CrossMark

The impact of federal incentives on the adoption of hybrid electric vehicles in the United States

Alan Jenn [a], Inês L. Azevedo [a,b,*], Pedro Ferreira [a,c]

[a] Department of Engineering and Public Policy, Carnegie Mellon University, Baker Hall 129, 5000 Forbes Avenue, Pittsburgh, PA 15213, United States
[b] Climate and Energy Decision Making Center, Carnegie Mellon University, Baker Hall 129, 5000 Forbes Avenue, Pittsburgh, PA 15213, United States
[c] H. John Heinz III College, Carnegie Mellon University, Hamburg Hall 3042, 5000 Forbes Avenue, Pittsburgh, PA 15213, United States

ARTICLE INFO

ABSTRACT

Starting in 2004, the federal government in the United States offered several nationwide incentives to consumers to increase the adoption of hybrid electric vehicles. This study assesses the effectiveness of the Energy Policy Act of 2005 in this regard using econometric methods and data between 2000 and 2010. Our model accounts for network externalities by using lagged sales as an independent variable. This approach helps to capture the exponential initial growth associated with the diffusion of new technologies and avoids overestimating the effect of the policy incentives. Our results show that the Energy Policy Act of 2005 increased the sales of hybrids from 3% to 20% depending on the vehicle model considered. In addition, we find that this incentive is only effective when the amount provided is sufficiently large.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

Efforts to promote the adoption of hybrid electric vehicles in the United States have been steadily increasing over the last decade in response to concerns over environmental impacts from fossil fuel combustion and to reduce consumption of foreign oil. Currently, hybrid electric vehicles (HEVs) represent the majority of available alternatives to traditional internal combustion engine (ICE) vehicles for personal transportation.

HEVs combine an internal combustion engine with an electric propulsion system that is powered by a large battery unit. The battery provides a higher fuel efficiency by using regenerative braking and preventing idling loses (by shutting off the engine), thus allowing most HEVs to at least raise their city-driving fuel efficiency to highway-driving fuel efficiency levels. The proposed benefits of higher fuel efficiency include less pollution and emissions as well as gasoline savings without sacrificing the service provided, though typically at higher prices. These benefits are the primary reasons prompting the

government to incentivize their use through tax credits and rebates. However, there is large uncertainty on whether these incentives have been able to induce adoption.

The Honda Insight and Toyota Prius were the first HEVs introduced in the market in the year 2000. Both models are offered only as HEVs. This was followed by the introduction of the Honda Civic Hybrid in 2002 as a hybrid variant of an originally ICE model. Since then, the number of make and models offering HEV alternatives has increased substantially. There are currently over 30 HEV models offered in the market. The majority are hybrid versions of ICE vehicles.[1] Fig. 1 shows the number of available HEV models over time, from 1999 through 2010.

Since the introduction of the Honda Insight and Toyota Prius in 2000, the government used several mechanisms to promote the adoption of HEVs. These mechanisms included a variety of incentives, both non-monetary and monetary. The first federal incentive was HR 1308, Section 319 of the Working Families Tax Relief Act of 2004 (Law No: 108-311) (Thomas, 2003). This Act established that the Internal Revenue Service (IRS) would provide a $2000 taxable income deduction to an alternative fuel vehicle purchase. This included HEVs. The incentive applied for two years starting on January 1, 2004 with an upper bound expense of approximately $400 million to the US government.[2] In 2005 the Energy Policy Act in 2005 (Law No: 109-58) (Barton, 2005),

---

[1] Hybridcars.com: Hybrid Market Dashboard.
[2] Assuming 35% income tax bracket and that all consumers capture the incentive.
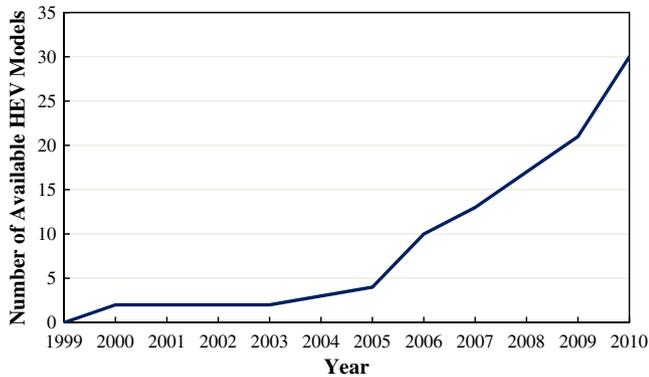
Fig. 1. Number of HEV models commercially available over time. Compiled by the authors using data from: www.autonews.com.

established a new set of incentives via a direct tax credit to consumers for the purchase of an HEV. This incentive was partially scaled to the fuel economy rating of the vehicle, so a greater efficiency would typically result in a higher incentive. In addition, a "phasing out" period was applied to the incentives: if any manufacturer sold 60,000 HEVs within one quarter, the incentives applied to their vehicles would halve twice over the course of the year before being phased out completely. This act was specifically aimed at reducing benefits for foreign vehicle manufacturing companies who had a larger command of alternative fuel vehicles at the time.[3] The Energy Policy Act of 2005 was successful in this regard as Toyota's incentives were phased out on September 30, 2007 and Honda's incentives were phased out on December 31, 2008. A full list of incentive amounts can be found in Table A1 included in the Supplemental Information. The policy ended on December 31, 2010 at an approximate total expense of $1.4 billion to the US government.[4]

The most recent incentive provided by the government was the Car Allowance Rebate System (also known as Cash for Clunkers), which gave a tax credit (either $3500 or $4500) for the trade-in of less fuel-efficient vehicle for a vehicle of higher fuel-efficiency (several hybrid models were offered). The program was in effect between July 1, 2009 and August 25, 2009. Yet, over 700,000 relatively more fuel-efficient vehicles were sold.[5]

This paper characterizes the impact that these federal incentives had in promoting the adoption of HEVs and shows how this effect looks like when accounting for the natural pace of adoption of new technologies.

