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Fuel for thought: Powertrain efficiencies of British vehicles

Matteo Craglia*, Leonardo Paoli, Jonathan Cullen

Cambridge University Engineering Department, Cambridge, CB21PZ, UK

Abstract

Improving vehicle fuel efficiency is critical to tackle climate change. This requires understanding the drivers of efficiency improvements in both the powertrain and vehicle body. This paper uses US coast down data to estimate the powertrain efficiencies of new British models in 2010 showing the differences between available models for the first time. Powertrain efficiency decreases with increasing engine capacity, and increases in vehicle mass are found to be more detrimental to vehicle efficiency than aerodynamic area. Finally, it is concluded that the difference between diesel and petrol powertrain efficiency grows with increasing vehicle size.

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Keywords: Powertrain; Efficiency; Engines; Vehicles; Energy Conversion; Fuel Consumption, Energy

1. Introduction

Promoting the efficient use of energy to deliver energy services is of paramount importance for reducing GHG emissions. Vehicles on sale in Great Britain have increased in size and weight in recent years as well as generally reducing fuel consumption [1]. These competing trends suggest decreases in fuel consumption are due to powertrain improvements. However, publicly available measures of fuel efficiency in vehicles are quantified as mpg or L/100km. These measures fail to distinguish between improvements in powertrain efficiency and improvements in the body of the vehicle.

Cullen & Allwood [2, 3] made the novel distinction between conversion devices and passive systems. The efficiency of the former is associated with the conversion of energy from one form to another (e.g. chemical to kinetic in a combustion engine); the latter is how efficiently useful energy (e.g. kinetic energy) provides an energy service (e.g.

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* Corresponding author. *E-mail address:* mamc4@cam.ac.uk

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vehicle km). This distinction gives greater insight into whether efficiency improvements have occurred in the powertrain or via light-weighting and aerodynamics and allows for a quantification of the potential for improvement.

The fuel consumption and emissions of vehicles in the EU are tested on a rolling road according to Directive 93/116/EC. To simulate the 'road load' (aerodynamic and friction) force at different vehicle speeds, rollers are programmed using data from a 'coast down' test. This information can be used to determine the kinetic energy requirements over a drive cycle and distinguish between the passive system and the conversion device efficiencies. This method has been previously used by *Lutsey* [4] and *Thomas* [5, 6] using coast down data made publicly available by the EPA [7] to determine the efficiency of powertrains in several US vehicles.

Unfortunately, road load data for vehicles in the EU is not publicly available and is deemed to be confidential information by vehicle manufacturers [8] meaning an adequate quantification of the powertrain efficiencies of British vehicles has not previously been performed. Furthermore, studies discussing improvements in fuel consumption, such as [1], have looked at the *average* of available models or the sales weighted *average*. Few studies consider the full spectrum of fuel consumption of vehicles available for sale. This makes it difficult to differentiate between the best available technology and efficiency laggards. This paper aims to fill this gap by studying British newly registered vehicles in 2010 on a sales weighted, model-by-model basis, distinguishing between the powertrain (conversion device) and vehicle body (passive system) efficiencies for the first time.

2. Methods

In this paper, a detailed dataset of British vehicles is assembled using coast down data from the US. This data is then used to determine the powertrain efficiency of individual British models applying the same methods *Lutsey* [4] and *Thomas* [5, 6] used for US models. This allows for an assessment of the relationships between engine efficiency and the efficiency of the vehicle body.

2.1. Data Collection

Coast down tests are a common way in the US and EU of determining the resistive 'road load' force on a vehicle at different speeds in order to calculate fuel consumption. The test involves accelerating a vehicle up to 120 km/h on a test track, engaging neutral gear and decelerating to rest.

