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Fuel demand on UK roads and dieselisation of fuel economy

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ABSTRACT

Because of high oil prices, and climate change policy, governments are now seeking ways to improve new car fuel economy thus contributing to air quality and energy security. One strategy is to increase dieselisation rates of the vehicle fleet. Recent trends in fuel economy show improvement since 1995, however, efforts need to go further if the EU Voluntary Agreement targets on CO_2 (a greenhouse gas emission standard) are to be achieved. Trends show diesel car sales have accelerated rapidly and that the advantage of new car fuel economy of diesel cars over gasoline ones is narrowing posing a new challenge. We estimate the demand for new car fuel economy in the UK. In the long-run consumers buy fuel economy, but not in the short-run. We found that long-term income and price changes were the main drivers to achieve improvements particularly for diesel cars and that there is no break in the trend of fuel economy induced by the agreement adopted in the 1990s. Policy should target more closely both consumer choice of, and use of, diesel cars.

1. Introduction

In this paper, we review recent impacts of the car market on fuel consumption and on CO_2 emissions on road and of the new car market. We estimate the price and income elasticity of demand for fuel economy (litres per 100 km) of new UK cars using a two-stage econometric model following (Engle and Granger, 1987) to investigate the drivers of this demand in the short- and long-run for the period 1978–2004.[1] We estimate how fuel economy of new cars (excluding data for sport utility vehicles or SUV's or 4×4s vehicles) is affected by: (1) fuel price changes; (2) increases in personal incomes; and (3) the introduction of the EU Voluntary agreements (standard) with car manufacturers for reductions in CO_2 emissions per kilometre (km). This paper reviews time-series data for the UK to disentangle these different effects on fuel economy for vehicles on UK roads. It is hoped that this will inform the debate on the combination of measures needed to improve fuel economy and to reduce national fuel consumption and CO_2 emissions from UK road transport. Fuel prices have increased by roughly 60% in 2002–2008 adding weight to policies that improve fuel economy. Increasing the penetration of diesel is seen as a solution to improve fuel economy but this can bring new problems when trying to mitigate fuel demand.

In the UK, new car fuel economy (all new car fleet) and on-road fuel economy (of the entire car fleet on the roads) have steadily improved since the late 1970s but the overall energy use of the sector, and emissions of greenhouse gas, have not fallen to the desired degree (Table 1). In Table 1, different measurements of new car fuel economy, which either include or exclude 4×4s are given. New car fuel economy determines, at least partly, on-road fuel economy improvements and future growth in road transport energy demand and CO_2 emissions. However, fuel economy (based on tests) of new cars differs from on-road fuel economy (not based on tests), (the difference is shown further discussed below) and because of this there is uncertainty in how effectively fuel economy changes, and its standards are in mitigating the growth in energy demand of this sector. How quickly on-road fuel economy improves is also dependent on vehicle sales and the rate of turnover of the vehicle stock (how fast old vehicles are replaced by new ones), which is determined by macroeconomic conditions (Greenspan and Cohen, 1996). There is evidence that the gap between the two measures of fuel economy continues to be large, although smaller than in previous decades.

The absence of improved on-road fuel economy is also influenced by driving styles, which lead to higher (or lower) than optimal speeds for fuel economy. Speed is elastic with respect to income according to a Danish study based on large cross sectional evidence (Fosgerau, 2005).

In the UK the 70 mph speed limit on motorways is exceeded by 57% of drivers, and the 30 mph limit on urban roads, is exceeded by 58% of drivers (DfT, 2004). Optimal speed for fuel economy lies

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[1] Note that we use the European measure of fuel economy in litres per 100 km. Hence, a reduction in the numerical value represents an improvement in fuel economy (fewer litres per 100 km). This is the inverse of the US measure of fuel economy in miles per gallon.

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Table 1
Trends in private car transport in the UK in 1975–2004.

	1975	1980	1990	1995	2005	Percent change pa. 1975–2004 (%)
Vehicle stock (1000s registrations)	12,526	14,660	19,742	20,505	26,208	+2.49
Fuel economy new gasoline cars (l/100 km) (excludes 4 × 4s)[a]	–	9.3	8.2	8.1	7.4	
Fuel economy (includes (4 × 4s); gasoline cars) (L/100 km)[b]	–			8.28*	7.50	–
Fuel economy (includes (4 × 4s); diesel) (L/100 km)	–	–	–	7.10*	6.28	–
On road fuel economy (gasoline equivalent L/100 km; diesel and gasoline)	10.35	10.45	9.66	9.35	9.90	
Vehicle km (billions per year)	182	227	328	351	397.2	+2.6
Energy consumption (million tonnes)	14.50	17.26	22.46	22.04	22.26	+1.44
Emissions CO_2 (million tonnes of carbon equivalent)	12.53	15.3	19.3	18.9	19.36	+1.46

[a] *Source*: DfT, 2006; Transport Statistics Great Britain, 2006, 2007 and DTI, 2006.
[b] The fuel economy data on 4 × 4s (SUV's) refers to 1997 not 1995. Fuel economy measures are not directly comparable because methodologies have changed. Vehicle km data excludes traffic of taxis.

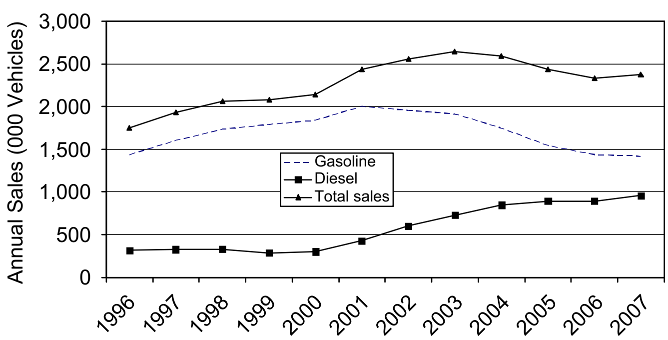

Fig. 1. Diesel penetration in UK car sales.

between 55 and 60 mph (Plowden and Hillman, 1996) or at 62 mph (Anable et al., 2006 based on EU Commission data). Not driving at the optimum speed on the most frequently used roads increases fuel consumption unnecessarily, especially as urban roads, motorways and minor urban roads account for almost 60% of the total distance driven, (TSGB, 2007). A great majority of vehicles are driven much faster than the speed that minimises fuel consumption. For example, a data sample on car speed for 2005 on motorways (DfT, Transport Statistics Bulletin, 2005) showed that 73% of drivers drive above the optimum speed; this level has not declined since 1995. Therefore, driving a car at non-optimum speed is the key factor in raising actual fuel consumption and in worsening on-road fuel economy (more litres per km-driven).

