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Gasoline Taxes and Consumer Behavior

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Abstract

Gasoline taxes can be employed to correct externalities associated with automobile use, to reduce dependency on foreign oil, and to raise government revenue. Our understanding of the optimal gasoline tax and the efficacy of existing taxes is largely based on empirical analysis of consumer responses to gasoline *price* changes. In this paper, we directly examine how gasoline *taxes* affect consumer behavior as distinct from tax-exclusive gasoline prices. Across a variety of specifications and estimation methods, we find that consumers respond more strongly to gasoline tax changes. Our main specification shows that a 5-cent tax increase would reduce gasoline consumption by 0.87 percent, significantly larger than the effect from an equivalent change in tax-exclusive prices. This difference suggests that traditional analysis could dramatically underestimate policy impacts of tax changes. We further investigate the differential effect from gasoline taxes and tax-exclusive gasoline prices on both the intensive and extensive margins of gasoline consumption. We discuss implications of our findings for the estimation of the implicit discount rate for vehicle purchases and for the fiscal benefits of raising taxes.

Key Words: automobile, consumer response, gasoline tax

JEL Classification Numbers: Q4, Q5, H3

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1. Introduction

The gasoline tax is an important policy tool to control externalities associated with automobile use, to reduce dependency on oil imports, and to raise government revenue. Automobile use imposes externalities including local air pollution, carbon dioxide emissions, traffic accidents, and traffic congestion (Parry, Walls, and Harrington, 2007). Although the gasoline tax is not the theoretically optimal tax for all of these externalities, a single tax avoids the need for multiple instruments (e.g., distance-based taxes and real time congestion pricing) and offers an administratively simple way to control these externalities at the same time. Besides correcting environmental externalities, the gasoline tax can reduce gasoline consumption and may mitigate concerns about the sensitivity of the U.S. economy to oil price volatility, constraints on foreign policy, and other military and geopolitical costs. Moreover, gasoline taxes at the federal and state levels are major funding sources for building and maintaining transportation infrastructure. Federal fuel taxes provide the majority of revenue for the Highway Trust Fund, which is used to finance highway and transit programs. Past increases in federal gasoline taxes have generated revenue for such programs, but the federal gasoline tax has stayed constant since 1993. Greater infrastructure investment needs and declining fuel tax revenues due to the recent economic downturn have led the Highway Trust Fund to be insolvent since 2008 and required Congress to provide funding from the General Fund.¹

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¹ In federal fiscal year 2010, \$51 billion of spending was committed from the Highway Trust Fund while the total revenue into the fund was just \$35 billion.

Growing concerns about climate change, air pollution, energy security, the national budget deficit, and insolvency of the Highway Trust Fund have brought renewed interests in increasing state and federal gasoline taxes. Understanding how gasoline tax changes affect automobile use and gasoline consumption is crucial in effectively leveraging this instrument to achieve these policy goals. An underlying assumption used in previous policy analysis on the effectiveness of higher gasoline taxes and the optimal gasoline tax is that consumers react to gasoline tax changes similarly to gasoline price changes. Consequently, the consumer response to oil-price induced changes in gasoline prices is often used as a proxy for the response to a commensurate change in the gasoline tax. The recent economics literature finds that consumers respond little to rising gasoline prices at least in the short run.² Together with the maintained assumption, these estimates suggest that a large increase in the gasoline tax would be required to significantly reduce fuel consumption. Not only may this exacerbate the perceived political cost of increasing gasoline taxes, but it may partially explain why U.S. policy makers have tended to favor Corporate Average Fuel Economy (CAFE) standards over gasoline taxes, despite the broad conclusion of a long literature examining fuel economy standards that gasoline taxes are more cost-effective in achieving targeted fuel reductions.³

The purpose of our paper is to test the maintained assumption that consumers respond to gasoline tax and tax-exclusive price changes in the same way. In contrast to the literature, our analysis directly estimates consumer responses to gasoline taxes by decomposing retail gasoline prices into tax and tax-exclusive components. We use three outcomes to examine consumer behavior over short time horizons: gasoline consumption, vehicle miles traveled (VMT), and vehicle fuel economy (miles per gallon, MPG). VMT represents the intensive margin, MPG represents the extensive margin, and total gasoline consumption is the combination of the two. Two separate data sets are employed in our analysis: aggregate state-level data that allow us to examine responses in gasoline consumption, and household-level data that allow us to examine responses in VMT and MPG. We find that rising gasoline taxes are associated with much larger reductions in gasoline consumption than comparable increases in gasoline prices. This result is robust across a variety of specifications and estimation methods. The results from our main

² A partial list includes Small and Van Dender (2007), Hughes, Knittel, and Sperling (2008), Bento et al. (2009), Li, Timmins, and von Haefen (2009), and Klier and Linn (2010). These studies often use variations in gasoline prices driven primarily by supply and demand shocks.

³ See, for example, Goldberg (1998), Congressional Budget Office (2003), Austin and Dinan (2005), Fischer, Harrington, and Parry (2007), Jacobsen (2010), and Anderson and Sallee (2011).

specification suggest that a 5-cent increase in the gasoline tax would reduce gasoline consumption by 0.87 percent, three times as large as the effect one would find from an empirical framework without separating gasoline prices into tax and tax-exclusive components. Dissecting the intensive and extensive margins, we find a significant differential effect in household MPG, especially among newer vehicles. Although we focus on short-term responses, the large effect of taxes on MPG suggests that the long-run response to taxes may also be greater than the long-run response to tax-exclusive gasoline prices. Our analysis on whether there exists a differential effect on VMT from the gasoline tax and the tax-exclusive price is inconclusive due to imprecise estimates.

While adding to the extensive literature on automobile purchase and utilization cited above, our study also fits into the growing literature on how persistence, salience, and other factors may cause consumers to respond to one component of retail prices, such as a tax or rebate, differently from other components.⁴ Among the existing studies, our research is perhaps most closely related to Davis and Kilian (2011). In the same context of gasoline consumption, they find a much larger price coefficient estimate (in magnitude) after instrumenting for the gasoline price variable using the state-level gasoline tax. They argue that the IV estimate of the price coefficient should be interpreted as capturing the consumer response to the gasoline tax.

Our research differs from their study in three important dimensions. First, our main goal is to test the maintained hypothesis that consumers respond to gasoline taxes in the same way as to tax-exclusive prices. Our empirical analysis includes these two price components in the regressions, which permits estimates of consumer responses to the two components. In contrast, Davis and Kilian (2011) use the tax-inclusive gasoline price as the key regressor in the gasoline demand equation and use gasoline taxes as the instrument for the price variable. They take the larger (in magnitude) price coefficient estimates from the IV regressions as evidence that consumers are more responsive to gasoline taxes. Nevertheless, their analysis does not directly produce an estimate of the elasticity of gasoline demand to gasoline taxes. Second, they use *monthly* state-panel data from January 1989 to March 2008 while our data are *annual* from 1966 to 2008. Therefore, their estimates may capture very short-term responses while ours represent effects over a longer term. Third, in addition to the gasoline consumption analysis using state-level data, we use household-level data to investigate the differential effect separately for the

⁴ For example, see Busse, Silva-Risso, and Zettelmeyer (2006), Chetty, Looney, and Kroft (2009), and Finkelstein (2009), Davis and Kilian (2011), Barandini and Weber (2012), Zheng, McLaughlin and Kaiser (2012), Scott (2012).

extensive and intensive margins. This analysis yields additional support for the finding of a differential response and sheds lights on the channels through which the differential effect arises.

Our main findings have several implications. First, they suggest that the gasoline tax would be more effective than the previous empirical literature has suggested at addressing climate change, air pollution, and energy security. Several recent proposals have called for higher gasoline taxes for either fiscal motives (see, e.g., the proposal of the Deficit Reduction Committee) to maintain the solvency of the Highway Trust Fund, or to internalize the cost of greenhouse gas emissions. By focusing on the effects of gasoline taxes, our paper speaks directly to the effectiveness of these proposals.

Second, separating gasoline taxes from tax-exclusive prices offers a strategy to address a challenging identification problem in environmental and energy economics. Energy efficiency-related policies such as CAFE are often advocated under the presumption that consumers use a high implicit discount rate to value future energy savings. Beginning with Hausman (1979) and Dubin and McFadden (1984), a long literature estimates the implicit discount rates consumers use to evaluate durable goods purchases. The identification problem arises because the econometrician does not observe a consumer's expectation of future energy costs. Consequently, it is impossible to estimate implicit discount rates without making assumptions on consumers' expectations of future energy prices. In some cases, assumptions of future expectations are innocuous (e.g., for regulated retail electricity markets) but in others, such as gasoline prices, which are subject to influences from numerous domestic and international factors, modeling consumer expectations is not straightforward.⁵ Nevertheless, as Section 5.1 illustrates, under assumptions regarding consumer perceptions on state and federal taxes, the implicit discount rate could be identified without making assumptions regarding consumer expectations of gasoline prices.

Finally, the results have implications for the literature on the optimal gasoline tax (e.g., Parry and Small (2005)). The literature estimates the optimal tax based partly on empirical estimates of the elasticity of gasoline consumption to gasoline prices, under assumptions that the gasoline tax and gasoline price elasticities of demand are the same. Our analysis focuses on short-term responses to gasoline taxes and tax-exclusive prices. Although we find evidence of

⁵ Anderson, Kellogg and Sallee (2012) offer an interesting look on consumer expectation of gasoline prices using survey data. We discuss their finding in relation to ours in detail in Section 3.5.

differential responses in gasoline consumption from lagged tax and price changes, we leave the estimation of long-run responses for future research.

The paper proceeds as follows. In section 2, we present some background on U.S. gasoline prices and taxes. We present our analysis of the aggregate state-level data in section 3 and present our analysis of the household-level data in section 4. In section 5, we discuss the implications of our results for the estimation of implicit discount rates and the elasticity of fiscal revenue. Section 6 concludes.

2. Background on U.S. Gasoline Prices and Taxes

Our empirical analysis employs changes in state gasoline taxes and tax-exclusive prices to investigate the effects of taxes on gasoline consumption, vehicles miles traveled, and vehicle choices. In this section, we discuss variation in U.S. gasoline prices and taxes.

Taxes make up a substantial portion of U.S. retail gasoline prices. As an illustration, we decompose gasoline prices into oil prices and excise taxes. We regress the tax-inclusive price for state s and year t on crude oil prices, federal and state excise taxes, state fixed effects, and state-specific linear time trends:

$$RetailPrice_{st} = \alpha_s + \beta OilPrice_t + \gamma \tau_{st} + \delta_s t + e_{st} \quad (1)$$

$RetailPrice_{st}$ is the retail price, $OilPrice_t$ is the crude oil price, and τ is the sum of federal and state excise taxes. The state fixed effects, α_s , capture time-invariant differences in gasoline prices that arise from differences in transportation costs. The linear time trends allow the retail prices in each location to adjust at a different linear rate over time. The coefficient on taxes is 1.03 and is statistically indistinguishable from 1, suggesting that gasoline taxes are heavily borne by consumers. This is consistent with the result in Marion and Muehlegger (2011), which finds that, under typical supply and demand conditions, state and federal gasoline taxes are passed fully on to consumers and are incorporated fully into the tax-inclusive price in the month of the tax change. Similar findings are also presented in Chouinard and Perloff (2004), Alm, Sennoga and Skidmore (2009), and Davis and Kilian (2011).

Based on these estimates, Figure 1 decomposes the average U.S. retail gasoline price (dashed line) into an oil component, a tax component, and the state fixed effects and time trends. Although much of the intertemporal variation in national gasoline prices is correlated with changes in oil prices, taxes constitute a significant portion of the tax-inclusive gasoline prices for much of the period. Table 1 reports the average nominal gasoline price, state gasoline tax, and federal gasoline tax, in cents per gallon for five-year intervals beginning in 1966 and ending in

2008. In addition, for each period the table reports the percentage of gasoline price changes explained by changes in gasoline taxes. The percentage varies substantially over time, rising with the federal gasoline tax (from 4 to 9 cpg in 1983, to 14.1 cpg in 1991, and then to 18.4 cpg in 1994) and state taxes, and falling during periods of volatile oil prices.

National averages obscure substantial cross-state variation in gasoline taxes. Figure 2 displays snapshots of per-gallon state gasoline taxes in 1966 and 2006. Figure 3 depicts changes in state gasoline taxes from 1966 to 1987 and 1987 to 2008. Figure 4 presents the mean, maximum and minimum state tax as well as the federal gasoline tax over the period. Although the mean state gasoline tax rises slowly over time, state taxes rise more quickly in some locations than in others. In 1966, the difference between the states with the highest and lowest gasoline taxes was 2.5 cpg. In 2008, the difference was 30 cpg; Georgia's excise tax was 7.5 cpg while Washington's excise tax was 37.5 cpg.

States vary substantially in the frequency and magnitude with which they change gasoline excise taxes. From 1966 to 2008, state per-gallon taxes changed in about 26 percent of the state-years.⁶ Gasoline taxes rose in 488 state-years and fell in 44 state-years, out of 2,064 total observations. Nebraska, North Carolina, and Wisconsin changed taxes most often, in 29, 24, and 24 years, respectively.⁷ Georgia only changed the gasoline tax twice during the period.

Figure 5 graphs the proportion of the tax-inclusive retail price made up by excise taxes. At the median, taxes make up approximately 26 percent of the after-tax price. This varies substantially over time and across states; the proportion is greatest during the late 1960s and late 1990s when oil prices were relatively low and taxes were relatively high. The proportion is lowest during the early 1980s and after 2005, when oil prices rose substantially. At the peak in 1999, the proportion varies from a low of 25 to 30 percent (at the 5th percentile) to a high of over 40 percent (at the 95th percentile).

Although gasoline taxes constitute a large proportion of after-tax fuel prices, relatively little research examines political and economic factors that drive state and national fuel taxes.⁸ The previous literature identifies a number of political and economic factors that correlate with

⁶ In the annual data, we only count years in which the average annual rate changed relative to the previous year. We do not count multiple changes over the course of a year as part of the total.

⁷ In fact, Nebraska changes its gasoline tax even more often than the annual figures suggest. From 1983 to 2008, for which we have monthly data, Nebraska changed its gasoline tax 56 times.

⁸ See e.g., Goel and Nelson (1999), Hammar, Lofgren and Stermer (2004), and Decker and Wohar (2007).

fuel tax changes, such as road revenues from other sources (Goel and Nelson (1999)), environmental regulation and trucking industry employment (Decker and Wohar (2007)), and government debt as a percent of GDP (Hammar, Lofgren, and Sterner (2004)). Finally, Doyle and Samphantharak (2008) use gasoline tax moratoria that were granted in Illinois and Indiana in 2000 to estimate the incidence of gasoline taxes. Although in this case taxes were waived in direct response to high gasoline prices, gasoline tax moratoria are very rare and constitute a negligible fraction of the observed variation. Overall, the past literature identifies political and economic factors correlated with tax changes, but the variables considered explain only a small fraction of total variation. We provide similar findings in our analysis below.

