JOINT TRANSPORT RESEARCH CENTRE

Discussion Paper No. 2007-16
December 2007

Long Run Trends in Transport Demand, Fuel Price Elasticities and Implications of the Oil Outlook for Transport Policy

Kenneth A. SMALL
University of California
Irvine, California, USA

Kurt VAN DENDER
Joint Transport Research Centre
Paris, France

ABSTRACT

This paper discusses the role of transportation in policies to address energy security and climate change. It focuses on three elements: the impact of energy prices on transport demand, the potential contributions of the transport sector to energy policies, and the interaction between energy and other policy concerns in transport. Transport is relatively unresponsive to broad-based price signals, in particular to changes in prices of fuels, but there nevertheless is considerable scope to improve the fuel efficiency of vehicle fleets. As a result, we should not expect energy policies to trigger dramatic changes in the nature of transport systems. Furthermore, this unresponsiveness suggests that it is relatively costly to reduce energy use in transport, and thus that efficient policies will probably not extract as much energy savings (in percentage terms) from transport as from other sectors. Reducing energy use in transport can be done with price incentives or with regulatory measures. But if reducing climate change is a primary goal, measures that mandate conservation need to be accompanied by others that make fossil fuels economically unattractive – for example broad-based carbon taxes. Otherwise, fossil-fuel reserves will remain economically usable and therefore will constitute a future source of carbon dioxide emissions. We argue that other transport problems, notably congestion, local air pollution, and accidents, are associated with considerably higher marginal external costs than are climate change and energy security. It follows that policies to deal directly with these other problems deserve high priority, regardless of energy policies.

1. INTRODUCTION

Recent years have seen the re-emergence of public debates on the desirability of managing energy consumption and on the effectiveness of various ways of doing so, in transport and other sectors of the economy. The impetus for increased interest in energy issues is twofold. First, oil is a prime source of energy, so that high and volatile oil prices and increased dependence on oil imports have strengthened concerns regarding energy security. Long term projections for oil prices are on the rise. For example, in 2000 the International Energy Agency used a price of $33/barrel for its baseline projection for 2030 (prices of 2005); in 2004 the figure was $40, and in 2005 it had risen to $55, reflecting a concern that higher oil prices are not a transitory phenomenon.[1] The second impetus is a growing consensus that the expected costs of climate change warrant measures to reduce greenhouse gas emissions, although just how quickly remains controversial (*e.g.* Arrow 2007, Schelling 2007).

The goal of this paper is to assess three factors: the impact of expected higher energy prices on transport demand, the potential contributions of the transport sector to energy policies, and the interaction between energy and other policy concerns in transport. Our focus is mostly on road passenger transport because it is a particularly large energy consumer and is often targeted for energy policies.

Section 2 starts with a review of past trends and projections for the future. Nearly all sources suggest continued strong growth in transport demand everywhere, especially in developing countries like China. This demand growth is part of the reason why oil prices have increased; but higher prices so far have not tempered growth much because their effects have been swamped by those of population and income.

Section 2.4 provides a more analytical perspective to determine the main factors driving energy demand in road passenger transport. We review recent econometric evidence, especially for the US, paying particular attention to studies that distinguish explicitly the components of fuel use (vehicle stock, average vehicle mileage, and average fuel economy). This review confirms that income is a key driver of transport demand; fuel prices matter as well, but less so. In addition, the impact of the fuel cost of driving, both on the demand for driving and on the demand for fuel, appears to decline as incomes

[1] Figures taken from CEC (2007, p. 26) and converted to 2005 prices using the US Consumer Price Index (CPI).

rise. A consequence is that the impact of fuel prices on fuel demand works increasingly through fuel economy improvements rather than through reductions in the amount for driving.

A broad conclusion from section 2 is that the elasticity of demand for oil will very likely decline. A consequence is that fuel taxes would need to increase more strongly in order to curb fuel consumption by a given amount. This does not affect the economic case for fuel taxes over alternative policies, but it does affect their political feasibility. When high fuel taxes are not politically feasible, then regulations of fuel economy become more attractive. In this sense, lower elasticities are "good news", as the increased driving resulting from the lower fuel cost of driving caused by better fuel economy – the so-called "rebound effect" – is limited; this of course enhances the effectiveness of fuel-efficiency regulations in achieving their objective of reducing fuel consumption. So, from the perspective of energy security, policy responses that mandate improved fuel economy seem to make sense. But if the goal also is to reduce greenhouse gas emissions, such regulations probably should be complemented by fuel or carbon taxes, because better fuel economy in itself may primarily alter the time pattern of oil usage rather than its cumulative total.

In section 3 we discuss the interaction between energy and other policy concerns in the transport sector. Energy policies affect transport problems, like local air pollution and congestion, that are more closely linked with the amount of driving than with the amount of fuel consumed. One implication is that even small increases in the amount of driving, resulting from fuel economy regulations that reduce fuel consumption, may have costly side-effects. Policy measures to control these side-effects are warranted, and some are in place: for example, local air pollution is controlled through per-mile emission limits. But apart from a few well-known cordon pricing schemes (Singapore, London, Stockholm) and some value pricing experiments (Southern California, Texas, Minnesota), congestion is largely uncontrolled.

In thinking about transport policy more broadly, one needs a yardstick by which to compare the importance of the various goals being addressed. We focus on one such yardstick: the marginal external costs of motor vehicle use from various sources. Using this, we find that more prosaic problems such as congestion, air pollution, and motor vehicle accidents demand a higher priority than energy problems as we search for ways to improve transport. We also suggest that transport is probably a sector of the economy that should contribute less than proportionally to reductions in energy use, as other sectors offer cheaper opportunities for fuel switching and conservation. These findings do not negate the significance of energy policy in transport, but they do offer a caution that energy must not become the only, or even the primary, consideration.

2. THE DETERMINANTS OF ROAD PASSENGER TRANSPORT DEMAND AND DERIVED ENERGY DEMAND IN THE LONG RUN

In this section, we review the main determinants of demand for passenger transport using motor vehicles, with a focus on energy consumption. We pay special attention to the US (section 2.1), which is the world's largest consumer of energy for transport purposes and for which abundant data are available. In section 2.2, we briefly consider trends in other countries, and in section 2.3 we look at projections and policies for the next few decades. In section 2.4, we consider evidence on the price sensitivity of transport demand for energy, including its size, manner of variation, and the decomposition of this price response into changes in the amount and the energy intensity of travel. Lastly, section 2.5 summarizes the insights obtained.

2.1 Trends in the US, 1970-2005

We first discuss trends in energy use and then look at its components (vehicle stock, fuel intensity, and mileage). The Transportation Energy Data Book (Davis and Diegel 2007) conveniently collects the relevant data.

Transport relies on petroleum, and usage keeps increasing

Petroleum consumption by all sectors in the US increased from 17.3 million barrels per day (mb/day) in 1973 to 20.8 mb/day in 2005.[2] That growth was not uninterrupted: consumption hit a low of 15.2 mb/day in 1983. Petroleum consumption from transport, however, grew steadily, from 9.05 mb/day in 1973 to 13.9 mb/day in 2005; consumption fell in all other sectors (residential, commercial, and electricity) except the industrial sector, where it grew slightly. As a consequence, the share of transport in total *petroleum* consumption grew strongly, from 52% in 1975 to 67% in 2005. The share of transport in total US *energy* consumption also grew, from 24.6% in 1973 to 28.2% in 2005. Transport relies almost exclusively on petroleum for its energy, with a 96% share in 1973 and in 2005. The petroleum shares are much lower, and declining, in other sectors.[3]

[2] Crude oil accounted for 90.6% of all petroleum used in 2005 (TEDB, Tables 1.2 and 1.3).

[3] See Davis and Diegel (2007), Tables 1.13 and 2.1 for the figures quoted in this paragraph.

These numbers illustrate that transport has not substituted out of petroleum, in contrast to other sectors. Combined with the fact that petroleum is relatively highly taxed in transport, this suggests that technological substitution to other sources of energy is particularly difficult in transport. An alternative response to high oil prices is to improve fuel economy. Such responses have taken place, in part because for some transport modes, the market mechanism has been complemented by regulatory interventions, most notably the corporate average fuel economy (CAFE) regulations on new passenger vehicles. But these responses have not been sufficient to offset the strong growth in transport activity.

Light-duty vehicle energy use dominates transport energy use

Next, we consider the breakdown of transport energy use by mode, expressed in trillions of British Thermal Units (btu); see Table 1. While total energy use in transport increased by 78% between 1970 and 2005, that increase was much more pronounced for highway modes (88%) than elsewhere (45%). The greatest growth was for light trucks, partly induced by the CAFE regulations;[4] but growth was substantial in the overall light vehicle fleet as well. Energy use by heavy trucks and aviation grew rapidly as well. Cars and light trucks together accounted for just under two-thirds of all transport energy use, in 1970 as well as in 2005. The shares accounted for by heavy trucks and aviation rose, while those of most other modes declined.

Energy intensity has declined strongly for most modes

Table 2 shows how energy intensity has evolved in transport, leading to several observations. First, all modes except water-borne freight are considerably more fuel efficient in 2005 than in 1970. Second, the strongest reduction in energy intensity occurred for commercial air transport, probably because of increasing aircraft size, higher occupancy rates, and improved technology. (General aviation did not share in this reduction.) On a per passenger-mile basis, commercial air travel is now as efficient as driving a car, but of course air travel tends to be over longer distances. Third, light trucks consume 1.4 times as much energy per passenger-mile as cars, even under the optimistic assumption that occupancy rates for trucks are as high as those for cars. Fourth, fuel efficiency improvements are no stronger for regulated light-duty vehicles than for unregulated modes. This suggests that, if there is a basis for targeting light-duty vehicles for fuel-economy regulation, it is that households make “worse” decisions on

[4] CAFE regulations were much stricter for cars, which probably induced manufacturers to produce light trucks as substitutes. We suspect furthermore that the prevalence of light trucks in the vehicle fleet became self-reinforcing by inducing changes in consumer preferences, due to a fad effect and/or an “arms race” as each driver seeks to avoid colliding with vehicles much larger than his or her own.

fuel economy than do commercial transport operators like trucking firms or air carriers.[5] Finally, buses are now less efficient per passenger-mile than cars, because of declining occupancy rates.

