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Rebound 2007: Analysis of U.S. light-duty vehicle travel statistics

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ABSTRACT

U.S. national time series data on vehicle travel by passenger cars and light trucks covering the period 1966–2007 are used to test for the existence, size and stability of the rebound effect for motor vehicle fuel efficiency on vehicle travel. The data show a statistically significant effect of gasoline price on vehicle travel but do not support the existence of a direct impact of fuel efficiency on vehicle travel. Additional tests indicate that fuel price effects have not been constant over time, although the hypothesis of symmetry with respect to price increases and decreases is not rejected. Small and Van Dender (2007) model of a declining rebound effect with income is tested and similar results are obtained.

1. Introduction

Increasing energy efficiency is a critical strategy for mitigating greenhouse gas emissions and reducing petroleum consumption by motor vehicles. Every major automobile manufacturing economy in the world has adopted some form of fuel economy or greenhouse gas emissions standards for motor vehicles (An et al., 2007). Improvements in energy efficiency reduce the variable cost of energy services and thereby encourage greater use of energy services (Khazzoom, 1980). The increased consumption of energy services "takes back" some of the potential reduction in energy use and so could be an important determinant of the effectiveness of energy efficiency improvements as a means of reducing greenhouse gas emissions from transportation (Khazzoom et al., 1990). This basic economic response has been termed the "rebound effect" and a substantial literature has attempted to measure it (Sorrell, 2007).

The magnitude of the rebound effect for motor vehicles also matters because increased vehicle travel may generate external costs: traffic congestion, tailpipe emissions and, arguably, some component of the costs of vehicle crashes. If the rebound effect is large, these costs can be a significant consideration in the overall costs and benefits of policies to improve energy efficiency (Fischer et al., 2007).

Three types of rebound effect have been identified (Greening et al., 2000). The *direct rebound effect* occurs when an increase in the energy efficiency of a particular service decreases the overall cost of that service, thereby inducing an increase in consumption. *Indirect rebound effects* can result from changes in the consumption of other goods and services induced by the change in the price of a particular energy service. *Economy wide rebound effects* occur when a reduction in the demand for energy reduces its price, encouraging increased consumption in other areas. This paper is concerned only with estimating the direct rebound effect of improvements in light-duty vehicle efficiency.

The most important event in the recent history of passenger car and light truck energy efficiency in the United States was undoubtedly the enactment of the Corporate Average Fuel Economy (CAFE) standards. The standards were enacted in December of 1975 and became effective on model year 1978 vehicles. The standards required passenger car fuel economy to almost double and light truck fuel economy to increase by approximately 60% over 1975 levels (Fig. 1). Each manufacturer was required to meet the standards individually. Greene (1990) showed that in the early years the standards were not binding for many foreign manufacturers but were for domestic manufacturers. Thus, in these years the industry-wide average tends to exceed the standards. Passage of the CAFE law was motivated by the oil price shock and gasoline shortages of 1973–1974, which also motivated fuel economy improvement between 1974 and 1977.

The history of light-duty vehicle travel and fuel consumption since 1977 shows a clear decoupling of the two brought about by increasing fuel economy (Fig. 2). U.S. motorists are today consuming on the order of 80 billion gallons less fuel than they would have had vehicle use and fuel use continued to increase in direct proportion.

The following section presents the theory of the direct rebound effect and its relationship to the elasticity of vehicle travel with respect to the cost of fuel and fuel efficiency. Previous empirical estimates of the rebound effect for light-duty vehicles are reviewed next, highlighting unresolved issues, including the

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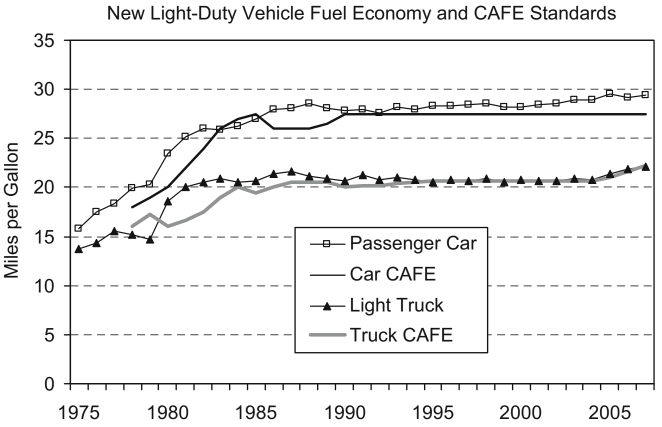

Fig. 1. New passenger car and light truck fuel economy and standards.

existence of a rebound effect for fuel economy, stability of the effect over time and the simultaneity of vehicle travel, fuel economy and vehicle stock. Section 4 describes the sources of the 1966–2007 national time series data used in this analysis, emphasizing that both the fuel economy and vehicle travel data depend to an important degree on estimation methods of the Federal Highway Administration (FHWA). Model specification, hypothesis tests and results are presented in Section 5.

2. Rebound effect of passenger car and light truck fuel economy

Travel by passenger cars and light trucks depends on a complex array of factors from the structure of the built environment and the supply of highway infrastructure to individuals' incomes and preferences. To move vehicles energy must be used and the cost of energy is the chief variable monetary cost of vehicle travel.[1] Gasoline or gasoline blended with up to 10% ethanol is the predominant source of energy to move light-duty motor vehicles in the United States and provides 98% of their energy needs, while diesel fuel provides only about 2% (Davis et al., 2008, Table 2.5).

Motor fuel consumption (F) is related to vehicle travel (V) and fuel economy in miles per gallon (E) by the identity: $F=V/E$. In the long run, both the amount of vehicle travel and the fuel economy of vehicles will be affected by the price of fuel (P). The price of fuel directly affects the amount of travel through the fuel cost per mile of travel ($P/E=Pe$, where $e=1/E$ is the rate of fuel consumption in gallons per mile). Economically rational consumers will consider not only the price of fuel, but the fuel cost per mile of travel in deciding how much to use their vehicles. The empirical evidence on whether motorists consider the fuel cost per mile or only the price of fuel is mixed (Greene et al., 1999; Small and Van Dender, 2005).

The price of fuel affects fuel use in the long run through the design of and technology embodied in motor vehicles when they are manufactured, as well as through the mix of vehicle sold.[2] Significant fuel economy improvements typically require completely redesigning vehicles from engines and transmissions to body shapes and materials. As a consequence, the full impact of fuel prices on the fuel economy of vehicles on the road evolves slowly over a period of about 15–20 years.[3] History confirms this timetable: the fuel economy improvements begun after 1975 were fully realized 15 years later in 1991 (Fig. 3). Over the period of a year or less, the average rate of fuel consumption per mile (e) for the stock of vehicles on the road can be influenced to a limited extent by the way vehicles are operated and maintained, and by marginal effects on new vehicle sales and used vehicle retirement.

The impact of a change in fuel economy on fuel use depends on the degree to which a reduction in the fuel cost per mile will induce more vehicle travel.[4] Taking the derivative of fuel use with respect to the rate of fuel consumption ($e=1/E$), it can be shown that the elasticity of fuel use with respect to the rate of fuel consumption ($\beta_{F,e}$) is equal to 1 plus the elasticity of vehicle travel with respect to fuel cost per mile ($\beta_{V,eP}$). Furthermore, the elasticities of vehicle travel with respect to the rate of fuel consumption (gallons per mile) is equal to the elasticity with respect to fuel cost per mile, which is equal to the elasticity of vehicle travel with respect to the price of fuel. Since fuel consumption is the inverse of fuel economy, the elasticity of vehicle travel with respect to fuel economy is the negative of the elasticity with respect to fuel consumption:

$$\beta_{F,e} = \frac{dF}{de}\frac{e}{F} = \frac{dV}{d(eP)}\frac{eP}{V} + \frac{eV}{F} = \beta_{V,eP} + 1$$

$$\beta_{V,e} = \frac{dV}{d(eP)}\frac{d(eP)}{de}\frac{e}{V} = \frac{dV}{d(eP)}P\frac{e}{V} = \beta_{V,eP} = \frac{dV}{d(eP)}e\frac{P}{V}$$

$$= \frac{dV}{d(eP)}\frac{d(eP)}{dP}\frac{P}{V} = \beta_{V,P} \qquad (1)$$

Dimitropoulos and Sorrell (2006) have termed $\beta_{V,e}$ definition 1 of the rebound effect and $\beta_{V,eP}$ definition 2. Most often, fuel cost per mile (eP) is used as a right-hand-side variable for empirical estimation. However, the rebound effect is concerned with the effect of changes in fuel efficiency, not the price of gasoline. Therefore, the more preferred empirical approach should be to test the impacts of the rate of fuel consumption (definition 1) and gasoline price separately and then to test the restriction on their coefficients implied by definition 2.

The theoretical exposition above assumes that fuel economy or fuel prices change while other things remain equal. In particular, the capital cost of motor vehicles is assumed to remain constant. In effect, the fuel efficiency improvement is assumed to be the result of pure technological change. When fuel economy increases

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[1] The other, significant variable cost is the traveler's time, which in most cases will be larger than the cost of fuel. For example, a traveler who values his time at $20/hr. and travels at an average speed of 40 mph is spending $0.50/mile in time cost. If his vehicle gets 20 mpg and gasoline costs $2.60/gallon, his fuel cost is $0.13/mile.

[2] Over a period as short as one year, the fuel economy of the stock of vehicles on the road is approximately constant, determined by their masses and the technology embodied in their designs. This is only approximately true because the on-road fuel economy of vehicles can be affected by fuel prices via how they are driven and changes in the relative use of more versus less efficient vehicles.