3. Aggregate Data Analysis

In this paper, we examine two distinct data sources: (1) aggregate data including gasoline consumption, taxes, and prices at the state level; and (2) household-level data on vehicle ownership and driving decisions. We employ the aggregate data to estimate gasoline consumption responses to tax and price changes, and we use the household-level data to examine two separate margins through which gasoline consumptions are affected: the extensive margin (vehicle choice) and the intensive margin (vehicle usage).⁹ In this section, we present our empirical strategy, data, and results using the aggregate data.

3.1 Empirical Methodology

To estimate the relative impact of tax and tax-exclusive price changes on aggregate gasoline consumption, we employ a similar empirical approach to Marion and Muehlegger (2008). We estimate the following linear equation, which decomposes the tax-inclusive retail price into a tax-exclusive component and the excise tax rate (which does not include ad valorem taxes):

$$\ln(q_{sy}) = \alpha \ln(p_{sy}) + \beta \ln\left(1 + \frac{\tau_{sy}}{p_{sy}}\right) + X_{sy}\theta + \delta_s + \phi_y + e_{sy} \quad (2)$$

where q_{sy} is the dependent variable, gasoline consumption per adult, by state and year; p_{sy} is the

⁹ Although state-level VMT measures are available, we do not use them to examine the intensive margin because of their well-known measurement errors.

tax-exclusive gasoline price; τ_{sy} is the total state and federal gasoline tax; X_{sy} is a vector of state-level observables; and δ_s and ϕ_y are state and year fixed effects. Within-state deviations from the national trend identify the correlation among the dependent variables, tax-exclusive gasoline prices, and tax ratios.

Following the above decomposition, we can derive the price and tax elasticities of demand from the coefficients in equation (2). Our analysis in the previous section as well as that in Marion and Muehlegger (2011) provide strong evidence that state taxes are fully (and rapidly) passed on to consumers. Under the assumption that consumers bear the entire tax, the tax-exclusive price is not affected by a change in the tax rate, $dp/dt = 0$. With this assumption, we take the derivative of equation (2) with respect to the price and tax and rearrange terms to obtain price and tax elasticities of gasoline demand:

$$\varepsilon_p = \alpha - \beta \frac{\tau}{p + \tau}; \quad \varepsilon_\tau = \beta \frac{\tau}{p + \tau}. \quad (3)$$

Similarly, we can derive the semi-elasticities, which are defined as the percent change associated with a unit increase in either the tax-exclusive price or gasoline tax:

$$\frac{\partial \ln(q)}{\partial p} = \frac{1}{p} \left(\alpha - \beta \frac{\tau}{p + \tau} \right); \quad \frac{\partial \ln(q)}{\partial \tau} = \beta \frac{1}{p + \tau}. \quad (4)$$

This approach provides a direct test of whether taxes are more strongly correlated with behavior than are tax-exclusive gasoline prices. If consumers respond equally to changes in the gasoline tax and tax-exclusive price (of the same size), α should be equal to β . The two semi-elasticities derived above would be the same and equation (2) reduces to a regression of quantity on the tax-inclusive gasoline price. If and only if, on the other hand, consumers respond more to a tax change than to a change in the tax-exclusive price (i.e., $\frac{\partial \ln(q)}{\partial \tau} > \frac{\partial \ln(q)}{\partial p}$), β should be larger than α . Because we use state fixed effects and annual data, we interpret the results as short-run effects.

3.2 Sources

We use a panel data on gasoline consumption, gasoline prices, and state and federal gasoline taxes by state-year from 1966 to 2008. The data are taken from annual issues of Highway Statistics Annual, published by the Federal Highway Administration. Tax-inclusive retail gasoline prices are from the Energy Information Administration State Energy Price Reports. The data contain demographic variables, including population and average family size

from the Current Population Survey, Bureau of Economic Analysis (BEA) and the Census; and per capita income, gross state product, and fraction of the population living in metropolitan statistical areas (MSAs) from BEA. The fraction of the population located in metro areas with rail transit is calculated from the Statistical Abstract of the United States. There are several additional vehicle-related variables from the Highway Statistics reports: the number of licensed drivers, number of registered cars and trucks, and miles of public roads. Except for the federal gasoline tax, all variables vary by state and year.

3.3 State Level Gasoline Consumption Results

Table 2 presents the main coefficient estimates from equation (2). The dependent variable is gasoline consumption per adult in logarithm. Each column reports a different specification.

Columns 1, 3 and 5 report estimates using the tax-inclusive gasoline price for comparison with the results when the gasoline price is decomposed into tax-exclusive and tax components. Each column adds additional controls: column 1 includes state fixed effects and year fixed effects; column 3 adds a set of demographic variables; and column 5 further adds state-specific quadratic time trends. The specification in column 5 provides estimates of -0.10 for the price elasticity of gasoline consumption, compared to -0.16 and -0.19 from regressions with fewer control variables (columns 1 and 3). These price elasticity estimates are consistent with previous results from the literature. Small and Van Dender (2007), using a shorter sample (1966-2001) of state-level data and a different estimation strategy, obtain estimates of -0.09 to -0.17 for the price elasticity of gasoline consumption. Using monthly data at the national level, Hughes, Knittel and Sperling (2008) find that the price elasticity ranges from -0.21 to -0.34 during 1975-1980 and -0.034 to -0.077 during 2001-2006. Espey (1998) provides a broad review based on hundreds of gasoline demand studies: the short-run price elasticity ranges from 0 to -1.36 with a median of -0.23 based on 363 estimates.

Columns 2, 4 and 6 separate the gasoline price into the tax-exclusive and tax components, successively adding more control variables. Through the text, we use the most inclusive specification in column 6 as our main/benchmark regression. The coefficient estimates on both the tax variable and the tax ratio become smaller in magnitude from column 2 to 4. Nevertheless, in all three regressions, the coefficient estimate on the tax variable is much larger than that on the tax ratio, and the hypothesis that the two coefficients are equal can be rejected at the one percent

significance level. One of the main focuses of our following analysis is to examine the robustness of this finding. The analysis in the next section shows that the finding is robust across a variety of different specifications and estimation methods.¹⁰

Because of the strong persistence of gasoline prices, taxes, and consumption, in column 7 we estimate equation (2) using feasible generalized least squares (FGLS) in which we allow for a state-specific first-order autocorrelation structure in the error term. The standard errors are robust to heteroskedasticity and correlation within states. Allowing for first order autocorrelation has virtually no effect on our results compared with those from our main specification. As before, we find that in the short run gasoline consumption responds more to taxes than to the tax-exclusive price.

The coefficient estimates on other variables are intuitively signed when precisely estimated. The short-run income elasticity, in line with the literature, is estimated to be 0.25 from the main specification and ranges from 0.22 to 0.33 across columns 3 to 7. The income elasticity estimate from Hughes, Knittel and Sperling (2008) ranges from 0.21 to 0.75 across model specifications. In the review by Espey (1998), the median short-run income elasticity is 0.39 with a range from 0 to 2.91 based on 345 estimates. The parameter estimates across the specifications suggest that gasoline consumption increases with car ownership and the number of drivers. Interestingly, the estimated effect of the access to light rail on gasoline consumption becomes negative only when state-specific trends are included in columns 6 to 7.

To assess the magnitude of the coefficient estimates on the price and tax variables, we calculate elasticity and semi-elasticities based on the parameter estimates in the main specification (columns 5 and 6 in Table 2). To calculate elasticities and semi-elasticities, we use the average price and tax in 1988, the year that matches the means over the sample period most closely. Panel A in Table 3 reports elasticities of gasoline consumption with respect to gasoline price, tax-exclusive price, and gasoline tax. Our parameter estimates lead to a tax elasticity of -0.076 and a tax-exclusive price elasticity of -0.037. Because of the differences in the scale of the gasoline tax and the tax-exclusive price, and the fact that it is more natural to compare the effects

¹⁰ Hughes, Knittel, and Sperling (2008) find that the price elasticity of gasoline demand decreased from late 1970s to early 2000s by comparing the estimates from two five-year periods in 1975-1980 and 2001-2006. In the same spirit, we have estimated separate coefficients on the tax and tax-exclusive variables by five-year time periods and find that, in six of the nine time periods, the coefficient on the tax variable is larger in magnitude and the difference is statistically significant. Although the tax variable is still larger in magnitude in the remaining time periods, the difference is not statistically significant. This suggests that our results are not driven by the time-period effects.

of a given monetary change in taxes or tax-exclusive prices, the remainder of the paper focuses on a measure that is akin to semi-elasticities: the percent change in gasoline consumption from a 5-cent per gallon increase in price or tax. The first column of Panel B shows that a 5-cent increase in the gasoline price, not differentiating the source of price change, reduces gasoline consumption by 0.29 percent. The calculations are based on the average tax and tax-exclusive gas price in 1988 (adjusted to 2008 dollars), which are close to the sample mean. The second column reports that a 5-cent increase in the tax-exclusive price reduces gasoline consumption by 0.15 percent while an equivalent change in the gasoline tax reduces gasoline consumption by 0.86 percent. The difference of 0.71 is statistically significant at the one percent level.

Figure 6 shows the difference between the effects from a 5-cent per gallon increase in the two components and the 95 percent confidence band from 1966 to 2008. Variation over time reflects temporal fluctuations in the tax-exclusive price and tax, particularly the tax-exclusive price. The difference is significantly different from zero in all years. The graph reinforces the finding that gasoline consumption responds more strongly to changes in gasoline taxes than tax-exclusive prices. The comparison highlights that the impact of gasoline tax on gasoline consumption would be significantly underestimated using the estimated effect from overall gasoline price changes, as is commonly done in existing policy analysis.

3.4 Identification and Additional Tests

We perform a host of additional analyses to examine alternative explanations for the estimated difference in the coefficients on the tax-exclusive gasoline price and the tax rate. We have assumed that the tax-exclusive price and tax rate are exogenous to other determinants of gasoline consumption. In the following, we first investigate the exogeneity of gasoline taxes by examining how the gasoline tax changes are determined. We then show additional regression results to examine the robustness of our finding to different modeling approaches.

3.4.1 Exogeneity of Gasoline Taxes

We take two approaches to examine the exogeneity of the gasoline tax. First, we compare the demographics of high tax and low tax states. We classify states as high tax by comparing the

state tax rate to the weighted average national tax rate in a given year.¹¹ We present the mean and standard deviations of the demographic variables for the high tax and low tax states in Table 4. In addition, we calculate the difference between the mean of the demographic variables in the high and low tax states and report whether the means are statistically distinguishable. Tax-exclusive prices are indistinguishable statistically, which is consistent with consumers bearing the majority of gasoline taxes. In addition, we do not find significant differences in per capita income, educational attainment, family size, vehicles per capita, urban population share, unemployment rates or state budgetary health, which is measured as a state's budget surplus (or deficit) as a percent of total expenditures. We do find that high tax states have slightly fewer drivers per capita and a slightly lower fraction of the population living in a metro area with a rail transit system, although even these differences are small in absolute value. Furthermore, states with above average gasoline prices tend to generate a slightly smaller share of Gross State Product (GSP) from manufacturing and mining.

States with higher than average gasoline taxes tend to elect U.S. senators and U.S. representatives who receive higher ratings from the League of Conservation Voters and elect a greater fraction of Democrats to the State senate. We do not find statistically significant differences between the fractions of Democrats elected to the State House of Representatives in high and low tax states, nor do we find that high tax states are more or less likely to elect a Democrat as a Governor.

Second, we test whether changes in economic or political variables predict state gasoline tax changes. We regress year-to-year changes in nominal state gasoline taxes (per gallon) on first-differenced economic and political variables. We include the socioeconomic variables (e.g. GSP per capita, unemployment, urbanization, and educational attainment), political variables (e.g. League of Conservation Voters scores for a state's congressional delegation, a dummy for a governor belonging to the Democratic Party, the fraction of a state's house and senate seats occupied by Democrats, and a state's budget surplus as a fraction of revenues), and industrial variables (e.g. manufacturing and mining GSP shares) from Table 4. Table 5 presents the results. Specifications (1) through (3) cover the full sample. Specifications (4) through (6) use a shorter

¹¹ Only five states are exclusively classified as above or below mean in all years. Gasoline taxes in Nebraska, Washington and West Virginia are above the national average in all years. Gasoline taxes for Missouri and Wyoming are below the national average in all years. Across all years, states in the 25th percentile report tax rates above the national average in nine or fewer years and states in the 75th percentile report gasoline taxes above the national average in 32 of the 43 years.

sample, but include several additional industrial and political variables. The three columns, for both samples, regress the change in state gasoline taxes on lagged, contemporaneous and leading changes of the explanatory variables. Across the six specifications, the only significant, consistent correlation we find is that past, current and future changes in state GSP are negatively correlated with gasoline tax changes (recall that the main regression model controls for GSP).¹² Collectively, the political and economic variables explain little of the variation in gasoline prices beyond what is explained by year fixed effects. The dependent variables are not jointly significant in any of the six specifications.

3.4.2 Instrumenting for the Tax-Exclusive Price and Additional Tests

Next, we turn to the exogeneity of the tax-exclusive price. The tax-exclusive gasoline price may not be exogenous to gasoline consumption if state-level demand or supply shocks are correlated with equilibrium prices and consumption. Including state GSP controls for demand shocks to some extent, but there may be other variables, such as supply-side shocks, that are correlated with both prices and consumption. We use crude oil prices to instrument and correct for the potential endogeneity of the tax-exclusive price. We construct two instruments: (1) the interaction of the tax-exclusive price in 1966 with the average annual price of imported crude oil, and (2) one plus the gasoline tax divided by the annual average price of imported crude oil.¹³ Both instruments are arguably exogenous to state-level gasoline demand or supply shocks. We present the instrumental variables (IV) results in Table 6. The first three columns replicate the specifications in columns 2, 4 and 6 of Table 2, using the slightly shorter sample for which our instruments are available (1968 to 2008). The next three columns present the IV results for the same specifications. Panel A reports the estimated coefficients from the regressions which panel B reports the implied semi-elasticities. After instrumenting, the point estimate for the coefficient on the log of the tax-exclusive price falls, while the point estimate for the coefficient on $\ln(1 + \text{taxratio})$ rises. In all six specifications, the coefficient on $\ln(1 + \text{taxratio})$ is significantly greater than the coefficient on the log of the tax-exclusive gasoline price. Moreover, the IV

¹² As an alternative specification, we also regressed a dummy of whether or not state gasoline taxes rise year-on-year on the first-differenced explanatory variables. We do not find consistent significant correlations between the explanatory variables and the timing of state gasoline tax increases.

¹³ We use the average price of imported crude oil rather than the more commonly used WTI or Brent crude spot price because the imported price series begins in 1968. Between 1985 and 2008, during which we observe all three series, the correlation coefficient between the imported crude oil price and the WTI and Brent crude oil spot prices is 0.9988 and 0.9989, respectively.

parameter estimates are close to those from the uninstrumented regressions, suggesting that the endogeneity of the tax-exclusive price may not be a serious problem.

To further investigate this issue, we conduct two analyses to examine the effects of omitted variables that may be correlated with state tax rates, tax-exclusive gasoline prices, and gasoline consumption, and may consequently drive a spurious difference between the estimated effects of the tax rate and tax-exclusive gasoline prices. Of particular concern are unobserved trending variables, i.e., omitted demographic trends affecting vehicle ownership or driving intensity that are correlated with the state gasoline tax.