Table 1. List of datasets used in this study

Organization & Dataset	Source	Description
Environmental Protection Agency (EPA) Coast Down Data	[7]	Make, model, equivalent test weight (ETW), capacity and 'A', 'B' and 'C' coast down constants of all new cars on sale in 2010 in the USA
Driver Vehicle Licensing Agency (DVLA) Table VEH0160	[10]	Make, model of different cars first registered in Great Britain as well as number of new registrations in 2010 but *not* L/100km
Vehicle Certification Agency (VCA) Car fuel and emissions information	[11]	Make, model, capacity and L/100km for every vehicle available for sale in the UK every year
Carfolio, Autoevolution, Vehicle technical specification online databases	[12]	Make, model, drag coefficient C_D, kerb weight, frontal area A_f

The method used in this paper can be divided into three main steps. Firstly, individual British vehicle models are matched between registrations [10] and L/100km rating [11]. 'Word matching' scripts are necessary to collect data for each model from the sources in table 1 as the make and model names *are not* exactly the same between datasets. Next, these vehicles are matched with the relevant model in the EPA coast down data [7]. From a total 1,977,294 new vehicle registrations in 2010, 557,240 registered vehicles were matched with all three datasets and 504,315 could not be matched to the registrations data. The remaining models are vehicles not present in the US market and thus could not be matched to the EPA coast down data. These vehicles are therefore grouped into their generic models (e.g. VW

Polo instead of POLO SE TDI 80) and their road load coefficients are determined in a third step by 'manually' looking up the drag coefficient (C_D), frontal area (A_f) and kerb weight from online specification databases [12]. Equations 1 and 2 are then used to determine the road load coefficients for a further 915,739 registered vehicles.

$$C = \rho_{air} \times C_D \times A_f \qquad (1) \qquad\qquad A = C_F \times m \times g \qquad (2)$$

Where ρ_{air}=1.2 kg/m^3, the rolling friction coefficient C_F is assumed constant for all vehicles equal to 0.0083 from [4].

In the US, vehicles are tested in inertia classes known as the equivalent test weight (ETW) to describe the additional weight of vehicles on the road above the kerb weight. This weight includes a full tank of fuel, 136 kg to simulate driver and luggage and the weight of optional equipment if it is expected to be fitted to over 33% of models [13]. Optional features in US vehicles are estimated by *MacKenzie et al.* [14] to weigh 136 kg in 2010. In comparison, EU test weight involves a 90% full fuel tank, 100 kg of driver and luggage and no optional equipment, meaning the US coast down vehicle data needs correcting to EU test weight accordingly.

2.2. Calculation of efficiency

The powertrain efficiency (η_{pt}) is defined here as the ratio between the kinetic energy supplied to the wheels and the fuel energy input during the *New European Drive Cycle* (NEDC) combined cycle (used in the EU). η_{pt} is determined by integrating the road load force F_D, over the drive cycle as described fully by *Lutsey* [4] & *Thomas* [5, 6] using the following equations:

$$F_D = A + Bv + Cv^2 \qquad F_I = m \times a \qquad F_{pt} = F_D + F_I \qquad \eta_{pt} = E_{pt}/E_{fuel} = \int F_{pt}\, ds \,/E_{fuel}$$

Where constants A, B and C describe the road load force from EPA coast down data and F_{pt} is the *positive* tractive force supplied by the powertrain to the wheels. The passive system efficiency, defined as the kinetic energy provided by the powertrain to overcome F_D over the drive cycle, is determined using equation 3. The units of passive system efficiency are kept in L/100km to facilitate comparison with vehicle fuel consumption. However, the subscript $_{\text{Kinetic}}$ is introduced to distinguish between an energy content of fuel and the kinetic energy provided by the powertrain to the wheels. 1 L_{Kinetic}=32.6 MJ.

$$\text{Passive System Efficiency, } L_{Kinetic}/100km = \eta_{pt} \times L/100km \qquad (3)$$

