THE ROAD FROM COPENHAGEN: FUEL PRICES AND OTHER FACTORS AFFECTING CAR USE AND CO2 EMISSIONS IN INDUSTRIALIZED COUNTRIES

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ABSTRACT

Using a unique panel data set of national level car ownership, use, fuel economy and fuel use, we analyze the apparent stabilization of fuel use and CO2 emissions from cars that set in from the early 2000s. We model the car stock, fuel intensity, and vehicle usage for 9 OECD countries using data from 1973-2007, examining how the relationships between these variables and fuel prices, incomes, and population density have changed over time. We include specifications accounting for unobserved heterogeneity across countries and over time, and also estimate these relationships simultaneously to account for interlinkages between the three. Our first finding indicates that the income elasticity of car ownership appears to decrease with time, suggesting potential saturation in industrialized countries. Second, there is only very weak evidence that fuel prices have driven on-road fuel economy, suggesting that other factors, including policies, may have played a more important role. Third, car usage is driven by the cost of driving, emphasizing the importance of the rebound effect when considering emissions reduction strategies, although these elasticities have decreased over time. From these observations we conclude that fuel economy standards and fuel taxes alone, at least in the levels recently seen, are unlikely to stabilize and reduce emissions in the long run. Transport policy measures designed to internalize variable-cost externalities, such as congestion pricing, are likely to be important additional policies, which also yield CO2 reductions as a co-benefit. These are key insights in the road from COP15 in Copenhagen, in the search for effective ways to reduce emissions from transport.

Keywords: transportation policy, CO2, fuel demand, fuel economy

1. BACKGROUND

Transportation is a slowly but steadily rising source of CO2 emissions from fossil fuel combustion, reaching around 25% of all CO2 in 2007 (IEA 2010) if international bunker fuels are counted. A recent global study of transport and CO2 emissions highlights the concern of policy makers over this sector, particularly the politically sensitive sector of light duty vehicles (IEA 2009). Subject to fuel economy standards or voluntary agreements on fuel economy in many jurisdictions (Schipper 2008; Clerides and Zachariadis 2008; Fontaras and Samaras 2007), there is a historic debate over how both fuel economy standards and fuel taxes affect consumption (Greene 1990; Greene 1998; Harrington 2008; Clerides and Zachariadis 2008). Without taking a position on the relative importance of standards versus fuel prices, taxes versus voluntary agreements, or other factors affecting fuel economy and fuel use, it is still important to understand how these factors affect fuel economy and fuel consumption. In particular, a growing recognition of the importance of rising car ownership and use, as shown dramatically for the developing world (IEA 2009), makes it clear that policy makers need to understand both how standards and fuel prices affect fuel economy as well as auto ownership and auto use.

This paper updates results first obtained by Johansson and Schipper (1997), which tested various models estimating these parameters on time-series cross-sectional data covering the early 1970s to 1992. The present study extends the data to 2007 for a subsample of the original countries studied by them, with revisions to data. The present paper focuses on income and price effects on these variables. Further work will study how new vehicle taxes and incentives and other factors, including fuel economy have affected ownership, car characteristics, car use and fuel consumption.

One reason for the importance of this analysis is the apparent plateau of both car use and fuel consumption from cars seen in a wide range of high income countries, e.g., Australia, Japan, Canada, the US and Europe (Millard-Ball and Schipper 2010). One factor contributing to flat fuel consumption has been voluntary fuel economy targets in Japan and Europe. Another factor has been the slightly tightened fuel economy standards for new light trucks in the US (EPA 2010). Moreover, rising fuel prices have also seemed to have an impact in inducing new car buyers to purchase increasingly more fuel economic cars since 2002, at least in the US (with no change in the standards on cars). To the extent that this plateau of both car use and fuel consumption through 2008 is mostly a function of higher fuel prices that have since receded, one might expect a return to growth in both car use and fuel consumption. But the making of voluntary agreements in Japan and EU mandatory, and the tightening of US fuel economy standards might help keep the lid on fuel consumption (e.g., see Fontaras and Samaras 2007 and 2010). If elasticity of car use is very low, and so-called rebound effects small (Hymel, Small and Van Dender 2010) we might expect improvements in fuel economy of new vehicles to offset most or all of the growth in car use. If by contrast the rebound effect in one form or another is large, then we might expect the current plateau in car use to yield to more growth.

2. LITERATURE REVIEW

Basso and Oum (2007) carried out extensive reviews of the literature using aggregate data to estimate the fuel consumption in light duty vehicles, focusing on gasoline but not considering detailed car usage and fuel economy. They acknowledge the problem of multiple fuels and noting that our previous work was one of the only papers tackling this problem. Our paper traces its roots to Johansson and Schipper (1997), henceforth JS, which provides the first international panel estimation of car ownership, car use, and fuel consumption attempting to disentangle the relationships of income and fuel prices with these three variables. One of the problems plaguing this work is the lack of availability of data on the growing stock of diesel cars and their fuel consumption, as noted by Sterner (2007), and Pock (2007). This problem has been addressed by work of Schipper, Fulton and Marie (2002) and Schipper and Fulton (2009), based on earlier work by Schipper et al (1994) and Schipper and Marie (1998). Most national authorities now publish a great deal of data on vehicle use and fuel consumption, permitting a good quantification of differences among fuels.

At the same time, Zachariadis (2006) discussed difficulties in analyzing even the baseline of fuel use and vehicle fuel economy. Zachariadis and Clerides (2008) analyzed the joint problem of price and fuel economy standard impacts, joining a old debate about the relative importance of standards vs. fuel prices affecting new vehicle fuel intensity and overall fuel consumption (Greene 1990). Ryan et al. (2009) examine the relationship between the impact of fuel taxes on the vehicle stock (through new vehicle sales) and the carbon intensity of the fleet, but did not examine vehicle usage. Recently Pock (2010) estimated key parameters of gasoline use using car stock and other variables, but similarly did not have access to data on car utilization or the data for diesel consumption used by JS. It is hoped therefore that the present work offers a step towards a better understanding of ownership, characteristics and use of automobiles and their fuels. As gasoline and diesel are both derived from petroleum with associated CO2 emissions, there is interest in both alternative liquid fuels with little or no CO2 (e.g., biofuels as used by dedicated alcohol vehicles in Brazil) or forms of electric traction, i.e., fuel cells, battery electric vehicles, or plug in hybrids. Analyzing the demand for these vehicles requires a clear understanding of the determinants of the vehicle stock, vehicle usage, and fuel used per unit of distance.

