Fuel Price Increases and the Timing of Changes in Household Driving Decisions

Melanie Cozad* and Jacob LaRiviere†‡

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Abstract

Using the oil price increase of 1979 as a natural experiment and several event study specifications, this paper finds evidence that the oil spike induced significant decreases in carbon emissions on both the intensive (miles driven) and extensive (auto fuel efficiency) margins. Further, it appears that substitution on the intensive margin occurred instantaneously whereas extensive margin substitution occurred with a significant lag. Given the timing of the changes, the results appear robust to the implementation of Corporate Average Fuel Economy (CAFE) standards over the same time period. These findings have important implications for estimating demand elasticities for durable goods with respect to energy prices and the price elasticity of fuels themselves.

*Assistant Professor, Department of Economics, University of Tennessee
†Assistant Professor, Department of Economics, University of Tennessee.
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1 Introduction

In order to develop a portfolio of national policies aimed at reducing energy use and greenhouse gas (GHG) emissions, there is significant interest in identifying the mechanisms through which firms and consumers decide to purchase new, more energy efficient durable goods. Some economists have recently proposed the use of temporary taxes as an impetus for inducing “greener” capital purchases at the firm level (Acemoglu, Aghion, Bursztyn, and Hemous (2011)). Smart meters relaying real time data on household energy use patterns inform the optimal granularity of energy policy. The speed and degree that households respond to energy price changes is an important question that relies on household beliefs about future energy price time paths. One set of household durable goods receiving immense attention due to their contribution to GHG and particulate matter emissions are passenger vehicles. According to the EPA, over 27% of GHG emissions originated in the transportation sector in 2009.

In order to better understand how households would respond to a potential government policy designed to induce more energy efficient consumption patterns, significant attention is given to how consumers alter their driving behavior and car purchases in response to changes in gasoline prices and how consumers perceive future gas prices (Kilian and Sims (2006), Edelstein and Kilian (2009), Kilian (2010), Knittel and Sandler (2010), Spiller (2010), Anderson, Kellogg, and Sallee (2010), Allcott, Mullainathan, and Taubinsky (2011), Allcott and Wozny (2011), Alquist, Kilian, and Vigfusson (2011), and Gillingham (2012)). Recent work has examined how households decisions to purchase new cars respond to changes in fuel prices. Edelstein and Kilian (2009) use a VAR specification to estimate how unexpected energy shocks have historically affected the composition of new auto sales. They find that households substitute to more fuel efficient cars and that total expenditures on new domestic autos fall relative to baseline due to decreased effective purchasing power. Klier and Linn (2010) use within model year gasoline price fluctuations to identify the effect of gasoline price increases on the composition of new car purchases and, like Edelstein and Kilian (2009), find that on average, gasoline price increases induce consumers to purchase relatively more fuel efficient cars. Li, Linn, and Muehlegger (2012) finds that households respond more strongly to increases in gasoline prices due to changes in tax policy than increases due to equivalent but transitory changes driven by market conditions and offer expectations uncertainty as one potential explanation. A related question is the speed with which consumers purchase those more fuel efficient vehicles when gasoline prices change. If gasoline prices increase unexpectedly, the timing of household purchases of more fuel efficient vehicles is an important question dependent on switching costs, gasoline price expectations, and the certainty of those expectations. This paper builds on Klier and Linn (2010), which examines the average response of households to increases in fuel prices on the extensive margin, by asking how the timing of household responses to increases in fuel prices differ at the intensive and extensive margins.

Using an event study design for the oil price shock of 1979-1981 and data from the Environmental Protection Agency, Federal Highway Administration, and Energy Information Administration, this paper
tests how an increase in gasoline prices affected the magnitude and timing of a fall in emissions from passenger vehicles. The oil price shock of 1979 is a plausible natural experiment to identify whether households respond to increases in gasoline prices differentially at the intensive and extensive margins. First, prices were relatively stable for years until April 1979 when they increased significantly and persisted at high levels over the next several years. Further, the oil price increase was largely predetermined with respect to US household behavior (Kilian (2010)). Our event study design identifies a significant effect of the oil price increases on both total passenger vehicle emissions and passenger vehicle emissions per mile driven. We find that households respond immediately by driving less as represented by emissions (intensive margin) when prices begin to rise, but they delay their decisions to make more fuel efficient driving decisions as represented by emissions per vehicle miles traveled (the extensive margin) by a significant amount.¹ These findings are robust to several specifications including robustness checks for the implementation of CAFE standards on new vehicles and macroeconomics fluctuations over the event time horizon.

It is important to note that the main contribution of this paper is using the 1979 oil price increase as a natural experiment to identify differential timing of intensive and extensive margin household responses to fuel price increases. Levels of responses on those margins, while important, are not the primary focus of this paper insofar as it matters for policy today. Specifically, Hughes, Knittel, and Sperling (2008) and Edelstein and Kilian (2009) show that households responded more inelastically in the short run to oil prices increases in the 2000s than in the late 1970s. However, we are not aware of any work that explicitly attempts to identify the relative timing of substitution on the intensive versus extensive margins in response to fuel price increases, nor a change in the timing of such responses across time.² The central finding in this study, asymmetric timing of intensive versus extensive margin substitution patterns, has modeling implications for household durable good purchases. As a result, this paper contributes to a larger literature identifying the mechanisms through which households alter their driving decisions. These mechanisms include the strength of household response to fuel price changes due to differential causes (e.g., policy changes versus changing market conditions), household perceptions of future energy prices, and the various mechanisms affecting intensive versus extensive margin driving decisions (Li, Linn, and Muehlegger (2012), Anderson, Kellogg, and Sallee (2010) and Gillingham (2012)).

