An Empirical Study on Rebound Effect of Hybrid Vehicle

Hao Tian

Honor Thesis

April 2017

Advisor: Dr. Michael S Delgado

1. Introduction

Improving energy efficiency is widely recognized as one of the most crucial means of tackling the climate change and energy crisis. However, economists also realized that with higher energy efficiency, the cost of using energy-consuming equipment decreased, causing the increased usage of equipment, and thus more consumption of the energy. This is what we called “rebound effect”. There are three types of rebound effect (Greening et al, 2000). The first type is the direct rebound effect. Improved energy efficiency of one equipment causes the increase of usage of that equipment directly, making the reduction of the total energy use unproportionate to the improvement of energy efficiency. The second type is the indirect rebound effect. Higher energy efficiency reduces energy cost. Consumers may use the saved cost to purchase other energy services, resulting in the indirect rebound effect. The third type is the economy wide rebound effect. Saved fund from the improved energy induces people to consume more in other areas. The motor industry has been putting effort on improving fuel efficiency for decades and has noticeable achievements. Hybrid car is one of them. Hybrid car, or Hybrid electric vehicle (HEV), has both electric motor and traditional internal combustion engine. In term of the level of the hybridization, hybrid vehicle can be categorized as Belt/muscle/micro hybrid, mild hybrid, full hybrid and plug-in hybrid (Friedman, 2003; Fontara et al, 2008). Modern hybrid cars are able to make the electric vehicle mode, charge-depleting mode and charge sustaining vehicle mode imperceptible in driving experience (Bradley & Frank, 2007). This ability allows vehicles to choose the most fuel-efficient model during different driving situations, and therefore improves the overall fuel efficiency dramatically. Given the high fuel efficiency of hybrid car, its rebound effect concerns us because it is difficult to make optimal policy without knowing how much energy it actually saves.

Extensive studies have been done on measuring the rebound effect of conventional vehicles and most of these studies confirm the existence of this effect. However, few studies introduce hybrid vehicles in their models. Our study is focused on the magnitude of the rebound effect of hybrid vehicles and the evolution of this effect through time. This paper only measures the direct short-run rebound effect of hybrid vehicles. Our models use two kinds of definitions of rebound effect.

Let M denote vehicle miles traveled; e denotes fuel efficiency, which is commonly known as mile per gallon. E = 1/e, which is gallon per mile (GPM).

$$\beta_{M,\,E} = \frac{\Delta M}{\Delta E} * \frac{E}{M}$$

The elasticity of vehicle miles traveled with respect to fuel efficiency is the first definition we use in our model.

Letting P denotes the price of fuel. P*E = C, fuel cost per mile (CPM).

$$\beta_{M,\,E} = \frac{\Delta M}{\Delta C} * \frac{C}{M}$$

This is the second definition of the rebound effect used in our model. The elasticity of vehicle miles traveled with respect to fuel cost per mile. Neither of our models indicate a significant rebound effect of hybrid vehicle.

Since we do not find a significant rebound effect of hybrid vehicle, our estimation of rebound effect has implication to policymakers that they should not worry about prompting hybrid vehicles. The increase in adoption in hybrid vehicles will bring proportional reduction in fuel consumption and greenhouse gases emissions.

2. Literature Review

2.1 Rebound Effect

Extensive researches have been done on measuring the rebound effect of conventional passenger vehicles. Greene (1992) estimated rebound effect of 0.13 for both short-run and long-run. He used the dataset published by Federal Highway Administration. This dataset contains annual vehicle mile traveled data ranging from 1957 to 1989. Jones (1993) estimated rebound effect based on the same dataset from Federal Highway Administration. His model also gave a short-run rebound effect of 0.13, but a much larger long-run rebound effect of 0.31. Small and Van Dender pointed that both Jones and Greene failed to disentangle lagged effect from autocorrelation. Their studies tried to fix this problem. Their model was based on the U.S. national pooled cross-sectional data from 1966 to 2001. The most important finding in their study was the discovery of the declining trend of rebound effect through time. Their model gave estimation of rebound effect of 0.045 for the short run and 0.222 for the long run. They believed the most important reason behind the declining trend was the increase in real income. When consumers have higher real income, the value of their time outweighs fuel spending. This is to say, fuel cost become a less important factor influencing people driving behavior. With the increase in fuel efficiency and decrease in fuel cost per mile, people have less incentive to drive more.

In his recent study, Linn (2013) pointed out that previous studies estimating rebound effect held some assumptions which were not sound in most cases. The first assumption was the absence of correlation between fuel efficiency and other attributions of vehicle. The second was the independence of vehicle miles traveled among vehicles for a household owning multiple cars. The third was the equal effect of fuel efficiency and fuel price on the VMT. Linn emphasized that majority of the studies held at least one of the three assumptions. He believed those inadequate assumptions caused inaccurate estimation. After releasing all of three assumptions, he gave estimations ranging from 0.2 to 0.4. Table 1 summarize estimations of rebound effect from different studies.

Table 1: Summary of the past estimation of rebound effect:
Sources: Sorrel and Dimitropoulos (2007)

Author (year)	Short-run	Long-run	Data	Estimation technique	Country
Mayo & Mathis (1988)	0.22	0.26	Time series 1958-1984, national	3SLS	U.S.
Greene (1992)	0.13	0.13	Time series 1957-1989, national	OLS	U.S.
Jones (1992)	0.13	0.31	Time series 1957-1990, national	OLS	U.S.
Schimiek (1996)	0.05-0.07	0.21-0.29	Time series, national	OLS	U.S.
Wheaton (1982)	0.06	0.06	XS 1972	OLS	25 OECD countries
Haughton & Sakar (1996)	0.09-0.16	0.22	Aggregate panel 1973-1992	2SLS	U.S.
Small & Van Dender (2007)	0.045	0.222	Cross sectional data, 1966-2001	3SLS	U.S
Pull & Greening	0.49		Rotating penal 1980-1990 (CES)	2SLS	U.S.
West	0.87		Cross sectional 1997 CES	Nested logit (discrete) & Instrumental variables (utilization)	U.S.
Linn	0.2-0.4		2009 NHTS	OLS & IV	U.S.

2. 2 Overview of Hybrid vehicle.

