The quality rebound effect in transportation

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Abstract

Energy is needed in society to provide energy services. Reducing the energy to deliver these services is at the core of energy efficiency. Energy services have both a quantitative and qualitative value. In the case of transportation, the quantity of service can be expressed simply in passenger kilometres, whereas quality aspects are affected by several vehicle attributes such as size and performance as well as travel times and comfort.

Improving energy efficiency can stimulate consumers to travel more and thus consume a greater quantity of transportation. This phenomenon is known as the 'rebound' effect and has been well studied. Less studied are rebound effects in quality of service; how reductions in travel costs, due to fuel price changes and technical efficiency improvements, can stimulate people to increase the quality of transport, for example by purchasing a larger vehicle.

Consumers continue to buy larger and more powerful vehicles in many countries. These purchasing trends mean that technical improvements in vehicle fuel consumption are undermined by shifts to larger vehicle segments. New hybrid and electric powertrains entering the market promise large improvements in fuel consumption. However, if these efficiency improvements stimulate shifts to even larger vehicles through quality rebound effects, the full potential energy savings may not materialise. Understanding and quantifying these quality rebound effects is therefore of paramount importance for energy modellers and policy makers.

This paper uses a unique dataset of vehicle sales in the UK between 2001 and 2017, to investigate the effects of fuel price, income and technical improvements on stimulating a shift to larger and more powerful vehicles. Econometric regression techniques are used to show increasing income and the growing share of diesel and hybrid powertrains partially explain the shift to large vehicles. This suggests vehicle taxes in larger segments have not been sufficiently high and need to be rectified.

Introduction

Reducing the demand for energy is key to reaching current climate targets and the transportation sector has one of the largest potentials to save energy (International Energy Agency 2018). Energy demand is driven by energy services such as mobility, thermal comfort or illumination, reducing energy demand can be achieved either through reducing the quantity of service required or by providing the service in a more energy efficient manner (Cullen & Allwood 2010).

Vehicle choice plays an important role in determining the energy used to deliver the transportation service. Consumers generally base their choices on the perceived quality of transport modes. The service quality of transport is partially dependent upon the attributes of vehicles used. These quality attributes desired by consumers are numerous and range from the easily quantifiable such as performance (measured in terms of power, torque, acceleration, top speed), size (measured as volume or mass), added features (four wheel drive, air conditioning, satnav etc.), to harder to quantify attributes such as aesthetics, social status (potentially quantifiable by cost or brand), comfort and others. The service quality of transport also includes factors that are exogenous to individual vehicle attributes and dependent upon the transport system as a whole, such as time to arrive from A to B (average speed per trip), punctuality and cost, to name a few. Whilst all of these factors affect vehicle choice or mode of transportation, only vehicle attributes are investigated in this study.

Fuel consumption/fuel economy is poor measures of real efficiency improvements. Vehicle fuel consumption can be improved with *technical efficiency improvements* such as light weighting, improved combustion, lubrication and aerodynamics. However, fuel consumption can also be negatively impacted by improving the perceived service quality of transportation via increases in vehicle size, performance and number of in-car accessories such as air conditioning and satnav. Increasing the power of a vehicle generally worsens the fuel consumption, as does increasing the size or the number of added features, which can increase mass (OECD/IEA 2017). Engineering technical efficiency improvements in vehicles can generally be used either to improve fuel consumption or to improve the perceived quality attributes of vehicles such as size and power.

Reducing fuel consumption, whilst beneficial for reducing emissions, can have unintended consequences. A well-studied case is the rebound effect, whereby efficiency improvements reduce the marginal cost of travel, stimulating consumers towards a greater quantity of travel. Fluctuating fuel prices can also cause similar rebound effects, increasing distance travelled when marginal travel costs are reduced (Sorrell et al. 2009). A large number of studies have sought to determine the relative magnitudes of these fuel price and fuel efficiency rebound effects and compare them to increases in quantity of travel spurred by increasing incomes (Dimitropoulos et al. 2016).

Considerably less studied are the effects that fuel efficiency improvements, changes in fuel price and other drivers can have on stimulating increases in vehicle quality attributes. This is important to understand, as the energy savings possible due to technical efficiency improvements may not be realised if they are offset by a shift to higher service quality with greater fuel consumption. This effect is defined here as the *Quality Rebound Effect* to distinguish it from the effect of marginal travel cost reductions on distance travelled, which will be dubbed the *Quantity Rebound Effect*.

It is particularly important to understand the quality rebound effect in light of the rapid penetration of new powertrains and vehicle technologies that have the *potential* to greatly improve fuel consumption, but may instead be used to offset `improvements' in size and acceleration.

To quantify the effect of fuel price changes and efficiency improvements on service quality requires quantifying quality in a single metric. Intuitively, quality is a function of vehicle attributes such as size and power. How can these be reconciled into a single unit? Two options seem the most appealing. The first might be looking at cost, and quantifying consumers' willingness to pay for each attribute. However, the willingness to pay for vehicle attributes is likely subjective to each driver. Similarly, the price that manufacturers charge for a given attribute may change over time. This makes quantifying quality in terms of costs problematic. An alternative is to find the effect of various vehicle attributes on fuel consumption and therefore quantify quality as lost potential improvements in fuel consumption.