The remainder of the paper is as follows: a simple theoretical model shows that if oil prices follow a random walk, then consumers will immediately switch to a more costly vehicle that gets higher miles per gallon. The next section introduces the empirical specification, data, and estimates. The fourth section discusses the findings and performs some robustness checks. Section five briefly concludes.

¹Throughout the paper we claim that emissions per vehicle mile travel is a good measure of fleet fuel efficiency due to GHG emissions being directly proportional to gallons of gasoline consumed.

²To be clear, many studies attempt to control for various timing issues between margins, but they do not explicitly attempt to identify these margins.
2 Theoretical Model

This section develops a simple theoretical model which highlights the implications of increased fuel prices on the timing of changes in household driving patterns. We do not wish to characterize the universe of possible driving behaviors but rather draw attention to the theoretical implications of an increase in fuel prices on substitution along the intensive versus extensive margins through two main channels: miles driven and average MPG ratings of the auto fleet.  

Consider a model in which a representative household gains utility from a composite consumption good, \( c \), and driving, \( d \). Assume that utility is strictly concave in driving. Each household is endowed with some wealth level, \( W_i \), and initially has a budget constraint \( W_i = c + P_g d \). The price of driving is the quotient of the price of gasoline and vehicle miles per gallon (MPG): \( P_d = \frac{P_g}{\text{MPG}_0} \). Assume that each household has the option of buying a new car with higher gas mileage, \( \text{MPG}_1 > \text{MPG}_0 \), for a fixed price of \( K \) in every period.\(^4\) If the household were to purchase the new car, they would maximize utility subject to the budget constraint \( W_i - K = c + \frac{P_g}{\text{MPG}_1} d \). As a result, the household’s indirect utility function can be expressed as:

\[
U(c^*(P_g, \text{MPG}, W_i, K), d^*(P_g, \text{MPG}, W_i, K)) = V(P_g, \text{MPG}, W_i, K).
\]  

By definition, the derivative of the indirect utility function with respect to the price of gasoline, \( P_g \), is negative while the derivative of the indirect utility function with respect to \( \text{MPG} \) is positive. The cross partial of the indirect utility with respect to \( P_g \) and \( \text{MPG} \) is negative due to the concavity of the utility function in driving. Put another way, an increase in the price of gas, \( P_g \), decreases utility less when \( \text{MPG} \) is higher. Therefore, as \( P_g \) increases the shadow price of having a given \( \text{MPG} \) increases. As a result, there exists some price of gasoline \( P^K_{g,i} \) over which a household characterized by wealth of \( W_i \) will be willing to pay \( K \) in order to drive an automobile with \( \text{MPG}_1 > \text{MPG}_0 \).

Assume, as is common in the literature on households beliefs about gasoline prices, that households forecast gasoline prices as a random walk: \( P_t = P_{t-1} + \epsilon_t \) where \( \epsilon \sim (0, \sigma_\epsilon) \) (see Anderson, Kellogg, and Sallee (2010) and Alquist, Kilian, and Vigfusson (2011)).\(^5\) Therefore, if gasoline prices increase there are immediately two effects. The first effect is the combination of the substitution and income effects in which households substitute away from driving toward the consumption of the numeraire good; this substitution of goods is along the intensive margin. The second effect occurs when \( P^K_{g,i} < P_t \) and the household purchases a new more fuel efficient car and can be called switching at the extensive margin (see Knittel and Sandler (2010) for a more thorough discussion).

\(^3\)A referee made the very astute point that there are several channels that could affect miles driven and MPG of the fleet in ways beyond the scope of the model developed here, such as carpooling or more fuel efficient driving behavior. These are valid additional channels to consider but leave a more complete theoretical model to future work.  

\(^4\)This assumption is tantamount to assuming perfectly functioning credit markets.  

\(^5\)This specification allows the possibility for negative gasoline prices, which is unlikely. Further restrictions are needed to eliminate this possibility. This model is presented for development of intuition only.
Intensive and extensive margin substitution are summarized in Figure 1 below. In Figure 1, the price of gasoline increases causing the budget constraint to rotate inward, increasing the amount of the numeraire good relative to driving. This effect is substitution on the intensive margin. After the curve rotates, the household compares their utility if they were to in effect purchase the new effective price of driving, \( P_d^2 \) for a price \( K \). In the figure, it is utility maximizing to purchase the new constraint and substitute at the extensive margin.

Recent well executed papers that estimate price elasticities of gasoline or driving behavior parameterize flow utility of driving to be linear in the price of gasoline (Gillingham (2012)). A linear in prices specification which implies households are risk neutral over the price of gasoline is justifiable because equilibrium is assumed in the market of cars making local deviations from equilibrium linear in prices. If risk-neutral households perceive future gasoline prices as a random walk then the econometrician would expect substitution on both margins simultaneously when there is a sufficiently large and unexpected gasoline price increase.