It is evident that car speed levels and fuel consumption are now increasingly becoming the focus of energy policy design. For example, in 2005 IEA (2005) recommended enforcing a speed limit of 56 mph on EU motorways as a measure to save oil consumption. Therefore, to not drive at optimal speed negates improvements in on-road fuel economy and leads to higher fuel use. The role of speed in worsening fuel economy requires further investigation.

Despite improvements in new car fuel economy in the UK since 1970 and the adoption of the EU Voluntary Agreements in 1998, energy demand and CO_2 emissions from private cars had not abated by 2004 because of the high growth in km-driven (vkm) partly supported by increased dieselization and a larger vehicle stock. Such emissions have remained constant within the last 15 years, although they did increase rapidly over the previous decades. Emissions have not fallen as much as was hoped although carbon emissions (diesel and gasoline) have increased below the growth in the vehicle stock (Table 1).

Fig. 1 shows the penetration of diesel in the UK passenger car market. Since diesel cars now account for almost 40% of total annual vehicle sales accurate monitoring of their on-road fuel economy and of their mileage is essential. Diesel cars have increased their market share since the Voluntary Agreement came into force (1998). Since the year 2000 diesel sales have doubled considerably.

The UK Dft does not report data on diesel mileage since its survey (National Travel Survey) monitors vehicle counts without recording vehicles by engine type. The report "Transport statistics Great Britain", nor transport trends, nor the National Travel Survey, in their current versions, publish statistics on vehicle use (in vehicle km) by fuel type or size. Data on mileage are key to explain future trends in motor fuel use.

However, the UK government expects that recent policy measures, including graduated fuel duty and Voluntary Agreements, will reduce fuel use of road vehicles by 6% by 2010 (Secretary of State for the Environment, 2006).[2] Improving vehicle fuel economy does not necessarily reduce other types of air pollutants (carbon monoxide (CO), black smoke (BS), hydrocarbons (HC), and nitrogen oxides (NO_x)), all of which are of particular concern for health and environmental reasons (UK Department of Health, 1998)). Improving fuel economy can worsen environmental pollution, if such improvement is achieved, by increasing dieselisation of the vehicle stock; diesel vehicles emit more particulates than gasoline vehicles.

The model and results presented in this paper enable a detailed examination of trends and policies that affect new car fuel economy, energy consumption and key technological characteristics, which determine fuel economy and pollution emission rates. Similar models are described in (Johnstone, 1995).[3]

The paper is structured as follows: Sections 2 and 3 contain a definition of fuel economy and describes the annual trends in traveled distance, the trend in CO_2/km-driven of passenger vehicles for both new cars and used vehicles, as well as a discussion on new car fuel economy regulation; Section 4 discusses a literature review; Section 5 gives an overview of the entire model; Sections 5 and 6 describe the two-stage co-integration equation of fuel economy and econometric results in the analysis of automotive (diesel) fuel economy. Section 7 concludes.

2. Mileage, vehicle use and vehicle size

Table 1 shows the changes in vehicle kilometres or vehicle use. A vkms traveled by personal transport has increased from 227 to

[2] Energy use in road transport in the last 30 years is explained mainly by two effects: First, UK drivers are now driving longer distances per journey on average (DfT, 2006), and second, the UK vehicle stock has grown strongly (Table 1).

[3] Johnstone (1995). For a model description of the Cambridge Multisectoral Dynamic Model (MDM) of the United Kingdom economy; see: Barker and Peterson (1987).

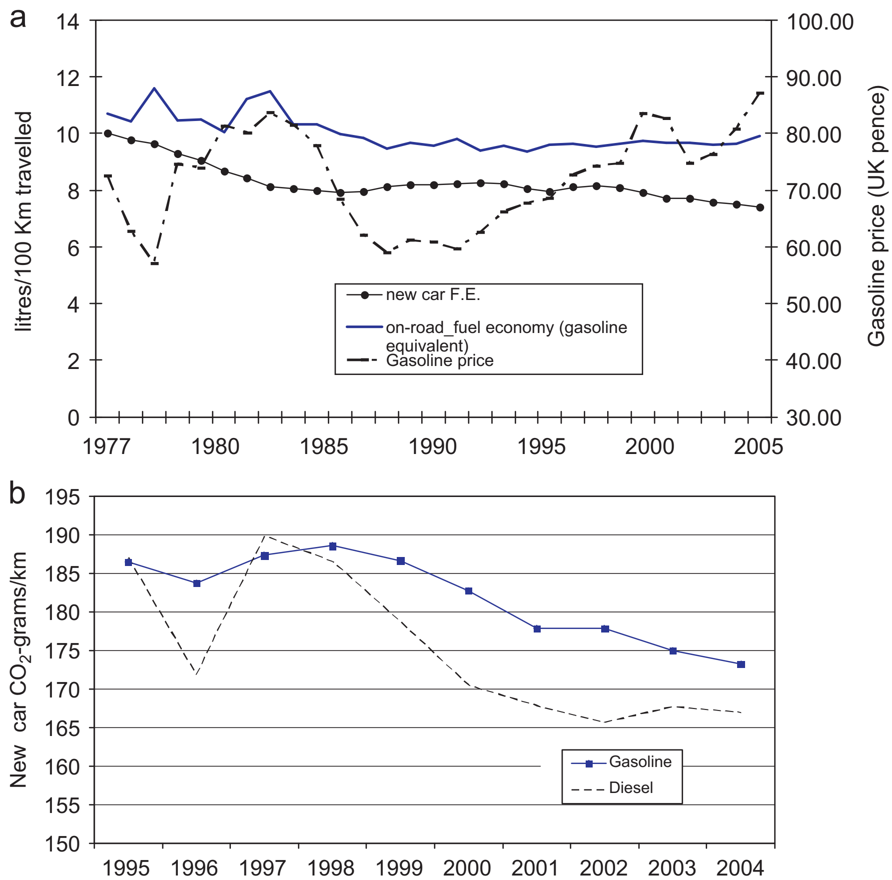

Fig. 2. (a) On-road fuel economy (gasoline equivalent) (diesel and gasoline), new car fuel economy and gasoline price on the "z" axis. (b) New car carbon dioxide emissions per distance driven (new car market average).