2. 2. 1 High fuel efficiency and low carbon emission

The combination of electric and internal combustion drivetrains significantly improves fuel efficiencies of hybrid cars. Table 2 selects some representative tests on measuring the fuel efficiency of hybrid vehicles.

Table 2: Tests on the fuel efficiency of hybrid vehicles.
Sources: Bradley and Frank (2009)

Test	Reduction in gasoline consumption(%)	Baseline gasoline consumption(L/100km)	Authors
EPRI HEV20 simulation	51.1	8.1	Electric power Research Institute, 2001
NREL PHEV30 simulation	64.2	10.4	Simpson, 2006
GT PHEV20 simulation	70.3	8.6	Golbuff, 2006
PHEV40 simulation	71	9.0	Markel, 2006
PHEV Taurus Vehicle	85.6	9.0	Frank, 2002
PHEV EnergyCS Prius	51.0	4.9	MacCurdy, 2006

As shown in the table 2, the reduction in fuel consumption is stunning, ranging from 50 percent to even more than 80 percent. Due to the high fuel efficiency, hybrid cars have lower carbon emission as long as the source of electricity is clean (Helm et al, 2010). As table 2 presents, many researches have confirmed the hybrid cars' ability of reducing carbon emission.

Table 3: Test on the reduction of carbon emission of CO_2
Source: Bradley & Frank (2009)

Hybrid car type	CO_2 reduction (baseline CO_2 emissions)	Author
Compact car PHEV	40% (200g/km)	Electric Power Research Institute, 2002
Mid-sized PHEV	44% (257g/km)	Electric Power Research Institute, 2001
Mid-sized PHEV	50% (235g/mi)	Kliesch, 2006
Mid-sized PHEV	58%	Clark, 2006

2. 2. 2 Government incentive

No surprise, the extraordinary high fuel efficiency and performance on reducing carbon emission catch the government attention and prompt them to make policies of promoting the penetration of hybrid cars. Gallagher and Muehlegger (2008) researched on different incentive means. Their analysis covered incentives of different governments from local level, state level to federal level. The period was from 2000 to 2006. Incentives included sales tax waivers, income tax credits and deduction and single-occupancy access to carpool lane. Results showed all strong or weak positive correlation between different incentive methods, and the sale tax waiver had the highest contribution to the adoption of hybrid cars.

2. 2. 3 Motivation of the hybrid cars buyers

Many studies try to find reasons why consumers choose hybrid car. Knowing the motives behind purchasing behavior helps policymakers to make more potent incentive to encourage adoption of hybrid cars. The first motivation is cost reduction. Kelvin (2007) researched owners of Prius who bought their cars from 2003 to 2007. He concluded that more than 73% of the Prius owners have strong financial motivation to buy their cars. Yet, the reality showed the opposite: majority of studies proved that hybrid vehicles have higher total cost of ownership (TCO) than conventional vehicles (Al-Alawi & Bradley, 2012). However, some buyers were still willing to pay for the extra cost of the hybrid cars because they have other motivations. The second motivation is the environmental symbolism. In their study of California early hybrid car market, Heffner et al (2007a, 2007b) stated that many early adopters of hybrid vehicle wanted to show their environmental awareness through hybrid cars. By comparing the Prius, which has unique physical appearance, with other hybrid cars that looks identical to their conventional model, Delgado et al (2015) found a signaling value of $587 or 4.5% of the car's value, further confirmed the motivation of exhibiting environmental awareness. Heffner et al also found the third motivation that was to conform the community value. They found that if some green consumers lived in a clustered green community, they would have the willingness to use hybrid to show that they were conform to the community value. The fourth motivation identified by Heffner et al was the acceptance of new technology. Those consumers were attracted by latest innovation, and therefore would like to buy a hybrid.

Table 4 motives identified in literature

Sources: Ozaki and Sevastyanova (2011)

Pay less to fuel	Being considerate to others
Sharing common values within their communities	Educating others about a new type of vehicle
Tax credit	Doing the right thing
Climate change awareness	Free parking
Reduction in pollutant	Independence of gasoline companies.
Free access to town centre	Sharing technological knowledge

Being part of socially responsible activity	Being a trendsetter of environment-friendly technology

3. Hypothesis

Drivers make their own decision of how much to drive each year. Therefore, the magnitude of rebound effect highly depends on the type of driver. As stated in the motives of the hybrid vehicle buyers, people who buy hybrid vehicles are generally seeking to either save cost or show their determination of doing good for the environment. Intuitively, people who care about the environment will be less prone to drive more even if they have more fuel-efficient cars. However, people who are motivated by cost-saving will drive more.

Because of the diversity of consumers, it is difficult to speculate the rebound effect of the hybrid cars. We are concerned with both the magnitude of rebound effect and the change of rebound effect through time. The mixture of different hybrid car buyers might change gradually given the fact that hybrid vehicles are relative new compared with conventional cars. When hybrid cars first came out, early adopters were those who cared about the environment or those who were enthusiastic for new technology. Driving hybrid vehicles could be an ideal way to demonstrate their personal values.

In contrast, those who were economically sensitive might have been more cautious about this new type of car. One reason being that hybrid vehicles were much more expensive than other comparable conventional cars. The second reason is that its ability of reducing energy expense had not been fully proven. However, after a few years, hybrid vehicle became more widely adopted and had substantiated its ability of reducing fuel cost. This may have attracted consumers who cared about cost more than doing good for the environment. The development of hybrid vehicles might have led to the change in component of different type of buyers, and potentially lead to the change in rebound effect.

Therefore, this paper is intended to test two hypotheses. The first null hypothesis is that the rebound effect of hybrid vehicles does not exist. The second null hypothesis is that the rebound effect of hybrid vehicles does not change through time.

4. Dataset

Our study uses the dataset organized by Sun, Delgado and Khanna (2016). This dataset collects data mainly from 2009 National Household Travel Survey conducted by U.S. Department of Transportation from March 2008 to May 2009. This survey contains 150,147 households, 309,163 vehicles, and 351,275 individuals. They extract variables reflecting vehicle usage condition, personal driving behaviors, major characteristics of vehicle and demographic information. Those variables include vehicle miles traveled, model, make, fuel efficiency (mile per gallon), commute distance, etc. This dataset only includes households with complete data on all variables of interest. Since data of hybrid vehicle only exist in the sample after 2000, they only introduced households who purchased new vehicles after 2000 to the dataset to avoid any systematic difference between hybrid vehicle buyers and those who bought brand new vehicles prior to 2000.