This is essentially a short run elasticity. The conclusion of Hughes, Knittel, and Sperling (2008) discusses the potential determinants of intensive margin substitutions. Most generally, our definition of intensive margin substitution is any action that involves not paying a fixed cost to reduce the price of driving.
regardless of household forecast uncertainty. Alternatively, if households are risk averse and forward looking in their decisions to purchase large durable goods like cars, then it is possible that forecast uncertainty in addition to expectations matter in purchasing more fuel efficient vehicles. In the second case, one example of the expected indirect utility from driving a more fuel efficient vehicle, suppressing $g$ for notational simplicity, is

$$V(P_t, MPG_1, W, K) + \left( \sum_{s=1}^{\infty} \delta^s E \left[ V \left( MPG_1, W, P_{t+s} \mid (P_t^{t+s-1}) \right) \right] \right)$$

$$P_{t+1} \sim N \left( P_t, \frac{1}{N} \sum_{n=1}^{N} \left( P_{t-n} - 1 \frac{1}{N} \sum_{n=1}^{N} P_{t+n} \right)^2 \right)$$

This functional forms in equation (3) is meant to be suggestive only and not meant as the correct model; as previously suggested other forms of uncertainty, such as upside price shock exposure, may be important (see Alquist, Kilian, and Vigfusson (2011) and Kilian and Vigfusson (2011)). Rather, it suggests that so long as the indirect utility function is concave in $P$, increased uncertainty over the price of gasoline, in this case due to volatility over the past $N$ periods, will always lower the expected net present value of any particular vehicle by Jensen’s inequality. Given that autos account for a significant portion of disposable income for many households, it is reasonable to expect some amount of curvature in the indirect utility function in $P$ stemming from curvature in the direct utility function. This situation would give rise to a delay in substitution on the extensive margin relative to the intensive margin in a neoclassical framework or in one with in which households are loss averse.

It is important to note before proceeding that given the reduced form nature of the empirical test here it is not possible to determine the underlying channels of the shifts on the intensive and extensive margins other than identifying they are both due to an unexpected increase in fuel prices. It is entirely possible that uncertainty over the time path of fuel prices does not drive the results in this paper. For example, reduced driving speeds will increase fleet fuel efficiency but so will households driving fuel efficient cars relatively more than less fuel efficient cars. Similarly, reductions of overall driving behavior may be due to several channels such as increased carpooling or combining errands. Finally, we assume perfect credit markets and perfect information in this section’s theoretical model. There are likely to be constraints along both of these dimensions which a more complete theoretical model would account for. Modeling these nuances and identifying the precise mechanism for the findings in this paper is, however, beyond the scope of this paper and left to future work.\footnote{In fact, our empirical results indicate that there is not an immediate substitution along the extensive margin. This implies that the above theoretical model is indeed incomplete.}

The level of total passenger vehicle emissions is a function of both total miles driven and auto fuel efficiency. Thus, this theoretical model predicts that total emissions should fall, ceteris paribus, when gasoline prices increase. Further, there is some threshold level for the price of gasoline when emissions
per vehicle mile traveled would decrease as well.\textsuperscript{8} Testing for the magnitude and timing of intensive and extensive margin substitution in the presence of a sudden and unexpected increase in fuel prices is the focus of the remainder of the paper.

3 Data and Empirical Specification

To test whether the oil shock of 1979 had an effect on both the level of emissions and the average fuel efficiency of passenger vehicles driven, data was collected from several sources. Because gasoline prices are endogenous to the demand for driving, we proxy for an exogenous component of them using an unexpected increase in West Texas Intermediate crude oil prices (Kilian (2010)). Since the oil price shock of 1979 was unexpected, it can be considered exogenous with respect to US gasoline consumption at monthly frequency. We use monthly data from January 1974 through December 1985 as our window for the event study. This time window was selected to center the oil price increase and to minimize the bias introduced by using excessively long time windows on the estimates of the effect of an unexpected and persistent gasoline price increase. This window is also ideal in that President Nixon imposed a speed limit law on January 2nd, 1974 mandating that all national highways were to have 55 mph speed limits which affects emissions per vehicle miles traveled (VMT). Finally, in 1986 oil prices fell and persisted at low levels for the remainder of the decade.

There are several reasons why emissions and emissions per VMT data are well-suited to identify differences in the timing of intensive and extensive margin substitutions by households due to energy price increases as opposed to other variables. Since carbon emissions are proportional to total gasoline consumed, it implies total emissions per vehicle mile traveled is proportional to gasoline consumed per vehicle miles traveled. As a result, use of monthly total motor fuel consumption kept by the Federal Highway Administration was considered as an alternative dependent variable. However, reporting requirements changed between December 1978 and January 1979 causing data inconsistencies during months in our time period. In addition, total motor fuel consumption data is susceptible to noise due to inclusion of large trucks and government vehicles.\textsuperscript{9} All of these problems are not present in the emissions data since it was collected independently and reflects actual driving behavior.

The data used in the analysis was taken from several sources. Data on monthly passenger vehicle emissions, excluding ethanol, were taken from the EPA. In constructing monthly passenger vehicle emissions, the EPA directed collection of state level random samples of driving behavior controlling for vehicle composition in the state and summed to construct national emissions. The state level data itself was not available

\textsuperscript{8}This partial equilibrium set up assumes that the choice set of vehicles is fixed. A general equilibrium model would permit auto sellers to change the schedule of vehicles offered, summarized by $K$ and $MPG_j$, as a function of gasoline prices.

