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From gallons to miles: A disaggregate analysis of automobile travel and externality taxes☆

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ABSTRACT

Policymakers have prioritized increasing highway revenues as rising fuel economy and a fixed federal gasoline tax have led to highway funding deficits. We use a novel disaggregate sample of motorists to estimate the effect of the price of a vehicle mile traveled on VMT, and we provide the first national assessment of VMT and gasoline taxes that are designed to raise a given amount of revenue. We find that a VMT tax dominates a gasoline tax on efficiency, distributional, and political grounds when policymakers enact independent fuel economy policies and when the VMT tax is differentiated with externalities imposed per mile.

1. Introduction

Personal vehicle transportation is central to the nation's economic prosperity and to households' way of life (Winston and Shirley (1998)). Unfortunately, driving also generates substantial congestion, pollution, and traffic accident externalities that cost American society hundreds of billions of dollars per year (Parry et al. (2007)). Based on the voluminous literature on consumers' demand for gasoline,[1] economists have paid the most attention to analyzing policies to reduce pollution and have long argued that gasoline taxes are more cost effective than Corporate Average Fuel Economy (CAFE) standards because they encourage motorists to both reduce their driving, measured by vehicle-miles-traveled (VMT), and to improve their vehicles' fuel economy.[2] In contrast, CAFE does not affect motorists' VMT in their existing (pre-CAFE) vehicles and it likely increases motorists' VMT in their new, post-CAFE vehicles because it improves fuel economy and reduces operating costs.

Unfortunately, policymakers have preferred to increase CAFE standards over time and to maintain the federal gasoline tax at its 1993 level of 18.4 cents per gallon. This inefficient approach has been compounded by policymakers' reliance on gasoline tax revenues to maintain and expand the highway system. Increasing CAFE standards, while improving the fuel economy of the nation's automobile fleet, has led to declines in gas tax revenues per mile and, along with the fixed gasoline tax, has led to shortfalls in the Highway Trust Fund, which pays for roadway maintenance and improvements. In fact, the U.S. Treasury has transferred more than $140 billion in general funds since 2008 to keep the Highway Trust Fund solvent (U.S. Congressional Budget Office (2016)). In the midst of this impasse, Congress reiterated its staunch opposition to raising the gasoline tax when they passed a new five year, $305 billion national transportation bill in 2015. The U.S. Congressional Budget Office projects that by 2026 the cumulative shortfall in the highway account will be $75 billion unless additional revenues are raised.[3]

Facing a limited set of options, some policymakers have become attracted to the idea of financing highway expenditures by charging motorists and truckers for their use of the road system in accordance with the amount that they drive, as measured by vehicle-miles-traveled. A VMT tax has the potential to generate a more stable stream of revenues than a gasoline tax because motorists cannot reduce their tax burden by driving more fuel efficient vehicles. The National Surface Transportation Infrastructure Financing Commission recommended that policymakers replace the gasoline tax with a VMT tax to stabilize transportation funding. Interest in implementing a VMT tax is growing at the state level on both coasts. Oregon has recruited more than 1500 volunteers and launched an exploratory study, "OreGO," of the effects

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[1] Havranek et al.'s (2012) meta-analysis drew on more than 200 estimates of the price elasticity of gasoline demand.

[2] Dahl (1979) conducted an early study of the gasoline tax; more recent work includes Bento et al. (2009) and Li et al. (2014).

[3] https://www.cbo.gov/sites/default/files/51300-2016-03-HighwayTrustFund.pdf

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of replacing its gasoline tax with a VMT tax. California is conducting a pilot VMT study and Hawaii and the state of Washington are expected to conduct one. On the east coast, Connecticut, Delaware, New Hampshire, and Pennsylvania have, as part of the I-95 Corridor Coalition, applied for federal support to test how a VMT tax could work across multiple states.[4]

The scholarly economics literature has paid little attention to the economic effects of a VMT tax because the oil burning externality is a direct function of fuel consumed and because, until recently, policymakers have not even mentioned it among possible policy options.[5] But given that (1) policymakers have become increasingly concerned with raising highway revenues as well as reducing fuel consumption, (2) travelers' attach utility to VMT, and (3) some automobile externalities (e.g., congestion and vehicle collisions) accrue more naturally per mile driven rather than per gallon of fuel consumed, it is important to know whether social welfare is increased more by a VMT tax than by gasoline taxes that are equivalent in terms of generating revenue or reducing fuel consumption. And to evaluate the long-run viability of both taxes, it is important to understand how they interact with separate but related government policies, including CAFE standards and highway funding that is tied to tax receipts. As we discuss in detail below, because each tax affects different drivers differently and because both taxes affect multiple automobile externalities, it is difficult to unambiguously resolve those issues on purely theoretical grounds.

In this paper, we develop a model of motorists' short-run demand for automobile travel measured in vehicle miles that explicitly accounts for heterogeneity across drivers and their vehicles, and we estimate drivers' responses to changes in the marginal cost of driving a mile in their current vehicles. The model allows us to compare the effects of gasoline and VMT taxes on fuel consumption, vehicle miles traveled, consumer surplus, government revenues, the social costs of automobile externalities, and social welfare. In theory, a gasoline tax should have the greatest impact on motorists who are committed to driving the most fuel inefficient vehicles, and a VMT tax should have the greatest impact on motorists who are committed to driving the most miles.

Our disaggregated empirical approach is able to overcome limitations that characterize the previous literature on gasoline demand, which has generally used aggregated automobile transportation and gasoline sales data.[6] Aggregate gasoline demand studies specify fuel consumption or expenditures as the dependent variable and measure the price of travel as dollars per gallon of gasoline at a broad geographical level. But data that aggregates motorists' behavior makes it impossible to determine their individual VMT, vehicle fuel efficiency, or the price that they normally pay for gasoline. Ignoring those differences and making assumptions about average fuel economy, gasoline prices, and VMT to construct an aggregate price per mile of travel will generally lead to biased estimates of the price elasticity of the demand for automobile travel and hence the economic effects of a VMT tax.[7]

We initially assess the economic effects of gasoline and VMT taxes that each: (1) reduce total fuel consumption by 1%, or (2) raise an additional \$55 billion per year for highway spending, which roughly aligns with the annual sums called for by the 2015 federal transportation bill. Surprisingly, we find that the taxes have very similar effects on social welfare. But when we account for the recent increase in CAFE standards that calls for significant improvements in vehicle fuel economy, and when we exploit the flexibility of a VMT tax by setting different rates for urban and rural driving, we find that a VMT tax designed to increase highway spending \$55 billion per year increases annual welfare by \$10.5 billion or nearly 20% more than a gasoline tax does because: (1) the differentiated VMT tax is better than the gasoline tax at targeting its tax to and affecting the behavior of those drivers who create the greatest externalities, and (2) the greater fuel economy that results from a higher CAFE standard effectively reduces a gasoline tax and its benefits, but has less effect on a VMT tax and its benefits.

Our empirical findings therefore indicate that implementing a VMT tax is a more efficient policy than raising the gasoline tax to improve the financial and economic condition of the highway system. Importantly, we also identify considerations that suggest that a VMT tax is likely to be more politically attractive to policymakers than is raising the gasoline tax.

2. The short-run demand for automobile travel

Households' demand for a given vehicle type and their utilization of that vehicle have been modeled as joint decisions to facilitate analyses of policies that in the long run may cause households to change the vehicles they own (e.g., Mannering and Winston (1985)). We conduct a short-run analysis that treats an individual motorist's vehicle as fixed; the average length of time that motorists tend to keep their vehicles suggests that the short run in this case is at least five years. We discuss later how our findings would be affected if we conducted a long-run analysis.

2.1. Demand specification

Conditional on owning a particular vehicle, individual *i*'s use of a vehicle *c* for a given time period *t* is measured by the vehicle-miles-traveled (VMT) accumulated over that time period, which depends on the individual's and vehicle's characteristics, and on contemporaneous economic conditions. We assume that individual *i*'s *utilization equation* in period *t* has a generalized Cobb-Douglas functional form given by:

$$VMT_{c(i)t} = f_{c(i)}\lambda_t p_{c(i)t}^{\beta_i} \tag{1}$$

The function $f_{c(i)}$, which we specify as $f_{c(i)} = \exp(\lambda_i + \theta Z_{c(i)})$, contains an individual fixed effect, λ_i, that captures individuals' unobserved characteristics that affect their utilization of a vehicle and a vector of vehicle characteristics, $Z_{c(i)}$, excluding fuel economy, which forms part of the price of driving a mile. To capture heterogeneity among drivers, the price elasticity, β_i, is specified as $\beta_i = \psi X_i$, where X_i includes driver and vehicle characteristics. The vectors θ and ψ are estimable parameters.

The price of driving a mile, $p_{c(i)t}$, is equal to the price of gasoline in month *t* for driver *i* divided by vehicle *c(i)*'s fuel economy; thus, this price is likely to vary significantly across drivers because different vehicles have different fuel economies and because the price of gasoline varies both geographically and over time. The utilization equation is more general than a standard Cobb-Douglas demand function for *VMT* because the price elasticity is allowed to vary by driver and vehicle characteristics and over time.

To estimate the parameters in Eq. (1), we take natural logs and combine terms to obtain the log-linear estimating equation

$$logVMT_{it} = \lambda_i + \theta Z_{c(i)} + \tilde{\lambda}_t + \beta_i \; log\left(p_{c(i)t}\right) + \varepsilon_{it} \tag{2}$$

[4] Moran and Ball (2016) provide a detailed discussion of the Oregon study and suggest that other states should follow it. The Illinois Senate has proposed legislation to roll back the state's motor fuel tax and replace it with a VMT tax within the state's boundaries. However, Illinois has not conducted an experiment, and it is not expected that its VMT legislation will be approved.

