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# EX-POST DECOMPOSITION ANALYSIS OF PASSENGER CAR ENERGY DEMAND AND ASSOCIATED $CO_2$ EMISSIONS

## ABSTRACT

This paper investigates, quantifies and ranks the factors influencing passenger cars energy demand and emissions. A vehicle stock-model approach is used for an ex-post decomposition analysis, based on administrative data, examining the impact seven underlying factors driving energy demand. The impact of methodological choice and model disaggregation are also explored. In light of the 2015 vehicle emissions scandal, the paper quantifies the difference between manufacturer-test vehicle performance and real world or “on-road” performance for a national stock model and determines the relative impact on passenger cars energy consumption. When examining the technical performance improvement, the choice of metric can lead to a distortion of 2.2 percentage points (14% overestimate) in the quantification of the efficiency improvement of the vehicle stock. The analysis pays particular attention to the influence of fuel or technology switching – which is often quoted as a factor influencing energy use and emissions but rarely quantified. Even when using litres per hundred-kilometre gasoline equivalent to measure the performance improvement, changes in the makeup of the stock can lead to distortion in the efficiency measure. The results of a full decomposition analysis highlight that technical performance improvements (energy efficiency improvements for the purpose of this paper), will not provide significant energy and emission savings when the impact on-road consumption is included. The paper concludes that technology switching in conjunction with policies targeting ownership and usage are the most effective measures to control passenger car energy consumption and associated $CO_2$ emissions.

**Keywords:** passenger cars, energy efficiency; fuel or technology switching; on-road consumption; LMDI-I; decomposition analysis;

## 1. INTRODUCTION

The International Energy Agency (IEA) estimates that the transport sector is responsible for 22% of energy-related carbon dioxide ($CO_2$) emissions (IEA, 2015a). Transport accounts for almost 19% of all energy[1] globally and its share of total final energy demand is 28% globally, with the figure increasing to 33% for OECD countries (IEA, 2015b). The transport sector has a significant dependence on oil, with a share of 94% of all global transport energy use in 2015 – a reliance that has not changed since the 1970’s (IEA, 2016). The expectation is that the share of transport energy demand and associated emissions will grow in developing economies in conjunction with economic growth. In the absence of diversification away from petroleum products, there are high expectations from energy efficiency in the transport sector.

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[1] 19% of total primary energy which is defined as the total requirement of all uses of energy including energy used to transform one energy form to another (e.g. burning fossil fuels to generate electricity) and energy used by the final consumer.

Energy efficiency in transport can be achieved through a number of approaches. These approaches include technical energy efficiency improvement (for example where the fuel economy or energy or emissions performance [gCO2/km] of the vehicle stock is improved), behavioural improvements (such as eco-driving and vehicle sharing), or policy measures, such as influencing vehicle purchasing trends, modal shift, logistics management or changing speed limits to name but a few.

The methods used to measure energy efficiency in transport give further insights into what is considered energy efficiency in the transport sector, but it is not a trivial exercise to quantify transport energy efficiency savings. Data limitations often hinder the possible indicators or metrics that can be calculated. Some improvements are extremely difficult to quantify due to a lack of data (Schipper, 2009) or lack of quality data (Schipper, 2011). In addition, behavioural changes cannot be counted on as long-term energy savings due to rebound effects (Schipper and Grubb, 2000), (Greening, 2004), (Biying et al., 2013).

Passenger cars[2] have been the focus of a lot of policy changes in many countries in recent years[3]. Fuel economy and emissions standards are among the most commonly advised and implemented policies to improve the energy efficiency (technical performance) of private transport vehicles (EU, 2009a), (IEA, 2015c). A problem with manufacturer fuel consumption and/or emissions ratings are that they are based on laboratory test fuel consumption values, which are very different to the real world vehicle performance or 'on-road'[4] performance. This was a known problem even before the revelations of the recent (2015) vehicle emissions scandals (Schipper et al., 1993), (Zachariadis, 2006) but it has been suspected of widening in recent years (Tietge et al,. 2015), (GFEI, 2016), (Tietge et al,. 2017).

Following an investigation into car manufacturer Volkswagen, in light of their admission to using cheat software to lower the nitric oxide emission ($NO_x$) from vehicles during USA emissions testing, the company issued a statement on November 3rd 2015 that vehicle $CO_2$ emissions and thus vehicle fuel consumption were also underestimated by the company (Volkswagen, 2015). This legitimately raised concerns about the validity of all vehicle emission and fuel efficiency labels. Indeed since November 2015 there have been further questions raised about the validity of more vehicle manufacturers' fuel and emissions performance (gCO2/km) values (Sorokanich, 2016), (Fontaras et al., 2017). The impact of real world fuel consumption as opposed to laboratory or 'on-road' consumption and its relative significance in influencing overall energy consumption is also quantified in this paper.

Ireland is an interesting case study for this paper due to recent and projected strong energy demand growth in transport and ambitious emissions targets. Within the European Union

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[2] Vehicles taxed for the purpose of private use, includes company cars and sports utility vehicles (SUVs).

[3] Examples of emissions based vehicles taxation can be found in the International Energy Agency Policies and Measures database (PAMS) database. (IEA, various years).

[4] The terms real world efficiency or on-road efficiency are used interchangeably in this paper and reference to the actual efficiency (l/100km or gCO2/km) of passenger cars when driven outdoors as opposed to in a laboratory test conditions.

(EU) a $CO_2$ based ‘Cap and Trade’ system, known as the Emissions Trading Scheme (ETS), has been in place since 2005. The ETS scheme includes electricity generating power stations, large-scale industrial plants, and, since 2012, aviation sector. All other greenhouse-gas emitting sources are collectively termed non-ETS emissions sources. Non-ETS emissions sources include energy consumption in the residential, transport, agriculture and waste sectors, as well as small businesses/industry. Also included are non-energy related agriculture and waste disposal emissions. The EU Effort Sharing Decision (Decision No 406/2009/EC) aims to limit EU non-ETS emissions and stipulates that Ireland must achieve a 20% reduction in non-ETS emissions from their 2005 levels by 2020 (EU, 2009b).

Transport emissions account for almost a quarter of Ireland’s total Greenhouse Gas emissions, more than a third of Ireland’s energy-related $CO_2$ emissions and 60% of energy related non-ETS $CO_2$ emissions. Transport energy-related emissions in Ireland fell by only 0.5% per annum between 2010 and 2014, and actually grew by almost 4% in 2014 and 5.9% in 2015, indicating the scale of the challenge in the transport sector (SEAI, 2016). In Ireland passenger cars have historically dominated in the road vehicle fleet, representing 78% of the road vehicle fleet in 1995 and still at 77 % in 2015 and the number of passenger cars in the Irish fleet grew doubled over the period 1995 to 2015 (Department of transport, 2016).

A recent decomposition analysis of passenger transport in Ireland was based on passenger kilometres and recommended; “Further research on passenger transport should seek to fill gaps in knowledge towards a better understanding of the causal factors underlying the identified trends in each mode” (Jennings et al., 2013). This paper aims to improve that understanding for passenger cars, based on a detailed stock model approach that facilitates the analysis of more causal factors. It is also interesting to base the decomposition analysis on a technology specific indicator, in this case litres per hundred kilometre (l/100km), rather than an activity-based indictor such as energy use per passenger kilometre. Unlike the technology-based indicator, which is independent of activity, depending on the disaggregation of the model used in the analysis the activity-based indicator can change significantly. A derived or calculated activity-based indicator is also more inclined to display fluctuating trends, not least when the denominator varies with different levels of disaggregation.

The paper is structured as follows; section 2 is a theoretical review, which frames the context and content of the methodological approach. The starting point in the efficiency indicators section (section 2.1) which examines the influence of the choice of efficiency or technical performance metric and fuel switching (technology switching) on a the quantification of efficiency in passenger cars. Improving the estimates for on-road fuel efficiency at a national or economy wide level are also considered in this section. Greater disaggregation using a detailed stock model is proposed in section 2.2. Identity equations for both energy and emissions using readily available administrative data are proposed to facilitate a detailed decomposition analysis. The choice of decomposition analysis methodology is discussed in section 2.3.

In section 3, the results section, Ireland is used as a case study to illustrate the methodological findings. Section 3.1 quantifies the impact of metric and methodology choice, as well as the how the methodology is applied. Section 3.2 explored the additional insights of underlying trends from an improved stock model for a full decomposition analysis. The influence of technology switching, biofuels blending, mileages, on-road fuel efficiency and the vintage of the vehicle stock on passenger car transport energy consumption are determined for the case study in section 3.3. In section 3.4 the factors examined are ranked and the most effective policy levers are discussed. Section 4 discusses areas for further development, which are currently restricted due to limited data availability. The conclusions based on the case study and more general conclusions are presented in section 5.

## 2. THEORETICAL REVIEW

Traditionally the efficiency of passenger cars is related to fuel economy or fuel consumption with measures such as litres per hundred kilometres (l/100km) or miles per gallon (mpg). These are still the most common metrics quoted by car manufacturers and the general public when discussing passenger car efficiency and are the starting point for the analysis in this paper.

It is interesting to use fuel economy as a starting point for analysis of a stock, not only because that is the vernacular of passenger car efficiency, but also as it provides a straightforward and relatable example of how different fuels, technologies and efficiency can be conflated and confused.