\textsuperscript{9}An alternative would be to use auto sales data as in Klier and Linn (2010). However, Ward’s auto data began collecting only in 1978. As a result, the late 1970s auto sales data is not sufficient to answer the timing of intensive and extensive margin consumption changes.
for our event window. These national level monthly estimates were reported to the EPA and are publicly available. Vehicle miles traveled data was taken from the US Department of Transportation and Federal Highway Administration. We proxy for retail gasoline prices with the real price of West Texas Intermediate, using 1983 as the base year.\textsuperscript{10} Finally in different specifications which add different combinations of control variables we use data from both the Bureau of Economic Analysis and the Saint Louis Federal Reserve.

There are potentially measurement problems associated with the VMT estimates and EPA emissions data. We assume that measurement error in both variables are uncorrelated with the right hand side variables. Because both variables are used on the left hand side and we include an intercept term in all specifications, we control for any resultant issues. Further, we have run all specifications with the log of the dependent variables to control nonlinear measurement errors and find identical results.

Figure 2: Oil Prices and CO2 Emissions

Figure 2 graphs the real price of oil in 2008 dollars and CO2 emissions from motor vehicle gasoline over this study’s time horizon. There is an unambiguous fall in emissions around the same time that oil prices begin to increase. While we employ a event study design to test for the effect of the increase in oil prices on emissions, note that the treatment does not occur in one month but over several months beginning in April and May of 1979. This issue is dealt with by varying the event date from 12 months before prices begin to increase to twelve months after.

The increased cost of gasoline caused by the oil price shock was not the only price change that may have affected demand for gasoline over this study’s time window. Gasoline rationing led to long lines at fueling stations as well thereby increasing the time cost of refueling. \textit{Ramey and Vine (2010)} finds that this

\textsuperscript{10}Findings are qualitatively similar when using other base years.
added cost was very important to households in the 1970s.\textsuperscript{11} As a result, while this back of the envelope calculation leads to an implied elasticity of MPG substitution and an implied elasticity of miles driven, the estimate is not precise. Rather, the object of this empirical specification is to identify the timing and relative magnitudes of intensive and extensive margin substitution behavior by households in response to an exogenous and unexpected price increase.

The major question of this paper is whether the oil price increase of 1979 significantly affected both total emissions and emissions per VMT at the national level and, if so, was the effect simultaneous. We use the following two different event study specifications to identify the relative effects of the 1979 oil price spike on the passenger vehicle emissions and emissions per VMT. In our case, the treatment is an exogenous, unexpected and persistent increase in oil prices. The initial increase in oil prices in early May 1979 may lead to reductions in household total emissions via reductions on the intensive margin, a decrease in total miles driven, and/or on the extensive margin, a decrease in emissions per VMT.\textsuperscript{12} Because we can observe the price of oil but cannot observe the household decision making process, however, this question is best answered using the test for structural change with an unknown breakpoint proposed by using the supremum of Wald statistics (Andrews (1993)). The method is similar to a Chow test except that Wald Statistics are used instead of t-tests, and critical values are augmented. In essence, the critical values are over distributions of test statistics rather than test statistics themselves. This method has been used before in policy settings where the date in which a policy becomes effective is unknown even though the date of policy implementation is (Piehl, Cooper, Braga, and Kennedy (2003)). The oil price increase of 1979 is particularly well-suited for this type of analysis because it led to an unanticipated increase in gasoline prices and it is unclear that households respond immediately on either the intensive or extensive margins.

There are several issues that must be addressed due to macroeconomic fluctuations and policy changes that occurred over the same time-frame as the event window. Edelstein and Kilian (2009) find that the 1982 recession was largely due to domestic factors. The estimates here imply that the household response to oil price increases on both the intensive and extensive margins occurred before these macroeconomic confounds. Still, robustness checks following the main results control for these issues in more detail.

For robustness, we estimate two types of time trend specifications. The specifications are:

\textsuperscript{11}Note, though, that the rationing in question occurred only in a subset of states and from May 1979- July 1979, Frech and Lee (1987) and show that the magnitude of the rationing was not very large in these months: the shadow cost ranged from 30% of the price of fuel in May 1979 to 8% of the price of fuel in July 1979. The effects on the extensive margin do not appear to be affected as a result. If time costs, then, are viewed strictly in terms on an increase in prices, the delay in extensive margin substitution is even more surprising.

\textsuperscript{12}Note that it is possible that driving behavior also adjusted such that total emissions fell but total miles traveled did not by less speeding behavior. This is an important margin for emissions reduction that can occur immediately when the price of oil increased (Burger and Kaffine (2009) and Wolff (2011)). Indeed, this is the reason why President Nixon decreased the speed limit on highways to 55mph in the early 1970s during that decades first oil price increase.
\[ y_t = \alpha + \sum_{i=1}^{11} \text{month}_i \delta_i + \sum_{s=1}^{N} t^s \delta_s + 1\{\text{post spike}_\tau\} \beta + x_t' \phi + \epsilon_t \quad (4) \]
\[ y_t = \alpha + \sum_{i=1}^{11} \text{month}_i \delta_i + 1\{\text{post spike}_\tau = 0\} \sum_{s=1}^{3} t^s \delta_s + 1\{\text{post spike}_\tau = 1\} \sum_{s=1}^{3} t^s \delta_s + \text{post spike}_\tau \beta + x_t' \phi + \epsilon_t \quad (5) \]

