Vehicle Carbon Dioxide Emissions and the Compactness of Residential Development

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Abstract

Vehicle carbon dioxide (CO_2) emissions have concerned many policymakers and researchers. Although the existing literature indicates that vehicle miles traveled (VMT) have been studied extensively, little research has examined household gasoline consumption directly. This study analyzes the effects of geographic, household characteristics and compactness of subdivisions on gasoline consumption, which can be converted to CO_2 emissions directly. The data used come from the 2001 National Household Travel Survey. The results show that VMT declines as the compactness of subdivisions increases, but vehicles tend to be driven at less efficient speeds in more compact subdivision. The reduced efficiency in driving speed is not strong enough to totally offset the reduced VMT, however, so that gasoline consumption and the associated CO_2 emissions still tend to be lower in more compact developments.

Introduction

Vehicle use and carbon dioxide (CO_2) emissions have attracted substantial attention in recent years. According to the Energy Information Administration (EIA), CO_2 has the largest effect on global warming of any monitored greenhouse gas.[1] About 33 percent of total U.S. greenhouse gas emissions are generated from the transportation sector, and, among these, CO_2 emissions represent 95 percent of the greenhouse gas emissions from mobile transportation sources (EPA, 2007).

[1] Other greenhouse gases include methane, nitrous oxide, various hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride.

Concerns about these numbers and their possible implications for climate change issues have prompted states such as California, Massachusetts, and Washington to require that developers quantify greenhouse gas emissions from vehicle use in large residential projects they are planning. California and Massachusetts currently do not provide any guidance on how to perform the calculations. King County in Washington actually provides a spreadsheet that enables developers to estimate greenhouse gas emissions for various types of development, with calculations based largely on national averages that use relatively little information about the nature of homes being built other than basic structure type (see http://www.metrokc.gov/permits/info/site/ClimateChange.aspx). Although the spreadsheet is useful in the sense that it enables developers to estimate emissions (as required by local ordinance) and, therefore, provides a mechanism that allows development to be approved, it provides little guidance on how a particular development may be better planned and executed to help reduce emissions. A need remains for statistical models that are able to estimate variables such as vehicle miles traveled (VMT) and CO_2 emissions from vehicle use at the level of a typical development and to show how they are related to characteristics of the development.

This article estimates household gasoline consumption and associated CO_2 emissions using data from the 2001 National Household Travel Survey (NHTS) and least square regressions to estimate gasoline consumption as a function of the geographic and household characteristics available in the NHTS data. Housing units per acre is used as a proxy for the compactness of a residential subdivision, and the estimates show how vehicle use, CO_2 emissions, and other related household travel variables respond to changes in subdivision compactness.

Following this introductory section, the second section of this article reviews the relevant literature. The third section addresses the NHTS data set. The fourth section explains how the equations to be estimated were constructed, and the fifth section presents and discusses the results. A separate section is devoted to subdivision compactness, because it is an explanatory variable of special interest; this section includes a discussion of why subdivision compactness may be related to travel behavior and how to interpret the results in light of complications such as self-selection. The final section offers a conclusion of the findings.

Literature Review

The relationship between built environment and travel has been heavily researched in the past two decades. More than 60 studies are covered in a survey article by Ewing and Cervero (2001). The features of the built environment analyzed in these studies is quite varied, but the dependent variables studied are usually trip frequencies, trip lengths, mode of transportation, person miles traveled, and either vehicle hours traveled (VHT) or VMT.

Cervero and Radisch (1996) modeled the number of trips per person and the probabilities of using a mode of transportation other than automobile, using a sample from the San Francisco Bay Area. They controlled for different neighborhood designs including traditional, mixed-use neighborhoods, and newer neighborhoods with separated land uses and curvilinear streets. Their results show that nonwork trip frequencies are similar for the two Bay Area communities studied and that transportation modes other than automobile are more likely to be used for nonwork trips in a traditional neighborhood.

Holtzclaw (1994) studied the impact of community density measures on average VMT per household and found that VMT is lower at higher household densities. The data set Holtzclaw used is also a regional sample from the San Francisco Bay Area. Ewing (1995) examined the impact of gross residential/employment density of traffic zones on VHT per household, using a data set from Palm Beach County, Florida. Frank, Stone, and Bachman (2000) studied both VMT and VHT per household, while controlling for household density and employment density. They found that in the Seattle area, VMT and VHT are lower in areas of high household density and employment density.

Recently, Glaeser and Kahn (2008) studied the CO_2 emissions from cars and air conditioners in large metropolitan areas. They found that low-density development, particularly in the South, is associated with far more CO_2 emissions than is higher density construction.

An issue that arises in such studies is whether estimated relationships between travel and built-environment variables are due to a selection effect—for example, individuals who prefer to drive less select pedestrian- or transit-friendly environments—or are due to an environment effect—for example, pedestrian- or transit-friendly environments cause individuals to drive less.