Literature Review

Goerlich & Wirl 2012 introduced much of the econometric foundations of the quality rebound effect though their analysis remained mostly qualitative. Other authors have looked at various effects of fuel economy and fuel prices on individual vehicle attributes. Ajanovic et al. 2012 look at the lost energy savings from increases in vehicle power. They use top down national statistics rather than data at vehicle model level and correlate the average trend in power with that of fuel consumption. Doing so at the aggregate level, rather than at the vehicle model level, risks omitting important explanatory variables (such as vehicle type and size) and missing underlying trends (such as shifts in vehicle segments and powertrain types).

Several authors have sought to decompose changes in fuel consumption into technical efficiency improvements and the effect of changes in various vehicle attributes. These technical improvements are quantified in terms of the hypothetical fuel consumption that vehicles could have attained had a number of vehicle attributes remained constant from a past year. The difference between this hypothetical fuel consumption and the real observed trend can be thought of as the effect that changes in vehicle service quality had on fuel consumption.

This approach uses regression models to explain the variance in fuel consumption of vehicles available for sale each year using a selection of vehicle attributes. Year fixed effects are used to quantify annual improvements in fuel consumption, independent of vehicle attributes such as size and power. This approach tends to use a regression model of the following form:

$$\ln(FC)_{it} = T_t + \beta \ln(X_{it}) + \epsilon_{it} \quad (1)$$

Where *FC* is the observed fuel consumption of vehicle *i* in year *t*, *T* are year fixed effects/dummy variables which take the value of 1 in year t and 0 otherwise, *X* is a vector of vehicle attributes such as power, size, weight etc., β is a vector of their respective regression coefficients and ε is an error term.

Knittel (2011) and MacKenzie & Heywood (2015) used this technique and focussed on passenger cars in the USA between 1980–2006 and 1975–2009 respectively. Together they showed that rates of technical efficiency improvement had not been linear over time in the USA and that manufacturers placed a higher emphasis on reducing fuel consumption in times of high oil price.

The studies by *Knittel* and *Mackenzie & Heywood* focussed on comparing the hypothetical fuel consumption had all vehicle attributes remained constant, to the average fuel consumption of models *available for sale*. This neglects the effect of shifts in vehicle sales. If the type of vehicles on the market remains similar, yet vehicle sales shift to larger cars (as has been the case in almost all countries (OECD/IEA 2017)) increases in vehicle 'quality' will have been considerably more than the average of vehicles available for sale might indicate.

Matas et al. (2017) followed the same methodology used by *Knittel* yet also sales weighted results. Their analysis focussed on Spain for years 1988 to 2013. The authors again used the regression results to disaggregate between technical improvements and vehicle attribute improvements, this time accounting for sales, and then correlated the changes in quality with national GDP and fuel prices. This elasticity of sales-weighted vehicle attribute changes with respect to fuel prices seems to be the closest quantification of the quality rebound effect to date. The authors found that a 1 % increase in fuel price is likely to lead to a decrease in vehicle quality such that fuel consumption improves by 0.02 %[1]. Similarly, a 1 % increase in GDP will result in an increase in fuel consumption of ~0.23 % for petrol cars and 0.35 % for diesel cars due to vehicle quality increases[2].

Other notable improvements made by *Matas et al.* include adequately treating petrol and diesel vehicles separately. If the two different technologies have fundamentally different regression coefficients, then grouping them together in one regression can lead to a misleading model. It also makes it difficult to distinguish between technical improvements and shifts in sales to more efficient powertrains. In Europe, diesel powertrain sales are quickly dropping which may result in real technical improvements being masked by the shift back to petrol engines.

The coefficients for hybrids and electric vehicles are likely to be even more different to conventional engines due to regenerative braking. This reduces the importance of weight on fuel consumption as inertia losses from braking can be recouped by charging the battery. This means each powertrain ought to be treated in separate regression models. However, this subtly changes the questions that can be answered with the results. Instead of answering the question ‘to what degree have technical efficiency improvements been spent on vehicle quality improvements rather than improving fuel consumption?’ the question can only be answered for each powertrain type individually.

This study follows a similar methodology to *Matas et al.* and investigates whether fuel price or income changes produced quality rebound effects. However, unlike *Matas et al.* which used a limited number of vehicle models each year in the Spanish market (~300/year) this study uses the full spectrum of new vehicles available each year (5,400/year) and focusses on Great Britain between years 2001 to 2017 due to the availability of data. The period of study covered is particularly significant as it covers the growth and subsequent decline in market share of diesel powertrain vehicles allowing for an insight into how a more efficient technology may have stimulated consumers to buy larger and more powerful vehicles over the time period. In addition to looking at petrol and diesel vehicles separately, this study also investigates technical improvements in hybrid vehicles for the first time. Previous studies were not recent enough to capture these important changes.

Methods

This study quantitatively investigates the underlying drivers effecting sales of larger and more powerful vehicles in Great Britain over the 2001–2017 period. The dataset used in the regression models is built from several sources and matched together.