First, we examine a shorter state-level panel where we have available *monthly* gasoline taxes, prices, and consumption from 1983 to 2008. As a further robustness check for omitted variables, we estimate a first-differenced version of (2) using the monthly data. First-differencing the higher frequency data makes it less likely the coefficients will be biased due to omitted variables. An omitted variable must change in the same month as the state excise tax to bias the coefficients of the first-differenced monthly specification. We present the results in Table 7. As a point of comparison, columns 1 and 2 re-create the earlier levels regressions from Table 2 using the shorter monthly panel.¹⁴ The estimated coefficients from the regressions in levels are similar to the earlier estimates using the longer, annual, panel. Columns 3 and 4 regress gasoline consumption on the tax-exclusive price and tax rate, after first-differencing. As in the levels regression, we find a significant difference between the coefficients on tax-exclusive price and the tax rate.

One drawback of using first-differenced monthly data arises if consumers shift consumption in response to anticipated changes in gasoline prices or taxes. In this case, first-differenced gasoline consumption may appear to be more responsive than in our levels regressions. As an additional check, we aggregate the data up to the season before first-differencing in columns 5 and 6. At the seasonal level, intertemporal substitution is unlikely to be a problem. Although the size of both coefficients declines, we continue to find a statistically significant difference between the coefficients on the tax-exclusive price and the tax rate. This suggests that the results in columns 3 and 4 are not being driven entirely by the strategic timing of gasoline purchases around tax changes.

¹⁴ When regressing in levels, we include state fixed effects and time fixed effects. In the first-differenced specification, we only include time fixed effects.

Figure 7 presents further evidence that omitted variables do not bias the estimates. Trends existing prior to gasoline tax changes would suggest the presence of omitted variables bias. The figure plots changes in gasoline consumption over time prior to and following a change in the gasoline tax that occurs between period 0 and period 1. The figure shows that gasoline consumption is stable prior to a tax increase and falls steadily after the increase. Thus, there is no evidence of a pre-existing trend. Gasoline consumption decreases after a tax decrease, but as noted above, there are very few tax decreases in the data.

Finally, we consider the dynamics in the effect of taxes and tax-exclusive prices on gasoline consumption. The specifications in Table 2 assume a log-linear and contemporaneous relationship between the dependent variables and the tax and tax-exclusive price. In the following, we examine potential asymmetric and lagged responses to price changes. There is some evidence in the literature that consumers respond more to gasoline price increases than to decreases. Because there are so few examples of tax decreases in the data (about one per state on average), it is not possible to assess statistically whether there is a differential tax response. It is possible to investigate asymmetric responses to tax-exclusive prices, however, by adding to the main specification the interaction of the tax-exclusive price with a dummy equal to one if the price increased between the previous and current years. If consumers respond more to a price increase than to a decrease, the coefficient would be negative, but in fact the coefficient is positive and statistically significant. The coefficient is quite small, however, and we do not find an economically meaningful difference in the response to tax-exclusive price increases.

Regressions in Table 8 investigate lagged responses by including lags of the tax-exclusive price and the tax. The results show that adding three lags of both variables reduces the point estimates on the current tax and tax-exclusive variables. The coefficients on the lags are larger than the coefficients on the current tax or tax-exclusive price, and are more precisely estimated, which is consistent with the patterns in Figure 7. The hypothesis is rejected at the five percent level that the sum of the current and lagged tax-exclusive coefficients equals those for the gasoline tax variable; the differential effect of gasoline taxes and tax-exclusive prices still exist. Thus, we find that even if we allow for lagged responses to taxes and tax-exclusive prices, we find a larger response to taxes than tax-exclusive prices. This suggests that a differential effect could exist even in long-run responses to gasoline tax and tax-exclusive price changes.

3.5 Explanations

A possible explanation for the larger response to gasoline taxes than tax-exclusive prices lies in the fact that the durable goods nature of automobiles implies that a change in fuel prices

depends on consumer expectations of future fuel costs. If consumers consider tax changes to be more persistent than gasoline price changes due to other factors, a larger response to gasoline taxes than prices could arise through vehicle choice in both the short and long run. Although the short-run response of VMT to gasoline price changes is unlikely to depend on the persistence of price changes, as our analysis suggests, the long-run response to persistent changes could be greater than to less persistent changes because of transaction costs involved in travel mode and intensity decisions (such as setting up carpooling or changing where to live and work).¹⁵

A formal test of this explanation is out of scope of this study. Nevertheless, in the following, we provide some suggestive evidence for its plausibility.

First, to examine the persistence of gasoline taxes and tax-exclusive prices, we conduct AR(1) regressions with these two variables using the state-level panel data and controlling for state and year fixed effects. Using the dynamic panel data approach in Blundell and Bond (1998), we obtain an AR(1) coefficient of 0.925 with a robust standard error of 0.018 for gasoline taxes and 0.775 with a robust standard error of 0.018 for tax-exclusive prices. This suggests that gasoline tax changes are more persistent even after including state and year fixed effects; of course, consumer perceptions of persistence could be different from these estimates, which we discuss further below. To examine what the difference implies in terms of the fuel cost, we calculate the increase in the total *expected* discounted fuel cost during a vehicle lifetime from a 5-cent increase in gasoline tax and tax-exclusive gasoline price in the current period. For an average car with a MPG of 25, assume that the VMT schedule during the lifetime decreases as in Lu (2007), the increase in the total expected discounted fuel cost from a 5-cent increase in current gasoline tax is \$163 under an annual discount rate of 5 percent, compared with \$96 for a 5-cent increase in tax-exclusive price. For an average light-truck with a MPG of 18, the increases in the total expected discounted fuel cost is \$248 and \$147, respectively. The larger difference is due to the lower MPG as well as the larger lifetime VMT for light trucks.

¹⁵ Because of publicity surrounding gasoline tax changes, such changes may be more salient than *equal-sized* changes in tax-exclusive prices (e.g., due to oil price shocks): a 5-cents increase in gasoline taxes could very well receive more attention from the media and consumers than an increase in tax-exclusive price of the same size. As a result, consumers may respond more to a tax increase than a commensurate increase in the tax-exclusive price. Recent empirical studies have shown that consumers are more responsive to salient price or tax changes (Busse, Silva-Risso, and Zettelmeyer (2006), Chetty, Looney, and Kroft (2009), and Finkelstein (2009)). In addition, Finkelstein (2009) finds that the salience of a tax system has a negative impact on equilibrium tax rates in the context of highway tolls. However, because retail gasoline prices are highly visible tax-exclusive price changes are highly visible as well, and salience may only partly explain the differential effects of gasoline taxes and tax-exclusive prices.

Based on survey data from 1993 to 2009 from the Michigan Survey of Consumers, Anderson, Kellogg and Sallee (2012) find that, on average, consumers assume that the expected future prices equals the current price. Nevertheless, this finding does not dismiss the persistence explanation for the following three reasons. First, their analysis is on overall gasoline prices and their finding does not rule out differential consumer beliefs for the two price components. Second, they document considerable cross-sectional heterogeneity in consumer beliefs. The degree of heterogeneity increases with gasoline prices, which suggests that some consumers do not expect gasoline price changes (and possibly tax-exclusive price changes) to be fully persistent. Third, they find the characteristics of consumer beliefs differ over time: they deviate substantially from a no-change forecast after the financial crisis hit in 2008. Our data period is from 1966 to 2008 and includes several episodes of economic downturns and volatile gasoline prices.

Our second piece of suggestive evidence is that if the explanation is true, consumers should respond more to tax changes in states that change their taxes infrequently. We use several alternatives to equation (2) to investigate this implication and we find supporting evidence. We calculate the number of times the state changes its tax from 1966-2008. Column 1 of Table 9 adds to the main specification the interaction of the tax variable with the number of times the state changes its tax. The coefficient on the tax variable is -0.41 (instead of -0.29 in the baseline). The coefficient on the interaction term is positive and statistically significant at about the 5 percent level. This suggests that the tax elasticity is smaller (in magnitude) for states that change their taxes more frequently and vice versa. In column 2, states are assigned quintiles based on the number of tax changes. Defining higher quintiles as states that change taxes more often, we expect smaller coefficients (in magnitude) for higher quintiles. The pattern holds, although the differences are not statistically significant.

The first two columns in Table 9 use the total number of tax changes over the entire sample. For some states there are time periods in which taxes change frequently and other periods when taxes change infrequently. Consequently, the total number of changes may not accurately reflect consumer perceptions about the persistence of taxes throughout the sample in some states. To address this possibility, columns 3-5 add the interactions of the tax variable with the number of tax changes during the past 15, 10 and 5 years. Column 6 uses the number of years since the last change. The elasticity of gasoline consumption to the gasoline tax tends to be smaller in magnitude for states that have frequently or recently changed their taxes, although the difference is only statistically significant in column 6 (the smaller sample sizes in the other columns may make it difficult to identify the difference, particularly in column 3).

4. Household Data Analysis

Vehicle purchase and driving constitute the extensive and intensive margins through which the gasoline price affects gasoline demand.¹⁶ The purpose of this section is to further examine how the gasoline tax and tax-exclusive gasoline prices affect the two margins. We conduct analysis on household vehicle purchase and travel using the 1995, 2001, and 2009 National Household Travel Survey (NHTS). The NHTS, conducted by agencies of the Department of Transportation through random sampling, provides detailed household-level data on vehicle stocks, travel behavior, and household demographics at the time of survey.

4.1 Empirical Methodology

We employ a similar empirical strategy to the one used to examine the aggregate data, but exploit the richer set of demographics and geographic characteristics present in the household-level data. For the analysis on vehicle fuel economy, we focus on households who purchased at least one vehicle (new or used) during the past 12 months. In the survey, the purchase time (year and month) is available for the recently purchased vehicles. For these households, it is possible to match the vehicle MPG and the gasoline price in the purchase month and the preceding months. We estimate the following equation to examine how gasoline prices affect vehicle purchases:

$$\ln(MPG_i) = \alpha_m \ln(p_i) + \beta_m \ln\left(1 + \frac{\tau_i}{p_i}\right) + X_i \theta_m + e_i \quad (5)$$

where i denotes a household. MPG_i is the average MPG of all the new and used vehicles (cars and light trucks) purchased during the past 12 months by household i . The key explanatory variables include the tax-exclusive gasoline price and the tax ratio. Importantly, the tax and price correspond to the household's state and the quarter of purchase. We include a large set of household demographics. We use quadratic functions for the non-categorical variables: household size, the age of the reference person, the number of adults, the number of workers and the number of drivers in each household. We include full sets of fixed effects for the categorical variables: household income, education of the reference person, MSA size, worker density by census tract, population density by census tract, rail availability, and urban and rural indicator variables. We also include fixed effects for year, month, and location (census division or state).

¹⁶ Vehicle scrappage is part of the extensive margin but is not examined in this paper due to data limitations.

To examine the effect of the tax-exclusive gasoline price and the gasoline tax on household travel behavior, we estimate the following equation:

$$\ln(VMT_i) = \alpha_v \ln(p_i) + \beta_v \ln\left(1 + \frac{\tau_i}{p_i}\right) + X_i \theta_v + e_i \quad (6)$$

where VMT_i is the daily total VMT across all vehicles belonging to household i . The VMT equation includes the same set of variables as the MPG equation with the exception of month dummies, which are constructed to match the travel period.

4.2 Sources

Household data from the NHTS provide detailed demographic characteristics about each household. Each household is categorized into one of eighteen income bins and eight education bins. The data include the number and age of adults and the numbers of workers and drivers in the household. In addition, the data provide detailed information about neighborhood (census tract) demographics such as rural and urban indicators, population, working population, housing density, and the availability of rail. Consequently, the NHTS data provide a detailed set of controls for characteristics that may vary with both a state's tax rate and the household's driving or purchase decisions.

For the MPG analysis, we use the 1995, 2001, and 2009 NHTS. The data include the make and model of the household's vehicles, which we match to the EPA fuel economy database to obtain MPG for each vehicle. Gasoline prices at the time of purchase are based on the gasoline prices used in the aggregate analysis. Because purchases of newer vehicles may respond more to price changes than purchases of older vehicles, our analysis is conducted on two separate samples. The first sample, with 52,128 observations includes households who purchased at least one used or new vehicle during the 12 months prior to the survey. The second sample focuses on newer vehicles. It has 30,363 households who purchased at least one vehicle during the past 12 months and all the vehicles purchased are less than four years old. Table 10 provides summary statistics for the two samples. The average MPG of vehicles in the two samples is almost the same and other variables are quite close as well. The households in sample 2 (those who purchased newer vehicles) have slightly smaller household size, higher income and more education.

We use a subset of the NHTS data to examine VMT. During the 1995 and 2001 installments, participants received an initial survey followed by a second survey several months later. In both, participants were asked to report odometer readings of all of their vehicles. We calculate daily VMT per vehicle across vehicles owned by a household by comparing the two

odometer readings for each vehicle. We also construct the average gasoline price during the odometer reading period based on the date of the odometer readings and weekly state gasoline prices. Unfortunately, not all survey participants report the second odometer reading and there are many missing values for the first odometer reading. We drop approximately two-thirds of the households in the 1995 and 2001 survey waves that have missing data for either of the two odometer readings for any of the vehicles owned by the household. The final VMT data set contains 28,303 observations. Table 11 reports summary statistics under sample 1.

To our knowledge, whereas the previous literature has used self-reported annual VMT, this is the first use of VMT data based on two odometer readings from the NHTS. We compare the results using odometer-based VMT with the results using self-reported annual VMT. The data set with self-reported annual VMT is larger and contains 61,795 observations. Table 11 reports summary statistics for the self-reported sample under sample 2.

To compare daily VMT based on the two types of VMT estimates, we use 24,528 households with both values. The (weighted) average daily VMT based on odometer readings is 49.9 with a standard deviation of 35.3, while the average self-reported daily VMT is 50.1 with a standard deviation of 45.4. The top graph in Figure 8 plots Kernel densities of the two VMT measures; the distributions of the two variables are quite similar. Nevertheless, the comparison of the two distributions masks the differences that exist for a given observation. We find that although the means of the two variables are quite close, the difference between the two measures (for a given household) can be quite large: the mean difference is 0.2 but the standard deviation is 38.5.

To further understand the difference, we compare the two VMT measures for two subsamples that are defined according to whether the odometer-based VMT is above or below the sample mean of 49.9 (which we refer to as high and low VMT households). The average daily odometer-based VMT for the two subsamples is 83.0 and 26.0, while the average self-reported daily VMT is 74.7 and 32.3 for the two subsamples. The middle graph in Figure 8 plots the kernel densities of the difference between the odometer-based and self-reported VMT for the high and low VMT subsamples separately, with vertical lines indicating the sample averages. Households who travel more tend to under-report their travel intensity, and those who travel less tend to over-report.

Given that two odometer readings could happen any time (2-6 months apart in general) during the year, part of the differences could be caused by seasonality in driving. To check if this is driven by seasonality, we compare the two measures month by month and find that the pattern still holds in each of the 12 months (see the bottom graph in Figure 8). To the extent that

gasoline prices are negatively correlated with travel, this finding implies that using self-reported VMT in the regression analysis could attenuate the effect of gasoline prices on travel demand.