### 2.1. Efficiency indicators

Comparing the two most dominate passenger car fuels, a litre of gasoline has an energy content (or energy density) of approximately 33 MJ whereas a litre of diesel has an energy content of 37 MJ, i.e. diesel has approx 11% higher energy content per litre. While both diesel and gasoline vehicles have internal combustion engines, gasoline engines are spark ignition, whereas diesel vehicles are compression ignition. In terms of technology performance diesel engines have a higher thermodynamic efficiency (~ 45%) than gasoline engines (~ 30%) (US DoE, 2003) and so diesel vehicles are approximately a third more efficient than gasoline vehicles (Schipper et al., 2002), (US DoE, 2017). Thus diesel vehicles are more likely to have lower volumetric consumption values (l/100km) than their gasoline counterparts.

When the technical performance of both fuels (or technologies) are combined into a single fuel consumption measure (i.e. l/100km) in order to track the efficiency for the entire stock, changes in the technology share of the stock can distort the rate of improvement. Therefore an increase in the share of diesel vehicles is likely to cause acceleration in the rate of improvement of the overall stock, when measured in litres per hundred kilometres. An example of the application of such simple averaging for vehicle stock l/100km can be seen for Ireland, the case study in this paper, in figure 5 of the following paper (Ó Gallachóir et.

al., 2009)[5]. The distortion may also be present even when other fuels are converted to l/100km gasoline equivalent (lge/100km). When associated with rapid changes in the stock, the calculation metric and implementation can become significant as discussed in detail in section 3.1.

A single efficiency indicator for all fuel types (which in this case also distinguishes by technology) does not facilitate isolating and quantifying the impact of fuel or technology switching, as this effect is subsumed into the efficiency effect.[6] Inter-fuel substitution is rarely included in energy decomposition analysis, although commonly included in energy-related emissions analysis. Ma and Stern included inter-fuel substitution in their analysis of industrial energy consumption in China but found it did not contribute significantly to changes in intensity (Ma and Stern, 2008).

Another problem encountered when vehicle manufacturer efficiency values are used as a measure of efficiency improvement of the vehicle stock, is a difference between the test value and the “on-road” consumption. In recent years vehicle manufacturers have tuned the performance of the vehicles to optimise the consumption to the test cycles and as a result the gap between the test performance and the real world performance has been widening (Weiss et al. 2011), (Tietge et al,. 2015). Previous studies such as (Zachariadis, 2006), (Weiss et al., 2011) and  (Duarte et al., 2015) have tried to quantify the difference between the test and real world vehicle consumption.

Portable emissions monitoring system (PEMS) on all vehicles is considered to be the most reliable method of measuring the difference between test and real world consumption, but this is prohibitively expensive and unwieldy solution. Research by the European Commission Joint Research Centre (JRC) comparing test results from the new European driving cycle (NEDC) test to result of on-road consumption quantified by PEMS concluded that certification data underestimates fuel consumption by 10-15% for gasoline vehicles and by 12-20% for diesel vehicles (Weiss et al., 2011).

There are also many numerical models or tools which can be used to estimate on-road consumption based on a number of vehicle parameters.  The number of vehicle and driving condition parameters require a more detailed model of on-road consumption included than in the top down stock energy decomposition exercise in this paper, so it was considered inappropriate to use any numerical model. Therefore the most practical and pragmatic way to estimate on-road consumption at the level of national energy statistics, and for this purpose of this paper, is to use a single factor for each vehicle fuel type that varies over the time period examined.

## 2.2. Model configuration

The trend in energy efficiency indicator does not necessarily explain the trend in overall energy consumption. The number of factors which could be influencing the overall passenger

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[5] While a straight-forward average was calculated for the stock l/100km change, the analysis was ultimately completed by using an energy consumption (MJ/litre) metric.

[6] Note that technology change in transport is very closely linked to fuel switching – which is also referred to as inter-fuel substitution.  However in this paper technology change is used to avoid confusion with the impact of biofuels.

cars energy consumption needs to be analysed so that the relative impact of additional factors on overall energy consumption and associated emissions can be examined and understood. An identity equation is the basis of a decomposition analysis. To this end the number of factors that can be included in an energy and emissions identity equation and the level of disaggregation is explored.

The overall energy consumption or emissions of passenger cars (E) can be simply represented as the product of the energy efficiency (I), by the annual average mileage (M) and the total number of vehicles Q in the stock (equation 1).

$$E = Q \times M \times I \text{ (1)}$$

For each technology the energy efficiency *I* in equation (1) can describe by equation (2) comprising vehicle fuel consumption (*FC*) - measured in litres per hundred kilometres (l/100km), an energy conversion factor based on energy density of the fuels (*DEN*) measured in Mega-Joules per litre (MJ/l)[7] and, in order to obtain a realistic measure of the stock vehicle efficiency, an on-road factor (*ORF*).

$$I = ORF \times DEN \times FC \text{ (2)}$$

Alternatively, for an emission based analysis, the factors in equation 3 are emissions performance (EP) measured in grammes $CO_2$ per kilometre ($gCO_2/km$) , a biofuels factor (B), which is the share or percentage of biofuels blended with fossil fuels (petroleum), in order to quantify the impact of blending biofuels and the same on-road factor (ORF) as included in equation 2.

$$I_{CO_2} = ORF \times B \times EP \text{ (3)}$$

In order to expand the measure of energy efficiency for passenger cars to cover the entire stock, the new passenger car efficiency is frequently combined with a crudely calculated stock efficiency. This is currently the method employed in the ODYSSEE[8] project for monitoring the efficiency of passenger cars in Europe. Such a rudimentary method of calculating the unit consumption for an entire passenger car stock is defined by equation 4, where $UC_{Stock}$ is the weighted average of the gasoline or diesel,

$$\mathrm{SUC}_{\mathrm{stock}_{\mathrm{t}}} = \frac{\left(\left(\mathrm{SUC}_{\mathrm{stock}_{(\mathrm{t}-1)}} \times \mathrm{N}_{\mathrm{stock}_{(\mathrm{t}-1)}}\right) + \left(\mathrm{SUC}_{\mathrm{New\ Stock}_{(\mathrm{t})}} \times \mathrm{N}_{\mathrm{New\ Stock}_{(\mathrm{t})}}\right)\right)}{\mathrm{N}_{\mathrm{stock}_{(\mathrm{t})}}} \text{ (4)}$$

Where *UC* is the unit consumption, either fuel consumption in litres per 100 kilometres (l/100km) or emissions in grams $CO_2$ per kilometre $CO_2$/km, *t* is the year and *N* is the number of cars.

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[7] For electric vehicles an equivalent gasoline fuel consumption figure is calculated by manufacturers.

8The European Union ODYSSEE (Online Database Yearly aSSessments of Energy Efficiency) project was set up in 1993 with the objective of developing indicators of energy efficiency for Europe. A number of sectoral indices and an overall economy wide energy efficiency index called ODEX (ODYSSEE energy efficiency index) indicators were developed. The collection and improvement of data relating to energy usage drivers, energy efficiency and CO2-related indicators were later added as objectives. For more information see: http://www.indicators.odyssee-mure.eu/

This coarse classification of new and existing vehicles (i.e. just two categories), provides an extremely aggregated stock model and does not take advantage of the detailed data on the vintage of vehicles available since the introduction of mandatory vehicle labelling and laboratory fuel efficiency tests. Also, this weighting does not truly reflect the usage of the stock. To reflect usage a weighting based on usage both the stock numbers and the annual average mileage of the stock, namely vehicle kilometres, need to be considered.

A proposed disaggregation of the vehicle stock by age (vintage), where the vintage is denoted by $v$ and fuel or technology denoted by $I$ is included in equation (5). Such disaggregation allows for the quantification of two additional factors, with the introduction of a technology share factor ($TS=Q_i/Q$) and a vintage share factor ($VS = Q_{i,v}/Q_i$), which facilitate quantification of the impact of technology switching and the age of the vehicle stock respectively

The following equation can be used to describe the energy consumption of the stock:

$$E = \sum_{i,v} Q * A_v * TS_i * VS_{i,v} * M_{i,v} * ORF_i * DEN_i * FC_{i,v} \quad (5)$$

Equation 5 can be used for an seven-factor decomposition analysis of passenger car energy consumption, examining the impact of the absolute number of vehicles in the stock, the fuel or technology[9] share, the vintage share, average annual mileages, the fuel consumption, energy density and on-road factor.

Similarly the overall $CO_2$ emissions of a passenger cars stock can be modelled as:

$$CO_2 = \sum_{i,v} Q * A_v * TS_i * VS_{i,v} * M_{i,v} * ORF_i * B_i * \mathrm{EP}_{i,v} \quad (6)$$

What is of interest in this paper is not the actual energy consumption or emissions but rather their change over time and the influence of the changes in the constituent factors to that overall change. A commonly used methodology in energy and emissions analysis is an index Decomposition Analysis (IDA) which measures the impact of a number of different factors over time. An advantage of using IDA for energy and emissions analysis is that it can be easily applied to readily available datasets, unlike structural decomposition analysis[10].

Most decomposition analysis of passenger cars use passenger-kilometres in their analysis (IEA, 2014), (O' Mahony et al., 2012), (Jennings et al., 2013). With a passenger-kilometres efficiency metric the resulting identity equation usually only contains three or four factors. While passenger-kilometres is the service demand and facilitates a broader analysis of passenger transport beyond passenger cars, a passenger-car only decomposition based on passenger-kilometres does not relate to readily available policy levers or the main drivers of passenger car energy demand growth. Many other models have been proposed for projecting

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[9] Delineation by fuel or technology are the same for the passenger car stock for this paper.