(*footnote continued*)
Empirically, these effects have been found to be very small, however (Greene et al., 1999; Greene and Hu, 1984).

[3] The design and tooling of vehicles is fixed two years in advance. Manufacturers redesign one-fifth to one-eighth of their product offerings each year in order to spread out capital expenditures and make efficient use of engineering resources. Thus, complete redesign of *new* vehicle offerings can be accomplished over a period of 5–10 years. These new vehicles gradually replace the existing stock of vehicles as older vehicles are retired. Simulations indicate that a cycle of fuel economy improvement requires 15–20 years for completion.

[4] As Dimitropoulos and Sorrell (2006, p. 7) point out, decreasing the energy costs of vehicle travel can also lead to an indirect rebound effect via a shift in sales towards larger or more powerful vehicles. This effect would need to be distinguished from changes in preferences due to increased income and other factors. When fuel economy increases are mandated by regulation sales shifts to larger, more powerful vehicles may be prevented. However, when the fuel economy standards differ for different vehicle types, such a substitution effect could be relevant.

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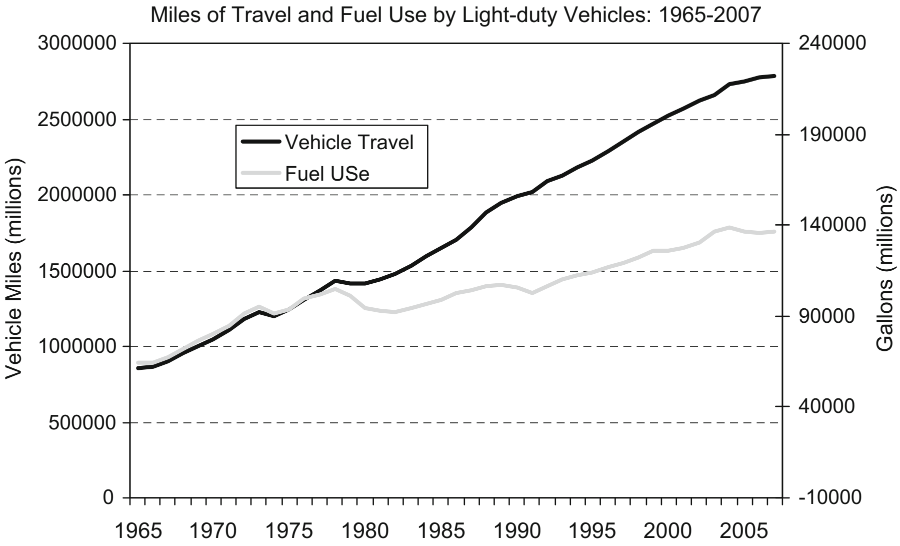

Fig. 2. Light-duty vehicle travel and fuel use: 1965–2007.

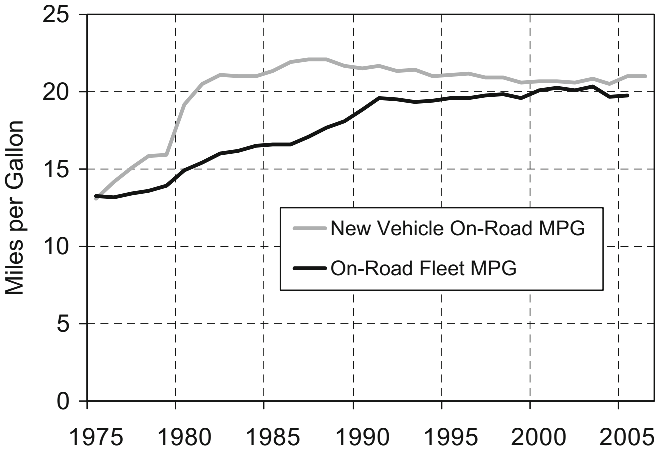

Fig. 3. Fuel economy of new light-duty vehicles and on-road fleet MPG, 1975–2007.

are required by regulation, this is not likely to be the case. Increased fuel economy is likely to come at a cost.

> First, we argue that capital costs form an important part of the total cost of providing energy services, and that the higher cost of energy efficiency conversion devices will reduce the magnitude of the rebound effect in many instances. (Dimitropoulos and Sorrell, 2006, p. 1)

Consider a vehicle with a fuel economy of 20 miles per gallon (0.05 gallons per mile) with an expected lifetime of 150,000 miles.[5] Suppose that regulations require the vehicle's fuel consumption to be decreased by 30% (fuel economy to be increased by about 40%) and that the technology required to achieve the reduction raises the price of the vehicle by $3000. Assuming a gasoline price of $2 per gallon, the fuel cost per mile will fall from $0.10 to $0.07, a reduction in the short-run cost per mile of travel of $0.03 or 30%. But if the increased capital cost of the vehicle is amortized over its 150,000 mile life, the long-run cost per mile will increase by $0.02 per mile to $0.09, a reduction in the long-run cost per mile from $0.17 to $0.16, only $0.01 or 10%. Given that the fuel economy of the fleet of vehicles on the road improves gradually over a period of about 15 years, according to this reasoning the rebound effect observed in the aggregate national annual time series data should not reflect the 30% reduction in short-run costs but rather the 10% reduction in long-run costs.

Economic trends over the study period (1966–2007) suggest that fuel cost should be a less important factor in travel decisions than they were forty years ago. Individuals produce vehicle travel by combining their own time, and expenditures that include fuel, maintenance, insurance, various fees and tolls, and the depreciation of the vehicle itself. During the study period the average transaction price of a new car increased by 25% (in constant dollars, Davis et al., 2008, Table 10.11) while average fuel economy increased by 50%. As a result, fuel as a share of the long-run financial costs of vehicle travel (excluding time costs) decreased substantially (Fig. 4). At the same time, real per capita income doubled, increasing the value of time as component of the full cost of vehicle travel. These changes would be expected to diminish the importance of fuel as a determinant of travel demand.

3. Previous estimates of the rebound effect

A number of studies have estimated the rebound effect for light-duty vehicles. Sorrell and Dimitropoulos (2007) provide the most comprehensive survey of the literature to date. Most studies base their estimates on the elasticity of vehicle travel with respect to fuel cost per mile, thereby constraining the elasticity of fuel price to be equal and opposite in sign to the elasticity of fuel economy. The most recently published study indicates that the impact of fuel price and fuel economy has been decreasing over time as incomes increase (Small and Van Dender, 2007). For the time period from 1966 to 2001, the study found a long-run rebound effect consistent with previously published studies, about −0.22. But for the period from 1997 to 2001, the long-run rebound effect had shrunk to −0.12, and the estimated short-run elasticity of fuel cost-per-mile was only −0.03. Evidence from the latest run-up in gasoline prices lends support to these findings. Considering the period from 2001 to 2006, Hughes et al. (2007) found a short-run fuel price elasticity of vehicle travel of −0.04.

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[5] More accurately these are discounted lifetime miles, reflecting the fact that future variable costs should be discounted to reflect present value.

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Estimates based on U.S. vehicle travel data published by the U.S. Department of Transportation (DOT), FHWA, covering the period from roughly 1950 to 1990, have found long-run rebound effects on the order of -0.1 to -0.3. These studies include national times series analyses (Table 1) and state-level, times series cross-sectional data (Table 2). Most analyses use log-linear (i.e., double log) lagged adjustment models but some tested linear models and found the fit to the data to be equally good. Most models were estimated using ordinary least squares (OLS) but models using state level data in particular have used simultaneous equation techniques such as two-stage least squares (2SLS) or three-stage least squares (3SLS). Results have not varied greatly depending on the model formulation or estimation method.

Studies based on survey data, on the other hand, vary considerably. Greene et al. (1999) used individual household survey data from five different years over the period 1984–1990 with substantial variation in gasoline prices. His result for the long-run elasticity of VMT with respect to fuel cost per mile is very consistent with the national time series and state time series, cross-section estimates (Table 3). U.S. studies using only a single year of survey data show the widest variability and the largest estimates of the rebound effect: 4–87%. Sorrell (2007) concluded that single year U.S. survey estimates, such as those of Puller and Greening (1999) and West (2004) shown in Table 3, are the least reliable since they reflect very little variation in fuel prices and present the greatest opportunity for spurious correlations between fuel economy and other determinants of vehicle travel. Pickrell and Schimek (1999) identified one possible cause of the high elasticity estimates from survey data. Their model estimated the elasticity of household vehicle travel to the price of gasoline. Fuel economy was not included. When the average of monthly retail prices in the state where the survey respondent resided was used as the gasoline price variable, a larger rebound effect was estimated (29–34%). When a national average price for the month in which the respondent participated in the survey was substituted a much lower rebound effect was estimated (4–8%). They found that state gasoline prices were correlated with population density in their survey data, making it difficult to disentangle their individual effects on vehicle use. States with high population density also tended to have the highest gasoline prices, chiefly due to higher tax rates. Thus, gasoline price appeared to be acting as a surrogate for spatial structure, a key determinant of motor vehicle trip length and frequency, creating an upward bias in the estimated price elasticity. On the other hand, the national monthly gasoline prices were also correlated

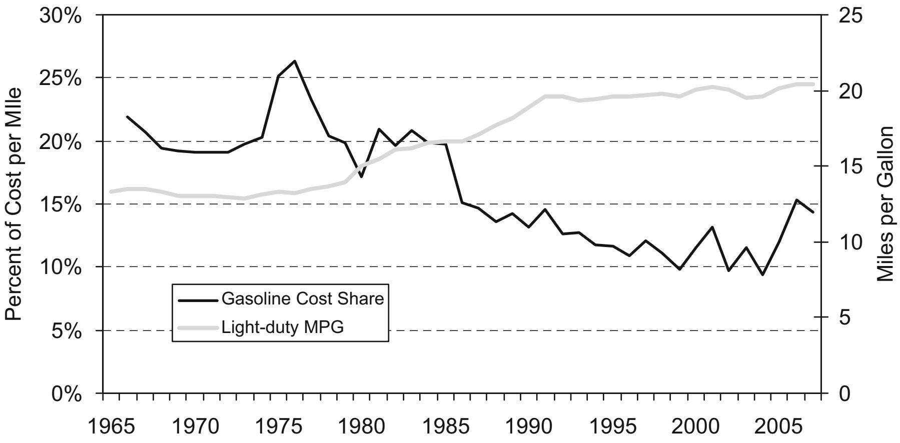

Fig. 4. Light-duty vehicle fuel economy and fuel cost share of operating costs.