The literature has studied how different factors shape the preferences of consumers when purchasing HEVs. A first paper by Sallee (2006) performs an in-depth study of the Toyota Prius market. Sallee measures the incidence of tax credits, or consumer's reaction not only to the tax incentive but also to other people's reactions. Specifically, Sallee uses the change in tax incentive from 2005 to 2006 when the Energy Policy Act of 2005 is implemented to investigate strategic shifting of Prius purchases during the fourth quarter of 2005, and concludes that consumers capture all the benefits of the tax incentives. A second paper by Kahn (2006) investigates environmentalism as a characteristic that affects purchasing behavior. Using the number of Green Party voters in an area as a measure of environmentalism from a variety of census data between 1999 and 2005 as well as from the 2001 National Household Transportation Survey data set, Kahn runs a series of regression models to look at differences in consumption and finds that an increase in the share of Green Party voters of 1% decreases the probability that a household owns an SUV (lower fuel economy vehicle) by nearly 20%. Similarly, Sexton and Sexton (2011) investigate

the willingness to pay of Prius owners' to appear environmentally friendly. In this paper, the authors suggest that individuals who are predisposed to favor environmental goods receive disproportionately greater utility from environmental products—even more so in the case of Priuses, whose unique design garners additional benefit from signaling environmental responsibility. This effect is termed "conspicuous consumption" and is found to be a statistically significant effect among Priuses' owners.

Three papers use econometric analysis to assess the influence of incentives on hybrid sales. Gallagher and Muehlegger (2011) use aggregate national HEV sales data per capita and fixed effects including as independent variables the presence of High-Occupancy Vehicle (HOV/carpool) lanes, tax credits, sales tax rebates and gas prices while controlling for environmentalism demographics in quarterly periods. Their results indicate that higher tax incentives are associated with more sales, the sales tax incentives having an impact larger than tax credits. HOV lanes, which require either 1 (HOV-1) or 3 (HOV-3) additional passengers besides the driver, exhibit mixed results. The authors find that HOV-1 does not have a significant impact on sales, while HOV-3 is significant in some states. Lastly, they find that a 1% increase in gas prices increases the per capita sales of HEVs between 0.7% and 1%. As one of the first econometric studies of hybrid vehicle incentives, the authors of this paper lay the groundwork for many of the explanatory variables used in follow-up regression models. However, these models do not account for positive network externalities in the adoption and diffusion of the new vehicle models (e.g. accounting for the natural growth of new technology), which is likely to positively bias several of their findings. Our paper is different in this regard. We explicitly allow the growth in the sales of HEVs to follow a S-shaped curve by including the lag of sales as a dependent variable in the regressions.

Another study performed by Chandra et al. (2008) examines the impact of tax rebates on HEV sales in Canada. Their study ranges across all the provinces in Canada, each of which offers different incentives. They generate counterfactual simulations, using a series of models that aggregate rebate values, which they compare to a base case. The latter is measured using existing market data for all HEV models sold in Canada from 2000 through 2006. The authors find that a $1000 increase in the rebate increased the market share of hybrids by approximately 31–38%. Similar to Gallagher and Muehlegger, this paper does not control for the relatively steeper adoption curves one would expect to observe when HEVs are first introduced in the market. Lastly, Diamond (2009) investigates the impact of government incentives for HEVs between 2000 and 2006 by state. He regresses the market share of HEV on vehicle miles traveled per capita, gas, incentives, HOV lane availability, income, and a "green planning capacity" index (a measure of environmentalism) using panel data and both fixed and random effects. This regression is performed on the three most popular hybrid models: Toyota Prius, Honda Civic Hybrid, and Ford Escape Hybrid, which accounted for over 50% of the total share of HEVs during the period of analysis. Diamond's results reveal that monetary incentives are either non-significant or affect negatively the sales of HEV. The author also performs separate regressions separately for each year and obtains drastically different coefficients from the panel regressions.

In sum, previous work in this field fails to account for network externalities in technology diffusion and adoption. Many studies applied to other technologies have established that these externalities lead cumulative adoption curves to take on S-shapes (Bass, 1969; Griliches, 1957), which consist of exponential growth followed by a change in concavity corresponding to a declining rate of adoption as the technology matures and reaches market saturation (Geroski, 2000; Mahajan and Peterson, 1985; Stoneman, 2002). Many studies have shown that the diffusion of new vehicle technologies, such as hybrid electric vehicles, plug-in hybrid electric vehicles and battery electric vehicles, also follows S-shaped curves (Balducci, 2008; Muraleedharakurup et al., 2010: McManus and Senter, 2009). However, econometric studies investigating the effect of policy instruments in automobile markets

---

[3] Press Release, Senator Carl Levin, "Energy Bill Moves Nation Toward Sounder Energy Policy" July 29, 2005.