397.2 billions vkms in 2005 (excludes taxis). The increase in vkms outpaces that of the vehicle stock (measured in vehicle registrations) in the same period. The increase in vkms shows two developments: it is larger than the increase in personal disposable income and (2) it tracks the increased dieselization of the UK's vehicle fleet, and the increase in sales of more powerful vehicles. For instance, in 2003 diesel cars were driven on average 21,082 km annually against 14,000 km for gasoline fleet (DfT, 2003). This translates to a 50% difference relative to recorded mileage of gasoline cars. This is confirmed by Schipper (2007) who finds that diesels are driven more than gasoline cars in Germany and France. Mileage is also correlated to vehicle size. For example, in 1996, just before the EU Voluntary Agreement was institutionalised, there were 1.7 million cars classed as efficient (below 1000 cc). This figure has fallen to 1.1 million cars by 2006. In the meantime, powerful cars circulating in UK roads (2000–2500 cc) increased to 9 million in 2006 from 1.1 million in 1996. Another development is that of vehicle power rating which has increased by approximately 7% (weighted average engine power using data on the UK's car stock) in 1996–2006 (DfT, 2007, Table 9.3) whilst new car fuel economy (both fuels, new car fleet average) has only improved by 10% in 1995–2005 (DfT, 2007, Table 9.3). It remains to be seen how the current economic downturn in the UK affects new car fuel economy and vehicle power. The increase in vehicle power goes hand in hand with consumer preferences for more powerful vehicles.

3. Historical data on UK fuel economy and fuel demand

Fuel economy data for the new car fleet (weighted by registrations), which we use in our study, was collected from DfT in its TSGB (2006). This source, in turn, uses data on fuel economy (based on tests) collected by the Vehicle Certification Agency (VCA, 2007). The EU directive 80/1268/(EC, 1999) describes these tests. The tests, determined by various EU directives, have been changed over a number of years to more accurately reflect the driving cycle.

Fig. 2a shows strong price response (UK pence/litre) (DTI, 2006) of fuel economy (litres/100 km) for gasoline cars (TSGB, 2006) and of on-road fuel economy (both gasoline and diesel; diesel is converted to gasoline at energy equivalent 1.12 gasoline litres per litre of diesel) for the UK economy in the period 1978–2005.[4] Fig. 1 shows two developments. First, on-road fuel economy in 2005 is not better than in 1988 (less litres per km). Second, in 2005 the gap between on-road and new car fuel economy (gasoline) is 32% (9.9/7.5) or 24% less fuel of new against fleet. In 1990 new cars consumed 15% less fuel than fleet. Figs. 2a and b are based on data on national fuel use and on distance driven for the UK.

New car fuel economy responded negatively (less gasoline consumed per kilometre) to higher gasoline prices during the 1980s (Figs. 2a and b). The second round of high gasoline price increases (1999–2000) did not lead to equally large adjustments in fuel economy compared to the first two rounds (1979–1981 and 1984).

[4] Official statistics prior to 2007 on new car fuel economy exclude SUVS (4-wheel drive) four wheel drive vehicles, but sales of SUV cars have increased, and so real world fuel economy level is higher (more litres per km) than estimated. Using average fuel consumption data of TSGB (2007) (recorded by the National Travel Survey), and the latest data on new car fuel economy (which includes SUVS) the gap is 13% for diesel cars for 2005.

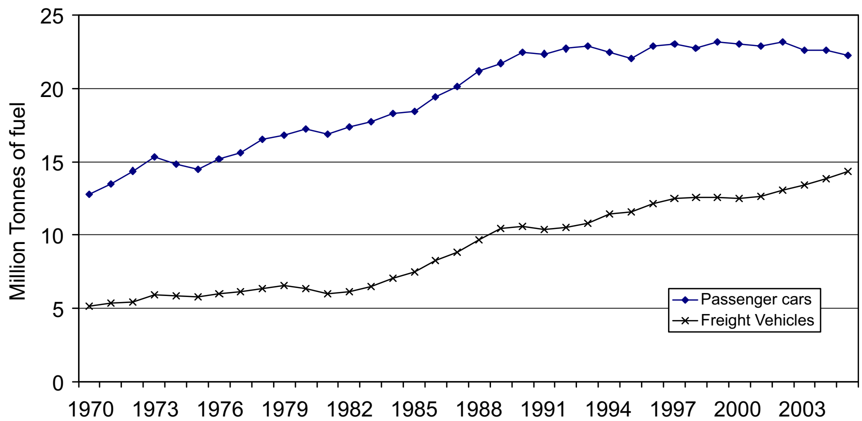

Fig. 3. Energy consumption (includes gasoline and diesel) passenger cars.

In the UK, new car fuel economy and on-road fuel economy (of the entire car fleet) have steadily improved since the late 1970s despite long periods of low real gasoline prices, excluding brief periods of price peaks in the early 1970s, 1980s and in early 2000 (Table 1).

Fig. 2a shows that on-road fuel economy (gasoline and diesel fuels) has peaked two times during the 70s and 80s. During 1978–1983 large investments were directed at both domestic and imported cars with a better fuel economy (Rice and Frater, 1989, p. 95), which after a time lag improves on-road fuel economy (Fig. 2a).[5] By 1985 on-road fuel economy improved significantly. Since the mid-80s improvements in on-road fuel economy have continued, however, the trend shows that improvements have slowed down significantly by the year 2000. A possible reason for the lack of improvement is the "rebound" effect, which implies that as fuel economy improves the cost per km declines encouraging further vehicle use (see, for example, (4CMR, 2006; Small and Van Dender, 2006) for the empirical treatment and definition of this issue).