Table 1
Estimates of the rebound effect, U.S. national vehicle travel based on time series.
Source: Sorrell and Dimitropoulos (2007) Table 4.6.

Author (year)	Short-run	Long-run	Time period	Functional form	Estimation method
Mayo and Mathis (1988)	22%	26%	1958–1984	Linear and log-linear	3SLS
Greene (1992)	9%	9%	1966–1988	Log-linear	OLS
Greene (1992)	Linear 5–19% Log-linear 13%	Linear 5–19% Log-linear 13%	1957–1989	Linear and log-linear	OLS
Jones (1993)	13%	30%	1957–1989	Linear and log-linear	OLS
Schimek, 1996	5–7%	21–29%	1950–1994	Log-linear	OLS

Table 2
Estimates of the rebound effect, U.S. state level data.
Source: Sorrell and Dimitropoulos (2007) Table 4.7.

Author (year)	Short-run	Long-run	Time period	Functional form	Estimation method
Haughton and Sarkar (1996)	9–16%	22%	1973–1992	Log-linear	2SLS
Small and Van Dender (2007)	4.5%	22%	1961–2001	Log-linear	3SLS

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Table 3
Estimates of the rebound effect using U.S. survey data.

Author (year)	Short-run	Long-run	Time period and survey used	Functional form	Estimation method
Goldberg (1996)	0%		CES 1984–1990	Log–log	IV
Greene et al. (1999)		23%	EIA RTECS 1979–1994	Log–log	3SLS
Pickrell and Schimek (1999)		4–34%	NPTS 1995 Single year	Log–log	OLS
Puller and Greening (1999)	49%		CES 1980–1990 Single year, cross-sectional	Log–log	2SLS
West (2004)	87%		CES 1997 Single year	Log–log	IV

CES is the U.S. Consumer Expenditure Survey.
EIA is U.S. Energy Information Administration.
RTECS is the Residential Transportation Energy Consumption Survey of the U.S. EIA.
NPTS is the U.S. Nationwide Personal Transportation Survey.

with seasonal variations in vehicle travel. In the summer months when travel demand is highest, gasoline prices are also highest. Thus, the latter approach would be expected to underestimate price elasticity due to simultaneous equation bias.

The literature on the effect of fuel prices on vehicle travel and fuel use has produced a relatively reliable quantification of the historical relationship between vehicle travel or fuel demand and the price of fuel. Reviews of the literature on the price elasticity of gasoline demand and its components can be found in Espey (1996), Dahl (1995), Dahl and Sterner (1991), and Dahl (1986). In general, the more recent the study, the smaller the sensitivity of fuel demand to price. Dahl (1995) found that more recent estimates of the long-run price elasticity of gasoline demand averaged −0.6, while earlier studies were typically in the range of −0.7 to −1.0. Espey (1996) reported an average of −0.5 for studies whose data were primarily post-1974. Using state-level data for 1970–1991, Haughton and Sarkar (1996) estimated long-run gasoline price elasticities in the range of −0.23 to −0.35. These results suggest that demand for gasoline has also become less sensitive to price over time.

4. National vehicle miles of travel (VMT) and related data

Total U.S. highway vehicle miles of travel by passenger cars and light trucks are estimated by the U.S. DOT, FHWA and published annually in table VM-1 of *Highway Statistics* (U.S. DOT/FHWA, 2007). The FHWA defines light trucks as 2-axle, 4-tire vehicles that are not passenger cars, while the CAFE law defines trucks as vehicles under 8500 lbs. gross vehicle weight[6] that are not passenger cars. State departments of transportation are the original source of FHWA's vehicle travel statistics. As the documentation of table VM-1 notes, states' definitions of passenger cars and light trucks vary from state to state (U.S. DOT/FHWA, 1996).

Apparently due to these differences, the FHWA first adds the state estimates of passenger car and light truck VMT together to form a national light-duty vehicle total. It then uses data on light truck registrations and average annual miles per light truck from surveys conducted approximately every five years and other sources to estimate light truck VMT. Because the division of VMT between light trucks and passenger cars is based on such estimation methods and because the methods have changed over time, total light-duty vehicle VMT is considered more reliable than its two components (Fig. 5). The FHWA recommends aggregating total light-duty vehicle VMT for purposes of comparison over time (U.S. DOT/FHWA, 1996, p. 8) and their advice is followed in the statistical analysis below.

Fuel use by type of highway vehicle, and fuel economy by vehicle type are estimated interdependently by the FHWA (see Schipper et al., 1993, for a detailed exploration of the implications of this method), by sharing out total highway fuel use, derived chiefly from motor fuel taxation statistics.

> Fuel consumed by all motor vehicles, a shown in VM-1 is a control total. It is extracted from Table MF-21 of Highway Statistics (Appendix G). The total is distributed among the vehicle types based on the miles per gallon for each vehicle type. Average miles traveled per gallon of fuel consumed is estimated using the TIUS (Truck Inventory and Use Survey, ed.) database. Miles per gallon are projected to the current data year using the previous year's data, TIUS estimates, and CAFE standards. (U.S. DOT/FHWA, 1996, p. 7)

Although the FHWA documentation does not explicitly say so, there is undoubtedly some iteration that must be done to reconcile VMT, fuel use and MPG estimates by vehicle type. Because light-duty vehicles consume 90% or more of the gasoline used on roads in the United States, the estimation of MPG by the FHWA and the reconciliation of VMT, MPG and fuel use numbers by vehicle type is not likely to result in extremely large errors from one year to the next. Total fuel use and total VMT (more precisely, traffic counts) are directly measured and significant year-to-year changes are not likely to be missed for such a large category as light-duty vehicles. Still, it is important to bear in mind that VMT and MPG by vehicle type are not directly measured but rather estimated interdependently by the FHWA. As we will see below, the FHWA methodology can produce anomalies.

Population data was obtained from the U.S. Census Bureau (2008). Personal income (Fig. 6) was taken from the U.S. Department of Commerce, Bureau of Economic Analysis (2008). The Consumer Price Index data are from the Bureau of Labor Statistics, Consumer Price Index, Table B.17 as reported in Davis et al. (2008). New car prices come from Davis et al. (2008, Table 10.11) and from the BLS quality adjusted vehicle price index.[7]

Gasoline price statistics are taken from the U.S. Department of Energy (DOE), EIA's *Annual Energy Review 2007*, Table 5.24 (U.S. DOE/EIA, 2008). The price series for "All Grades" in nominal prices is used, deflated by the consumer price index (CPI-U series). However, the gasoline price series began in 1978. It was extended backward to 1976 by taking a weighted average of EIA's unleaded and leaded regular price series. From the published statistics it can be inferred that the 1978 all grades price is a 41%/59% weighted average of the leaded regular and unleaded regular prices, respectively. The weights were linearly extrapolated to 100% leaded regular in 1975 in order to estimate the 1976 and 1977 prices. The EIA leaded regular price series were used for 1975 and all preceding years. These interpolations are

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[6] Gross vehicle weight comprises the empty weight of a vehicle plus the weight of the maximum cargo it is rated to carry.

[7] Other variables tested but not statistically significant were the number of licensed drivers in each year taken from the FHWA's *Highway Statistics* (table DL-1c) and population by age group, from the U.S. Census Bureau.

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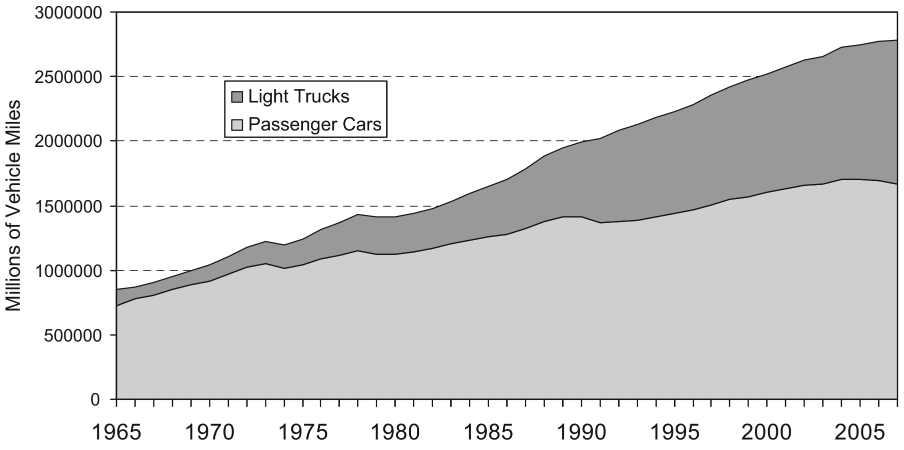

Fig. 5. Vehicle travel by U.S. passenger cars and light trucks: 1965:2007.