[4] Obtained by multiplying the incentive amounts in each month by the respective per vehicle model.

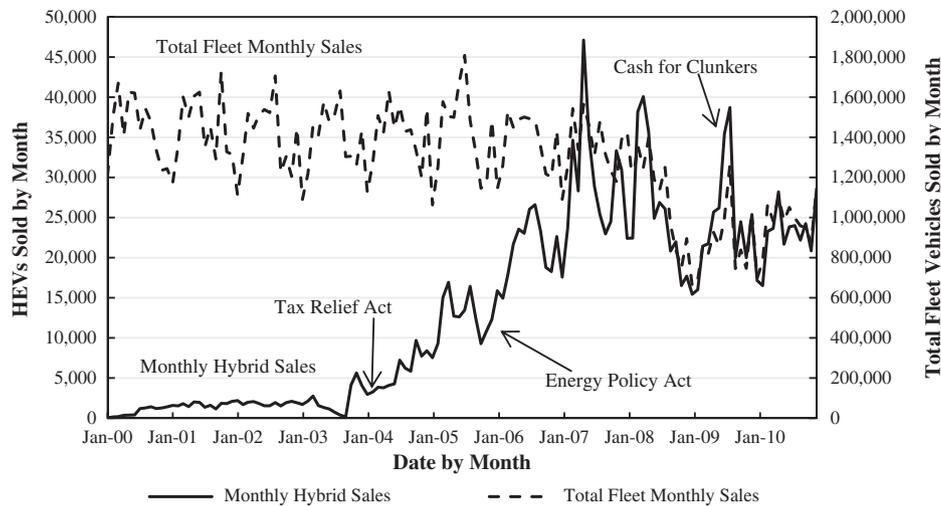[5] Department of Transportation Press Release August 26, 2009.

Fig. 2. Hybrid electric vehicle and total fleet monthly sales in the US from January 2000 to December 2010. Compiled by the authors using data from: www.autonews.com and www.hybridcars.com.

have not yet incorporated this effect. As such, they may lead to biased findings for the effect of incentives and other covariates on the sales of HEVs.

In this paper, we employ an S-shaped growth curve for the sales of HEVs. This, however, requires us to use a spatial-autoregressive model (SAR) with the lag of sales as a dependent variable to capture the autocorrelation in sales over time. This way, we allow the baseline sales from which growth occurs in every period to change over time. The field of spatial econometrics has been well developed for over thirty years (Anselin, Thirty years of spatial econometrics, 2010) with a variety of established methods for model estimation (Anselin, 2005; Anselin et al., 2008; LeSage, 2008). Our estimation procedure employs a generalized method of moments (GMM) estimator, in which we use deeper lags of our lagged dependent variable as instruments, a method that has been developed over the last decade (Conley, 1999; Kelejian and Prucha, 1998; Lee, 2007).

Jaffe and Stavins (1995) study the effect of policy instruments on technology diffusion. They employ a lagged dependent variable to control for adoption of thermal insulation in new home construction. Their econometric estimation explicitly estimates the lagged dependent variable (measuring efficiency) as a parameter in the shape of the adoption curve. Similarly, Hannan and McDowell (1990) employ a lagged dependent variable in order to accommodate the growth of banking ATMs as a control. Their specification is slightly different from the model employed in our paper, as they use two lag periods. In both papers, the authors find the coefficients on the covariates to be statistically significant using lagged dependent variables as controls. They conclude that this approach is the most appropriate to account for the correct shape of the adoption curve for new technologies.

The rest of this paper is organized as follows: Section 2 presents the data used in the analysis, Section 3 explains the methodology used, Section 4 shows and discusses our results and Section 5 concludes discussing applications of this study.

2. Data

2.1. Vehicle sales data

We use national monthly sales of HEVs and of other light duty vehicles by make and model from 2000 through 2010. Monthly sales data of HEVs were obtained from the "Data Center Archives" of www.autonews.com for the period January 2000 to December 2005 and from the "Hybrid Market Dashboard" of www.hybridcars.com for the period January 2006 to December 2010. Sales of light duty passenger vehicles by month, make and model were parsed from the former

data source for the whole duration of the panel. Fig. 2 shows the total monthly fleet sales as well as the monthly sales of HEVs.

HEV sales are dominated by the Toyota Prius, which match all other HEV sales combined since the introduction of HEVs in 2000 until mid-2006. While overall sales of light duty-vehicles remained relatively constant between 2004 and 2008, the sales of HEVs increased significantly over these years. Following the spike in oil prices in the summer of 2008, overall vehicle sales decreased 35% until mid-2010. Sales of HEVs decreased only 18% during these two years and therefore the market share of HEVs has been mostly increasing since 2004 as Fig. 3 depicts. Sales of HEVs were highest in May of 2007, when a record of Priuses were sold, possibly due to a massive advertising campaign led by Toyota during the first quarter of 2007,[6,7] Both in June and July of 2009, there was another sudden spike in the sales of HEVs, likely attributable to the Cash for Clunkers Program. Fig. 2 also shows the implementation dates for the three federal incentives that incentivized HEVs purchases between 2000 and 2010: the Tax Relief Act of 2004, the Energy Policy Act of 2005, and the Cash and Clunkers in July and August of 2009.