Handy (2005) reviewed the empirical evidence regarding the relationship between the built environment and physical activity behaviors. She pointed out that the available evidence on the question of self-selection is limited. A few papers tried to explore the possibility of self-selection, including Greenwald and Boarnet (2001), who used neighborhood characteristics as instrumental variables to control for self-selection; in addition, Bagley and Mokhtarian (2002) provided a more sophisticated analysis using a structural equations modeling approach. Other papers tried to control for self-selection using other methods, such as a quasi-experimental design by Handy and Mokhtarian (2005); to tease out selection effects they compared residents who had recently moved into eight neighborhoods in northern California with residents of the same neighborhoods who had lived there for more than 1 year. Cao, Mokhtarian, and Handy (2006) reviewed more than two dozen studies that attempted to control for self-selection in some fashion and reported that virtually every one of these studies still found that some aspect of the built environment had a statistically significant influence on travel behavior.

The NHTS Data

Much of the research on travel behavior uses specialized data sets from specific local areas. The conclusions drawn from these studies may be quite useful but are often difficult to generalize to the national level. When a national data set is employed to analyze household behavior, it is often from the NHTS (see http://nhts.ornl.gov/), which the Federal Highway Administration (FHWA) in the U.S. Department of Transportation conducts at somewhat irregular intervals. The stated purpose of the NHTS is to provide information to assist transportation planners and policymakers who need comprehensive data on travel and transportation patterns in the United States. The NHTS is designed to capture all trips undertaken by all household members in all households; it is not limited to work travel behavior.

Data for the most recent survey (officially titled the 2001 NHTS) were collected through computer-assisted telephone interviews between March 2001 and May 2002. The survey was based on list-assisted random digit dialing design, employing a systematic sampling technique to generate a representative sample of all U.S. households with telephones. The 2001 national NHTS design was based on a sampling rate of roughly 1 in every 4,000 U.S. households. The response rate was approximately 80 percent.

In principle, the NHTS can be used to analyze any of the travel behavior variables described in the survey article by Ewing and Cervero (2001). Of these variables, VMT is likely to have the strongest correlation with gasoline consumption and CO_2 emissions, although gasoline consumption will also depend on the type of vehicles owned and how they are driven.

In this regard it is interesting to note that the NHTS data set also includes an explicit estimate of gasoline consumed per household. Because greenhouse gas emissions and climate change are issues of increasing public interest, and because CO_2 emissions can be computed directly from gasoline consumption using a simple conversion factor available from the EIA, it is perhaps peculiar that the NHTS gasoline consumption variable has not been used more often.

The primary purpose of this study is to analyze the effects of compactness of development and other possible explanatory factors on gasoline consumption and CO_2 emissions. To facilitate comparison with other studies, however, and to show how CO_2 emissions are related to other aspects of vehicle use, this study also analyzes VMT, the efficiency of the vehicles owned, and the efficiency of the speed with which vehicles are driven.

To conduct the analysis, it is necessary to derive some vehicle use variables from the raw numbers in the NHTS microdata set. For households that own more than one vehicle, the average efficiency of the vehicles owned (in miles per gallon) is derived as a weighted average for each vehicle in the household, with the weights determined by VMT for each vehicle. Average speed driven is calculated as the household's total miles driven on all trips in a recorded travel day divided by total hours spent on these trips.[2] The inefficiency of the speed with which the vehicles are driven is computed as the difference between the average speed household vehicles are driven and the theoretical optimal speed of 45 miles per hour.[3]

Data on the built environment in the 2001 NHTS may seem limited compared to a wish list of variables land use planners would like to investigate, but a number of useful geographic variables are available. The NHTS data do not identify individual states but indicate the four principal Census regions. The data set also indicates whether a household is in a metropolitan statistical area

[2] The NHTS contains several data files, including household, person, vehicle, and travel day trips files. We merged all other data files to household files to obtain needed information. For example, VMT and gasoline consumption are from the vehicle file, and total miles driven and total hours spent on these trips are from the travel day trips file.

[3] The FHWA's measure of vehicle efficiency adjusts for many factors, such as average miles driven per day, seasonal temperature variations, humidity, and road surface conditions. FHWA uses average miles driven per day to categorize most of the driving done as "highway" or "city." Highway driving is assumed to be characterized by less frequent stops, long trip length, and, thus, greater efficiency; city driving is assumed to be characterized by more frequent stops, short trip length, and, thus, lower efficiency. The NHTS data do not contain enough information, however, to reproduce the FHWA's estimates of vehicle efficiency. Instead, we calculated the difference between average trip speed and a theoretical optimal speed. The optimal speed is considered to be about 45 miles per hour for motor vehicles with internal combustion engines, as reported in Ewing et al. (2007). Speeds above or below this "sweet spot" should result in lower efficiency and higher gasoline consumption.