The number of light-duty vehicles and their usage increased on a per capita basis

In 1970 there were 0.48 vehicles per capita, against 0.80 in 2005; for the same years, average annual per capita vehicle use increased from 5,440 to 10,087 miles. Business fleet vehicles are used even more intensively, at approximately 25,000 miles per year. The net impact is that total highway travel in the US grew at a 3.2% annual rate for 1970–1995, and a somewhat lower 2.1% rate for 1995–2005.[6] However, recent traffic data suggest that extended high gasoline prices can eventually interrupt such trends: travel on all roads and streets apparently *declined* by 0.4% between April 2006 and April 2007.[7] Thus high fuel prices can sometimes reduce travel by enough to outweigh the positive (and possibly declining) effect of rising income.

The average trip length in the US has crept upward from 8.7 miles in 1983 to 10.0 miles in 2001 (Pisarski 2006, Fig. 3-7). The average length of a work trip has risen considerably faster, from 8.5 miles to 12.1 miles during the same time period. Much of the growth in commuting trip length is driven by a dramatic rise in suburb-to-suburb commuting trips and a less dramatic but still important rise in commuting trips from suburbs to central cities (Pisarski 2006, Fig. 3-9). It is noteworthy that only 22% of all trips are commuting trips (NHTS 2001). Trips for shopping and for personal business now represent 46% of all trips; however, some of this travel is probably as hard to avoid as commuting travel and harder to shift to other modes.

Summary

Improvements in energy efficiency are not strong enough to compensate for the rise in energy demand caused by increased travel, so that transport energy use continues to increase. There are, however, recent indications that sufficiently high energy prices can slow the growth in travel sufficiently to curtail energy use.

---

[5] Various explanations of why households under-invest in fuel economy have been put forward, for example “consumer myopia” (possibly because private discount rates exceed social ones) and loss aversion (consumers undervalue future fuel savings because they are unsure about them and risk averse). See Greene and German (2007). There also is evidence that consumers do not accurately calculate benefits from fuel economy (e.g. Turrentine and Kurani, 2007), but this does not imply systematic errors in the direction of underinvestment.

[6] The source for these figures is Davis and Diegel (2007), Tables 8.2, 7.3, and 3.4.

[7] US FHWA (2007). These preliminary data are extrapolated from a fairly small number of traffic counting locations, and are less reliable than the final estimates (derived from the Highway Performance Monitoring System) published for earlier periods.

Table 1. Transport energy use (measured in btu): modal composition and change, USA, 1970 and 2005

	Highway						Non Hwy					
	Car	Light Truck	Motor-cycle	Bus	Heavy Truck	All Hwy	Air	Water	Pipe-line	Rail	All Non Hwy	All
% overall energy use												
1970	55.06	9.99	0.05	0.84	10.09	76.02	8.49	5.45	6.43	3.60	23.98	100.00
1990	40.22	20.61	0.11	0.77	15.44	77.15	9.62	6.69	4.27	2.27	22.85	100.00
2005	33.38	29.61	0.10	0.70	16.71	80.49	9.05	4.99	3.07	2.40	19.51	100.00
Change in energy use by mode, 1970 = 100												
1990	102.5	289.2	342.9	129.5	214.7	142.3	158.9	172.0	93.2	88.5	133.7	140.27
2005	107.8	526.8	385.7	148.1	294.7	188.3	189.5	162.6	85.1	118.4	144.7	177.84

Source: derived from Davis and Diegel, 2007, Tables 2.7 and 2.8

Table 2. Energy intensity by mode (btu per "output mile"), USA, 1970 - 2005

	Passenger modes										Freight					
	car		LT		Transit bus		Cert. air carrier		Rail transit		HT		Rail		Water	
	btu/pm	ind.	btu/pm	ind.	btu/pm	ind.	btu/pm	ind.	btu/pm	ind.	btu/vm	ind.	btu/tm	ind.	btu/tm	ind.
1970	4868	100	6709	100	2472	100	10282	100	2157	100	24960	100	691	100	545	100
1975	4733	97	6252	93	2814	114	7826	76	2625	122	24631	99	687	99.4	549	101
1980	4279	88	5527	82	2813	114	5561	54	2312	107	24757	99	597	86.4	358	66
1985	4110	84	5008	75	3423	138	5053	49	2809	130	23343	94	497	71.9	446	82
1990	3856	79	4842	72	3794	153	4875	47	3024	140	22795	91	420	60.8	387	71
1995	3689	76	4505	67	4310	174	4349	42	3340	155	22096	89	372	53.8	374	69
2000	3611	74	4545	68	4515	183	3952	38	2729	127	23448	94	352	50.9	473	87
2005	3445	71	4874	73	na	na	3264	32	2784	129	20539	82	337	48.8	514	94

Legend: pm is passenger-mile, vm is vehicle-mile, tm is ton-mile
Source: Davis and Diegel, 2007, Tables 2.13, 2.14, 2.16
Note: Davis and Diegel, 2007, do not provide btu/pm for light trucks - we converted btu/vm using car occupancy rates (which are likely higher)

2.2 Trends in other IEA countries

Oil consumption for transport in all countries belonging to the International Energy Agency (IEA) grew from roughly 600 million tons of oil equivalent (Mtoe) to 1,000 Mtoe between 1970 and 2000. Growth in transport was steady, despite a drop in overall oil consumption in the late 1970s and early 1980s (IEA 2001). Transport relies nearly entirely on oil as its source of energy (approximately 97% in OECD countries: IEA 2002).

Within surface transport, the pattern of energy consumption by mode tends to lie between two extremes: US and Japan. The US has the highest share accounted for by cars and light trucks (66% in 1995), whereas Japan has the lowest (52%). The situation is reversed for truck freight (29% share in the US, 38% in Japan) and for passenger transport by bus and rail (just 1% in the US, 7% in Japan). Thus while the US stands out in its dominance of light-duty passenger vehicles, such vehicles account for the majority of energy consumption for land transport in all IEA countries.

According to IEA (2001), new car fuel economy in the US was roughly on the same level as in Japan and Australia over the period 1980–2000. (It was considerably higher in Europe.) However, the fuel economy of *light trucks*, used mostly for passenger transport and especially prevalent in the US, is much lower than that of cars. Overall fuel efficiency of passenger-vehicle fleets rose modestly from 1980 to 2000 in most IEA nations; but in the US such improvements came to a complete standstill in the late 1990's, mainly because of the explosion of light truck use. Another way to look at this is that fuel use per unit weight has declined strongly everywhere, but vehicle weight has increased, especially in the US.

Regarding travel demand, IEA (2002) shows that in several European countries (France, UK, the Netherlands), vehicle-km per capita increased from roughly 3,000 to 6,000 between 1970 and 1997. This growth rate is greater than that in the US; however, since the *level* in these European countries is still less than half that in the US, it does not seem likely that Europe will converge anytime soon to US levels of per capita driving.

To summarize, patterns and trends in the US and other IEA countries are not fundamentally different. However, the levels are quite different: the US exhibits persistently higher rates of vehicle ownership and usage and lower fuel efficiency, the latter due in part to the higher prevalence of light trucks in US passenger fleets.

2.3 Future developments

OECD countries now represent 70% of worldwide transport energy use; but according to IEA projections this will decline to 55% in 2030 and to 45% in 2050. The growing share of transport in oil demand is not limited to IEA or OECD Countries, and it is likely to continue. Transport in 1997 already represented 54% of oil consumption in the OECD and 33% in the rest of the world; these shares are projected to increase to 62% and 42%, respectively, by 2030 (IEA, 2006). Fulton and Eads (2004) remark that the growing share of transport in total oil demand leads to a decline in the overall price sensitivity of oil demand, because transport demand is less price-elastic than demand for other energy services. This decline may lead to larger price volatility in response to supply shocks, which in turn is one of the factors driving the recent surge of popular interest in energy policy.

The growth in energy use can be decomposed into changes in transport demand and in the energy intensity of vehicles in use. Eads (2006) projects that globally, light-duty vehicle usage will grow by 1.9% per year for 2000–2050, while energy intensity declines by 0.4% per year; the net result is that total energy demand for passenger transport will grow by 1.5% per year. For air transport, energy use grows by 2.6% per year, deriving from annual demand growth of 3.3% and fuel economy improvements of 0.7%. For trucks, energy use grows by 1.9% per year, with demand increasing at a rate of 2.6% and efficiency improving by 0.7% per year. Projected growth is faster in developing countries, but vehicle ownership there is not expected to reach US levels by 2050, nor will per-capita transport demand reach OECD levels. The main driver for transport demand growth is per capita income. (The IEA assumptions about income growth imply roughly that by 2050, the former Soviet Union, Eastern Europe, and China will reach OECD income levels of 2000, whereas India will by 2050 reach the same level attained by China in 2025.)

Energy consumption in transport is a policy concern in many nations with large markets for motor vehicles. The US, Europe, and Japan use various combinations of fuel taxes, vehicle taxes, and energy efficiency regulation of new cars, but the emphasis varies. Fuel economy is regulated in many parts of the world, but it was introduced in the EU and in Japan only recently, and there is no regulation in India and Mexico, where transport demand is likely to grow strongly in the near future (Plotkin 2004). In addition, there are large differences in the stringency of fuel economy regulation, differences that are likely to continue (An *et al*., 2007). The EU and Japan have the most ambitious targets. The US has laxer standards than most other countries, but the current policy impetus seems to be towards stricter regulation. China plans to converge to the strictest standards, but will need time to do so. Regulations are in place in Brazil and South-Korea, but they are not very ambitious.

An *et al*. (2007), reviewing policy developments, suggest that there is increasingly widespread reliance on fuel efficiency regulations. A main reason is that further increases in fuel prices are politically difficult – in rich countries because they are mostly high already, and in poor countries because of concerns about equity (and, we would add, because of political stability). Thus, it is reasonable to expect further regulation-induced declines in the fuel intensity of motor vehicles in many parts of the world.