3. DATA

The data set contains annual data for 9 OECD countries between 1973-2007, gathered over 20 years by a team led by Schipper (Schipper et al 1993; Schipper and Marie 1999; Schipper 2008; Schipper 2010 in press). Countries include the U.S.A, Japan, U.K., Australia, Italy, France, Canada, Sweden, and Germany (which is separated into West Germany and Germany – see below for discussion). Data on car stocks and annual use by fuel (gasoline, diesel, and for a few countries LPG or propane), fuel consumption and fuel economy are taken from official or authoritative national sources (see Appendix for more details). “Cars” includes all automobiles and light trucks or registered as such but used in households rather than as commercial vehicles. These make up a significant part of the light truck/SUV vehicle stock in Australia, Canada and the U.S. and a significant share of household vehicles in those countries.

There are minor between-country variations in methodology that should be noted. Some countries derive fuel economy via car utilization surveys, dividing surveyed distances driven by fuel use. Others (notably France or Australia) survey both vehicle use and fuel consumption. It is recognized that there are small uncertainties in the quantities of gasoline demanded because some is used for commercial light trucks and mini buses/vans or motorcycles. For diesel, the potential uncertainties are larger because the same fuel is used by trucks and buses, but authorities in the countries where diesel car fuel is important, i.e., European countries, have developed surveys to quantify levels of consumption for passenger vehicles (Schipper and Fulton 2009). Since the usage of cars gives rise to externalities like congestion, accidents, and noise independent of fuel economy (Parry, Walls and Harrington 2007; IEA 2009), it is important to understand as independently as possible vehicle use, fuel economy and fuel consumption. The magnitude of externalities associated with vehicle usage may be greater than those associated with fuel consumption (Parry, Walls and Harrington 2007), and studies of only fuel use without considering driving distance (e.g., Pock 2007; Pock 2010) miss this important variable that ultimately contributes significantly to restraining fuel consumption from a baseline. Mean driving distance is taken as a function of vehicle kilometers per vehicle per year.

In this study, fuel intensity (I) refers to the ratio of fuel use to distance traveled, and is quoted in liters of fuel/100 km with the fuel and its energy content specified (e.g. gasoline, diesel, LPG or another fuel). Fuel economy (FE) is the inverse of fuel intensity and is measured in km/liter or miles per gallon, with FE [MPG] = 235.21/FI [L/100 km]. The advantage of using fuel intensity is that it is directly proportional to tailpipe CO2 emissions intensity (in grams CO2/km) according to the CO2 released in combustion of each fuel. Lower heat of combustion is used for all countries, and CO2 emissions are counted only at the tailpipe and given as indicators. Note that in the present work we consider not simply the volumes of fuel consumed but the energy content, which is 12% greater for diesel than for gasoline. Where we cite an average fuel intensity of the stock (in liters of fuel/100 km), we have counted diesel fuel at its higher energy content, thus 1 liter of diesel = 1.12 liters of gasoline. Figure 1 demonstrates fuel intensity trends by country, exhibiting a slight decreasing trend over time. The notable exception is a dramatic decrease in fuel intensity in the United States during the late 1970s and 80s as a result of the oil crisis. Figures 2 and 3 display car stock and mean driving distance for all countries studied from 1973 to 2007.

Figure 1. On Road Car Fuel Intensity, 1973-2007
(liters of gasoline equivalent/100 km)

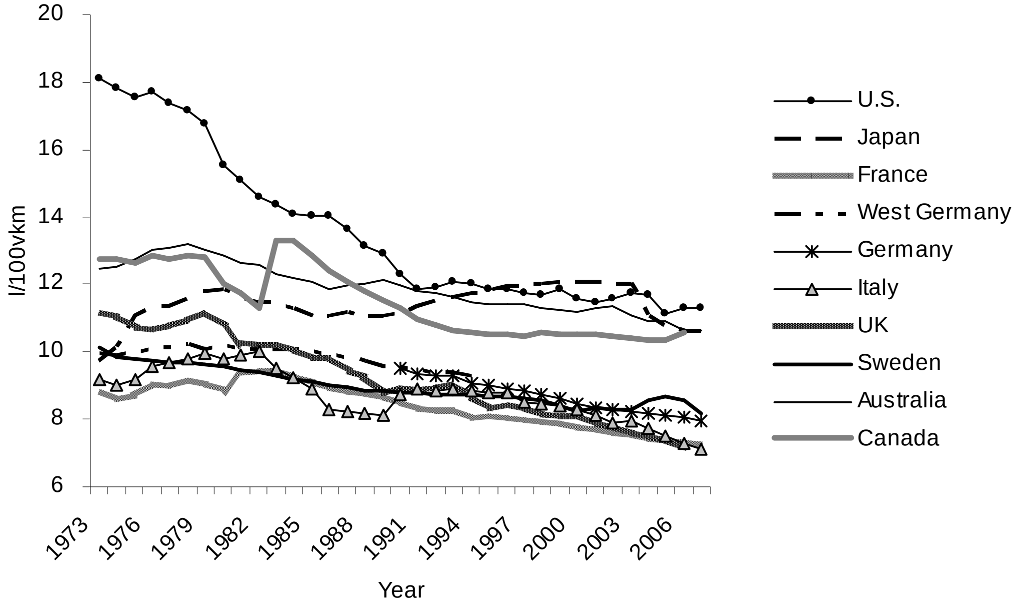
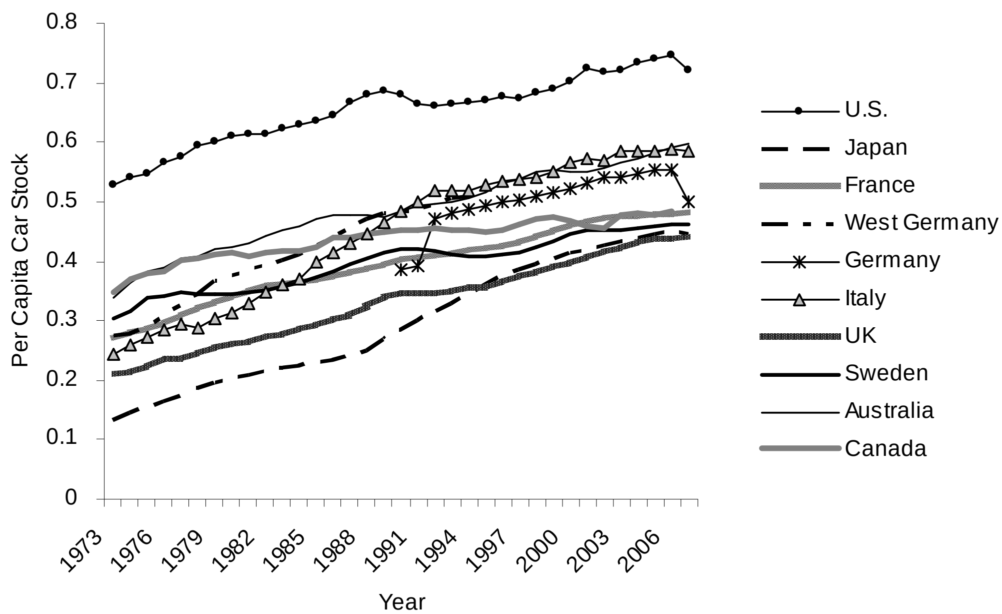
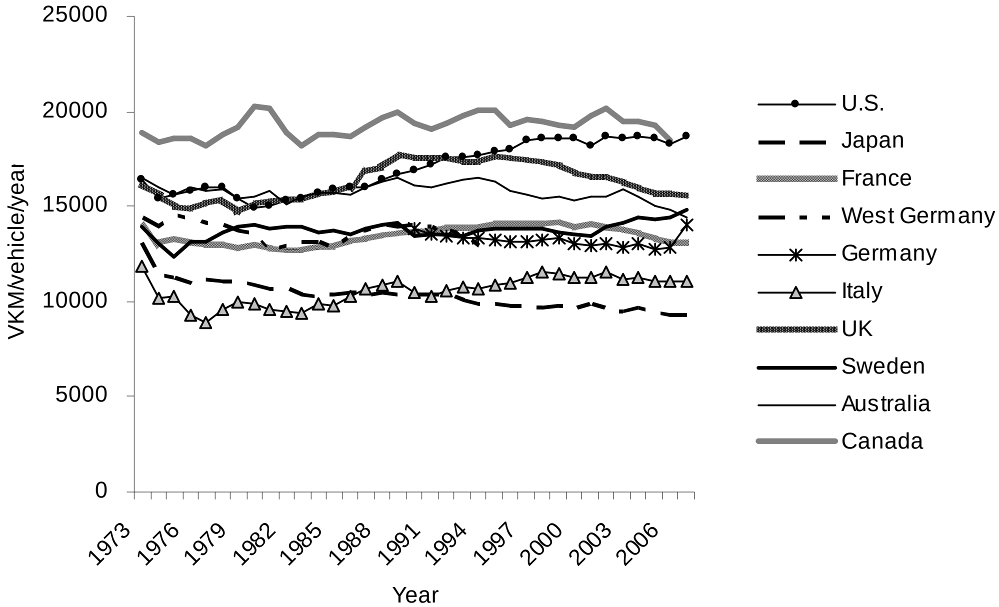