[5] An exception is Parry (2005), who calibrated a theoretical model that suggested that VMT taxes could out-perform gasoline taxes at reducing automobile externalities. The disaggregated empirical approach that we take here enables us to assess the taxes' distributional effects by carefully identifying who is affected by each tax, and to formulate a differentiated VMT tax, which increases efficiency.

[6] McMullen et al. (2010) estimated the behavior of a cross-section of drivers in Oregon to compare the distributional effects of a VMT tax and a gasoline tax, but a cross-sectional model cannot control for the potential bias that is caused by unobserved household and city characteristics that are likely to be correlated with the price of gasoline, vehicle fuel economy, and vehicle miles driven.

[7] Levin et al. (2014) find that aggregating gasoline prices tends to reduce the estimated elasticity of gasoline demand.

where the tilde denotes the logarithm of the time fixed effects and ε_{it} is an error term. All of the parameters can then be estimated by least squares. We specify the gasoline price as a price per mile because we are not analyzing vehicle choice; thus, we would expect that the gasoline price would influence the VMT decision only through the price per mile.[8] Because we do not have access to the income of drivers in our sample, we used the average income in a driver's zip code and age group; but we found that its effect on VMT was statistically insignificant, in all likelihood because of our imprecise income measure. Thus, we allow income to have an independent effect on VMT that is captured by the individual driver fixed effects.

2.2. Data

Estimating the model requires us to observe individual drivers' VMT over time along with sufficient information about their residential locations and their vehicles to accurately measure the prices per mile of driving their vehicles. We obtained data from State Farm Mutual Automobile Insurance Company on individual drivers, who in return for a discount on their insurance, allowed a private firm to remotely record their vehicles' exact VMT from odometer readings (a non-zero figure was always recorded) and to transmit it wirelessly so that it could be stored.[9] All of the vehicles were owned by households and were not part of a vehicle fleet. State Farm collected a large, monthly sample of drivers in the state of Ohio from August 2009, in the midst of the Great Recession, to September 2013, which was well into the economic recovery. The number of distinct household observations in the sample steadily increased from 1907 in August 2009 to 9955 in May 2011 and then stabilized with very little attrition thereafter.[10] The sample consists of 228,910 driver-months.

The drivers included in our sample are State Farm policyholders who are also generally the heads of their households. The data set included driving information on one vehicle per household at a given point in time. A driver's vehicle selection did not appear to be affected by seasonal or employment-related patterns that would lead to vehicle substitution among household members because fewer than 2% of the vehicles in the sample were idled in a given month. In addition, we estimated specifications that included a multi-driver household dummy to control for the possibility of intra-household vehicle substitution and interacted it with the price per mile; we found that the parameter for this interaction was statistically insignificant and that the other parameter estimates changed very little. It is possible that vehicle substitution was less in our sample than in other household automobile samples because the household head tended to drive the vehicle that was subject to monitoring by State Farm; thus, we consider later how our conclusions might be affected if intra-household vehicle substitution occurred more frequently than in our sample.

The sample also contains information about each driver's socioeconomic characteristics, vehicle characteristics, and county of residence, which is where their travel originates.[11] To measure the price of driving one mile over time, we used the average pump price in a driver's county of residence for each month from 2009 to 2013 from data provided by the Oil Price Information Service. Fig. A1 in the appendix plots the county-level average gasoline prices in each month of our sample and shows that those prices fluctuated greatly over time, which accounted for most of its variation in the sample; however, average gasoline prices also varied across counties within a month.[12]

Given the low rate of intra-household vehicle substitution and our inclusion of individual fixed effects, we are able to identify the effect of changes in gasoline prices on individual motorists' VMT. We measured the fuel economy of the driver's vehicle by using the vehicle's VIN to find the vehicle year, make, model, body style, and engine type and matched that information to the Environmental Protection Agency's (EPA) database of fuel economies.[13] Following the EPA, we used the combined fuel economy for each vehicle, which is the weighted average of the vehicle's fuel economy on urban and highway drive cycles. Finally, as noted, because State Farm does not collect individual drivers' income, we allowed income to be entirely absorbed by the individual fixed effects.[14]

Table 1 reports the means in our sample (and, when publicly available, the means in Ohio, and the United States) of drivers' average monthly VMT, the components of the price of driving one mile, vehicle miles per gallon and the local price of a gallon of gasoline, the percentage of older vehicles, average annual income, and the percentage of the county population in an urban area.[15] Most of the means in our sample are comparable with those for Ohio, when available, and for the nation. In particular, the means of the most important variables for determining the elasticity of VMT with respect to the price of gasoline per mile do not suggest any sample bias. However, the share of newer cars in our sample is considerably greater than the share in the United States, which is plausible for a sample composed of individual drivers who self-select to subscribe to recently introduced telematics services that allow their driving and accident information to be monitored in return for a discount from State Farm. In other words, compared with other drivers, drivers in our sample appear to be more likely to have made a recent decision to purchase a new or slightly-used vehicle, but this characteristic does not necessarily indicate that our sample suffers from significant bias because, as noted, important driver and vehicle characteristics are aligned with state and national figures.

To explore the potential bias in our findings, we identified the most important characteristic of our sample drivers that appeared to deviate significantly from the characteristics of other drivers in Ohio by obtaining county-month level data from State Farm that included household and vehicle characteristics of all drivers in the (Ohio) population. Using that data, we constructed sampling weights based on the driver's county of residence because our sample is overrepresented by drivers from the most populous counties. Those sample weights also aid us in extrapolating our findings to the rest of the United States, and they are important for properly measuring how driving is allocated between rural and urban areas within Ohio. Column 4 of Table 1 reports the means of our data after it has been reweighted based on the driver's

8 In fact, we found that the gasoline price alone had a statistically insignificant effect on VMT.

9 We are grateful to Jeff Myers of State Farm for his valuable assistance with and explanation of the data. We stress that no personal identifiable information was utilized in our analysis and that the interpretations and recommendations in this paper do not necessarily reflect those of State Farm. All of the households in the sample received a discount on their insurance regardless of how much they drove. But consistent with State Farm policies for all drivers that it insures, the total discount varied in accordance with VMT, as indicated by State Farm "VMT buckets," with less need for a household to prove low VMT, such as by submitting pictures of the vehicle's odometer every few months.

10 Less than 2% of households left the sample on average in each month. This attrition was not statistically significantly correlated with observed socioeconomic or vehicle characteristics.

11 According to the most recent National Household Travel Survey (NHTS) taken in 2009, roughly half of all vehicle trips were less than 5 miles, suggesting that driving is concentrated in individuals' counties of residence. The NHTS is available at: http://nhts.ornl.gov

12 The ordering of counties' average gasoline prices also changed considerably over time. Nearly 50% of the time that a county's gasoline prices were in the bottom quartile in a given month, that county's prices were not in the bottom quartile in the following month, and nearly 30% of the time that a county's gasoline prices were in the top quartile in a given month, that county's prices were not in the top quartile in the following month. We obtained additional evidence of the variation in gasoline prices by analyzing the residuals of a regression of county-month gasoline prices on county and month fixed effects. We found that the residuals ranged from −19 cents to +22 cents with a standard deviation of 3 cents. The correlation between those residuals and their one-month within-county lag was only 0.31, suggesting that substantial variation in gas prices exists beyond county and month fixed effects.

13 We are grateful to Florian Zettelmeyer and Christopher Knittel for assistance in matching VINs to vehicle attributes.

14 Gillingham (2014) conducts a detailed empirical study of California motorists and finds that their VMT elasticities vary with income and other demographics.

15 Average annual income in our sample is based on the average annual income of the zip codes where drivers in the sample live.

Table 1
Means and standard deviations of the variables in our sample, Ohio, and the US[d].

	Our sample	Ohio	US	Our sample reweighted
Monthly VMT (miles)[a]	878.79 (619.68)	798.88	788.87	890.61 (627.92)
Gas price (March 2013 \$/gal)[b]	3.44 (0.35)	3.38	3.70	3.44 (0.35)
Miles per gallon[c]	20.90 (3.82)	n.a.	21.6	20.85 (3.82)
Average annual income (real 2013\$)[e]	51,548 (21,414)	49,437	54,639	51,371 (21,469)
% Older Vehicles[f]	0.17 (0.38)	n.a.	0.75	0.17 (0.38)
Share of population in a driver's county that is in an urban area[g]	0.81 (0.20)	0.78	0.81	0.78 (0.23)

[a] US and Ohio Monthly VMT for March 2013 are calculated from the FHWA March 2013 *Traffic Volume Trends*.
[b] Gas Price from *Oil Price Information Service*.
[c] MPG for Ohio and US from FHWA 2013 *Highway Statistics*.
[d] Means of variables with standard deviations for our sample in parentheses; n.a. indicates that the value for a variable was not publicly available.
[e] Average annual income in our sample is based on the average annual income of the zip codes where drivers in the sample live. Median household income for Ohio and US obtained from the 2010 *American Communities Survey*.
[f] Defined as more than 4 years old. The figure for the U.S. was constructed using automobile sales data from the St. Louis Federal Reserve Bank and from estimates of scrappage rates in Jacobsen and van Benthem (2015).
[g] Urban population as defined in the 2010 U.S. Census.

county of residence. The means do not change significantly, but the data now align better with the share of the Ohio population that lives in urban areas.