There is concern that omitted variables in the above specifications are changing over time and could bias the estimate of the coefficient on the variable of interest, \( \beta \). We address this concern in two ways. First, as previously noted we select a narrow and symmetric time window around the event. Second, we use an array of flexible polynomial time trend controls for omitted time-varying factors.\(^{13}\) To the extent that there is a long run trend in emission or emissions per vehicle mile travelled, all such decreases not occurring due to a structural break in the data at the time of treatment (e.g., the \( 1\{\text{post spike}\} \) variable) will be accounted for by the time trend.\(^{14}\)

In each specification, the dependent variable \( y_t \) is either \( \text{emissions}_t \) or \( \frac{\text{emissions}}{\text{VMT}}_t \) and the treatment date is \( \tau . \)\(^{15}\) Specification (4) is a \( N^{th} \) degree polynomial time trend. We estimated fourth to ten degree polynomial trends and report the results for the seventh, eighth and ninth degree time trends. The eighth degree time trend offered the best visual fit and the highest pseudo \( R^2 \). Specification (5) estimates the same equation with two third degree time trends that are discontinuous at the time of the treatment. Specification (5) offers more flexibility around the treatment and is our preferred specification.\(^{16}\)

We expect that the coefficient on the \( \text{post spike} \) variable is negative for both emissions and emissions per VMT. As a result, we test the null hypothesis that the coefficient on the \( \text{post spike} \) variable is zero: \( H_0 : \hat{\beta} = 0 \). For each specification, (4) and (5) we vary the date of treatment \( \tau \) from July 1978 through July 1980 and allow the sup-Wald test statistic to select the treatment date. We choose this strategy for several reasons. First, the oil price increases didn’t occur over one month but over several months beginning in late April and early May 1979. Second, given that individual households’ driving habits, car selection within their suite of cars, and new and used car purchases are all unobserved in our data means that their reaction

\(^{13}\)This empirical specification has been implemented by Piehl, Cooper, Braga, and Kennedy (2003), DiNardo and Lee (2004), Davis (2008), and Bento, Kaffine, Roth, and Zaragoza (2012) in sharp regression discontinuity designs to control for such omitted time-varying factors. While we do not use panel data as in some of those studies, our specification is identical to the main specification in in Davis (2008). Further, because the de-trended left hand side variables are stationary making our approach essentially identical to Piehl, Cooper, Braga, and Kennedy (2003), who use the same strategy to identify the size and timing of an effect of a change in policy.

\(^{14}\)Because we use a high order polynomial and both pre and post-break polynomials, we control for non-linear long run effects of emissions or emissions per VMT.

\(^{15}\)The monthly de-trended left hand side variables in both specifications are stationary both before and after the selected breaks; they reject the null hypothesis of a unit root using augmented dickey fuller test.

\(^{16}\)While it is possible to perform an SVAR analysis of the effect of changes in oil prices on emissions, such a specification does not answer the specific question of this paper. Rather an SVAR approach would address the average change in oil prices on emissions as opposed to the change in emissions from a one-time increase in oil prices after a long period of consistent prices.
to the oil price increase may have been delayed. Third, this specification allows us to condition that any change in emissions per VMT must come after any decrease in total emissions to be logically consistent.

### 3.1 Results

Results of the various time trend specifications are not shown in table form but rather in Figures 3 and 4 as it is the most effective way to present our results. We report point estimates from our most preferred specifications below.

![Figure 3: Wald Statistics for Treatment Window: Emissions](image)

Figure 3 shows the Wald statistics for the coefficient point estimates on the post spike variable on total emissions over all 25 estimates in the time window and the associated asymptotic 95% and 99% critical values taken from Andrews (1993). Every specification in Figure 3 selects April 1979 as the beginning of the treatment. This may be somewhat surprising given that prices begin to increase in very late April and early May of 1979. However, it is reasonable given two factors. First, while oil prices are collected as monthly averages, emissions data are only collected at the month level at the end of each month biasing the April 1979 emissions dependent variable down. Second, April 1979 is a month in which households drive less than average and the observed value in April 1979 is within the estimated 95% confidence interval for those dates, even ignoring the treatment. The fact that it was below average means that it is included in the post-treatment period. Indeed, running the intensive margin regression with VMT as the dependent variable, the Andrews test selects May 1979 as the data of the break. The magnitudes of the implied change

17Trimming is $\pi_1 = \frac{55}{144}$ and $\pi_2 = \frac{79}{144}$ for Figure 3 and $\pi_1 = \frac{64}{144}$ and $\pi_2 = \frac{79}{144}$ for Figure 4.
Figure 4: Wald Statistics for Treatment Window: Emissions per VMT

in emissions of running that specification accord with the estimates we have here.\textsuperscript{18}

Figure 4 shows the Wald statistics for the coefficient point estimates on the \textit{post spike} variable on emissions per VMT for all 16 estimates in the time window (April 1979-July 1980) and the associated asymptotic 90\% and 95\% critical values taken from Andrews (1993). All specifications are significant at the 10\% level in November 1979, and two at the 5\% level, implying a delay of six months from the initial price increase. One would expect there to be a significant effect on emissions per VMT given the stability of oil prices leading to the increase.