Figure 2. Car Stock Per Capita, 1973-2007



Note: The drop in German per capita value is due to a shift in statistics that eliminated the 10% of the stock that was actually not active.

Figure 3. Mean Driving Distance, 1973-2007



Note: The increase in the value for Germany 2007 reflects the statistical downward shift in number of cars whole holding total kilometers driven constant.

Income is measured as GDP in constant 2000 USD at purchasing power parity (PPP), which facilitates between-country comparisons. Population density is measured by the number of people per square kilometer, and was derived by dividing population data by the total land area in each country. Fuel price was calculated by taking the quantities of gasoline and diesel consumed by automobiles (from national sources) and weighting these by the prices of gasoline and diesel. Since diesel contains more energy, its price is reduced by 1.12, the ratio of energy content of diesel to gasoline. All prices are deflated to 2000 using a national deflator, then converted to real US$ at the purchasing power parity conversion rates published by the Organization for Economic Cooperation and Development (OECD). Mean fuel cost per kilometer was derived as the product of fuel price and fuel intensity. Because of the increased use of lower priced diesel, our fuel cost per kilometer is somewhat lower than that implied by using gasoline alone. (This calculation allows us to use the assumption that fuel-price elasticity is equal to fuel-intensity elasticity (JS)). Where LPG or CNG was significant (Netherlands, Italy, Australia) prices were assumed to be those of diesel, which is close to what national data show.

The data set is complete for the U.S., Japan, France, Italy, the UK, Sweden, and Australia from 1973-2007, and for Canada from 1984-2006. However, the original data set included West Germany, whereas for obvious reasons German data since 1994 includes transportation and economic indicators for all of Germany. Due to significant disparity between all of Germany and just West Germany, they are treated as two separate countries in the model. Thus, “West Germany” includes data from 1973-1994, and “Germany” includes data from 1995-2007.

4. METHODOLOGY

Total fuel demand per capita (Q) can be calculated by taking the product of automobile stock per capita (S), fuel intensity (I), and mean driving distance per car per year (D), where Q = S*I*D. Following the methodology of JS, we initially model each fuel demand component separately using a log-log specification. Each model includes specifications with country fixed effects and time fixed effects (yearly dummies) in order to control unobserved heterogeneity specific to countries and over time that could be correlated with our variables of interest. We represent country fixed effects as η_i, and time fixed effects as ξ_t. In all three models, u_{it} is assumed to be a mean zero, possibly heteroskedastic, error term.

Automobile Stock Per Capita

We posit the following relationship for automobile stock per capita, fuel price, income, and population density:

$$lnS_{it} = \alpha_0 + \alpha_1 lnS_{i,t-1} + \alpha_2 lnP_{it} + \alpha_3 lnY_{it} + \alpha_4 lnG_i + \eta_i + \xi_t + u_{it} \quad (1)$$

where S_{it} is automobile stock per capita in country *i* and year *t*. We include the lagged dependent variable (S_{it-1}) in some specifications, in order to model the vehicle stock dynamically, following the logic of a partial adjustment model. Including a lagged dependent variable also is useful for calculating long-run steady state elasticities. Exogenous variables include P_{it}, the price of fuel in country *i* and year *t;* Y_{it}, per capita income in constant 2000 dollars in country *i* and year *t;* and G_i, the population density in country *i.*

Fuel Intensity

Fuel intensity is estimated using the same variables as automobile stock per capita:

$$lnI_{it} = \beta_0 + \beta_1 lnI_{i,t-1} + \beta_2 lnP_{it} + \beta_3 lnY_{it} + \beta_4 lnG_i + \eta_i + \xi_t + u_{it} \quad (2)$$

where I_{it} is fuel intensity in country *i* and year *t*.