While increased fuel-efficiency regulations may generate benefits, their value in mitigating climate change is reduced by the fact that they affect the timing, rather than the cumulative amount, of emissions from fossil fuels. The advantages from lowering greenhouse-gas emissions today will to some extent be at risk in the future as the unused stock of fossil fuels remains attractive economically in the absence of measures to raise its price. Strong investments in the efficiency of conventional, carbon-intensive transport technology will if anything tend to *reduce* the price of fossil fuels – indeed, when the discussion turns to energy security that is one of its explicit purposes. Many analysts seem not to have recognized that in this sense, the goals of less climate change and less petroleum dependence are at odds with each other. Thus if fuel-efficiency regulations are used in lieu of price increases, it is important to also use complementary policies to prevent prices from falling and/or to promote technological innovation in alternative energy sources.

Of course, the effectiveness of such complementary policies is subject to limitations. One is that that before investors will embark on major projects to find alternative ways of producing energy, they need assurance that the motivating policies will remain in place for a long time. Another is that high fuel prices for consumers create incentives for manufacturers only to the extent that consumers respond to the fuel costs of travel. This latter concern is the subject of the next subsection, where recent research is shown to suggest that this responsiveness is small and likely declining.

2.4 The price elasticity of fuel demand

This section discusses our own recent work on estimations of the price elasticity of demand for gasoline. There is already a lot of research on this elasticity, but we think ours is particularly informative for the topic at hand, for several reasons. First, we measure not only the price elasticity but two distinct responses that underlie it: changes in amount of driving and changes in fuel intensity. Second, the first of these distinct responses also tells us the magnitude of the “rebound effect,” which is one potentially important by-product of fuel efficiency regulations. Third, we investigate how these underlying responses to fuel prices depend on factors like income, the degree of urbanization, and fuel costs. We find that the responsiveness of driving to fuel costs declines with income and urbanization, and increases with the initial level of fuel costs. Considering the magnitudes of these dependencies, by far the most likely outcome for the future is that this responsiveness will decline further, a prediction that substantially affects how transport policies should be designed.

Our work uses a 39-year cross-sectional time series of US states (plus District of Columbia) covering years 1966-2004. This is a three-year extension of the data set used in Small and Van Dender (2007a); otherwise, the methodology reported here is very similar to that paper.[8]

We decompose changes in fuel consumption into three parts: changes in travel per adult (*M*) for a given vehicle stock, changes in vehicle stock per adult (*V*), and changes in the average fuel intensity of vehicles (*Fint*). These changes are specified as three simultaneous equations, estimated simultaneously in logarithms.[9] In this way we overcome one of the confusing aspects of the past literature, which only rarely has accounted for the fact that fuel efficiency (the inverse of *Fint*) is chosen jointly with travel and vehicle stock. (We envision although do not formally model a decision process in which consumers and motor-vehicle manufacturers interact in new-vehicle markets while responding to constraints or incentives set by regulation.) We can then measure the "structural elasticity" of travel with respect to fuel cost per mile, $\varepsilon_{\hat{M},PM}$, accounting for responses both through fleet expansion and through utilization of a given size fleet.[10] Empirically, we find that ignoring the simultaneous determination of travel and fuel intensity would seriously overestimate the magnitude of that elasticity.

[8] See Small and Van Dender (2007a,b) for further methodological details.

[9] The equations are estimated using three-stage least squares. In order to account for fixed factors affecting a given state, we use a "fixed effects" specification which estimates a separate constant term in each equation for each state.

[10] This structural elasticity comes from the first two of our equations, explaining travel and vehicle fleet size. Small and Van Dender (2007a) show that it can be written in terms of the elasticities measured within these two equations:

$$\varepsilon_{\hat{M},PM} = \frac{\varepsilon_{M,PM} + \varepsilon_{M,V}\varepsilon_{V,PM}}{1-\varepsilon_{M,V}\varepsilon_{V,M}}$$

where $\varepsilon_{M,PM}$ denotes the elasticity of travel with respect to fuel cost per mile in the travel equation; $\varepsilon_{M,V}$ denotes the elasticity of travel with respect to vehicle fleet in that same equation; and where $\varepsilon_{V,M}$ and $\varepsilon_{V,PM}$ denote the elasticities of vehicle fleet size with respect to amount of travel and to cost per mile, both within the second equation. Cost per mile of travel, P_M, is defined as the price of fuel times fuel intensity. Thus $\varepsilon_{\hat{M},PM}$ depicts the result of a hypothetical exogenous change in P_M (or of an endogenous change in P_M caused by an exogenous change in regulations affecting fuel intensity); yet the actual estimation of these component elasticities accounts for the simultaneous determination of

Travel (M) is generally assumed by us and others to respond to fuel cost per mile P_M rather than responding separately to its separate components (fuel price and fuel intensity). For this reason, the elasticity $\varepsilon_{\hat{M},PM}$ provides information about two different policies. It is part of the price elasticity of gasoline (since gasoline price is one component of P_M); at the same time it measures the responsiveness of travel to changes in fuel efficiency (the other component of P_M). In the latter context, the responsiveness is often called the "rebound effect," so called because it offsets a portion of the fuel savings that would result from an increase in fuel efficiency in the absence of any behavioural response.[11] Following convention, we define the positive quantity $b \equiv -\varepsilon_{\hat{M},PM}$ as the rebound effect, and express it as a percentage. For example, if $\varepsilon_{\hat{M},PM}$ =-0.20, the rebound effect is said to be 20%.

Our empirical system also accounts for the slowness with which changes can occur, *e.g.* because changes in the vehicle fleet require purchases and retirements of vehicles. In this way we distinguish between short and long run responses. Technically, this is achieved by including lagged values of the dependent variables.[12] In the travel equation, this is equivalent to assuming that there is a desired level of travel and that any difference between this desired level and the level attained in the previous year is diminished in one year by a fraction (1-α^m), where α^m is the coefficient of the lagged value of the variable. Thus the short-run response (that occurring in the same year) is smaller than the long-run response. The long-run rebound effect is approximately:[13]

---

vehicle stock, vehicle usage, and fuel intensity within the estimation sample. Empirically, we find that $\varepsilon_{M,V}$ is very small, so that $\varepsilon_{\hat{M},PM}$ differs little from $\varepsilon_{M,PM}$.

[11] A distinction can be made between direct and economy-wide rebound effects. Our estimate concerns the direct effect, as it is limited to the effect of increased fuel economy on travel while holding constant all other factors except vehicle stock. But wider economic effects clearly exist that affect energy consumption: for example, consumers will spend some of their saved energy expenditures on other goods that also consume energy. Empirical evidence on such indirect effects is relatively scarce. According to one review, computable general equilibrium models generate values of the economy-wide rebound effect of around 50%, whereas a UK macro-econometric model generates a value of 7% (Sorrell 2007, p.58).

[12] Another dynamic effect we account for is autocorrelation among the error terms in each equation; however, our specification is comprehensive enough that autocorrelation, which is indicative of important omitted variables, is quite small. In previous research, using shorter time periods, it has been difficult to distinguish between autocorrelation and lagged dependent variables, which is important to do in order to distinguish short- and long-run responses.

[13] A more precise relationship accounts for the fact that in the three-equation system, the lagged values in more than one equation can affect the long-run response; specifically:

$$b^L = \frac{-\varepsilon_{M,PM} \cdot (1-\alpha^v) - \alpha^{mv}\beta_2^v}{(1-\alpha^m)(1-\alpha^v) - \alpha^{mv}\alpha^{vm}}$$

$$b^L \cong \frac{b^S}{1-\alpha^m} = \frac{-\varepsilon_{\hat{M},PM}}{1-\alpha^m} \; .$$

As indicated, our main innovation over previous studies is to specify the equation determining vehicle travel so that the “rebound effect” is not a constant, but rather varies with income, fuel price, and urbanization. This is accomplished by specifying the equation for *vma* (the logarithm of vehicle-miles travelled per adult) so that the logarithm of fuel cost per mile, *pm*, appears not only as a single variable (with coefficient β_{pm}), but also interacted with other variables including itself. We define three such variables: *pm***inc*, *pm***pm*≡*pm*^{2}, and *pm***Urban*; we call their coefficients β_1, β_2, and β_3. Then the structural elasticity in this equation, which is approximately the negative of the rebound effect, consists of four terms:[14]

$$\varepsilon_{M,PM} = \frac{\partial(vma)}{\partial(pm)} = \beta_{pm} + \beta_1 \cdot inc + 2\beta_2 \cdot pm + \beta_3 \cdot Urban \; . \tag{1}$$

The results of estimating the model are quite similar to what we found for the slightly shorter time period used in Small and Van Dender (2007a). The most important coefficients are summarized in Table 3.

---

where α^v is the coefficient of the lagged dependent variable in the equation explaining vehicle stock, α^{mv} is the coefficient of vehicle stock in the equation explaining travel, α^{vm} is the coefficient of travel in explaining vehicle stock, and β_2^v is the coefficient of *pm* (the logarithm of cost per mile) in the equation explaining vehicle stock. All the dependent variables are expressed in logarithms. See Small and Van Dender (2007a), equation (7).

[14] The factor 2 in this equation is a consequence of properties of the derivative of the quadratic function (*pm*)^2.

Table 3. Selected estimation results for the three-equation model, 1966-2004

Equation and variable	Coefficient symbol	Coefficient estimate	Standard error
Equation for *vma*:			
pm	$_{pm}$	-0.0407	0.0042
*pm*inc*	$_{1}$	0.0696	0.0132
*pm*pm*	$_{2}$	-0.0169	0.0064
*pm*Urban*	$_{3}$	0.0255	0.0100
inc		0.1044	0.0134
Lagged *vma*	^{m}	0.7980	0.0120
Equation for *fint*:			
pf+vma		-0.0297	0.0064
cafe		-0.0882	0.0110
Lagged *fint*	^{f}	0.8450	0.0127

Notes to Table 3:
vma = logarithm of vehicle-miles traveled per adult
pm = logarithm of fuel cost per mile (normalized)
inc = logarithm of income per capita
Urban = fraction of population living in urban areas
fint = logarithm of fuel intensity, *i.e.* log (1/*E*) where *E* = fuel efficiency
pf = logarithm of fuel price
cafe = variable reflecting how far the CAFE standard is above the desired fuel efficiency based on other variables (Small and Van Dender 2007a, section 3.3.3)
pf+vma is log (price of fuel * vehicle-miles traveled), representing the logarithm of the incremental annual fuel cost of a unit change in fuel intensity; thus it may be interpreted as the logarithm of the "price" to the user, in terms of extra annual operating cost, of vehicle features that cause higher fuel intensity.