3. Estimation results

Our analysis has a primary interest in estimating the price elasticity of VMT that varies with driver and vehicle characteristics, $\beta_i = \psi X_i$. Identification of the parameters ψ is achieved through individual drivers' differential responses to changes in the price of gasoline per mile based on the fuel economy of their vehicles. Biased estimates of ψ would therefore arise from omitted variables that are correlated with gasoline prices and that affect drivers' VMT differently based on their vehicles' fuel economy. As noted, the drivers' fixed effects capture their unobserved characteristics that may be correlated with observed influences on VMT, especially the price of driving one mile that is constructed in part from the fuel economy of the drivers' vehicles. In addition, macroeconomic and weather conditions could affect the price of gasoline paid by drivers and how much they traveled by automobile. Thus we controlled for that potential source of bias by including county level macroeconomic variables (the unemployment rate, the percent of population in urban areas, employment, real GDP, and average wages and compensation) and weather variables (the number of days in a month with precipitation and the number of days in a month with a minimum temperature of less than or equal to 32 degrees).[16]

Drivers' responses to a change in the price per mile could vary in accordance with a number of factors, including how much they drive, whether they live in an urban or rural area, and the fuel economy and power of their vehicles.[17] Thus we captured drivers' heterogeneous responses by interacting the price per mile with dummy variables for drivers indicating that they: (1) had high VMT (defined as average monthly VMT that exceeded the median average monthly VMT in the sample), (2) drove a low MPG vehicle (defined as average fuel economy on urban and highway drive cycles that was below the 25th percentile fuel economy in the sample), (3) drove a vehicle with high engine displacement (defined as engine displacement that was above the 90th percentile engine displacement in the sample),[18] and (4) lived in a rural area (defined as a county at or below the 10th percentile in the sample in terms of the percentage of its population that lived in an urban area as defined by the 2010 U.S. Census). And we specified additional heterogeneity for rural and non-rural drivers by interacting the rural dummy variable with the price per mile and high VMT and with the price per mile and low MPG. Of course, driver heterogeneity could also be captured through interactions of the price per mile and additional driver and vehicle characteristics and through alternative definitions of the characteristics we used; however, exploratory estimations indicated that the interactions we specified above were best able to capture drivers' heterogeneous responses in a robust and economically significant manner. Finally, we discuss how our welfare analyses are affected if we do not account for drivers' heterogeneity.

In Table 2, we present the parameter estimates of the model using the county-based sample weights, in which observations are evenly weighted within each Ohio County in proportion to the county's population. We present in the first column a bare-bones specification with only the price per mile and then we gradually expand that specification in the other columns to include interaction effects that capture motorists' heterogeneity. The full specification in column 4 shows that the estimated coefficients of the price per mile and its interactions generally have statistically significant effects on VMT, and that the estimated coefficients of the interactions affect the magnitude of the estimated baseline coefficient of the price per mile in plausible ways.

Specifically, drivers with high VMT have a lower price elasticity (in absolute value) compared with other drivers' elasticity, in all likelihood because their longer distance commutes and non-work trips that contribute to their high VMT, regardless of whether they live in urban or rural areas, make it less likely that they can adjust their VMT in response to changes in the price per mile. Drivers of vehicles that have low MPG have higher vehicle operating costs per mile than other drivers, which gives them a greater economic incentive to adjust their VMT in response to changes in the price per mile.[19] All else constant, drivers who live in rural areas may be more price sensitive than other drivers because they are generally less affluent than drivers who live in more urbanized areas. But both high VMT and low MPG rural drivers are apparently less able or willing than other rural drivers are to adjust their automobile work and non-work trips and thus less likely than other rural drivers are to adjust their VMT in response to changes in the price per mile. Finally, drivers of powerful vehicles with high engine displacement, and undoubtedly a higher sticker price, tend to be more affluent than other drivers are and have preferences for those particular vehicles that make them less inclined to adjust their VMT in response to changes in the price per mile.[20]

The variation in our data, which underlies the statistical significance of the price variable and its interactions with driver and vehicle characteristics, is that vehicle fuel economy ranges from 12 to 34 miles per gallon, which when combined with the variation in the price of gasoline implies a price of driving one mile that ranges from 8.6 cents to 33.7 cents. We stress that it would not be possible to estimate the heterogeneous, or even homogeneous, effects of the price per mile on VMT with

[16] Data on the county level unemployment rate and level of employment, average wages and compensation, and real GDP are from the U.S. Bureau of Labor Statistics; data on the percent of population in urban areas are from the U.S. Census; and monthly weather data are from the National Climatic Data Center of the National Oceanographic and Atmospheric Administration.

[17] We later show that those variables are also the important determinants of differences in the relative welfare effects of a gas tax and a VMT tax, so it is important for our policy analysis to allow drivers' elasticities of VMT with respect to price to be heterogeneous in those variables.

[18] The vast majority of high displacement vehicles in our sample are the powerful trims of large trucks, full-size SUVs (e.g., a GMC Yukon), or passenger vans. Powerful “muscle cars,” such as a Corvette, account for the remaining high displacement vehicles.

[19] Knittel and Sandler (2015) also find that drivers of low MPG vehicles respond more to changes in fuel prices than do other drivers.

[20] As indicated in footnote 18, the high displacement vehicles in our sample include performance vehicles that certain people prefer to purchase for work (e.g., a large truck), home production (e.g., a full-size SUV), or for pleasure (e.g., a “muscle car”).

Table 2
Parameter estimates of Vmt model. (Dependent variable: ln(VMT)).

Independent variables	County weights	County weights	County weights	County weights
ln(price per mile($))	−0.1497**	−0.1625**	−0.1911***	−0.1731***
	(0.0644)	(0.0628)	(0.0569)	(0.0551)
ln(price per mile($))·High VMT[a]		0.1121**	0.1117**	0.1047**
		(0.0528)	(0.0517)	(0.0513)
ln(price per mile($))·High VMT·rural[a]		0.2079*	0.1951*	0.1883*
		(0.1228)	(0.1083)	(0.1054)
ln(price per mile($))·rural[a]		−0.3823***	−0.3474***	−0.3292***
		(0.1323)	(0.1113)	(0.1076)
ln(price per mile($))·low MPG[a]			−0.0593*	−0.1180***
			(0.0315)	(0.0375)
ln(price per mile($))·Low MPG·rural[a]			0.1553**	0.1410*
			(0.0737)	(0.0720)
ln(price per mile($))·High displacement[a]				0.1198**
				(0.0506)
SUV dummy	0.2643***	0.2629***	0.2622***	0.2341***
	(0.0390)	(0.0389)	(0.0391)	(0.0417)
Older vehicle dummy	−0.0311**	−0.0305**	−0.0307**	−0.0347***
	(0.0124)	(0.0124)	(0.0124)	(0.0117)
N	228,910	228,910	228,910	228,910
Month dummies	Yes	Yes	Yes	Yes
Weather controls[b]	Yes	Yes	Yes	Yes
Macroeconomic controls[c]	Yes	Yes	Yes	Yes
Household fixed effects	Yes	Yes	Yes	Yes
Adjusted R^2	0.6000	0.6003	0.6005	0.6008

All robust standard errors are clustered at the county level.
*** Significant at the 1% level.
** Significant at 5% level.
* Significant at 10% level.
[a] The definitions of high VMT, rural, low MPG, and high displacement are given in the text.
[b] Weather controls include the number of days in a month with precipitation and the number of days a month with minimum temperature of less than or equal to 32 degrees.
[c] Macroeconomic controls include at the county level: the unemployment rate, the percent of the population in urban areas, level of employment, real GDP, and wages and compensation.

aggregate data because VMT could not be expressed as a function of the price of automobile travel per mile.

The price elasticity obtained from the full model for drivers who do not have high VMT, do not have a vehicle with low MPG or high engine displacement, and do not live in rural areas is −0.17, which is plausible. Accounting for all the interactions, the range of the elasticities is roughly −0.60 to slightly greater than zero, which is also plausible given the significant heterogeneity that we capture.[21] Finally, the parameter estimates are robust in two important ways: (1) The estimates in the full model changed very little when we estimated it without the sample weights, which indicates that the ability of the State Farm sample to generate price elasticities that are representative of the population does not appear to be affected much by households' self-selection to subscribe to telematics services, and (2) As shown in Table 2, the parameter estimates and statistical reliability were generally stable as we improved our understanding of drivers' heterogeneity by including additional interactions but those interactions per se did not drive any of the basic results.

To get a feel for how the elasticities based on the full model compare with elasticities obtained from aggregate gasoline demand models, we note that the average elasticity of VMT with respect to the price of automobile travel per mile is −0.117. We estimated that the elasticity of the demand for *gasoline* with respect to gasoline prices was −0.124 in our sample, which is somewhat larger than the average short-run elasticity of −0.09 reported in Havranek et al.'s (2012) meta-analysis of aggregate models, and it is noticeably larger than our own estimate of the aggregate price elasticity of demand for gasoline in Ohio of −0.0407 (0.0099) and the range of aggregate elasticity estimates for the nation, −0.034 to −0.077, in Hughes et al. (2008). We attribute this difference to our use of disaggregate data, which as Levin et al. (2014) find, results in higher estimates of gasoline demand elasticities.

Finally, we explored the direct effect on VMT of various vehicle types, based on size classification, and vehicle attributes and we found some statistically significant effects. Table 2 shows that SUVs tend to be driven more per month than other household vehicles, in all likelihood because those vehicles are versatile and can be used for both work and various non-work trips, while older vehicles tend to be driven less per month than newer vehicles, in all likelihood because drivers enjoy using newer vehicles and their up-to-date accessories for a broad variety of trips.[22]

We explored alternative specifications of the VMT demand model and subsamples to enrich the analysis and to perform robustness checks. First, we estimated our full model on a subsample that did not include data generated during the Great Recession—that is, we removed monthly observations from 2009 through the first half of 2010—and we found little change in our parameter estimates and their statistical significance (e.g., accounting for all the interactions, the range of the elasticities was still roughly −0.60 to slightly greater than zero.) Second, we tested whether our results were affected by time-varying unobservables by estimating separate regressions on several subsamples of shorter length. This change resulted in coefficients that reflected seasonal patterns, but did not reveal any fundamental differences in their underlying values.