DATA

The unbalanced panel dataset used in this paper is created by matching vehicle sales data to other information on vehicle technical characteristics. Vehicle sales data is sourced from the *UK Department for Transport* (DfT) (UK Department for Transport 2018). This provides annual new registration data at manufacturer and detailed model level (including some trim level characteristics) for vehicles in Great Britain between years 2001 and 2017[3]. Using regular expressions, the fuel type, transmission type (Manual/Automatic) and some entries of engine power, turbo-charging and driven wheels could be extracted for each model. Other technical details on each vehicle are relatively limited in this dataset with no information on engine capacity, vehicle mass, fuel consumption or dimensions. To add these variables, data from the European Environment Agency (EEA 2018) is used to supplement vehicle technical data for years 2010–17.

To find the remaining fuel consumption values and engine size of vehicles, data from the *UK Vehicle Certification Agency* (VCA) (UK Vehicle Certification Agency 2018) is used. Since vehicle model names are different in this dataset to the DfT data, fuzzy matching algorithms are used to find the best match for each vehicle. Vehicles are screened by manufacturer, fuel type and any other known technical details such as engine capacity, hybridisation, turbocharging, driven wheels and transmission before being given a score based on the similarity of model names. If the score is above a user-defined threshold, the best match is selected. All matches are manually screened for errors.

Further missing information on variables such as weight and engine power is supplemented with publicly available online technical datasets (www.carfolio.com 2017) using the fuzzy matching algorithms. The use of matching scripts allowed for a larger number of vehicle models to be analysed compared with previous work. High-level trends are compared to external sources for validation (OECD/IEA 2017; SMMT 2018).

Vehicles are then grouped into size segments with the aid of clustering and classification algorithms based on vehicle dimensions and body types. These allowed vehicles to be grouped into one of seven segments: City Car, Medium Car, Small Sedan, Large Sedan, SUV/MPV (Sports Utility Vehicle/Multiple Passenger Vehicle), Sports and Small SUV (further details in the appendix). The fuel consumption of each vehicle is expressed as Litres/100 km tested over the NEDC combined cycle and converted to gasoline equivalent for all vehicles.

Fuel price data for the UK (inclusive of excise taxes) is sourced from the IEA energy prices and taxes database (IEA 2018). These prices are deflated using a consumer price index sourced from the OECD (OECD 2018). Data on real household income is sourced from the Institute for Fiscal Studies and is quoted as median income after housing costs (IFS 2018).

Discussion

This section will initially introduce trends in the British vehicle market between 2001 and 2017 before presenting two sets of regression model results. The first aims to disaggregate trends in fuel consumption into technical efficiency improvements and quality improvements, the second regresses technical efficiency improvements, fuel price and income changes with the quality improvements to see test for correlations.

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[1] Though the results were only significant for petrol cars at the 10 % level and were not significant for diesel.

[2] Results with GDP were significant at the 1 % level.

[3] Vehicles are screened to only include M1 type vehicles (cars) and remove N1 vehicles (vans, caravans etc.).

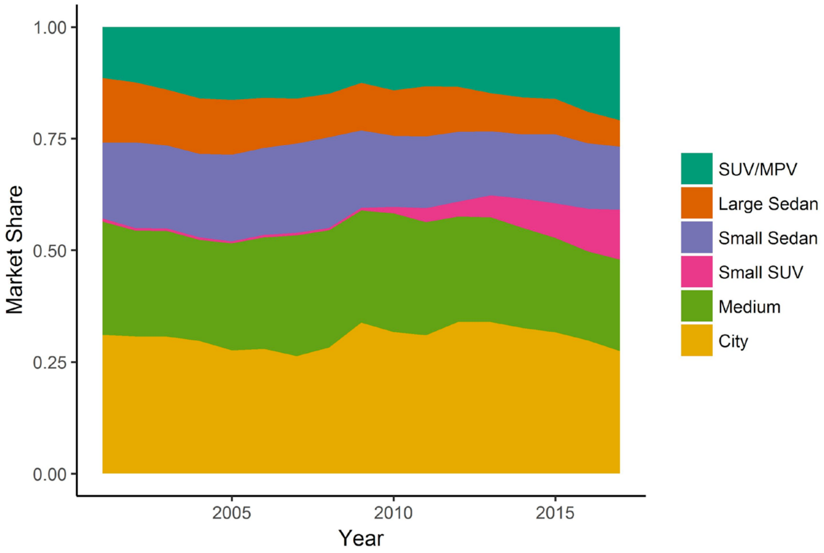

Figure 1. Trends in British vehicle size segment market share 2001–2017. Sports segment not shown purely for visualization purposes.

TRENDS IN THE BRITISH VEHICLE MARKET 2001–2017

Figure 1 shows the market shares of different size segments in the British market. In the years before the financial crisis of 2008/9 City and Medium cars accounted for over half of the British market though their market share was dropping steadily in favour of SUV/MPV segment and Small sedans. The shock of the financial crisis caused the total number of registrations to drop precipitously between 2008 and 2011. Sales suffered in particular in the larger vehicle segments meaning smaller segments increased as a share of the total. However, since the financial crisis the share of smaller vehicles has again begun to drop, partly due to the high popularity of the small SUV segment. Figure 1 suggests that since 2001, SUV/MPV type vehicles took market share from large sedans, while small SUVs acquired market share from the city and medium car segments.