Because the observations used for our VMT analysis only constitute about one-third of the full sample, it is important to know how representative the estimation sample is. Table 12 compares the characteristics of the subsample of participants who report two odometer readings with the characteristics of the full 1995 and 2001 samples. We find that the mean tax-exclusive price and gasoline taxes for the VMT subsample and full sample compare quite closely. Households in the estimation sample are slightly older (mean age 50.66 vs. 49.59) and less likely to live in an MSA with a subway system (14 percent vs. 16 percent). Overall, however, the mean and the 10th and 90th percentiles of the variables are quite similar for the full sample and the estimation sample. Figures 9 and 10 show the distributions of the categorical variables for both samples. Similarly to the other variables, the distributions for these variables are very similar for the full NHTS and the estimation samples. These comparisons suggest that the estimation sample may be representative of the full NHTS sample, but we treat the estimation results with caution.

The empirical strategy for gasoline consumption and VMT uses cross-state and time-series variation in the tax-exclusive prices and gasoline taxes. An important concern is that the tax-exclusive prices, taxes, and the dependent variables may be correlated with omitted variables. To investigate this possibility, we examine whether gasoline taxes and tax-exclusive prices are correlated with the independent variables. In particular, we separate states according to whether they have high gasoline taxes or tax-exclusive prices. Across the samples, we compare the means and the 10th and 90th percentiles of the independent variables. In general, we find that the distributions are quite similar, which is consistent with the assumed exogeneity of tax-exclusive prices and taxes.

4.3 Results

Table 13 reports key parameter estimates and elasticities for 12 regressions, examining how gasoline prices and taxes affect the fuel economy of recently purchased vehicles. Panel A shows six regressions of the effect of the tax-inclusive gasoline price on average MPG of recently purchased vehicles. Columns 1 to 3 use sample 1 (all households), and columns 4 to 6 use sample 2 (households purchasing newer vehicles).

Columns 1 to 3 differ according to whether census division dummies or state dummies are included. The parameter estimates are very similar and are statistically significant. The elasticity of MPG with respect to the tax-inclusive gasoline price is 0.065 in the preferred specification, which includes state dummies. The elasticity estimates from sample 2 (presented in

columns 4 to 6) are similar across the three specifications, and they are only slightly larger than their counterparts from sample 1. The elasticity estimates are close to those in several recent studies: mall and Van Dender (2007) estimate a short-run elasticity of 0.044; Gillingham (2010) finds a medium-run (2-year) fuel economy elasticity of 0.09; Klier and Linn (2010) estimate an elasticity of about 0.12 using monthly data.

Panel B shows regressions that separate the gasoline tax from the tax-exclusive gasoline price; columns are analogous to those in Panel A. Columns 1 to 3 shows that the gasoline tax has a larger effect than the tax-exclusive gasoline price. The difference between the semi-elasticities for the tax and tax-exclusive price is 0.68 percent and statistically significant in column 3 when state dummies are included. The difference between the semi-elasticities is stronger for newer vehicles: it is one percent in column 6. This comparison is intuitive: if the differential effect is driven by the durable good nature of automobiles, we would expect a stronger effect among newer vehicles that have a longer remaining lifetime.¹⁷ Supporting this hypothesis, Busse, Knittel, and Zettelmeyer (2009) find that the adjustment in the new vehicle market to gasoline price changes is primarily in market shares, while it is primarily in vehicle prices in the used vehicle market.

The gasoline prices are matched to the month of vehicle purchase in the specifications presented above. We also estimate the same regressions using the 3-month or 12-month averages of the gasoline price and tax (including the purchase month and months prior to purchase). The results (not reported) are very similar to those in Table 13, but the parameter estimates are less precise. This may reflect the fact that the average gasoline price is a noisier predictor of the expected future gasoline prices.

For the VMT analysis, Table 14 presents key parameter estimates, VMT elasticities, and semi-elasticities. The six regressions in Panel A include total gasoline prices on the right side, while those in Panel B separate tax-exclusive prices from gasoline taxes. The dependent variable in columns 1 to 3 is the log of household daily odometer-based VMT (sample 1), and that in columns 4 to 6 is the log of self-reported VMT (sample 2).

The VMT elasticity with respect to gasoline prices from sample 1 ranges from -0.33 to -0.50 in the three specifications. The preferred specification in column 3 with state dummies provides an estimate of -0.39. When separating gasoline taxes from tax-exclusive gasoline prices

¹⁷ We also run regressions using older vehicles (age four or older) and we cannot reject the hypothesis of no differential effects from gasoline tax and tax-exclusive price.

in Panel B, the VMT elasticity with respect to gasoline taxes is not statistically significantly different in the second and third specifications. This could reflect more limited variations in gasoline taxes changes than for the MPG analysis in the previous section (recall that the VMT analysis only uses the 1995 and 2001 NHTS because the second odometer readings were not collected in the 2009 survey). In all specifications, the percent changes in VMT from a 5-cent gasoline tax increase are larger than those from changes in tax-exclusive gasoline prices of the same magnitude. However, none of the differences are statistically significant.

We conduct the same analysis in columns 4 to 6 based on self-reported VMT. We use average gasoline prices over the same period as VMT reporting. The VMT elasticity to gasoline prices is -0.27 from column 4, while it is smaller in magnitude and statistically insignificant in columns 5 and 6. The regressions in the second panel separate the gasoline tax from the tax-exclusive gasoline price. There are no statistically significant differential effects on VMT from the tax-exclusive gasoline price and gasoline tax. Nevertheless, when state dummies are included, the difference in the VMT effect is quite large in magnitude with equally large standard errors. We conduct additional regressions using self-reported VMT data based on a larger sample that also includes data from the 2009 NHTS. The findings, not reported here, are qualitatively the same. The difficulty in obtaining precise estimates of the VMT responses to gasoline price changes is common in studies using household-level survey data. Based on Consumer Expenditure Survey from 1984-1990, Goldberg (1998) reports imprecise and large estimates of the effects of gasoline price on quarterly VMT in a unified model of vehicle demand and utilization.

Although we find that vehicle purchase decisions (as reflected in average MPG) respond more strongly to gasoline tax changes than commensurate tax-exclusive price changes, there is no statistically significant evidence of a differential effect for VMT. This contrast could be viewed from two rather different angles. First, the limited variations in gasoline taxes in the VMT analysis could prevent us from precisely estimating a differential effect. Second, the findings could reflect different natures of MPG and VMT decisions. As discussed above, if consumers view gasoline tax changes as more persistent than changes in other components of gasoline prices, their vehicle purchase decisions could react more strongly to gasoline tax changes due to the durable good nature of automobiles. Regarding VMT, although gasoline prices could affect consumers' day-to-day travel decisions, the underlying cause of price changes

(e.g., whether they are from gasoline tax changes or oil price shocks) should not matter for their travel decisions (e.g., how to go to work) in the short run.¹⁸

5. Implications

Our central and robust finding of differential responses to gasoline taxes and tax-exclusive prices has important implications for the effectiveness of using gasoline taxes to address climate change, air pollution, and energy security. In particular, gasoline taxes would be more effective at reducing gasoline consumption than suggested by previous empirical estimates of the effect of gasoline price changes on gasoline consumption. The results also have implications for the implicit discount rate and the tax revenue from gasoline taxes, which we discuss in this section.

5.1 Implicit Discount Rate

Our analysis points to an empirical strategy to deal with a challenging identification problem in estimating implicit discount rates in consumer decisions. To understand this, consider consumers' vehicle purchase decisions when facing an array of choices that have different upfront costs (i.e., purchase price), future operating costs (e.g., fuel costs), and other vehicle characteristics. Due to the durable good nature of automobiles, a rational consumer makes the decision based on total (discounted) expected costs and total (discounted) utility to be derived from the vehicle. To examine how consumers trade upfront purchase costs with future operating costs, researchers often estimate the implicit discount rate in a vehicle demand or hedonic framework.

A high discount rate is interpreted as evidence that consumers fail to properly consider future costs. The undervaluation of future fuel cost savings is a manifestation of the “energy paradox”. If present, it could hinder the effectiveness of gasoline taxes and hence lend support for CAFE standards. Whether, and to what extent, the energy paradox holds in the automobile sector is still a contentious empirical issue.¹⁹ This is partly due to the identification challenge researchers face in the empirical analysis because neither consumers' discount rates nor their

¹⁸ In the long run, because of adjustment costs tax changes could have a larger effect than changes in tax-exclusive prices on consumer location decisions (and, hence, travel distance and possibly travel mode). The long-run response remains an open question.

¹⁹ Allcott and Wozny (2010) and Sallee, West and Fan (2010) are among recent studies using very rich data sets to investigate this issue. Helfand and Wolverton (2010) offers a recent review.

expectation of future gasoline prices is observed. Consequently, it is not possible to estimate implicit discount rates without making assumptions on consumer expectations of future gasoline prices.

In the following, we use a canonical vehicle demand model to illustrate how separating gasoline taxes from tax-exclusive gasoline prices can aid the identification of the implicit discount rate. The central argument is that consumers treat taxes as more persistent than tax-exclusive prices, which is consistent with the results and the estimates of the AR(1) specification described in section 3.5.

The vehicle demand model is a linear model that can be estimated using market-level sales data. This model can be derived from a multinomial logit model:

$$\ln(s_j / s_0) = \alpha c_j + X_j \beta + e_j, \quad (7)$$

where j is the index for a model (e.g., a 1999 Toyota Camry) and 0 indexes the choice of not purchasing a new vehicle (denoted as the outside good). s_j is the market share of model j . c_j is the total expected cost during the vehicle's lifetime. X_j is a vector of vehicle attributes that capture consumer utility from the vehicle. The present value of the total expected cost of owning vehicle j is equal to:

$$c_j = vp_j + \sum_{t=1}^T \frac{1}{(1+r)^t} \frac{p_t^e VMT_t}{MPG_j} = vp_j + \sum_{t=1}^T \frac{1}{(1+r)^t} \frac{(\tau_t^e + ep_t^e) VMT_t}{MPG_j}, \quad (8)$$

where vp_j is the vehicle price. T is the vehicle's lifetime and r is the discount rate. p_t^e is the expected gasoline price at year t , which is the sum of the expected gasoline tax (τ) and tax-exclusive gasoline price (ep). In order to estimate parameters in equation (7), one needs to make assumptions on the discount rate and expected future gasoline prices. If consumers view the gasoline tax as being (more) permanent in nature, the identification of the implicit discount rate is possible by assuming $\tau_t^e = \tau$, without making an assumption on future tax-exclusive gasoline prices ep_t^e .

Decomposing c_j into tax and tax-exclusive components, equation 7 can be written as the following:

$$\begin{aligned} \ln(s_j / s_0) &= \alpha \left[vp_j + \frac{\tau}{MPG_j} \sum_{t=1}^T \frac{VMT_t}{(1+r)^t} + \frac{ep}{MPG_j} \sum_{t=1}^T \frac{VMT_t ep_t^e}{(1+r)^t ep} \right] + X_j \beta + e_j \\ &= \alpha vp_j + \gamma_1 \frac{\tau}{MPG_j} + \gamma_2 \frac{ep}{MPG_j} + X_j \beta + e_j \end{aligned} \quad (9)$$

where γ_1 is equal to $\alpha \sum_{t=1}^T \frac{VMT_t}{(1+r)^t}$ assuming that the VMT profile is the same across vehicles.

$\frac{\tau}{MPG_j}$ is tax dollars per mile for vehicle j and $\frac{ep}{MPG_j}$ is the tax-exclusive dollars per mile, both

of which can be easily constructed from available data. Equation (9) can be estimated in a linear framework. With estimates for α and γ_1 , we can recover the implicit discount rate with a given VMT profile over the vehicle's lifetime. Relaxing the assumption of vehicle-invariant VMT profile is straightforward and would entail nonlinear estimation to recover the implicit discount rate simultaneously with other model parameters.

We estimate the above model using sales data at the vehicle model level in 22 MSAs from 1999 to 2006 (Li, Timmins, and von Haefen 2009). To save space, we do not report the full results and they are available upon request. In the estimation, we control for vehicle price endogeneity using product characteristics of other vehicle models produced by the same firm and other firms, which are standard instruments in the vehicle demand literature (Berry, Levinsohn and Pakes 1995). To control for possible endogeneity of gasoline prices, we use similar instruments as in the state-level analysis: the crude oil price interacted with gasoline prices prior to the sample period.

When using overall gasoline prices to identify the discount rate by assuming a random walk process, the estimates suggest a large implied discount rate (0.42), implying significant undervaluation of future fuel costs. When estimating the model by separating gasoline taxes from tax-exclusive prices, we find that vehicle choices are more responsive to gasoline taxes, consistent with our findings in the household analysis. The parameter estimates imply a much smaller discount rates (0.11), which is more in line with market interest rates (e.g., for auto financing). A more flexible demand model (e.g., taking into account consumer heterogeneity) would be desired for a full evaluation of the implicit discount rate and is left for future work. Our purpose here is to illustrate the point that consumers' differential responses to gasoline taxes and tax-exclusive prices can be exploited to identify the implicit discount rate.

5.2 Tax Elasticity of Tax Revenues

Finally, our approach may have implications for fiscal policy related to gasoline taxes. As an illustration, we calculate the change in tax revenues associated with a 5 cent-per-gallon increase in federal gasoline taxes based on (1) a naive estimate using the tax-inclusive semi-elasticity in column 1 of Table 3; and (2) the corresponding tax semi-elasticity estimate from column 2 of Table 3. The naive estimate would imply that a 5 cent-per-gallon increase in state

gasoline taxes would increase tax revenues approximately 12.4 percent in 2008. This corresponds to tax revenue of about \$4 billion, which is about one-quarter of the deficit for the Highway Trust Fund forecasted by the Congressional Budget Office. Using the separately estimated tax and price coefficients, a 5 cent-per-gallon tax increase would raise tax revenue by 11.2 percent. Interestingly, the naive prediction does not substantially overestimate the implied increase in tax revenues associated with a gasoline tax increase. Gasoline demand is sufficiently inelastic and gasoline taxes are sufficiently far from the revenue maximizing level so as to make the distinction between techniques less relevant for fiscal policy.²⁰

6. Conclusion

Despite multiple policy goals that the gasoline tax can help to achieve, the United States taxes gasoline at the lowest rate among industrialized countries. In 2009, average state and federal gasoline taxes were 46 cents per gallon, compared to \$3.40 per gallon in the United Kingdom. Heightened environmental and energy concerns, a record national budget deficit, and an insolvent Highway Trust Fund have renewed interest in raising the gasoline tax in the United States. Estimates of the effects of higher gasoline taxes often rely on the estimated gasoline demand elasticity with respect to *gasoline taxes*, with an implicit assumption that the consumer response to a gasoline tax change is the same as to a commensurate change in tax-exclusive gasoline prices.

This paper investigates this underlying assumption by separately estimating consumer responses to gasoline taxes and the tax-exclusive gasoline price. We examine the short-run impacts of changes in these two components on gasoline consumption, vehicle miles traveled, and vehicle choices using both state-level and household-level data. We find strong and robust evidence that gasoline tax changes are associated with larger changes in gasoline consumption and vehicle choices than are commensurate changes in the tax-exclusive gasoline price.