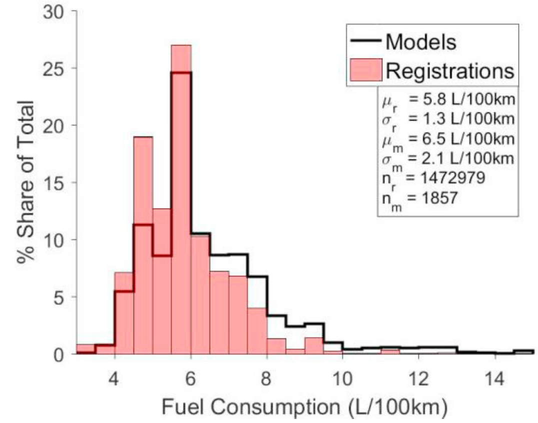
2.3. Limitations of methods

The *Vehicle Certification Agency* (VCA) fuel consumption data used in this investigation uses the NEDC drive cycle which is known to not be fully representative of real, on-road fuel consumption [8]. Furthermore, manufacturers reportedly change the specifications of vehicles during coast down tests (e.g. by fitting low rolling resistance tyres) to reduce drag [8] which could again cause discrepancies with on-road efficiencies. Although the NEDC cycle has its limitations, it still provides a useful standard for comparison between models. US vehicle models may differ slightly in specification from similar British models (e.g. safety standards); this is assumed to not significantly change vehicle kerb weight or road load coefficients.

In the absence of further information, C_F (equation. 2) is assumed constant for the 'manually' estimated road load coefficients. In reality, it is likely to change slightly between vehicles, though *Lutsey* [4] shows the variation to be only ±4.8%. Regenerative braking efficiencies are not currently collected by the EPA so cannot be evaluated in this investigation. Finally, only 1,472,979 registered vehicles out of the 1,977,294 new registrations in 2010 were matched. This is primarily due to difficulties matching specific models between the VCA and registrations datasets; data is collected by different departments of the UK *Department for Transport* and vehicle model names are not identical between data sets. However, the average L/100km (5.8 L/100km) and share of diesel vehicles (46.1%) are very similar to other industry publications [15].

3. Results and Discussion

3.1. What is the efficiency of new cars in the Britain in 2010?



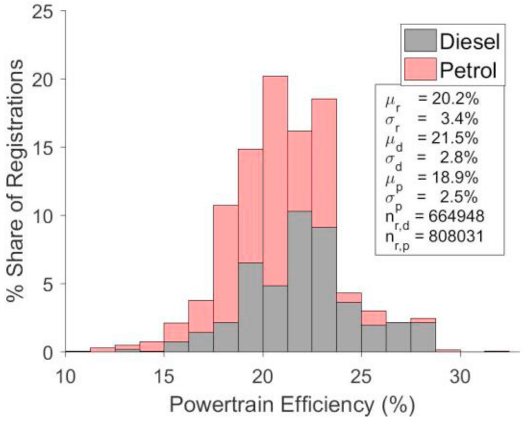
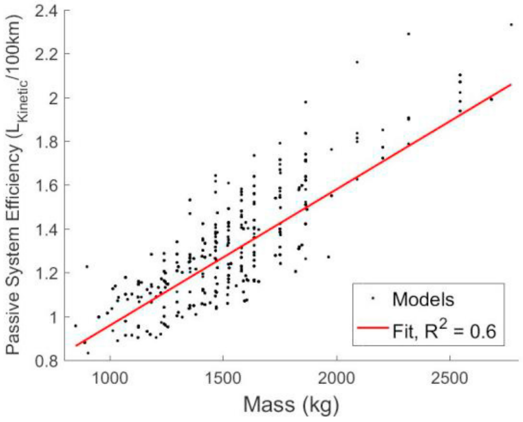


Figure 1 Fuel consumption GB 2010. Black line shows models grouped by L/100km vs. share of models. Red bars show L/100km vs share of registrations. Mean μ, std σ, number n shown for available models (m) and registration weighted (r).

Figure 2 Powertrain efficiency η_{pt} vs % registered vehicles, stacked for diesel and petrol. Mean μ, std σ, shown for newly registered diesel (d), petrol (p) and total (r).