(MSA) and provides some information about the MSA's population, although it does not identify individual metropolitan areas specifically. The NHTS data also indicate whether a home is located in an MSA with a rail transportation system, although they include no information about how close the transportation system comes to a particular home.

Perhaps of more interest, especially to residential land developers, is the fact that the NHTS data contain information about the block group (size in square miles and number of housing units) in which a particular household is located. Block groups are defined by the Census Bureau to capture approximately 500 housing units on average, roughly equivalent to the size of many residential subdivisions. Thus, density of development in a block group, measured in housing units per square mile, provides information at a scale that the actions of individual developers can influence—subject to restrictions imposed by local government approval and zoning decisions. For convenience, housing units per square mile is converted to housing units per acre and referred to as "subdivision compactness." The NHTS data do not show the compactness of the subdivision precisely, but group it into six categories—ranging from fewer than 0.08 units per acre, to more than 7.81 units per acre.[4]

When investigating effects of a subdivision attribute on travel behavior, it is important to control for household characteristics as much as possible. Household and housing unit characteristics available in the 2001 NHTS microdata file include gender, race, age, education level of the householder, household income, household size, whether the unit is single-family detached, and whether the unit is owner occupied. Income is measured by six categories, with the lowest income category to be the excluded category.[5]

The NHTS has one national sample and nine add-on samples that cover smaller geographic areas. We used the national sample in this study. The national sample contains two types of households: "100 percent households" and "usable households." A 100 percent household means 100 percent of household adults finished the survey; a usable household means more than 50 percent of the household adults finished the survey. We used the 100 percent households sample to avoid potential bias caused by the missing information in a household, which left us a sample size of 22,178.

Some key variables in this sample have missing values. Exhibit 1 shows the descriptive statistics and the number of nonmissing observations for each variable we used. In general, the number of missing observations is small but is highest for the travel-related measures that are used as dependent variables in the models. Thus, the size of the sample used in each model is restricted primarily by the number of nonmissing observations for the dependent variable. Since the number of missing values is relatively small, however, the bias resulting from item nonresponse should not be excessive. We used the weights that are provided in the data set for the purpose of inflating the national sample to the total number of 107 million households in the United States.

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[4] The categories seem to break at odd places because in the data set the variable is expressed as housing units per square mile. We converted this to housing units per acre to generate a measure that is easier to visualize, but it results in categories that break at odd fractions of a housing unit.

[5] The six household income categories are the following: income under $20,000, income $20,000–$34,999, income $35,000–$49,999, income $50,000–$64,999, income $65,000–$79,999, income $80,000 and more. In the exhibits, these six categories are adjusted for inflation and are shown in 2007 dollars.

Exhibit 1

Descriptive Statistics

Variable	Percent/Average	Nonmissing Observations
Gallons of gasoline used	1,130	20,532
Vehicle miles traveled	23,926	20,850
Efficiency of vehicles owned (miles per gallon)	20.6	20,520
Inefficiency of speed driven*	18.8	19,100
Single-family detached home	67.7%	22,178
Owner-occupied home	70.2%	22,178
Number of persons in household	2.6	22,178
Number of workers in household	1.4	22,178
Male householder	40.5%	22,178
Black householder	9.6%	21,986
Hispanic householder	8.2%	21,986
Other minority householder	12.7%	21,986
Share of householders with at least a bachelor's degree	32.0%	22,098
Age of householder	48.6	22,178
Household income**		20,814
Below $23.5K	22.6%	
$23.5 to $41.1K	19.2%	
$41.1K to $58.8K	19.4%	
$58.8K to $76.4K	11.7%	
$76.4K to $94.0K	9.7%	
$94.0K and up	17.4%	
Block group density		22,178
Fewer than 0.08 unit per acre	14.4%	
0.08 to 0.39 unit per acre	13.9%	
0.39 to 1.56 units per acre	21.1%	
1.56 to 4.69 units per acre	31.0%	
4.69 to 7.81 units per acre	9.1%	
7.81 units or more per acre	10.5%	
Region		22,178
Northeast	19.1%	
Midwest	23.5%	
South	36.2%	
West	21.2%	
Metropolitan/urban characteristics		22,178
MSA with rail transport system	27.7%	
Urban, nonmetropolitan	8.8%	
Rural, nonmetropolitan	11.3%	
Rural, MSA population under 1 million	5.0%	
Urban, MSA population under 1 million	18.2%	
Rural, MSA population 1 to 3 million	2.4%	
Urban, MSA population 1 to 3 million	19.3%	
with density < 0.39 unit per acre	1.5%	
Rural, MSA population 3 million and up	1.9%	
Urban, MSA population 3 million and up	33.2%	
with density < 0.39 unit per acre	1.9%	

MSA = metropolitan statistical area.