A delay of six months on the extensive margin is intuitive in the sense that households may want to be sure that gasoline prices stay elevated before substituting on the extensive margin. However, it provides evidence that while consumers may expect energy prices to follow a random walk, all of the information about extensive margin substitution is not embedded solely in expectations but perhaps in higher moments of household forecasts as well. Oil prices had nearly doubled relative to their pre-spike average by November 1979. An alternative explanation is the existence of a planning period over which cars purchases are made. In each case, though, the evidence suggests that there is a significant lag that affects household response to energy price increases on the extensive margin, whether it be via purchases of more fuel efficient goods or different use patterns of existing goods. This intuitive point is vital when considering estimating demand

\textsuperscript{18}It would have been feasible to conduct this study using VMT as the dependent variable in order to test for the response on the intensive margin. The implied fall in emissions using point estimates from the VMT specification is similar than what we find looking directly at emissions. If we had used VMT as the dependent variable, the main result of the paper holds: the delay we find using emissions per VMT is still present.
elasticities of durable energy intensive goods.

Figure 5: Time Trend and Residuals: Emissions (April 1979) and Emissions per VMT (November 1979)

Figure 5 shows the plotted values of residuals for a regression of emissions and emissions per VMT on monthly dummies. The fitted lines show the predicted values obtained after regressing the residuals on the appropriate break (April 1979 or November 1979) and the time trend (8th order or 3rd order discontinuous). Figure 5 is intended to show the magnitude of the break in the monthly de-trended data. All specifications show a significant break at the time of the treatment. Further, Figure 5 shows that a break in emissions per VMT did not occur earlier in the time series providing visual evidence of a delayed effect.

Table 1 shows the point estimates for the estimates of the baseline case in (4) and (5) with no control variables for an eighth order polynomial and pre and post treatment third order time trends. The third degree discontinuous time trend is our preferred specification due to its flexibility. All analysis that follows uses point estimates from specifications (2) and (4) as a result, but qualitatively similar calculations follow from using the point estimates of the eighth order polynomial time trend.\footnote{We also performed an IV specification with monthly oil prices used as an instrument for gasoline prices. Using the IV specification we find that the QLR test selects the same months along both the intensive and extensive margins. The magnitudes of the point estimates are also roughly the same (-6.4 and -.022). This is expected if the event study design is valid. Those results are available upon request.}

The point estimate for the more flexible polynomial finds a significant coefficient of -5.44 for total emissions, or that the oil price shock decreased emissions by 5.44 million metric tons per month (MMT), or...
Table 1: Main Specification Results

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Robust standard errors in parentheses. December is the base month.
Significance level based on Andrews (1993) asymptotic critical values. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

roughly 7.01% of total emissions during that month and a decrease of roughly 7.33% over the study window after oil prices begin to rise. Given that oil prices increased by roughly 100% and total emissions fell by 7.33% MMT, the back of the envelope implied lower bound on short-run elasticity of emissions with respect to fuel price is -0.073. Taking the average oil price over the data before May 1979 and after May 1979 implies a oil price increase of 55.16%. The resultant upper bound on the short-run emissions elasticity is -0.146. This lower bound of the elasticity of emissions on oil price is in line with recent literature using alternate estimation methods: other recent papers find short-run price elasticities of gasoline demand between -0.21 and -0.34 (Hughes, Knittel, and Sperling (2008) and Kilian and Murphy (2011)). Davis and Kilian (2010) use an IV approach to estimate a -0.143 one year emissions elasticity with a permanent 10% increase due to a gas tax, although they estimate a elasticity of gasoline demand with respect to price roughly three times as large. Finally, Yatchew and No (2001) find a long run gasoline price elasticity, -0.8, roughly three times the short-run elasticities found in the literature. This is consistent with the relative magnitudes of the effects we find on the intensive and extensive margins.

Using specification (4), the coefficient on emissions per VMT is significant at the 10% level for November 1979 and is -0.021. The interpretation of this coefficient is that there was a decrease in $-2.1 \times 10^{-5}$ metric tons of CO2 per vehicle mile traveled (VMT), or roughly -3.47%. Put another way, there was a 3.47% decrease in $CO_2$ emissions per vehicle mile traveled due to the persistent oil price shock of 1979. Extrapolating this figure up to total monthly VMT, total emissions fell by 2.591 MMT in November of 1979 due to substitution on the extensive margin. Looking at the long run fall in total emissions of 4.365 MMT, 48.06% of the decrease was due to long run substitution on the extensive margin, while 51.94% was due to other factors such as driving fewer miles and taking other forms of transportation. While the main contribution of this
paper is relative timing of intensive versus extensive margin substitution patterns, these estimates are in line with the estimates of Knittel and Sandler (2010). 20

Table 2: Emissions as Dependent Variable and Real Oil Price

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<tr>
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<td></td>
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Robust standard errors in parentheses. December is the base month.
Significance level based on Andrews (1993) asymptotic critical values. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Emissions per VMT as Dependent Variable and Real Oil Price

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<tr>
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Robust standard errors in parentheses. December is the base month.
Significance level based on Andrews (1993) asymptotic critical values. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 2 and Table 3 show results for emissions and emissions per VMT for the same specification as above when including differenced oil price lags. We difference oil prices due to the high autocorrelation of oil prices. All breaks occur in the same month and are significant in each case. We do not report the estimates on coefficients of the differenced oil price lags but they are almost all have the expected sign and are available upon request. This provides evidence that our event study methodology is sound in that when controlling

20 See Jacobsen (2010) for an excellent analysis of households willingness to adopt more fuel efficient cars in the face of higher operating costs in the form of binding CAFE standards.
for average effects of oil price on emissions, the initial findings are confirmed. In fact, when these average effects of oil prices on emissions are controlled for, the results for emissions per VMT become even more significant. Therefore, we are confident that the oil price shock was unexpected and identifies the intensive and extensive margin substitutions accurately.