[10] Structural decomposition analysis (SDA) can measure more effects than IDA, such as indirect factors influencing energy use. However the choice of methodology is usually determined by data availability, as SDA relies on input-output tables outside of the industry and services energy end-use sectors there is very little application of SDA. A detailed comparison in IDA and SDA is available in a study by (Hoekstra and van den Bergh, 2003).

energy consumption in passenger transport, such as (Hennessy & Tol, 2010) and (Daly & Ó Gallachóir, 2011) for projecting the passenger car stock for the case study in the paper. However, as the focus of this paper is an ex-post analysis equations (5) and (6) can be directly linked to readily available administrative data and therefore are chosen as the basis for the analysis in this paper. The model was implemented in Microsoft excel.

Two common emissions tools in Europe are COPERT (Computer programme to calculate emissions from road transport) and HBEFA (Handbook of Emission factors). In these models total emissions are calculated as the combination of vehicle fleet and activity data selected by the user and emission factors calculated by the model. In the case of COPERT emission factors are speed-dependant, whereas HBEFA use a 'traffic situation' approach (Franco et al., 2012). Factors such as driving behaviour, vehicle configuration and traffic conditions are regarded as highly influential, even often neglected factors (e.g. side winds, rain, road grade), have significant contributions in fuel consumption in real world driving ((Fontaras et al., 2017)). However these factors cannot be easily linked to energy policy levers and do not address the underlying driver of energy demand and thus emissions. Therefore, a separate emissions model not considered for the purposes of the decomposition analysis in this paper.

### 2.3. Choice of decomposition methodology

There are many different forms of IDA but they can be broadly categories in three different categories. They are Laspeyres based analysis; Divisia based analysis and an ‘other’ category. The Laspeyres based methodologies are based directly on changes relative to a particular point (a single year or scenario). Divisia method employs a continuous function of change between two points (i.e. a starting and final year or a baseline and another scenario). The other category includes indices based on mean rate of change of the variables examined. In the analysis in this paper two different years are used but it is also possible to compare two difference scenarios.

It is not intended to provide an overview or description of the different IDA methodologies or the history of their development in economics, energy or emissions analysis in this paper, the following papers provide a comprehensive coverage (Ang and Zhang, 2000), (Ang, 2004), (Ang et al., 2009).

It is also not intended to compare the pros and cons of various IDA methodologies in this paper. Other studies, such as (Ang, 2004), (Cahill and Ó Gallachóir, 2010), (Ang et al., 2009) (Kesicki, 2012) and (Ang, 2015) have identified the Log Mean Divisia Index (LMDI-I) method as the most appropriate method for perfect decomposition, hence this is the methodology chosen for the analysis in the paper.

In this form of decomposition analysis the log mean of two points is used as a weighting factor to combine the relative logarithmic changes of the number of factors being examined between those points. LMDI-I also meets the criteria most pertinent to this study namely; of being consistent in aggregation and simple to convert between its multiplicative and additive forms (ANG, B. W. & LIU, F. L., 2001).

Once the decision about the decomposition analysis methodology made there are still a number of choices in respect to how a decomposition analysis is implemented. One such choice is whether to use a multiplicative (ratio or product form resulting in percentage change) or additive form (absolute change). As the multiplicative can be derived from the additive in the LMDI-I methodology (ANG, B.W., 2012) the choice is not significant but rather likely to be driven by data availability. In this case a yearly data is available a multiplicative form is chosen but results are presented for both forms. The multiplicative form of LMDI-I is defined as follows for the intensity factor I:

$$R_i^t = exp\left[\sum_i \frac{L(E_i^T,E_i^0)}{L(E^T,E^0)} \times ln\left[\frac{I_i^T}{I_i^0}\right]\right] \quad (7)$$

Where

$$L(a,b) = \frac{a-b}{ln(a)-ln(b)}$$

With a, b > 0 and a≠b; ln= natural log, exp =exponential. $E^T$ is the energy consumption in year T. $E^0$ is the energy consumption in year 0 and i denotes the sub-sector.

Another choice is whether to use a chained or unchained format. Chaining relates to whether a period-wise calculation (between a fixed base year and another year) or time-series calculation (between adjacent years or a rolling base-year which the results aggregated over the total period examined) is used. While the chained form is generally recognized as being more accurate both chained and unchained calculations are investigated in this paper.

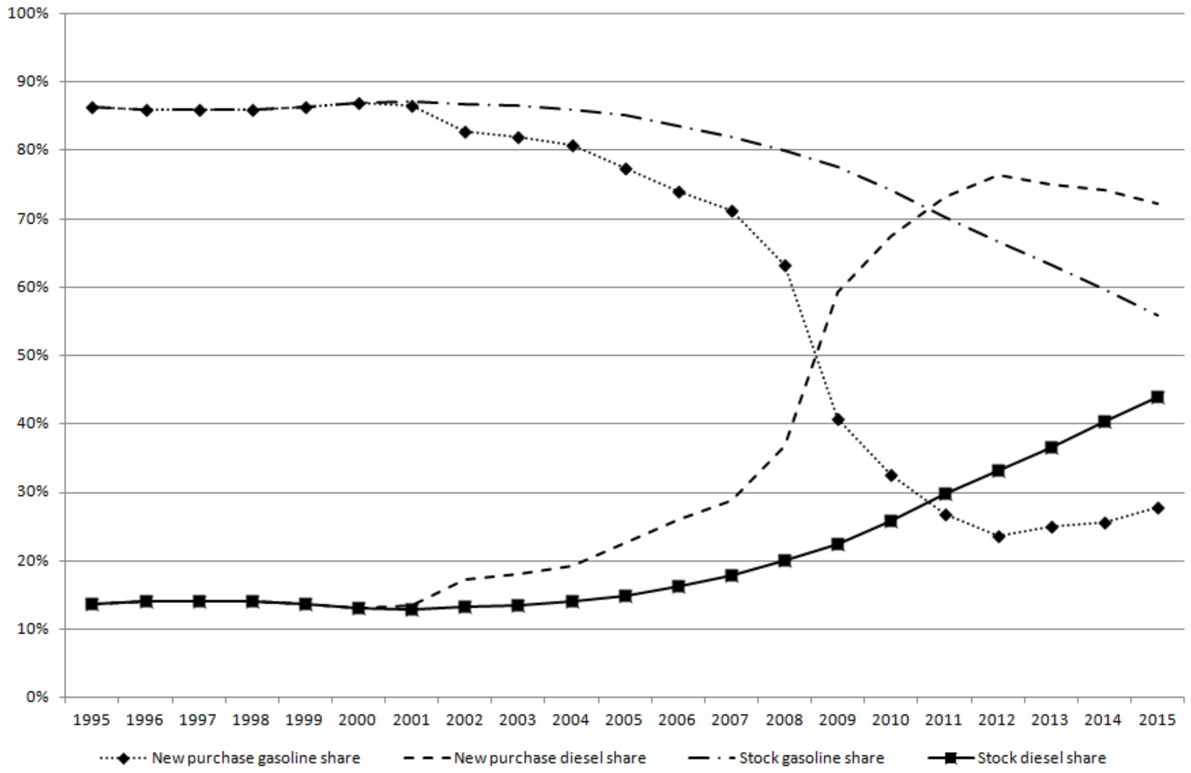
While a recent paper followed a similar approach this paper, namely comparing the results of different decomposition analysis methodologies for passenger cars (Mishina and Muromachi, 2012), the proposed analysis approach (Modified Laspeyres Index Method) developed in that paper was not evaluated relative to the index number tests – in particular the index number factor reversal test. Therefore only the Paasche and LMDI-I decomposition analysis methods were considered in this paper. In addition, the vehicle weight used in that analysis is not data that is readily available and cannot be easily linked to policy levers.

## 3. RESULTS

In this section the Irish passenger car stock is used as a case study to explore the analysis introduced in the methodology section (section 2). Ireland is an interesting case study as the passenger car stock recently experienced significant dieselisation (see figure 1).

A rich dataset on the average fuel consumption of new vehicle purchase are calculated and monitored by the Sustainable Energy Authority of Ireland (SEAI), to estimate the efficiency of new vehicles purchased (SEAI, 2014). Using two different dataset, namely the Vehicle Registration Unit (VRU) data, which includes the make, model and year of all cars in the stock), and matching the model type with UK database on model, the fuel consumption and emissions performance of the stock is established.

Figure 1 Irish passenger car technology (fuel) stock shares



Note that as gasoline and diesel vehicles make up more than 99% of the Irish passenger car stock, and as the remaining vehicle types are not categorised consistently in official statistics, only these technologies are considered for this historical case study (Department of transport, 2016). In terms of fuels examined, gasoline, diesel and the biofuels that are blended with gasoline and diesel are considered in the analysis.

### 3.1. Impact of metric and methodology choice

The Irish new passenger car stock efficiency, as measured using fuel consumption (l/100km), improved by 34% between 1995 and 2015 for both gasoline and diesel vehicles when measured separately. When combined into a single volumetric measure (l/100km), weighted by the vehicle stock share of each technology type, the overall improvement was 38%.