Finally, we estimated models that included lagged prices per mile to capture any adjustments by motorists to price changes, but the lags tended to be statistically insignificant and their inclusion only slightly reduced the estimated effects of the current price per mile, although the combined effect of current and lagged gasoline prices was similar to the effect reported here. More importantly, even if motorists delayed their responses to price changes, our main policy simulations would not be affected because we assess the economic effects of a permanent increase in either the gasoline or VMT tax.

4. Welfare analysis

The gasoline tax is currently used to charge motorists and truckers for their use of the public roads, to raise highway revenues, and to encourage motorists and truckers to reduce fuel consumption. However, as noted, the federal component of the tax has not been raised in decades and the Highway Trust Fund is currently running a deficit that is projected to grow substantially unless more funds are provided to maintain and repair the highway system.[23] It is therefore of interest to assess the social welfare effects of raising the federal gasoline tax or, alternatively, of introducing a VMT tax to achieve both highway financing objectives and to reduce externalities from fuel consumption and highway travel.

Advances in communications technology have made it possible to implement a VMT tax in any state in the country. Specifically, an inexpensive device can be installed in vehicles that track mileage driven in states and wirelessly upload this information to private firms to help states administer the program. Motorists are then charged lump sum for their use of the road system each pay period, which is normally a month. For example, the cost of Oregon's experimental VMT tax program is $8.4 million. For privacy reasons, data older than 30 days are deleted once drivers pay their VMT tax bills.

[21] The drivers with slightly positive elasticities appear to be quite unusual because they have high VMT, drive vehicles with high engine displacement, do not drive vehicles with low fuel economy, and do not live in rural areas. Accordingly, they account for less than 0.5% of the drivers in our sample.

[22] The relationship between VMT and SUVs and older vehicles is identified based on households who own more than one vehicle in our sample over time, which means that within a household, SUVs tend to be driven more than non-SUVs and newer vehicles tend to be driven more than older vehicles.

[23] Recently, some states have raised their gasoline tax to pay for upgrading roads and bridges.

We use our full model of VMT demand to extrapolate our results for Ohio to the United States. The effect on social welfare of a gasoline or VMT tax that is designed to achieve a certain change in fuel consumption or highway finance consists of (a) changes in motorists' welfare and government revenues and (b) changes in the relevant pollution, congestion, and safety automobile externalities. Motorists' welfare is adversely affected because the taxes will cause them to reduce their vehicle miles traveled by automobile, which they highly value (Winston and Shirley (1998)). Similar to Hausman (1981), we obtain the short-run indirect utility function for each motorist given by:

$$V_{it}(p) = f_{c(i)}\lambda_t \frac{p_{c(i)t}^{\beta_i+1}}{\beta_i+1} + C \tag{3}$$

where C is a constant of integration and other variables and parameters are as defined previously.[24] Under a gasoline or VMT tax that changes the price of driving one mile from p_{it}^0 to p_{it}^1, the change in driver i's welfare is given by $V_{it}(p_{it}^1) - V_{it}(p_{it}^0)$, and we can aggregate the effects of a tax policy over all drivers as:

$$\Delta V_t = \sum_i V_{it}(p_{it}^1) - V_{it}(p_{it}^0) \tag{4}$$

Note that the original prices per mile, p_{it}^0, the counterfactual prices p_{it}^1, and the changes in consumer surplus are likely to vary significantly across individual motorists because they drive different vehicles, use them different amounts, and respond differently to changes in the price per mile in accordance with their VMT, residential location, and their vehicles' fuel economy and engine displacement. A gasoline tax and a VMT tax have different effects on the change in the cost of driving a mile for almost every driver because the VMT tax increases the cost of driving a mile by the amount of the tax, while the gasoline tax increases the cost of driving a mile by the amount of the per-gallon tax divided by the individual driver's fuel economy. Thus, a VMT tax increases the price of driving a mile by the largest percentage for drivers of fuel efficient vehicles because it is a fixed charge and because drivers of fuel-efficient vehicles incur the lowest operating cost per mile, while a gasoline tax increases the price of driving a mile the most for drivers of fuel-inefficient vehicles.

If we denote the change in government revenues by ΔG_t and the change in the cost of automobile externalities by ΔE_t, then the change in social welfare from either a gasoline or VMT tax, ΔW_t, is given by

$$\Delta W_t = \Delta V_t + \Delta G_t + \Delta E_t \tag{5}$$

In order to calculate ΔE_t, we need estimates of the marginal external cost of using a gallon of gasoline and of driving both urban and rural miles. We measure the external cost per gallon of gasoline consumed by including its climate externality. We use the Energy Information Agency's estimate of 19.564 lbs of CO_2 equivalent emissions per gallon of gas consumed and the Environmental Protection Agency's midrange estimate of the social cost of carbon of \$40 per ton of CO_2 in 2015 to obtain a marginal externality cost of \$0.393/gal.[25]

The marginal external cost per mile consists of: (1) the congestion externality (including both the increased travel time and increased unreliability of travel time), (2) the accident externality, and (3) the local environmental externalities of driving. We use estimates from Small and Verhoef (2007), which are broadly consistent with estimates in Parry et al. (2007), adjusted to 2013 dollars and divided into urban and rural values of \$0.218/urban mile driven and \$0.038/rural mile driven.[26] The estimates developed by those authors include an average congestion externality that does not vary by time of day, which is appropriate for our purposes because neither a gasoline tax nor a VMT tax as currently proposed would vary by time of day. Finally, our findings were robust to alternative assumptions that could be used to construct the externality estimates.[27]

We consider the welfare effects of a gasoline and a VMT tax to achieve two distinct objectives by policymakers: (1) to reduce the nation's fuel consumption 1% per year, and (2) to raise \$55 billion per year to fund highway expenditures, which is roughly in line with the annual sums called for in the new federal transportation bill passed by Congress in 2015. Consistent with our short-run model, we assume that motorists do not change vehicles in response to the taxes. We also assume that the effect of a change in the price per mile on VMT is the same whether the change comes from a gasoline tax or a VMT tax because a VMT tax has not been implemented in the United States and no evidence exists on whether a gasoline and VMT tax would generate different behavioral responses. However, our model does capture drivers' heterogeneity, which is a potentially important source of significant differences in how drivers will respond to the two taxes.

Our initial simulations also assume that the government requires automakers to continue to meet the current CAFE standard, which forces motorists into more fuel efficient vehicles than they might otherwise drive. In subsequent simulations, we explore how the economic effects of a gas or VMT tax would vary in the presence of a higher CAFE standard. By improving fuel efficiency, CAFE standards could induce a rebound effect, which we model directly by allowing the increase in vehicle fuel economy to decrease the cost of driving.

Because we are analyzing heterogeneous drivers and vehicles, economic theory cannot unambiguously indicate whether a gasoline tax or a VMT tax will produce a larger improvement in social welfare. But it is useful to identify the important influences on the welfare effects of the two taxes and the conditions under which one will generate a larger welfare gain than the other. Recall, that the additional per mile cost to a driver of a VMT tax is just the VMT tax, while the additional per mile cost of a gasoline tax is the gas tax divided by the vehicle's fuel economy. Fig. 1 presents a flow chart that: (1) identifies the important driver and vehicle characteristics that determine the welfare effects of each tax, and (2) shows how the heterogeneity of drivers and their vehicles culminate in certain conditions whereby the gasoline tax generates a larger welfare gain than a VMT tax produces and vice-versa.

The important characteristics are a vehicle's fuel economy, which for heterogeneous vehicles we denote as a low MPG or a high MPG vehicle; a driver's vehicle utilization, which for heterogeneous drivers we denote as low VMT or high VMT; and a driver's gasoline price elasticity of demand, ε, which for heterogeneous drivers we denote as low ε or

[24] We obtain the indirect utility function in Eq. (3) by applying Roy's Identity to the VMT demand Eq. (1) and by assuming a constant marginal utility of income to facilitate welfare analysis.

[25] http://www3.epa.gov/climatechange/EPAactivities/economics/scc.html. Note that this estimate of the climate externality is substantially higher than the estimates used by Parry (2005), Parry and Small (2005), and Small and Verhoef (2007) because it incorporates more recent advances in estimating the social cost of carbon that feed into the EPA's current estimate of this social cost.

[26] For the increased travel time externality, we use \$0.049/mi for urban drivers and \$0.009/mi for rural drivers and following Small and Verhoef (2007), we multiply those values by 0.93 to get the marginal external cost of decreased travel time reliability and add this cost to the cost of increased travel time to obtain a total congestion externality of \$0.129/mi for urban drivers and \$0.023/mi for rural drivers. The accident externality for urban drivers adapted from Small and Verhoef is \$0.073/mi. We use the ratio of the rural and urban congestion externalities to approximate the rural accident externality of \$0.013/mi. Finally, following Small and Verhoef (2007), Parry (2005), and Parry and Small (2005), we assume that the local pollutant externality accrues per mile of driving rather than per gallon. We assume that urban driving produces a local pollutant externality of \$0.016/mi and use the ratio of the rural and urban congestion externalities to approximate the rural local pollutant externality of \$0.002/mi.

[27] Specifically, we noted that we used an accident externality for urban drivers of \$0.073/mi and an accident externality for rural drivers of \$0.013/mi, but our main findings were robust to using \$0.073/mi as the accident externality for both urban and rural drivers. Our main findings were also robust to increasing or decreasing the assumed total per-mile externalities by 10% and to including an externality that arises because additional police services and road maintenance may be required. It might be of interest to explore how our main findings would change if a higher gasoline tax or a new VMT tax led to a change in the assumed values of the externalities. But that would be difficult to determine here because we do not formulate a general equilibrium model. More importantly, it is not clear how, if at all, the values of the per-mile externalities would change.