Table 4 and Table 5 show results for emissions and emissions per VMT for the same specification as above when including combinations of income and the federal funds rate as controls for the macroeconomy and lending costs in addition to differenced current and lagged oil prices. All breaks occur in the same month when significant in each case. The change in emissions and emissions per VMT becomes even more significant when controlling for macroeconomic effects. In sum, the results appear robust to various specifications.

### 3.2 Validity of Results

The previous section provided several robustness checks to the empirical specifications used in identifying the effect of the 1979 oil price spike on emissions. This subsection is devoted to the validity of the event study design and establishing the correct counterfactual.

![Figure 6: Real Oil, CAFE Standards and Emissions per VMT over Study Window](image)

In demonstrating an empirical break for both total emissions and a delayed break for emissions per VMT, the event study design assumes that there is nothing else correlated with the timing of the treatment that would affect the dependent variables. It is important to note that CAFE standards on the composition of new vehicle fleets started in 1978. The implementation of CAFE standards are shown with monthly detrended emissions per VMT over this study’s event window in Figure 6. Figure 6 shows that the implementation of
CAFE standards coincide with a drop in emissions per VMT. However, there are several important caveats. First, emissions per VMT flatten from 1982-1984, while CAFE standards are still becoming more stringent. Second, there is a clear long run downward trend after 1985, even though CAFE standards are flat after 1985. Third, when real oil prices begin to rise in the 2000s, there is a significant fall in emissions per VMT even when emissions’ standards were becoming less stringent (Knittel and Sandler (2010)). Fourth, the increase in CAFE standards of one MPG only applies to all new cars and does not apply to consumers’ decisions on driving behavior, purchases of used cars, or decisions to drive a different car from the suite of cars they own. With respect to used car purchases, there substantial evidence that the used car market responds to increased gasoline prices (Busse, Knittel, and Zettelmeyer (2011), Kahn (1986), and Gillingham (2012)).

The most direct evidence that the implementation of CAFE standards do not bias our results is in carefully evaluating this study’s methodology. The QLR test for a structural break in emissions per VMT is flexible enough to select the month in which oil prices begin to rise unexpectedly, April 1979, as the month in which there is an effect on emissions per VMT.\footnote{Put another way, the test does not weight the probability that a break occurred in one month relative to another.} We find no evidence of such an immediate effect. Looking at Figure 4, in no specification is the Wald statistic for April 1979 close to being significant. As a result, we fail to reject the null hypothesis that there is a no contemporaneous effect on the intensive and extensive margins. The implication of failing to reject the null hypothesis of no contemporaneous effect on the intensive and extensive margins is that households decision making process on the extensive margin evolves over time differently than their decision process on the intensive margin.

To further address whether the decrease in emissions per VMT was caused by the implementation of CAFE standards in the late 1970s rather than consumers’ unconstrained decisions to purchase more fuel efficient vehicles consider the set of new cars produced. The EPA keeps data on the number of new cars produced for US drivers every year and the composition of those new cars by MPG bands ranging from 5-10 MPG, 10-15 MPG, 15-20 MPG, up to 50 MPG. The yearly data set dates from 1975 to current. One robustness check to see what the effect of the CAFE standards were between 1979 and 1980 is to examine the percent of driving that would need to be performed by newly produced cars relative to the existing fleet in order to account for the observed decrease in emissions per VMT.

To find the percent of miles driven which would need to come from new cars to order to account for the observed change in emissions per VMT, we collect data from several sources. Figure 7 shows the composition of new cars in the US by MPG band for the years of our study as collected by the EPA. These data are weighted by vehicles produced; for example, if one million cars were produced for the US market for model year 1979, then 485,000 of them had an MPG rating between 15 and 20. Unfortunately, with MPG band sales weighted distributions are unavailable and despite contacting the Agency, no finer data was available from the EPA. As a result, we can infer what the average MPG of new autos were using lower, average and upper bounds of the MPG bands by multiplying the percent of sales for each band and summing across bands. More precisely, if bound type $j = \{ \text{lower, average, upper} \}$ with each MPG band $k$ is used for a year
we define

$$MPG_t^j = \sum_{k=1}^{K} MPG_k^j \cdot s_{k,t}$$  \hspace{1cm} (6)$$

where $s_{k,t}$ is the share of production in year $t$ of MPG band $k$. For example, $s_{(25-30),1980} = .127$ and $MPG_{(25-30)}^{average} = 27.5$. There are two additional caveats regarding this calculation. First, the CAFE standard in 1980 was 20 MPG for new cars which is in between the lower and average bounds for new auto MPG in that year. Second, Sallee and Slemrod (2011) finds that automakers bunch their cars’ fuel efficiency so as to just avoid paying fines for gas guzzler taxes, which occur at the bottom of the 16-20 MPG range over this time period. Their result implies the technique here might overstate MPG of new autos. Taken together, these estimates of average new auto MPG ratings by model year are plausible.