Other data sources of this dataset include Council for Community and Economic Research, and the Green Plan Capacity (GPC) index from Resourced Renewal Institute (Siy at al. 2001). Those sources provide quarterly data of gasoline prices at city level from 2000 to 2009.

Since their analysis is also focused on the analysis of gasoline powered vehicle for personal travel use, this dataset excludes any vehicles for commercial usage, for example trucks, golf carts, motorcycle, etc. Vehicles classified as automobile, station wagon, van, sport utility vehicle but have commercial plates are also excluded.

Table 5: Data summary:

Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
mpg	48,153	26.25	4.73	13.10	65.78
Vehicle purchase year	48,153	2,005.14	2.14	1998	2009
Buy year real gas price	48,153	1.91	0.49	0.89	4.37
Gas price 2008	48,153	3.51	0.17	3.15	3.92
Commute distance	48,153	8.07	10.87	0.00	74.99
Age	48,153	56.64	15.17	18.00	92.00
Share female	48,153	0.56	0.30	0.00	1.00
Vehicle miles traveled	48,153	21,687.06	14,817.27	3.07	278,868.70
Number of Adults	48,153	1.88	0.61	1.00	7.00
Number of workers	48,153	0.99	0.87	0.00	6.00
Number of drivers	48,153	1.86	0.65	1.00	7.00
Family Income	48,153	12.45	5.07	1.00	18.00
Vehicle Count	48,153	1.95	0.81	1.00	11.00
Highest Education	48,153	3.62	1.11	1.00	5.00

5. Model

Our models use two kinds of definitions: elasticity of vehicle miles traveled with respect to fuel efficiency and elasticity of vehicle miles traveled with respect to fuel cost per mile. We use log-log form to measure only the short-run rebound effect. The regression uses method of OSL.

The response variable is logVMT: natural logarithm of vehicle miles traveled. The right-hand side variables contain: logGPM: natural logarithm of gallon per mile;

logCPM: natural logarithm of fuel cost per mile; Year: vehicle purchase year. Hybrid: dummy variable of hybrid vehicle; 10 continuous control variables contain real gas price in purchase year, family income, household size, vehicle count, number of adults, number of workers, education level, commute distance, age, share female; 4 dummy variables include state, race, Hispanic, urban; 11 additional dummy variables of multiple type of vehicles: Tahoe, Escape, Yukon, Civic, Accord, RX, Mariner, Altima, Camry, Prius, Highlander, VueGreenline.

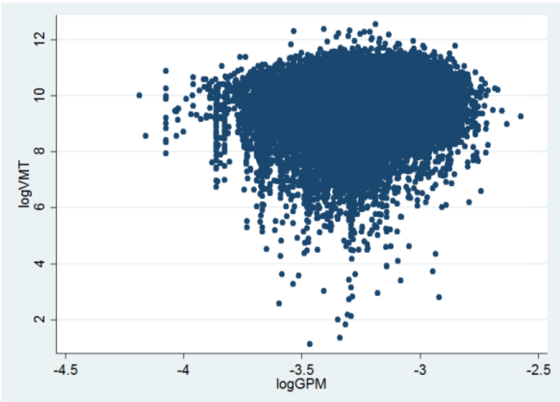

Figure 1: logVMT vs log GPM

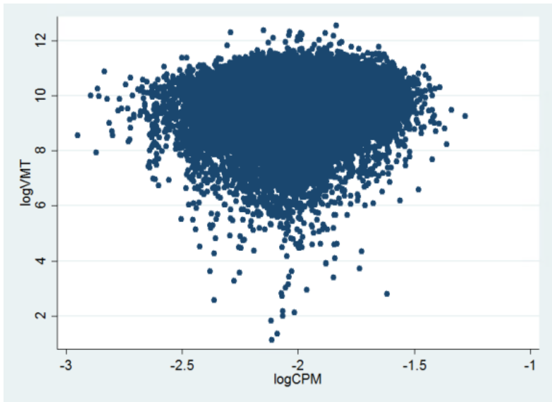

Figure 2: logVMT vs logCPM

Regressing logVMT on logGPM and logCPM, both scatterplots indicate that it seems log VMT has polynomial relationship with logGPM and logCPM. In fact, the models contain polynomial terms indeed give best result. Among all the polynomial models, the ones contain cubic, square and linear term give best results.

The following table shows the models we use.

Table 6: Model

Model 1		**Model 2**	
Response Variable	LogVMT	**Response Variable**	LogVMT

Explanatory Variables	LogGPM3*Year	**Explanatory Variables**	LogCPM3*Year
	LogGPM2*Year		LogCPM2*Year
	LogGPM*Year		LogCPM*Year
	LogGPM3*Hybrid		LogCPM3*Hybrid
	LogGPM2*Hybrid		LogCPM2*Hybrid
	LogGPM*Hybrid		LogCPM*Hybrid
	Control Variables		Control Variables

6. Results

Results show that hybrid vehicles and conventional vehicles share the same models under both two definitions. The models contain interaction terms of hybrid are not significant. Even if hybrid vehicle does not have its own model, we still would like to know the rebound effect in general level. After removing all hybrid interaction terms, the models become significant. In our new models, some interaction terms are not significant in 1998 and 1999, but the interaction terms are significant at 10% level from 2000 to 2009 under both models.