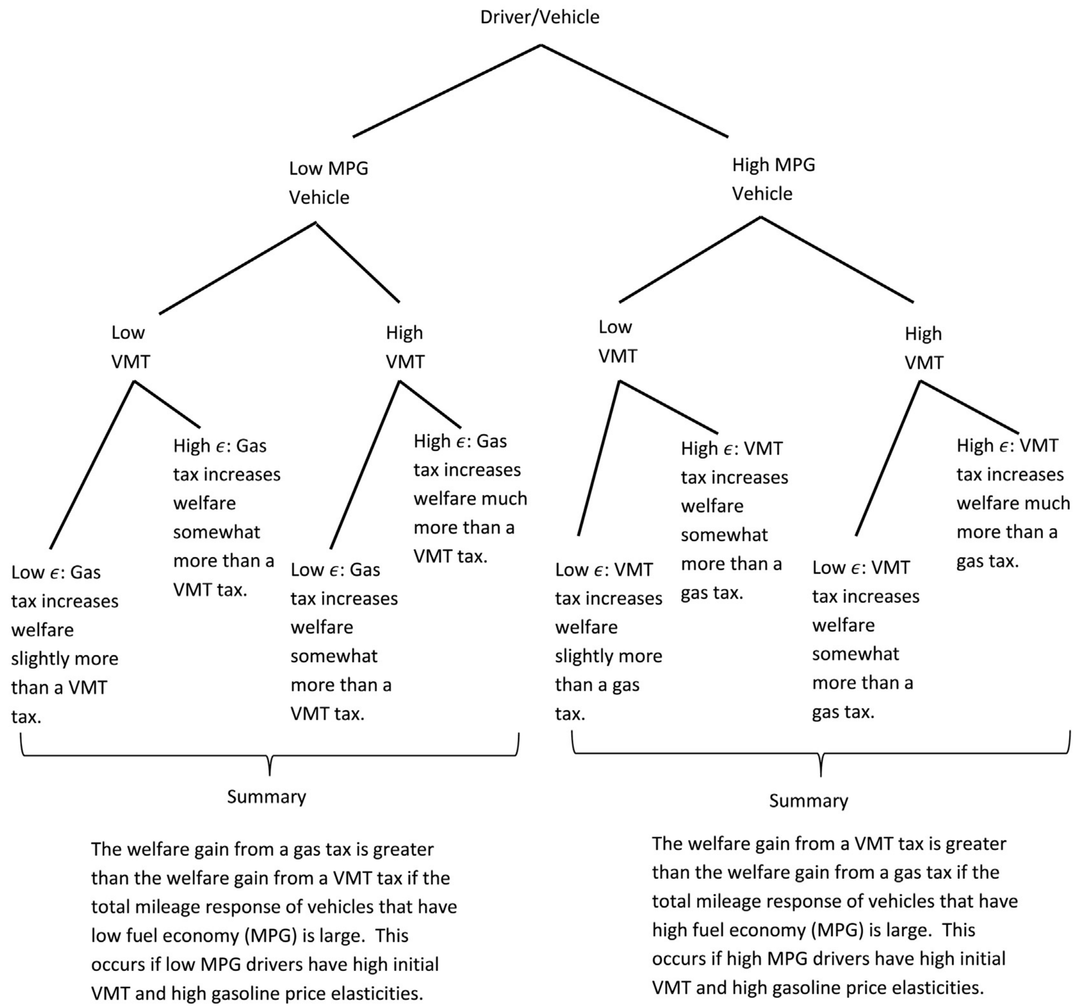

Fig. 1. Comparative welfare effects of a gasoline and VMT tax for different types of drivers and vehicles.

high ε. We assume we are not fully internalizing the observed fuel consumption, congestion, and safety automobile externalities; thus, social welfare is improved by taxes that increase a driver's cost per mile and reduce a driver's fuel consumption and VMT. As noted, a gasoline tax increases the price of driving a mile the most for drivers of fuel-inefficient vehicles and a VMT tax increases the price of driving a mile the most for drivers of fuel efficient vehicles; thus, a gasoline tax improves welfare more than a VMT tax does as the share of drivers with low MPG vehicles increases, while the VMT tax improves welfare more than a gasoline tax does as the share of drivers with high MPG vehicles increases.

Of course, the relative welfare effects of the taxes also depend on drivers' behavior, VMT and their demand elasticities, and how their behavior interacts with their vehicles' fuel economy. The figure shows those interactions and provides a more comprehensive summary that indicates, subject to certain conditions, that the welfare gain from a given gasoline tax is greater than the welfare gain from a given VMT tax when drivers' vehicles have low MPG *and* drivers have a high VMT and demand elasticity because they reduce total mileage more than they would in response to a VMT tax.[28] Conversely, the relative welfare gain from a given VMT tax and a gasoline tax is even greater when drivers' vehicles have high MPG *and* drivers have a high VMT and demand elasticity because they reduce total mileage by more than they would in response to a gasoline tax.

In sum, the important measure for determining the comparative welfare effects of the two taxes is the weighted average of the total mileage response, as determined by the elasticity and initial VMT, of low MPG drivers compared with the response by high MPG drivers. If low MPG drivers' total response is larger, then the gasoline tax improves welfare by more than the VMT tax does. If high MPG drivers' total response is larger, then the VMT tax improves welfare by more than the gasoline tax does.[29]

4.1. Initial findings

In the initial simulations presented in Tables 3 and 4, we compare the effects of a 31.2 cent per gallon gasoline tax and a 1.536 cent per mile VMT tax because each tax reduces total fuel consumption by 1%, and we compare the effects of a 40.8 cent per gallon gasoline tax and a 1.99 cent per mile VMT tax because each tax raises $55 billion per year for highway spending. In light of the preceding discussion that

[28] There are two relevant conditions. First, the division between “low” and “high” MPG is the fuel economy that sets the VMT tax equal to the gasoline tax divided by fuel economy; thus, the division varies based on the particular VMT tax and gasoline tax being compared. Second, the comparisons assume that the per-mile externality and the per-gallon externality are fixed, but the benefits of a gasoline tax also increase relative to a VMT tax as the per-gallon externality increases relative to the per-mile externality (and vice versa).

[29] In accordance with the composition of VMT between risky drivers and their vehicles and less risky drivers and their vehicles, the total mileage response could also affect the safety externality because of driver heterogeneity. In particular, accidents are likely to increase if the change in VMT increases the probability that a risky driver driving a large car will hit a driver in a smaller car. However, we do not know how the changes in VMT induced by the gasoline and VMT taxes would affect this probability; thus, we do not analyze the safety externality any further here, but we suggest that more detailed data would facilitate pursuit of this potentially important issue.

Table 3
Annual net benefits ($2013) from a gasoline tax and VMT tax to reduce fuel consumption 1%.

	31.2 cent/gal gas tax	1.536 cent/mile VMT tax
Effect on:		
VMT (billion miles)	−29.5	−30.6
Consumer Surplus ($billions)	−42.4	−42.9
Government Revenues ($billions)	42.2	42.7
Congestion ($billions)	−2.84	−2.94
CO_2 ($billions)	−0.56	−0.57
Accidents ($billions)	−1.61	−1.67
Local Air Pollution ($billions)	−0.35	−0.36
Total External Costs ($billions)	−5.4	−5.5
Net Benefits ($billions)	5.1	5.3

Source: Authors' calculations. Some columns may not sum precisely due to rounding. Total external costs include a government service externality and a local air pollution externality in addition to the congestion, accident, and CO_2 externalities listed.

Table 4
Annual net benefits ($2013) from a gasoline tax and VMT tax to raise $55 billion per year for highway spending.

	40.8 cent/gal gas tax	1.99 cent/mile VMT tax
Effect on:		
VMT (billion miles)	−38.0	−39.1
Consumer Surplus ($billions)	−55.4	−55.5
Government Revenues ($billions)	55.0	55.2
Congestion ($billions)	−3.66	−3.76
CO_2 ($billions)	−0.73	−0.72
Accidents ($billions)	−2.07	−2.13
Local Air Pollution ($billions)	−0.45	−0.46
Total External costs ($billions)	−6.9	−7.1
Net Benefits ($billions)	6.5	6.7

Source: Authors' calculations. Some columns may not sum precisely due to rounding. Total external costs include a government service externality and a local air pollution externality in addition to the congestion, accident, and CO_2 externalities listed.

explained why heterogeneous drivers could potentially have different responses to the two taxes and that the taxes could potentially have different welfare effects, it is surprising that we find that the gasoline and VMT taxes have remarkably similar effects on the nation's social welfare in the process of reducing fuel consumption and raising highway revenues.[30]

The gasoline and VMT taxes reduce fuel consumption 1%, while they increase annual welfare by $5.1 billion and $5.3 billion respectively via reductions in the various external costs, especially congestion and accidents, with the loss in consumer surplus and increase in government revenues essentially offsetting each other. We reach virtually the same conclusion for a gasoline and VMT tax that each raise $55 billion per year for highway spending, as annual welfare is increased by $6.5 billion and $6.7 billion respectively. To be sure, our externality estimates suggest that the externality per mile is substantially larger than the externality per gallon that is expressed per mile, which suggests that a given decrease in VMT would reduce automobile externalities more than would a comparable decrease in gasoline consumption.[31] But from the perspective of the framework in Fig. 1, we did not find notable differences in the welfare effects of the two taxes because the weighted average of the mileage responses of the various sub-groups that comprise drivers of high fuel-economy vehicles and that comprise drivers of low fuel-economy vehicles was similar.

We stress that without a disaggregate model, we could not perform the preceding simulations because it would be very difficult to know the magnitude of the VMT tax that is appropriate to compare with a gasoline tax to achieve the same reduction in fuel consumption and the same increase in highway revenues, and to properly account for the change in externalities that is critical for the welfare assessment.