Figure 2 (left) shows the sales-weighted fuel consumption of each segment over the period. Whilst the fuel consumption of all segments has been improving over time, the shifts in sales to the larger segments, which have higher fuel consumption, has reduced the potential of these energy efficiency improvements. Figure 2 (right) shows the share of diesel powertrains in each size segment. Diesel powertrains saw rapid uptake between 2001 and 2012, particularly in larger size segments. This stimulated improvements in segment average fuel consumption. However, after the diesel gate scandal in 2015 (US EPA 2015) the share of diesel powertrains in each segment has dropped significantly. This reduced the rates of improvements in fuel consumption and actually led to a worsening between years 2016 and 17 as consumers reverted to less efficient gasoline vehicles.

Figure 3 (left) shows the relative fuel consumption of each segment compared to the Medium car segment. This shows that the gap between the fuel consumption of larger segments and the Medium segment has been decreasing over time. This is mostly due to larger share of diesel powertrains in larger vehicles, which helped to reduce their fuel consumption. However, it is possible that it may also have stimulated consumers to buy more of the larger vehicles. If that is the case then a portion of the technical efficiency benefits of diesel vehicles was spent on increasing the size of vehicles rather than reducing their fuel consumption.

Figure 3 (right) shows that, with the exception of the small SUV segment (which had a low market presence before 2010), the power of all segments has continued to increase over time clearly showing that quality attributes continue to increase at the expense of fuel consumption. It can also be seen that the drop in diesel share since 2015 has not been met with a drop in power or share of large vehicles. This suggests that once technical improvements stimulate shifts to larger cars they may not be as easily reversible.

QUANTIFYING TRENDS IN TECHNICAL EFFICIENCY AND QUALITY IMPROVEMENTS

This section presents the results of the regression models used to disaggregate changes in fuel consumption into technical efficiency improvements and trends in vehicle quality. Table 1 shows the regression coefficients on models run separately by powertrain type for petrol, diesel and hybrid vehicles. The coefficients on the power and vehicle frontal area (the product of vehicle height and width) variables can be interpreted as the percentage change in vehicle fuel consumption that would be induced by a 1 % increase in any of these three variables. The coefficients on all other categorical variables (e.g. transmission manual vs. automatic) represent the change in log fuel consumption associated with each parameter.

Results on hybrid vehicles are presented for the first time, though the year fixed effects only become statistically significant from the year 2008 onwards due to the small number of models in preceding years. Although other powertrain types such as battery electric vehicles and plug-in hybrids are present in the UK database of vehicles, they are currently only present in a small number of models and sales and could not deliver statistically significant results.

The regression coefficients are quite different between petrol, diesel and hybrid powertrain vehicles suggesting split regression models are indeed needed. Coefficients are broadly of similar size to past estimates though true comparisons can only be made between models using the same explanatory variables. However, the variance explained by the dependent variables (R^2 coefficients) is lower than in the studies by *Matas et al.* and

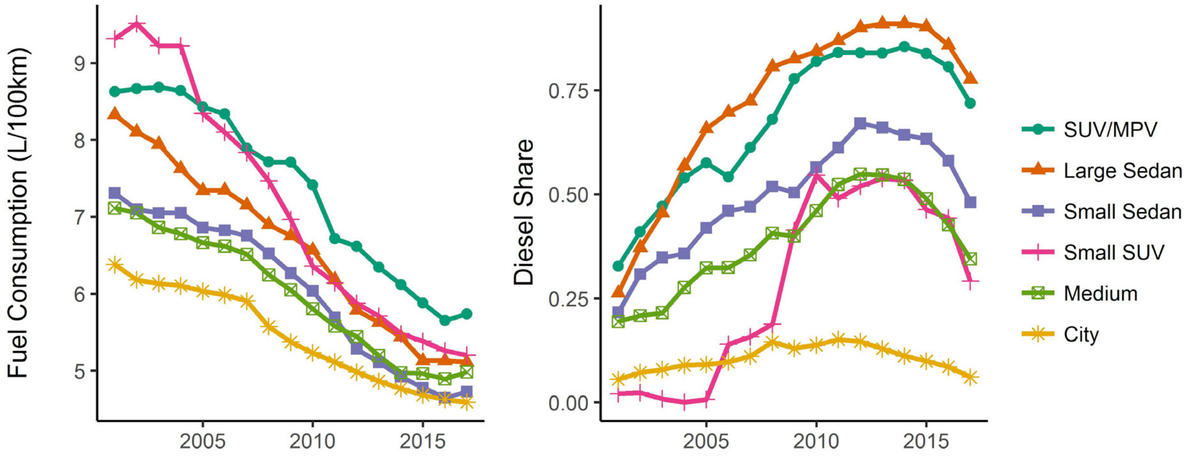

Figure 2. Trends in sales weighted, type-approval fuel consumption (NEDC) (left) and diesel shares (right) of British vehicles 2001–2017 by size segment. Sports segment not shown purely for visualization purposes.