**Measured as the difference from the theoretic optimal speed of 45 miles per hour.*

***Income categories are adjusted for inflation and shown in 2007 dollars.*

Source: 2001 National Household Travel Survey, Federal Highway Administration

On average, each household observed in the NHTS data set represents about 4,800 U.S. households. The average weight in the NHTS is about twice the value of the average weight in the American Housing Survey,[6] but it is much smaller than the average weights in other governmental surveys that collect detailed information on household behavior, such as the Consumer Expenditure Survey (about 17,000) and the Residential Energy Consumption Survey (about 22,000). The Bureau of Labor Statistics conducts the Consumer Expenditure Survey primarily to establish the weights in the Consumer Price Index. The EIA conducts the Residential Energy Consumption Survey to provide information on the use of energy in residential housing units in the United States. The only nationally representative survey that has drastically lower average weight than any of the surveys mentioned above is the American Community Survey, but it is not comparable because it does not collect very detailed information about household behavior.

Estimating Equations

The models estimated in this study are single equation regressions, where the dependent variable is one of the following: gasoline consumption, VMT, average efficiency of vehicles owned, and inefficiency of the speed at which the vehicles are driven. The explanatory variables include the household, housing unit characteristics, and geographic characteristics—including the measure of subdivision compactness—shown in exhibit 1. The general approach is to be inclusive and use all relevant information available in the NHTS to mitigate, to the extent possible, bias resulting from omitted variables.

To adjust for social and economic differences among households, the models employ a list of NHTS variables that has been established for this purpose—specifically, the NHTS-based set of travel forecasting models called the Transportation Analysis and Simulation System (TRANSIMS), which the Environmental Protection Agency and the U.S. Department of Energy have developed.[7] The TRANSIMS operates by generating "synthetic households" for a particular area, usually based on Census data, and then applying a simulation model to those households. The output of the simulation is travel behavior for households that have the characteristics of the synthetic households. This study employs simple regressions rather than a simulation model, but the data set used is the same as the one used to calibrate the TRANSIMS simulation—the NHTS—and the regression models employ all the NHTS household and housing unit characteristics that are used in the TRANSIMS.

In an attempt to make complete use of the geographic information available in the NHTS, we tried all the regional, metropolitan area, and urban-rural status variables as explanatory variables in the models in addition to the measure of subdivision compactness. The number of these variables is not large, and they are primarily categorical, so we tried many cross-product effects (for example, urban-rural status of the area crossed with the population size category of the MSA), and we

[6] In the 2006 American Housing Survey, 18,535 observations have weights equal to zero. The average weight is calculated with these observations excluded.

[7] For more information, see http://tmip.fhwa.dot.gov/transims/. For more information about creating synthetic households, see the paper by Beckman, Baggerly, and McKay (1995).

retained any that produced a regression coefficient of an economically significant magnitude in the final model.

In general, we did not use statistical significance as a criterion for retaining geographic variables in the models. None of the models, for instance, showed a statistically significant difference between the Midwest and the West census regions, yet the models retain a separate indicator variable for the Midwest region. Exhibit 1 shows descriptive statistics for all the variables used in any of the models.

Regression Results

Results of regressing household gasoline consumption, VMT, vehicle efficiency, and the inefficiency of the speed driven on the explanatory variables discussed previously, one equation at a time using ordinary least squares (OLS), are shown in exhibit 2.

The results show that household and housing unit characteristics all have effects on gasoline consumption that are statistically significant at the .01 level. In particular, the model estimates that gasoline consumption tends to be higher for households that are larger, contain more workers, have higher incomes, own their homes, live in single-family homes, are younger, are less well educated, and are headed by someone who is male, white, or Hispanic.

Some of these results (such as the finding that larger households use more gasoline) are quite intuitive. Others (such as some of the effects of race and ethnicity on gasoline consumption) are perhaps more surprising. It is important to remember that the model controls for all these factors (as well as the factors mentioned in other sections of the article) simultaneously. Thus, when the model finds that households with higher incomes tend to consume more gasoline over the course of a year, this finding is concluded after controlling for the size, incomes, race, and other factors of the household—as well as for characteristics of the area in which the home is located, to the extent those characteristics are available in the data.

The gasoline consumption model also finds that, all else being equal, gasoline consumption tends to be lowest for households in the Northeast region and highest for households in the South region. The strongest result the gasoline consumption model finds among the urban and metropolitan area variables is that households in urban areas consume less gasoline than households in rural areas, although, for the sake of completeness, the model analyzes all urban/metropolitan-size combinations available in the data. For example, the model estimates that a household in an urban area in an MSA with a population under 1 million consumes about 276 fewer gallons of gas than a household living in a rural area not in an MSA, all else being equal.

Nevertheless, the model estimates that a household would on average use about 70 fewer gallons of gas if it were in an MSA with access to rail transportation. Although we know that rail commuting is available in a limited number of metropolitan areas and that a minority of households uses rail transportation, the presence of rail transportation reduces gasoline consumption by about 70 gallons per household.