It can be seen from figure 2 that the Irish passenger new car purchases underwent significant fuel or technology switching over the period examined, in particular from 2008 onwards following the introduction of an emissions based vehicle registration and annual road tax[11] in that year. The share of diesel vehicles in the new vehicles sales, which had been constant at 14% between 1995 and 2001, and only gradually increased to 29 % by 2008, dramatically increased to 76% by 2012 subsequent to the tax change, prior to dropping back slightly to 72% in 2015 (figure 1). For new passenger cars the aggregated improvement of the new vehicle stock was falsely inflated by 4 percentage points (or a 12% overestimate) relative to the actual improvement when a volumetric measure of efficiency is used (l/100km). There is still a difference of 1.6 percentage points (a 3% overestimate) relative to the energy

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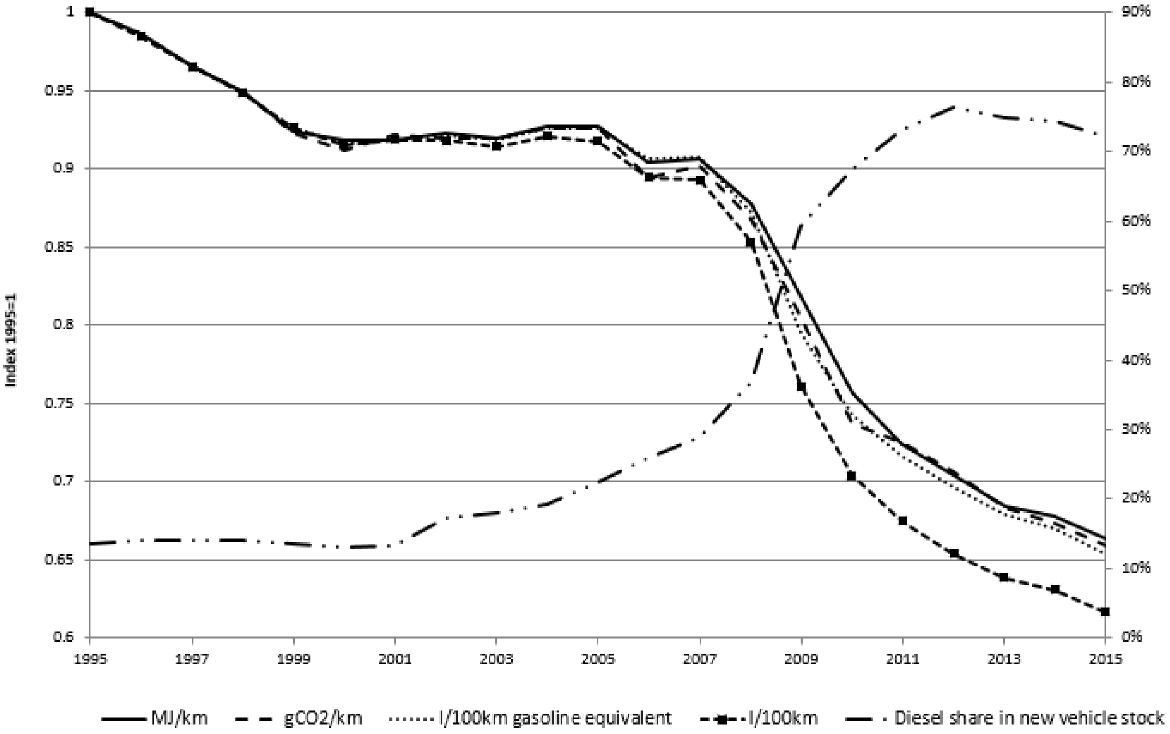
[11] Referred to as the tax change for the rest of this paper

efficiency improvement (MJ/km) even when the metric used to measure energy efficiency is litres per 100 kilometres gasoline equivalent (lge/100 km). This appears to be related to the sharp rise in the share of diesel vehicles.

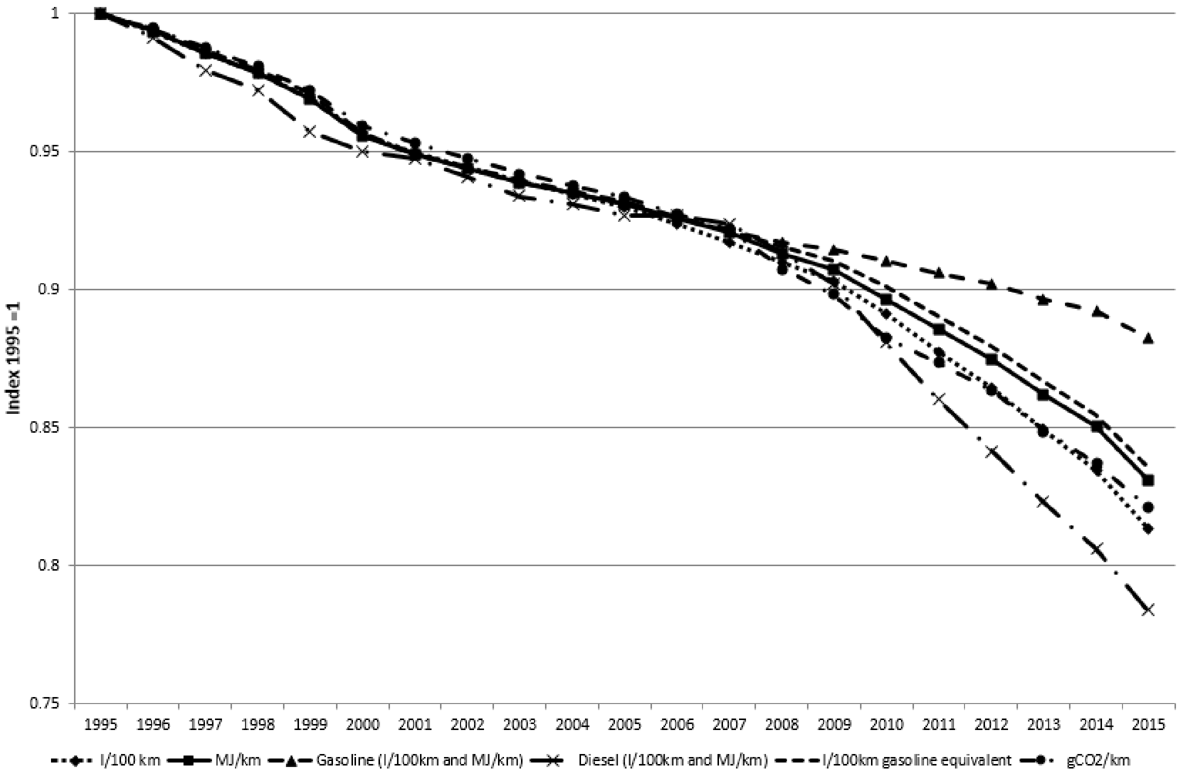
Figure 2 Comparison of different metrics to measure the energy efficiency improvement of different new vehicle technologies



Also included in figure 2 is the new car stock improvement measured in specific emissions performance (gCO2/km). The improvement in the emissions performance (gCO2/km) index is not coincident with to the rate of improvement in energy efficiency (MJ/km) as both are measured directly by tests. Some fuel may not be fully combusted during the test cycle or as the calorific value of the fuel may not be tested directly and vary slightly from the assumed number, leading to a slight divergence in trends between the fuel economy and the emissions performance.

Figure 3 presents the same indicators as figure 2, but this time represents the entire vehicle stock rather than just newly purchased vehicles. For the entire stock gasoline and diesel technologies improve at different rates, with gasoline vehicles improving by 11.71% over the twenty year period and diesel improving by 21.61%. The same trend as new vehicles can be seen for the entire stock, with the fuel economy metric overestimating by 2.2 percentage points (a 14% overestimate). The lge/100km metric for the entire stock underestimates the improvement by 2%.

Figure 3 Comparison of different metrics to measure the energy efficiency improvement of different vehicle technologies for the entire stock



Note it is possible to use the volumetric fuel consumption to calculate the rate of efficiency improvement without any distortions due to energy density by first calculating the index of improvement for the individual fuels before being combined them into an aggregated index. The result of such a calculation is included in Table 1, which also compares the results of a number of different methodologies.