Mean Driving Distance

We use a similar relationship to automobile stock and fuel intensity, with the addition of fuel cost per km and automobile stock per capita as explanatory variables:

$$lnD_{it} = \gamma_0 + \gamma_1 lnD_{i,t-1} + \gamma_2 lnC_{it} + \gamma_3 lnY_{it} + \gamma_4 lnG_i + \gamma_5 lnS_{it} + \eta_i + \xi_t + u_{it} \quad (3)$$

where D_{it} is mean annual driving demand per car in country *i* and year *t.* In addition, the mean driving distance is assumed to be a function of car stock in country *i* and year *t*, S_{it}. This variable is included under the assumption that the mean driving distance per vehicle (versus per person) will be related to the number of vehicles per capita.

5. RESULTS

The models described in section 4 were separately estimated for the original period of study (1973-1992), for the new data (1993-2007), and the entire updated data set (1973-2007). Tables 1, 2 and 3 include results from several different specifications to give a sense of the importance of fixed effects to capture unobserved heterogeneity and the influence of adding lagged dependent variables. The simplest approach, an OLS regression, ignores any unobserved heterogeneity correlated with our observables either across counrties or over time. Our final specification addresses the possible endogeneity issue from using a lagged dependent variable by instrumenting for the lagged dependent variable with the second lag of the dependent variable (i.e., an Arellano-Bond estimator using one previous lag as the instrument). We first present the results of estimating each equation (1)-(3) separately, and then present results from simulatenously estimating the system of equations.

Car Stock Per Capita

Following equation (1), α_2, α_3 and α_4 represent the short term price, income and population density elasticities. Table 1 reports results for a number of methods, and discussion here will focus on the country fixed effects model, including time dummies and the lagged dependent variable. The results are consistent across both time periods, with income as the only significant variable. The significance of income is not surprising. As per capita income increases, more people can afford cars, and thus car stock will increase. We observe an income elasticity of 0.196 over the entire time period. However, there appears to be a structural shift between the two periods, with this trend decreasing over time. Between 1973-1992, income elasticity is 0.271, whereas between 1993-2007 income elasticity is only 0.085. Therefore, for a corresponding increase in income, individuals are buying fewer cars. All of the countries in the study are OECD countries, and thus have not experienced any surge in development-related growth in car stock. Thus, it seems likely that we are observing a “leveling” between the two periods, as shown in Figure 2, and that car ownership may be reaching saturation in the countries in our study, which are all higher income countries.

Population density is significant in the 1973-1992 period but not in the later period or the overall regression, with a negative elasticity of 0.221. Higher population density might mean more urbanization (although this is not always the case). Consequently families do not necessarily need two cars for a number of reasons, such as greater access to public transportation or scarce parking, which could potentially lead to a decrease in car stock. The disappearance of this trend over time could be due to increased suburbanization (vs. urbanization), changes in the use of public transportation, or cultural shifts. Exploring this further to look at urbanization rather than population density appears to be a useful line for future work.

It is unclear how fuel price affects car stock. Intuitively, a higher fuel price might lead to less demand for cars, but these effects may be overwhelmed when we account for heterogeneity across countries. In the models where fuel price is found to be significant (1, 3, 5, 6, and 7 for the entire period), there is a small, negative effect.

Table I – Car Stock Per Capita

	OLS	OLS Time Dummies	OLS LDV	OLS Time Dummies and LDV	Country Fixed Effects	Country Fixed Effects and Time Dummies	Country Fixed Effects LDV	Country Fixed Effects, Time Dummies and LDV	Arellano -Bond Estim.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1973-2007									
Fuel Price	-0.097**	0.059	-0.011***	-0.002	-0.089**	-0.186***	-0.020**	-0.005	0.009
	(0.034)	(0.046)	(0.003)	(0.004)	(0.033)	(0.046)	(0.007)	(0.008)	(0.022)
Income	1.081***	1.833***	-0.016*	0.026	1.328***	0.910***	0.107***	0.196***	0.278*
	(0.055)	(0.160)	(0.007)	(0.017)	(0.049)	(0.126)	(0.023)	(0.040)	(0.116)
Pop. Dens.	-0.029***	-0.028***	0.003***	0.002***	-1.140***	-1.172***	-0.122***	-0.079*	-0.262*
	(0.006)	(0.006)	(0.001)	(0.001)	(0.121)	(0.120)	(0.028)	(0.031)	(0.107)
LDV			0.974***	0.972***			0.887***	0.905***	0.879***
			(0.005)	(0.006)			(0.018)	(0.022)	(0.036)
R^2	0.707	0.746	0.997	0.997	0.872	0.906	0.994	0.995	
N	308	308	299	299	308	308	299	299	289
1973-1992									
Fuel Price	0	0.157**	-0.009	0.001	0.129***	0.01	-0.003	0.015	0.004
	(0.045)	(0.058)	(0.006)	(0.006)	(0.026)	(0.039)	(0.008)	(0.013)	(0.025)
Income	1.491***	2.376***	-0.019	0.019	1.440***	1.246***	0.198***	0.271***	0.263
	(0.100)	(0.175)	(0.021)	(0.029)	(0.045)	(0.112)	(0.033)	(0.053)	(0.149)
Pop. Dens.	-0.054***	-0.051***	0.004***	0.003**	-0.742***	-0.798***	-0.242***	-0.211**	-0.333*
	(0.008)	(0.009)	(0.001)	(0.001)	(0.148)	(0.162)	(0.050)	(0.064)	(0.162)
LDV			0.981***	0.978***			0.846***	0.858***	0.871***
			(0.008)	(0.009)			(0.021)	(0.026)	(0.089)
R^2	0.746	0.799	0.996	0.996	0.922	0.942	0.988	0.989	
N	176	176	167	167	176	176	167	167	157
1993-2007									
Fuel Price	-0.116**	-0.078	-0.011**	-0.009	0.035	-0.023	-0.014	0.001	-0.019
	(0.044)	(0.071)	(0.003)	(0.005)	(0.029)	(0.031)	(0.011)	(0.013)	(0.016)
Income	0.801***	0.968***	-0.004	0.006	0.627***	-0.17	0.116***	0.085**	0.111**
	(0.089)	(0.202)	(0.012)	(0.019)	(0.064)	(0.119)	(0.029)	(0.031)	(0.035)
Pop. Dens.	-0.001	-0.001	0.002*	0.002	-0.405**	-0.444**	-0.084	-0.107	-0.079
	(0.007)	(0.007)	(0.001)	(0.001)	(0.138)	(0.131)	(0.059)	(0.058)	(0.130)
LDV			0.973***	0.972***			0.831***	0.796***	0.849***
			(0.008)	(0.008)			(0.024)	(0.046)	(0.132)
R^2	0.464	0.471	0.996	0.997	0.694	0.876	0.968	0.972	
N	132	132	122	122	132	132	122	122	112