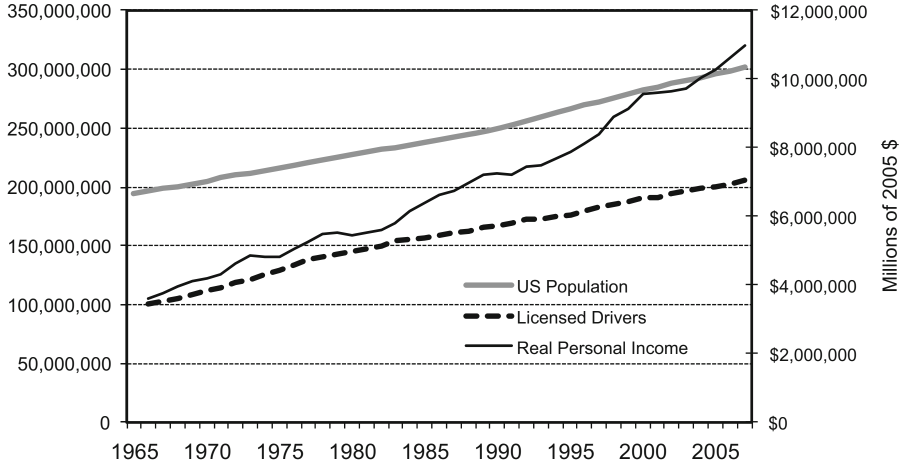

Fig. 6. U.S. population, licensed drivers and personal income: 1965:2007.

not likely to introduce significant errors as can be seen by inspection of the several gasoline price series shown in Fig. 7.

4.1. *The effect of federal fuel economy standards*

The U.S. CAFE Standards undoubtedly had a significant effect on the fuel economy of new passenger cars and light trucks (see Fig. 1) that cannot be ignored in any equation that attempts to explain either new vehicle or total on-road fleet average fuel economy. If vehicle travel and fuel consumption are to be estimated as simultaneous equations, a variable that effectively represents the fuel economy standards is required. Small and Van Dender (2007) used state level data from before fuel economy standards went into effect (1966–1977) to estimate a lagged adjustment equation to predict what fuel intensity (1/MPG) would have been in the absence of fuel economy standards.[8] Only three variables were statistically significant in the fuel intensity equation, lagged fuel intensity, a dummy variable for 1974 and 1975 and a time trend. The time trend was interpreted by the authors as representing technological change. Fuel price was not statistically significant but had the expected sign. Given that fuel price is the only important driving factor for fuel economy in the equation, aside from the time trend, its lack of statistical significance creates doubts about the validity of the methodology. This equation was then used to predict the (long-run) desired fuel intensity for each state. The state fuel intensities were aggregated to national fuel intensity by weighting by state vehicle travel. Small and Van Dender measured the strength of the CAFE regulation by a variable equal to the ratio of the mandated fuel economy[9] to the desired fuel economy whenever the mandated fuel economy was greater, and 1.0 when it was not. However, from Fig. 1 in the authors' paper it is clear that the desired fuel economy was equal to or greater than the mandated fuel economy only in 1979.

Apparently considering this result less than satisfactory, Small and Van Dender (2007) then developed an alternate version of their CAFE variable by first removing the time trend from their initial equation for desired fuel economy and using that equation

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[8] The U.S. CAFE standards were enacted in December of 1975 to take effect in 1978. However it is reasonable to use data through 1977 since manufacturers generally "lock in" their product plans two years in advance. Thus, even though the manufacturers were aware in 1976 and 1977 that the standards were coming, there was little they could do to change the designs of vehicles sold in those model years.

[9] The mandated CAFE levels are based on EPA dynamometer test values. They were adjusted downward by multiplying by 0.85 to reflect real-world driving in order to be comparable to the FHWA fuel economy data.

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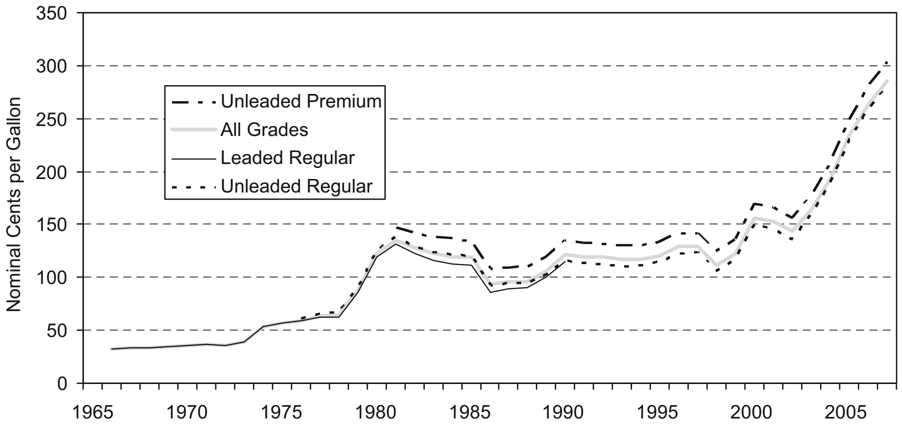

Fig. 7. Gasoline price data series: 1965:2007 (DOE/EIA, 2008).

to predict a new variable they called *cafe_prelim*. However, this equation includes only the statistically significant dummy variable and the statistically insignificant vehicle price variable. The new variable *cafe_prelim* was used to replace the time trend in a newly estimated equation for desired fuel economy based on the entire sample of data. Setting the *cafe_prelim* variable to zero, the new equation is used to predict a new desired efficiency variable.

For the period 1966–1977 the *cafe_prelim* variable is equal to the dependent variable (FHWA fuel intensity) minus the estimated time trend and the residuals from the initial regression. The authors' interpretation of this variable is that it represents pressure from CAFE regulations. Given its construction, another interpretation might be that it represents desired fuel economy in the absence of technological change. Because the only statistically significant variables in the entire methodology are a time trend and a dummy variable, one can only hope that it represents what the authors intend it to represent. The authors themselves express dissatisfaction with both equations.

> On the negative side, we find that with our alternate calculation procedure, our estimates of desired fuel efficiency are not robust to adding trend variables in the reduced form equation itself. In the end, we can offer no judgments about which version of *cafe* better depicts the tightness of regulations as perceived by market participants. (Small and Van Dender, 2007, p. 50)

The method of Small and Van Dender (2007) does not seem to produce an adequate representation of the effect of fuel economy standards. A more robust approach is needed. The method used here is to directly estimate what the total on-road light-duty vehicle fuel economy would have been had all manufacturers exactly met the fuel economy standards. The assumption of this method is that manufacturers used the standards as the basis for planning fuel economy improvements for the period from 1978 to 2007 but that actual new vehicle fuel economy might deviate from those plans, for example, if fuel prices changed significantly. The Hausman test will then be used to determine if the data support simultaneous determination of on-road vehicle fuel economy and vehicle travel.

The CAFE standards apply to *new* passenger cars and light trucks, not to the population of vehicles on the road. Greene (1990) demonstrated that for domestic manufacturers, the CAFE standards were a binding constraint throughout the decade from 1978 to 1988, but for some foreign manufacturers they were not binding. In the years since, there has been substantial progress in vehicle technologies enabling higher fuel economy. Over the same period, there has been no improvement in fuel economy (0%) but substantial increases in horsepower (77%) and weight (25%) (U.S. EPA, 2008, Table 2). If the CAFE standards had not been a binding constraint on the market during those years, at least some of the technology would have been applied to increasing fuel economy rather than holding fuel economy constant while increasing horsepower and weight.

The fuel economy of the existing stock of vehicles, however, can be affected to a limited extent by driving behavior and maintenance, shifts in the distribution of new vehicles sold, and changes in the rate of stock turnover. Thus, on-road fleet fuel economy could vary above or below what would be expected assuming a normal rate of fleet turnover and typical driving behavior. This suggests formulating a CAFE variable that equals what the average fuel economy of the on-road vehicle stock would have been had the standards been met exactly given the rate of turnover of the vehicle stock. This is approximated here by assuming that new passenger cars exactly met the passenger car standard and new trucks exactly met the truck standard. The actual numbers of passenger cars and light trucks in operation by model year in each calendar year from 1978 to 2007 are used as weights for the MPG values to compute a fleet harmonic mean fuel economy.[10] An on-road adjustment factor of 0.85 is applied in every year. Vehicle use is estimated to decline with age at the rate of 4% per year (Pickrell and Schimek, 1999). The three resulting CAFE variables are plotted in Fig. 8, along with the FHWA estimates of passenger car, light truck and combined light-duty vehicle fuel economy.

Three features of Fig. 8 are noteworthy. First, the FHWA on-road fuel economy numbers track the predicted CAFE numbers closely.[11] (The combined light-duty vehicle estimates are considered the most reliable, for reasons given above.) Second, there are two distinct periods during which the estimated on-road fuel economy exceeds the predicted CAFE number: 1980–1985 and 1991–1992. Both are periods of relatively high fuel prices. Third,

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[10] To the extent that rates of vehicle scrappage changed as a function of fuel prices or other factors and affected fleet average fuel economy, this will not be reflected in the constructed CAFE variable, since the variable reflects the actual numbers of vehicles in operation by model year and not what they would have been in the absence of fuel price changes and other factors. Such effects will be less important, however, since model year fuel economy is not changed over time in constructing the CAFE variable

[11] This could also be because the FHWA uses new vehicle fuel economy data along with other data to estimate on-road fleet fuel economy, as noted above.