We compare new model year auto fuel efficiency to data collected by the department of transportation for existing fleet characteristics which calculate actual MPG of the passenger vehicle fleet as a whole. According to US Department of Transportation highway summary statistics, in 1979 the passenger vehicle fleet averaged 14.62 MPG in 1979 and 15.98 MPG in 1980. Further, new cars comprised 2.6% of the total number of cars on the road in 1980 according to registration data from the US DOT Historical Statistics. Given that the passenger vehicle fleet in 1979 averaged 14.62 MPG, it implies that new cars would have had to account for 25.3% of total miles driven if average new cars had fuel efficiency 20 MPG and the CAFE standard was perfectly binding. Using low and average new auto MPG bands give 37.1% and 22% respectively.\(^{22}\)

While this intensity of use for new autos is certainly possible, it seems unlikely. It is more likely the set of new cars were not driven uniformly. Put a different way, cars that far exceeded the unconstrained CAFE MPG equilibrium - both new and used- received a far greater portion of miles than lower MPG cars in the fleet starting in November 1979. This interpretation is consistent with recent work by Busse, Knittel, and

\(^{22}\)Note that considering the upper bound for new auto fuel efficiency does not make sense if the CAFE standard was binding.
Zettelmeyer (2011). Put another way, in order for CAFE standards to dictate these results households’ unconstrained new car purchase decisions would have to be insufficient to meet the CAFE standard on their own. While such an event is possible, it implies that an increase in user costs of 100% (the increase in gasoline prices between April 1979 and November 1979), did not increase unconstrained household choice of fuel efficiency as measured by MPG by at least 10%.\footnote{This number is calculated by taking the average new car MPG in 1979, 18.22, and calculating the percentage change to reach 20 MPG.}

An alternative way to address whether CAFE standards drove the differential timing of substitution along the intensive an extensive margin is to examine emissions per VMT in subsequent years when the CAFE standard was ratcheted up. Figure 6 shows that starting on both January 1, 1981 and January 1, 1982 the CAFE standard on new cars increased by two miles per gallon in each year, double the one year increase between 1979 and 1980. If the results in this paper are driven by implementation of CAFE standards then one might expect to see similar results in November of 1980 and 1981 when new model year cars begin to come on the market.

To test whether subsequent CAFE standards had a significant effect consider an augmented version of equation (4):

\[
\frac{\text{emissions}}{\text{VMT}}_t = \alpha + \sum_{i=1}^{11} \text{month}_i \delta_i + \sum_{s=1}^{N} t^s \delta_s + 1\{\text{post Nov}1979\} \beta + x_t' \phi + \sum_{s=1980}^{1982} 1\{\text{post Nov}_s\} \psi + \epsilon_t
\]

In equation (7) we replicate the 7th through 9th order polynomial time trends including the full set of macro controls from Table 5, but also include dummy variables for November of 1980, 1981 and 1982. These indicator variables are one for all time periods starting in November of each year. If the coefficient on 1post Novs is significant, it implies the implementation of CAFE is correlated with significantly lower emissions per VMT and implies the lagged results in the previous section are not caused by household optimization decisions but by changes in policy. We performed the same robustness check for other nearby months (October and December) with similar findings.

Table 5 shows that in no specification was any individual subsequent month associated with a stricter CAFE standard significant nor were the months jointly significant. The inclusion of these variables also does not affect the significance of the break selected by the QLR test. The lack of significance of subsequent CAFE implementation constraints is further evidence that CAFE were not a binding constraint over this time period but rather households were switching to more fuel efficient cars within the fleet based upon private optimization decisions.

A final problem with this approach is identifying the appropriate counterfactual. Given that the treatment dates for which total emissions and emissions per VMT fall significantly are not identical, there is no clear way to identify the correct apportionment of the reduction in emissions due to substitution on the intensive
versus the extensive margin. As a result, we do not wish to over emphasize our point estimates for intensive and extensive margin substitution, but rather their relative magnitudes and timing of the effects we find. We can say, though, that the total effect from emissions per VMT reduction accounted for 50% of total emissions reductions over the entire study’s time-frame.

4 Conclusion

We use an event study design to test whether a sudden unexpected increase in fuel prices leads to simultaneous substitution on the intensive and extensive margins. This study suggests that the oil price increase of 1979 led to a significant fall in CO2 emissions from passenger vehicles of between 7-14%. We find that roughly 50% of the fall in emissions was due to substitution on the extensive margin with the rest coming from substitution on the intensive margin. The effect on emissions per VMT occurred significantly later than the fall in total emissions implying that households changed their behavior on the intensive margin immediately but delayed their decisions on the extensive margin. The delay implies, and a simple theoretical model shows, that while households forecast energy prices as a random walk, changes in their forecast uncertainty
can alter their incentives to purchase more fuel efficient vehicles.\textsuperscript{24} However, there several other potential explanations for why there could be a delay on the extensive margin: planning periods for purchase of new or used cars, information gathering, learning about more efficient driving behavior, etc... are also potential explanations and further theoretical work is needed to inform which channels could lead to such a delay. Given that roughly 50\% of the fall in total emissions was due to substitution on the extensive margin, the observed delay on the extensive margin is an important finding and merits further study.

\textsuperscript{24}This explanation has found support in other work on the relative effects of gasoline price increases due to permanent tax increases versus market driven fuel price increases Li, Linn, and Muehlegger (2012). Future work should examine the timing of response with respect to market driven versus tax driven fuel price increases.
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<th>Federal Funds Rate</th>
<th>Effect Size</th>
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All specifications select April 1979.

All specifications include monthly indicators and differences in oil prices.

December is the base month for the monthly indicators.

QLR Significance based on * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. 
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All specifications select November 1979.

All specifications include monthly indicators and differences in oil prices.

December is the base month for the monthly indicators.

QLR Significance based on * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$. 
References