Notes: (i) Heteroskedasticity-robust standard errors in parentheses
(ii) * p<0.05, ** p<0.01, *** p<0.001

Fuel Intensity

Due to variations in fuel economy standards (or lack of standards) across time and between the countries studied, estimating fuel intensity can be fairly complex.[1] In addition, changes in fuel intensity due to consumer demand or policy mandates require a technology response by manufacturers and will be subject to a significant lag. Even including shifts in consumer

[1] Put simply, only the US had standards, which Canadian manufacturers adhered to voluntarily, given the tight relationship the Canadian market has to the US market. A few EU countries had "voluntary agreements" on new vehicle fuel economy in the 1970s or 1980s, but it was not until 1995 that the EU developed an agreement with all manufactures selling in Europe that from 1998 to 2008 new vehicle CO2 intensity would fall to 140 grams/km, approximately equal to 6 l/100 km of gasoline, a goal that was not reached.

preferences to less powerful and lighter cars, which can be dramatic, the car stock still takes nearly two decades to turn over. As with car stock, equation (2) is estimated with and without fixed effects, with a variety of different specifications. β_2, β_3, *and* β_4 represent short term elasticities for fuel price, income, and population density respectively.

The effect of fuel price on fuel intensity is significant in the static models for all three periods, demonstrating a negative elasticity. The loss of significance in the fixed effects models perhaps demonstrates the policy-driven nature of fuel intensity trends, with heterogeneity across countries and over time overwhelming the effects of fuel price in these models. Income elasticity is typically negative, and significance disappears with the introduction of time dummies. The negative income elasticity is an interesting result, as it seems to imply that as income increases, consumers either demand more fuel efficient cars or governments pass more stringent fuel efficiency standards. It seems reasonable that the opposite would be true, and that an increase in income would actually lead to an increase in fuel intensity as consumers care less about the cost of driving and thus do not demand more fuel efficient cars, or buy larger, more expensive cars which are less fuel efficient. However, many of the countries in the dataset are relatively wealthy European countries, which tend to have smaller, less powerful cars, and (more recently) stricter fuel economy standards, and thus lower fuel intensity. These policies may well be correlated with income, which would lead to negative elasticity. After controlling for time trends, this result becomes insignificant, suggesting that we were only capturing the spurious correlation from fuel intensity is declining at the same time that income has been rising.

Table 2 – Stock On-road Fuel Intensity

	OLS	**OLS Time Dummies**	**OLS LDV**	**OLS Time Dummies and LDV**	**Country Fixed Effects**	**Country Fixed Effects and Time Dummies**	**Country Fixed Effects LDV**	**Country Fixed Effects, Time Dummies and LDV**	**Arellano-Bond Estim.**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**	**(9)**
1973-2007									
Fuel Price	-0.348***	-0.309***	-0.012*	-0.008	-0.005	-0.004	-0.006	0.009	-0.036*
	(0.025)	(0.034)	(0.005)	(0.006)	(0.025)	(0.042)	(0.008)	(0.009)	(0.016)
Income	-0.292***	0.134	-0.025***	-0.021	-0.268***	0.274*	-0.061***	0.037	0.095
	(0.033)	(0.127)	(0.007)	(0.020)	(0.040)	(0.124)	(0.012)	(0.033)	(0.075)
Pop. Dens.	-0.016***	-0.010*	0	0	-0.319***	-0.177	0.028	0.021	-0.030
	(0.004)	(0.004)	(0.001)	(0.001)	(0.096)	(0.110)	(0.037)	(0.034)	(0.068)
LDV			0.975***	0.981***			0.897***	0.893***	0.911***
			(0.010)	(0.010)			(0.027)	(0.028)	(0.065)
R^2	0.533	0.636	0.987	0.989	0.558	0.63	0.952	0.96	
N	308	308	299	299	308	308	299	299	289
1973-1992									
Fuel Price	-0.279***	-0.226***	-0.016	-0.01	0.075*	0.135**	-0.002	0.028	-0.038
	(0.038)	(0.036)	(0.008)	(0.009)	(0.031)	(0.047)	(0.015)	(0.018)	(0.024)
Income	-0.184**	0.341*	-0.056***	-0.049	-0.152**	0.658***	-0.054*	0.077	0.189
	(0.065)	(0.165)	(0.015)	(0.026)	(0.054)	(0.138)	(0.022)	(0.058)	(0.114)
Pop. Dens.	-0.021***	-0.014*	0	0	-0.566**	-0.103	-0.123	-0.121	-0.098
	(0.005)	(0.006)	(0.002)	(0.002)	(0.171)	(0.206)	(0.077)	(0.068)	(0.140)
LDV			0.964***	0.971***			0.854***	0.839***	0.871***
			(0.011)	(0.012)			(0.054)	(0.059)	(0.085)
R^2	0.413	0.548	0.981	0.984	0.372	0.546	0.888	0.908	
N	176	176	167	167	176	176	167	167	157
1993-2007									
Fuel Price	-0.370***	-0.440***	-0.007	0.005	-0.077**	0	-0.017	0.019	-0.020

	(0.032)	(0.055)	(0.007)	(0.008)	(0.024)	(0.036)	(0.016)	(0.019)	(0.036)
Income	0.011	-0.248	-0.003	0.027	-0.397***	0.031	-0.043	0.08	-0.179***
	(0.060)	(0.168)	(0.015)	(0.028)	(0.072)	(0.155)	(0.042)	(0.057)	(0.043)
Pop. Dens.	-0.008	-0.007	-0.001	-0.001	0.529***	0.581***	0.085	0.137	0.344*
	(0.006)	(0.006)	(0.001)	(0.001)	(0.156)	(0.153)	(0.080)	(0.093)	(0.168)
LDV			1.001***	1.010***			0.915***	0.805***	0.572***
			(0.019)	(0.018)			(0.068)	(0.085)	(0.143)
R^2	0.681	0.704	0.993	0.994	0.546	0.698	0.879	0.903	
N	132	132	122	122	132	132	122	122	112

Notes: (i) Heteroskedasticity-robust standard errors in parentheses
(ii) * p<0.05, ** p<0.01, *** p<0.001

Mean Driving Distance

Following equation (3), γ_2, γ_3, γ_4, and γ_5 represent the short term elasticities of fuel cost per kilometer, income, population density, and per capita car stock. Mean driving distance has long been known to increase as the cost per km of driving decreases, an effect often known as the “rebound effect” in reference to the rebound in fuel consumption from increased driving after implementation of fuel economy standards. Hymel et al. (2010) found a short term elasticity of driving with respect to the cost per mile of driving of -0.047, which suggests that if we reduce the cost per km of driving by 10%, the driving distance should increase by 0.47. In our specification, we can also examine the relationship between fuel cost per km and mean driving distance, which has an analogous interpretation to the “rebound effect.” Our coefficient on the fuel cost per km is highly significant across all categories over 1973-2007, with a short-term elasticity of -0.044 in our specification with time and country fixed effects and a lagged dependent variable. Interestingly, this estimate is very much in line with the estimate by Hymel et al.