Model result:

Table 7: Model 1: response variable: logVMT

(Full model result shown in Appendix A)

Variable	Coef.	Std. Err.	t	P > |t|	95% Conf. Interval	
logGPM3*Year						
1998	0.462466	0.666701	0.69	0.488	-0.84428	1.769209
1999	-0.70313	0.511685	-1.37	0.169	-1.70604	0.299782
2000	-0.77002	0.442282	-1.74	0.082	-1.6369	0.09686
2001	-0.54645	0.215108	-2.54	0.011	-0.96807	-0.12484
2002	-0.48358	0.21443	-2.26	0.024	-0.90386	-0.06329
2003	-0.49569	0.205016	-2.42	0.016	-0.89752	-0.09385

2004	-0.4017	0.207418	-1.94	0.053	-0.80824	0.004847
2005	-0.4311	0.200494	-2.15	0.032	-0.82408	-0.03813
2006	-0.44212	0.195469	-2.26	0.024	-0.82524	-0.059
2007	-0.50734	0.191677	-2.65	0.008	-0.88303	-0.13165
2008	-0.43811	0.197051	-2.22	0.026	-0.82433	-0.05188
2009	-0.74314	0.347394	-2.14	0.032	-1.42404	-0.06224
LogGPM2*Year						
1998	1.229434	4.576571	0.27	0.788	-7.74071	10.19958
1999	-6.21701	3.679391	-1.69	0.091	-13.4287	0.994649
2000	-6.74233	3.243254	-2.08	0.038	-13.0992	-0.38551
2001	-5.29087	2.03598	-2.6	0.009	-9.28142	-1.30032
2002	-4.8745	2.033881	-2.4	0.017	-8.86094	-0.88807
2003	-4.96474	1.978991	-2.51	0.012	-8.84359	-1.08589
2004	-4.35884	1.998899	-2.18	0.029	-8.27671	-0.44097
2005	-4.54478	1.957905	-2.32	0.02	-8.3823	-0.70726
2006	-4.61256	1.926049	-2.39	0.017	-8.38764	-0.83748
2007	-5.0463	1.904092	-2.65	0.008	-8.77835	-1.31426
2008	-4.54679	1.933259	-2.35	0.019	-8.336	-0.75757
2009	-6.69762	2.720934	-2.46	0.014	-12.0307	-1.36455
logGPM*Year						
1998	-6.28827	9.293424	-0.68	0.499	-24.5035	11.92697
1999	-18.1484	8.216115	-2.21	0.027	-34.2521	-2.04473
2000	-19.1187	7.68561	-2.49	0.013	-34.1826	-4.05479
2001	-16.7432	6.489541	-2.58	0.01	-29.4628	-4.02358
2002	-16.0641	6.490762	-2.47	0.013	-28.786	-3.34208
2003	-16.24	6.413005	-2.53	0.011	-28.8096	-3.67045
2004	-15.2819	6.453034	-2.37	0.018	-27.9299	-2.63388
2005	-15.5691	6.393212	-2.44	0.015	-28.0999	-3.03833
2006	-15.6769	6.342654	-2.47	0.013	-28.1086	-3.24523
2007	-16.3969	6.311735	-2.6	0.009	-28.7679	-4.02576
2008	-15.5138	6.348603	-2.44	0.015	-27.9572	-3.07048
2009	-19.3111	7.093437	-2.72	0.006	-33.2144	-5.40789

Table 8: Model 2: response variable: log VMT

Variable	Coef.	Std. Err.	t	P > |t|	95% Conf. Interval	
logCPM3*Year						
1998	0.363943	0.965071	0.38	0.706	-1.52761	2.255495
1999	-0.61968	0.693162	-0.89	0.371	-1.97828	0.738931
2000	-0.88977	0.678745	-1.31	0.19	-2.22012	0.440583
2001	-0.60658	0.230156	-2.64	0.008	-1.05769	-0.15547
2002	-0.4949	0.227979	-2.17	0.03	-0.94174	-0.04806
2003	-0.51574	0.212211	-2.43	0.015	-0.93168	-0.09981
2004	-0.35674	0.211199	-1.69	0.091	-0.77069	0.057212
2005	-0.33849	0.198188	-1.71	0.088	-0.72694	0.049958
2006	-0.40808	0.19068	-2.14	0.032	-0.78181	-0.03434
2007	-0.51331	0.183002	-2.8	0.005	-0.872	-0.15463
2008	-0.36406	0.192535	-1.89	0.059	-0.74143	0.013313
2009	-0.85856	0.504962	-1.7	0.089	-1.84829	0.131173
LogCPM2*Year						
1998	0.301737	3.97844	0.08	0.94	-7.49606	8.099533
1999	-3.40977	2.991913	-1.14	0.254	-9.27396	2.454421
2000	-4.68361	2.888012	-1.62	0.105	-10.3442	0.976936
2001	-3.51049	1.27877	-2.75	0.006	-6.01689	-1.00408
2002	-3.05707	1.272716	-2.4	0.016	-5.55161	-0.56253
2003	-3.15911	1.217078	-2.6	0.009	-5.5446	-0.77362
2004	-2.53788	1.219587	-2.08	0.037	-4.92829	-0.14748
2005	-2.44364	1.173393	-2.08	0.037	-4.74351	-0.14378
2006	-2.72239	1.144547	-2.38	0.017	-4.96572	-0.47906
2007	-3.15649	1.116648	-2.83	0.005	-5.34513	-0.96784
2008	-2.47352	1.147796	-2.16	0.031	-4.72321	-0.22382
2009	-4.70044	2.284953	-2.06	0.04	-9.17897	-0.2219
logCPM*Year						
1998	-2.79104	4.472484	-0.62	0.533	-11.5572	5.975084
1999	-6.25562	3.668113	-1.71	0.088	-13.4452	0.933929
2000	-7.66772	3.550473	-2.16	0.031	-14.6267	-0.70875

2001	-6.42083	2.407718	-2.67	0.008	-11.14	-1.70167
2002	-5.97728	2.405874	-2.48	0.013	-10.6928	-1.26173
2003	-6.11538	2.360022	-2.59	0.01	-10.7411	-1.4897
2004	-5.53876	2.370951	-2.34	0.019	-10.1859	-0.89166
2005	-5.41478	2.331458	-2.32	0.02	-9.98447	-0.84509
2006	-5.69859	2.303614	-2.47	0.013	-10.2137	-1.18348
2007	-6.14443	2.279296	-2.7	0.007	-10.6119	-1.67698
2008	-5.39105	2.301415	-2.34	0.019	-9.90185	-0.88024
2009	-7.91277	3.094618	-2.56	0.011	-13.9783	-1.84728

Rebound effect result calculated based on the model results

Table 9: Rebound effect of hybrid vehicle:

	Model 1: definition 1			Model 2: definition 2		
Year	Rebound effect	95% Conf. Interval		Rebound Effect	95% Conf. Interval	
1998	3.00	-59.22	60.83	2.08	-36.12	37.74
1999	-1.32	-50.65	50.63	-1.06	-32.19	32.16
2000	0.08	-38.02	38.69	0.14	-23.40	24.06
2001	0.10	-24.79	25.45	0.06	-16.34	17.00
2002	0.23	-24.73	25.32	0.24	-16.10	16.68
2003	0.15	-24.63	25.28	0.11	-16.46	17.11
2004	0.48	-24.80	25.41	0.48	-16.39	17.00
2005	0.34	-24.71	25.32	0.46	-16.47	17.08
2006	0.33	-23.56	24.15	0.33	-15.79	16.38
2007	0.17	-23.31	23.97	0.16	-15.66	16.32
2008	0.13	-24.35	24.69	0.18	-16.32	16.66
2009	-0.29	-35.06	36.29	-0.33	-22.06	23.30

Table 10: Rebound effect of conventional vehicle:

	Model 1: definition 1			Model 2: definition 2		
Year	Rebound effect	95% Conf. Interval		Rebound Effect	95% Conf. Interval	
1998	0.81	-52.70	54.31	0.62	-30.87	32.48
1999	-0.01	-41.60	41.57	-0.04	-24.81	24.78
2000	0.33	-36.11	36.78	0.42	-21.74	22.40
2001	0.33	-22.14	22.80	0.34	-14.55	15.21
2002	0.29	-22.12	22.70	0.31	-14.56	15.15
2003	0.32	-21.53	22.18	0.33	-14.24	14.89
2004	0.31	-21.64	22.26	0.31	-14.30	14.91
2005	0.30	-21.25	21.85	0.29	-14.10	14.70
2006	0.30	-20.98	21.57	0.29	-13.97	14.56
2007	0.33	-20.74	21.40	0.32	-13.84	14.50
2008	0.17	-21.34	21.68	0.15	-14.25	14.59
2009	0.62	-30.41	31.65	0.54	-18.78	20.01

7. Discussion

Confidence intervals of the rebound effect have wide range and contain zeros for all years. In conclusion, we do not find rebound effect in hybrid vehicles. Furthermore, because confidence intervals for all years are insignificant, we further conclude that the rebound effect does not change through time. Possible reasons could be that most hybrid drivers care about environment. When they get a more fuel-efficient vehicle, they still consciously maintain previous driving behaviors because they do not want to consume more gas and emit more greenhouse gases. The percentage of the people who care about environment outweighs those who don't. Another potential explanation is that fuel efficiency and fuel cost are not key driving forces of driving behavior of hybrid car buyers. As Small and Van Dender (2007) stated in their study, rebound effect declines as real income increases. This is to say, when people have higher income, their time value is higher than the fuel cost.

Additionally, we also did not find a significant rebound effect for conventional vehicle. We are aware of that our estimation is different with majority of studies. The first possible reason is that the sample of data we use is different with other studies. The second possibility is that our study is not able to control some variables which can significantly influence model result. Future studies can explore what those variables are and make new estimation after introducing those variables.

Appendix A: Full model results

Table 11: Result of mode l:

Variable	Coef.	Std. Err.	t	P > |t|	95% Conf. Interval	
BuyYearRealGasPrice	0.059096	0.010277	5.75	0	0.038953	0.079239
Race						
2	0.001374	0.013972	0.1	0.922	-0.02601	0.02876
3	-0.11486	0.019031	-6.04	0	-0.15216	-0.07756
4	0.063392	0.037355	1.7	0.09	-0.00982	0.136609
5	-0.00814	0.056502	-0.14	0.885	-0.11889	0.102603
6	0.030507	0.039967	0.76	0.445	-0.04783	0.108841
7	0.04622	0.026831	1.72	0.085	-0.00637	0.098809
8	0.008139	0.032554	0.25	0.803	-0.05567	0.071946
Number of Drivers	0.123545	0.009193	13.44	0	0.105526	0.141563
Family Income	0.016945	0.00072	23.55	0	0.015535	0.018356
Household Size	0.023233	0.003716	6.25	0	0.015948	0.030517
Vehicle Count	0.318118	0.00492	64.66	0	0.308474	0.327761
Hispanic	-0.01217	0.015433	-0.79	0.43	-0.04242	0.018077
Number of Adults	0.023969	0.009123	2.63	0.009	0.006088	0.041851
Urban	-0.12098	0.006505	-18.6	0	-0.13373	-0.10822
Number of Workers	0.063415	0.004595	13.8	0	0.054408	0.072422
Highest Education	0.027458	0.002898	9.47	0	0.021778	0.033139
Commute	0.008833	0.000295	29.9	0	0.008254	0.009412
Age	-0.00881	0.000271	-32.48	0	-0.00935	-0.00828
Share Female	-0.15499	0.009403	-16.48	0	-0.17342	-0.13656
Tahoe	0.553237	0.424596	1.3	0.193	-0.27898	1.385452
Escape	0.045616	0.173462	0.26	0.793	-0.29437	0.385604
Yukon	-0.24018	0.600173	-0.4	0.689	-1.41652	0.936171
Civic	0.302958	0.104967	2.89	0.004	0.097222	0.508695
Accord	0.177956	0.18107	0.98	0.326	-0.17694	0.532854
RX	-0.08635	0.425811	-0.2	0.839	-0.92095	0.748246