2.2. Policies: Tax Relief Act, Energy Policy Act and Cash for Clunkers

Our main interest is to study whether the introduction of the Energy Policy Act of 2005 accelerated the sales of HEVs. To this end we code a variable, called $EPACT_{i,t}$ that equals the dollar incentive provided to vehicles of model i at time t. This variable is zero for all models before the Energy Policy Act was implemented as well as for all models to which the Act does not provide an incentive. Table A1 in the Supplementary Information shows how these incentives changed across hybrid models and over time. Coding $EPACT_{i,t}$ simply as a dummy variable, indicating whether the Energy Policy Act of 2005 applied to vehicles of model i at time t, yields qualitatively similar results to the ones presented later in this paper. These results are available upon request.

We also control for the introduction of other policies that might have had an impact on the sales of vehicles, such as the Tax Relief Act of 2004 and the Cash for Clunkers program of 2009. For this purpose, we code a dummy variable, called $Taxrelief_{i,t}$ indicating whether the Tax Relief Act applies to vehicles of model i at time t. Finally, we add a dummy variable called $Cashforclunkers_{i,t}$ indicating whether this program applied to

---

[6] Maynard, Micheline. "With waiting lists filled, Toyota starts advertising the Prius". The New York Times. February 8, 2007. http://www.nytimes.com/2007/02/08/business/worldbusiness/08iht-toyota.4526592.html.

[7] Isidore, Chris. "Prius' new option: Incentives for buyers". CNN Money. February 8, 2007. http://money.cnn.com/2007/02/08/news/companies/prius_sales/index.htm.
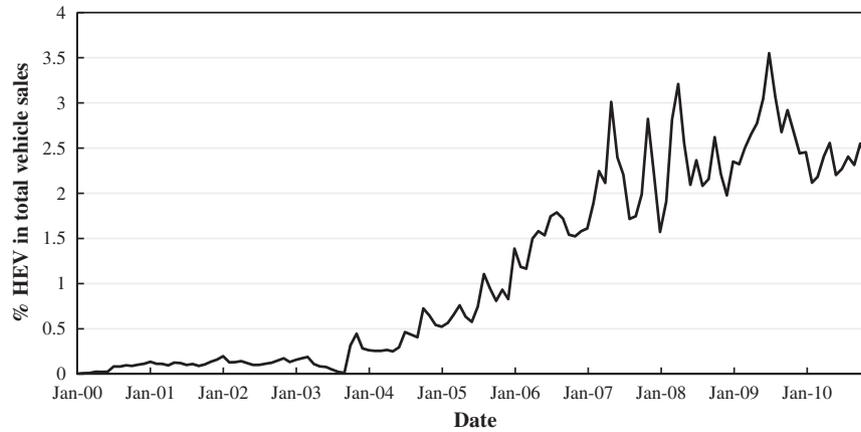
Fig. 3. Percentage of hybrid electric vehicle monthly sales. Compiled by the authors using data from: www.autonews.com and www.hybridcars.com.

vehicles of model i at time t. The Cash for Clunkers program applied to some models during July and August 2009, thus this variable is always zero for all models for all other months in our panel.

2.3. Other data

2.3.1. Other data related to vehicle sales
We control for the following factors that might impact the sales of certain types of models:

Advertising campaign by Toyota: From January through May of 2007, Toyota launched a massive advertising campaign, which might have increased the sales of Prius. To capture this potential effect we introduce a dummy variable, called $priusad_{i,t}$, which equals 1 for this model during these months;

Models discontinued by manufacturers: Some manufacturers discontinued some vehicle models during our period of analysis. To account for these cases, we included a dummy variable, called *production stoppage*$_{i,t}$ indicating whether model i has been already discontinued at time t. This variable should capture sharp decreases in the sales of these vehicles;

Vehicles produced domestically or imported: Imported vehicles typically sell in different amounts than their domestic counterparts. To capture this effect, we coded a dummy variable, called $import_i$, indicating whether model i is imported.

2.3.2. Macro-economic variables[8]
We added the following macro-economic variables in the models to account for changes in the economic climate throughout our panel:

Unemployment[9]: We control for the unemployment rate because, everything else equal, a higher unemployment rate should translate into less disposable income which, in turn, would typically lead to fewer sales of vehicles.

Gas prices[10]: We control for gas prices because a high gas price may lead consumers to substitute towards more fuel efficient vehicles, such as hybrids. However, we note that consumers may not necessarily respond quickly to increases in gas prices. To account for this we introduce lagged gas prices in the regression models. Later in this paper we report results with gas prices lagged six-month,

which provide the highest statistical significance for this covariate. Using other lags for the price of gas does not change our results.

We also tested numerous other macroeconomic variables for robustness purposes, such as GDP, income and interest rates. These results can be provided upon request.