For measuring the "rebound effect," our primary interest is in the first four coefficients shown in Table 3. The short-run rebound effect for average conditions in this sample is approximately $-\beta_{pm}$=0.0407, *i.e.* 4.07%, while the long-run rebound is 4.95 times this value, or 20.1%. The coefficients for the three interacted variables involving *pm* (*i.e.*, β_1, β_2, and β_3) show that the magnitude of the rebound effect declines with increasing income and urbanization, and increases with increasing fuel cost of driving. The net result is that the rebound effect declined substantially over time – which we confirmed by estimating the equation (without the three interaction terms) separately for time periods 1966-1989 and 1990-2004, with the result that the rebound effect fell by half from the earlier time period to the later one.[15]

The coefficient of *inc* confirms the conventional expectation that vehicle-miles travelled rises with rising income: the income-elasticity is approximately 0.1 in the

[15] More precisely, the short-run rebound fell from 4.8% to 2.9%, while the long run rebound fell from 21.1% to 7.7%. These declines are not in the same proportion because the estimated coefficient of the lagged dependent variable also changed between time periods.

short run and 0.5 in the long run. The coefficient α^m of lagged *vma* shows that the long-run effect of any variable on vehicle miles travelled (VMT) is about $1/(1-\alpha^m)$=4.95 times larger than the corresponding short-run effect. This may seem surprising given our finding that changes in the size of the fleet play only a small role. However, changes in travel can occur either quickly, for example through carpooling or trip chaining, or over a longer period, for example through changes in home and workplace locations or even in land-use patterns.

Our equation system also measures the extent to which the fleet-average fuel efficiency is adjusted in response to fuel prices. The short-run elasticity is approximately the coefficient of *pf*+*vma* in Table 3, or -0.03, implying a long-run elasticity of -0.15.[16]

We show in Table 4 various implied elasticities, computed at two different sets of values for the explanatory variables *inc*, *pm*, and *Urban.* One set is the average values over our sample and the other is the average values over the last five years of the sample.[17]

---

[16] The precise equations for the short-run and long-run elasticities of fuel efficiency with respect to fuel price, again accounting for feedbacks across all three equations, are shown as equation (9) in Small and Van Dender (2007a).

[17] The third elasticity shown is the price elasticity of gasoline consumption, calculated as follows: $\varepsilon_{F,PF} = \varepsilon_{\hat{M},PM} \cdot (1+\varepsilon_{\tilde{I},PF}) + \varepsilon_{\tilde{I},PF}$, where $\varepsilon_{\hat{M},PM}$ and $\varepsilon_{\tilde{I},PF}$ are the elasticities reported in the previous two rows of the table. This equation is derived by USDOE (1996, p. 5-11) and Small and Van Dender (2005, eqn. 6); the term $(1+\varepsilon_{\tilde{I},PF})$ was inadvertently omitted in Small and Van Dender (2007a) when calculating elasticities of gasoline consumption, causing those elasticities to be slightly overstated – see Small and Van Dender (2007b) for the correct values for the shorter (1966-2001) data set used in those papers.

Table 4. Estimated Elasticitites

	1966-2004		2000-2004	
Average values (real 2006 $):				
Household income ($/year)	26,506		33,669	
Fuel price ($/gal)	1.91		1.69	
Calculated elasticities:	Short run	Long run	Short run	Long run
Vehicle-miles traveled	-0.041	-0.210	-0.011	-0.057
Fuel intensity	-0.035	-0.193	-0.031	-0.191
Fuel consumption	-0.074	-0.363	-0.041	-0.237
Rebound effect (%)	4.1%	21.0%	1.1%	5.7%

Source: Small and Van Dender (2007c), estimating using full data set.

Elasticities are with respect to fuel cost per mile for Vehicle-miles traveled, and fuel price for other quantities.

Columns labeled "1966-2004" use average income and fuel cost for the entire sample period.

Columns labeled "2000-2004" use average income and fuel cost for the last five years of the sample period.

Standard errors are approximately as follows:

(a) 1966-2004, short run: 0.004 for "Vehicle-miles traveled", 0.020 for "Fuel efficiency" and "Fuel consumption".

(b) 2000-2004, short run: 0.007 for "Vehicle-miles traveled", 0.020 for "Fuel efficiency" and "Fuel consumption".

(c) Long run: 5-6 times as large as for short run.

Under average conditions over our entire sample period, the measured rebound effect is 4.1% short run and 21.0% long run. However, these values are found to fall dramatically when we consider conditions that prevailed in 2000-2004: over those years the rebound effect on average is just 1.1% short run and 5.7% long run.

Why should rising income diminish the rebound effect? Our model provides no direct answer, but there are some plausible explanations. First, higher incomes cause the share of fuel expenditures in total expenditures to decline, which may lead to lower elasticities. Second, higher incomes lead to higher values of time, so that time costs of travel become relatively more important than fuel costs. Higher fuel costs then translate into proportionally smaller increases in the generalized price of travel (which is the sum of time and money costs), and assuming that drivers respond mainly to this generalized price, this reduces the elasticity with respect to the money costs. However, there are reasons why higher incomes could lead instead to larger elasticities: the share of discretionary driving is likely higher for higher income households, and it is easier to cut back on such driving than on “mandatory” travel. Hughes *et al.* (2006) find larger price elasticities of gasoline demand for higher incomes than for lower income households, while at the same time finding that this elasticity declines over time.[18]

The elasticity of fuel intensity, unlike that of travel, is found to be almost constant, even though we tried specifications that would allow it to vary. This elasticity is somewhat under-researched, with results varying widely depending largely on type of data set. Our results for its absolute magnitude, namely short-run and long-run values of 0.031 and 0.191 over the recent period, are quite similar to the estimates of 0.017 and 0.150 obtained by Li, Timmins and von Haefen (2006), who more directly measure the responses of consumers in the form of model-specific decisions about scrappage and new-vehicle purchases.

The long-run price elasticity of gasoline in our estimates is -0.363 over the entire sample, declining modestly in magnitude to -0.237 over the last five years. With the travel component declining sharply and the fuel-intensity component approximately constant, travel is becoming a notably smaller component of the response to fuel prices. The finding that responses to fuel prices take place through changes in fuel economy more than through changes in the amount of driving is confirmed by a study for twelve OECD countries by Johansson and Schipper (1997), and more recently in a meta-analysis (an econometric analysis of earlier estimates of the fuel price elasticity of the demand for fuel) by Brons et al. (2007).[19]

What about the future? In a nutshell, our results suggest that fuel consumption by passenger vehicles has become more price-inelastic over time, and that it is increasingly dominated by changes in fuel efficiency rather than in amount of driving. Furthermore, our results identify two main reasons for this: rising incomes and falling real fuel prices. One of these – rising incomes – can be presumed to characterize the future as well, whereas the other – falling real fuel prices – probably cannot. So we need to consider the relative magnitudes of these two factors.

---

[18] Yet another factor is that richer households own more vehicles, allowing them to respond to fuel price increases by using the more fuel-efficient vehicles more intensively. This seems mainly a short-run reaction, and would tend to make them respond less through changes in travel but more through changes in average realized fuel efficiency. Basso and Oum (2007) discuss conflicting evidence from cross-sectional studies on the relationship between income and the price elasticity. Most recently, Wadud *et al*. (2007a,b) find, as we do, that the price elasticity is smaller at higher incomes.

[19] The meta-analysis does not investigate whether the price-elasticity of fuel consumption depends on income. However it does test whether it depends on a pure time trend, after all other measured determinants are controlled for, finding no evidence of such dependence. This result is consistent with our model, which also finds no significant time trend in the rebound effect, even when the three interaction terms in the estimating equation are removed. We interpret this to indicate that a simple time trend is inadequate to capture the effects of the complex changes in income, urbanization, and fuel cost over the time periods covered by the various studies.

Real income in the US grew at 1.4% per year over the period 1984–2004 (US Bureau of Labor Statistics 2007). As for gasoline prices, the US Energy Information Agency (EIA) projects in its "reference case" that they will be roughly constant in real terms after declining slightly from a spike in 2005-2006.[20] The EIA also considers low- and high-price cases; in the latter, real prices rise on average by 1.4% per year. In the high-price scenario, then, rising incomes are causing the rebound effect to diminish by 0.097 percentage points per year, while rising fuel prices are causing it to rise by 0.047 percentage points per year.[21] Thus even in a scenario projecting high growth of fuel prices, the influence of income growth dominates; it would do so even more if we used the 2.3%/year income growth projections from US EIA (2007) over the period 2005-2030. Thus we should expect the rebound effect and the price-elasticity of fuel consumption both to continue to become smaller.[22]

2.5 Summary

The demand for oil as a source of energy is likely to grow along with income, especially outside the OECD. With an upward sloping supply curve, this results in higher prices. In addition, the share of the transport sector in total oil demand will likely increase: this reduces the overall elasticity of oil demand, given that transport has very limited access to alternative technologies in the short term. Moreover, the elasticity of fuel demand in transport declines as incomes increase, a pattern which we identified for the US and which we expect applies elsewhere also. This further reduces the price elasticity of oil demand. The declining elasticity implies that short-run supply shocks have bigger price effects and that long-run demand will not be curbed strongly as prices rise.

A common policy response to (real or perceived) excessive costs of reliance on oil is to mandate fuel-economy improvements in the transport sector. Such policies may well be justified, especially when households are thought to under-invest in fuel economy, and when higher fuel taxes are difficult to implement. It is not straightforward, however, that regulation of fuel economy in itself contributes to the mitigation of climate change. The reason is that better fuel economy alters the rate of emissions, but not necessarily their time-aggregated total. This suggests that, if

---

[20] See US EIA (2007), "Year-by-Year Reference Case Tables (2004-2030)," Table 3, for average price of motor gasoline. Prices are projected to decline slightly in real (inflation-adjusted) terms, by an average of 0.2% per year, over the period 2005-2030.

[21] These numbers are calculated from the figures in Table 3, using equation (1), as 0.0696*0.014*100 and 2*0.0169*0.014*100, respectively.