The finding that not all variations in gasoline prices are created equal has important implications for transportation and tax policies. First and foremost, our work indicates that fuel

²⁰ The calculations in the text are based on estimates obtained using the full sample and applied to tax rates and prices in the final year of the sample. Alternatively, we can estimate separate coefficients on the tax-exclusive and tax variables for each five-year time period, and perform the calculations using the coefficient estimates from the most recent time period. Using these estimates, a 5 cent-per-gallon increase in state gasoline taxes raises revenue 12.2 percent under the naive estimate, and 10.5 percent using the separately estimated tax coefficient.

taxes may be a more effective measure of reducing gasoline consumption or inducing consumers to adopt more fuel efficient vehicles than previously thought. Second, our research shows that gasoline tax changes could provide a useful means of identifying the implied discount rate and to quantify the extent of an energy paradox in automobile demand. Third, our estimates suggest that traditional analysis on gasoline taxes may slightly overestimate the fiscal benefits of a gasoline tax.

Our research points to three questions that warrant further investigation. First, recent studies have estimated that the optimal gasoline tax in the United States is more than twice as large as the current level (Parry and Small, 2005, and West and Williams, 2007). These studies employ the long-run consumer response to gasoline prices as one of the key inputs for analysis. Our analysis provides evidence of a differential effect of lagged price changes. Nevertheless, the precise long-run estimates and their implications for the optimal gasoline tax are unknown. Second, we conjecture that the greater persistence of tax changes may explain the main results. Further work is needed to assess the importance of these factors and investigate others. Perhaps most importantly is the question of generality. Our finding suggests that it may be important to consider the source of the price variation when estimating price elasticities of demand and conducting policy analysis for other goods and services.

7. References

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Figures and Tables

See following pages.

Figure 1: Gasoline Price Decomposition

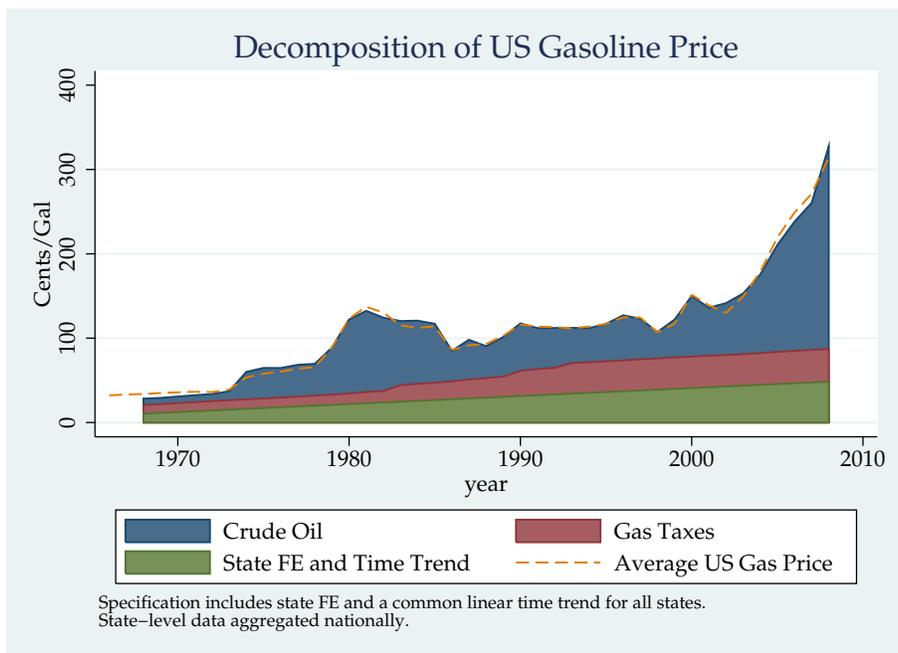
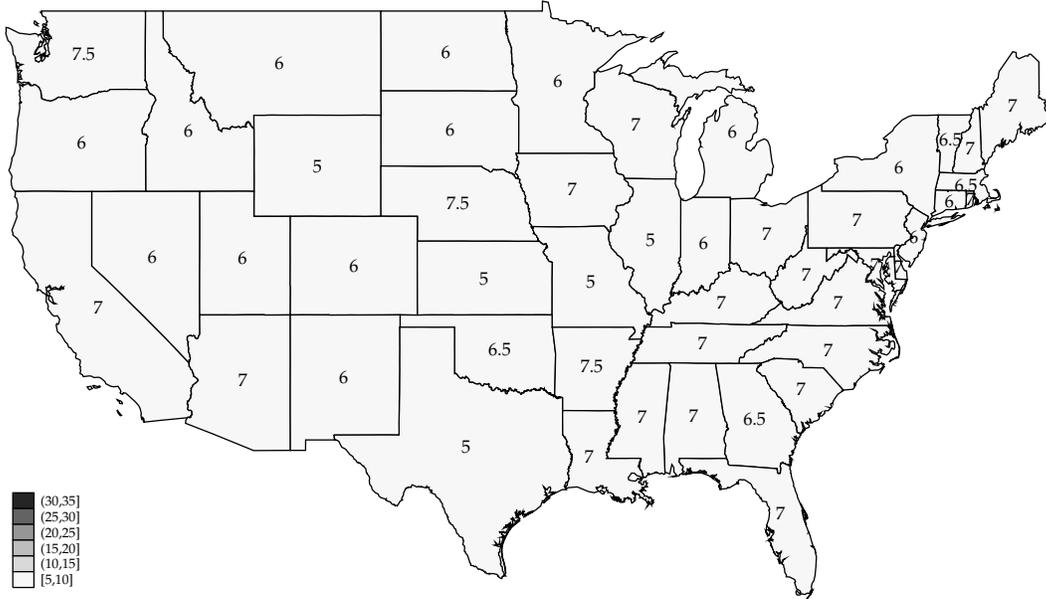


Figure 2: State Gasoline Tax Rates

State Gasoline Taxes (cpg), 1966



State Gasoline Taxes (cpg), 2006

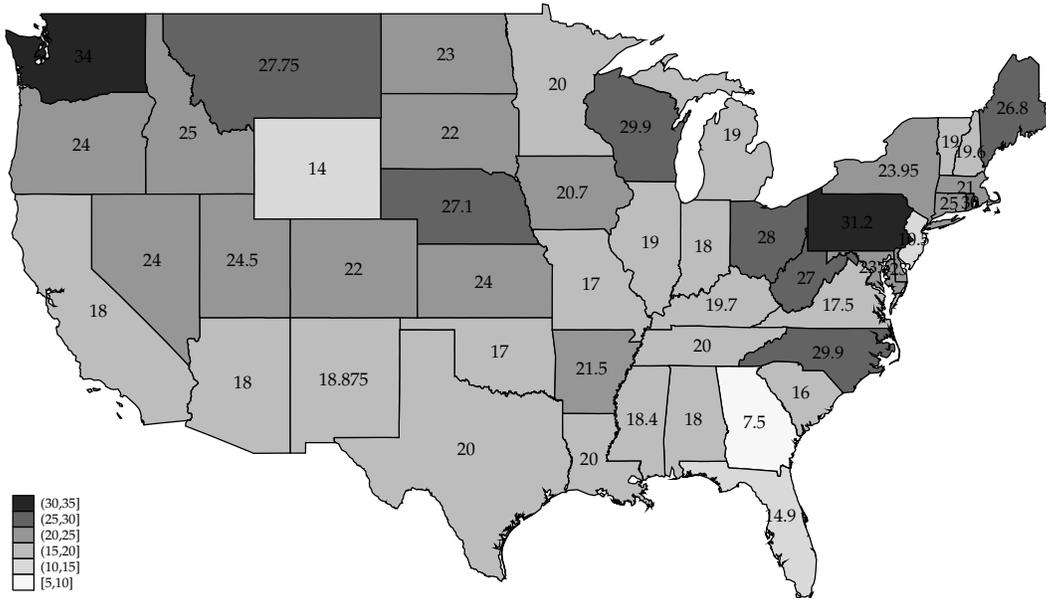
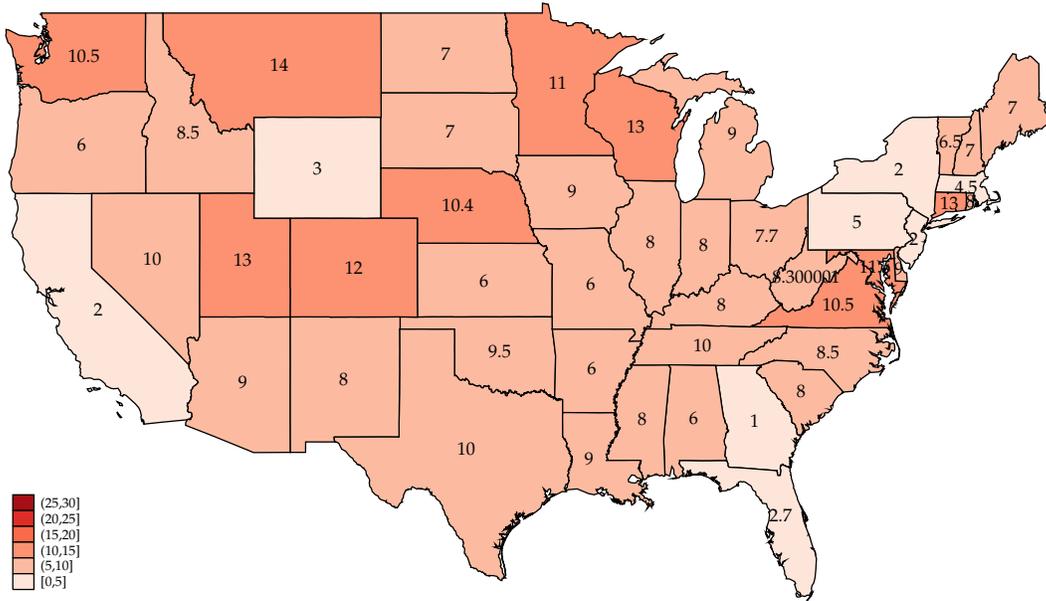


Figure 3: State Gasoline Tax Rates

State Tax Increase, 1966 to 1987 (cpg),



State Tax Increase, 1987 to 2008 (cpg),

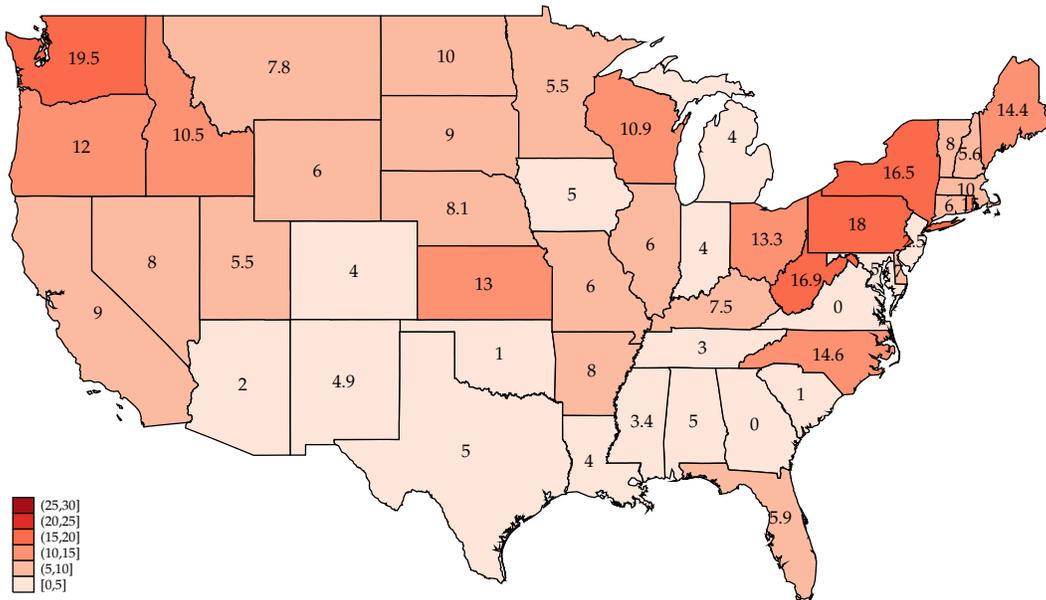


Figure 4: Distribution of Gasoline Taxes, by year

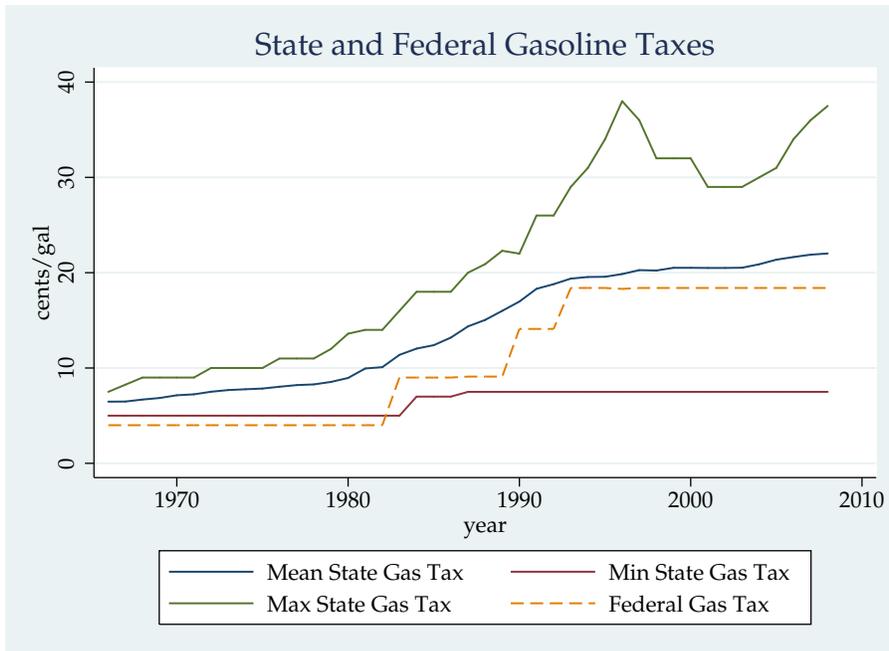


Figure 5: Tax Fraction of Retail Price, by year

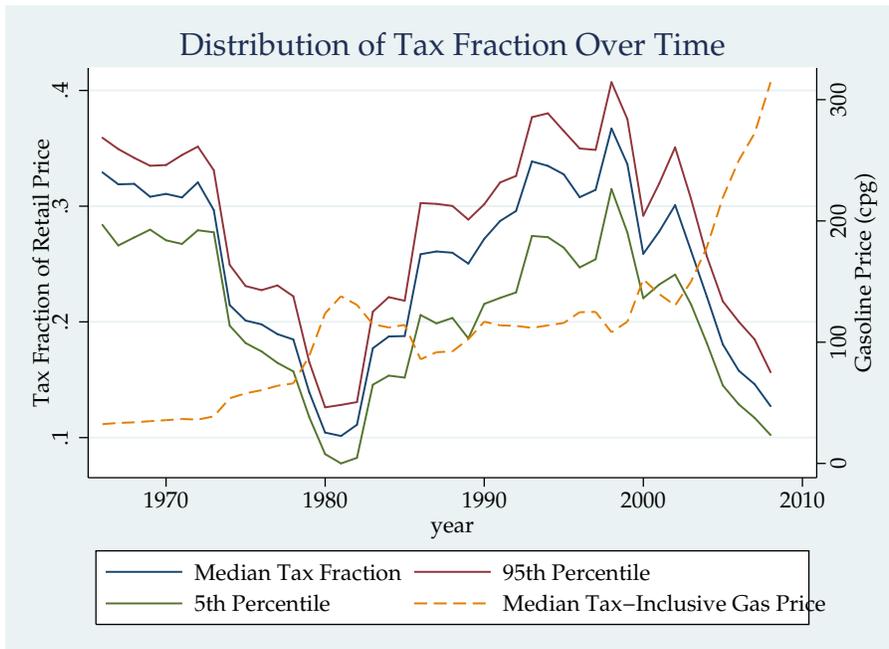


Figure 6: Differences between the Effects from a 5-cent Increase in Gasoline Taxes and Tax-exclusive Prices and 95% Confidence Band