Mariner	0.32978	0.346621	0.95	0.341	-0.3496	1.009162
Altima	0.500549	0.601881	0.83	0.406	-0.67915	1.680243
Camry	0.075257	0.157401	0.48	0.633	-0.23325	0.383764
Prius	0.161709	0.062126	2.6	0.009	0.039942	0.283476
Highlander	-0.01114	0.181624	-0.06	0.951	-0.36713	0.344844
VueGreenLine	0.230096	0.600181	0.38	0.701	-0.94627	1.406459
_cons	-8.65175	6.980434	-1.24	0.215	-22.3335	5.02999
State id						
2	0.176724	0.090649	1.95	0.051	-0.00095	0.354398
3	0.150207	0.098365	1.53	0.127	-0.04259	0.343004
4	0.070289	0.072798	0.97	0.334	-0.0724	0.212975
5	0.087333	0.072258	1.21	0.227	-0.05429	0.228959
6	0.179214	0.098598	1.82	0.069	-0.01404	0.372467
7	0.156345	0.10118	1.55	0.122	-0.04197	0.354659
8	-0.24949	0.104956	-2.38	0.017	-0.4552	-0.04377
9	0.171267	0.096478	1.78	0.076	-0.01783	0.360366
10	0.12469	0.072291	1.72	0.085	-0.017	0.266381
11	0.198766	0.07295	2.72	0.006	0.055784	0.341749
12	0.040202	0.103307	0.39	0.697	-0.16228	0.242685
13	0.131879	0.074264	1.78	0.076	-0.01368	0.277437
14	0.039879	0.109947	0.36	0.717	-0.17562	0.255376
15	0.104024	0.080156	1.3	0.194	-0.05308	0.261132
16	0.165765	0.074177	2.23	0.025	0.020379	0.311152
17	0.168373	0.100161	1.68	0.093	-0.02794	0.364691
18	0.20633	0.099213	2.08	0.038	0.011871	0.40079
19	0.179489	0.094652	1.9	0.058	-0.00603	0.365008
20	0.170231	0.089086	1.91	0.056	-0.00438	0.344842
21	0.175793	0.087972	2	0.046	0.003367	0.348219
22	0.181583	0.129622	1.4	0.161	-0.07248	0.435644
23	0.179936	0.082822	2.17	0.03	0.017605	0.342267
24	0.186451	0.091711	2.03	0.042	0.006695	0.366206
25	0.14678	0.089082	1.65	0.099	-0.02782	0.321383

26	0.26447	0.101214	2.61	0.009	0.06609	0.462849
27	0.122391	0.101552	1.21	0.228	-0.07665	0.321434
28	0.217694	0.072604	3	0.003	0.075389	0.36
29	0.19514	0.102229	1.91	0.056	-0.00523	0.39551
30	0.142411	0.077424	1.84	0.066	-0.00934	0.294163
31	0.168715	0.134345	1.26	0.209	-0.0946	0.432032
32	0.072714	0.083431	0.87	0.383	-0.09081	0.236239
33	0.273259	0.099222	2.75	0.006	0.078783	0.467736
34	0.01214	0.096689	0.13	0.9	-0.17737	0.20165
35	0.080896	0.072318	1.12	0.263	-0.06085	0.222641
36	0.164058	0.082096	2	0.046	0.003149	0.324967
37	0.213581	0.10122	2.11	0.035	0.015189	0.411974
38	0.033554	0.095973	0.35	0.727	-0.15456	0.221663
39	0.052785	0.081348	0.65	0.516	-0.10666	0.212228
40	0.134563	0.107721	1.25	0.212	-0.07657	0.345697
41	0.22433	0.073363	3.06	0.002	0.080537	0.368123
42	0.138988	0.076628	1.81	0.07	-0.0112	0.28918
43	0.25398	0.075148	3.38	0.001	0.10669	0.40127
44	0.201718	0.072181	2.79	0.005	0.060242	0.343195
45	-0.01394	0.098035	-0.14	0.887	-0.20609	0.178213
46	0.171175	0.072389	2.36	0.018	0.029291	0.313059
47	0.167506	0.076307	2.2	0.028	0.017945	0.317068
48	0.104451	0.090747	1.15	0.25	-0.07342	0.282316
49	0.14784	0.076346	1.94	0.053	-0.0018	0.297479
50	0.227214	0.101213	2.24	0.025	0.028836	0.425593
51	0.087625	0.103491	0.85	0.397	-0.11522	0.29047

Table 12: result of model 2:

Variable	Coef.	Std. Err.	t	P > |t|	95% Conf. Interval	
BuyYearRealGasPrice	0.059145	0.010278	5.75	0	0.039001	0.079289
Race						
2	0.00146	0.013972	0.1	0.917	-0.02592	0.028845
3	-0.11652	0.019027	-6.12	0	-0.15381	-0.07922
4	0.063353	0.037353	1.7	0.09	-0.00986	0.136566
5	-0.00846	0.056503	-0.15	0.881	-0.1192	0.102292
6	0.029638	0.039966	0.74	0.458	-0.0487	0.10797
7	0.046759	0.026832	1.74	0.081	-0.00583	0.099349
8	0.007855	0.032553	0.24	0.809	-0.05595	0.071659
Number of Drivers	0.123477	0.009193	13.43	0	0.105459	0.141495
Family Income	0.016948	0.00072	23.55	0	0.015537	0.018358
Household Size	0.023506	0.003715	6.33	0	0.016224	0.030789
Vehicle Count	0.318512	0.004918	64.77	0	0.308874	0.328151
Hispanic	-0.01184	0.015435	-0.77	0.443	-0.04209	0.018413
Number of Adult	0.023692	0.009123	2.6	0.009	0.00581	0.041573
Urban	-0.12042	0.006507	-18.51	0	-0.13317	-0.10766
Number of Workers	0.063421	0.004595	13.8	0	0.054414	0.072428
Highest Education	0.027372	0.002898	9.45	0	0.021693	0.033051
Commute	0.008818	0.000295	29.86	0	0.00824	0.009397
Age	-0.00881	0.000271	-32.47	0	-0.00934	-0.00828
Share Female	-0.15486	0.009402	-16.47	0	-0.17329	-0.13643
Tahoe	0.554068	0.4246	1.3	0.192	-0.27815	1.386289
Escape	0.044989	0.173473	0.26	0.795	-0.29502	0.384998
Yukon	-0.24376	0.600185	-0.41	0.685	-1.42013	0.93261
Civic	0.298483	0.104538	2.86	0.004	0.093587	0.50338
Accord	0.174849	0.181067	0.97	0.334	-0.18004	0.529743
RX	-0.08756	0.426121	-0.21	0.837	-0.92276	0.747642
Mariner	0.329136	0.34662	0.95	0.342	-0.35024	1.008515