Most, but not all, of the geographic effects in the gasoline consumption model are significant at the .01 level, despite the fact that many of the explanatory variables are likely to be collinear. For

Exhibit 2

OLS Estimate (1 of 2)

Independent Variable	Dependent Variables							
	Gallons of Gasoline Used		Vehicle Miles Traveled		Efficiency of Vehicles Owned (mpg)		Inefficiency of Speed Driven**	
	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.
Intercept	694	39.3	14832	833	21.95	0.22	10.20 *	0.47
Single-family detached home	95.8 *	15.6	1645 *	331	– 0.66 *	0.09	0.02	0.19
Owner-occupied home	72.0 *	16.3	1297 *	346	– 0.66 *	0.09	– 0.60 *	0.19
Number of persons in household	93.5 *	5.28	1789 *	112	– 0.33 *	0.03	0.18 *	0.06
Number of workers in household	264 *	8.20	6384 *	175	0.51 *	0.05	– 1.02 *	0.10
Male householder	101 *	12.1	1633 *	258	– 0.18 *	0.07	– 0.54 *	0.14
Black householder	– 80.8 *	21.0	– 1201 *	444	0.34 *	0.12	1.28 *	0.25
Hispanic householder	26.4	34.6	315	731	– 0.38	0.19	1.33 *	0.41
Other minority householder	– 72.2 *	28.5	– 1072	605	0.66 *	0.16	0.13	0.34
Householder has at least a bachelor’s degree	– 87.8 *	13.9	– 1294 *	296	0.96 *	0.08	– 0.03	0.16
Age of householder	– 2.84 *	0.45	– 61.0 *	9.52	– 0.03 *	0.00	0.12 *	0.01
Household income $23.5K to $41.1K	31.4	18.4	720	388	0.36 *	0.10	– 1.57 *	0.22
Household income $41.1K to $58.8K	168 *	18.9	3285 *	401	0.32 *	0.11	– 2.40 *	0.23
Household income $58.8K to $76.4K	278 *	22.5	5241 *	477	0.17	0.13	– 3.51 *	0.27
Household income $76.4K to $94.0K	315 *	24.5	5753 *	523	0.04	0.14	– 3.17 *	0.29
Household income $94.0K and up	464 *	22.3	8597 *	474	– 0.32 *	0.12	– 3.27 *	0.26
0.08 to 0.39 unit per acre	– 91.3 *	24.0	– 1600 *	510	0.76 *	0.13	1.63 *	0.28
0.39 to 1.56 units per acre	– 93.0 *	28.9	– 1886 *	614	0.63 *	0.16	2.29 *	0.34
1.56 to 4.69 units per acre	– 201 *	29.8	– 4248 *	635	0.57 *	0.17	4.34 *	0.35
4.69 to 7.81 units per acre	– 218 *	35.3	– 4623 *	749	0.65 *	0.20	6.09 *	0.42
7.81 units or more per acre	– 312 *	37.4	– 6574 *	795	0.47	0.21	7.81 *	0.45
Living in Northeast Region	– 83.9 *	19.5	– 1803 *	415	0.68 *	0.11	1.02 *	0.23
Living in Midwest Region	13.9	18.2	65.0	388	0.23	0.10	0.38	0.22
Living in South Region	70.2 *	16.8	1100 *	358	0.25 *	0.09	– 0.17	0.20
MSA with rail transport system	– 73.4 *	25.4	– 865	539	0.62 *	0.14	0.92 *	0.30

Exhibit 2

OLS Estimate (2 of 2)

Independent Variable	Dependent Variables							
	Gallons of Gasoline Used		Vehicle Miles Traveled		Efficiency of Vehicles Owned (mpg)		Inefficiency of Speed Driven**	
	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.
Rural, MSA population under 1 million	– 109 *	31.1	– 2589	662	– 0.07	0.17	0.37	0.37
Urban, MSA population under 1 million	– 276 *	30.2	– 5445 *	643	0.01	0.17	3.93 *	0.36
Rural, MSA population 1 to 3 million	25.8	41.4	– 129	878	0.04	0.23	0.26	0.49
Urban, MSA population 1 to 3 milion	– 272 *	32.8	– 5114 *	698	0.64 *	0.18	3.50 *	0.39
with density <0.39 unit per acre	77.8	54.6	1,733	1165	– 0.43	0.30	– 0.5	0.64
Rural, MSA population 3 million and up	65.6	49.2	384	1052	– 0.4	0.27	0.65	0.59
Urban, MSA population 3 million and up	– 190 *	37.1	– 3816 *	790	– 0.05	0.21	2.98 *	0.44
with density <0.39 unit per acre	86.7	49.8	510	1061	– 0.2	0.28	– 1.55 *	0.59
Urban, nonmetropolitan	– 171 *	30.3	– 3425 *	646	– 0.41	0.17	3.40 *	0.36
Number of observations used	20,356		20,673		20,353		18,948	
Adjusted R square	0.2705		0.2645		0.0742		0.1786	

mpg = miles per gallon. MSA = metropolitan statistical area. OLS = ordinary least square.