Table 1Comparison of different calculation methods for the efficiency of the new passenger car stock

| Metric | Description of index calculated. | Index change since 1995 (1995=1) | Δ to LMDI I | Notes |
|---|---|---|---|---|
| Fuel economy litres per 100 kilometres (l/100km) | Stock absolute calculated | 0.6132 | +8.3% | 1 |
| | Stock absolute technology share weighted | 0.6164 | +7.8% | 2 |
| | Paasche aggregated indices | 0.6625 | +0.27% | 3 |
| | LMDI-I aggregated indices | 0.6647 | -0.0006% | 4 |
| Fuel economy litres per 100 kilometres gasoline equivalent (lge/100km) | Stock absolute calculated | 0.6527 | +1.8% | 1 |
| | Stock absolute technology share weighted | 0.6623 | +0.3% | 2 |

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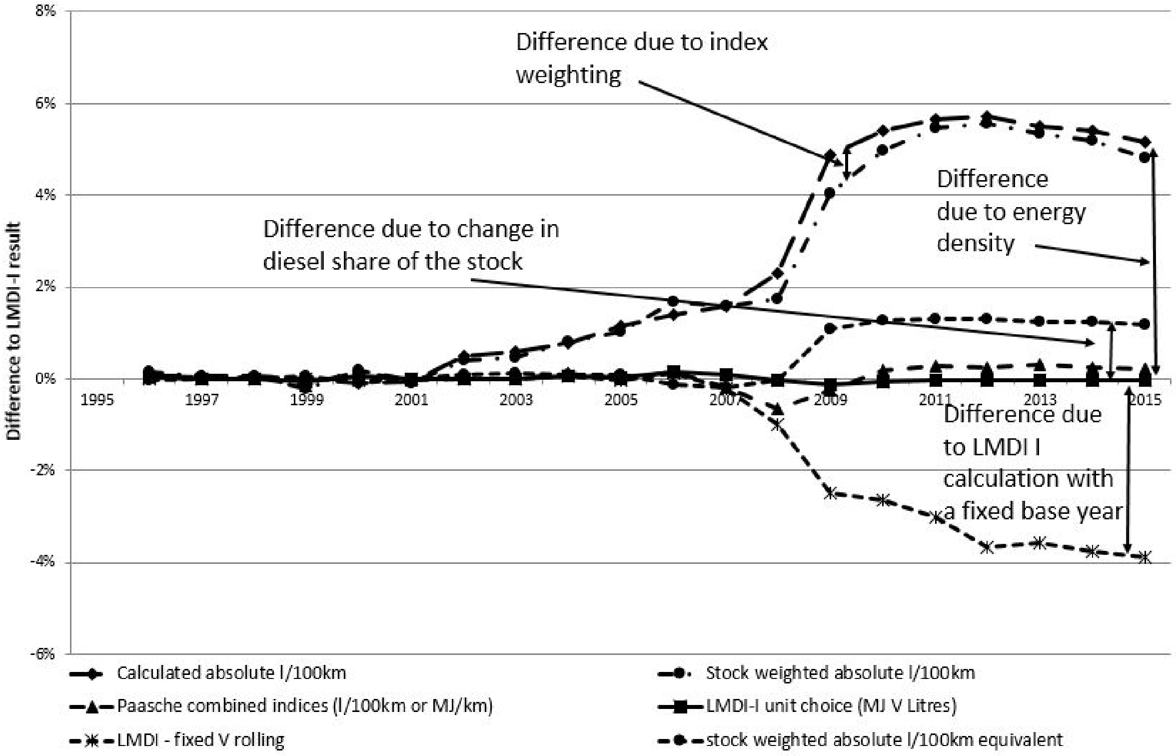
|---|---|---|---|---|
| | Paasche aggregated indices | 0.6625 | +0.27% | 3 |
| | LMDI-I aggregated indices | 0.6643 | – | 4 |
| Energy consumption (MJ/km) | Stock absolute calculated | 0.6527 | +1.8% | 1 |
| | Stock absolute technology share weighted | 0.6535 | +1.7% | 2 |
| | Paasche aggregated indices | 0.6625 | +0.27% | 3 |
| | LMDI-I aggregated indices | 0.6643 | – | 4 |
| | LMDI absolute technology share weighted | 0.6643 | | 5 |
| | LMDI aggregated indices fixed-base year (unchained) | 0.7035 | -5.6% | 6 |

Notes:

1. The stock calculated fuel economy or energy consumption performance is the total litres or energy divided by the total vehicle kilometres. When calculated in fuel economy (l/100km) the different energy densities of the fuel exaggerate the improvement, hence the 4 percentage point difference (an 11% over estimate) relative to the change calculated using energy consumption.
2. The difference between the stock weighted calculations of fuel economy or energy consumption is due to the stock weighting not representing the activity (vehicle-kilometre) share of the stock.
3. It is interesting to note that the difference in units of the indicator (l/100km or MJ/km) does not impact of the Paasche (fuel weighted index) calculations.
4. Note the results of the LMDI-I analysis are slightly different for the two metrics compared, even though the results of the Paasche analysis are the exact same when measured in different unit. This is because the multiplicative LMDI-I coefficients are slightly different when calculated in different units. However, this difference can be considered negligible. There is no different between the results of an LMDI-I analysis based on the absolute energy consumption or the index of change in the energy consumption.
5. When both technology metrics are calculated using LMDI-I index, there is no different between using the weighted of the absolute energy consumption or the weighted average of the index of change in the energy consumption.
6. The results of an unchained LMDI-I analysis gives a results that is not close to the individual improvement of the technologies examined.

Further comparison of the indices of energy efficiency improvements using different metrics, as described in figure 4 and table 1, leads to the observation is that the rapid change of the share of diesel vehicles in the stock enhances the size of the distortion in the overall measure of efficiency of the stock. It can be seen from figure 4, that where the stock share changes rapidly (2007 - 2009), there is an associated increase in the margin of error between the volumetric based indicator (l/100km), the lge/100km metric and the energy based metric (MJ/km). The difference between the index of energy efficiency measured in volumetric terms (l/100km) or in energy term (MJ/km) increases over time, and is strongly correlated (0.998) to the rapidly changing technology share in the stock.

Figure 4 Comparison of different energy efficiency measures relative to the result of LMDI-I analysis



The choice of the weighting in the analysis being either based on stock numbers or based on vehicle mileages also contributes to a distortion in the results. The more accurate weighting to use is based on activity (vehicle kilometres) rather than stock numbers. As can be seen in table 1 the impact of the index weighting depends on the metric, with the greatest impact for new passenger cars (a 1.5 percentage point difference) related to the lge/100 km metric.

Further, it can be seen from figure 4 that the fuel density was not the only factor to influencing the distortion or error in the calculation. The choice in decomposition methodology and the choice of the setup of the decomposition analysis can also have a significant impact.

While it has been proposed that using an unchained system is likely to exclude the influences of fluctuating parameters (Cahill and Ó Gallachóir, 2010), it can be seen that this is not true in the case study examined. For new cars there was a 5.6% underestimate in the efficiency improvement (MJ/km) when a fixed based year estimate was compared to that of a rolling base year.

A significant difference between the case study examined in this paper and that of Cahill (Cahill and Ó Gallachóir, 2010), is that a technology specific indicator rather than an activity-based indicator is used. This means that fluctuating variables are less likely to change the efficiency indicator. As the expected outcome of the change in energy efficiency should be of the order of the individual fuel or technology improvements, it is obvious from the results included in table 1 and figure 4 that the unchained LMDI-I analysis is not accurate.

Therefore using an unchained analysis does not constitute a solution for filtering the impact of fluctuating parameters on an index. Rather than an unchained calculation being path independent it actually follows the logarithmic path between the starting and final years analysed.

The distortion in the absolute changes, due to the different energy densities of the fuels examined, in conjunction with the activity weighting reinforces the need for a better stock model. This stock model should also include a fuel or technology split in order to accommodate isolating the impact of fuel or technology switching from the impact of energy efficiency.

It should be noted that similar distortions or erroneous quantification of the efficiency improvement are likely to occur in the analysis by other countries or regions, especially when associated with rapid change in the technology makeup of the stock. A scenario where is this likely is in developing economies where transport demand is anticipated to accompany economic growth.

## 3.2. Impact of model configuration

The results of a 3-factor LMDI-I decomposition analysis are presented in Table 2. The growth in the vehicle stock numbers (activity) resulted in the most significant increased in passenger cars energy consumption in Ireland over the 20-year period 1995 to 2015, at an increase of 128%. The fall in the average annual mileage of passenger cars is linked to the growth in the number of vehicles per households, where second or third vehicles per household become more commonplace and there is a corresponding reduction in the mileage per vehicle. Over the period 1995 to 2007 there was significant growth in the Irish economy (257% or just over 11% per annum growth in GDP) which resulted in a 216% (or 10% per annum on average) increase in disposable income (CSO, 2015a & 2015b). Households or families could afford to purchase and run more than one vehicle which had the overall impact of decreasing the average annual mileage of the passenger car stock; although with higher vehicle ownership the net effect was overall mileage growth

Table 2LMDI-I 3 factor decomposition analysis modeled by fuel but with a crude (2 category) vintage model

| % change | Stock | Mileages | Efficiency |
|---|---|---|---|
| Overall | 120.50 | -13.62 | -11.27 |

While there was a fall in the annual average mileage per vehicle of 17% for gasoline vehicles and 8% for diesel vehicles, there was an overall increase of 1.4% for the total stock average mileage per vehicle (due to a shift to diesel fuelled vehicles), a significantly different trend to the rate of improvement of energy efficiency (16% for the entire stock, 11% for gasoline and 21% for diesel). Therefore it seems unlikely that the mileage impact and energy efficiency impact are of a similar scale. This is a finding that merits further investigation and is likely to be strongly linked to the crude and limited stock model of only two vintage categories, namely; new and existing (as detailed in equation 4), which is leading to the underestimation the efficiency improvement.

### *3.2.1. Disaggregation by vintage*

Based on administrative data in Ireland passenger cars can be disaggregated into vintage categories from 1 to 16 years old with a final category of 17 years or older. Using the detailed vintage stock model with a full three-factor LMDI-I decomposition analysis, the efficiency improvement is quantified as 20%, almost twice that when estimated using a crude stock model using just two vintage categories. The result clarifies that the relative impact of the efficiency and mileages are very different, contrary to the results using the crude stock model.

This highlights the important of using as much disaggregated data as is available and the significant impact that the stock model can have on the analysis results. Such disaggregation also adds a dimension of policy interest, as the average vehicle age is something that can be influenced by policies, such as mandatory vehicle roadworthiness tests for older vehicles, vehicle scrappage schemes or even policies to target the market average efficiency of vehicles by encouraging the purchase of newer vehicles.