2.3.3. Summary statistics
Table 1 below displays the summary statistics for the main variables used in this paper. US vehicle monthly sales peaked at 52,400 for the best-selling ICE vehicle model. This is only considerably higher than the highest monthly sales of the Toyota Prius, which peaked at 24,000 in May 2007. At the lowest, there were models (that were not discontinued) that sold no vehicles during an entire month. This typically happens to some sports and luxury vehicles. The average US sales per model are lower than the HEV sales per model because there are much fewer hybrid models and a significant share of the non-hybrid models do not sell many units per month.

3. Empirical strategy

We perform econometric regressions to understand the effect of the incentives for hybrids in the Energy Policy Act of 2005 on the sales of HEVs. We study this relationship for monthly vehicle model sales from 2000 through 2010 using the control variables described in Section 2.3 (imports, production stoppage, Prius advertising campaign, unemployment and gas prices). We show that the EPACT had a statistically significant non-linear effect with higher incentive amounts leading to a disproportionately larger effect on sales. We also show that a traditional fixed effects model, which does not account for the S-shaped curve for technology adoption, finds a severely positively biased effect for this incentive.

Table 1
Summary statistics.

Variable	Mean	Std. dev.	Min	Max
Monthly US vehicle sales (by model)	3540	5500	0	52,400
Monthly HEV sales (by model)	1520	2950	0	24,000
Tax Relief Act of 2004*	0.00323	0.0567	0	1
Energy Policy Act of 2005	49.6	314	0	3400
Cash for Clunkers*	0.0172	0.13	0	1
Import*	0.567	0.496	0	1
Production stoppage*	0.103	0.304	0	1
Prius ad campaign*	0.00021	0.0145	0	1
Unemployment index	5.96	1.84	3.8	10
Gas prices	2.42	0.611	1.35	4.14
Hybrid*	0.049	0.216	0	1

Observations: 23,843; the total number of models is 431, from which 33 are HEVs;
* indicates a dummy variable.

---

[8] All variables in nominal values for consistency.
[9] Data from: U.S. Department of Labor, Bureau of Labor Statistics. data.bls.gov/timeseries/LNS14000000.
[10] U.S. Energy Information Administration. Monthly Reviews.

We capture the initial exponential growth of sales in adoption by adding a lagged dependent variable to the regression, as follows:

$$\ln\left(S_{i,t}\right) = \alpha + \pi \ln\left(S_{i,t-1}\right) + \beta\left(EPACT_{i,t}\right) + \gamma\left(x_{i,t}\right) + u_i + \varepsilon_{i,t} \qquad (1)$$

i represents a vehicle model and t represents the time period ranging from 1 through 132 (representing each month from January 2000 through December 2010). $S_{i,t}$ represents monthly vehicle sales by model. EPACT represents the dollar incentive provided per vehicle over its allotted period of implementation (see Table A1 in the Appendix). x includes control variables, as described in Section 2.3, and variables that control for other policies, as description in Section 2.2, which may influence the consumers' decisions to purchase a vehicle. In this regression, all of the non-dummy variables (unemployment and gas prices) were transformed by using the natural log. Finally, u_i is a vector of unobserved vehicle model specific time constant effects and $\varepsilon_{i,t}$ represents the unobserved error term.

The addition of lagged sales as an independent variable in our setup violates strict exogeneity, which is an essential assumption of Ordinary Least-Squares (OLS). In order to overcome this challenge, we follow Arellano and Bond (1991) and use a generalized method of moments estimator (GMM) to estimate the fixed effects regression in the Eq. (1). We instrument previous lags ($S_{i,t-1}$) using two sets of different lagged instruments and we use the J Hansen statistic to verify that our model is not overspecified.

One of the benefits of using panels or differences across vehicles in regression models is the ability to implicitly capture unobserved characteristics inherent to each vehicle model in the fixed effects term, u_i, or difference them out (using first differences). For this reason, vehicle characteristics such as price (captured by the manufacturer's suggested retail price) or fuel economy, which do not change much over time, are not explicitly included in our models but their effects are still accounted for.[11] Also, we cluster standard errors at the vehicle model level to account for serial correlation in our data.

In addition, we suspect that the EPACT behaves non-linearly, with a particularly larger effect for vehicles provided with a larger incentive. Thus, we also provide results by splitting EPACT into two categories: above and below its approximate average amount ($1000). The resulting model is as follows:

$$\ln\left(S_{i,t}\right) = \alpha + \pi \ln\left(S_{i,t-1}\right) + \beta_1\left(EPACT^{high}_{i,t}\right) + \beta_2\left(EPACT^{low}_{i,t}\right) \\ + \gamma\left(x_{i,t}\right) + u_i + \varepsilon_{i,t} \qquad (2)$$

$EPACT^{high}$ represents the dollar amount of incentive by vehicle for any hybrids receiving over $1000 of incentive and $EPACT^{low}$ represents the dollar amount of incentive by vehicle for any hybrids receiving under $1000 of incentive.