Schipper and Tax (1994) give five reasons to explain why fuel economy on test will differ from on-road fuel economy: first the formulae used to represent the real driving cycle from road test data; second, actual conditions on all parts of the cycle (hills, weather, road curvature and road surface); third, driver behaviour, which usually increases fuel consumption; fourth, lack of vehicle maintenance; fifth, test values fail to represent cars actually sold. This is because: (1) cars tested are optimized for testing, and (2) contain more fuel intensive features (larger engines, turbocharging, etc.), which is not shown in the tests or sales weightings (Schipper and Tax, 1994, p. 261).

Fig. 2b depicts the changes in CO_2 emissions per kilometre-driven during 1995–2004 for new gasoline and diesel cars. The figure shows that although diesel CO_2 emissions are generally lower than gasoline for most of the period. The trends also show that the advantage of diesels over gasoline cars is being narrowed. For example, in 1997 diesel emissions match those of gasoline in 1997–1998. Fig. 2b shows that the ratio of CO_2 emissions per distance traveled (of average new cars) has declined since 1995, with diesel cars in particular showing steeper reductions in emissions per kilometre driven.

New car fuel economy in the late 80s and early 90s was affected by: (a) a change in vehicle test cycle, which meant that official fuel economy figures were artificially inflated, (b) a focus on air quality meant that cars became heavier, and (c) engineering capability was diverted away from CO_2 emissions.

The absence of fuel economy standards coupled with low gasoline prices during 1987–1993 meant that new car fuel economy improvements were partially reversed during that period. The new car fuel economy level for 1993 remained at the same level as for 1983. After 1993, improvements in new car fuel economy began to appear. This was a result of policy developments, including the linking of company car tax to CO_2 emissions, the introduction of vehicle excise duty based on CO_2 emissions and of Voluntary Agreements based on CO_2 emissions reductions (discussed below), together with gasoline price changes (partly driven by the fuel duty escalator policy) and income effects.

Total fuel demand for passenger cars in 2005 (gasoline and diesel) accounted for 38% of total UK oil consumption. Total fuel demand (Fig. 3) has shown a large increase from the 70s to 2005.

This demand (Fig. 3) grew significantly in the 1980s and 1990s but has recently reached a plateau, albeit at a record historical level. The demand for fuel, and hence CO_2 emissions, from the domestic transport sector is expected to level out and fall by 2020, because of saturation effects and further policy measures (DTI UEP, 2006).

4. The history of vehicle fuel economy regulation 1970–2005 in the UK

Following the oil price shocks of the mid-1970s, various policy packages have been deployed to improve fuel economy of the new car fleet. Table 2 shows a short summary of the policies that have been deployed. An innovative policy (not listed below) could be the inclusion of passenger transport in the EU Emissions Trading Scheme by 2012. Other measures include tax relief based on engine size and CO_2 emissions, R&D incentives for technologies and biofuels (renewables fuel obligation).

Falling oil prices and the robust deregulatory government policy of the 1980s reduced concerns by policy makers in fuel

Table 2
Policy targeting fuel economy improvement.

Year introduced	Policy, description	Success
1978–1985	Voluntary target: 10% decrease in fuel consumption	Target met
1993	Fuel duty (tax on final price in fuel	Partial
1995	EU Voluntary Agreement target: 25% decrease in CO_2 per km driven)	Partial
	Vehicle excise duty (based on CO_2 emissions)	Partial
2012	EU mandatory agreement	Unknown

[5] In this paper we do not explicitly account for technology diffusion. It is probable that imports of Japanese, Italian and French vehicles, which are more fuel efficient, in the 70s and early 80s significantly improved (fleet wide) fuel economy of UK vehicles.

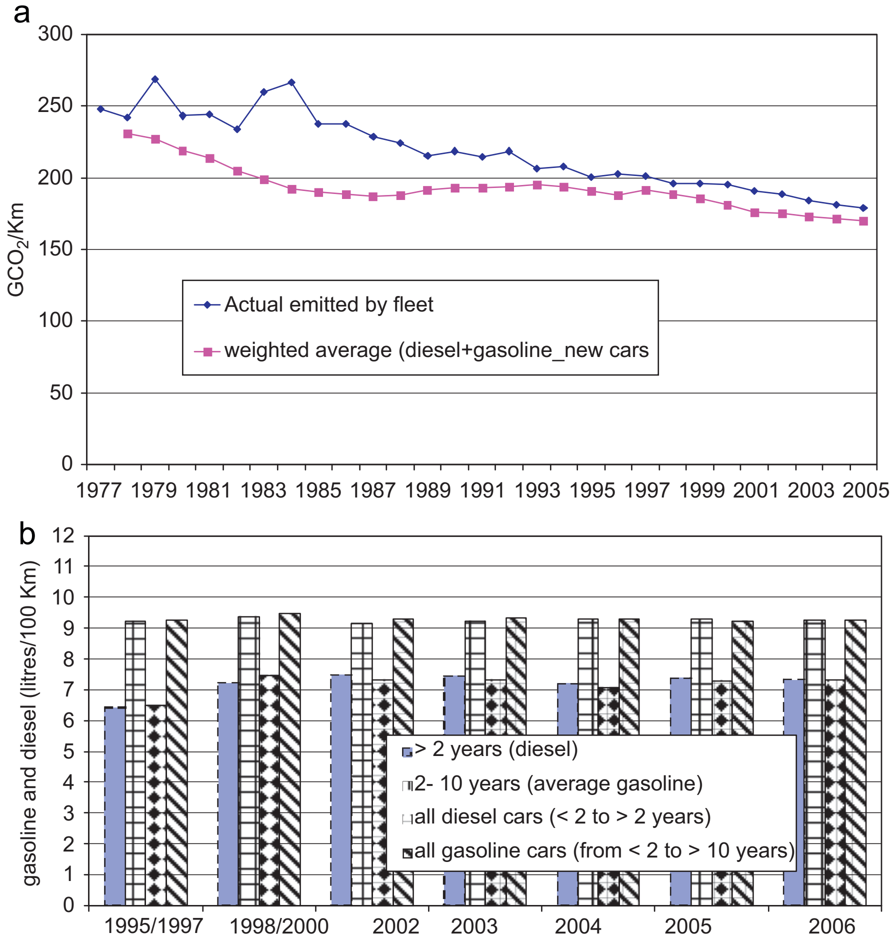

Fig. 4. (a) On-road CO_2 emissions (gasoline–diesel). (b) On-road fuel economy (by fuel) and vehicle age (DfT, 2007, National Travel Survey).

economy. However, in the 90 s concerns about CO_2 emissions led to renewed political interest. In 1993, a fuel duty escalator was introduced, but in 2000 it was frozen so that it could not increase with the real rate of inflation. In 2007, however, the fuel duty was increasing faster than inflation and the fuel duty was raised by 2 p./l in October 2007. (Guardian, Oct. 10, 2007).