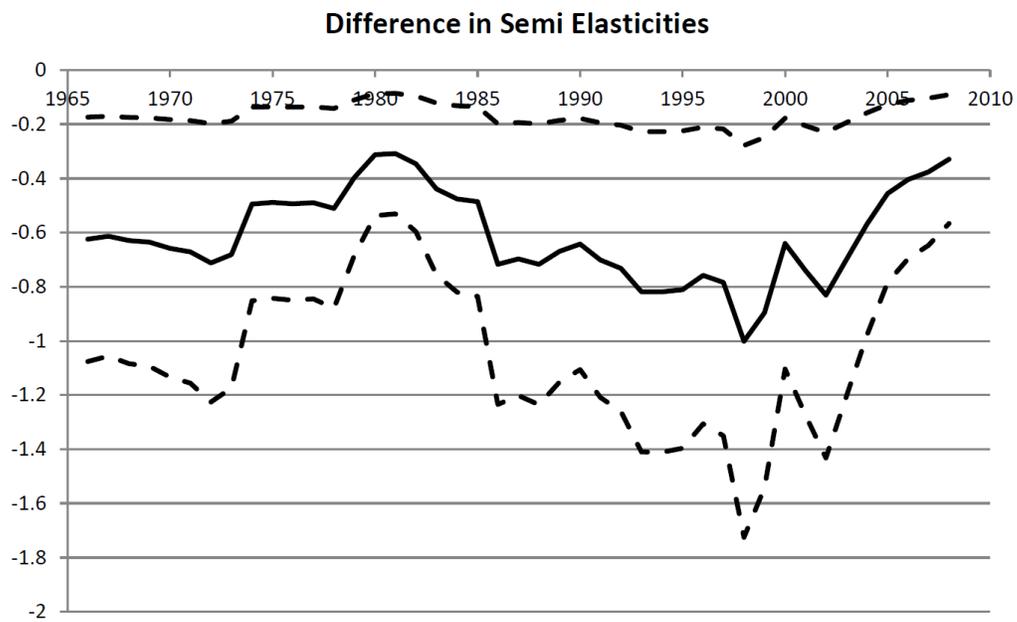


Figure 7: Change in Gas Consumption, pre- and post-tax change

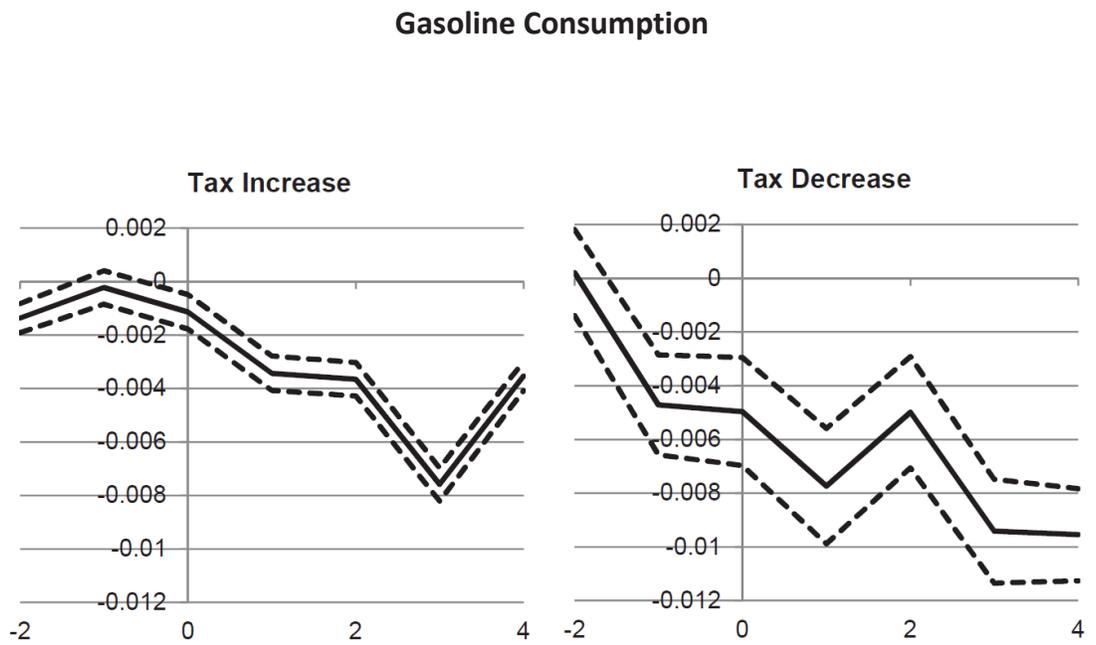


Figure 8: Densities of Daily VMT from Odometer Readings and Self-reported Annual VMT

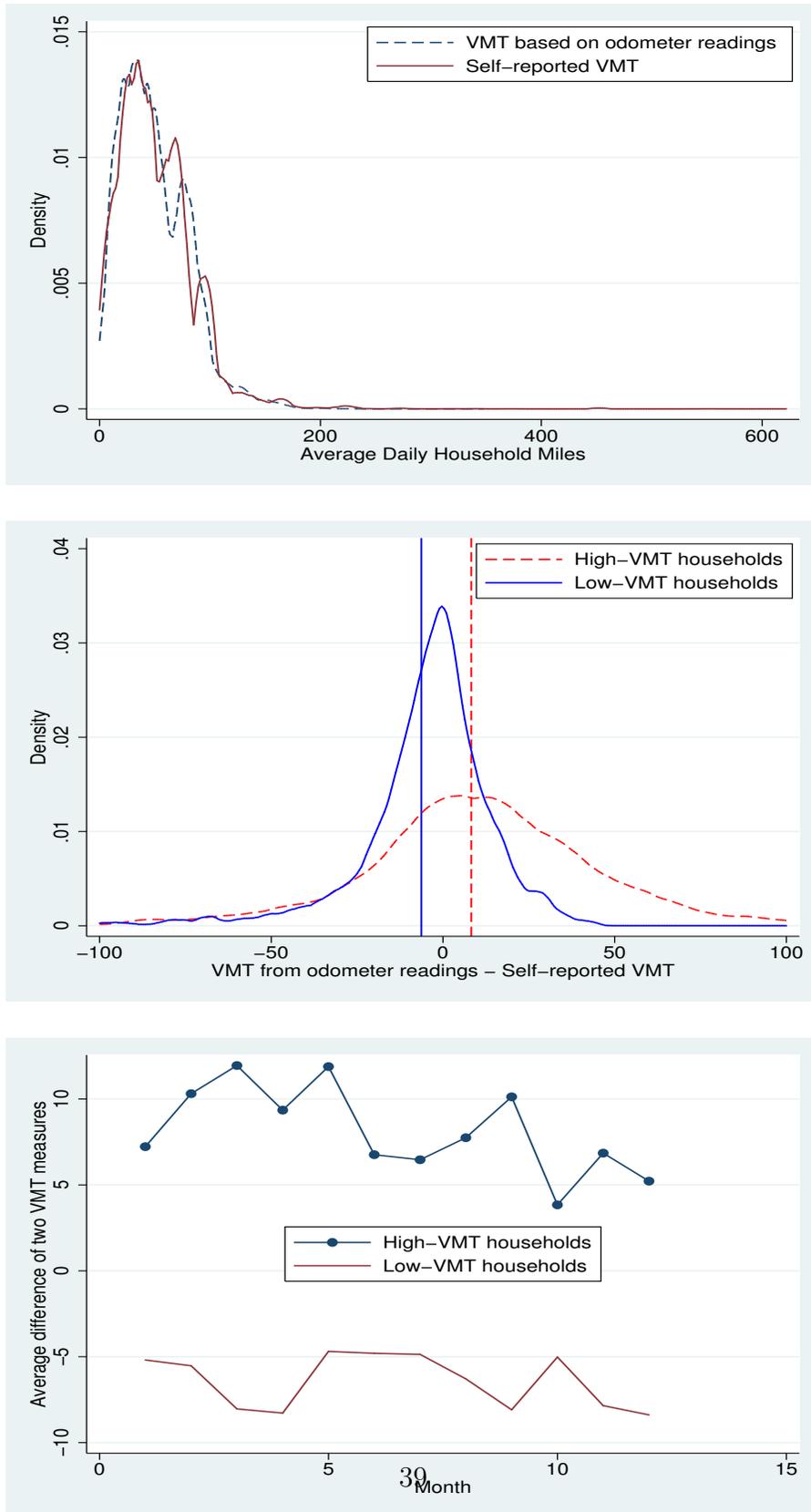


Figure 9: Summary Statistics for NHTS Categorical Variables

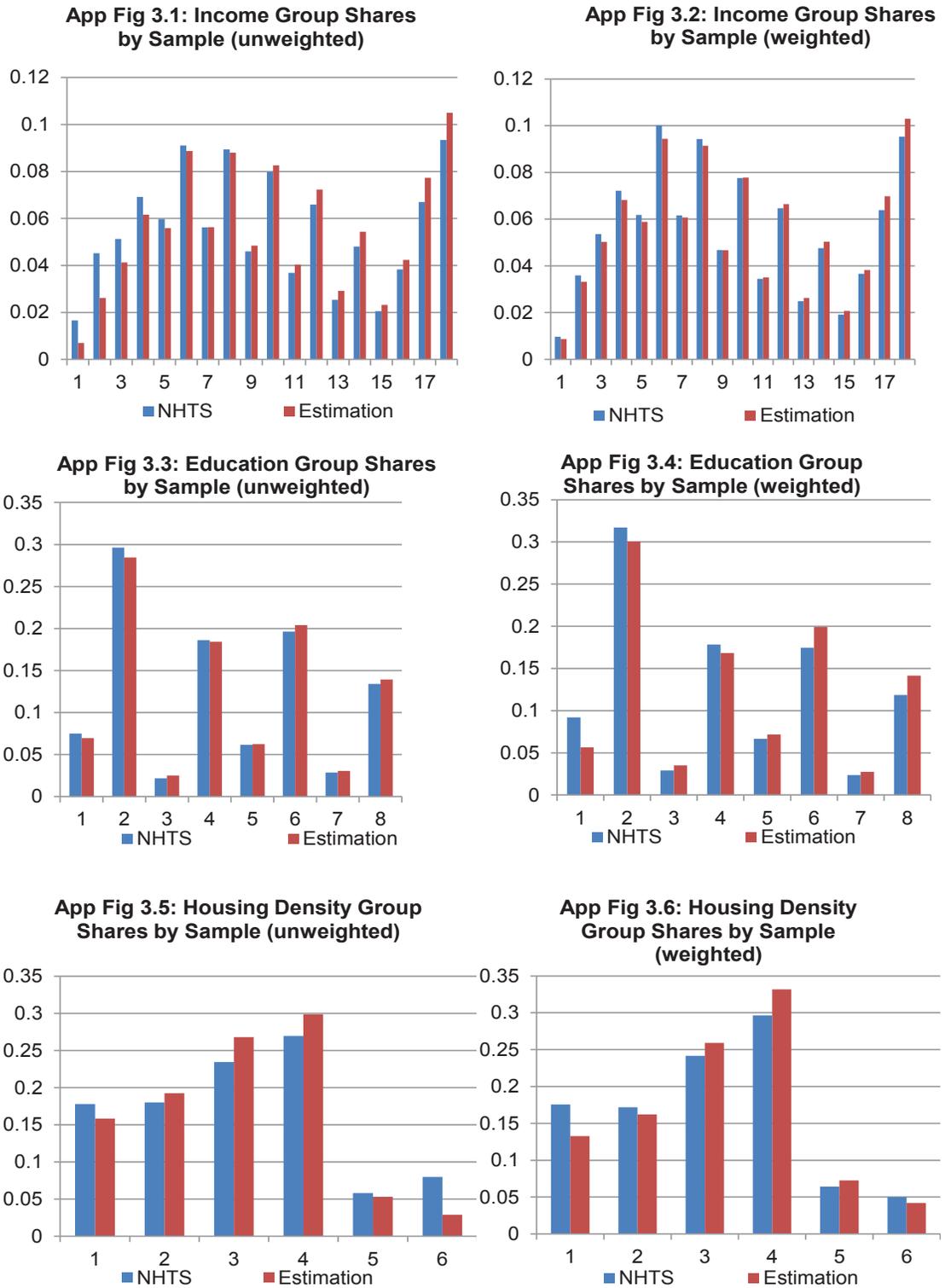
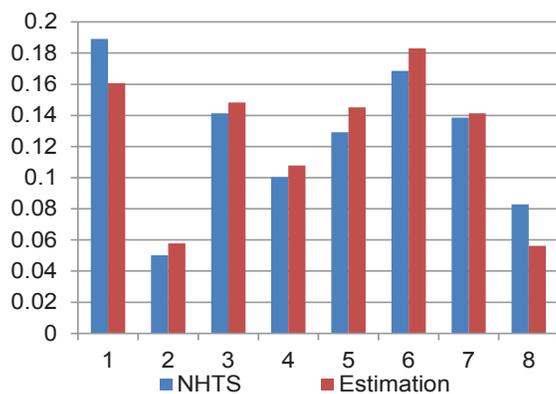
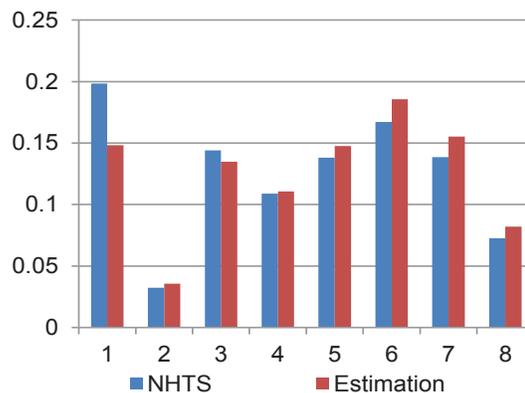


Figure 10: Summary Statistics for NHTS Categorical Variables (Cont.)