[22] At some point our equations predict that the rebound effect would become zero and then negative; obviously this is contrary to theory and must be regarded as a limitation of extrapolating our equations beyond the primary range of the data set on which they are estimated.

strong reductions in CO_2 emissions are desired, fuel economy regulation needs to be complemented by other policies such as a carbon tax.[23]

We have in this section focussed on the connection between energy and transport. In the next section, we put the discussion in the broader framework of transport policy.

3. ENERGY POLICY IN TRANSPORT

We now turn to factors that shape the relative advantages of various transport policies toward energy and other goals. We attempt to create a uniform framework by considering the marginal external costs of fuel-related and other transport externalities.

Long before energy issues rose to their present degree of prominence, transport was an important and often problematic sector in the economies of nations and cities. The many problems identified with the transport sector include large and irreversible investments, financial mechanisms, subsidies, implications for regional economic growth and inter-regional integration, congestion, safety, and negative spillovers to non-users through air pollution, noise, aesthetics, wildlife disruption, water quality, availability of open space, and other mechanisms. These problems have elicited numerous policy responses, some of which increase and some of which lessen the amount of transport undertaken. Furthermore, these policies are often thought to have far-reaching implications for local, regional, and national economies, and they certainly involve strong impacts on government budgets.

One must consider, then, the interaction of energy objectives with the objectives of these other policies. Will attention to energy make other goals easier or harder to achieve? Do these other goals alter in significant ways the optimal response to energy problems? Even aside from other goals, how much of a role should transport policy play in achieving energy objectives? And just how big is energy when viewed as a part of the overall policy environment for the transport sector?

One way to tackle these issues is by asking what responses would markets bring about in an ideal world where prices could be brought into perfect alignment with marginal social costs – *i.e.*, with the extra costs incurred by all members of society,

[23] If economy-wide rebound effects are large, which is uncertain but possible (cf. footnote 8), this is an additional reason for combining fuel economy regulations with fuel or carbon taxes.

including the decision maker, due to particular economic decisions.[24] This involves looking at each as a market failure, and asking what would happen if that failure could be eliminated within the market system. For example, if we knew the costs global climate change, of macroeconomic disruptions due to reliance on unstable or monopolistic energy suppliers, and of consumers' myopia or lack of information enabling them to optimally trade off energy efficiency against purchase price, and if we could trace these costs to specific economic decisions, then we would know how much prices would have to change in order to confront each decision-maker with the marginal social costs of those consumption decisions. We could then ask how decision-makers would react to such changes in price signals. How much would they curtail transport energy use, and through what mechanisms? Such an analysis provides a guide as to what changes would be the most efficient ones to target, using public policy, if in fact it is not feasible to bring about the theoretically desirable price signals.

The same type of analysis can be done for other transport problems, and has in fact been done in considerable detail for two of the most important – congestion and air pollution – and in a more sketchy fashion for others including noise and safety. Once again, this produces a set of hypothetical responses that thereby become appropriate candidate targets for public policy.

By comparing the resulting behavioural responses across the problems targeted, we obtain answers to the questions asked above. In some cases, behavioural responses to remedy one problem would exacerbate another; in other cases, the responses may work together, "killing two birds with one stone". Furthermore, by considering the relative magnitudes of the price signals involved, one can quantify the judgment involved in the last question posed: how big are these problems relative to each other?

A comprehensive analysis of this type would consume a work the size of an encyclopaedia. We provide here a first cut, by considering two questions. First, what are the relative sizes of the marginal external costs of various transport problems, when averaged over a large class of users? (Marginal external cost means that part of the marginal social cost not incurred by the decision maker.) Second, how

[24] This is a simplification, as the presence of market failures and policy concerns outside the transport sector implies that optimal transport prices likely deviate from marginal social costs; in the jargon, we are in "second-best". The exact nature of such deviations is difficult to determine, but recent research suggests that the deviations may be smaller in the transport sector than in other sectors, because price changes in transport do not strongly exacerbate other inefficiencies in the economy, notably those related to labor taxes (West and Williams, 2007). At any rate, it is very likely that second-best transport pricing would align charges more closely with external costs than is the case for the current price structure, so that the comparison discussed in the text is a useful one.

dramatically do those costs vary across user groups or local situations? And if they do vary, do the responses that would be undertaken in response to internalizing those costs also vary? If so, then there is a strong case for looking at closely targeted policies that can bring about such diverse responses; if not, then a blunt instrument that changes average behaviour may be adequate. Local air pollution, and to a stronger extent congestion, are examples of externalities where blunt approaches are not usually considered to be effective because what is needed is a set of changes in very specific situations like driving in big cities during peak periods, or driving a vehicle whose emission control mechanisms are not working.

Table 5 collects estimates of marginal external cost due to several types of transport problems. They are classified according to whether they vary mainly in proportion to fuel consumption, which is the case for climate change and oil dependency, or in proportion to vehicle-miles travelled. For comparison, the former are converted to a marginal cost per vehicle-mile, using the fleet average fuel efficiency for passenger vehicles (*e.g.* 22.9 mi/gal for the US in 2005). Note however that in terms of the thought experiment described above, the best policy responses to fuel-related and mileage-related externalities are quite different. Raising the price of fuel induces not only a mileage reduction but a substantial increase in fuel efficiency, the latter increasingly dominating as described in the previous section. As emphasized by Ian Parry and Small (2005), this difference dramatically affects the (second-best) optimal use of a fuel tax to address mileage-related externalities: using their numbers, the tax rate would be set at only roughly 40 percent of the value that would be calculated by multiplying the cost/mile figures by fuel efficiency. Conversely, using a distance-related tax (sometimes called a VMT tax) to address a fuel-related externality such as global warming would fail to elicit one of the most important responses needed, which is an increase in fuel efficiency of vehicles.

Table 5. Marginal external costs from automobiles, US cents/mile, 2005 prices

	Harrington-McConnell (US & Europe)		Sansom *et al.* (UK)		Parry *et al.* (US)	High Fuel-related[a] (US)
	Low	High	Low	High		
Fuel-related: [a]						
Climate change	0.3	1.2	0.5	2.0	0.3	3.7
Oil dependency	1.6	2.7	n.a.	n.a.	0.6	2.4
Driving-related:						
Congestion	4.2	15.8	31.0	35.7	5.0	5.0
Air pollution	1.1	14.8	1.1	5.4	2.0	2.0
Noise, Water	0.2	9.5	0.1	2.5	n.a.	n.a.
Accidents	1.1	10.5	2.6	4.5	3.0	3.0
Total	8.5	54.5	35.3	50.1	10.9	16.1
Percent fuel-related	22	7	1	4	8	38

Sources: Harrington and McConnell (2003), Table 3; Sansom *et al.* (2001); Ian Parry, Walls and Harrington (2007), Table 2. “High Fuel-related”.: same as Parry *et al.* except for climate change ($0.76/gal, from Stern 2005) and oil dependency ($0.55/gal, from the high end of range in Lieby (2007), Table 1.

Notes: All numbers converted to 2005 US price levels. n.a. means not estimated, in some cases due to an explicit argument that the quantity is small. Fuel-related costs are converted from per gallon to per mile using prevailing average fuel efficiency.

The fuel-related costs portrayed in Table 5 are potentially very large in aggregate. Taking the “high” values of the last column, and multiplying by just the 2.99 trillion vehicle-miles travelled in the US in 2005, they come to $111 billion for global warming and $72 billion for oil dependency annually.

Yet it appears that other, more prosaic, transport problems are even larger. The three studies listed in Table 5 (excluding the last column) are unanimous in finding that congestion involves larger external costs than fuel-related externalities, and except for the “low” Harrington-McConnell values, the same is true of air pollution and accidents. In nearly all cases, congestion alone is found to outweigh the fuel-related externalities by a large margin. These findings may seem surprising until one realizes that congestion and air pollution have tangible and serious effects on most urban residents on a daily basis. Congestion consumes huge amounts of time, and air pollution produces demonstrable mortality. Climate change and oil dependency, by contrast, have effects that, as best as can be determined from the admittedly imperfect modelling available, are in the distant future, capable of substantial amelioration by other means, and/or simply not very large when spread over the enormous number of vehicle-miles producing the estimated aggregate impacts.

What about variation? The figures in Table 5 are national averages, but some of these costs vary strongly over time and place. For example, a recent French study, discussed in Grange (2007), finds that the marginal external congestion costs of driving in urban traffic are about ten times as high as those of driving in interurban traffic. This conclusion is corroborated by other studies, which in addition point out that the congestion costs depend strongly on time of day (*e.g.* Proost *et al.* 2002). This is a second reason why fuel taxes are not well suited to deal with congestion. There is strong evidence that the response to imposing targeted congestion charges (*i.e.*, ones that vary by time and place) would involve a lot of shifting of trips across time periods, modes, and routes, and much less overall reduction of trips; thus the most efficient policies would aim at shifting trips in this manner rather than simply reducing all trips.

Similarly, pollution costs from motor vehicle-use vary widely depending on location, fuel type, age of vehicle, and vehicle maintenance practices. for example, pollution costs are higher for diesel than gasoline cars, because of the high health costs associated with emissions of small particulates. This casts some doubt on whether the European “dieselization” strategy to increase fuel economy is opportune, as it increases emissions of particulates unless particulate filters become universal. The US may embark on a “hybridization” strategy, which avoids the particulates issue but which also involves expensive technology. More generally, given the high costs of further improvements of emission abatement technology, one may question the desirability of this policy approach, as policies to reduce emissions from small numbers of gross polluters become more attractive (Small, 1997).

If we use the higher fuel-related figures in the last column of the table, the picture changes somewhat – although even then fuel-related externalities do not dominate other externalities. However, we think these higher figures are not well supported by existing evidence. In order to support this claim, we now consider more carefully the sources of the estimates shown for fuel-related externalities, first for climate change (section 3.1) and then for oil dependency (section 3.2).

3.1 Marginal external costs of motor-fuel consumption due to climate change

The climate-change cost calculated by Parry *et al.* (2007), shown in the next to last column of the table, is based on a damage estimate of US$25 per tonne carbon, *i.e.* $25/tC, at 2005 prices.[25] This figure is consistent with results from a number of reviews including Cline (1990), Nordhaus (1994), ECMT (1998, p. 70), and Tol et al. (2000).[26] More recent reviews include Tol (2005), who reaffirms the validity of relatively low costs,[27] and Stern (2006, pp. 287-288), who argues for much higher costs as discussed below.