The main policy measure to reduce vehicle CO_2 emissions is now the UK's participation in the European Union Voluntary Agreements to stimulate technical improvements in vehicle efficiency. In the late 1990s, the European Commission secured Voluntary Agreements with European (ACEA), Japanese (JAMA) and Korean (KAMA) car manufacturers to reduce new car CO_2 emissions to 140 gCO_2/km between 1998 and 2008/2009. This represents a cut of 25% on the 1995 levels. The 140 gCO_2/km target is a sales-weighted average to be met at a European level by each motor manufacturing association. The UK, which started from a level above the European average position (mainly due to the lower level of diesel use in the UK) is likely to be one of the countries with a higher average emissions per kilometre. The UK government's central forecast for new cars in the UK was 162 gCO_2/km for 2008. In February 2007, the European Commission published a communication which proposed a mandatory new car fuel efficiency target of 130 gCO_2 by 2012. Legislative proposals were expected by the end of 2007. The possibility of including road transport in the EU emissions trading system was also under consideration.

Fig. 4a shows on-road CO_2 emissions per kilometre for the entire vehicle stock, (emissions are calculated by using data on fuel consumption and actual km-driven) and CO_2 for new cars (weighted average of gasoline and diesel). The gap has narrowed in recent years but continues to be large. In 2005 the gap between on-road CO_2 per kilometre and that of new cars was 5.1% compared to 9.8% in 1980.

Emissions per km of new cars include assumptions on average vehicle speed and follow the national atmospheric emissions inventory maintained by NETCEN on behalf of DEFRA and are based on equations from the Transport Research Laboratory which link emissions factors to vehicle speed (TSGB, 2005, p. 46).

Data show that the trend in actual emissions (grams of CO_2/km-driven) initially widens from that of new car emissions between 1978 and 1992 but after 1992 the gap in emissions narrows. The slope in emissions of new cars (and that of on-road vehicle fleet) shifts downwards after the accelerated introduction of diesel cars during the early 1990s.[6] The rate of decline in fuel economy (in terms of CO_2/km) of new UK vehicles is so far insufficient to achieve the 2008 target of 140 g CO_2/km given in the EU agreement.[7] As of 2006, new car fuel economy stands at 167.7 g CO_2/km, which would imply an unrealistic annual reduction of around 14 g CO_2/km to reach the 2008 target. In

[6] Data for kilometres driven and for fuel efficiency of new cars (DfT, 2006, Table 2.8). Data on vehicle stock from DfT (2006).

[7] Other main policy measures to reduce the ratio of CO_2/km-driven include the fuel duty escalator (to 1999), the graduated vehicle excise duty (now based on CO_2 emissions from £0 for Band A to £220/yr for Band G), and the company car tax (now also based on CO_2 emissions). In addition, a renewables transport fuel obligation will be introduced from 2008 to 2009 for an annual increase of the proportion of fuels to be renewable (bio) fuels. The UK government assumes that the carbon emitted from burning biofuel is equal to the carbon absorbed by the atmosphere by the crop as it grows. Indirect CO_2 and other emissions may not fall, but increase, when vehicles are powered by biofuels.

2007 the UK's DfT had revised its fuel economy data so that it included 4×4s (SUV's) by fuel type, however, the data does not cover fuel economy on SUV's prior to 1997.

Fig. 4b depicts the evolution of on-road gasoline and diesel cars (using DfT data). The advantage in fuel economy of diesel versus that of gasoline cars is being narrowed (Fig. 4b). In older vehicles the gap was 43% (1995) but by 2006 it fell to 26%. This narrowing trend also reflects changes in new car CO_2/km of (Fig. 2a). UK DfT should report mileage of diesel cars to capture evolution of on-road fuel economy (the publication "Transport Statistics Great Britain" should include the split in mileage between gasoline and diesel cars).

5. Literature review on fuel economy and gasoline demand

The following list of studies on fuel economy is far from complete, readers can refer to Bonilla and Foxon (2007) who summarise a large number of fuel economy studies. Among the most prominent studies are the following ones. Three studies, which focus on the OECD region (Small-Van Dender, 2006; Zachariadis and Clerides, 2006; Johansson-Schipper, 1997), report widely different elasticities ranging from −0.01 to −0.6. The Johansson–Schipper study is the first study that examines on-road fuel economy for the OECD. An important study is by Baltagi and Griffin (1983), using various econometric estimators, who find wide price elasticity estimates ranging from −0.08 to −0.17 (lag distribution model) and −0.64 to −0.92 (various estimators). Baltagi and Griffin also find widely varying income elasticities: 0.61–0.84.

Many studies give typically wide variations of price elasticity of fuel economy because of differences in functional form, period of estimation and estimation technique. However, few studies on new car fuel economy, have used the error-correction (ECM) framework, which covers an entire vehicle market. Second, studies give inadequate attention to fuel economy and to models of fuel economy explicitly (Graham and Glaister, 2002). Third, unlike Witt (1997) and Greene (1990), who examine selected car makes, our model includes data on aggregate fuel economy. To our knowledge, most studies have not used the co-integration technique to estimate fuel economy of gasoline using short- and long-run models.

However, the co-integration methods, with or without ECM have been applied by (Bentzen, 1994; Samimi, 1995; Eltony and Al-Mutairi, 1995; Ramanathan, 1999) for the purpose of estimating gasoline demand. The Ramanathan and Bentzen studies use the ECM within a co-integration approach. The approach has also been applied in a vector ECM framework, for the analysis of energy consumption (Masih, 1997).