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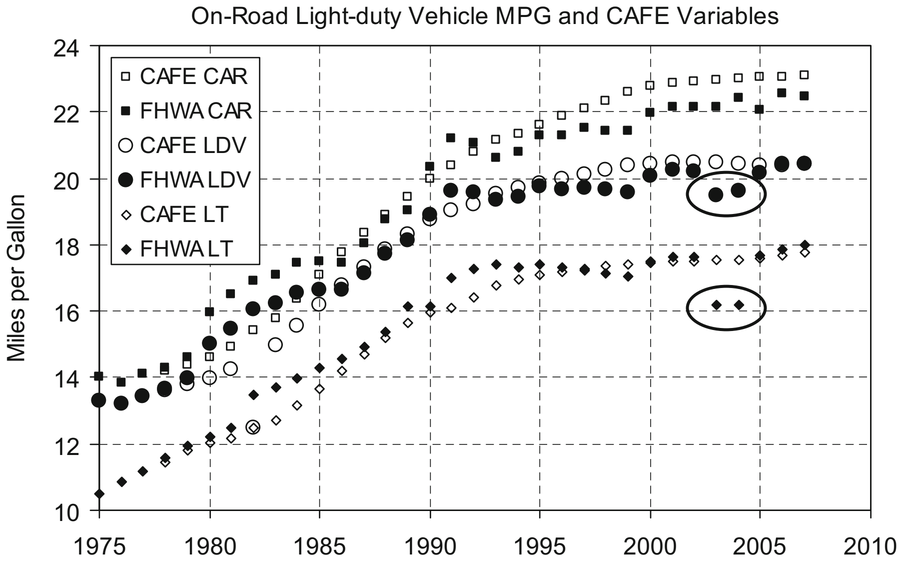

Fig. 8. Constructed CAFELDV variable and FHWA on-road average fuel economy data for passenger cars and light trucks.

the FHWA estimates for 2003 and 2004 for light trucks appear to be anomalies, and they affect the combined estimates as expected. As of the time of writing, the FHWA had not changed the light truck estimates for 2003 and 2004. The reader is reminded that the combined light-duty vehicle CAFE variable (CAFE LDV) in Fig. 8 is used to represent the effect of the CAFE standards in the regressions predicting light-duty vehicle fuel economy presented below, rather than the individual passenger car and light truck numbers. Some key inferences depend strongly on the validity of the MPG data. In these cases, the hypotheses were retested, either including a dummy variable for 2003 and 2004 or replacing the suspect 2003 and 2004 MPG numbers with values linearly interpolated between 2002 and 2005. The conclusions were unaltered by this substitution.

5. Models and hypotheses

The most important question is whether the empirical data support the existence of a rebound effect. This was tested by estimating the effects of the price of gasoline and the rate of fuel consumption (1/MPG) separately. Using national time series data from 1950 to 1994 Schimek (1996) estimated the elasticities of vehicle travel with respect to fuel price and with respect to fuel economy individually. He found a short-run elasticity of real gasoline price of −0.06 and of miles per gallon of +0.05, almost precisely equal and opposite in sign as theory would predict. However, Small and Van Dender (2007) reported that the direct effect of fuel economy (miles per gallon) or fuel consumption (gallons per mile) on vehicle miles traveled was statistically insignificant. Only when fuel cost per mile (gasoline price divided by miles per gallon) was used as the right-hand-side variable was fuel efficiency statistically significant. However, that formulation *imposes the hypothesis* that fuel price and fuel economy to have equal and opposite effects.

> A second caveat is that our study, like virtually all others, imposes the theoretical restriction that people choosing how much to drive care about the fuel cost of driving a mile, but not separately about its individual components (fuel price and fuel efficiency). Unfortunately, we find that this restriction is not supported by a model that relaxes it – in fact, the latter model suggests that the amount of driving responds to fuel prices but not to changes in fuel efficiency. (Small and Van Dender, 2007, p. 43)

Greene et al. (1999) concluded that the survey data on which their study was based did not reject the hypothesis of equal and opposite effects but, of course, this is not the same as confirming it.

A second important question is whether the rebound effect has remained constant over time and, if not, why it varies. Gately (1992) argued that the rebound effect should be expected to vary over time in proportion to the fuel cost share of total vehicle travel costs. His reasoning was that the elasticity of vehicle travel with respect to total monetary costs (excluding the costs of time) appeared to be approximately constant at about −1. If this were true, then the elasticity of vehicle travel with respect to fuel cost per mile would be approximately the negative of fuel's share of total monetary vehicle travel costs. Let C be the non-fuel, long-run costs per mile of travel, let K be a constant term representing other factors that affect the amount of travel and let β_V be the elasticity of travel with respect to total costs per mile. If $\beta_V = -1$, then the elasticity of travel with respect to fuel cost per mile (eP) is just the fuel cost share of total cost per mile.

$$V = K(C+eP)^{\beta_v}$$

$$\frac{dV}{d(eP)}\frac{eP}{V} = \frac{eP}{V}\frac{d}{d(eP)}K(C+eP)^{\beta_V} = \frac{eP}{V}\beta_V K(C+eP)^{\beta_V - 1} = (-1)\frac{eP}{(C+eP)} \tag{2}$$

Eq. (2) implies that the rebound effect will vary with the price of fuel in the linear model. For this reason, Gately (1992) suggested that the linear lagged adjustment model might be preferred to the log–log formulation.

Using time series, cross-sectional data for states, Small and Van Dender (2007) developed and tested a model in which the rebound effect varied with the logarithm of per capita income. The reasoning behind this formulation was that as incomes rise, the time cost of travel becomes more important relative to fuel costs.

6. Results

Linear lagged adjustment models for light-duty vehicle travel were estimated using the E-Views6^{TM} software (Quantitative

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Micro Software, 2007) and the 1966–2007 national time series data. The dependent variable was total light-duty vehicle miles of travel (LDVMT) and right-hand side variables were the real price of gasoline (RGASPRICE), the light-duty vehicle fuel consumption in gallons per mile (FC), real total personal income (RPERSINC), the number of light duty vehicles registered (LDVEH), a dummy variable representing the price shock years of 1974 and 1979 (DUM7479), and the lagged value of the dependent variable (LDVMT(−1)). C and A_1 through A_6 are coefficients to be estimated. The function log() indicates Naperian logarithms of the variables:

$$\log(\text{LDVMT}) = C + A_1\log(\text{RGASPRICE}) + A_2\log(\text{FC}) + A_3(\text{RPERSINC}) + A_4\log(\text{LDVEH}) + A_5\,\text{DUM7479} + A_6\log(\text{LDVMT}(-1)) \tag{3}$$

Results of estimating the linear lagged adjustment model for VMT using ordinary least squares are shown in Table 4. Augmented Dickey–Fuller (ADF) unit roots tests showed that all variables (except DUM7479) could not reject the null hypothesis of a unit root in levels form. However, the null hypothesis of unit roots was rejected for all variables in first differences. The ADF test on the residuals from the regression rejected the hypothesis of a unit root at the 0.01 level, indicating that the variables in Eq. (3) are co-integrated. All variables *except fuel consumption* are statistically significant and have the expected signs. FC is not statistically significant and is expected to have a negative sign (increasing fuel consumption per mile should reduce VMT) but does not. Total personal income is statistically significant at the 0.06 level. The fit of model to data is very close, with an adjusted R^2 of 0.9996. The Breusch–Godfrey Serial Correlation LM test statistics for both first- and second-order autocorrelation do not reject the hypothesis of no autocorrelation. The Breusch–Pagan–Godfrey heteroskedasticity test also does not reject constant error variance. At the mean, the estimated short-run gasoline price elasticity of vehicle travel is $-0.049 = -463.5 * (193.0/1838201)$, and the long-run elasticity implied by the lagged adjustment formulation is −0.30 at the sample mean values.

Small and Van Dender (2007) tested the hypothesis that the elasticity of vehicle travel with respect to the price of fuel was equal to the elasticity with respect to the rate of fuel consumption (gallons per mile) and found, as did Greene et al. (1999), that the data did not reject that hypothesis. As a consequence, they estimated the rebound effect as the elasticity of vehicle travel with respect to fuel cost per mile, which imposes that constraint.

The hypothesis that the elasticities of gasoline price and fuel consumption are equal at their sample means was tested for this data set using the Wald Test and rejected at the 0.01 level. This is a new finding and indicates that not only is the direct fuel economy rebound effect not statistically significant in the linear lagged adjustment model, but the hypothesis of equal elasticities for gasoline price and fuel consumption is rejected at the means of the variables. Accepting this hypothesis is necessary in order to justify using fuel cost per mile as a representation of the rebound effect. This result also holds in the log–log form of the vehicle travel equation as will be shown below.

The log–log form of the lagged adjustment equation has been frequently preferred because it produces constant elasticities (Table 5). Unit root tests showed that, in levels, only the log of vehicle stock rejected the hypotheses of unit roots. The residuals from the regression, however, did reject the hypothesis of unit roots, indicating that the variables are cointegrated. Once again, all variables are statistically significant and have the expected signs except for the log of fuel consumption. This model too fits the data closely and easily passes the Breusch–Godfrey LM test for first-order serial correlation and the Breusch–Pagan–Godfrey test

Table 5
Log-linear lagged adjustment VMT Model 2 (OLS).

