-.2181268	-.0869055	-.2891062
1568.	Texas	-.1768404	-.0356537	-.255071
1601.	Utah	-.2281016	-.1112768	-.3143393
1630.	Vermont	-.2036059	-.1054404	-.276358
1661.	Virginia	-.1590095	-.0292359	-.2538781
1703.	Washington	-.1398065	-.0167611	-.2134105
1737.	West Virginia	-.2423126	-.069841	-.3422683
1780.	Wisconsin	-.1873488	-.0446903	-.2669973
1809.	Wyoming	-.1890598	.0295592	-.3208669

Appendix G: Program File

Attached on Blackboard

Appendix H: Statistical Output File

Attached on Blackboard