4.2. Extending the analysis

As noted, policymakers have generally preferred to use tighter Corporate Average Fuel Economy standards to increase fuel economy.[32] But by raising overall fuel economy and fuel economy for certain types of vehicles, a change in CAFE standards will also change the effect of a VMT tax or increased gasoline tax on welfare. Indeed, the most recent CAFE standards call for new passenger cars and light trucks to achieve average (sales-weighted) fuel efficiencies that were projected to be as high as 34.1 miles-per-gallon by 2016 and 54.5 miles-per-gallon by 2025.[33] To meet those standards, it is reasonable to assume that over time average vehicle fuel efficiency will improve considerably from its current sales-weighted average of roughly 25 miles-per-gallon. Because it is not clear how, if at all, other attributes of a vehicle may change with more stringent fuel economy standards, we assume other non-price vehicle attributes remain constant.[34]

Another relevant consideration for our analysis is that because the (marginal) costs of local pollution and congestion externalities associated with driving are significantly greater in urban areas than they are in rural areas, efficiency could be enhanced by differentiating a VMT tax in urban and rural geographical areas to reflect the different externality costs. As described earlier, the technology that is used to implement a state-wide VMT tax could be refined to differentiate that tax for specific geographical areas in a state. It is much harder to implement an urban-rural differentiated gasoline tax that is based on a motorist's driving patterns because that tax is paid when gasoline is purchased. Thus, motorists could fill up their tank in a lower-taxed rural area and use most of the gasoline in the tank in a higher-taxed urban area.

We explore the effects of those changes in the context of our highway funding policy by recalculating the welfare effects of gasoline and VMT taxes that raise at least $55 billion per year for highway spending under the assumptions that (1) average automobile fuel economy improves 40%, which is broadly consistent with projections in the Energy Independence and Security Act of 2007[35] and with policymakers' recent CAFE fuel economy goals, and (2) the VMT tax is differentiated for automobile travel in urban and rural counties. Given the first assumption, we determine the rebound effect by assuming that when vehicle fuel economy increases 40%, the cost of driving a mile decreases by a corresponding amount and that the increase in motorists' VMT is determined by our empirical model.

We stress that our assumption that every vehicle's fuel economy is 40% greater is due to technological change caused by an exogenous policy

[30] All gasoline and VMT taxes presented in our simulation results are in addition to the state and federal gasoline taxes that currently exist. In order to use our sample of Ohio motorists to extrapolate results to the national level, we used the results from our sample for March 2013 and assumed that it was reasonable to scale them so they applied for an entire year. We used our county-level weights to get an annual estimate of the welfare effects for the state of Ohio and then scaled that result to the nation by assuming that an Ohio resident was representative of a U.S. resident in March 2013 (using an inflator of 316.5 million (U.S. Population)/11.5 million (Ohio Population)).

[31] Parry (2005) reached a similar conclusion based on the parameter values he assumed.

[32] Higher gasoline taxes (or the introduction of a VMT tax) might also induce automobile firms to innovate more in fuel efficiency. For example, Aghion et al. (2016) find that higher tax-inclusive fuel prices encourage automobile firms to innovate in clean technologies.

[33] President Trump announced that he would reconsider the Obama administration's initiative that automakers must achieve an average 54.4 miles per gallon across their fleets by 2025. However, any efforts to roll back those standards would undoubtedly be contested in court by state regulators and environmental groups.

[34] A complete welfare analysis of CAFE is beyond the scope of this paper; thus, we treat the implementation of CAFE as exogenous and we do not account for higher vehicle prices and other changes in non-fuel economy vehicle attributes. Those effects would not change the relative welfare effects of a gasoline and VMT tax.

[35] http://georgewbush-whitehouse.archives.gov/news/releases/2007/12/20071219-1.html.

shock (i.e., higher CAFE standards). Although we do not model new vehicle adoption jointly with VMT, it is reasonable to assume that there will be a future period in which each vehicle's fuel economy is 40% greater because of the standards, especially because new footprint-based CAFE standards (which are a function of vehicle size) provide an incentive for automakers to increase all of their vehicles' fuel economy. We also assume that our original VMT model parameter estimates are not affected by the change in fuel economy, which means that drivers would not adjust their response to a change in the price-per-mile if they drove more fuel efficient vehicles because of a higher CAFE standard. We perform sensitivity analysis by exploring the effects of alternative assumptions about how the new CAFE standards would affect vehicle fuel economy.

To solve for differentiated urban and rural VMT taxes, we assume that the ratio of the urban to rural VMT tax is equal to the ratio of the urban to rural marginal external cost of driving a mile. Therefore, we first need to calculate the total (per mile and per gallon) externality for urban and rural driving. We do so by calculating the monthly weighted average urban and rural fuel economy using the percentage of the population in each vehicle's county that is urban, which results in an average urban fuel economy of 21.28 MPG and an average rural fuel economy of 21.11 MPG in March 2013. We therefore assume that the urban climate externality is the same as the rural climate externality at $0.0185 per mile. Thus the total urban marginal external cost of a mile is $0.2365 and the rural marginal external cost of a mile is $0.0565 for a ratio of 4.19. Each driver's vehicle is then assumed to be driven in urban or rural areas in the same proportion as the population of the driver's county. So, for example, if a driver lives in a county where 80% of the population is urban, then we assume that before the differentiated VMT tax is implemented that 80% of the miles of the driver's vehicle are urban. Finally, we determine the taxes that satisfy the preceding ratio and that generate at least $55 billion per year.

We present the effects of each assumption on social welfare separately in Tables 5 and 6 and jointly in Table 7. Table 5 shows the effects on VMT and social welfare if automobile fuel economy grows 40%; thus, the gasoline tax is increased even more, to nearly 55 cents/gal, to generate revenues of at least $55 billion annually. The original VMT tax of 1.99 cents per mile raises somewhat more than $55 billion annually, but we do not change the tax because we believe that it would be unlikely that federal transportation policymakers would reduce an existing tax to produce a lower stream of highway revenues. Note also that the same VMT tax of 1.99 cents per mile in the preceding Table 4 generates results that are different from those in Table 5 because the vehicles associated with the results in Table 5 are 40% more efficient than the vehicles associated with the results in Table 4. So, the base cost per mile is lower, which means that people drive more and that a VMT tax of 1.99 cents per mile creates a larger percentage change in the cost of driving, resulting in a larger change in VMT and higher government revenues.

Given the base case that fuel economy has improved 40% under current automobile taxation policy, we find that motorists' vehicle miles traveled would decrease 3.5 billion miles more under a new VMT tax than they would under an increase in the gasoline tax. Recall that technological advance that leads to an increase in vehicle fuel economy will generally lead to an increase in vehicle miles traveled (the rebound effect), but this response will be better mitigated by a VMT tax than by a gasoline tax because post-CAFE-vehicles use less fuel per mile. To be sure, the higher gasoline tax does reduce fuel consumption more efficiently than a VMT tax, but the social benefit of those savings is small relative to the reduction in external costs, especially congestion and accidents, caused by lower VMT. Accordingly, as implied by the framework in Fig. 1, the VMT tax increases welfare by more than the gasoline tax does because it has a greater effect on the total mileage responses of all drivers.[36]

Table 5
Annual net benefits ($2013) from a gasoline tax and VMT tax to raise at least $55 billion per year for highway spending, assuming average automobile fuel economy improves 40%.

	54.9 cent/gal gas tax	1.99 cent/mile VMT tax
Change in:		
VMT (billion miles)	−53.5	−57.0
Consumer Surplus ($billions)	−55.5	−57.9
Government Revenues ($billions)	55.0	57.3
Externalities ($billions)	−9.4	−9.9
Net Benefits ($billions)	8.9	9.4

All changes are relative to a 40% improvement in fuel economy without either tax in place.
Source: Authors' calculations. Some columns may not sum precisely due to rounding.

Table 6
Annual net benefits ($2013) from a gas tax and differentiated urban-rural VMT tax to raise at least $55 billion per year for highway spending.

	Gas tax (40.8 cent/gallon)	Differentiated VMT tax (0.575 cent/rural mile and 2.409 cent/urban mile)
Change in:		
VMT (billion miles)	−38.0	−36.1
Consumer Surplus ($billions)	−55.4	−55.4
Government Revenues ($billions)	55.0	55.0
Externalities ($billions)	−6.9	−7.9
Net Benefits ($billions)	6.5	7.5

Source: Authors' calculations. Some columns may not sum precisely due to rounding.

Table 6 shows that when we differentiate the VMT tax by increasing it in urban areas to 2.4 cents per mile and decreasing it in rural areas to 0.575 cents per mile, it reduces automobile externalities and increases total welfare by more than the original gasoline tax of 40.8 cents per gallon does, even though the VMT tax has a smaller effect on total VMT. Thus, by differentiating the tax, it provides a second instrument to better tailor the tax to the external cost of driving and reduce the most socially costly VMT. The result—more than a 15% increase in net benefits compared with the gasoline tax—suggests that even this relatively minor differentiation of the VMT tax could improve welfare substantially.

Finally, when we simultaneously account for both improvements in fuel economy and introduce an urban-rural differentiated VMT tax in Table 7, we find that if policymakers want to raise at least $55 billion per year for highway spending while also implementing higher CAFE standards, then a differentiated VMT tax would produce a $10.5 billion annual increase in social welfare, which amounts to a $1.6 billion or nearly a 20% improvement in social welfare compared with an increase in the gasoline tax that could generate revenues to fund the same amount of highway spending. Moreover, the differentiated VMT tax's efficiency advantage over the gasoline tax would increase if that tax were more precisely differentiated in accordance with the variation in automobile externalities, especially congestion, in every U.S. metropolitan area.