Figure 1 shows the vehicle fuel consumption of available models and registration-weighted models in Great Britain in 2010. It can be seen a wide spread of models were available for sale in 2010 but that consumers tended to register vehicles with better fuel consumption. Figure 2 shows the registration-weighted distribution of powertrain efficiency in Great Britain in 2010 split by fuel type. British powertrain efficiencies vary between a minimum of 7.8% and maximum of 31.5% with a registration-weighted mean of 20.2% in 2010. Diesel powertrains are found to be on average 2.6% more efficient than petrol engines. Having shown the spread in efficiencies of British vehicles, the following discussion focuses on the reasons behind these differences in efficiency.

3.2. What are the main factors affecting passive system efficiency?



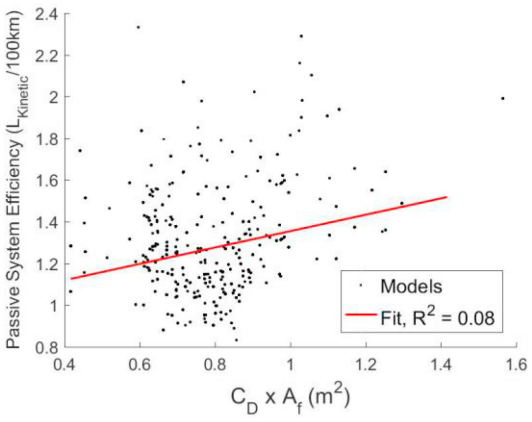


Figure 3 Passive system efficiency vs. Mass (ETW)

Figure 4 Passive system efficiency vs. Aerodynamic area (C_DA_f)

A vehicle with poor passive system efficiency requires more kinetic energy over the course of a drive cycle. Figures 3 and 4 plot the two main factors affecting passive system efficiency: vehicle mass (ETW) and aerodynamic area

(C_DA_f). Figure 3 shows mass has a much higher influence (R^2 =0.60) on passive system efficiency than aerodynamic area. One of the reasons for this is that a large period of the combined NEDC cycle is 'city' driving where vehicle speeds are low, reducing aerodynamic losses and giving more importance to inertia forces.

3.3. *What are the main factors affecting engine efficiency?*

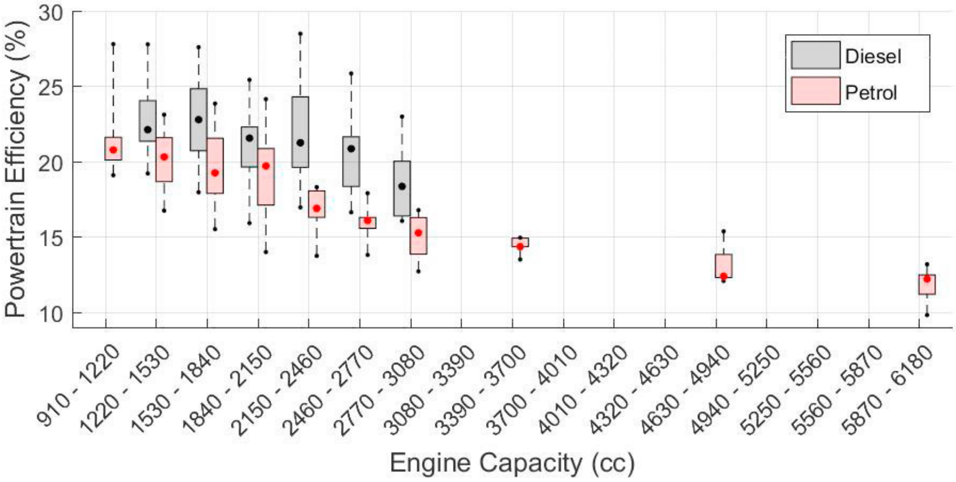


Figure 5 Powertrain efficiency vs. engine capacity boxplot showing 5th, 25th, 50th, 75th and 95th percentiles & split by fuel type

In figure 5, the relationship between engine capacity (cc) and η_{pt} is presented as a boxplot with models in groups of similar engine capacity and split between diesel and petrol. The powertrain efficiency of petrol engines decreases with increasing engine capacity; this may be due to factors such as larger engines possibly operating at sub-optimal conditions during the NEDC test, changes in displacement/cylinder as well as significant increases in power. This trend is less significant for diesel engines and helped by the fact there are fewer large capacity diesel engines available in 2010 British cars. This low frequency of high capacity diesel engines is due to the fact a diesel is likely to have higher torque than a petrol engine of similar capacity. Hence, larger vehicles are run with relatively low capacity diesel engines compared to petrol. Unfortunately, data could not be collected on individual vehicle's power rating or number of cylinders and will be the aim of future work in order to assess the potential benefits of downsizing.