6. Overview of the two-stage error-correction model

In the main model, aggregate fuel economy (of all new cars) is estimated over the historical period on the basis of co-integrated equations to establish if there is a long-run relationship between macroeconomic variables and fuel economy. The ECM method, as reported in Alogoskoufis and Smith (1991), involves reparameterisation of dynamic linear regression models in terms of differences and levels.

Fuel economy equations, are specified in technological terms, but are integrated with behavioural (consumer demand for fuel economy, personal income) and institutional responses (voluntary emission reductions and other measures). Fuel economy is linked to the economic functions described below.

6.1. Estimating fuel economy of new cars in the UK

In this section we define our econometric model of new car fuel economy. The model is estimated using time-series data from 1978 to 2003 to capture the price and income elasticities of fuel economy for UK cars (see Appendix for data sources). Our models capture consumer preferences via purchases of higher or lower new car fuel economy, resulting from sales of larger or smaller vehicles.

We use the Engle and Granger, 1987 error-correction mechanism (ECM) model. The two-stage procedure that we use here is suggested by Hall (1986) and Engle and Granger (1987). The procedure involves a long-run and a short-run treatment of fuel economy. In this formulation, the residual of the long-run equation, for fuel economy, in Eq. (1) gives the ECM term. The ECM term is then used in the short-run Eq. (2) as an explanatory variable, with its coefficient representing the speed of adjustment towards the long-run trends. The long-run equation is given in levels and the short-run is defined in first differences. Eqs. (1) and (2) are applied to new car fuel economy of diesel engines.

The choice of explanatory variables of our model follows other studies.[8] The long-run fuel economy for diesel new vehicles is estimated using the following equations:

$$\ln FE_{i,t} = \beta_{0,i} + \beta_{1,i} \ln RPDI_t + \beta_{2,i} \ln PFU_{i,t-1} + \beta_{3,i} \ln STA_{i,t} + ECM_t \tag{1}$$

$$\begin{aligned}\Delta \ln FE_{i,t} = {} & b_1 + b_2 \Delta \ln(PFU_{i,t}) + b_3 \Delta \ln(FE_{i,t-1}) + b_4 \Delta \ln(RPDI_t) \\ & - \phi(\ln FE_{i,t-1} - \beta_0 - \beta_1 \ln RPDI_{t-1} - \beta_2 \ln PFU_{i,t-2} \\ & - \beta_3 STA_{t-1}) + \varepsilon_t \end{aligned} \tag{2}$$

where,

$$\Delta \ln(FE_{i,t}) = \ln FE_{i,t} - \ln FE_{i,t-1} \tag{3}$$

And the rest of X_k variables are transformed similarly,

$$\Delta \ln(X_{k\ t}) = \ln X_{k\ t} - \ln X_{k\ t-1} \tag{4}$$

where, Δ is the first differences of the natural logs; *FE* the fuel economy of new cohort of fuel i in year t. (l/100 km);[9] *RPDI* the real personal disposable income (000's £); $PFU_{i\ t}$ is the price of fuel i in year t (UK p./liter); *STA* the fuel economy standard (dummy variable); *ECM* the error-correction term; i the fuel type (diesel); ln the natural logarithms.

And coefficients,

ϕ = coefficient of the *ECM* or speed of adjustment of new car fuel economy;
$b_{3,i}$ = desired fuel economy from period t to period $t-1$;
b_i = coefficients to estimate;
ε_t = residual error;
$\beta_{1,i}$ = coefficients to estimate;
φ_{t-1} = coefficient for error-correction term with one year lag.

The dummy variable (*STA*) was set up as an interaction dummy variable for gasoline fuels. The dummy should capture if the Voluntary Agreement, introduced in 1995 to meet 140 g CO_2/km by 2008, reduced the ratio of litres of fuel consumed per km-driven. In (Eqs (1) and (2)) two dynamic effects were introduced: past fuel economy and past fuel prices. Because car manufacturers need time to adjust vehicle engines to a higher fuel economy, a term for past fuel price was introduced.

[8] Sterner and Dahl (1992); Small and Van Dender, 2006 and Zachariadis and Clerides (2006).

[9] Fuel economy data of new cars were registration weighted. The figure was obtained by grouping the models in the official new car fuel consumption list into 100 cc engine size bands (DfT, 2006, p. 48).

Hence, long-run fuel economy, with all variables in logs, was estimated as a function of real personal disposable income, a lagged gasoline price and a dummy variable. The time (observation) specific dummy must also capture the effects on new car fuel economy such as: (a) the ownership tax imposed annually since 1997 (based on six bands according to carbon emissions); and (b) the EU Voluntary Agreement on CO_2 emissions of cars. In (Eq. (1)) it is not possible to capture explicitly the changes in the mix of vehicles in the fleet (although new car fuel economy data should partly reflect such changes), nor is it possible to capture increases in weight of vehicles resulting from safety legislation.

The fuel economy variable was transformed by taking differences in annual data which allowed the model to capture the short-run response of the fuel economy. In Eq. (2) changes in fuel economy were spurred by changes in gasoline price, real personal disposable income and past fuel economy. Hence this model is dynamic. Eq. (2) uses the residuals from the long-run equation, ECM_{t-1}, which serves to force the short-run variations back to the long-term trend; this equation relates changes in fuel economy as a function of explanatory variables and a disequilibrium error captured by the *ECM* term. Values for *ECM* are estimated in the long-run Eq. (1). Eq. (2) shows the estimated ECM coefficient, ϕ, representing the speed of adjustment towards the long-run trends.

Eq. (2) can also be seen as a model using growth rates in the right and left hand variables following transformation of the variables.