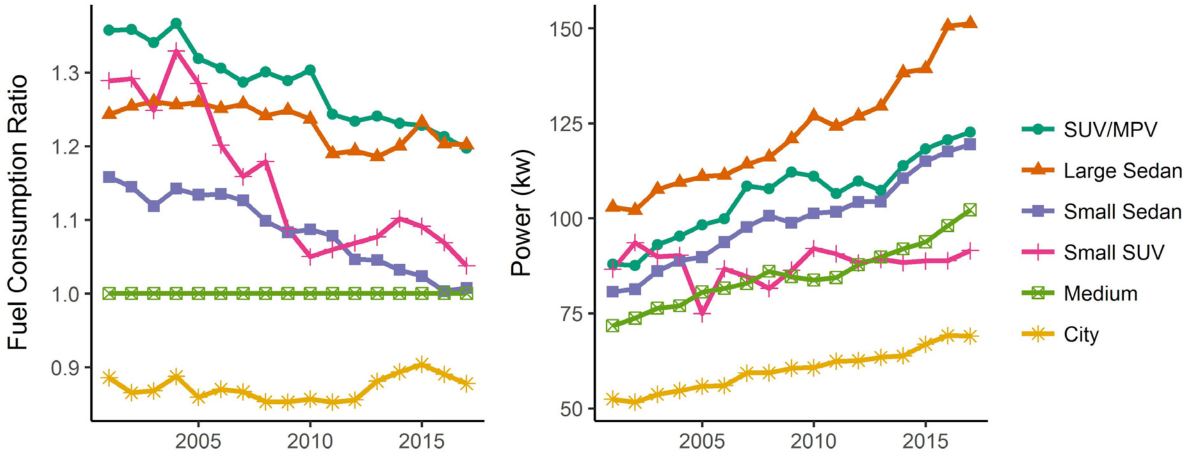

Figure 3. Relative fuel consumption Ratio of segment fuel consumption to Medium segment, e.g. $(L/100\ km)_{SUV/MPV}/(L/100\ km)_{Medium}$ (not sales weighted) (left) and sales weighted power (right) of British vehicles 2001–2017 by size segment. Sports segment not shown purely for visualization purposes. The high volatility of the small SUV segment is due to the low number of models and sales before 2010.

Mackenzie & Heywood. This is likely due to two factors. The first is that the present study uses a larger number of vehicles than previous studies, thereby including the full spectrum of vehicle designs; vehicles with high residual fuel consumption not explained by the model are found to have atypical designs (e.g. the Land Rover Defender, which has unusually low power for its size and mass). The second is that the year fixed effects is based on vehicle sales year (like that of *Matas et al.*) rather than vehicle model year (like that of *Knittel* and *Mackenzie & Heywood*).

The regression models presented in Table 1 aim to isolate all vehicle attribute effects on fuel consumption and thereby leave the effects of technical efficiency improvements in the year fixed effects (Table 4 in Annex). Using these fixed effects, the hypothetical fuel consumption had vehicle attributes remained constant at 2001 levels can be quantified. Figure 4 presents' trends in sales weighted fuel consumption for each type of powertrain as well as the expected fuel consumption had vehicle attributes (such as power and size) remained constant at 2001 levels.

Results suggest that the majority of technical improvements in petrol-powered vehicles have translated into fuel consumption improvements. In particular, quality improvements were lowest at the height of the financial crisis in 2009 when new vehicle sales dropped sharply, particularly in the larger vehicle segments (Figure 1). This reduced average vehicle size and power thus reducing the gap between sales weighted fuel consumption and the hypothetical fuel consumption had vehicle attributes remained at 2001 levels. Over the period studied, Petrol vehicles could have improved by 38 % if vehicle power and size had not changed. Instead petrol vehicles improved by 29 %.

The lost potential technical efficiency improvements for diesel-powered vehicles were even larger. Diesel cars could have theoretically improved fuel consumption by 41 % had vehicle attributes not increased. Instead, vehicle attribute changes

Table 1. Regression results, dependent variable is log type-approval fuel consumption (Litres of gasoline equivalent/100 km), standard errors for each coefficient are included in parentheses. Each model also includes year fixed effects which are presented in the end notes.

	Petrol	Diesel	Hybrids
(Intercept)	-5.18 (0.139)***	-9.641 (0.177)***	-4.321 (2.057)*
log(kw)	0.375 (0.002)***	0.309 (0.003)***	0.437 (0.014)***
log(Area)	0.382 (0.009)***	0.693 (0.012)***	0.297 (0.14)*
SUV/MPV	0.09 (0.003)***	0.085 (0.004)***	-0.131 (0.036)***
Large Sedan	0.045 (0.002)***	0.031 (0.003)***	-0.101 (0.021)***
Small Sedan	0.013 (0.002)***	0.009 (0.003)**	-0.155 (0.015)***
Small SUV	0.066 (0.003)***	0.078 (0.004)***	-0.126 (0.061)*
Medium	0.022 (0.002)***	-0.005 (0.003)	-0.024 (0.019)
Sports	0.195 (0.004)***	-0.071 (0.001)***	
Manual	-0.03 (0.001)***		
AWD	0.04 (0.002)***	0.06 (0.002)***	0.092 (0.039)*
Turbo	-0.068 (0.001)***		
R^2	0.852	0.78	0.847
R^2adj	0.852	0.78	0.842
Observations	46,368	34,172	705

*Statistical significance of t-tests: * p<0.05, ** p<0.01, *** p<0.001.*

meant that fuel consumption only improved by 23 % between 2001 and 2017.