Quantifying such costs is of course highly speculative, due especially to three features of climate change. The first is the highly uncertain effect of emissions on specific climate outcomes; it is usually handled by acknowledging the uncertainty and stating results in terms of a specific assumed climate outcome, most often based on reports of the Intergovernmental Panel on Climate Change (IPCC).

---

[25] One tC means one metric ton or tonne (1000 kg) of carbon. Given that carbon comprises a fraction 12/44=0.27 of the weight of a carbon dioxide molecule, $1 per tC is equivalent to $3.67 per metric ton of CO2. According to National Research Council (2002, p. 85), one tC is the carbon content of 413 gallons of gasoline.

[26] See, for example, the discussions in Small and Verhoef (2007, ch. 3) and Parry and Small (2005). The damage estimate of $25/tC is also consistent with the "shadow price" of carbon coming out of optimization models of economically efficient paths toward greenhouse gas control, the most well-known being a series of models developed over many years by William Nordhaus, of which a recent version is the regional integrated model of climate and the economy, or RICE model (Nordhaus 1994). Nordhaus (2007b) describes a recent calculation using this model as leading to a carbon price of $17/tC in year 2010 (stated at year 2005 prices) rising to $70/tC in 2050. The "optimal" calibration reported in Nordhaus (2007a) produces a price of $35/tC in 2015, $85/tC in 2050, and $206/tC in 2100. These numbers encompass all the estimates underlying Table 5 except for Stern's. The damage estimate can also be compared to the actual trading prices of carbon permits in the EU's Emissions Trading Scheme. If the market is working smoothly (a highly debated proposition in this case), these prices should reflect the marginal costs to industry of enacting controls to meet the mandates of the EU under the Kyoto Protocol. In actual experience this market has fluctuated substantially, with prices between €6 and €30 per tonne of carbon dioxide during a period covering most of 2004-06 (Convery and Redmond 2007, Fig. 2), which equate to $27–$138/tC (given that the carbon atom constitutes 12/44 of the atomic weights in a molecule of CO2, and using the average 2004-06 exchange rate of 1€=$1.25). These figures suggest that in Europe, at least, the marginal control cost has been pushed to well above the lower estimates of marginal damage cost in Table 5.

[27] Tol (2005) reviews 103 estimates of marginal CO2 damage costs, taken from 28 separate studies done by 18 distinct research groups. The median estimate is $14/tC, but the estimates are highly skewed to the right, with unweighted mean $93/tC and standard deviation $203/tC. The mean estimate declines substantially, to $43/tC, when only peer-reviewed studies are included; so does the standard deviation, to $83/tC. There is a clear effect of methodology – especially using a very low interest rate for discounting and using "equity weights" to aggregate across countries – in accounting for most of the higher estimates. Tol concludes: "Using standard assumptions about discounting and aggregation, the marginal damage costs … are unlikely to exceed $50/tC, and [are] probably much smaller" (p. 2064).

The other two features, however, give rise to two sources of major differences among analysts. One is the unknown form of human adaptation to problems building up over decades and centuries. The other is differences of opinion about the appropriate analytical procedure for aggregating effects occurring over long time intervals. We consider each of these sources of controversy in turn.

Human adaptation to climate changes may occur in many ways, including changes in crops (*e.g.* Mendelsohn et al., 1994), public health measures, new water storage facilities, coastline protection measures, and human migrations. Tol (2005) and a working group of the IPCC (Martin Parry *et al.* 2007) provide thorough discussions. Such adaptive measures are expected to greatly reduce the damage that would otherwise occur. To take one example, the European Commission (2007, p. 10) estimates that European damages from a 56 cm rise in sea level in the 2080s would be approximately €18 billion per year without adaptation but €3 billion with adaptive measures. Similarly, the relevant IPCC working group notes that “adaptation costs for vulnerable coasts are much less than the costs of inaction” (Parry *et al.* 2007, p. 40). Some adaptive measures will be extremely costly, but these costs will be spread over many decades. Some, like migrations, may turn out to exact a terrible human toll, just as do natural catastrophes and various failures of governmental policies today. And adaptive measures cannot mitigate all damage: species extinctions, flooding, damage to deteriorating aquatic environments, fresh water shortages, and many other adverse effects are very likely to occur despite adaptation. Of course, such adverse events are already occurring today, primarily for other reasons; so the relevant questions become quantitative ones of how much and at what cost.

Measurement of the ultimate costs is full of hazards, but real progress has been made, especially with respect to converting damages to monetary costs. The evidence so far does not indicate that such costs dominate the more prosaic costs of congestion and air pollution that we have become accustomed to in the field of transport. An analogy with a different transport problem may be useful. The collapse of a well-used bridge in Minneapolis in August 2007 elicited expressions of great urgency for dealing with the problem of US infrastructure deterioration. Yet the resulting 13 deaths are far less than just one day’s average fatalities from US motor-vehicle accidents (116 in 2004). So which is the larger national problem: infrastructure deterioration or routine safety? It is this kind of question that is implicitly addressed by cost figures like those in Table 5. To the extent they are valid, the appropriate conclusion is not to ignore the problems with smaller costs; it is rather to maintain perspective relative to other problems, even prosaic ones, when setting priorities.

The second major source of differences among analysts is the matter of “discounting” future costs in order to aggregate them into a number applicable to an emission produced at a specified time (*e.g.* today). This is a technical debate, largely over the ethical meaning and economic interpretation of parameters that characterize modern models of economic growth. In what Weitzman (2007) calls the “majority view” of most economists, distant economic consequences should be discounted at interest rates on the order of 4%–6%. This view relies in large part on the fact that observed savings behaviour appears to be roughly consistent with a long-term growth model in which people discount their own or their descendants’ future utility at very modest interest rates (the so-called “pure rate of time preference”), and simultaneously seek to smooth their consumption in a world where long-term growth is making them richer. The consumption smoothing part of this justification can be stated equivalently as an ethical position against income inequality across generations. In this interpretation, since future generations are likely to be richer than us, we would discount the advantage to them resulting from any sacrifice by us. Yet another justification is that the world economy is capable of generating returns on investments of at least 4%–6%, and these returns may be used to mitigate or compensate for the adverse future consequences of climate change.

There is actually little disagreement among economic analysts about the principles just stated. The disagreement comes in the form of numerical parameters. The “majority view” infers from savings behaviour that people apply a pure rate of time preference of 1–3% per year, both for themselves and for descendants to whom they bequeath wealth. Others, however, argue that for purposes of policy any such preferences must be overridden by an ethical principle that future generations are just as important as current ones. Most prominently, the *Stern Review* issued by the UK Treasury (Stern 2006) argues that the only legitimate basis for a pure rate of time preference is uncertainty over whether those future generations will actually be alive, resulting in use of a pure rate of time preference of just 0.1%. As for the aversion to income inequality, Stern uses a parameter that implies indifference between a given *percentage* loss in world output at any point in time; whereas the “majority view” is for a greater aversion to income inequality so that one would not accept a 1% cut in living standards today in order to achieve a 1% increase at some time when people are ten times richer. The implications of Stern’s assumptions is an actual discount rate of only 1.4% per year (Weitzman 2007).

Nordhaus (2007) argues that these two parameter assumptions used by Stern, taken together, are inconsistent with people’s observed behaviour, in particular implying they would choose to save much more than they do. (See however the rebuttal to this type of argument in Stern, 2006, pp. 47-48.) More transparently, Nordhaus provides some numerical examples of the implications of using Stern’s 1.4% social discount rate. Suppose a “wrinkle in the climatic system” threatens to reduce world consumption by 0.1% forever, starting in year 2200. It could be averted by sacrificing 56% of one year’s world consumption today. Stern’s methodology produces the result that we should undertake that expense; the low interest rate for discounting turns the climate wrinkle, which might never even be noticed, into a catastrophe in present value terms.

It is worth noting that the *Stern Review* itself, despite its language of catastrophe, does not project world per capita consumption to decline in real terms, even with uncontrolled climate change. Rather, in the worst of all the cases calculated, it is projected to grow to 8.6 times today’s level by year 2200, instead of to 13.2 times as it would in the absence of climate change.[28] Yet because this reduced income continues forever, and is discounted at only 1.4% per year, it has a present value equivalent to reducing per capita consumption by 14.4% every year from now to forever (Stern 2006, Table 6.1). Thus Stern would evidently recommend that we cut world consumption if necessary by 14%, starting today and lasting forever, in order to prevent our descendants from having to live with a lower income growth than they otherwise would enjoy. Would we really accept such a bargain? These examples illustrate the hazards to common sense that accompany arguments about long time periods with very low discount rates.

Weitzman (2007) provides an insightful discussion of a possible alternative rationale for the parameter values used by Stern. In Weitzman’s view, the most important issue is uncertainty about the prospects and consequences of unlikely but extremely damaging results of climate change – events such as collapse of a continental ice sheet or reversal of a major ocean current. Neither Stern nor his critics have a way to model this type of uncertainty rigorously. Weitzman posits that because of this, Stern may have “tweaked” his parameter values intuitively to reflect it. The trouble is, such uncertainty takes us into possibilities that we know little about and cannot model well. Weitzman’s own conclusion is that the “majority view” provides a good starting point for immediate policy, but that the uncertainty justifies a crash program of research and policy debate aimed at learning about the potential adaptations to and ultimate consequences of small-probability catastrophes. Weitzman also shows, using several examples, that the response called for may well be closer to that coming out of Stern’s model than that from the majority view.

[28] These numbers are calculated from Stern’s assumed 1.3 percent per year growth rate of per capita output in the absence of human-induced climate change, applied for a period of 200 years, and diminished by 35.2 percent according to the 95th-percentile loss in the worst scenario shown, that labelled “High Climate, market impacts + risk of catastrophe + non-market impacts” (described on p. 156 and in Figure 6.5c). Nordhaus (2006, p. 18) makes a somewhat similar calculation in a working-paper version of his 2007 critique.