6.2. Stationarity and co-integration tests

To establish if co-integration applies to models (1) and (2) tests were performed for unit roots and co-integration. Unit roots (using criterion of Dickey and Fuller (1981)) tests were performed for each series in (1) and (2) with a univariate basis for both fuels. Dickey and Fuller tests do not show stationarity for all variables in levels (hence unit roots are present). After first differencing, the same variables in Eq. (1), tests only show stationarity, $I(1)$, for the series of personal income (with and without a lag) while tests are indeterminate for the other variables. In the multivariate case, the Engle Granger ADF test was also performed on the residuals of Eq. (2). The Engle Granger, and the ADF test, show stationarity ($I(0)$) in the residuals of Eq. (2) with a significant *t*-statistic of −4.75 (at 8.1% probability). This test was performed on a model (with first differences and in natural logs) containing fuel economy, personal disposable income, past fuel price and past fuel economy and the *ECM* parameter, as in Eq. (2).[10]

Using the analogous variables the Engle Granger ADF test for diesel gave a *t*-statistic of 3.93 (significant at 15% probability level) without lags and a *t*-statistic of 2.64 (one lag). These tests were indeterminate in ascertaining stationarity. Single series tests were also weak for stationarity.

The β's of Eqs. (1) and (2) represent the elasticities of fuel economy with respect to the explanatory variables. The use of these equations allowed distinctions to be made between short- and long-run changes in fuel economy.

7. Results

In this section we present the results of our econometric model for gasoline (market average) fuel economy for the entire UK new car market. The values for the relevant coefficients can be taken as the short-run and long-run fuel price elasticity of fuel economy. Econometric results are tabulated in Tables 3 and 4, respectively. These results assume symmetric responses of fuel economy to price changes and to the other independent variables.

7.1. Fuel economy of diesel vehicles

In the long-run equation, in Eq. (1), the most significant and strongest effects on new car fuel economy are income and diesel price (estimate of −0.47; and −0.39 of Table 3). This means that consumers buy fuel economy in the long-run. Both coefficients show plausible ranges and both are highly statistically significant at more than 1% probability. The coefficient shows a low speed of adjustment showing that, in the first year, 5% of the adjustment occurred towards the long-run solution,

For consumers with higher incomes, it appears that fuel economy is negatively associated with income in the long-run; this effect is significant at less than 10% (Table 3). A 10% increase in income was linked to a 47% decrease in litres per 100 km of fuel economy. This indicated that higher incomes allow consumers, over time, to buy more fuel efficient vehicles. The opposite result, however, would be expected if consumers were to shift to larger cars: higher incomes increase consumption per kilometre as shown by the short-run model in Table 4.

Likewise price effects behaved similarly in the long-run (Table 3). The response of fuel economy was negative with an elasticity of −0.39: price increases improved fuel economy (less litres per km). This result shows that new car fuel economy reacts to the standard but by a small margin. Fuel economy movements respond mainly to the influence of income followed by fuel price and to a markedly less extent to the dummy.

There was also a small negative, and statistically significant, dummy effect (Voluntary Agreement) on fuel economy, in the long-run equation. The dummy coefficient should capture (in addition to the Voluntary Agreement) the graduated vehicle excise tax, and company car tax measures in the pre-1995 and post-1995 periods. In that model fuel economy improved as fuel prices increased and as the above policies were introduced. However, the effect of our dummy was much less than that of price.

One difficulty in gauging the effect of the dummy on fuel economy is that both price and the Voluntary Agreement appeared at the same time, in fact fuel prices began to increase around the middle of the 90s. Other events blurring the effect on fuel economy included shifts in consumer taste favouring larger vehicles.

In the short-run model (as in the long-run model, Table 4) the coefficient on price was smaller than that of income. This shows that price is a worse predictor of fuel economy in the short-run model. The coefficient on past fuel economy ($FE_{(t-1)}$), in first difference, was statistically insignificant and negative: past fuel economy decreases today's fuel economy (fewer litres per km). Gately (1990) (with an estimate of 0.78) and Small and Van Dender, 2006 (with an estimate of 0.81) report positive responses to past fuel economy. The short-run consumers do not buy fuel economy since they prefer larger and more powerful cars, this explains the positive income coefficient (Table 4).

Our estimated (long-run) price elasticities of fuel economy are within the range of values reported in the literature for the UK, OECD, US and other countries. One reason for our slightly higher elasticities (Tables 3 and 4) is that we use cost per litre of fuels while other authors, examining the US (Gately ,1990, Greene, 1990; Small-Van Dender, 2006), use cost per mile, to estimate

[10] Time-series processor (version 4) and Oxmetrics (version 4) were used to estimate Engle Granger tests and the ADF tests. Full results are available from authors.

Table 3
Long-run equation coefficients for fuel economy (diesel)[a].

Variable	Probability values (of *t*-ratios)	Estimated coefficients	Rsq. = 0.38 and Obs = 25
Intercept	0.001	9.93	
RPDI	0.005	−0.475	
PFU	0.029	−0.393	
STAN (dummy)	0.031	−0.183	

[a] Estimated using Oxmetrics V.4. Period of observation: 1978–2003.

Table 4
Short-run coefficients for co-integrating fuel economy equations[a] (gasoline).

Variable	Probability values: (of *t*-ratios)	Estimated coefficients	Rsq. = −0.10 and Obs = 25
Intercept	−0.111	−0.04	
RPDI	0.176	1.31	
PFU	0.704	−0.22	
FE(−1)	0.776	−0.10	
ECM(−1)	1	0.05	

[a] See Eqs. (1) and (2) for definitions of variables shown at the head of each row. All equations are estimated in Oxmetrics V.4. Period of observation: 1978–2003 with lag terms.

price effects on fuel economy.[11] Second, in comparison to other studies we examined more periods of considerable diesel price volatility. For instance, prices were volatile in the 1999–2003 period. Third in the case of income responses of fuel economy, unlike other studies, we included real personal disposable income instead of per capita income, the latter being commonly used to obtain income elasticity of fuel economy.

Dahl (1995, pp. 16) found an income elasticity of −0.21 (long-run) using evidence from eight studies and so our estimates were close to the consensus. The elasticities of new car fuel economy (diesel) lie in the range of those of diesel cars as Bonilla and Foxon (2007) found.

Our calculated long-run income elasticity (diesel with −0.47) values are above the range of international studies. The negative sign on income elasticity (Table 3) is confirmed by (Zachariadis and Clerides, 2006; Dahl, 1995; Small and Van Dender, 2006; Johansson and Schipper, 1997). The models give inelastic responses of fuel economy to price and income.[12]

Interestingly the short-run behaviour of fuel economy, in Eq. (2), shows the changes in the profile of car purchases in terms of higher or lower fuel economy. Such changes occur from year to year in the car market. However, the long-run behaviour, in Eq. (1), captures technological change in vehicle engines partly driven by price and income effects, since such changes require many years to emerge.