An uncertainty analysis on the average annual mileage figures in introduced in section 3.3.4, but even with the large variation examined in that section, the ranking of the impact of changes to the average annual mileage does not change. Note the results of the mileage uncertainty analysis are included in brackets in table 3.

Table 3COMPARISON ON THE LMDI-I 3-FACTOR DECOMPOSITION ANALYSIS FOR OVERALL ENERGY COMSUMPTION AND ENERGY CONSUMPTION BY FUEL

| %change | Stock | Mileages | Efficiency |
|---|---|---|---|
| Overall | 137.8<br>(108.2) | -13.4<br>(-19.0) | -19.6<br>(-19.4) |
| Gasoline | 36.3<br>(26.8) | -16.7<br>(-10.5) | -16.6<br>(-17.0) |
| Diesel | 548.5<br>(556.9) | -8.32<br>(-9.37) | -22.7<br>(-23.3) |

Note: the numbers in the brackets are the result of the analysis for which a mileage decay rate of 2% per annum is introduced, as well as a significant change in diesel mileages which reflects usage of 'new dieselists' as closer to petrol mileages.

When three separate time periods are examined as presented in table 4, a different picture emerges again. It can be seen that the growth in the overall stock of vehicles, especially between 1995 and 2007, had the most significant impact on energy consumption. The reduction in average annual mileage over the period 2000 to 2008 resulted in a greater decrease in energy consumption than the decrease in vehicle energy consumption (MJ/km). This trend was reversed between 2008 and 2013 when the efficiency improvement had a far greater impact than the change to the average annual mileages, influenced by both EU and Government policies.

Table 4 3-factor decomposition for different time periods

| | 1995 - 2015 | 1995-2000 | 2000-2008 | 2008-2015 |
|---|---|---|---|---|
| Stock activity | 6.00 | 6.27 | 8.66 | 5.35 |
| Stock mileage | -0.58 | -0.03 | -1.09 | -0.65 |
| Stock efficiency | -0.83 | -0.65 | -0.73 | -1.59 |
| | | | | |
| Petrol activity | 2.35 | 6.53 | 6.11 | -6.47 |
| Petrol mileage | -0.68 | -0.02 | -1.13 | -1.08 |
| Petrol efficiency | -0.75 | -0.64 | -0.80 | -1.12 |
| | | | | |
| Diesel activity | 20.70 | 5.15 | 19.15 | 52.79 |
| Diesel mileage | -0.39 | -0.07 | -0.99 | 0.00 |
| Diesel efficiency | -0.91 | -0.70 | -0.48 | -2.24 |

### *3.2.2. Disaggregation by technology and time*

Examining the individual technologies separately reveals different trends. The technological efficiency improvement rate of the entire gasoline vehicles stock at 14% was close to the diesel stock improvement of 18% between 1995 and 2015. However, there was a greater reduction in energy demand due to a reduction in average annual mileage of gasoline vehicles -14% than the reduction of just -8% in diesel vehicles, over the same period. The growth in the number of gasoline vehicles resulted in an increase in energy demand of 47% over the period considerably less that the increase in energy demand of 414% due the growth of the diesel passenger cars stock.

Furthermore examining different time periods it can be seen from table 4 that the growth in the number of diesel vehicles over the seven-year period (2008 to 2015) was responsible for almost three quarters of the overall impact of the growth in stock numbers of that fuel for the entire 20-year period (1995 - 2015). Even more significant, the change in the efficiency over the same six-year period nearly doubled relative to the change that had taken place between 1995 and 2008. The same cannot be said for the change in the efficiency of gasoline vehicles, which had the greatest impact between 2000 and 2009. There was a significant drop in the number of vehicles in the gasoline stock between 2008 and 2015, due to significant fuel or technology switching in the passenger car stock.

## 3.3. Examining more factors

As presented in table 4 and in sections 3.2.1. and 3.2.2 that the impact of the different trends of the individual fuels cannot be determined from the analysis of the overall stock. However adding a dimensionless or unit less parameters which represents the technology share of the stock (TS in equation 5), the impact of technology switching can be quantified and then compared relative to the other factors examined. However interpretation of this factors need careful consideration as described in the next section, section 3.3.1.

Similarly, a vintage share parameter (VS in equation 5) can be added to clarify the overall impact of changes to the age profile of the stock on energy and emissions. Thus extending the decomposition analysis from the three-factor (equation 1) to a five-factor analysis (equation 5) facilitates understanding the influence of changes to the passenger cars stock of the fuel mix share and the vintage share. The full results of the five-factor analysis by fuel and overall are provided in table 5 and are discussed further in the section 3.3.5.

Table 5 LMDI-I 5-FACTOR DECOMPOSITION ANALYSIS FOR OVERALL ENERGY COMSUMPTION

| % change | Stock | Mileages | Efficiency | Aging | Technology Share |
|---|---|---|---|---|---|
| Overall | 98.27<br>(98.28) | -13.40<br>(-19.00) | -19.57<br>(-19.39) | 4.76<br>(-0.09) | 14.49<br>(5.09) |

Note: the numbers in the brackets are the result of the analysis for which a mileage decay rate of 2% per annum is introduced, as well as a significant change in diesel mileages which reflects usage of ‘new dieselists’ as closer to petrol mileages.

### 3.3.1. *Technology switching*

The overall growth in the number of vehicles remained the most significant factor driving increasing energy consumption over the period 1995  to 2015, resulting in a 94% increase in energy consumption (see table 4).  The growing share of diesel vehicles in the stock caused a 12% energy increase between 1995 and 2015, but when examining the impact of different time periods it can be seen that the period 2008 to 2015 showed the most significant increase in the diesel stock and the technology share (TS) factor.

The cost of diesel vehicles (technology cost) are more expensive that gasoline PLDVs, but the cost of diesel as a fuel has historically been lower than petrol.  The fuel cost difference is primarily driven by different taxation level (such as excise duty) being applied to gasoline and diesel, because of the reliance on diesel in the freight transport sector. The heuristic that generally applies is that it is financially advantageous to pay a premium for the diesel vehicle technology, where the vehicle mileage is at the higher end of the PLDV range (Schipper et al., 2002).

It is interesting to note that while the impact on fuel economy or energy consumption of an increased share of diesel vehicles is to accelerate the improvement in that metric, the overall impact of an increased diesel share is increased energy consumption and emissions.  This is primarily because diesel vehicles have traditionally had significantly greater mileage than gasoline vehicles.

### 3.3.2. *Biofuels*

The main reasons for biofuels blending are to reduce reliance on imported petroleum products and also reduce associated green house gas emissions. So while the impact of biofuels is ranked at the least significant impact in terms of energy consumption, it is worth exploring the impact in terms of $CO_2$ emissions.

The impact of biofuels on $CO_2$ emissions, while remaining relatively small when compared to the other factors examined increased threefold compared to the contribution that biofuels make to the reduction in energy demand. This highlights the emissions reductions can be decoupled from technical vehicle efficiency improvement by inter-fuel substitution or technology switching.

However, it should be noted that there are environmental sustainability questions related to the production of some biofuels.  Depending on production methods and direct and indirect land use change, first generation biofuels sourced from oil crops, sugars and cereals can have small greenhouse gas emissions savings (EU, 2009c). Concerns about indirect land-use change due to biofuels from crops grown on land that could be used for food and feed markets, started a push towards biofuels from alternative sources such as wastes and algae in Europe (EU, 2015). However, significant volumes of these second generation biofuels are not yet currently available for blending.

### *3.3.3.  Mileages and mileage uncertainty analysis*

The average passenger cars mileage by fuel type in Ireland is calculated from a national roadworthiness test database on odometer readings. As new vehicles are exempt from the roadworthiness tests until they are four years old, the average mileage of the new cohort of smaller engine sized diesel vehicles largely still remains to be seen.  By comparing the purchasing pattern to gasoline fuelled vehicles and attributing these vehicle mileages to diesel vehicles in the same engine sized band, a further insight into the impact of fuel switching in the passenger cars fleet is gained.

An uncertainty analysis was introduced on the average mileages used for diesel vehicles purchased since 2008.  Prior to the tax change in July 2008, it was only economical to purchase a diesel vehicle if you had significant mileage (SEAI, 2014).  However, since the tax change diesel vehicles became more available and the purchasing trends changed – there is reason to believe that so-called “new dieselists” (Schipper, 2011) do not significantly change their travel patterns (mileages) from when they owned gasoline vehicles.

To examine the possible impact of a reduction in diesel mileages and extreme case was examined, where all diesel vehicles purchased from 2008 were attributed mileages of gasoline vehicles.  The results, included in brackets in Table 3 and 5, demonstrate that while the absolute impact of mileage change is increased consumption, the ranking of the impact of the mileages does not change relative to efficiency improvements or any of the other factors examined.

Many studies have found that the average mileage of vehicles reduces as the vehicles age (Van den Brink and Van Wee, 2001), (Schipper, 2009). A mileage decay factor was also introduced in order to reflect the fact that newer cars a driven more that older vehicles. A mileage decay factor of 2% per annum had been previously calculated for the Irish passenger car fleet (Daly & Ó Gallachóir, 2011). The impact of the mileage factor can be seen in the results in brackets in tables 2 and 3. Introducing a mileage decay factor does not change the order of ranking of the vehicle mileage impact compared to the other factors examined in the decomposition analysis and is therefore not considered significant in the test case examined.