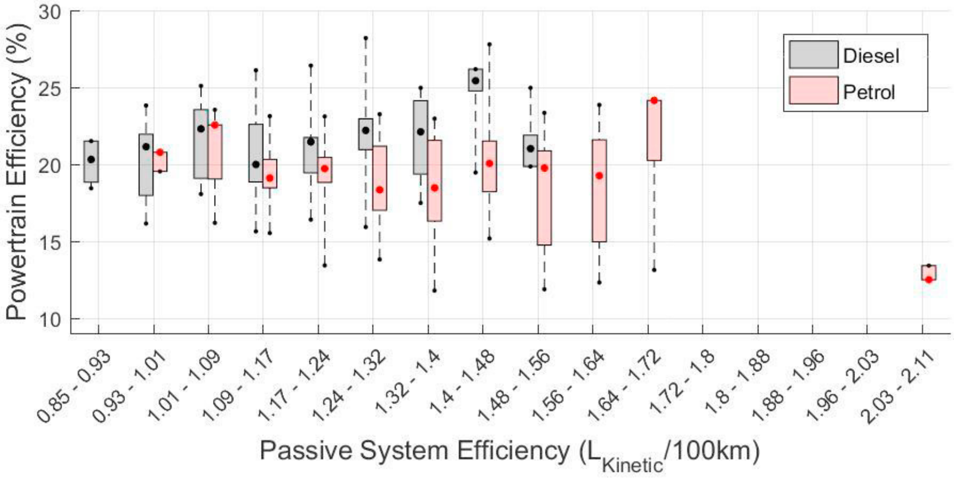


Figure 6 Powertrain efficiency vs. passive system efficiency boxplot showing 5th, 25th, 50th, 75th and 95th percentiles & split by fuel type

3.4. What is the relationship between engine efficiency and passive system efficiency?

Figure 6 shows the relationship between the powertrain efficiency of models available in the dataset and their passive system efficiency. The data is presented as boxplots in groups of similar passive system efficiency and split between petrol and diesel powertrains. It can be seen that *petrol* vehicles in the lower right half of figure 6, require larger kinetic energy inputs (less efficient passive system) and have lower powertrain efficiencies. This is because they tend to be fitted with larger cc engines (e.g. Aston Martin) with lower η_{pt} as seen in figure 5. For diesel vehicles, figure 6 shows worse passive system efficiency vehicles have *more* efficient engines in them. This leads to the conclusion that the importance of fuel type is greater for larger, less efficient vehicles. For example, a small vehicle with low kinetic energy requirements will have a comparable powertrain efficiency with a diesel engine as it would with a petrol engine. Conversely, a larger vehicle (with worse passive system efficiency) is likely to have considerably better powertrain efficiency with a diesel engine than with a petrol engine.

4. Conclusion and Future work

This paper uses coast down data to quantify the powertrain efficiency of British vehicles for the first time; this can help to distinguish between efficiency improvements in the body of a vehicle or the powertrain. It is found that the choice between a petrol and diesel engine is of greater importance on powertrain efficiency for larger vehicles than for smaller cars with better passive system efficiency. The results also show that vehicle mass has a greater impact upon vehicle passive system efficiency than aerodynamic area (C_DA_f), showing particular emphasis needs to be directed towards light-weighting vehicles. Future work will investigate the relationships between powertrain efficiency and vehicle power for which data could not be found. This paper has also shown how useful coast down data can be to give a high-level insight into the efficiency of vehicles; making EU coast down data publicly available would improve the transparency of vehicle testing and has the potential to aid consumer choice.

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