4. Results and analysis

4.1. Understanding the effect of EPACT incentives on sales

Table 2 shows our main regression results.[12] Models (1) and (2) correspond to Eqs. (1) and (2) in Section 3, respectively. Dummy variables for months have been used in each case to control for unobserved seasonal effects or time trends. In model (1) we show that the Energy Policy Act had a positive and statistically significant effect on the sales of

[11] For all HEV models, the manufacturer's suggested retail price (MSRP) and fuel economy (fueleconomy.gov) stay constant during the lifetime of one generation of vehicle model (5–8 years). The largest observed increase/decrease was less than 5% and both variables typically dropped out of the regression results.
[12] We ran several other variants of these models as a robustness check, accounting for different lags and using different controls, for which the authors upon request can provide the results.

Table 2
Effect of EPACT on ln(sales) using fixed effects regression with a generalized method of moments estimator (GMM) to account for exponential growth in the diffusion of HEVs, also splitting EPACT into above and below its average amount ($1000).

Variables	(1)	(2)
	lnsales	lnsales
taxrelief	−0.0143	−0.0173
	(0.0740)	(0.0741)
epact	**4.60e-05***	
	(2.35e-05)	
epactlow		**-1.41e-06**
		(6.35e-05)
epacthigh		**4.54e-05***
		(2.37e-05)
cashforclunkers	−0.492***	−0.491***
	(0.0958)	(0.0959)
import		
prodstop	−0.680***	−0.680***
	(0.0583)	(0.0583)
priusad	0.206	0.227
	(0.145)	(0.143)
lnunemp	−8.085**	−8.095**
	(3.286)	(3.286)
lnunemph	0.168**	0.166**
	(0.0810)	(0.0813)
lngas6	−3.199	−3.180
	(6.628)	(6.628)
lngas6h	0.604***	0.596***
	(0.180)	(0.180)
Llnsales	0.908***	0.908***
	(0.00861)	(0.00861)
Llnsalesh	−0.0377	−0.0368
	(0.0271)	(0.0271)
Monthly time dummies	Yes	Yes
Observations	20,787	20,787
R-squared	0.917	0.917
Number of groups	335	335
Instruments (lags used)	Sales(1–6)	Sales(1–6)
Hansen J stat	0.112	0.108

Robust standard errors in parentheses.
*** p < 0.01, ** p < 0.05, * p < 0.1.
Notes: 1. Values in bold represent the coefficients of most interest for this analysis; 2. Results for other instruments available upon request. 3. taxrelief = dummy for the Tax Relief Act; epact = incentive amount from EPACT; epactlow = incentive amount from EPACT, for vehicles where incentive was less than $1000; epacthigh = incentive amount from EPACT, for vehicles where incentive was higher than $1000; cashforclunkers = dummy variable for Cash for Clunkers; import prodstop = dummy for vehicle production stoppage; pruis ad = dummy for prius advertising campaign; lnunemp = natural log of employment; lnunemph = interaction terms for natural log of employment and hybrid vehicles; lngas6 = gasoline prices, lagged by 6 months; lngas6h = interaction term for gasoline prices, lagged by 6 months with hybrid vehicles; Llnsales = lagged sales term; Llnsalesh = lagged sales term interacted with hybrid vehicles.

HEVs. Sales increase by 0.0046% per dollar of incentive, on average. When we split the EPACT into a high and low incentive amount (model (2) in Table 2), we find that only $EPACT^{high}$ is statistically significant. The effect of EPACT is therefore confined to hybrid vehicles receiving incentives over $1000. The significance of the EPACT impact disappears for vehicles with small incentive amounts. The EPACT for vehicles with large incentive amounts captures, both in statistical significant as well as in magnitude, the effect obtained in model (1). Qualitatively, this means that consumers may not be easily swayed towards purchasing a hybrid vehicle when only a small incentive is present given the relatively large monetary premium associated with HEVs. We note that the J Hansen statistic indicates that our models are not overspecified, which increases our confidence in the sets of instruments used and thus in our findings.

4.2. Bias from using traditional fixed-effects

We compare the results obtained in the preceding section using the Arellano–Bond estimator to the ones obtained using fixed-effects without lagged sales. Full results for the latter are shown in Supplementary
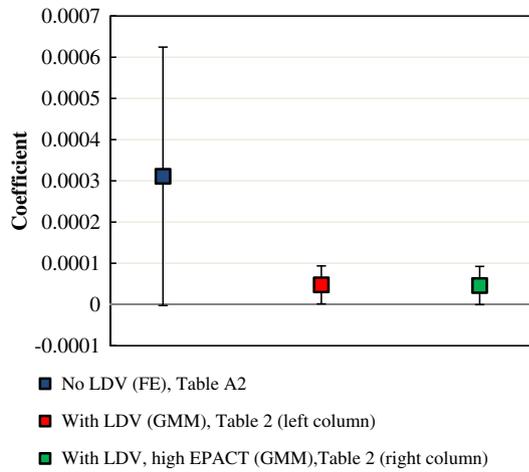
Fig. 4. Coefficient for the Energy Policy Act of 2005 using fixed-effects and the Arellano–Bond estimator and the associated 95% confidence intervals. LDV = lagged dependent variable; FE = fixed-effects; GMM = general method of moments.