### *3.3.4. On-road or real world consumption*

A further uncertainty analysis was introduced to examine the impact of the difference between on-road and laboratory test vehicle efficiencies. In 2015 an ICCT (International Council on Clean Transportation) publication (Tietge, U., et al, 2015) highlighted that difference of up to 40% are now common, as manufacturers optimise for test procedures, whereas previously the difference had previously assumed to be approximately 15-25% (Schipper and Tax, 1994) or more recently 20 to 25% (Fontaras & Dilara, 2012). The ICCT 2017 update further raised the difference to 42% (Tietge, U., et al, 2017).

The on-road factor will vary from country to country due to different driving styles, road infrastructure, settlement patterns and the size of urban centres. The factor within a country can vary from year to year with changes in speed limits, congestion and route changes (e.g bypass roads or longer or increased motorways). On-road factors for Ireland were previously estimated for 2005 by comparing spending patterns to bottom up estimates of the volume of fuels used (Daly & Ó Gallachóir, 2011) based on data from the national statistics office Household Budget Survey.

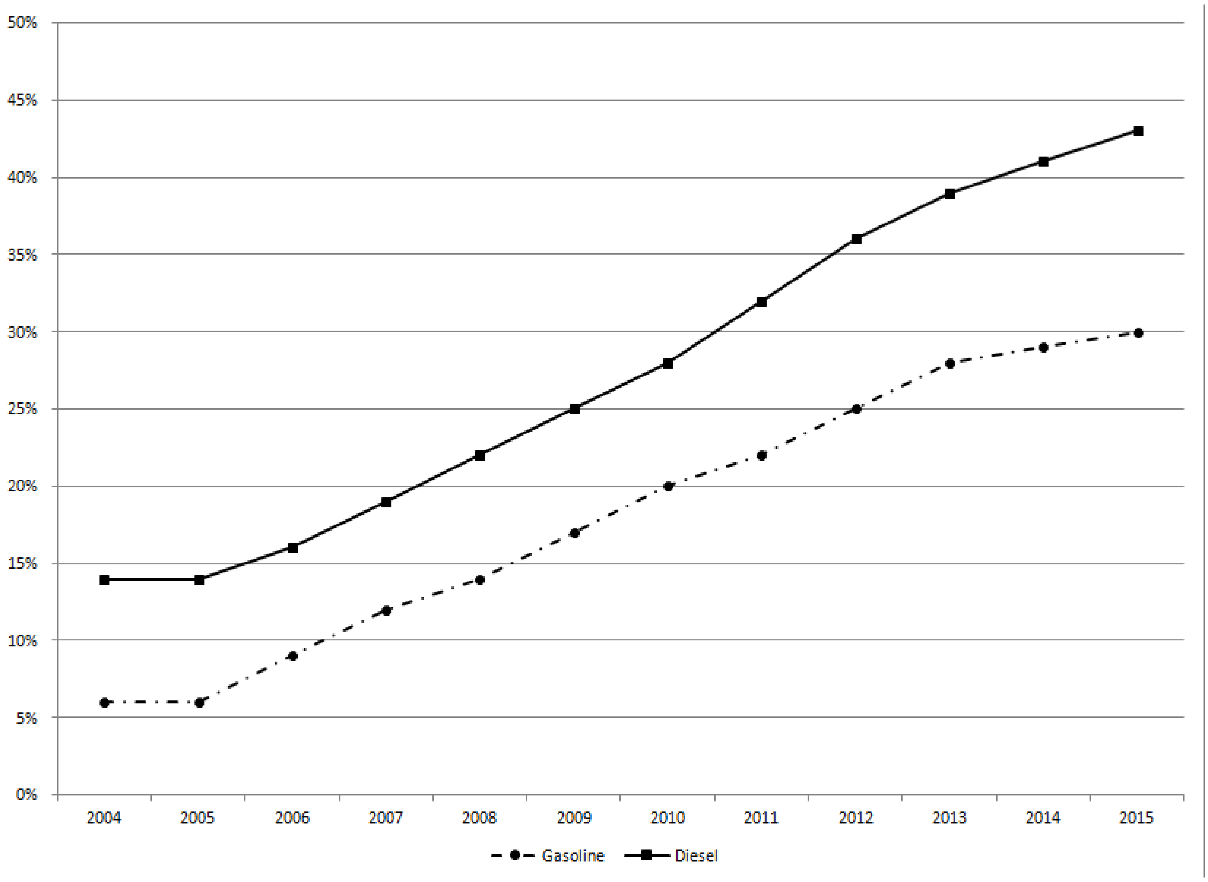
While that analysis used the same constant value for all years, as more recent Household Budget Survey is now available for this paper another reference point was calculated based on the same methodology which provided an estimate to 2010. A linear interpolation was used to estimate the on-road factor for the intervening years (2006-2009) between surveys. To get a more up-to-date figure without the availability of another Household Budget Survey, the estimated total volume from the improved bottom up model was compared to the total consumption reported by the National Oil Reserve Agency (NORA) – the Irish agency with responsibility for maintaining national oil stocks (NORA, 2015). This is only the case for gasoline consumption, as the motor diesel consumption is not attributed to the various road transport end uses (light and heavy duty road freight vehicles) and thus contains the total consumption of private and public passenger vehicles as well as light- and heavy-duty road freight vehicles.

Table 6 Calculated on-road factors for Ireland from 2005 to 2015

| | 2005 | 2006 | 2007 | 2008 | 2009 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Gasoline | 6% | 9% | 12% | 14% | 17% | 20% | 22% | 25% | 28% | 29% | 30% |
| Diesel | 14% | 16% | 19% | 22% | 25% | 28% | 32% | 36% | 39% | 41% | 43% |

The relative difference between the household budget survey gasoline and diesel on road factors for the entire vehicle stock was used to estimate the diesel on-road factor. This resulted in factors that increased over time from the 2005 estimates to a gasoline and diesel on-road factor of 30% and 43% respectively for 2015 (see table 6) - which is similar to the factor estimated by other studies mentioned in the first paragraph at the start of this section (section 3.3.4). The on-road factor for both gasoline and diesel are also increasing over time as shown in figure 5, this reflects that growth in the stock of the number of vehicles that were tuned to run optimally for vehicle labelling tests.

Figure 5 Difference between average laboratory test values and on-road performance for a vehicle stock



### 3.3.5. *Vehicle vintage and aging*

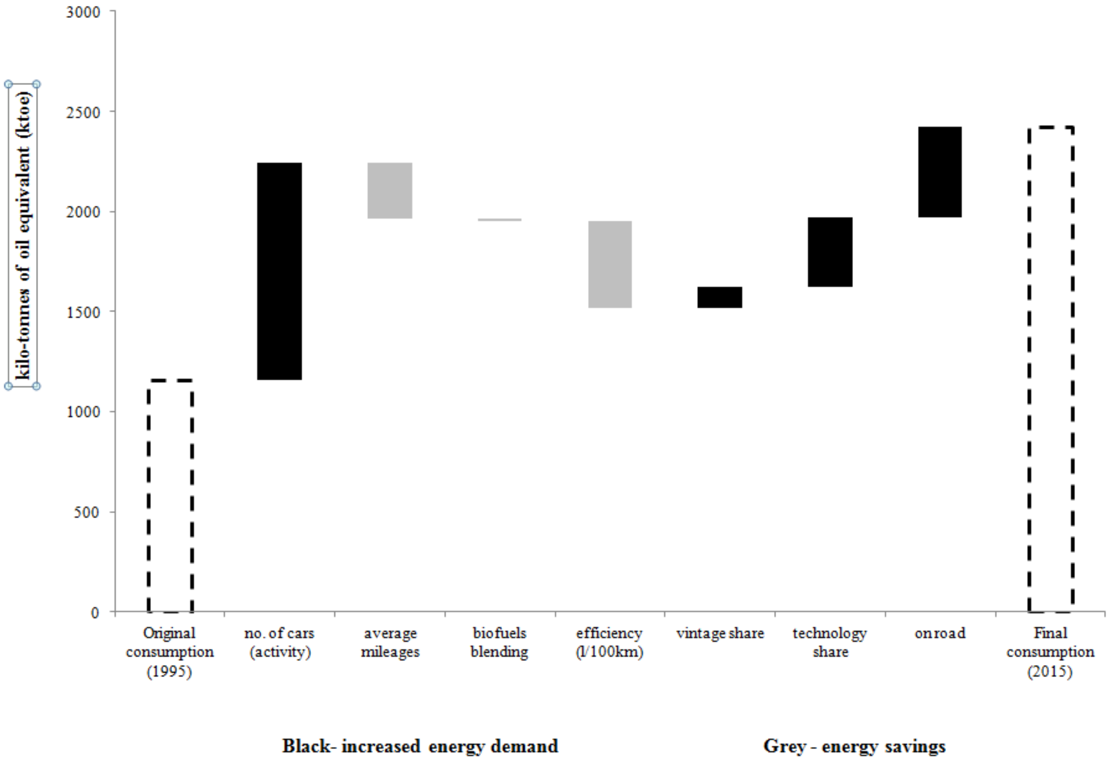
The change in the vintage shares of the stock also resulted in an increase in overall energy consumption but at a 4.8% increase, however this influence was less than a third of that of the technology switching from gasoline to diesel vehicles. While influencing the vintage of the fleet (over average age of the fleet) is a readily accessible policy lever, there should be caution when interpreting the aging factor. The analysis includes deterioration in fuel efficiency from the year after the initial purchase; however it is unreasonable to expect the entire fleet to be as efficient as newly purchased vehicles, so there should be tolerance to allow for a reasonable average age of a vehicle. Furthermore it may not make sense either economically or environmentally (Van Wee et al., 2000), (Hennessy & Tol, 2010), (Grigolon et al., 2016) to encourage a significantly younger fleet, especially for non-vehicle manufacturing economies. However, it could be argued that in conjunction with a change in technology, incentivising a younger vehicle fleet is an option that merits further analysis.