The results are similar for hybrid powertrain vehicles (though the year fixed effects are only significant after 2008). Before 2007, the majority of hybrid powertrain models available on the market were small sedans (e.g. Toyota Prius). From 2008 onwards, a larger number of SUVs (e.g. Lexus RX 450h) and large sedans entered the market (with higher vehicle attributes) pushing up sales weighted fuel consumption. The regression model suggests that had vehicle attributes remained constant at 2001 levels (similar to a Toyota Prius), the fuel consumption of hybrid vehicles could have been 3.0 L/100 km rather than today's average of 3.9 L/100 km. Hybrids could therefore have improved by 41 %, instead they improved by just 22 %.

A greater share of potential efficiency improvements were lost in diesel and hybrid vehicles than petrol vehicles due to larger relative increases in size and power. This is because the shifts away from petrol powertrains occurred mostly in the larger size segments. Having discussed the scale of the lost technical efficiency improvements across each powertrain, the next question is how much of these increases in vehicle size and weight were stimulated by efficiency improvements in vehicles? This is the quality rebound effect.

Table 2 presents results of various simple regression models investigating the determinants of changes in vehicle quality. These look at how different combinations of fuel price, median national income and technical efficiency improvements might have stimulated the shifts to larger vehicles. The dependent variable here is an index of quality improvement relative to 2001 levels. Petrol and Diesel vehicles are investigated separately and hybrids are excluded in this analysis, as not all of the year fixed effects was statistically significant.

Fuel price is not statistically significant in any of the regression models on petrol vehicles and only slightly significant for diesel powertrains (and small in magnitude) meaning there is little evidence over the time period that consumers based purchasing decisions on the price of fuel at the pump. This may be due to the short time period investigated, the highly volatile fuel price over recent years, or that consumers simply are myopic with respect to fuel price. Models 1 and 3 suggest income is positively correlated with increasing vehicle quality. These results suggest that for every 1 % increase in income, average fuel consumption would worsen by between 0.24–0.38 % for petrol cars and 0.57–0.68 % for diesel vehicles. However, median British income increased relatively smoothly over the period investigated without any sharp changes that might test this correlation further meaning these findings remain premature.

Finally, to test for the quality rebound effect, Models 1 and 2 show that technical efficiency improvements may be loosely correlated with increasing vehicle. These results would suggest that for every 1 % improvement in technical efficiency, approximately 0.1 % is lost to increasing vehicle attributes.

Conclusions and Recommendations

This paper investigated how technical efficiency improvements and fuel price changes may stimulate consumer trends towards larger and more powerful vehicles. Initial evidence suggests that the growth from 2001 in diesel powertrains, which offered significant technical efficiency improvements over conventional petrol engines, stimulated a shift to larger and more powerful vehicles. Similar trends were observed in later years for hybrid powertrain vehicles, though the relatively low numbers of vehicles mean the results remain preliminary and a longer time series would strengthen these conclusions.

Had vehicle attributes in diesel and hybrid vehicles not increased, fuel consumption could have theoretically improved by 41 % in both cases. Instead, vehicle attribute changes in both types powertrain meant that fuel consumption only improved by approximately 22–23 %. Interestingly, the drop in diesel powertrain share after 2015 was not met with a similar drop in average vehicle size or power suggesting a certain degree of hysteresis in consumer trends. These results suggest that vehicle taxes in larger segments have not been sufficiently high to maximise efficiency improvements by dissuading shifts to larger vehicles. These are particularly necessary when new, more efficient powertrains are introduced into the market to maximise the potential efficiency improvements.

Regression models to investigate the drivers of increases in vehicle size and power show tentative evidence that increasing income is associated with higher size and power of vehicles. Findings also suggest that increasing technical improvements in vehicles have also stimulated consumers to purchase larger vehicles. However, models showed no evidence that fluctuations in fuel prices had significant impacts on vehicle attributes over the time period studied. Further work is needed to verify this finding which may only be true at the aggregate national level. Future work will also investigate the growing difference between real world fuel consumption and the type-approval values used in this initial research in order to gain a more realistic measure of technical efficiency improvements and the lost potential due to increasing vehicle size and power.