Altima	0.494508	0.60166	0.82	0.411	-0.68475	1.673769
Camry	0.064927	0.157767	0.41	0.681	-0.2443	0.374153
Prius	0.161294	0.061384	2.63	0.009	0.04098	0.281607
Highlander	-0.0114	0.181627	-0.06	0.95	-0.36739	0.344594
VueGreenLine	0.235556	0.600203	0.39	0.695	-0.94085	1.411962
_cons	4.969977	1.557524	3.19	0.001	1.917209	8.022745
State id	0.123477	0.009193	13.43	0	0.105459	0.141495
2	0.193595	0.090686	2.13	0.033	0.015848	0.371341
3	0.169399	0.098394	1.72	0.085	-0.02345	0.362252
4	0.087058	0.072842	1.2	0.232	-0.05571	0.229829
5	0.073528	0.072259	1.02	0.309	-0.0681	0.215157
6	0.20085	0.09864	2.04	0.042	0.007515	0.394186
7	0.152898	0.101188	1.51	0.131	-0.04543	0.351229
8	-0.24161	0.104986	-2.3	0.021	-0.44739	-0.03584
9	0.194656	0.096528	2.02	0.044	0.005461	0.383852
10	0.134309	0.072326	1.86	0.063	-0.00745	0.276069
11	0.21208	0.072985	2.91	0.004	0.069028	0.355131
12	0.032152	0.103317	0.31	0.756	-0.17035	0.234655
13	0.153021	0.074321	2.06	0.04	0.007351	0.298691
14	0.049406	0.109961	0.45	0.653	-0.16612	0.264931
15	0.11496	0.080198	1.43	0.152	-0.04223	0.272148
16	0.176567	0.074213	2.38	0.017	0.031108	0.322026
17	0.191129	0.10021	1.91	0.056	-0.00528	0.387541
18	0.221909	0.099243	2.24	0.025	0.027391	0.416427
19	0.199261	0.094672	2.1	0.035	0.013703	0.384819
20	0.184853	0.089128	2.07	0.038	0.010162	0.359545
21	0.185266	0.088009	2.11	0.035	0.012768	0.357764
22	0.193411	0.129646	1.49	0.136	-0.0607	0.447519
23	0.189539	0.08285	2.29	0.022	0.027152	0.351927
24	0.212635	0.091757	2.32	0.02	0.03279	0.39248
25	0.169631	0.089136	1.9	0.057	-0.00508	0.344339
26	0.283886	0.101223	2.8	0.005	0.085488	0.482284

27	0.13469	0.101568	1.33	0.185	-0.06438	0.333764
28	0.232906	0.072654	3.21	0.001	0.090502	0.375309
29	0.20535	0.102248	2.01	0.045	0.004942	0.405758
30	0.160332	0.077477	2.07	0.039	0.008476	0.312189
31	0.175163	0.134357	1.3	0.192	-0.08818	0.438504
32	0.083582	0.083473	1	0.317	-0.08003	0.24719
33	0.289596	0.099252	2.92	0.004	0.09506	0.484131
34	0.016952	0.096698	0.18	0.861	-0.17258	0.206482
35	0.079331	0.072343	1.1	0.273	-0.06246	0.221123
36	0.17769	0.08213	2.16	0.031	0.016713	0.338666
37	0.237692	0.101262	2.35	0.019	0.039218	0.436167
38	0.035662	0.09599	0.37	0.71	-0.15248	0.223803
39	0.062953	0.081391	0.77	0.439	-0.09657	0.222481
40	0.141052	0.107752	1.31	0.191	-0.07014	0.352247
41	0.247887	0.073423	3.38	0.001	0.103978	0.391796
42	0.156914	0.076678	2.05	0.041	0.006625	0.307204
43	0.276665	0.075205	3.68	0	0.129262	0.424068
44	0.220228	0.072222	3.05	0.002	0.078672	0.361784
45	-0.00121	0.098072	-0.01	0.99	-0.19343	0.191015
46	0.188507	0.072444	2.6	0.009	0.046517	0.330497
47	0.176234	0.076345	2.31	0.021	0.026596	0.325872
48	0.104426	0.090762	1.15	0.25	-0.07347	0.28232
49	0.156204	0.076382	2.05	0.041	0.006494	0.305914
50	0.232702	0.101229	2.3	0.022	0.034292	0.431112
51	0.110526	0.103511	1.07	0.286	-0.09236	0.313408

Appendix B: Rebound effect calculation procedure

Rebound effect calculation:

Under the log-log form, the elasticity, which is defined as rebound effect in our study, is the derivative of logVMT with respect to logGPM or logCPM.

For the first model, logVMT = A_1*(logGPM)^3 + A_2*(logGPM)^2 + A_3*logGPM + Control variables.

Rebound effect = $\frac{\partial logVMT}{\partial logGPM} * \frac{logGPM}{logVMT}$ = 3*A_1*(logGPM)^2 + 2*A_2*logGPM + A_3

For different years, logGPM will use the logGPM under that year.

We use the same principal for the calculation of the second definition of rebound effect.

Rebound effect = $\frac{\partial logVMT}{\partial logCPM} * \frac{logCPM}{logVMT}$ = 3*A_1*(logCPM)^2 + 2*A_2*logCPM + A_3

For different years, logCPM will use the logCPM under that year.

Table 13: log GPM and log CPM

		1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Conventional	logGPM	-3.315	-3.247	-3.233	-3.245	-3.240	-3.249	-3.232	-3.240	-3.252	-3.259	-3.275	-3.299
	logCPM	-2.066	-1.981	-1.979	-1.989	-1.986	-1.995	-1.977	-1.985	-1.998	-2.006	-2.023	-2.049
Hybrid	logGPM	-3.621	-3.790	-3.373	-3.608	-3.599	-3.688	-3.675	-3.738	-3.635	-3.646	-3.714	-3.706
	logCPM	-2.406	-2.589	-2.148	-2.329	-2.281	-2.426	-2.382	-2.454	-2.370	-2.382	-2.436	-2.446

Confidence interval calculation procedure:

Model 1:

Since the rebound effect equal to 3*A_1*(logGPM)^2 + 2*A_2*logGPM + A_3

Variance of it equal to Var(A1)*(3*(logGPM)^2)^2 + Var(A2)*(2logGPM)^2 + Var(A3) + 3*2*(logGPM)^3*Cov(A1, A2) + 3(logGPM)^2*Cov(A1, A3) + 2logGPM*Cov(A2, A3)

Model 2:

Rebound effect equal to 3*A_1*(logCPM)^2 + 2*A_2*logCPM + A_3

Variance of it equal to $Var(A1)*(3*(logCPM)^2)^2 + Var(A2)*(2logCPM)^2 + Var(A3) +$
$3*2*(logCPM)^3*Cov(A1, A2) + 3(logCPM)^2*Cov(A1, A3)$
$+ 2logCPM*Cov(A2, A3)$

Reference:

Al-Alawi, B. M., & Bradley, T. H. (2012). Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. *Applied Energy*.