Small and Van Dender also emphasize that the rebound effect has been decreasing over time as incomes have risen and highways become more congested. We find similar results by comparing our coefficients of the fuel price elasticity prior to 1992 and after 1992. Prior to 1992, it appears that there is a highly statistically significant elasticity of driving with respect to fuel price per km of -0.061 in our specification with time and country fixed effects and a lagged dependent variable. However, after 1992, the cost per km coefficient in the same specification becomes smaller (-0.012) and statistically insignificant from zero. This may imply a structural shift in how consumers respond to the cost per km, perhaps due to the factors Small and Van Dender point out.

Car stock is also significant, although only in the latter period. As car stock per capita increases, each vehicle may be driven less, although total vehicle kilometers or passenger kilometers may still be increasing. It is possible that the significance of this effect in the period from 1993-2007 is due to additional congestion, which could lead to an overall decrease in mean driving distance per car per year. As expected, population density is significant in the overall regression, with a negative elasticity of -0.129, as well as in the earlier period, which mirrors the results found in the per capita car stock regressions. We view this as evidence tthat denser countries have a higher share of transit, and thus there is slightly less value to car ownership at the margin. However, this effect disappears in the later period, which may point to a greater trend emerging regarding the decreasing importance of population density in overall fuel consumption trends. Perhaps as ownership in denser countries increased, the effect of higher density in transit ridership as an alternative diminished, and thus the variable of density proves less important in explaining our results.

Table 3 – Mean Driving Distance

	OLS	OLS Time Dummies	OLS LDV	OLS Time Dummies and LDV	Country Fixed Effects	Country Fixed Effects and Time Dummies	Country Fixed Effects LDV	Country Fixed Effects, Time Dummies and LDV	Arellano-Bond Estim.
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
1973-2007									
Car Stock	-0.051	-0.101	0.014	0.01	-0.337***	-0.404***	-0.052*	-0.080**	-0.236
	(0.044)	(0.054)	(0.010)	(0.007)	(0.037)	(0.029)	(0.023)	(0.025)	(0.142)
Cost/Km	-0.192***	-0.142***	-0.008	-0.006	-0.153***	-0.147***	-0.048***	-0.044***	-0.106***
	(0.032)	(0.040)	(0.007)	(0.008)	(0.014)	(0.017)	(0.010)	(0.011)	(0.031)
Income	0.12	0.472**	-0.003	-0.003	0.433***	0.107	0.086**	0.017	0.158
	(0.071)	(0.146)	(0.013)	(0.019)	(0.050)	(0.063)	(0.031)	(0.035)	(0.147)
Pop. Dens.	-0.061***	-0.059***	0	0	-0.352***	-0.527***	-0.092*	-0.129**	(0.362)
	(0.005)	(0.005)	(0.001)	(0.001)	(0.072)	(0.067)	(0.043)	(0.047)	(0.193)
LDV			0.987***	0.997***			0.744***	0.794***	0.088
			(0.010)	(0.008)			(0.050)	(0.041)	(0.159)
R²	0.478	0.495	0.985	0.99	0.498	0.621	0.804	0.869	
N	308	308	299	299	308	308	299	299	289.000
1973-1992									
Car Stock	0.023	0.021	0.007	0.016	-0.204*	-0.174**	0.011	-0.045	-0.314*
	(0.064)	(0.078)	(0.015)	(0.013)	(0.080)	(0.065)	(0.050)	(0.052)	(0.152)
Cost/Km	-0.176***	-0.177**	-0.003	-0.013	-0.136***	-0.129***	-0.054**	-0.061***	-0.134**
	(0.043)	(0.053)	(0.010)	(0.011)	(0.021)	(0.023)	(0.016)	(0.017)	(0.048)
Income	0.044	0.072	0.048	-0.028	0.247*	-0.332**	0.039	-0.092	0.205
	(0.137)	(0.231)	(0.030)	(0.034)	(0.116)	(0.119)	(0.077)	(0.072)	(0.140)
Pop. Dens.	-0.052***	-0.052***	0	0.001	-0.159	-0.487***	-0.004	-0.149	-0.502*
	(0.007)	(0.007)	(0.002)	(0.001)	(0.114)	(0.118)	(0.072)	(0.098)	(0.253)
LDV			0.980***	0.998***			0.592***	0.644***	0.018
			(0.018)	(0.015)			(0.066)	(0.067)	(0.097)
R²	0.481	0.488	0.977	0.985	0.376	0.597	0.664	0.752	
N	176	176	167	167	176	176	167	167	157.000
1993-2007									
Car Stock	-0.162	-0.169	-0.001	0.003	-0.383***	-0.686***	-0.170*	-0.250*	-0.436***
	(0.111)	(0.128)	(0.012)	(0.010)	(0.070)	(0.111)	(0.066)	(0.098)	(0.128)
Cost/Km	-0.247***	-0.092	-0.013	0.008	-0.046	-0.016	-0.029	-0.012	-0.056
	(0.053)	(0.075)	(0.008)	(0.010)	(0.024)	(0.030)	(0.016)	(0.016)	(0.030)
Income	0.338**	0.793***	-0.001	0.045	0.232***	0.001	0.100*	0.032	0.062
	(0.123)	(0.234)	(0.018)	(0.024)	(0.068)	(0.096)	(0.049)	(0.048)	(0.098)
Pop. Dens.	-0.063***	-0.062***	0	0	-0.254	-0.459**	-0.104	-0.193*	-0.289
	(0.008)	(0.008)	(0.001)	(0.001)	(0.169)	(0.169)	(0.085)	(0.086)	(0.153)
LDV			0.991***	0.990***			0.771***	0.776***	0.755**
			(0.009)	(0.008)			(0.061)	(0.064)	(0.235)
R²	0.494	0.519	0.994	0.996	0.32	0.47	0.728	0.801	
N	132	132	122	122	132	132	122	122	112

Notes: (i) Heteroskedasticity-robust standard errors in parentheses
(ii) * p<0.05, ** p<0.01, *** p<0.001

Simultaneous Estimation of the System of Equations

Seemingly Unrelated Regression (SUR)

Seemingly unrelated regression (SUR) estimation is similar to our previous estimations in that each equation of the system of equations (1)-(3) is estimated separately, but with one key difference: SUR allows for cross equation correlations in the error terms. Given the likely relationships between car stock, fuel intensity, and vehicle usage, we would expect there to be correlations between the error terms in each of these equations (i.e., the residuals for some countries are high in all three equations). SUR takes advantage of these correlations through a feasible generalized least squares procedure, which may sometimes lead to more significant coefficients.