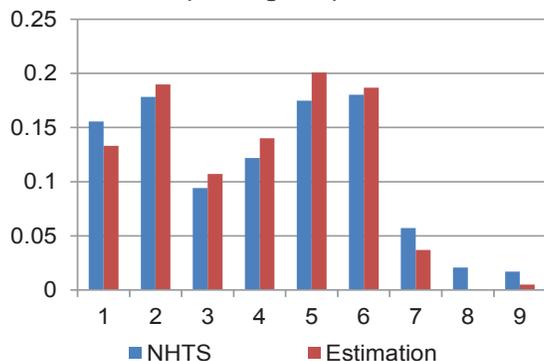
App Fig 3.7: Worker Density Group Shares by Sample (unweighted)



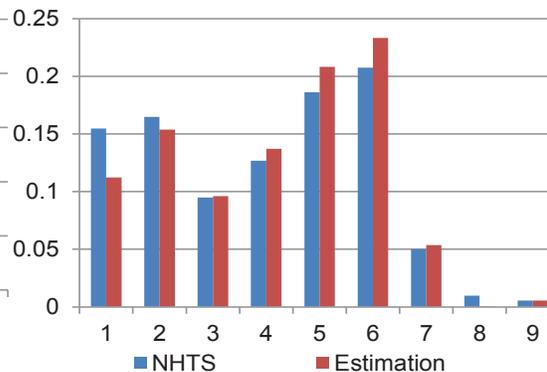
App Fig 3.8: Worker Density Group Shares by Sample (weighted)



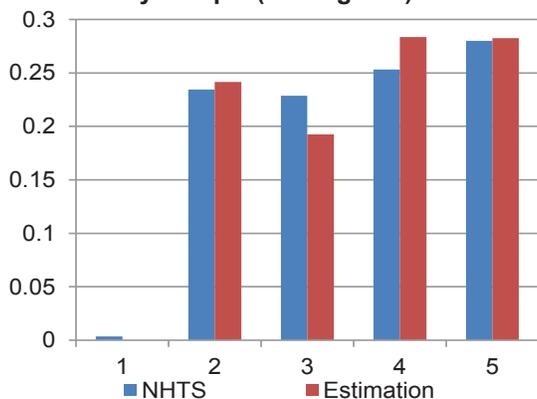
App Fig 3.9: Population Density Group Shares by Sample (unweighted)



App Fig 3.10: Population Density Group Share by Sample (weighted)



App Fig 3.11: Urban Group Share by Sample (unweighted)



App Fig 3.12: Urban Group Share by Sample (weighted)

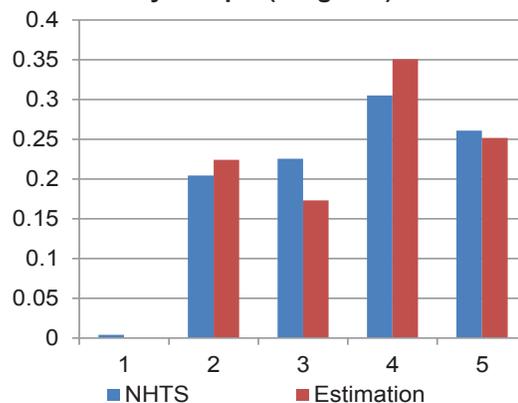


Table 1: Nominal Prices and Taxes (cpg), over time

Period	Average Tax-Inclusive Retail Price	Average State Tax	Average Federal Tax	Tax Fraction of Retail Gasoline Price	Percent of Retail Gas Variation Explained by Tax Changes
1966 - 1970	34.0	6.7	4.0	31.5%	48.3%
1971 - 1975	44.6	7.6	4.0	26.0%	2.3%
1976 - 1980	80.4	8.4	4.0	15.4%	2.1%
1981 - 1985	121.8	11.2	7.0	14.9%	19.3%
1986 - 1990	98.0	15.1	10.1	25.7%	11.4%
1991 - 1995	113.9	19.1	16.7	31.4%	25.5%
1996 - 2000	125.0	20.3	18.4	30.9%	2.2%
2001 - 2005	163.3	20.8	18.4	24.0%	2.0%
2006 - 2008	278.0	21.8	18.4	14.5%	0.6%

Table 2: Coefficient Estimates from Gasoline Consumption Regressions

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Dependent Variable: Log Gasoline Consumption per Adult							
Log(gas price)	-0.192*** (0.061)		-0.157*** (0.048)		-0.097** (0.037)		
Log(tax-excl. gas price)		-0.207*** (0.061)		-0.163*** (0.048)		-0.113*** (0.038)	-0.098*** (0.021)
Log(1 + tax ratio)		-0.765*** (0.176)		-0.470*** (0.086)		-0.292*** (0.084)	-0.250*** (0.045)
Average family size			0.001 (0.013)	-0.003 (0.012)	0.007 (0.011)	0.006 (0.010)	-0.005 (0.006)
Log(road miles/capita)			0.110*** (0.017)	0.112*** (0.016)	0.005 (0.028)	-0.004 (0.027)	0.006 (0.017)
Log(income/capita)			0.330*** (0.064)	0.292*** (0.059)	0.266*** (0.052)	0.246*** (0.049)	0.221*** (0.029)
log(cars/capita)			0.079*** (0.029)	0.076** (0.029)	0.062** (0.024)	0.060** (0.024)	0.063*** (0.011)
log(trucks/capita)			0.031 (0.019)	0.031* (0.018)	-0.005 (0.017)	-0.004 (0.017)	-0.005 (0.009)
log(drivers/capita)			0.131*** (0.044)	0.119** (0.045)	0.050* (0.029)	0.051* (0.029)	0.034** (0.015)
Share urban pop.			-0.057 (0.257)	-0.045 (0.259)	0.457 (0.501)	0.364 (0.512)	-0.194 (0.322)
Population share with access to light rail			0.034** (0.014)	0.021* (0.013)	-0.061*** (0.012)	-0.063*** (0.012)	-0.045*** (0.016)
State FE	X	X	X	X	X	X	X
Year FE	X	X	X	X	X	X	X
State Quadratic Trends					X	X	X
State-specific Autocorrelation							X
Observations	2064	2064	2064	2064	2064	2064	2064
R-Squared	0.897	0.905	0.942	0.944	0.973	0.973	0.982

Notes: The dependent variable is the log gallons of gasoline consumed per adult, by state and year. Standard errors in all columns are clustered by state. Column (7) is estimated by feasible generalized least squares, allowing for first order, state-specific autocorrelation.

Table 3: Elasticities and Effects of Price Changes on Gasoline Consumption

Variables	(1)	(2)
Panel A: Elasticity of Gasoline Consumption		
Gas price	-0.097** (0.037)	
Tax-excl. gas price		-0.037 (0.029)
Gas tax		-0.076*** (0.022)
Panel B: Percent Change in Gasoline Consumption from \$0.05/gallon Increase		
Gas price	-0.286** (0.109)	
Tax-excl. gas price		-0.148 (0.116)
Gas tax		-0.864*** (0.248)

Notes: Table reports estimated elasticities and estimated percent changes in gasoline consumption from a \$0.05/gallon increase implied by the main specifications of Table 2 (columns 5 and 6). Standard errors, clustered by state, are reported in parentheses. Panel B calculates the elasticities and semi-elasticities using the average tax and tax-exclusive gas price in 1988 (24.1 cpg and 69.2 cpg), which are close to the sample mean. Both are adjusted to 2008 dollars, the last year of our sample.

Table 4: Comparison of States Above and Below Mean Tax Rate

Variables	Below Mean Tax	Above Mean Tax	Difference
State gas Tax	12.00 (5.18)	16.46 (7.26)	4.46***
Tax-exclusive price	86.17 (56.56)	84.05 (52.60)	-2.12
GSP per capita	19,854 (12,622)	19,678 (13,586)	-176
Fraction of adults graduating HS	70.862 (11.691)	70.700 (14.124)	-0.163
Fraction of adults with BA	18.202 (5.920)	18.350 (6.731)	0.148
Mean family size	3.461 (0.391)	3.440 (0.393)	-0.021
Autos per capita	0.691 (0.093)	0.684 (0.103)	-0.007
Drivers per capita	0.922 (0.077)	0.905 (0.074)	-0.017***
Urban population share	0.708 (0.198)	0.719 (0.189)	0.010
Pop. share in MSA with rail	0.092 (0.182)	0.074 (0.191)	-0.018**
Avg. Senate LCV rating	42.8 (30.5)	53.6 (29.9)	10.8***
Avg. House LCV rating	42.3 (0.182)	50.1 (0.191)	7.72***
Democrat Governor	0.534 (0.499)	0.520 (0.499)	-0.014
Fraction of Democrats in State Senate	0.571 (0.182)	0.588 (0.208)	0.018**
Fraction of Democrats in State House	0.572 (0.171)	0.583 (0.198)	0.011
Percent Budget Surplus	0.082 (0.099)	0.076 (0.119)	-0.006
Manufacturing Share of GSP	0.168 (0.064)	0.151 (0.071)	-0.017***
Mining Share of GSP	0.029 (0.062)	0.021 (0.042)	-0.008***
Unemployment Rate	0.036 (0.031)	0.036 (0.033)	0.000

Notes: States are grouped above or below mean tax relative to the weighted average state gasoline tax in each year. Standard deviations are in parentheses. *, **, and *** denote that the difference in means is statistically significant at the 10%, 5%, and 1% levels. League of Conservation Voters scores are available from 1983-2008. GSP shares are available from 1985-2008.

Table 5: Gasoline Taxes and Political Environment

	Explanatory Var., 1966-2008			Explanatory Var., 1985-2008		
	Lagged	Contemp.	Leading	Lagged	Contemp.	Leading
GSP per capita (000s)	-0.164*** (0.0564)	-0.107** (0.0430)	-0.119** (0.0482)	-0.120* (0.0603)	-0.0954** (0.0472)	-0.106* (0.0534)
Mean family size	-0.0377 (0.246)	0.105 (0.163)	0.119 (0.165)	-0.0113 (0.474)	-0.683 (0.443)	-0.657 (0.452)
Autos per capita	0.269 (0.903)	0.751 (0.642)	0.715 (0.650)	0.538 (1.038)	-0.505 (0.757)	-0.580 (0.779)
Drivers per capita	0.471 (0.852)	-0.655 (0.535)	-0.645 (0.560)	0.382 (1.164)	-0.526 (0.749)	-0.528 (0.813)
Fraction of adults graduating HS	0.0885 (0.0893)	0.00714 (0.0860)	0.00339 (0.0854)	0.0808 (0.155)	-0.0644 (0.148)	-0.0799 (0.149)
Fraction of adults with BA	-0.0557 (0.281)	-0.113 (0.208)	-0.121 (0.208)	-0.112 (0.365)	-0.249 (0.305)	-0.305 (0.317)
Urban population share	-8.958 (9.594)	-11.05 (9.127)	-12.49 (9.380)	11.86 (15.93)	-7.765 (15.75)	-9.675 (16.81)
Pop. share in MSA with rail	-0.573 (0.529)	0.195 (0.844)	0.210 (0.843)	0.350 (3.239)	0.176 (1.228)	0.297 (1.144)
Democrat Governor	0.0951* (0.0524)	0.0847 (0.0815)	0.0851 (0.0812)	0.0645 (0.0689)	0.0697 (0.117)	0.0708 (0.117)
Fraction of Dem. in State Senate	-0.166 (0.335)	-0.312 (0.489)	-0.302 (0.491)	0.567 (0.512)	-0.302 (0.927)	-0.271 (0.945)
Fraction of Dem. in State House	0.158 (0.471)	0.839* (0.448)	0.831* (0.449)	0.528 (0.817)	0.668 (1.153)	0.658 (1.155)
Unemployment Rate	0.0331 (0.0382)	0.0117 (0.0274)	0.0138 (0.0279)	-0.132* (0.0659)	0.0230 (0.127)	0.0438 (0.143)
Percent State Budget Surplus	-0.103 (0.204)	-0.131 (0.261)	-0.139 (0.284)	0.165 (0.456)	-0.283 (0.381)	-0.321 (0.436)
Avg. Senate LCV rating				0.000423 (0.00232)	-0.00129 (0.00200)	-0.00195 (0.00200)
Avg. House LCV rating				0.00769* (0.00398)	0.00136 (0.00233)	0.00141 (0.00241)
Manufacturing Share of GSP				0.494 (3.250)	1.290 (3.042)	1.226 (3.099)
Mining Share of GSP				-7.144 (9.131)	6.666* (3.355)	7.152** (3.438)
Observations	1607	1653	1607	923	969	923
R-Squared	0.214	0.221	0.222	0.179	0.193	0.195
p-value on F-test of joint-significance	0.13	0.15	0.16	0.31	0.45	0.47

Notes: Standard Errors clustered at the state level. All specifications include year fixed effects. *, **, and *** denote significance at the 10%, 5% and 1% levels.

Table 6: IV Estimates of Gasoline Demand

Variables	Uninstrumented (1968-2008)			Instrumented (1968-2008)		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Regression Coefficients						
Log(tax-excl. gas price)	-0.214*** (0.0598)	-0.161** (0.0494)	-0.122** (0.0382)	-0.104*** (0.0199)	-0.136*** (0.0194)	-0.0697** (0.0240)
Log(1 + tax ratio)	-0.732*** (0.175)	-0.469*** (0.0898)	-0.290** (0.0895)	-0.795*** (0.179)	-0.501*** (0.0913)	-0.323*** (0.0828)
Panel B: Percent Change in Gasoline Consumption from \$0.05/gallon Increase						
Tax-Excl Gas Price	-0.100 (0.206)	-0.160 (0.162)	-0.188 (0.119)	-0.041 (0.115)	-0.027 (0.100)	-0.051 (0.104)
Gas Tax	-2.163*** (0.518)	-1.385*** (0.265)	-0.856*** (0.143)	-2.350*** (0.529)	-1.479*** (0.270)	-0.955*** (0.245)
State FE	X	X	X	X	X	X
Year FE	X	X	X	X	X	X
Covariates		X	X		X	X
State Quadratic Trends			X			X

Notes: The dependent variable is the log of gasoline consumption per adult. The standard errors (in parentheses) are clustered by state. All specifications include year and state fixed effects. The log of the oil price interacted with the tax-exclusive gasoline price in 1966 and 1 + gasoline tax / oil price instrument for the tax-exclusive gasoline price and 1 + tax ratio. Covariates are identical to those in Table 2 and include average family size, log road miles per adult, log number of registered cars per capita and log number of registered trucks per capita, log number of licensed drivers per capita, log real income per capita, fraction of the population living in metro areas, and fraction of population living in metro areas with rail transport. Semi-elasticities are calculated using the average tax and tax-exclusive gas price in 1988 inflated to 2008 dollars.

Table 7: Gasoline Taxes, tax-exclusive Prices, and Consumption, monthly

Variable	<u>Levels</u>		<u>First-differenced</u>		<u>First-differenced Seasonal Data</u>	
	(1)	(2)	(3)	(4)	(5)	(6)
Log(gas price)	-0.196*** (0.030)		-0.248*** (0.030)		-0.109* (0.057)	
Log(tax-excl. gas price)		-0.217*** (0.028)		-0.365*** (0.047)		-0.172*** (0.061)
Log(1 + tax ratio)		-0.414*** (0.046)		-0.769*** (0.157)		-0.394*** (0.140)
Observations	14,898	14,898	14,763	14,763	4,893	4,893
R-squared	0.987	0.987	0.446	0.446	0.466	0.467

Notes: The dependent variable is the log of gasoline consumption per adult. All specifications include time fixed effects. Levels regressions also include state fixed effects. Robust standard errors are clustered by state. *, **, and *** denote significance at the 10%, 5%, and 1% levels.