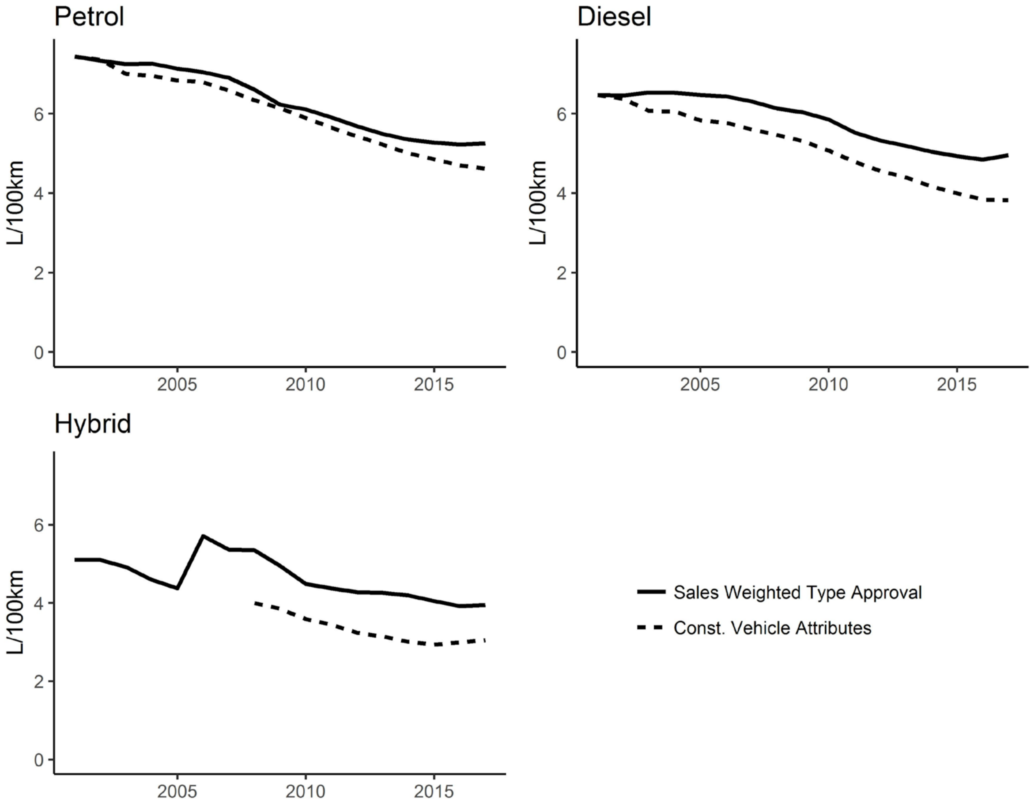

Figure 4. Sales weighted fuel consumption and hypothetical fuel consumption if power, size and other vehicle attributes had remained constant at 2001 levels. Results are presented where year fixed effects are statistically significant for Petrol, Diesel and Hybrid vehicles separately.

Table 2. Regression results, dependent variable is quality index composed from technical improvements and sales weighted fuel consumption, standards errors for each coefficient are included in parentheses.

	Petrol			**Diesel**		
	Model 1	Model 2	Model 3	Model 1	Model 2	Model 3
(Intercept)	-1.4 (0.44)**	0.02 (0.01)**	-2.22 (0.4)***	-3.33 (0.42)***	0.04 (0.01)**	-3.98 (0.36)***
log(Income)	0.24 (0.07)**		0.38 (0.07)***	0.57 (0.07)***		0.68 (0.06)***
log(FuelPrice)	-0.03 (0.02)	-0.03 (0.03)	-0.01 (0.03)	0.05 (0.02)*	0.06 (0.05)	0.06 (0.02)*
log(Tech_ index)	-0.07 (0.02)*	-0.12 (0.02)***		-0.05 (0.02)*	-0.15 (0.03)***	
R2	0.824	0.683	0.719	0.949	0.701	0.929
R2adj	0.784	0.638	0.679	0.937	0.658	0.919
Observations	17	17	17	17	17	17

*Statistical significance of t-tests: * $p<0.05$, ** $p<0.01$, *** $p<0.001$.*

References

Ajanovic, A., Dahl, C. & Schipper, L., 2012. Modelling Transport (Energy) Demand and Policies – an introduction. *Energy Policy*, 41.

Cullen, J.M. & Allwood, J.M., 2010. The efficient use of energy: Tracing the global flow of energy from fuel to service. *Energy Policy*, 38 (1), pp.75–81. Available at: http://dx.doi.org/10.1016/j.enpol.2009.08.054.

Dimitropoulos, A., Oueslati, W. & Sintek, C., 2016. The Rebound Effect in Road Transport, (113).

EEA, 2018. Monitoring of CO_2 emissions from passenger cars – Regulation (EC) No 443/2009.

Goerlich, R. & Wirl, F., 2012. Interdependencies between transport fuel demand, efficiency and quality: An application to Austria. *Energy Policy*, 41, pp. 47–58. Available at: http://dx.doi.org/10.1016/j.enpol.2010.10.015.

IEA, 2018. Energy Price and Taxes.

IFS, 2018. Living Standards, Inequality and Poverty. *UK Institute for Fiscal Studies*.

International Energy Agency, 2018. *World Energy Outlook 2018*, OECD. Available at: https://www.oecd-ilibrary.org/energy/world-energy-outlook-2018_weo-2018-en [Accessed December 13, 2018].

Knittel, B.C.R., 2011. Automobiles on Steroids : Product Attribute Trade-Offs and Technological Progress in the Automobile Sector. *The American Economic Review*, 101 (7), pp. 3368–3399.