**Coefficient is significant at 1-percent level.*

***Measured as the difference from the theoretic optimal speed of 45 miles per hour.*

example, income is likely to be correlated with race and owner occupancy; subdivision density is likely to be correlated with urban-rural status. The effect of collinearity is to increase the standard errors on the coefficients of the relevant explanatory variables and reduce the statistical significance of the coefficients. In general, this collinearity does not seem to be a problem in the gasoline consumption model.[8]

We conducted a thorough sensitivity analysis on the gasoline consumption model to determine how the coefficients vary in the absence of some explanatory variables. The results are shown in the appendix, where columns (1) through (5) show the coefficients with some explanatory variables excluded. We find that the coefficients on household and housing unit characteristics are robust regardless of whether geographic and compactness variables are included. When the household and housing unit variables are excluded from the model, we find that the adjusted R-square drops significantly and the coefficient on intercept increases dramatically. This finding means that excluding such variables creates serious omitted variable bias, and thus it is crucial to include them in the model.

The compactness variables have negative effects on gasoline consumption in all sensitivity checks, and the magnitude increases while the compactness increases. When we exclude some explanatory variables from the model, however, the magnitude is, in general, bigger than the case when we include the full set of variables. This result implies that the omitted variables enlarge the effects of subdivision compactness. Therefore, the model we chose to estimate consists of all the relevant information and thus is least likely to have omitted variable bias.

By itself, the VMT model provides little insight on household travel behavior that is not evident in the gasoline consumption model. The statistical significance and relative size of the coefficients on the explanatory variables within each of the two regressions, in general, are similar.

Factors that increase gasoline consumption have a tendency to also increase the efficiency of the speeds at which the vehicles are driven. For example, additional workers in a household are associated with increased gasoline consumption but also with reductions in the inefficiency of the speeds at which the vehicles are driven. An urban location in a metropolitan area is associated with a relatively strong reduction in gasoline consumption but also with an increase in the inefficiency of driving speeds. It is possible to interpret this as a congestion effect (less efficient driving speeds).

The model for efficiency of vehicles owned has less explanatory power than the others shown in the exhibit, with an adjusted R-square under .1 and fewer coefficients on independent variables that are statistically significant. Nevertheless, some of the results are potentially interesting—for example, all else being equal, a household headed by someone who has at least a bachelor's degree tends to own vehicles that get about 1 more mile to the gallon than vehicles owned by households headed by someone who does not have at least a bachelor's degree.

[8] In addition, we tested the explanatory variables for multicollinearity using the Variance Inflation Factor. The test statistics show no significant evidence of multicollinearity in the model.

Subdivision Compactness

The explanatory factor that is the primary focus of this study is the block-group, housing-unit density or "subdivision compactness" variable. To illustrate the effect of this particular variable, exhibit 3 uses the regression results to estimate annual gasoline consumption and CO_2 emissions for a hypothetical subdivision with 100 households, assuming the average household and housing unit characteristics, under different assumptions about the subdivision's compactness. Gasoline consumption—the variable estimated in the model—is converted directly into CO_2 emissions by applying the factor obtained from the EIA, which is based on the number of carbon atoms in a gallon of gasoline and assumes complete combustion.[9]

The exhibit shows that the estimated gasoline consumption decreases as the subdivision becomes more compact, controlling for the household and geographic factors available in the NHTS data. For example, the estimated gasoline consumption is about 90,700 gallons for a subdivision of 100 households and a density of 1.56 to 4.69 units per acre. As the subdivision becomes more compact, the estimated gasoline consumption decreases to less than 80,000 gallons in the case where the density is more than 7.81 housing units per acre. Because CO_2 emissions are computed as a simple ratio of gasoline consumption, CO_2 emissions also decline in exhibit 3 as the subdivision becomes more compact, controlling for other factors.

This finding raises a question—why, since typical vehicle use undoubtedly involves many trips beyond the boundaries of an individual subdivision, would subdivision compactness matter? Several hypotheses are possible. One possible explanation is that homes located closer to each other foster social interactions among neighbors, leading to a tendency to occasionally visit neighbors rather than drive to a relatively remote location for entertainment. This explanation would be generally consistent with the findings of Glaeser and Sacerdote (2000) that individuals in large apartment

Exhibit 3

Estimated Annual CO_2 Emissions From Vehicles for 100 Housing Units

Compactness of Subdivision (housing units per acre)	Estimated Results				
	CO_2 Emissions (1,000 lbs.)	Gasoline Used (1,000 gals.)	Vehicle Miles Traveled (1,000 mi.)	Efficiency of Vehicles Owned (mpg)	Inefficiency of Speed Driven*
Fewer than 0.08	2,313.9	119.5	2,472	20.7	16.0
0.08 to 0.39	2,137.2	110.4	2,312	21.4	17.7
0.39 to 1.56	1,965.9	101.5	2,232	21.5	19.9
1.56 to 4.69	1,756.7	90.7	1,996	21.4	21.9
4.69 to 7.81	1,724.6	89.1	1,958	21.5	23.7
7.81 or more	1,542.9	79.7	1,763	21.3	25.4

mpg = miles per gallon.