An urban-rural differentiated VMT tax also appears to have favorable distributional effects. Fig. 2 shows that the difference between the loss in consumer surplus from a gasoline tax and the urban-rural differentiated VMT tax with a 40% increase in fuel economy increases with average household income. In fact, the highest income categories account for most of the difference between the two taxes' effect on consumer surplus because higher-income drivers are more likely than lower-income drivers to live in urban areas where their VMT imposes greater externalities.[37]

We also explored how the distributional effects of the differentiated VMT tax varied by county characteristics and we found, not surprisingly,

[36] In practice, improvements in fuel economy would not be homogeneous across vehicle makes because some automakers would have to increase their fleet's fuel economy significantly to comply with more stringent standards (e.g., the American automakers), and other automakers would be near full compliance and have to increase their fleet's fuel economy only slightly (e.g., Honda and Hyundai). Accounting for automaker fuel economy heterogeneity would not change our overall finding on the relative efficacy of a VMT tax compared with a gasoline tax, but the potential rebound effect for the least fuel efficient vehicle fleets would be greater than the potential rebound effect for the most fuel efficient vehicle fleets.

[37] Recall that we do not have drivers' individual incomes and we therefore measure income as the average household income of the zip-code where the driver lives, which reflects the fact that incomes are higher in urban zip-codes.

Table 7
Annual net benefits ($2013) from a gas tax and differentiated urban-rural VMT tax to raise at least $55 billion per year for highway spending, assuming fuel economy increases by 40%.

	Gas tax (54.9 cent/gallon)	Differentiated VMT tax (0.575 cent/rural mile and 2.409 cent/urban mile)
Change in:		
VMT (billion miles)	−53.5	−52.2
Consumer surplus ($billions)	−55.5	−57.6
Government revenues ($billions)	55.0	57.0
Congestion ($billions)	−5.13	−6.12
CO_2 ($billions)	−0.73	−0.69
Accidents ($billions)	−2.90	−3.46
Local air pollution	−0.62	−0.75
Total external costs ($billions)	−9.4	−11.0
Net Benefits ($billions)	8.9	10.5

Source: Authors' calculations. Some columns may not sum precisely due to rounding. Total external costs include a government service externality and a local air pollution externality in addition to the congestion, accident, and CO_2 externalities listed.

that (1) the most populous counties reap the largest benefits because they have the greatest VMT, and (2) the most urbanized counties reap the largest benefits because they incur the greatest external costs of driving.

As discussed below, those distributional effects increase the relative political attractiveness of a differentiated VMT tax, but distributional considerations do place a political limit on the extent that efficiency improvements can be pursued. A first-best tax policy without a 40% improvement in fuel economy (see appendix Table A1), where emissions taxes are based on gasoline consumed and congestion, accident, and local air pollution charges are based on VMT, would result in a loss of nearly $500 billion of consumer surplus in return for a net welfare gain of $28 billion. And although the welfare gain increases with a 40% improvement in fuel economy, the far more modest differentiated VMT tax analyzed here to finance a specific increase in highway spending would generate a notable share of the first-best benefits with much less redistribution that would undoubtedly raise insurmountable political objections.

4.3. Robustness and qualifications

We have found that an urban–rural differentiated VMT tax is more efficient and, in all likelihood, more progressive than a gasoline tax. However, it is important to subject that finding to some sensitivity tests and appropriately qualify it. First, we compared the gasoline and differentiated VMT tax under the assumption that the new CAFE standards would result in a 40% improvement in the fuel economy of all vehicles. Alternatively, we conducted the comparison under the assumptions that automakers would satisfy the new fuel economy standards by: (1) improving the fuel economy of only their most fuel efficient vehicles (specifically, the fuel economy of vehicles at or above the median fuel economy was increased by 70%; the fuel economy of other vehicles was unchanged), and (2) improving the fuel economy of only their least fuel efficient vehicles (specifically, the fuel economy of vehicles below the median fuel economy was increased by 90%; the fuel economy of other vehicles was unchanged). The difference between the welfare improvement from a differentiated VMT tax and a gasoline tax slightly increases under the first assumption and it slightly decreases under the second assumption, but welfare improves from a differentiated tax by at least 17% more than from a gasoline tax.

Second, it is useful to consider how the findings have been affected by our allowing for heterogeneity in the price elasticity. As shown in the bare-bones model in the first column of Table 2, if we did not do so, the estimated price coefficient would be −0.1497, which is less than the estimated weighted average price coefficient of −0.1548 that we obtain when using the estimates in the last column of the table.

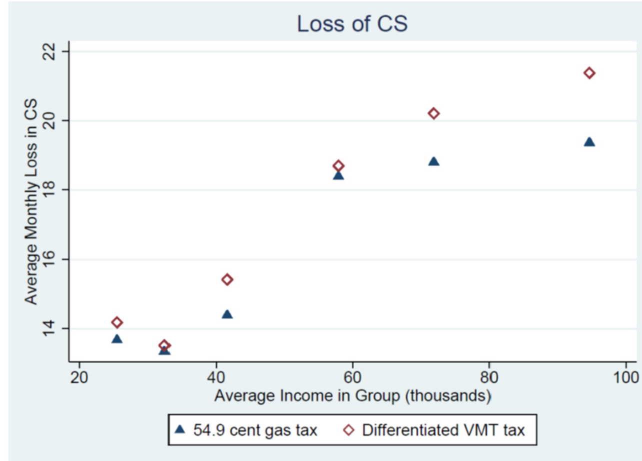

Fig. 2. Comparative distributional effects of a gasoline tax and a differentiated VMT tax.

Using the coefficients in the bare-bones model to perform our welfare calculations, we find for the same scenario in Table 7 (a 40% improvement in fuel economy and the introduction of a differentiated urban/rural VMT tax) that the differentiated VMT tax still generates roughly a 22% higher welfare gain than the gasoline tax generates, but the magnitude of both welfare gains increase because: (1) the high-VMT drivers are less price elastic than are low-VMT drivers; thus, the lower price elasticity applies to a larger number of miles and $55 billion for highway spending can be raised with a smaller gasoline and VMT tax, which results in a smaller loss in consumer surplus; and (2) for a given revenue target, the lower price elasticity results in a smaller change in VMT, which is the source of welfare improvement. Thus, the welfare gains are smaller in our model that allows for heterogeneity in the price coefficient; but, of course, that model does a more precise job than the homogeneous model does of measuring which motorists are changing their behavior in responses to the taxes and of measuring the tax levels that would achieve the fuel and revenue goals and the changes in externalities that would result from those taxes.

Our analysis should also be qualified for several reasons. First, we pointed out that we do not have a random sample of motorists; instead, the sample consists of motorists who drive newer cars than do motorists in the population. Thus we tested for whether drivers of older cars in our sample (defined as more than four years old) have a different response to changing gas prices than do other drivers and we found the effect was highly statistically insignificant and small. Of course, older cars in our sample are not as old as cars found in the general population, but our finding indicates that there is little evidence of bias within our data. We found in Table 2 that newer vehicles are driven more than older vehicles, which might increase our welfare gains but not necessarily the relative welfare effects of the gas and VMT taxes. Finally, it is reassuring that the characteristics of people in our sample are comparable to the characteristics of people in Ohio and the U.S. populations. And we did correct for any potential selectivity bias in the one variable where the sample characteristics differed from the characteristics in the Ohio population by constructing sampling weights based on county population and we found that our basic findings on the relative efficiency effects of the gasoline and VMT tax did not change.[38] At the same time, it is possible that the sample has prevented us from capturing some distributional effects for lower-income motorists who may be underrepresented in the sample.

Second, it is possible that the multi-vehicle households in our sample engage in less intra-household vehicle substitution than do multi-

[38] In Table 7, the welfare benefits from a differentiated VMT tax are 18% higher than the benefits from a comparable gasoline tax. If instead we conduct the analysis without weights, the welfare benefits of a differentiated VMT tax are still 18% higher than the benefits from comparable gasoline taxes.

vehicle households in the population because the household head tended to be the primary, if not exclusive, driver of the vehicle for which State Farm collected data.[39] Greater household vehicle substitution caused by a higher gasoline tax could effectively increase the average fuel efficiency per mile driven and reduce gasoline tax revenues and the per-mile externality benefits of a gasoline tax. But a VMT tax would not have this effect on household behavior and highway revenues.

Third, we assumed that motorists' share of urban and rural miles is proportional to the population of their counties. Departures from this assumption may affect the extent of the benefits of the differentiated VMT tax; but they will not affect the general point that a plausible urban-rural differentiated VMT tax will generate larger welfare gains compared with a uniform VMT tax.

Finally, in a long-run analysis, motorists can reduce the cost of a gasoline and VMT tax by purchasing more fuel efficient vehicles and by changing their residential location (for example, by moving closer to work to reduce their commuting costs). It is possible that those taxes may have different effects on households' vehicle and housing investments, but we have no evidence to characterize those different effects.[40] Generally, households' vehicle purchases and utilization in the long run are uncertain and this uncertainty suggests that it is important to assess how the two taxation policies affect households' actual driving and social welfare in their current vehicles in the presence of CAFE.

Of course, allowing consumers to make additional utility maximizing responses to an efficient policy change should increase welfare if those responses do not generate additional external costs. We have found that social welfare gains from the taxation policies increase when we assume motorists drive more fuel efficient vehicles and that a differentiated urban-rural VMT tax produces greater welfare gains than a gasoline tax produces. Motorists may change their residential locations and by moving closer to work, they would increase social welfare by reducing fuel consumption and VMT. However, such responses would reduce highway revenues and may call for higher gasoline and VMT taxes than in our previous case to meet revenue requirements.[41] Similarly, drivers may purchase more fuel efficient vehicles in response to a gasoline tax, which would increase fuel savings but potentially lead to a rebound effect with more vehicle miles traveled. Determining how those long-run responses would affect the relative welfare effects of a gasoline and a differentiated VMT tax is an important avenue for future research but beyond the scope of this study.