MacKenzie, D. & Heywood, J.B., 2015. Quantifying efficiency technology improvements in U.S. cars from 1975–2009. *Applied Energy*, 157 (2015), pp. 918–928. Available at: http://dx.doi.org/10.1016/j.apenergy.2014.12.083.

Matas, A., Raymond, J.L. & Dominguez, A., 2017. Changes in fuel economy: An analysis of the Spanish car market. *Transportation Research Part D: Transport and Environment*, 55, pp. 175–201. Available at: http://dx.doi.org/10.1016/j.trd.2017.06.025.

OECD/IEA, 2017. International Comparison of Light-duty Vehicle Fuel Economy 2005–2015 Ten years of fuel economy benchmarking. *IEA Publications*. Available at: http://www.iea.org/publications/freepublications/publication/wp15ldvcomparison.pdf.

OECD, 2018. Consumer Price Indicies Database. Available at: https://stats.oecd.org/Index.aspx?DataSetCode=PRICES_CPI.

SMMT, 2018. New Car CO2 Report 2018,

Sorrell, S., Dimitropoulos, J. & Sommerville, M., 2009. Empirical estimates of the direct rebound effect: A review. *Energy Policy*, 37(4), pp.1356–1371.

UK Department for Transport, 2018. Table VEH0160: Vehicles registered for the first time by make and model. *Vehicles Statistics*.

UK Vehicle Certification Agency, 2018. Car fuel and emissions information.

US EPA, 2015. Notice of Violation on Clean Air Act to Volkswagen AG Sep 18, p. 6.

www.carfolio.com, 2017. Vehicle Technical Specification Database.

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Annex

SEGMENTATION DETAILS

Vehicles from a single reference year (2013 was chosen) are segmented into size segments with the aid of clustering algorithms based on vehicle dimensions. These vehicles are split into one of six segments shown in Table 3. Next, the vehicle models are given a model group (e.g. from VW GOLF TSI AUTO to VW GOLF) and the segment that each model group pertains to is used to fill in other years of data (e.g. a BMW 3 series in 2013 is allocated to the small sedan segment, this is used to match a BMW 3 series in year 2001 to the small sedan segment even though it's dimensions may be different to the 2013 version). Any models in a certain year without a segment are allocated one using classification trees on dimensions of vehicles in the same year (e.g. the Rover 25 wasn't sold in 2013 so a model in 2001 wasn't given a segment, however it has similar dimensions to a BMW 3 series in the year 2001 so could be classified into the small sedan segment). Each model group is only allocated to one segment for all years and all model variants (e.g. a BMW 3 series will always be a small sedan in all years).

Table 3. Vehicle size segmentation. Models are classified based on dimensions each year using clustering algorithms.

Size Segment	Example models
City Car	Smart, Skoda Citigo, Audi A1
Medium Car	Ford Focus, BMW 1 series, Audi A3
Crossover	BMW X1, Mini Countryman, Suzuki SW4
Small Sedan	BMW 3 series, Mercedes C class, Audi A4
Large Sedan	Audi A6, BMW 5 series, Mercedes E class
SUV/MPV	BMW X3/X5, VW Sharan, Audi Q7
Sports	Ferrari, Lamborghini

FURTHER REGRESSION RESULTS (YEAR FIXED EFFECTS)

Table 4. Year fixed effect coefficients and standard errors in parentheses.

Year fixed effects

	Petrol	Diesel	Hybrid
(Intercept)	-5.18 (0.139)***	-9.641 (0.177)***	-4.321 (2.057)*
Year 2002	-0.011 (0.003)***	-0.015 (0.006)**	0 (0.14)
Year 2003	-0.061 (0.003)***	-0.064 (0.005)***	-0.152 (0.107)
Year 2004	-0.067 (0.003)***	-0.067 (0.005)***	-0.235 (0.106)
Year 2005	-0.084 (0.003)***	-0.104 (0.005)***	-0.286 (0.109)
Year 2006	-0.091 (0.003)***	-0.114 (0.005)***	-0.211 (0.111)
Year 2007	-0.122 (0.003)***	-0.145 (0.005)***	-0.205 (0.106)
Year 2008	-0.16 (0.003)***	-0.17 (0.005)***	-0.245 (0.104)*
Year 2009	-0.192 (0.003)***	-0.197 (0.005)***	-0.281 (0.102)**
Year 2010	-0.233 (0.003)***	-0.243 (0.005)***	-0.352 (0.101)***
Year 2011	-0.276 (0.003)***	-0.3 (0.005)***	-0.393 (0.101)***
Year 2012	-0.315 (0.003)***	-0.35 (0.005)***	-0.454 (0.101)***
Year 2013	-0.355 (0.003)***	-0.387 (0.005)***	-0.486 (0.101)***
Year 2014	-0.396 (0.003)***	-0.439 (0.005)***	-0.53 (0.1)***
Year 2015	-0.428 (0.003)***	-0.483 (0.005)***	-0.553 (0.1)***
Year 2016	-0.459 (0.003)***	-0.522 (0.005)***	-0.534 (0.1)***
Year 2017	-0.477 (0.003)***	-0.526 (0.005)***	-0.515 (0.1)***

*Statistical significance of t-tests: * p<0.05, ** p<0.01, *** p<0.001.*