**Measured as the difference from the theoretic optimal speed of 45 miles per hour.*

Notes: Estimates for an urban subdivision in a northeastern metropolitan area with a population of 3 million and up and a rail transport system. Distribution of household and housing unit characteristics as shown in exhibit 1.

[9] The conversion factor is 19.36 pounds of CO_2 per gallon of gasoline used. The EIA routinely uses the assumption of complete consumption to estimate CO_2 generated by burning fossil fuels (EIA, 2007).

buildings are more likely to socialize with their neighbors and to socialize in public spaces within the neighborhood. Large apartment buildings by their nature, of course, tend to be associated with compact subdivisions.

Another possible explanation is that, within a particular metropolitan area, development tends to be denser near employment or shopping centers, and the compactness variable would be acting as a proxy for the closeness to employment and shopping centers. Even in these cases, however, it would be plausible to argue that subdivision compactness may in some cases play a causal role—for example, if a somewhat densely settled residential area induces strip malls and shopping centers to be built nearby.

A similar chicken-or-egg argument could be made for public transportation. Dense residential development could be induced near a transportation node, or a transportation node could be deliberately placed so that it is near dense development. The data available in the NHTS do not enable us to distinguish between these or other alternative hypotheses, but they do allow us to demonstrate that a significant relationship between subdivision compactness and gasoline consumption persists after controlling for a substantial number of other factors.

The question of self-selection still remains. The models do not distinguish the case in which households first determine their travel behavior and then choose a compact subdivision that accommodates this behavior from the case in which households first choose a compact subdivision environment that subsequently influences their travel behavior.

We tend to agree with Ewing et al. (2007) who, in chapter 4, conclude that, from a public policy perspective, it may not always be important to distinguish self-selection from the case in which environment influences behavior. If the available supply of existing housing in a particular market area does not perfectly accommodate households with a strong preference for reduced gasoline consumption, providing new housing in subdivisions with the right characteristics can give these households someplace to go. In this way, more compact development may lead to reduced gasoline consumption either by directly causing a change in household behavior or by accommodating households with a preexisting desire to drive less.

By some standards, the relationship between subdivision compactness and vehicle CO_2 emissions reported in exhibit 3 may seem relatively modest. Subdivisions that qualify to be in the bottom row of the table are more than 95 times more compact than subdivisions in the top row, yet gasoline consumption and CO_2 emissions in the bottom row are only about one-third lower. On the other hand, many would consider a one-third reduction in CO_2 emissions to be a significant achievement.

To further help place the compactness numbers in context, we note that 1.56 to 4.69 housing units per acre translates into about 0.21 to 0.64 acre per unit, which is a fairly typical lot size for new construction. About 31 percent of single-family detached homes completed in 2006 were built on lots falling into this size range. Nearly 80 percent are on lots that are 0.64 acre or smaller (exhibit 4). Lot sizes, in general, will be smaller, however, than acres per housing unit measured over a block group or subdivision, because a subdivision will also typically include roads and other public spaces.

Exhibit 4

Land per Housing Unit

Housing Units per Acre Categories in NHTS Data	Converted to Acres per Housing Unit	Lot Sizes for New Single-Family Detached Units Completed in 2006 (%)
7.81 or more	Fewer than 0.13 acre	23.3
4.69 to 7.81	0.13 to 0.21 acre	24.9
1.56 to 4.69	0.21 to 0.64 acre	31.2
0.39 to 1.56	0.64 acre to 2.56 acres	14.1
Fewer than 0.39	2.56 acres or more	6.5

NHTS = National Household Travel Survey.

Source: U.S. Census Bureau, 2006 Survey of Construction

Exhibit 3 also shows estimated VMT and vehicle/driving efficiency measures. It reveals relatively little relationship between efficiency of vehicles owned and subdivision compactness, except that residents in the least dense subdivisions tend to own less efficient vehicles. It does show, however, a relationship between subdivision compactness and the average speeds at which vehicles are driven. As the subdivision becomes more compact, the estimated results show that vehicles are driven fewer miles, but they tend to be driven at less efficient speeds. This congestion effect is not strong enough to completely offset the effect of reduced VMT. So, on balance, households in more compact development still tend to use less gasoline and thus generate fewer CO_2 emissions from vehicles.

Conclusion

The NHTS is the primary data set produced by the federal government for the purpose of analyzing household travel behavior. This article has shown how that data can be used to estimate the efficiency of vehicles owned, how far they are driven, how efficiently they are driven, the amount of gasoline they consume, and the associated CO_2 emissions for a particular subdivision. In turn, these estimates can be used to show how, controlling for the demographic and other geographic variables in the NHTS, these household travel variables are related to the compactness of the subdivision, measured in housing units per acre.