The results from the SUR regression are similar to those observed in the previous specifications. Fuel price is highly significant for car ownership, an effect which dropped out in many of the previous estimations. Income is also significant, which reflects the theory that higher income is correlated with increased car ownership. Income is also significant for fuel intensity, with a negative elasticity of 0.247, which is very similar to the elasticity observed for the overall period in the results above. Cost per kilometre and car stock remain central to explaining car usage patterns. See Table 4 below for results over the entire period of analysis.

Table 4 – SUR Results, 1973-2007

Car Stock		**Fuel Intensity**		**Mean Driving Distance**	
Fuel Price	0.929***	**Fuel Price**	-0.162	**Car Stock**	-0.040*
	(0.011)		(0.111)		(0.020)
Income	0.155***	**Income**	-0.247***	**Cost/Km**	-0.031**
	(0.023)		(0.053)		(0.010)
Pop Dens.	-0.043	**Pop Dens.**	0.338**	**Income**	0.002
	(0.024)		(0.123)		(0.036)
LDV	-0.061***	**LDV**	-0.063***	**Pop. Dens.**	-0.063
	(0.005)		(0.008)		(0.039)
				LDV	0.855***
					(0.029)
R^2	.99	**R^2**	.99	**R^2**	.99
N	274	**N**	274	**N**	274

Notes: (i) Heteroskedasticity-robust standard errors in parentheses
(ii) * p<0.05, ** p<0.01, *** p<0.001

Full Information Maximum Likelihood (FIML)

In the previous specifications, we are estimated each of the three equations separately. However, we recognize that the equations are related. For example, the vehicle stock is the dependent variable in equation (1) and is an explanatory variable in equation (3). By estimating the system of equations simultaneously, we allow for these interrelationships to be explicitly accounted for. To do so, we can either perform a three-stage least squares (3SLS) estimation, or if we iterate the process to solve for the variance-covariance matrix and estimated parameters until convergence, our estimates converge to the full information maximum likelihood (FIML) estimates. This latter approach is the one we take (although estimation of the system of equations by 3SLS provides similar results). We use first differences to control for changes over time, which is similar in concept to the time dummies used above. Table 4 includes results from estimating the three equations simultaneously. In this estimation we do not address possible endogeneity from the lagged dependent variable, but future work will do so.

The results do not seem dramatically change from the previous estimations. Beyond the lagged dependent variable, income is the only statistically significant determinant of the size of the vehicle stock, with an elasticity of 0.177. In terms of fuel intensity, price is statistically significant, which varies somewhat from previous estimations, although some of the models showed moderate positive price elasticities (notably the Arellano-Bond estimator). If we increase price, fuel intensity declines, with a short run elasticity of 0.03. We also observe similar results for mean driving distance, with a rebound effect of just under 10%. Income is also significant, with an elasticity of 0.20.

Table 5 – FIML Results, 1973-2007

Car Stock		**Fuel Intensity**		**Mean Driving Distance**	
Fuel Price	-0.009	**Fuel Price**	-0.025*	**Car Stock**	-0.095
	(0.011)		(0.012)		(0.108)
Income	0.177**	**Income**	0.058	**Cost/Km**	-0.096***
	(0.058)		(0.058)		(0.014)
Pop Dens.	-0.315	**Pop Dens.**	0.211	**Income**	0.192*
	(0.547)		(0.406)		(0.093)
LDV	0.330**	**LDV**	0.196**	**Pop. Dens.**	0.007
	(0.104)		(0.075)		(0.005)
				LDV	-0.068
					(0.056)
R^2	0.326	**R^2**	0.103	**R^2**	0.240
N	284	**N**	284	**N**	284

Notes: (i) Heteroskedasticity-robust standard errors in parentheses
(ii) * p<0.05, ** p<0.01, *** p<0.001

Long Term Trends

Since our model specifications that include a lagged dependent variable represent a partial adjustment model, we can derive the steady state long term elasticities by noting that in the steady state the dependent variable and lagged dependent variable are the same. This implies for example that the long run price elasticity in terms of car stock is $\alpha_2/(1-\alpha_1)$. Using the results from the FIML model, long run elasticities are included in Table 6 below. Income elasticity of car stock per capita, which was significant in the FIML regression, as well as a number of the independent specifications above, has a long run elasticity of 0.264, indicating that long run trends point to the increasing effect of income on car ownership over time. The decrease in the elasticity of cost per kilometer is particularly interesting. This suggests that consumers become less sensitive to given changes in cost over time. Future work will calculate standard errors for these point estimates using the delta method.

Table 6 – Long Run Elasticities, 1973-2007

Car Stock		**Fuel Intensity**		**Mean Driving Distance**	
Fuel Price	-0.013	**Fuel Price**	-0.031	**Car Stock**	-0.089
Income	0.264	**Income**	0.072	**Cost/Km**	-0.090

Pop Dens.	-0.470	**Pop Dens.**	0.262	**Income**	0.192
				Pop. Dens.	0.007

5. IMPLICATIONS FOR POLICY

Car ownership, fuel economy, and car usage are all crucial to understanding the driving forces behind fuel consumption. Insights into how factors such as fuel price, income, population density and the cost of driving per kilometer in turn provide signals to transport policymakers regarding effective CO_2 stabilization and reduction measures. However, traditional responses to addressing these issues, such as the recent strengthening of CAFE standards in the U.S. and making the EU Voluntary Standards mandatory (Fontaras and Samaras 2009), and the use of emissions-based vehicle taxation in Europe (such as the "bonus-malus" program in France (Cuenot 2009), are important. Yet these are limited in their ability to adequately address transport externalities because they only address fuel economy of new vehicles. In particular, each of the factors considered demonstrates the surprisingly limited effect of fuel price. Our results indicate that an increase in fuel prices tends to provide downward pressure on fuel intensity. Thus, a policy which increases the cost of fuel, such as a tax, may lead to increased demand for fuel efficient vehicles, which may eventually lead to more fuel efficient technologies and a lower cost of driving, yet with only a small offsetting rebound effect as an increase in car usage. Of course, understanding the effectiveness of any given policy can quite complex, with secondary effects constraining outcomes. Fundamentally though, these results imply that a price mechanism may have some impact in shifting technology and improving fleet fuel economy.