Bradley, T. H., & Frank, A. A. (2007). Design, demonstrations and sustainability impact assessments for plug-in hybrid electric vehicles. *Renewable and Sustainable Energy Reviews, 13*(1), 115-128. doi:10.1016/j.rser.2007.05.003

Clark, C. (2006). Environmental benefits of plug-in hybrid electric vehicles. In: ZEV technology symposium, Sacramento, CA; 25-27 September

Delgado, M. S., Harriger, J. L., & Khanna, N. (2015). The value of environmental status signaling. *Ecological Economics*, *111*, 1-11. doi:10.1016/j.ecolecon.2014.12.021

Electric Power Research Institute, (2001). Comparing the benefits and impacts of hybrid electric vehicles options for compact sedan and sport utility vehicles. Electric Power Research Inst, Palo Alto

Electric Power Research Institute. (2002). Comparing the benefits and impacts of hybrid electric vehicle options for compact sedan and sport utility vehicles.

Fontaras, G., Pistikopoulos, P., & Samaras, Z. (2008). Experimental evaluation of hybrid vehicle fuel economy and pollutant emissions over real-world simulation driving cycles. *Atmospheric Environment, 42*(18), 4023-4035. doi:10.1016/j.atmosenv.2008.01.053

Frank, A. A. (2002). Battery dominant hybrid electric vehicle systems development and evaluation.

Friedman, D. (2003). A new road: The technology and potential of hybrid vehicles. Union of Concerned Scientists 2003.

Gallagher, K. S., & Muehlegger, E. (2008). Giving green to get green? Incentives and consumer adoption of hybrid vehicle technology. *Journal of Environmental Economics and Management*.

Gaines, L., & Singh, M. (1995). Energy and Environmental Impacts of Electric Vehicle Battery Production and Recycling. *SAE Technical Paper Series*. doi:10.4271/951865

Golbuff, S. (2006). Optimization of a plug-in hybrid electric vehicle.

Greening, L. A., Greene, D. L., & Difiglio, C. (2000). Energy efficiency and consumption — the rebound effect — a survey. *Energy Policy, 28*(6-7), 389-401. doi:10.1016/s0301-4215(00)00021-5

Heffner, R. R., Kurani, K. S., & Turrentine, T. S. (2007a). Symbolism in California's early market for hybrid electric vehicles. *Transportation Research Part D: Transport and Environment, 12*(6), 396-413. doi:10.1016/j.trd.2007.04.003

Heffner, R., Kurani, K., & Turrentine, T. (2007b). Symbolism and the adoption of fuel- cell vehicles. *World Electric Vehicle Association Journal*.

Klein, J. (2007). Why people Really buy Hybrids. Topline Strategy Group Report, Topline Strategy

Kliesch, J., & Langer, T. (2006). Plug-in hybrids: An environmental and economic performance outlook. American Council for an Energy- Efficient Economy, September

MacCurdy, D. (2006). PHEV Prius test program by Sacramento Municipal Utility District. In: ZEV technology symposium, 25–27 Sacramento, CA, September

Markel, T. (2006). Plug-in hybrid electric vehicles. In: Clean cities congress and exposition. Phoenix, Arizona.

Ozaki, R., & Sevastyanova, K. (2011). Going hybrid: An analysis of consumer purchase motivations. *Energy Policy, 39*(5), 2217-2227. doi:10.1016/j.enpol.2010.04.024

Simpson, A. (2006). Cost-benefit analysis of plug-in hybrid electric vehicle technology. n: 22nd international battery, hybrid and fuel cell electric vehicle symposium and exposition (EVS-22), Yokohama, Japan, October 23–28

Greene, D. L. (1992). Vehicle Use and Fuel Economy: How Big is the "Rebound" Effect? *EJ The Energy Journal, 13*(1). doi:10.5547/issn0195-6574-ej-vol13-no1-7

Haughton, J., & Sarkar, S. (1996). Gasoline Tax as a Corrective Tax: Estimates for the United States, 1970-1991. *EJ The Energy Journal, 17*(2). doi:10.5547/issn0195-6574-ej-vol17-no2-6

Jones, C. T. (1993). Another Look at U.S. Passenger Vehicle Use and the 'Rebound' Effect from Improved Fuel Efficiency. *EJ The Energy Journal, 14*(4). doi:10.5547/issn0195-6574-ej-vol14-no4-6

Linn, J. (2013). The Rebound Effect for Passenger Vehicles. RFF Discussion Paper 13-19.

Puller, S. L., & Greening, L. A. (1999). Household adjustment to gasoline price change: An analysis using 9 years of US survey data. *Energy Economics, 21*(1), 37-52. doi:10.1016/s0140-9883(98)00006-1

Schimek, P. (1996). Gasoline and Travel Demand Models Using Time Series and Cross-Section Data from United States. *Transportation Research Record: Journal of the Transportation Research Board, 1558*, 83-89. doi:10.3141/1558-12

Small, K. A., & Dender, K. V. (2007). Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect. *EJ The Energy Journal, 28*(1). doi:10.5547/issn0195-6574-ej-vol28-no1-2

Sun, S., M. S. Delgado and N. Khanna, 2016. “Hybrid vehicles and household driving behavior: implications for miles traveled and gasoline consumption,” working paper.

West, S. E. (2004). Distributional effects of alternative vehicle pollution control policies. *Journal of Public Economics, 88*(3-4), 735-757. doi:10.1016/s0047-2727(02)00186-x

Wheaton, W. C. (1982). The Long-Run Structure of Transportation and Gasoline Demand. *The Bell Journal of Economics, 13*(2), 439. doi:10.2307/3003465