In particular, the estimates show that gasoline consumption and the associated CO_2 emissions decline as the compactness of a subdivision increases. In addition, the estimates show that vehicles tend to be driven at less efficient speeds as the compactness of a subdivision increases. The lack of efficiency, however, is not strong enough to offset the reduced VMT, so that the predicted gasoline consumption and CO_2 emissions still tend to be lower in a more compact development.

The statistical relationship between compactness of development and reduced consumption of gasoline does not necessarily prove that a causal relationship between the two variables exists, but it does demonstrate that increased compactness and reduced gasoline consumption are complementary in the sense that they tend to occur together. Local jurisdictions with a policy objective of reduced CO_2 should take this finding into account and at least consider the possibility of allowing more housing units to be built per acre of land as part of an overall strategy.

Appendix

Sensitivity Analysis (OLS Estimates) (1 of 2)

Independent Variable	Dependent Variable: Gasoline Consumption									
	(1)		(2)		(3)		(4)		(5)	
	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.
Intercept	367	33.1	686	35.6	1467	25.74	1406	24.76	629 *	38.6
Single-family detached home	145 *	15.5	97.8 *	15.6					113 *	15.4
Owner-occupied home	146 *	16.4	79.3 *	16.3					86.4 *	16.3
Number of persons in household	96.3 *	5.37	91.5 *	5.29					95.3 *	5.29
Number of workers in household	264 *	8.36	262 *	8.22					263 *	8.22
Male householder	100 *	12.3	101 *	12.1					98.5 *	12.1
Black householder	– 130 *	20.8	– 67.0 *	20.6					– 91.6 *	20.9
Hispanic householder	– 20.1	35.2	34.6	34.7					12.2	34.6
Other minority householder	– 107 *	29.0	– 73.9 *	28.5					– 74.4 *	28.6
Householder has at least a bachelor's degree	– 131 *	14.1	– 91.9 *	13.9					– 92.8 *	13.9
Age of householder	– 3.62 *	0.46	– 3.04 *	0.45					– 2.89 *	0.45
Household income $23.5K to $41.1K	22.2	18.8	28.7	18.5					30.9	18.4
Household income $41.1K to $58.8K	152 *	19.3	165 *	19.0					170 *	18.9
Household income $58.8K to $76.4K	247 *	22.9	272 *	22.5					280 *	22.5
Household income $76.4K to $94.0K	262 *	24.9	304 *	24.5					319 *	24.6
Household income $94.0K and up	401 *	22.3	451 *	22.1					472 *	22.3
0.08 to 0.39 unit per acre			– 166 *	21.7			– 84.4 *	27.3		
0.39 to 1.56 units per acre			– 286 *	20.0			– 140 *	32.9		
1.56 to 4.69 units per acre			– 415 *	18.9			– 299 *	33.9		
4.69 to 7.81 units per acre			– 449 *	25.8			– 407 *	39.8		
7.81 units or more per acre			– 565 *	27.6			– 578 *	41.6		
Living in Northeast Region					– 92.4 *	22.0	– 106 *	22.0	– 79.4 *	19.5
Living in Midwest Region					34.6	20.6	5.09	20.5	24.9	18.2
Living in South Region					46.6 *	18.7	3.44	18.8	89.8 *	16.7
MSA with rail transport system					– 53.0	28.8	– 9.30	28.8	– 88.0 *	25.3

Appendix

Sensitivity Analysis (OLS Estimates) (2 of 2)

Independent Variable	Dependent Variable: Gasoline Consumption									
	(1)		(2)		(3)		(4)		(5)	
	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.
Rural, MSA population under 1 million					– 72.0 *	35.3	– 51.9	35.4	– 128 *	30.8
Urban, MSA population under 1 million					– 420 *	25.2	– 227 *	34.4	– 391 *	22.2
Rural, MSA population 1 to 3 million					147 *	47.0	174 *	47.2	– 2.16	41.1
Urban, MSA population 1 to 3 milion					– 409 *	25.3	– 154 *	37.2	– 416 *	22.5
with density <0.39 unit per acre					306 *	55.9	95.2	62.3	167 *	48.9
Rural, MSA population 3 million and up					219 *	55.5	230 *	56.1	33.6	48.6
Urban, MSA population 3 million and up					– 329 *	32.2	– 66.6	42.1	– 340 *	28.4
with density <0.39 unit per acre					354 *	49.3	93.7	56.8	197 *	43.1
Urban, nonmetropolitan					– 295 *	30.1	– 175 *	34.6	– 247 *	26.3
Adjusted R square	0.2382		0.2635		0.0360		0.0496		0.2669	

MSA = metropolitan statistical area. OLS = ordinary least square.

**Coefficient is significant at 1-percent level.*

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