Information, Table A2. This comparison, depicted in Fig. 4, highlights the importance of accounting for network externalities in the diffusion of HEVs. The effect of the EPACT remains positive and statistically significant with fixed effects without lagged sales but now each additional dollar of incentive provided increased sales of 0.031%. This result is robust when using other combinations of control covariates. The inclusion of the lagged dependent variable to account for exponential growth reveals the importance of using the correct functional form to estimate the effect of policy instruments on the diffusion of new technologies, such as the EPACT. In this case, failing to do so would lead us to measure an effect one order of magnitude off the true size.

4.3. How did the EPACT affect the sales of different vehicles?

Fig. 5 shows the impact of the EPACT on the sales of vehicles across different vehicle types using the results obtained with the Arellano–Bond estimator. This figure reveals that, for example, at the full incentive amount of $3150, the Toyota Prius experienced a 15% increase in sales over the vehicles that would have been sold in absence of such incentive. Our results indicate that EPACT has statistically

significant effect on the different models sold, through varying in magnitude from 3% to 20%.

4.4. Insights from control variables

The results from our control variables provide additional insights into the transportation market and are thus worth analyzing. For example, higher levels of unemployment are associated with lower overall vehicle sales, as one would expect. In fact, Fig. 6 shows a sharp decline in vehicle sales in 2008 when the unemployment rate rose significantly. Our findings indicate that a 1% increase in the unemployment index is associated with about an 8% decrease in the sales of cars, on average. The effect of unemployment on the sales of hybrid vehicles is statistically significant but only negligibly lower.

Gas prices are not statistically significant for ICE vehicles in the GMM model estimations. However, the interaction of gas prices with the hybrid vehicle dummy yields a positive elasticity of about a 0.6%. These results seem to indicate that rising gas prices may not necessarily dissuade consumers from purchasing ICE vehicles, but that more hybrid vehicles are purchased in the months following high gas prices.

5. Conclusions

This paper aims at understanding the impact that federal incentives had in promoting the adoption of HEVs. Using national data on vehicle sales between 2000 and 2010, we find that the Energy Policy Act of 2005 had a positive and statistically significant effect on the sales of hybrid vehicles. However, we also show evidence that only sufficiently large incentive amounts yield an effect on sales. Sales of hybrid vehicles increased by 0.0046% per dollar of incentive but only when the latter was above $1000.

Another goal of this paper is to understand the importance of accounting for network externalities in the diffusion of technology. Network externalities result in an initial natural exponential growth in adoption that occurs even if no policy incentives are in place. Comparing fixed-effect results with and without lagged sales as a control variable, we show that failing to account for this growth overestimates the effect of EPACT in one order of magnitude. However, using the latter approach requires us to resort to a generalized method of moments (GMM) using deeper lags of sales as instrumental variables. Still, our results show clearly that failing to use the appropriate functional form to capture the adoption of HEVs over time leads to significantly biased results.
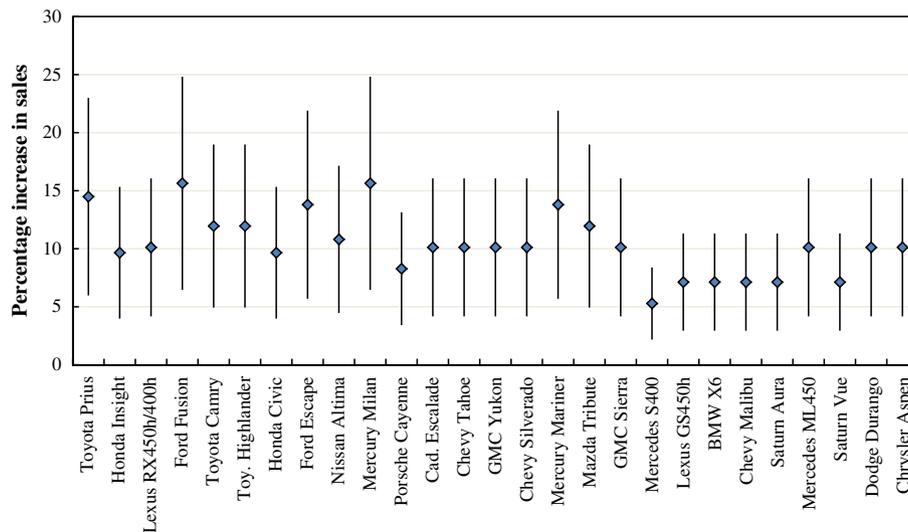

Fig. 5. Estimated increase in sales due to the Energy Policy Act of 2005 (when incentive active and over $1000) by vehicle model and associated 95% confidence intervals.
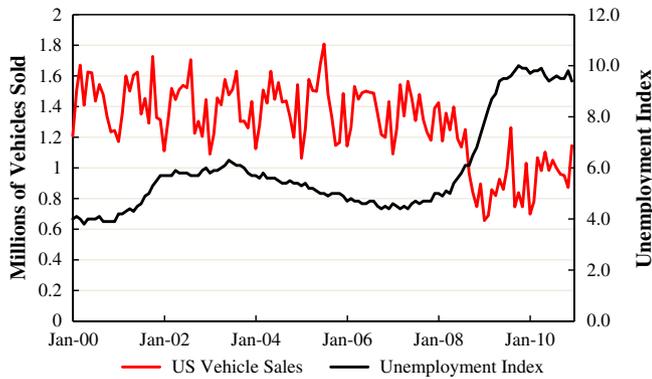
Fig. 6. Comparison of vehicle sales with unemployment index. Figure constructed by the authors using data from Autonews.com and the Bureau of Labor Statistics.