Dependent variable: LOG(LDVMT)
Method: least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	t-Statistic	Prob.
C	−1.607	0.613	−2.624	0.013
LOG(RGASPRICE)	−0.051	0.009	−6.032	0.000
LOG(FC)	0.032	0.028	1.139	0.263
LOG(RPERSINC)	0.141	0.050	2.811	0.008
LOG(LDVEH)	0.106	0.035	3.038	0.005
DUM7479	−0.050	0.007	−6.984	0.000
LOG(LDVMT(−1))	0.777	0.062	12.492	0.000
R-squared	1.000	Prob(F-statistic)		0.000
Adjusted R-squared	0.999	Mean dependent var		14.371
S.E. of regression	0.008	S.D. dependent var		0.338
Sum squared resid	0.002	Breusch–Godfrey		
Log likelihood	142.699	F-statistic		0.021
F-statistic	11,384.88	Obs × R-squared		0.026

Table 4
Linear lagged adjustment VMT Model 1 (OLS).

Dependent variable: LDVMT
Method: Least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	t-Statistic	Prob.
C	19,659.17	67,538.15	0.291	0.773
RGASPRICE	−463.487	62.770	−7.384	0.000
FC	601,170.1	691,037.2	0.870	0.390
RPERSINC	2.15E−05	1.13E−05	1.907	0.065
LDVEH	0.001	0.000	3.970	0.000
DUM7479	−65,156.72	10,447.46	−6.237	0.000
LDVMT(−1)	0.836	0.046	17.970	0.000
R-squared	1.000	F-statistic		14,588.41
Adjusted R-squared	1.000	Prob(F-statistic)		0.000
S.E. of regression	12,643.13	Mean dependent var		1,838,201.
Sum squared resid	5.43E+09	S.D. dependent var		591,546.3
Log likelihood	−441.578			

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for heteroskedasticity. The estimated short-run gasoline price elasticity of −0.051 is nearly identical to the linear model at its mean. The long-run elasticity implied by the lagged adjustment model is −0.23, virtually identical to the value of −0.22 obtained by Small and Van Dender (2007) using a simultaneous equation formulation applied to state level data. A Wald Test that the short-run elasticities of gasoline price and fuel economy (miles per gallon) are equal and opposite in sign is likewise rejected for the log-linear model at the 0.01 level. Thus, neither the linear nor the log–log model provides empirical support for a direct rebound effect of fuel economy.

Stability of the log-linear model was tested using the Cusum and Cusumsq statistics. The Cusum test showed no evidence of instability. In the Cusumsq test, the Cusumsq statistic barely exceeds the 5% bounds during the years 1986–1988, suggesting possible instability in the years following the collapse of world oil prices in 1986. Plots of recursive coefficient estimates indicated that the coefficients of personal income, DUM7479, and the lagged dependent variable remained relatively stable as observations were added. The coefficients of the price of gasoline, fuel consumption per vehicle mile and the vehicle stock decreased markedly in absolute value over time. The recursive coefficient estimate plots for LOG(RGASPRICE) and LOG(FC) are shown in Fig. 9a and b. The trends are generally consistent with Small and Van Dender (2007) observation that the rebound effect has been decreasing over time.

6.1. *Testing the endogeneity of fuel economy and vehicle stock*

Using a time series of state data, Small and Van Dender (2007) formulated simultaneous equation models of vehicle travel, vehicle stock and fuel economy in order to include interdependencies among the variables and to avoid simultaneous equations bias in estimating the rebound effect. Using household panel data, Greene et al. (1999) also considered a simultaneous equation formulation necessary. The estimates presented above are not based on simultaneous equation estimation methods because the national time series data do not indicate that vehicle travel, vehicle stock and fuel cost per mile are simultaneously determined. Schimek (1996) also found that the national time series data from 1950 to 1994 did not support simultaneity in a three equation model of the number of vehicles, vehicle travel and fuel efficiency. The results below are consistent with his results although his model formulation is somewhat different.

The Hausman test for simultaneous equation bias first estimates ordinary least squares regressions for the suspected endogenous variables using instrumental variables. The residuals from the regression are then added to the vehicle miles of travel equation as an additional right-hand-side variable. If the coefficient of the residual is statistically significant, simultaneous equation bias is indicated.

The logarithm of fuel consumption was regressed against the following instrumental variables: logarithm of real gasoline price, log of the constructed CAFE variable, log of real personal income, and the dummy variables for 1974 and 1979 (fuel shortages) and 2003 and 2004 (data anomalies). The results are shown in Table 6. By far the most important variable is the constructed CAFELDV variable, whose coefficient is approximately −1, implying that a 1% increase in the standards (miles per gallon) would eventually produce a 1% reduction in the rate of fuel consumption (gallons per mile) of the vehicle stock. The real price of gasoline has the expected negative sign but a relatively small elasticity of −0.13, indicating that in the short run a doubling of the price of gasoline might cause a 10% or greater decrease in fuel consumption per mile through such actions as fuel efficient driving behavior, shifting VMT within a household to its more fuel efficient vehicles, better maintenance, as well as shifts in sales towards more efficient vehicles and increased scrappage of less efficient vehicles within the year. Personal income is not significant at the 0.05 level

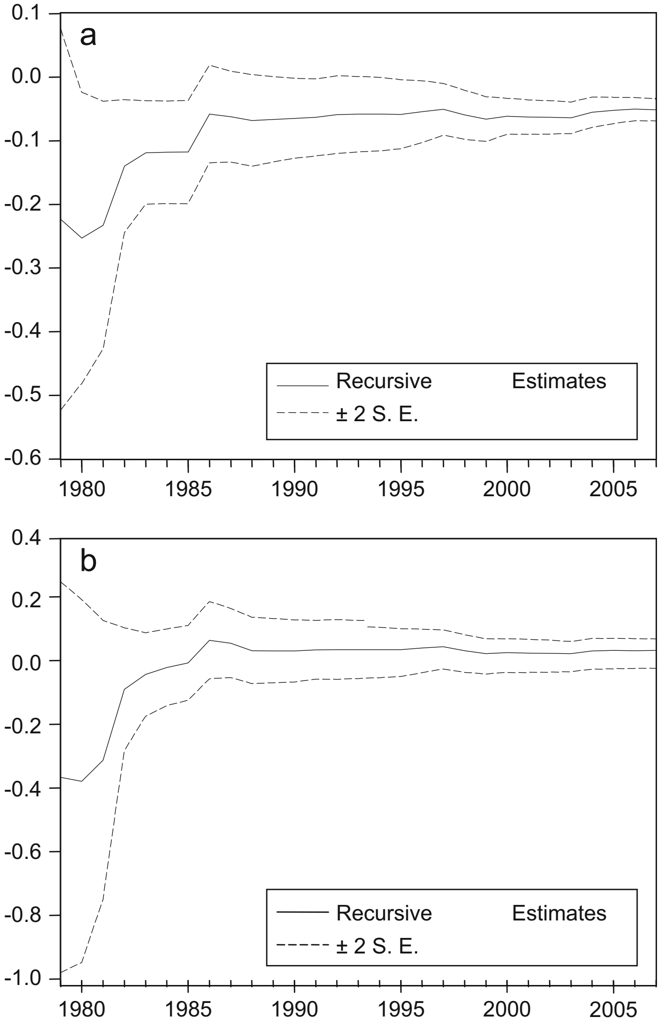

Fig. 9. (a) Recursive coefficient estimate of the log of the real price of gasoline. (b) Recursive coefficient estimates of the log of fuel consumption per mile.

Table 6
Regression of LOG(FC) on instrumental variables.

Dependent Variable: LOG(FC)
Method: Least squares
Sample (adjusted): 1966 2007
Included observations: 42

Variable	Coefficient	Std. error	*t*-Statistic	Prob.
C	−0.471	0.625	−0.754	0.456
LOG(RGASPRICE)	−0.127	0.021	−6.002	0.000
LOG(CAFELDV)	−1.077	0.067	−16.115	0.000
LOG(RPERSINC)	0.060	0.038	1.582	0.123
DUM7479	0.020	0.016	0.305	0.200
DUM0304	0.039	0.015	2.543	0.015
R-squared	0.988	*F*-statistic		615.657
Adjusted *R*-squared	0.987	Prob(*F*-statistic)		0.000
S.E. of regression	0.020	Mean dependent var		−2.809
Sum squared resid	0.015	S.D. dependent var		0.177
Log likelihood	107.274	Durbin–Watson stat		0.448

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but does have a positive sign, possibly indicating that as incomes rise motorists opt for acceleration and speed over fuel economy. Of the two dummy variables only the data anomalies dummy is significant.

The residuals from the fuel consumption regression were retained and added to the previous list of right-hand side variables in the VMT regression. The result is shown in Table 7.

The residual is not statistically significant, with a t-statistic of 0.26 and significance level of 0.8. Thus, the Hausman endogeneity test does not indicate that fuel economy is endogenous in the vehicle travel equation based on national time series data. This does not mean that fuel economy is not affected by the current values of the exogenous variables (e.g., gasoline price). It does imply that the MPG variable is not correlated with the error term of the VMT equation and that OLS estimators will not suffer from simultaneous equations bias.

The endogeneity of vehicle stock was tested with a similar result. Instrumental variables in the log–log vehicle stock equation were the real price of gasoline, the number of licensed drivers, real personal income, the BLS new car price index (2005 = 1), and the two dummy variables.[12] Only the number of licensed drivers was statistically significant. When the residuals were added to the vehicle travel equation the coefficient of the residuals was again not statistically significant, indicating a lack of correlation between vehicle stock and the error term of the VMT equation.