Models, for the long and short-run, show that fuel demand per kilometre-driven, of private vehicles, is price inelastic (Tables 3 and 4), implying that fuel consumption per km will fall less than proportionately to changes in fuel prices. One possible reason for this inelastic response to price is that once the fuel efficient technology is introduced fuel price sensitivity is diminished.

8. Conclusion

In the early 90s and in 2005 on-road fuel economy and that of new cars continues to significantly diverge wasting motor fuel. This gap has barely fallen in 2005. Among the reasons for this gap are driving at less than optimal speed, consumer choice for larger vehicles, fuel switching to diesel, increase in market share of larger and more powerful cars, among other reasons. On-road fuel economy in 2005 is not better than in 1988 (less litres per km). In 2005 the gap between on-road and new car fuel economy (gasoline) is 24% less fuel of new against fleet. In 1990 new cars consumed 15% less fuel than fleet. In contrast to actual fuel economy the new car fuel economy has improved but this improvement is insufficient for meeting the EU Voluntary Agreement of which the UK is signatory. In all likelihood the UK will fail to meet the targets of the agreement. As a result fuel demand will increase more than it needs to. The highly popular diesel cars increase mileage and thus national fuel consumption. A possible weakness of relying on diesel cars to meet the Voluntary Agreement is that diesel cars are driven more than gasoline ones.

Our models of fuel economy capture consumer preferences for higher or lower new car fuel economy. Average fuel economy of new cars was found to be (1) inversely linked to diesel price and incomes and (2) to be more sensitive to diesel price changes than to the introduction of the EU agreement. For diesel fuels, our models show that there is a long-run relationship among fuel economy, real fuel prices, real personal disposable income and the presence of the fuel economy standard. The long-run diesel equation, in contrast to the short-run, shows that consumers will buy fuel economy. Short-run responses, for gasoline show that at higher incomes, consumers will buy higher fuel intensity rather than fuel economy. Similarly, in the short-run, there is inertia between past fuel economy and current fuel economy for both fuels.

Interestingly the short-run model of fuel economy captures the changes in the profile of car purchases in terms of higher or lower fuel economy. While the long-run model captures technological change in vehicle engines partly driven by price and income effects, since such changes require many years to emerge.

Improvements in new car fuel economy and in the on-road fuel economy ultimately shape the evolution of energy consumption. How quickly the improvement occurs will depend on car sales and the rate of vehicle stock turnover, which depends on macro-economic conditions.

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[11] Our price elasticity estimates lie close to those (upper bound) of Johansson and Schipper, (1997) for fleet fuel economy using different data and technique, but lie in the range of Gately (1990). Our estimates are below those of Atkinson and Halvorsen (1984), Their data, however, is marked by high gasoline prices hence its high price response. Sweeney (1979) finds a lower price elasticity with data of 1957–1974, a period of largely low gasoline prices. Zachariadis and Clerides (2006) report slightly higher elasticities than our results. In a meta analysis a similar price response of fuel economy is found: Brons et al. (2007) estimate a fuel economy elasticity of 0.31 with respect to a change in fuel price using data on 43 primary studies with 312 elasticity observations.

[12] Please note that our estimated price and income elasticity are based on data from periods of high gasoline price (late 1970s early 1980s) and low gasoline price (early 1980s and 1990s), explaining our different estimates, compared to other literature. Our data set is largely dominated by the low energy price period.

Appendix

Data Sources

Most data are sourced from the UK's Department of Transport (DfT) publication *Transport Statistics Great Britain*. Data are also sourced from the Department of Trade and Industry's (DTI) website.

- Real personal disposable income
  1970:2004
  Cambridge Econometrics Ltd., Database
- Road transport energy use by vehicle type, split by Derv and petrol
  Table 2.6: road transport energy use by vehicle type, split by Derv and petrol, 1970–2003
  1970:2004
  Dft (NETCEN) 2005
  DTI website: DTI.gov.uk,
- Energy consumption of road transport (tonnes of oil equivalent)
  1970:2004
  Table 2.1: transport energy consumption by type of transport and fuel, 1970–2005
  DTI (2006)
- Final energy consumption (tonnes of oil equivalent)
  1970:2004
  Table 1.5: final energy consumption, by fuel, (1) 1970–2005
  DTI (2006)
- Emission factors of gasoline and diesel cars
  Defra website: www.defra.gov.uk
- Vehicle kilometres (billion per year)
  1970:2004
  DFt (2005), Transport Statistics Great Britain (2005), Traffic-data tables
  Table 7.1
- Vehicle stock
  1970:2004
  TSGB, Table 9.1: Motor vehicles currently licensed: 1950–2007
- Vehicle sales
  1995–2007 Table 11: cars licensed by propulsion type: 1998–2007. Vehicle licensing statistics, Transport statistics bulletin, 2005.
  The data for new car fuel economy (sales weighted) of both gasoline and diesel engines, and of diesel and of gasoline prices are sourced from:
  DfT's Transport Statistics Great Britain (TSGB, 2005, 2006, 2007). Data prior to 1994, for new vehicle fuel economy, was obtained from Mellor (1993). The data for fuel economy are sales (registration) weighted thus avoiding giving undue importance to diesel or gasoline cars in total car sales.
- Fuel economy (l/100 km) of new gasoline and diesel cars
  1970:2004
  TSGB, Table 2.8: fuel consumption factors for cars and lorries
  For 1978–1980 (see Mellor)
- Gasoline and diesel prices (Uk p./liter)
  1970–2004
  DTI website, Table 4.13: typical retail prices of petroleum products 1970–2005, Table: 4.1.3 (Department of Trade and Industry (DTI), Digest of United Kingdom Energy Statistics (DUKES)
  Prices are deflated using the Cambridge Econometrics database on GDP deflators.
- Population
  Eurostat website: http://epp.eurostat.ec.europa.eu
- Motor vehicle power
  Calculated using data from: Table 9.3: motor vehicles licensed at end of year: by tax class, body type and engine size: 1996–2006. TSGB, 2007

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