Table 8: Coefficient Estimates: Lagged Prices and Taxes

Variable	(1)	(2)
Log(gas price)	-0.066* (0.034)	
1-year lag gas price	-0.019 (0.024)	
2-year lag gas price	-0.037* (0.019)	
3-year lag gas price	-0.066** (0.029)	
Log(tax-excl. gas price)		-0.060 (0.036)
1-year lag tax-excl. gas price		-0.029 (0.027)
2-year lag tax-excl. gas price		-0.037 (0.022)
3-year lag tax-excl. gas price		-0.065** (0.031)
Log(1 + tax ratio)		-0.084 (0.078)
1-year lag Log(1 + tax ratio)		-0.117* (0.064)
2-year lag Log(1 + tax ratio)		-0.106* (0.056)
3-year lag Log(1 + tax ratio)		-0.157** (0.072)
Specification	Total gas price	Separate tax from tax-excl. price

Notes: The dependent variable is the log of gasoline consumption per adult. Specifications are the same as in columns 5 and 6 of Table 2, except that 1-, 2-, and 3-year lag of the gas price and tax variables are added.

Table 9: Effect on Gas Consumption of Frequency of Tax Changes

Variables	(1)	(2)	(3)	(4)	(5)	(6)
Log(tax-excl. gas price)	-0.132*** (0.038)	-0.143*** (0.033)	-0.085** (0.040)	-0.141*** (0.042)	-0.141*** (0.039)	-0.155*** (0.044)
Log(1 + tax ratio)	-0.410*** (0.100)		-0.106 (0.052)	-0.255** (0.097)	-0.338*** (0.106)	-0.357*** (0.116)
Total tax changes * tax variable	0.0056* (0.0029)					
First quintile * tax variable		-0.421*** (0.097)				
Second quintile * tax variable		-0.400*** (0.089)				
Third quintile * tax variable		-0.210* (0.112)				
Fourth quintile * tax variable		-0.328*** (0.080)				
Fifth quintile * tax variable		-0.326*** (0.084)				
Tax changes past 15 yrs * tax variable			0.0002 (0.0056)			
Tax changes past 10 yrs * tax variable				0.0065 (0.0082)		
Tax changes past 5 yrs * tax variable					0.0012 (0.0014)	
Yrs since last change * tax variable						-0.0111*** (0.0035)
Observations	2,064	2,064	1,344	1,584	1,824	2,064

Notes: The dependent variable is the log of gas consumption per adult. Specifications are the same as for column 2 of Table 2, except that additional control variables are added. The number of times the state changes its tax during the sample is calculated. Column 1 includes the interaction of the log tax ratio with the number of times the state changes its tax. States are separated into quintiles depending on the number of tax changes, where higher quintiles indicate more tax changes. Column 2 includes interactions of a set of dummy variables equal to one if the state is in the corresponding quintile with the tax ratio variable. Columns 3-5 use the number of tax changes in the past 15, 10, or 5 years instead of the number of changes during the entire sample; column 6 uses the number of years since the last tax change. Columns 3-6 also include the corresponding variables for the number of tax changes or number of years since the last change, which are not reported.

Table 10: Summary Statistics: MPG of Recently Purchased Vehicles

Variable	Sample 1: All Purchases				Sample 2: Newer Vehicles			
	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Average MPG	21.42	5.13	10.00	49.80	21.40	5.30	10.12	49.25
Tax-excl. gas price	1.59	0.74	0.70	3.94	1.60	0.75	0.70	3.94
Gas tax	0.42	0.07	0.24	0.69	0.42	0.07	0.24	0.69
Household size	2.97	1.43	1	14	2.82	1.35	1	14
Number of drivers	2.10	0.83	0	10	2.06	0.76	0	10
Number of adults	2.11	0.79	1	10	2.07	0.73	1	10
Number of workers	1.60	0.94	0	10	1.55	0.90	0	10
Age of reference person	45.20	14.53	17	92	46.99	14.64	17	92
Household income	10.66	5.21	1	18	12.10	4.93	1	18
Education of ref. person	3.02	1.13	1	5	3.23	1.11	1	5
MSA size	4.12	1.45	1	6	4.16	1.39	1	6
Worker density	1,201	1,446	25	5,000	1,227	1,436	25	5,000
Population density	3,610	4,903	50	30,000	3,636	4,747	50	30,000
With rail	0.21	0.41	0	1	0.24	0.43	0	1
Without rail	0.79	0.41	0	1	0.76	0.43	0	1
Second city	0.19	0.39	0	1	0.18	0.38	0	1
Suburban	0.27	0.45	0	1	0.31	0.46	0	1
Town and country	0.41	0.49	0	1	0.39	0.49	0	1
Urban	0.12	0.33	0	1	0.12	0.33	0	1

Notes: Sample 1, with 52,128 observations, includes households who purchased at least one vehicle within the past year, from the 1995, 2001, and 2009 NHTS. Sample 2, with 30,363 observations, includes households who purchased at least one vehicle during the past year such that all the vehicles purchased are less than four years old. Tax-exclusive gasoline price and gasoline tax correspond to the purchase month (and are averaged in case of multiple vehicle purchases). Household income, education of reference person, MSA size, worker density, and population density at the Census tract level are all categorical variables.

Table 11: Summary Statistics: Household VMT

Variable	Sample 1: Odometer Readings				Sample 2: Self-reported VMT			
	Mean	S.D.	Min.	Max.	Mean	S.D.	Min.	Max.
Average daily VMT	50.82	35.71	0.01	347.96	58.94	50.03	0.00	499.09
Tax-excl. gas price	1.07	0.12	0.74	1.69	1.13	0.13	0.87	1.68
Gas tax	0.46	0.06	0.29	0.71	0.45	0.06	0.29	0.68
Household size	2.33	1.32	1	12	2.51	1.38	1	14
Number of drivers	1.69	0.67	0	6	1.79	0.73	-8	10
Number of adults	1.74	0.66	1	8	1.83	0.71	1	9
Number of workers	1.16	0.88	0	6	1.32	0.91	-8	10
Age of reference person	50.98	16.42	17	88	47.85	16.12	17	88
Household income	9.33	4.96	1	18	9.48	4.96	1	18
Education of reference person	3.09	1.18	1	5	3.02	1.15	1	5
MSA size	4.06	1.40	1	6	4.10	1.42	1	6
Worker density at census tract	1,397	1,507	25	5,000	1,396	1,531	25	5,000
Population density at census tract	4,000	4,907	50	30,000	3,890	4,856	50	30,000
With rail	0.22	0.41	0	1	0.21	0.41	0	1
Without rail	0.78	0.41	0	1	0.79	0.41	0	1
Second city	0.21	0.41	0	1	0.21	0.41	0	1
Surbaban	0.32	0.47	0	1	0.29	0.45	0	1
Town and country	0.34	0.47	0	1	0.37	0.48	0	1
Urban	0.13	0.34	0	1	0.13	0.34	0	1

Notes: Sample 1, with 28,303 observations, is from the 1995 and 2001 NHTS and includes households who reported two odometer readings for each of the vehicles owned. Sample 2, with 61,795 observations, includes households with self-reported annual VMT for each vehicle owned. In sample 1, the tax-exclusive gasoline price and gasoline tax are averaged during the period of the two odometer readings. Household income, education of reference person, MSA size, worker density, and population density at the Census tract level are all categorical variables.

Table 12: Comparison of NHTS and Estimation Subsample

Panel A: Unweighted											
	Full NHTS Sample				Estimation Subsample						
	N	Mean	SD	10th	90th	N	Mean	SD	10th	90th	
tax-exclusive price	45,459	0.89	0.12	0.75	1.04	34,234	0.89	0.12	0.76	1.05	
Tax	41,389	0.40	0.04	0.35	0.45	34,234	0.40	0.04	0.35	0.45	
Household size	106,831	2.60	1.34	1.00	4.00	34,234	2.56	1.29	1.00	4.00	
Number of drivers	106,831	1.85	0.77	1.00	3.00	34,234	1.88	0.70	1.00	3.00	
Number of adults	111,850	1.89	0.82	1.00	3.00	34,234	1.91	0.65	1.00	3.00	
Number of workers	106,831	1.36	0.96	0.00	2.00	34,234	1.35	0.94	0.00	2.00	
Age	111,850	49.59	18.79	29.00	74.00	34,234	50.66	15.67	31.00	73.00	
MSA has subway	111,850	0.16	0.37	0.00	1.00	34,234	0.14	0.34	0.00	1.00	

Panel B: Weighted											
	Full NHTS Sample				Estimation Subsample						
	N	Mean	SD	10th	90th	N	Mean	SD	10th	90th	
tax-exclusive price	45,459	0.87	0.12	0.74	1.04	34,234	0.89	0.12	0.75	1.05	
Tax	41,389	0.37	0.04	0.32	0.44	34,234	0.37	0.04	0.32	0.42	
Household size	106,831	2.54	1.34	1.00	4.00	34,234	2.53	1.35	1.00	4.00	
Number of drivers	106,831	1.85	0.73	1.00	3.00	34,234	1.84	0.73	1.00	3.00	
Number of adults	111,850	1.89	0.70	1.00	3.00	34,234	1.88	0.70	1.00	3.00	
Number of workers	106,831	1.30	0.94	0.00	2.00	34,234	1.31	0.93	0.00	2.00	
Age	111,850	50.25	16.15	30.00	73.00	34,234	49.76	15.97	30.00	73.00	
MSA has subway	111,850	0.20	0.40	0.00	1.00	34,234	0.22	0.41	0.00	1.00	

Table 13: Gasoline Taxes, Tax-Exclusive Prices, and Vehicle MPG

	Sample 1: All Purchases			Sample 2: Newer Purchases		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Effect from Total Gas Price						
Log(gas price)	0.076 (0.017)	0.069 (0.018)	0.065 (0.019)	0.084 (0.026)	0.082 (0.027)	0.076 (0.028)
R-squared	0.054	0.056	0.059	0.082	0.084	0.091
% Δ in MPG: 5c \uparrow gas price	0.236 (0.052)	0.214 (0.056)	0.200 (0.058)	0.258 (0.079)	0.253 (0.084)	0.233 (0.0086)
Panel B: Separating Gas Tax and Tax-exclusive Price						
Log (tax-excl. gas price)	0.087 (0.020)	0.085 (0.019)	0.105 (0.029)	0.099 (0.024)	0.111 (0.027)	0.134 (0.037)
Log(1 + tax ratio)	0.151 (0.082)	0.174 (0.073)	0.288 (0.126)	0.201 (0.067)	0.274 (0.077)	0.405 (0.148)
R-squared	0.053	0.055	0.059	0.082	0.085	0.091
Elasticity w.r.t. tax-excl. gas price	0.051 (0.015)	0.044 (0.017)	0.038 (0.016)	0.052 (0.023)	0.047 (0.023)	0.040 (0.023)
Elasticity w.r.t. gas tax	0.035 (0.019)	0.041 (0.017)	0.067 (0.029)	0.047 (0.016)	0.064 (0.018)	0.094 (0.034)
% Δ in MPG: 5c \uparrow tax-excl. price	0.158 (0.047)	0.137 (0.050)	0.117 (0.050)	0.162 (0.070)	0.143 (0.071)	0.123 (0.072)
% Δ in MPG: 5c \uparrow gas tax	0.418 (0.277)	0.482 (0.202)	0.798 (0.348)	0.552 (0.187)	0.759 (0.213)	1.124 (0.410)
Difference in % changes	0.260 (0.245)	0.345 (0.224)	0.682 (0.361)	0.396 (0.218)	0.616 (0.236)	1.001 (0.433)
Census division dummies	No	Yes	No	No	Yes	No
State dummies	No	No	Yes	No	No	Yes
Observations	52,128	52,128	52,128	30,363	30,363	30,363

Notes: The dependent variable is the log of average household MPG. Columns 1 to 3 are based on all households who purchased at least one vehicle during past 12 months prior to the survey. The dependent variable is the log of the average MPG across all vehicles purchased during the past 12 months. Columns 4 to 6 focus on households who purchased at least one vehicle during the past 12 months, and all the vehicles purchased are less than four years old. All regressions include the variables listed in Table 10. We use dummy variables for the categorical variables. Sampling weights are used in all regressions. Clustered standard errors at the state level are reported in parentheses.

Table 14: Gasoline Taxes, Tax-exclusive Prices, and Household VMT

	Sample 1			Sample 2		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: Effect from Total Gas Price						
Log(gas price)	-0.497 (0.11)	-0.329 (0.113)	-0.391 (0.133)	-0.274 (0.156)	-0.122 (0.123)	0.108 (0.284)
R-squared	0.447	0.448	0.45	0.361	0.362	0.363
% Δ in VMT: 5c \uparrow gas price	-1.563 (0.344)	-1.035 (0.351)	-1.230 (0.417)	-1.214 (0.694)	-0.543 (0.504)	0.481 (1.260)
Panel B: Separating Gas Tax from Tax-exclusive Price						
Log(tax-excl. gas price)	-0.373 (0.084)	-0.329 (0.113)	-0.469 (0.256)	-0.253 (0.182)	-0.066 (0.145)	-0.246 (0.42)
Log(1 + tax ratio)	-0.124 (0.072)	-0.339 (0.21)	-0.604 (0.815)	-0.387 (0.334)	-0.273 (0.147)	-1.423 (1.3)
R-squared	0.447	0.448	0.45	0.361	0.362	0.364
Elas. w.r.t. tax-excl. gas price	-0.362 (0.092)	-0.249 (0.089)	-0.296 (0.101)	-0.142 (0.219)	0.013 (0.139)	0.161 (0.18)
Elas. w.r.t. gas tax	-0.149 (0.088)	-0.097 (-0.080)	-0.173 (0.233)	-0.111 (0.096)	-0.078 (0.042)	-0.407 (0.372)
% Δ in VMT: 5c \uparrow tax-excl. price	-1.171 (0.265)	-0.782 (0.281)	-1.312 (0.448)	-0.631 (0.972)	0.056 (0.617)	0.716 (0.798)
% Δ in VMT: 5c \uparrow gas tax	-1.454 (0.850)	-0.945 (0.584)	-1.924 (2.595)	-1.231 (1.064)	-0.870 (0.468)	-4.532 (4.142)
Difference in % changes	-0.288 (0.905)	-0.163 (0.582)	-0.611 (2.634)	-0.510 (1.806)	-0.926 (0.783)	-5.248 (4.185)
Census division dummies	No	Yes	No	No	Yes	No
State dummies	No	No	Yes	No	No	Yes
Observations	28,303	28,303	28,303	61,795	61,795	61,795

Notes: The dependent variable in all specifications is the log of daily household VMT for all vehicles owned. Columns 1 to 3 are based on households who reported two odometer readings for each of the vehicles owned from the 1995 and 2001 NHTS. Columns 4 to 6 are based on self-reported annual VMT. All regressions include the control variables listed in Table 11. We use dummy variables for the categorical variables. Sampling weights are used in all regressions. Clustered standard errors at the state level are reported in parentheses.