Energy economists have observed asymmetric responses of demand to changes in the prices of petroleum products (e.g., Dargay and Gately, 1997). Responses to price increases greatly exceed responses to price decreases. The asymmetries are generally attributed to irreversible technological change and the impacts of policies such as energy efficiency standards. The possibility that vehicle travel may respond asymmetrically to price or fuel economy was tested using the method of Dargay and Gately (1997). Whether in log or linear form, year-over-year increases are accumulated as a “rise” version of the variable while year-over-year decreases are accumulated as a “fall” version. Let p be the price of gasoline in year t. The PRICERISE and PRICEFALL variables are defined as follows:

$$\begin{aligned}\mathrm{PRICERISE}_t &= \sum_{t=1}^{T}\max(0,p_t-p_{t-1})\\ \mathrm{PRICEFALL}_t &= \sum_{t=1}^{T}\min(0,p_t-p_{t-1})\end{aligned} \tag{4}$$

If the response to price is symmetrical, the coefficients of PRICERISE and PRICEFALL will be equal, and the same as the coefficient of price.

The results of the asymmetry tests are less than entirely decisive but do not reject the hypothesis of symmetry. Results for the linear model are shown in Table 8. PRICERISE and PRICEFALL (which replace RGASPRICE) both have negative coefficients, but PRICEFALL’s is much smaller and not statistically significant. Neither of the analogous coefficients of fuel consumption (FCRISE and FCFALL) is statistically significant. A Wald test for the simultaneous equality of gasoline price coefficients and equality of the fuel efficiency coefficients does not reject the hypothesis of symmetry at the 0.2 level. The same test applied to the double log form of the model also did not reject symmetry but the significance level was smaller: 0.09.

Table 7
Hausman test for endogeneity of fuel economy.

Dependent variable: LOG(LDVMT)
Method: Least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	*t*-Statistic	Prob.
C	−1.637	0.631	−2.593	0.014
LOG(RGASPRICE)	−0.051	0.009	−5.844	0.000
LOG(FC)	0.034	0.029	1.152	0.258
LOG(RPERSINC)	0.148	0.057	2.609	0.014
LOG(LDVEH)	0.100	0.041	2.424	0.021
DUM7479	−0.050	0.007	−6.887	0.000
Log(LDVMT(−1))	0.777	0.063	12.309	0.000
RESIDFC	0.026	0.101	0.261	0.795
R-squared	1.000	Mean dependent var		14.371
Adjusted *R*-squared	1.000	S.D. dependent var		0.338
S.E. of regression	0.008	Akaike info criterion		−6.573
Sum squared resid	0.002	Schwartz criterion		−6.238
Log likelihood	142.741	Hannan–Quinn criter.		−6.451
F-statistic	9491.093	Durbin–Watson stat		1.929
Prob(*F*-statistic)	0.000			

The above results are quantitatively similar to Small and Van Dender (2007) results with two important differences. First, the 1966–2007 U.S. national time series data do not support the existence of a direct rebound effect of fleet average light-duty vehicle fuel economy on light-duty vehicle miles of travel. This inference is generally consistent with previous studies, including Small and Van Dender (2007), but is more definitive in that the hypothesis of equal and opposite effects of fuel economy and the price of gasoline is rejected by the data for the first time. Second, the 1966–2007 national time series data do not support the simultaneity of vehicle travel, fuel economy and vehicle stock. This latter difference may be more easily explained. Given an expected vehicle life of approximately 15 years (Davis et al., 2008), the size of the vehicle stock and its fuel economy is largely predetermined by previous purchase decisions. Changes from year to year in fuel economy may be adequately explained by CAFE standards and changes in the price of gasoline, and year-to-year fluctuations in the stock of vehicles may be explained by changes in income and the prices of vehicles. The case for state-to-state, or household level simultaneity of these variables appears to be much stronger.

The lack of empirical evidence for a rebound effect of fuel economy on vehicle miles of travel requires an explanation. On the one hand, the theory is compelling. Why should the response to a change in fuel economy not be symmetrical to a change in gasoline price, since the two affect fuel cost per mile of travel in equal and opposite ways? A possible explanation that upholds the validity of the theory is that the manner in which fuel economy improvements were brought about (fuel economy regulations) increases the cost of new vehicles, inducing an offsetting effect by increasing the fixed cost of vehicle travel. Another explanation may lie in the “experimental design” of the historical data, i.e., a gradual change in the level of fuel economy, making its impact more difficult to estimate than that of fuel price, whose changes have often been sudden and large.

Estimates of the rebound effect published in the economics literature aim to measure the effect of reduced fuel cost per mile of travel (price per gallon divided by miles per gallon) on the amount of travel, *other things equal.* In particular, the stock of motor vehicles is typically included as a right-hand-side variable. However, when manufacturers raise fuel economy in response to

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[12] It can be argued that the BLS new car price index and the on-road vehicle stock may be simultaneously determined. Omitting the new car price index does not change the results.

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Table 8
Test for asymmetry in linear lagged adjustment model for vehicle travel.

Dependent variable: LDVMT

Method: Least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	*t*-Statistic	Prob.
C	−39,632.28	45,347.61	−0.874	0.389
PRICERISE	−704.530	149.701	−4.706	0.000
PRICEFALL	−192.236	178.114	−1.079	0.289
FCRISE	6,788,103.	5,758,704.	1.075	0.291
FCFALL	−2,743,952.	2,097,563.	−1.308	0.200
RPERSINC	4.64E−05	1.80E−05	2.581	0.015
LDVEH	0.001	0.001	2.049	0.049
DUM7479	−58,221.61	11,315.19	−5.145	0.000
LDVMT(−1)	0.763	0.063	12.030	0.000
R-squared	1.000	F-statistic		11,312.85
Adjusted *R*-squared	1.000	Prob(*F*-statistic)		0.000
S.E. of regression	12,434.000	Mean dependent var		1,838,201
Sum squared resid	4.95E+09	S.D. dependent var		591,546.3
Log likelihood	−439.652			

fuel economy standards they do so primarily by adding more expensive fuel economy technology, thereby increasing the cost of the vehicle (NRC, 2002). Whether the increased cost of this technology will be less than or greater than the value of fuel saved is usually a subject of heated debate, and in any case will depend on how high the standards are set. How capital costs and variable energy costs are perceived by consumers is yet another unresolved issue. Regardless, in the long run the cost of operating a vehicle unquestionably depends on the cost of the vehicle as well as the cost of fuel (plus other costs such as insurance, maintenance, etc., some of which may increase with vehicle price). A certain amount of vehicle depreciation is a function of time, the rest being chiefly a function of use. Goodwin et al. (2004) put the average elasticity of vehicle travel with respect to vehicle cost at −0.4 based on three studies with a range from −0.2 to −0.6. Dargay (2007) found a similar effect in an analysis of the effects of fuel and car prices on vehicle travel in the UK: other things equal, more expensive cars were driven less. She was skeptical of the result, however, and noted the dearth of empirical evidence on the relationship between car price and vehicle use. Nevertheless, in the long run, the rebound effect of lower fuel costs brought about by fuel economy standards should be, in theory, to some degree offset by the increased cost of fuel economy technology.

As an illustration, suppose that fuel economy regulations require a 33% decrease in fuel consumption per mile. Evaluated using a rebound elasticity of −0.1, this would imply a 3.3% increase in vehicle travel. If the increase in vehicle price for technologies to achieve these fuel economy gains is equal to the discounted present value of fuel saved, the net decrease in long-run vehicle operating costs would be roughly zero. The increased long-run (capital) cost per mile of travel would offset the decreased short run (variable) cost. This would imply that the standards had been set above the point at which the marginal cost of increasing fuel economy was equal to the marginal *private* benefit of the resulting fuel savings. This could easily be the case if the marginal social value of reduced fuel consumption were believed to exceed the taxes on motor fuel. This also assumes that motorists perceive that the capital invested in a vehicle is used up with vehicle use. Whether or not consumers actually perceive short-run and long-run costs in this way is an empirical question, deserving of further study.

Table 9
Rebound effect as a function of log of per capita income.

Dependent variable: LOG(LDVMT)

Method: Least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	*t*-Statistic	Prob.
C	1.859	0.528	3.518	0.001
LOG(CPM)	−0.272	0.072	−3.797	0.000
LCPMINC	0.071	0.021	3.368	0.002
LOG(LDVEH)	0.039	0.036	1.092	0.283
DUM7479	−0.047	0.007	−6.958	0.000
LOG(LDVMT(−1))	0.828	0.037	22.416	0.000
R-squared	0.999	*F*-statistic		11,909.71
Adjusted *R*-squared	0.999	Prob(*F*-statistic)		0.000
S.E. of regression	0.009	Mean dependent var		14.371
Sum squared resid	0.003	S.D. dependent var		0.338
Log likelihood	139.293			

6.2. Re-estimating the small and Van Dender model with national time series data

Despite the rejection of equal effects of fuel price and fuel consumption, it is still of interest to determine whether the national times series data also support Small and Van Dender's (2007) conclusion that the rebound effect has declined over time as per capita income has increased. In these estimations, it is recognized that theory is being allowed to overrule the empirical data.