Beyond the need to reduce CO_2 emissions, transportation policymakers need to consider a range of negative externalities relating to driving, such as congestion, air pollution, noise, safety and other social costs that are not captured in the immediate cost of driving. If the overall cost of driving is decreased through regulatory mechanisms, a likely result would be an increase in overall driving, exacerbating the social cost of transportation (in absence of CO_2 emissions). These effects need to be carefully considered when implementing transportation policy. Other evidence (Parry, Walls and Harrington 2008) suggests that the externalities of fuel (imports) and CO2 (climate) are small compared with those of local air pollution, congestion, and safety. Imposing these on the use of vehicles may be as important or more important when expressed as costs/km of car use. Certainly congestion and safety are somewhat time and place dependent, but they are variable costs. One way of reflecting safety more accurately is to price part of automobile insurance according to actual distance driven, so-called pay as you drive insurance (Parry 2007; Bordhoff and Noel 2008).

6. FURTHER RESEARCH

It is important to note that due to data limitations, these models exclude a number of explanatory variables which may also affect fuel demand. Owning and using a car include a number of costs which vary country to country, including vehicle licensing fees, registration fees, energy tax, purchase taxes, import fees, etc. In some countries, such as the UK or US special tax concessions may accompany "green cars"; in others, the light taxation of cars bought by employers for their employees ("company cars") may represent a significant amount of the new vehicle stock, vehicles that are sold after two or three years as used cars. These cars tend to be larger and more expensive than cars bought by private citizens (Schipper et al 1993). The same is true for diesel cars, which, while in theory offering greater efficiency than similar gasoline cars, tend to be bought as larger models both to provide more power and because buyers are wealthier than those buying gasoline cars (Schipper and Fulton 2009). According to a recent report by the German Economic Institute, "CO_2 emissions have become the leading basis of assessment for car taxes in most European countries" (DIW, 2009). Ryan et al (2009) have also attempted to assess the impact of differences in incentives across countries.

The effects noted above can be significant, and in some cases (incentives) could work beyond fuel prices while in other cases (company cars) could offset other forces buyers in a given country face. Clearly more work is required both to model new cars and their characteristics (not simply their test fuel economy) as well as how car usage and indeed ownership varies as a function of both incomes and fuel prices as well as car prices, "incentives", and other factors that could influence both the marginal costs of owning and using cars as well as marginal benefits.

As of this writing, however, differences in fuel taxes are still important among European countries or between the US on the one hand and Canada or Australia on the other. These differences reach to about an implied carbon tax of $100/tonne (e.g. Sweden) and much more if the US is compared with Europe or Japan. In order to account for this variation between countries beyond fuel prices, JS incorporated an additional variable, *T*, which attempted to account for various new-vehicle or annual taxes and fees not embodied in fuel taxes as a constant across time. These models have excluded *T,* or any other taxation parameter, which may introduce omitted variable bias into the models and also lead to complications in comparing the original results with the updated data. Future work will study the effects of taxation and incentives. With both OECD countries and increasingly developing countries experimenting with various incentives, standards and other schemes to reduce fuel us and carbon dioxide-emissions, and in some cases reduce car use itself (i.e., through congestion pricing), more work is clearly warranted to understand better how various measures so far have in fact affected fuel use or emissions as a key to understanding future policies.

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APPENDIX: MAIN DATA SOURCES

For each country, data was obtained from either a set of official and semi-official data sources or from a noted national authority. The key data include numbers of vehicles by fuel, average annual vehicle distance driven by fuel, fuel economy by fuel, and thereby total fuel use by fuel.

United States

Oak Ridge Transport Energy Data Book (TEDB, cited as Davis et al. in the bibliography), US EPA for new vehicle fuel economy, Federal Highway Administration's Table VM1, Bureau of Transport statistics. The share of light trucks, their annual distances driven and fuel use are taken from various editions of TEDB and interpolated between the years in which surveys ere taken by the Truck (Vehicle) Inventory and Utilization Survey.

Australia

Data from 1984 through 2007 were tabulated by Apelbaum and Associates (2008), based on regular surveys of road vehicle use and fuel consumption and other official sources. Data for previous years were complied by Schipper et al (1998) as well as by Apelbaum for that 1998 study.

Canada

The Office of Energy Efficiency of Natural Resources Canada publishes exhaustive tables on all aspects of vehicles, vehicle activity, and fuel use for each branch of transport in Canada back to 1990 and in some cases back to the 1970s. Data are linked to surveys and other information collected by Transport Canada.

France

ADEME, the French Agency for Environment, publishing yearbooks on Energy Efficiency Trends and yearly updates on motor vehicles. The Ministiere des Equipments publishes yearly data called "Bilan de la Circulation" that give data on vehicle use.

Germany

Verkehr in Zahlen, published yearly by Deutsches Institut fuer Wirtschaft (DIW) in Berlin for the Federal Ministry of Transport, provides key data on vehicle fuel economy and use. DIW provided the new vehicles fuel economy and CO_2 emissions data in regular publications.

Italy

The Unione Petrolifera has assumed responsibility for motor vehicle trends and published them in their latest forecast (in 2007), Previsioni di Domanda Energetica e Petrolifera Italiana 2007- Italiana 2007-2020, and again in 2009.

Japan

Energy Data Modelling Center Energy in Japan Handbook for 2008/9 and yearly tables published by the Ministry of Land Transport and Infrastructure accessible for the most recent years

U.K.

Department for Transport. *Transport Statistics of Great Britain* and Dept. for Trade and Industry *Digest of UK Energy Statistics*, as well as spreadsheets available online from DfT.

European Council of Ministers of Transport. European Transport Data Base and material submitted to ECMT from ACEA, the European car manufacturers'association, for new vehicle charactieristcs through 2000. From 2000 onward these data are provided by the European Union at http://ec.europa.eu/environment/air/transport/co2/co2_monitoring.htm

Sweden

Data for historical years were tabulated by Schipper et al (1994, 1995) from an exhaustive survey of historical Swedish sources. More recent data are taken from the Central Bureau of Statistics (SCB) for numbers of vehicles and driving distance, Statens Institute for Kommunikations Analyser (now Trafikanalys), and the Swedish Road Authority, which publishes an annual vehicle use and fuel consumption overview.