This technical discussion may seem to disconnect from the main thrust of Stern's and many other people's analyses of climate change. These writings are filled with descriptions not of happy people enjoying living standards ten times greater than today's, but rather of terrible disruptions to their well-being. Yet the technical analysis just described is the one that underlies Stern's damage figure of US$96 per tonne CO2 (at 2005 prices), equivalent to $352/tC or $0.85/gal for gasoline.[29] Part of Weitzman's critique is that Stern may have adapted the parameters of a highly technical and, perhaps, ultimately unsatisfactory analysis using conventional growth theory in order to capture the possibilities, even if remote, that the world will turn out much worse than the scenarios being modelled. Unfortunately, there does not at present seem to be an adequate basis for analysis of such contingencies within a decision-theoretic framework.

3.2 Marginal external costs of motor-fuel consumption due to oil dependency

Some sophisticated analysis has gone into measuring a marginal social cost for fuel consumption due to oil dependency. One of the most thorough and recent is Leiby (2007). Ian Parry and Darmstadter (2003) provide a useful review, citing studies producing estimates of from zero to US$0.33/gal; their own preference is $0.125/gal. (See also Davis and Diegel 2007, table 1.8.) Leiby (2007, Table 1) obtains a range by considering likely parameter values within a single model: when divided by 42 gal/bbl, his range is $0.16–$0.55 per gallon, with a preferred value of $0.32. We include the value $0.55/gal in our "High fuel-related" column of Table 5.

However, we have severe reservations about accepting these numbers as indicators of the marginal value of reducing oil imports. The costs of oil dependency are essentially the total cost to a national or regional economy (specifically that of the US) of various features of the world oil market that cause problems to a nation relying heavily on oil imports. Specifically, the features considered by these authors are a "monopsony premium" and the costs of macroeconomic disruptions. The first is rightly described Leiby as a foregone opportunity: because the US is a large part of the world oil market (on the buying side), it could, by exerting coordinated national policy, reduce our import demand as seen by the Organization of the Petroleum Exporting Countries (OPEC) and thereby reduce OPEC's monopoly power. But the lion's share of the monopsony premium consists of curtailing the transfer of wealth abroad to OPEC nations, not a saving of world resources. Indeed, the analysis takes

[29] We have restated Stern's figure of $85 (Stern 2006, p. 287) from year 2000 to year 2005 prices, using the 13.4% growth of US Consumer Price Index over that time.

as given that the inefficiency of OPEC's monopoly power is by reducing world consumption below efficient levels; so it is unclear that further reducing world consumption would create worldwide benefits. Rather, it is mainly an attempt to reduce a transfer occurring through the workings of world trade. It seems to us inconsistent to use a worldwide perspective in valuing climate-change costs while adopting a parochial perspective in valuing oil dependency costs.

This leaves costs of macroeconomic disruption. There is evidence that normal price fluctuations in world oil markets are magnified by the distortion of monopoly power, and that resulting fluctuations in oil prices tend to cause macroeconomic instability, in particular recessions following oil-price increases. These recessions carry an economic cost that can be regarded as an external cost to the consumption decisions of individual economic decision-makers. We do not disagree with this analysis, although it must be qualified by recognizing that both of these pathways are subject to institutional factors which may change – in particular, national banks are becoming more savvy about counteracting oil-price shocks. But as with OPEC monopoly power, the obvious implication is that market prices are too high, not too low. Thus macroeconomic disruption is not an argument for raising the price facing decision-makers, in the usual manner of an unpriced external cost. Rather, as acknowledged by Leiby, it is an argument for other policies that reduce the extent of price fluctuations or their adverse impacts on macroeconomic performance.

Thus both components of the oil-dependency costs, as measured by current studies, may be seen as indicators of the potential value to the economy of a large nation or region of reducing the proportion of its supply consisting of imports from monopolized and/or unstable sources. It is less clear how exactly reducing transport use of conventional oil fuels brings about this desired result. Curtailing demand, for example by fuel-efficiency standards or incentives to reduce motor-vehicle travel, would come partly from domestic sources (which are currently producing some oil at very high marginal cost due to high world prices). Thus such reductions cannot be taken one for one as reductions in imports, and in fact it's unclear whether they would even change the *fraction* of US consumption represented by imports. Thus while oil dependency may well be a problem that warrants action, the relevant factors are more country-specific and the relevant policies more specific to trade and macroeconomic conditions than the other problems discussed here. Furthermore, simply raising the price is not obviously a solution, since many of the drawbacks of oil dependency result from the price being artificially high.

To summarize, oil dependency is an argument for interventions to reduce the market power of oil producers by promoting conservation or substitutes for oil. It has significance for transport policy, but it does not provide an argument for fuel taxes or for other interventions that would raise the domestic price. On the contrary, oil dependency and climate change have offsetting effects on world oil consumption, the first reducing it and the second increasing it relative to a social optimum. To put it differently, if one takes climate change as the truly overriding policy problem, then one must welcome the possibility that world oil markets are organized in such a way as to keep current oil consumption artificially low.

3.3 Implications of analysis of marginal external costs

We believe that damage estimates of the orders of magnitude shown in Table 5, excluding the right-most column, are the best guides to transport policy within the limitations of quantifiable uncertainty. Several unpriced external costs of motor vehicle travel appear to have larger measurable external costs – when traced specifically to motor vehicle use – than those of climate change and oil dependency.

This finding does not imply that control measures are unwarranted. On the contrary, when totalled over the trillions of vehicle-miles currently being driven throughout the world, these costs are large and warrant significant policy interventions. It is less clear that they are amenable to amelioration through transport policy. Furthermore, even from a broader policy perspective, there are tradeoffs. Reducing greenhouse gases and energy insecurity are important and valuable activities, but so are other uses of our resources. For example, IPPC (2007) notes that the ability of poorer nations to cope with the climate change that is already certain to occur is greatly affected by their development path; so one must weigh greenhouse gas control against development needs in circumstances where they compete for funds or attention.

More specifically for transport, we reach two conclusions. First, one must pay attention to the side effects of control measures on such prosaic but real costs as air pollution, traffic accidents, and above all congestion. The idea that climate change is so overwhelmingly catastrophic that it trumps all other environmental or transport policies – an idea expressed or implied by some recent writings – is wrong and quite dangerous.

Second, an ideal approach to controlling energy use is not likely to reduce motor vehicle travel very much. We know from our study of demand elasticities that users would curtail travel only slightly if faced with its fuel-related external costs. Furthermore, it seems likely that abatement costs are higher in transport than in some other sectors (e.g. Knockaert and Proost, 2005), which suggests that it is more effective to focus abatement efforts elsewhere. An ideal approach will accomplish most of its results through technological changes specifically targeted to energy savings, mostly through the use of more fuel-efficient vehicles and perhaps also through alternative fuels. By choosing technological solutions when permitted, consumers will avoid more thoroughgoing behavioural changes such as changes in travel mode, trip patterns, and home and work location, which evidently are more costly for them.

Combining the marginal-cost analysis with our review of fuel-consumption elasticities, it appears that transport is not the ideal sector to target for solutions to energy problems. It surely can and should play a role, but not the dominant one that some assume. Where, then, might we find a better avenue for energy policy? Many analysts have identified electricity production from fossil fuels as a promising one because it entails more economical opportunities for fuel switching or conservation. To review the electricity sector would take us outside our scope, but we can cite one statistic that helps make the point. Ian Parry (2005) discusses the implications of the "majority view" of the external cost of carbon emissions, taking it to be $30/tC. Applying an externality tax of this magnitude would raise the price of gasoline by $0.07 per gallon, not enough to have much effect on motor-vehicle fuel consumption. But applying such a carbon charge to coal would more than double coal prices![30] This would have significant effects on producer, and maybe even consumer, decisions about electricity production and use. It would of course also affect other industrial uses of coal, which are increasing at a frightening rate in fast-growing economies like that of China.

4. CONCLUSION

Our analysis suggests that transport is relatively unresponsive to broad-based price signals, in particular to changes in prices of fuels. The main exception to this is that there is considerable scope to improve the fuel efficiency of vehicle fleets, mainly through technological changes but also to some extent through consumer choices among vehicle sizes and types. As a result, we should not expect to see dramatic changes in modal shares or in the nature of transport systems. Furthermore, this unresponsiveness suggests that it is costly to reduce energy use in transport, relative to other economic activities, and thus that efficient policies will probably not extract as much energy savings (in percentage terms) from transport as from other sectors.

[30] The US price of coal in 2003 was $19.68 per metric ton (US EIA 2006, Table 7.8, converted to metric tons) with carbon content 0.75 (O'Hara 1990, Table 6), implying a price of $26/tC.

A perennial policy issue is whether to address problems with price incentives (in this case, higher prices) or with regulatory measures. Our review suggests that either approach can work. Using prices has the disadvantage that quite large price increases are needed to obtain much response, and this may be beyond the political capacity of most countries. Fuel efficiency regulations are a relatively quick way to reduce oil imports where energy security is a concern, and the danger of inducing more travel as a side effect is probably minor. But if reducing climate change is a primary goal, we think it is important to supplement any regulations with either technology policies or some price-oriented policies because otherwise the stock of fossil fuels remains available and attractive for future use, making it that much harder to move toward a global path of lower carbon-dioxide emissions.

Broad-based carbon taxes remain an excellent tool for climate control. Their impacts on transport would be modest, mainly in the form of promoting technological improvements and vehicle-mix shifts that increase fuel efficiency. This is at it should be, because it reflects relatively high costs of reducing oil use in transport. There are other sectors, especially those that burn coal, that make better targets for energy policy.

Our review of marginal external costs suggests that energy policy could be the “tail wagging the dog” in transport. Other transport problems, notably congestion, local air pollution, and accidents, are associated with considerably higher marginal external costs than are climate change and energy security. It follows that policies to deal directly with these other problems deserve high priority, regardless of energy policies.