Following the formulation of Small and Van Dender (2007), the logarithm of light-duty vehicle miles of travel was regressed against the logarithm of fuel cost per mile (CPM) and the product of the logarithms of fuel cost per mile and real per capita income. Thus, the rebound effect becomes a linear function of the log of per capita income, which is used to represent the value of travelers' time. The hypothesis is that as the value of time increases fuel cost becomes a relatively less important determinant of the demand for travel. Other variables included in the regression were the logarithm of vehicle stock, the dummy

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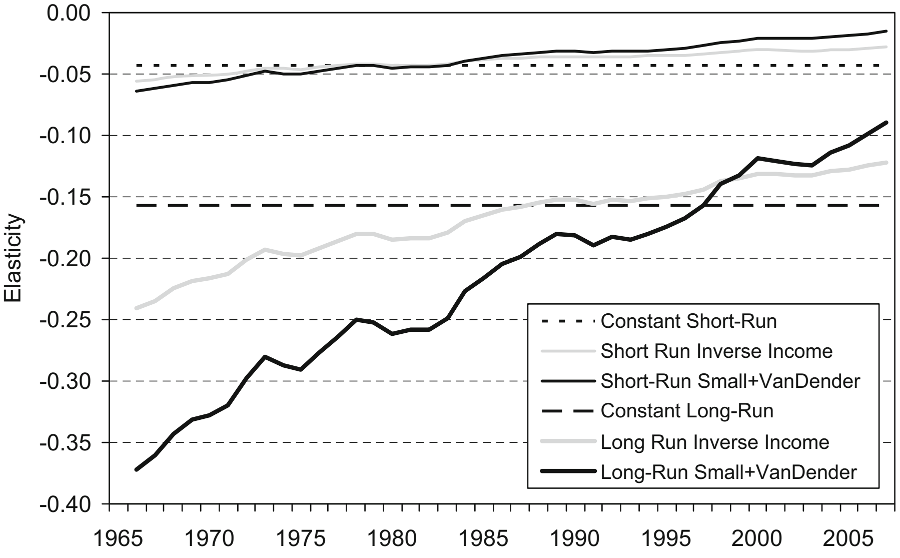

Fig. 10. Estimates of the rebound effect as a functions of per capita income, 1966–2007.

variable for 1974 and 1979, and the lagged value of VMT. The log of real personal income was dropped due to statistical insignificance. This is problematic because it is unclear to what extent the interaction of income and cost per mile is also reflecting the effect of income alone. The results are shown in Table 9. The rebound effect (the elasticity of fuel cost per mile) is the following function of the logarithm of real per capita income:

$$\beta_{SR} = -0.27 + 0.7(\log(pcinc)) \qquad \text{Short run}$$
$$\beta_{LR} = \frac{[-0.27+0.7(\log(pcinc))]}{[1-0.83]} \qquad \text{Long run} \tag{5}$$

Both coefficients are statistically significant at the 0.01 level. The implied pattern of the long-run elasticity of light-duty vehicle travel with respect to fuel cost per mile is shown in Fig. 10.

Small and Van Dender noted that while their formulation fitted the historical data well, it could not be extrapolated far into the future without running the risk of predicting a rebound elasticity greater than zero. This would imply that reducing the fuel cost per mile of vehicle travel would decrease the quantity of travel, a decidedly counterintuitive effect. The authors recognized that an alternative functional form might be needed. If income is assumed to have its effect via the total cost (time plus monetary) of vehicle travel, then the rebound effect should probably decrease with the inverse of income. For simplicity, assume that the total cost of vehicle travel can be represented as a(pcinc)+X, where X is the total monetary cost of travel per mile and includes fuel costs (eP). In Eq. (2) above, $C=X-eP$. The coefficient a translates per capita income (Y) into a time cost per mile (and so depends on average speed)[13]:

$$\frac{dV}{d(eP)}\frac{eP}{V} = \frac{eP}{V}\frac{d}{d(eP)}K(aY+X)^{\gamma} = \frac{eP}{V}\gamma K(aY+X)^{\gamma-1} = \frac{\gamma(eP)}{aY+X} \tag{6}$$

Two alternative formulations of the elasticity of fuel cost per mile as a function of the inverse of income were tested. The first assumes that $\beta_{V,eP}=b_0+b_1/\text{pcinc}$, while the other eliminates the constant term, $\beta_{V,eP}=b/\text{pcinc}$. The first formulation resulted in insignificant coefficients for the constant term of the income elasticity, as well as for the logarithms of personal income and vehicle stock. The second formulation was more satisfactory; however, vehicle stock was not statistically significant (Table 10).

Table 10
Rebound effect as a function of the inverse of personal income.

Dependent variable: LOG(LDVMT)

Method: Least squares
Sample (adjusted): 1967 2007
Included observations: 41 after adjustments

Variable	Coefficient	Std. error	*t*-Statistic	Prob.
C	0.144	0.576	0.249	0.805
LCPMOVRINC	−1.035	0.190	−5.464	0.000
LOG(RPERSINC)	0.112	0.048	2.326	0.026
LOG(LDVEH)	0.042	0.032	1.332	0.191
DUM7479	−0.045	0.007	−6.634	0.000
LOG(LDVMT(−1))	0.766	0.157	13.395	0.000
R-squared	0.999	*F*-statistic		12,514.56
Adjusted *R*-squared	0.999	Prob(*F*-statistic)		0.000
S.E. of regression	0.085	Mean dependent var		14.371
Sum squared resid	0.003	S.D. dependent var		0.338
Log likelihood	140.308			

Empirically, the results are similar to those found by Small and Van Dender (2007). The authors reported an estimated short-run rebound effect of 2.2% and long-run rebound effect of 10.7% for 2001. The inverse income model estimated here implies a short-run rebound effect of 3.1% and a long-run effect of 13.1% for the same year (Fig. 10). This is notable given the differences in data (national time series in this study, state cross-sectional times series in Small and Van Dender) and the differences in method of estimation and equation formulation. The inverse income formulation generally shows a slower rate of change in the rebound elasticity over time, as might be expected.

Both models indicate that the rebound effect from 1966 to 1983 was about two to three times larger than at present. Both models indicate that using time constant elasticities would overstate the rebound effect at present and even more so in the future when incomes will presumably be higher.

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[13] In reality, the value of time spent traveling varies enormously not only across individuals but depending on a variety of circumstances. This simple assumption is used to suggest that an inverse function of income may be a reasonable alternative to the logarithm of income.

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7. Discussion and inferences

Several studies have estimated the rebound effect of motor vehicle fuel efficiency on vehicle travel in the United States. With few exceptions, these studies find a relatively small rebound effect, on the order of −0.2 in the long run. These conclusions may have to be revised. Using national time series data for 1966 to 2007, this study finds a statistically significant elasticity of vehicle travel with respect to fuel price, but no statistically significant elasticity of vehicle travel with respect to fuel economy. This result is not new, having been previously reported by Small and Van Dender (2007). What is new is the finding that the hypothesis that the elasticities of vehicle travel with respect to fuel price and fuel efficiency (gallons per mile) are equal, as predicted by theory, is now rejected by the national time series data.

The rejection of equal effects of gasoline price and fuel efficiency may not contradict rational economic behavior if it is due to the countervailing effect of increased vehicle purchase costs due to fuel economy improvements required by the CAFE standards. Higher vehicle costs would increase the long-run cost per mile of driving and there is some evidence that higher vehicle prices lead to lower levels of vehicle travel but more definitive research is needed. In particular, it would be useful to know whether vehicle travel responds to changes in long-run capital costs in the same way it responds to changes in short-run variable costs. There is also the possibility that data shortcomings and a relatively poor "experimental design" in the historical data also contributed. Additional investigation of this result is warranted.

Two studies have suggested that the rebound effect may have decreased over time, and may be much smaller today than it was in the 1970s and 1980s. Gately (1992) hypothesized that the rebound effect varied with the fuel cost share of total vehicle operating costs. Small and Van Dender (2007) acknowledged that this hypothesis was reasonable but found a stronger relationship between per capita income and the rebound effect, based on state level data for the period 1966 to 2002. Recursive coefficient tests on the linear and log-linear models support this inference, showing a decline in the absolute values of coefficients for gasoline price and fuel efficiency after 1980.

Although the hypothesis that fuel cost per mile could be used as a right hand side variable in place of separate gasoline price and fuel efficiency variables was rejected by the data, the possibility of a decreasing rebound effect as a function of income was explored using Small and Van Dender's (2007) formulation of the rebound effect as a function of income. The results obtained here with national time series data are quite consistent with Small and Van Dender's estimates using state level time series, cross sectional data. An alternative formulation of rebound elasticity as an inverse function of income produced a similar but less dramatic decline. The inverse function should be more consistent with the hypothesis that the causal factor in the declining rebound effect is the value of time, and has the advantage that it will not lead to an eventual reversal in the sign of the rebound effect as income grows. The results imply that if there has been a direct rebound effect of fuel efficiency on light-duty vehicle travel in the United States over the period of this study, it is by now on the order of 10%. Still, these results must be interpreted with great caution in light of the rejection of fuel cost per mile as the appropriate variable for estimating the rebound effect.

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Table A1
Projected rebound effect.

	Projected rebound effect, assuming 1.5% per capita income growth (%)
2008	−12.0
2009	−11.8
2010	−11.6
2011	−11.5
2012	−11.3
2013	−11.1
2014	−11.0
2015	−10.8
2016	−10.7
2017	−10.5
2018	−10.3
2019	−10.2
2020	−10.0
2021	−9.9
2022	−9.7
2023	−9.6
2024	−9.5
2025	−9.3
2026	−9.2
2027	−9.0
2028	−8.9
2029	−8.8
2030	−8.6

Appendix A. Future extrapolation of the rebound effect

Assuming a per capita income growth rate of 1.5%, the estimated rebound effect shown in Fig. 10 can be projected for future years (Table A1).

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