Finally, it should be cautioned that the results obtained in this study are at a relatively low level of resolution given the constraints associated with the data available. We could not conduct an analysis at the regional level, which would shed more light on the role of policy incentives on the adoption of HEVs. It may well be the case that only combinations of incentives, including federal, state and local incentives, can cause substantial changes in consumer behavior. Such combination of incentives could help explain why there is a proportionally higher registration of hybrids in states such as California, Washington and Virginia.

Acknowledgments

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx. doi.org/10.1016/j.eneco.2013.07.025.

References

Anselin, Luc, 2005. Spatial Econometrics. Econometrica, Urbana-Campaign.
Anselin, Luc, 2010. Thirty years of spatial econometrics. Pap. Reg. Sci. 89 (1).
Anselin, Luc, Le Gallo, Julie, Jayet, Hubert, 2008. Spatial Panel Econometrics. The Econometrics of Panel Data. Springer-Verlag, Berlin Heidelberg, pp. 625–660.
Arellano, M., Bond, S., 1991. Some tests of specification for panel data: Monte Carlo evidence and an application to employment equations. Rev. Econ. Stud. 58, 277–297.
Balducci, P.J., 2008. Plug-in Hybrid Electric Vehicle Market Penetration Scenarios. Pacific Northwest National Laboratory, Richland (PNNL-17441).
Barton, Joe, 2005. H.R.6 Energy Policy Act of 2005. April http://thomas.loc.gov/cgi-bin/bdquery/z?d109:H.R.6.
Bass, Frank M., 1969. A new product growth for model consumer durables: the bass model. Manag. Sci. 50 (12), 1833–1840.
Chandra, Ambarish, Gulati, Sumeet, Kandlikar, Milind, 2008. Evaluating tax rebates for hybrid vehicles. Working Paper (http://www.rff.org/Documents/Events/Academic%20Seminars/082410_gulati_hybrid_rebates.pdf).
Conley, T.G., 1999. GMM estimation with cross sectional dependence. J. Econ. 92, 1–45.
Diamond, David, 2009. The impact of government incentives for hybrid-electric vehicles: evidence from US states. Energy Policy 972–983.
Gallagher, Kelly Sims, Muehlegger, Erich J., 2011. Giving green to get green? The effect of incentives and ideology on hybrid vehicle adoption. J. Environ. Econ. Manage. 61 (1), 1–15.
Geroski, P.A., 2000. Models of technology diffusion. Res. Policy 29, 603–625.
Griliches, Zvi, 1957. Hybrid corn: an exploration in the economics of technological change. Econometrica 501–522.
Hannan, Timothy H., McDowell, John M., 1990. The impact of technology adoption on market structure. Rev. Econ. Stat. 164–168.
Jaffe, Adam B., Stavins, Robert N., 1995. Dynamic incentives of environmental regulations: the effects of alternative policy instruments on technology diffusion. J. Environ. Econ. Manag. 29 (3), S43–S63.
Kahn, Matthew E., 2006. Do greens drive hummers or hybrids? Environmental ideology as a determinant of consumer choice. J. Environ. Econ. Manag. 129–145.
Kelejian, Harry H., Prucha, Ingmar R., 1998. A generalized spatial two-stage least squares procedure for estimating a spatial autoregressive model with autoregressive disturbances. J. Real Estate Financ. Econ. 17 (1), 99–121 (Kluwer Academic Publishers).
Lee, Lung-fei, 2007. GMM and 2SLS estimation of mixed regressive, spatial autoregressive models. J. Econ. 489–514.
LeSage, James P., 2008. An Introduction to Spatial Econometrics. Revue D'Économie Industrielle, pp. 19–44.
Mahajan, Vijay, Peterson, Robert A., 1985. Models for Innovation Diffusion. SAGE Publications, Inc.
McManus, Walter, Senter Jr., Richard, 2009. Market Models for Predicting PHEV Adoption and Diffusion. University of Michigan Transportation Research Institute.
Muraleedharakurup, Girish, McGordon, Andrew, Poxon, John, Jennings, Paul, 2010. Building a better business case: the use of non-linear growth models for predicting the market for hybrid vehicles in the UK. Ecological Vehicles and Renewable Energies.Monaco.
Sallee, James M., 2006. The Incidence of Tax Credits for Hybrid Vehicles. University of Michigan, Job Market Paper (Paper, 2006. http://www.economics.uci.edu/files/economics/docs/recruitment/w08/sallee.pdf).
Sexton, Steven E., Sexton, Alison L., 2011. Conspicuous Conservation: The Prius Effect and Willingness to Pay for Environmental Bona Fides. Job Market Paper (http://areweb.berkeley.edu/fields/erep/seminar/s2011/Prius_Effect_V1.5.3.pdf).
Stoneman, Paul, 2002. The Economics of Technological Diffusion. Blackwell Publishers.
Thomas, William M.H.R., 2003. 1308 Working Families Tax Relief Act of 2004. March http://thomas.loc.gov/cgi-bin/bdquery/z?d108:H.R.1308.