5. Further considerations in our assessment

We pointed out that distributional considerations—namely, progressivity and geographical effects—appear to favor a new VMT tax over raising the federal gasoline tax. Further political considerations do so as well. Congress's steadfast refusal to raise the federal gasoline tax since 1993 is consistent with polls indicating that large majorities of Americans oppose higher taxes on gasoline (see, for example, Nisbet and Myers (2007)). Indeed, strong opposition to higher state gasoline taxes also exists as indicated by New Jersey, which had the second lowest gasoline tax in the country, shutting down hundreds of highway projects in the summer of 2016 because state lawmakers failed to reach a deal to raise the gas tax. Subsequently, New Jersey raised its gasoline tax but only after it cut its sales taxes and started phasing out its estate tax.

Kaplowitz and McCright (2015) found that motorists' support for gasoline taxation was unaffected regardless of whether they were informed of (1) the actual pump price of gasoline, (2) hypothetical variations in actual fuel prices, and (3) high gasoline prices in other advanced countries. Given that we estimate that a 54.9 cents per gallon gasoline tax would be necessary to finance additional annual highway spending, in addition to the current federal gasoline tax of 18.4 cents per gallon, voters are likely to be overwhelmed by nearly a four-fold increase in the gasoline tax.

The federal gasoline tax is also associated with inefficient government expenditures. Since the 1950s, it has been used to comprise the federal Highway Trust Fund that finances federal highway spending. Winston and Langer (2006) argued that trust fund expenditures have been significantly compromised by formulas that do not efficiently allocate the majority of revenues to the most congested areas of the country and by wasteful earmarks or demonstration projects. And in recent years, policymakers and commentators have repeatedly pointed out that the gasoline tax is associated with a funding stream that is insufficient to keep the highway system in good repair.

In contrast, a VMT tax represents a new more efficient policy, which does not have the gas tax's tainted reputation, and it may be less subject to voter concerns that the revenues it generates would be wasted and produce little improvement in automobile travel.[42] To be sure, efficient spending of a centrally collected transportation tax may fall prey to political pressures at all levels of government. However, an advantage of a VMT tax is that it bears a direct connection to motorists' demand for automobile travel, and the transparency of that connection would hopefully expose inefficient allocations of the revenues that are raised.

Generally, policymakers have a status quo bias toward existing policies and are more inclined to introduce a new policy, such as a VMT tax, instead of reforming a current one, such as the gasoline tax.[43] A differentiated VMT tax may also be more politically palatable than the gasoline tax because its level of 0.575 to 2.409 cents per mile, which we estimate would fund the same amount of additional annual highway spending as an increased gasoline tax, appears to be "small."

Another important consideration is salience. Li et al. (2014) found that consumers respond more to gas tax changes than to gas price fluctuations. Unfortunately, we cannot use our data to provide additional evidence on this matter or to determine whether consumers would respond more to a new VMT tax than to a gasoline tax increase or vice-versa, especially because the method that policymakers would use throughout the country to collect VMT taxes is not clear. We can say that a less salient tax may be more politically palatable, but it would result in lower net benefits because drivers' responses to the tax would be lower (Finkelstein (2009)).

On balance, it appears that (1) the long-run resistance to raising the gasoline tax, (2) its association with inefficient and widely criticized government policy, and (3) the new approach represented by a seemingly small but relatively efficient VMT tax that is currently being tested in actual driving environments suggest that the VMT tax offers political advantages over raising the gasoline tax.

[39] The lack of intra-household vehicle substitution here may differ from the extent of such substitution that researchers have found for drivers in other contexts (for example, Gillingham (2014)).

[40] For example, both taxes may encourage motorists to purchase more fuel efficient vehicles, but to "downgrade" their vehicle quality by not purchasing certain expensive options. It is not clear which tax, if either, may cause greater downgrading by motorists.

[41] Langer and Winston (2008) found that households changed their residential locations in response to congestion costs and that the greater urban density resulting from congestion pricing produced a significant gain in social welfare. Although we do not account for the externalities caused by urban sprawl in this work, including those costs would increase the welfare gains of the gas and VMT taxes.

[42] Highways have also not been built and maintained optimally (Small et al. (1989)), and are subject to regulations that inflate their production costs (Winston (2013)). However, it is not clear that the funds from a VMT tax could be allocated only to highways that do not suffer from those inefficiencies.

[43] Marshall (2016) argued that the problem of regulatory accumulation exists because government keeps creating new regulations, but almost never rescinds or reforms old ones.

In the long run, it is expected that the nation will adopt a fleet of driverless vehicles, which will improve fuel economy and reduce operating costs by reducing congestion and stop and go driving (Langer and McRae (2016)). Similar to an exogenous increase in fuel economy caused by higher CAFE standards, the improved traffic flow would increase the relative social benefits of VMT taxes. From a political perspective, it is noteworthy that Congressman Earl Blumenauer of Oregon has argued that the same data collection platform that is being used in the OreGO pilot project could easily integrate VMT charges as part of a payment platform for driverless vehicles and even tailor those charges to peak-period travel.[44] Karpilow and Winston (2016) and Winston (2017) suggest that auto travelers may be more likely to accept differentiated VMT taxes in the new driving environment because a notable fraction of them would find it economically advantageous to not own cars, but to simply order them when they need transportation as part of a subscription service. Hence, the perception of VMT taxes may change because ride-sharing travelers would be accustomed to paying a charge per use that includes surge charges and tolls, as many pay today with Uber and Lyft, so differentiated VMT taxes may be perceived as similar to those charges.

6. Conclusion

Although motorists' demand for automobile travel is one of the most extensively examined topics in applied economics, we have filled an important gap in the empirical literature by showing the importance of taking a disaggregate approach to properly specify and estimate the effect of the price of a vehicle mile traveled on VMT, which has enabled us to provide what appears to be the first national assessment of the efficiency and distributional effects of a VMT tax using disaggregate panel data. Our assessment has also considered the efficiency and distributional effects of a gasoline tax and some other relevant factors.

Given state and federal policymakers' interest in a practical solution to the projected ongoing shortfall in highway funding, our assessment is timely and important and shows that a differentiated VMT tax could (1) raise revenues to significantly reduce the current and future deficits in the Highway Trust Fund, (2) increase annual social welfare $10.5 billion, and (3) dominate a gasoline tax designed to generate an equivalent revenue stream on efficiency, distributional, and political grounds. Our findings therefore support the states' planning and implementation of experiments that charge participants a VMT tax and potentially replace their gasoline tax with it, and they support the federal government implementing a VMT tax instead of raising the federal gasoline tax.

As noted, a major potential efficiency advantage in the long run of the VMT tax over the gasoline tax is that it could be implemented to vary with traffic volumes on different roads at different times of day. And it could also be implemented to vary with pollution levels in different geographical areas at different times of the year and with the riskiness of different drivers to set differentiated prices for motorists' road use that could accurately approximate the true social marginal costs of automobile travel. At the same time, we have indicated that such charges would entail a significant gain in government revenues but a significant cost in consumer surplus. If policymakers implement a VMT tax to stabilize highway funding, we recommend that they carefully explore the potential efficiency advantages of aligning the tax with varying externalities created by different types of highway travel, while mindful that distributional effects limit the extent to which they can pursue efficiency improvements.

[44] Earl Blumenauer, "Let's Use Self-Driving Cars to Fix America's Busted Infrastructure," *Wired*, May 20, 2016.

Appendix A. Appendix

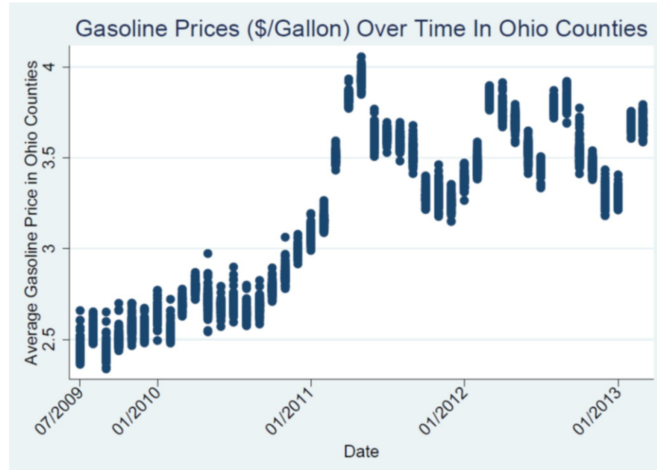

Fig. A1. Behavior of gasoline prices ($/gal) over time in Ohio counties.

Table A1
Annual net benefits ($2013) from a first-best combination of gasoline and VMT taxes.

	39.3 cent/gal gas tax, 21.8 cent/urban mile and 3.8 cent/rural mile VMT tax	39.3 cent/gal gas tax, 21.8 cent/urban mile and 3.8 cent/rural mile VMT tax if fuel economy increases 40%[a]
Change in:		
VMT (billion miles)	−863	−989
Consumer surplus ($billions)	−521	−520
Government revenues ($billions)	389	379
Congestion ($billions)	−85.3	−97.5
CO_2 ($billions)	−16.3	−13.4
Accident ($billions)	−48.3	−55.2
Local air pollution	−10.4	−11.9
Total external costs ($billions)	−160	−178
Net benefits ($billions)	28.6	36.7

Source: Authors' calculations. Some columns may not sum precisely due to rounding. Total external costs include a government service externality and a local air pollution externality in addition to the congestion, accident, and CO_2 externalities listed.
[a] All changes are relative to a 40% improvement in fuel economy without either tax in place.

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