REFERENCES

An, Feng, Deborah Gordon, Hui He, Drew Kodjak, and Daniel Rutherford, 2007, *Passenger vehicle greenhouse gas and fuel economy standards: a global update*, International Council on Clean Transportation

Arrow, Kenneth J., 2007, "Global climate change: a challenge to policy," *Economists' Voice*, June. Berkeley Electronic Press, www.bepress.com/ev

Basso, Leonardo and Tae Hoon Oum, 2007, Automobile fuel demand: a critical assessment of empirical methodologies, *Transport Reviews*, 27, 4, 449-484

Brons, Martijn, Peter Nijkamp, Eric Pels, and Piet Rietveld, 2007, A meta-analysis of the price elasticity of gasoline demand – a SUR approach, *Energy Economics*, forthcoming

CEC, 2007, Commission staff working document accompanying "Limiting global climate change to 2 degrees Celsius – the way ahead for 2020 and beyond," SEC(2007) 8, Commission of the European Communities

Cline, William R., 1990. *The Economics of Global Warming*. Institute for International Economics, Washington, D.C.

Convery, Frank J., and Luke Redmond, 2007, "Market and price developments in the European Union Emissions Trading Scheme," *Review of Environmental Economics and Policy*, 1(1):88-111.

Davis, Stacey C. and Susan W. Diegel, 2007, *Transportation Energy Data Book, Edition 26*, U.S. Department of Energy – Oak Ridge National Laboratory, ORML-6978

Eads, George, 2006, Transportation, energy, and emissions: an overview, Presentation at the Symposium on "Global Energy and Climate Change", UCLA Conference Center, Lake Arrowhead, California, October 2006

ECMT, 1998. *Efficient Transport for Europe: Policies for Internalization of External Costs*. European Conference of Ministers of Transport, Organization for Economic Cooperation and Development, Paris.

European Commission, 2007, "Adapting to climate change in Europe – options for EU action," Green Paper, report SEC(2007) 849, June 29.
http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52007DC0354:EN:NOT

Fulton, Lew and George Eads, 2004, IEA/SMP model documentation and reference case projection, http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=MTE0Njc (accessed on September 3, 2007).

Grange, Natalie, 2007, Comment Bercy peut procéder, *Bulletin des Transports et de la Logistique*, 3187, 487-488.

Greene, David and John German, 2007, “Fuel economy: the case for market failure,” Presentation at the Asilomar 2007 Conference on Transportation and Climate Policy. http://www.its.ucdavis.edu/events/outreachevents/asilomar2007/presentations%20list.php, accessed on 06 September 2007).

Harrington, Winston and Virginia McConnell, 2003, *Motor Vehicles and the Environment*, Resources for the Future Report (April), http://www.rff.org/rff/Documents/RFF-RPT-carsenviron.pdf.

Hughes, Jonathan E., Christopher R. Knittel, and Daniel Sperling, 2006, *Evidence of a Shift in the Short-Run Price Elasticity of Gasoline Demand*. Institute of Transportation Studies, University of California, Davis, Research Report UCD-ITS-RR-06-16.

IPPC (2007) “Summary for Policymakers,” In: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, pp. 7-22. http://www.ipcc-wg2.org/index.html, accessed 11 September 2007.

IEA, 2001, Saving oil and reducing CO2-emissions in transport, IEA/OECD, Paris, France.

International Energy Agency, 2002, Transportation and Energy, International Energy Agency and Organization for Economic Cooperation and Development, Paris (http://www.iea.org/textbase/papers/2002/transportation.pdf; accessed on September 3, 2007).

International Energy Agency, 2006, World Energy Outlook 2006, IEA/OECD, Paris.

Johansson, Olof and Lee Schipper, 1997, Measuring the long run fuel demand of cars: separate estimations of vehicle stock, mean fuel intensity and mean annual driving distance, *Journal of Transport Economics and Policy*, 31, 277-292.

Knockaert, Jasper, and Stef Proost, 2005, Transport sector, in: Bert Willems, Johan Eyckmans, and Stef Proost (eds)., *Economic aspects of climate change policy, a European and Belgian perspective*, Leuven, Belgium: Acco, 99-110.

Leiby, Paul N., 2007, Estimating the Energy Security Benefits of Reduced U.S. Oil Imports, Report No. ORNL/TM-2007/028, Oak Ridge National Laboratory, Oak Ridge, Tennessee, February.

Li, Shanjun, Christopher Timmins, and Rogher H. von Haefen, 2007, "Do gasoline prices affect fleet fuel economy?," working paper, Duke University and North Carolina State University, July.

Mendelsohn, Robert, William D. Nordhaus, and Daigee Shaw, 1994, The impact of global warming on agriculture, American Economic Review, 84, 4, 753-771.

Nordhaus, William D., 1994. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA, MIT Press.

Nordhaus, William D., 2006, "The *Stern Review* on the economics of climate change," Working Paper 12741, National Bureau of Economic Research, Cambridge, Mass., December.

Nordhaus, William D., 2007a, "A review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, 45: 686-702.

Nordhaus, William D., 2007b, "To tax or not to tax: alternative approaches to slowing global warming," *Review of Environmental Economics and Policy*, 1(1): 26-44.

O'Hara, Fred ,Jr., 1990. *Glossary: Carbon Dioxide and Climate*. ORNL/CDIAC-39, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, Tennessee, Third Edition. http://cdiac.ornl.gov/pns/convert.html

Parry, Ian W.H., 2005, "Should fuel economy standard be raised?" *Reources*, 159 (fall), Resources for the Future, Washington, D.C., 15-19.

Parry, Ian W.H. and Joel Darmstadter, 2003, "The costs of U.S. oil dependency," Discussion Paper 03-59, Resources for the Future, Washington, D.C., December. http://www.rff.org/Documents/RFF-DP-03-59.pdf

Parry, Ian W.H., Margaret Walls, and Winston Harrington, 2007, "Automobile Externalities and Policies," *Journal of Economic Literature*, 45: 373-399.

Parry, Martin L., Osvaldo F. Canziani, Jean P. Palutikof and Co-authors, 2007, "Technical Summary," in: M.L. Parry, O.F. Canziani, J.P. Palutikof, P.J. van der Linden and C.E. Hanson, Eds., *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of* *the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK, pp. 23-78. http://www.ipcc-wg2.org/index.html, accessed 11 September 2007.

Pisarski, Alan E., 2006, *Commuting in America III: the third national report on commuting patterns and trends*, National Cooperative Highway Research Program Report 550 and Transit Cooperative Research Program Report 110, Washington: Transportation Research Board.

Plotkin, Steven E., 2004, *Fuel economy initiatives: International Comparisons*, in *Encyclopedia of Energy*, Vol. 2, Elsevier

Proost, Stef, Van Dender K., De Borger B. *et al*., 2002, How large is the gap between present and efficient transport prices in Europe?, *Transport Poli*cy, 9(1), 41-57

Sansom, Tom, Chris Nash, Peter Mackie, Jeremy Shires, and Paul Watkiss, 2001, *Surface transport costs and charges - Great Britain 1998*, ITS Leeds in association with AEA Technology Environment

Schelling, Thomas C., Climate change: the uncertainties, the certainties, and what they imply about action, *Economists' Voice*, June. Berkeley Electronic Press, www.bepress.com/ev

Small, Kenneth. A., 1997, Economics and urban transportation policy in the United States, *Regional Science and Urban Economics*, 27, 671-691
Small, Kenneth A. and Kurt Van Dender, 2007a, Fuel efficiency and motor vehicle travel: the declining rebound effect, *The Energy Journal*, 28, 1, 25-51

Small, Kenneth A. and Kurt Van Dender, 2007b, Fuel Efficiency and Motor Vehicle Travel: The Declining Rebound Effect, Working Paper 05-06-03, Department of Economics, University of California at Irvine (revised). http://www.economics.uci.edu/docs/2005-06/Small-03.pdf

Small, Kenneth A. and Kurt Van Dender, 2007c, The Changing Responses to Fuel Efficiency Policies for Motor Vehicles, *Access*, Berkeley: University of California Transportation Center (forthcoming)

Small, Kenneth A. and Erik T. Verhoef, 2007, *The Economics of Urban Transportation*, London: Routledge

Sorrell, Steve, 2007, The Rebound Effect: An Assessment of the Evidence for Economy-wide Energy Savings from Improved Energy Efficiency, UK Energy Research Centre, London, October

Stern, Nicholas, 2006, *The Economics of Climate Change: The Stern Review*, HM Treasury, London. www.hm-treasury.gov.uk/independent_reviews/stern_review_economics_climate_change/stern_review_report.cfm

Tol, Richard S.J., 2005, "The marginal damage costs of carbon dioxide emissions: an assessment of the uncertainties," *Energy Policy*, 33: 2064-2074.

Tol, Richard S.J., Samuel Fankhauser, Richard Richels and J. Smith, 2000, "How Much Damage will Climate Change Do? Recent Estimates." *World Economics* 1: 179-206.

Turrentine, Thomas S. and Kenneth S. Kurani (2007) Car buyers and fuel economy?. *Energy Policy* 35: 1213-1223

US EIA, 2006, *Annual Energy Review 2006*. Report No. DOE/EIA-0384(2006). Washington, D.C.: US Energy Information Agency. http://www.eia.doe.gov/emeu/aer/

US EIA, 2007, *Annual Energy Outlook 2007 with Projections to 2030*. Report DOE/EIA-0383. Washington, D.C.: US Energy Information Agency, February. http://www.eia.doe.gov/oiaf/aeo/index.html

US FHWA, 2007, "Traffic volume trends: April 2007," Office of Highway Policy Information. http://knowledge.fhwa.dot.gov/cops/hcx.nsf/All+Documents/C2ADEF03A3D7529785257316003C1281/$FILE/TvtMonthlyReport%20Apr%202007.xls

US National Research Council, 2002, *Effectiveness and Impact of Corporate Average Fuel Economy (CAFE) Standards,* Washington, DC: National Academy Press.

Wadud, Zia, Daniel J. Graham, and Robert B. Noland, 2007a, "Gasoline demand with heterogeneity in household responses," Working paper, Centre for Transport Studies, Imperial College London.

Wadud, Zia, Daniel J. Graham, and Robert B. Noland, 2007b, "Modelling fuel demand for different socio-economic groups," Working paper, Centre for Transport Studies, Imperial College London.

Weitzman, Martin L., 2007, "A review of the *Stern Review on the Economics of Climate Change*," *Journal of Economic Literature*, 45: 703-724.

West, Sarah and Roberton C. Williams III, 2007, Optimal taxation and cross-price effects on labor supply: estimates of the optimal gas tax, *Journal of Public Economics*, 91, 593-617