### 3.4. Ranking of factors examined

The impact of the energy efficiency improvement should not be considered in isolation from the on-road impact, and when both factors are examined together it can be seen that energy efficiency improvements cannot be relied upon to control or limit energy and emissions in passenger car transport. This is because the on-road impact will counter at least some – if not all- of energy efficiency improvements claimed by vehicle manufacturers.

In the test case examined the on-road factor and energy efficiency improvement were ranked as the second and third most influential factors respectively but with opposite effects the net impact of both factors combined was that none of the efficiency improvements calculated from vehicle manufacturer labels were realised. The impact of the increasing on-road factor over time is to significantly increase energy consumption and was second in magnitude to the growth of the stock, negated 80% the reduction in demand from the combined impact of efficiency improvements and reduced annual average mileages. This can be clearly seen from the results of a seven factor analysis included in figure 6.

Figure 6 Results of full seven-factor energy LMDI-I decomposition analysis



At best the net impact of technical energy efficiency improvements as measured on-road are relatively small and are likely to be more difficult to improve further in future, thus a higher proportion of efficiency improvements must arise from behavioural factors, such as tyre pressure monitoring and gear shifting.

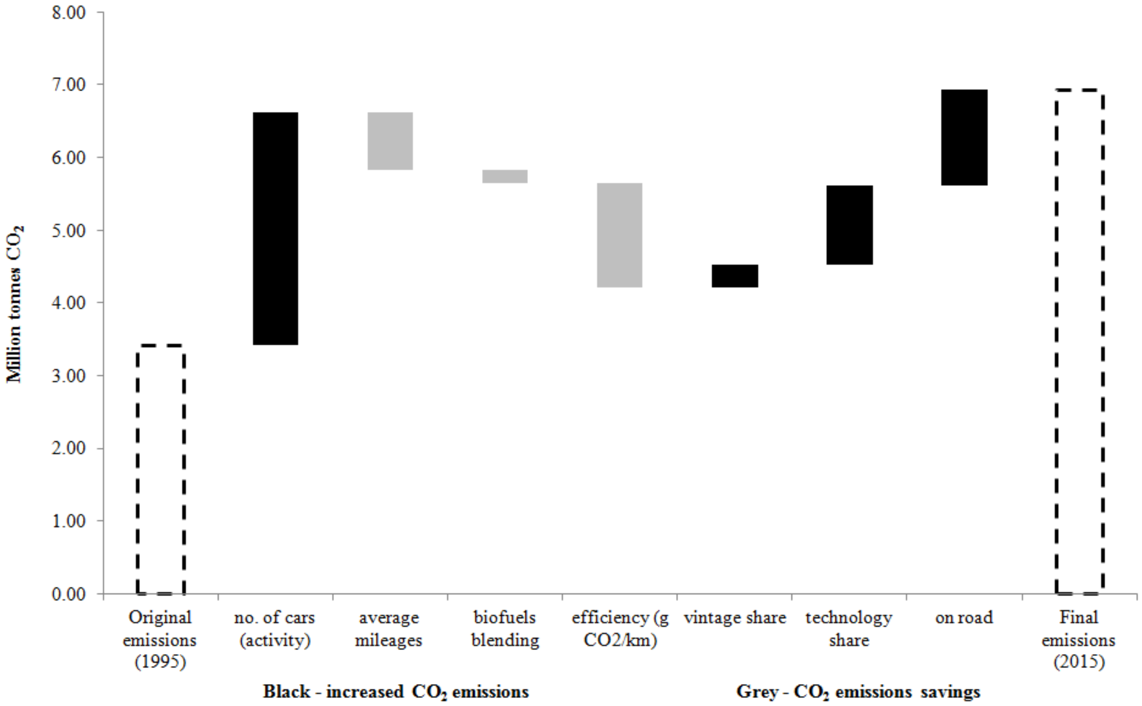
It is interesting to note that the overall impact of the shift toward diesel vehicles, the fourth most influential factor in the test case examined resulted in an increase in energy consumption as quantified by the technology share factor in the test case examined.

Technology switching, in conjunction with measures to control the passenger car stock size and usage, are needed in order to maintain or decrease current passenger car energy consumption and associated emissions.

The impact of vehicle mileages on overall energy consumption over the period examined exerting a downward pressure on consumption was interesting, even though such an impact should be considered in the context of the overall increase of the vehicle stock number. Although ranked as the fifth most influential factor in terms of magnitude, significantly the mileage factor had the most significant energy and emissions curtailment impact if on-road vehicle performance is used as the measure of the efficiency improvement.

Interpreting the aging factor is not as straight forward as the improved efficiency of newer vehicles is account for in the efficiency factor. Notwithstanding that caveat, it can be concluded that the aging fleet is not a major influence in terms of energy or emissions in the Irish passenger car fleet. Furthermore the results of the $CO_2$ emissions analysis presented figure 7 further confirm that aging is one of the least significant factors influencing overall emissions, as biofuels move from having the least impact in energy terms to have more of an influence than aging when ranking the influence on $CO_2$ emissions.

Figure 7 Results of full seven-factor LMDI-I decomposition analysis for $CO_2$ emissions



## 4. DISCUSSION: DATA GAPS AND FUTURE ANALYSIS

In order to understand the drivers of passenger car energy consumption and associated emissions additional focus on gathering data to allow for more accurate modelling of the on-road factor, as well as consumer choices and additional behavioural factors are necessary.

The new European driving cycle (NEDC) was introduced in the 1980's and last updated in 1997. As the cycle was not developed to measure fuel consumption of $CO_2$ emissions, was replaced with a new worldwide harmonised light vehicles test procedure (WLTP) from June 2017. It is mandatory for all new car models from September 2017 and for all new cars from September 2018. However, it is still recommended to use random testing and PEMS to test vehicles in real world driving conditions (Tietge et al,. 2017).

Perhaps the EU could also adopt a similar stance to the US EPA (United States Environment Protection Agency) which requires auto manufacturers to revise fuel economy labels if relevant information becomes available that show that values are too high (US EPA, 2017). The data also continues to support earlier findings that enforcement in the United States is far more effective and stringent than in Europe (German, J., 2017).

Inherent in the European agreement with car manufacturers on fuel efficiency are improvements from other factors include rolling resistance (tyre pressure) and eco-driving. However as these factors relate to behaviour, they are both difficult to model and rely on for actual savings. Further efforts to monitor the impact of behaviour could be combined with the efforts to quantify the difference between test consumption figures and on-road or real-world consumption values.

Disaggregation of the Irish passenger car stock by engine size band would provide another dimension for characterising the stock, related to purchasing trends, to be included directly in the decomposition analysis. The growth in the average engine size of the stock is linked to the increasing share of diesel vehicles. There has also been a trend of increasing engine-sized diesel cars both internationally (Schipper, 2011), (Sprei and Karlsson, 2013), (Zachariadis, 2013), as well as in the new diesel car stock in Ireland (SEAI, 2014), which reduces some of the supposed carbon emission benefits of these cars.

Anecdotally this engine-size growth is also linked to the prevalence of diesel cars as a choice for company cars. Unfortunately, an authoritative data source on company car statistics is not available in Ireland. Data on company cars would be interesting as recent tax changes, such as the special zero tax rating on electric vehicles under benefit in kind (BIK) rules in Budget 2018.

Further data mining could possibly provide the breakdown in mileages by engine size band. However it should be noted that as odometers reading are only available for passenger cars that are four years or older, there will be a significant unknown in variation of mileage by vehicle age if analysis is limited to the Irish NCT (National Car Test) database.

An aging factor could also be included for every year the cars of a particular vintage remain in use within the stock, as it is widely recognised that fuel economy (l/100km) deteriorates with age and that older cars are serviced less frequently. Only one study quantified an aging decay factor as a constant of 0.3% per annum which is the same for all fuel types (Van den Brink and Van Wee, 2001). This is the value used included in the case study included in this paper, but as it does not change over time this again factor cannot influence the results of a decomposition analysis. If more detailed empirical data on the impact of aging on fuel efficiency were available, and if that aging factor varied over time the analysis could be extended to an eight factor decomposition analysis.

## 5. CONCLUSION

An indicator commonly quoted for the energy efficiency of passenger cars is the fuel consumption (or fuel economy) measured in litres per 100 kilometres (l/100km) is problematic for a number of reasons. Firstly, a single metric used to convey the overall stock fuel economy value is distorted by the different energy densities of the various fuels used for passenger cars. As shown in the Irish case study this distortion led to a 12% overestimation of the passenger car new vehicle fleet efficiency improvement.

Secondly, a single indictor does not facilitate isolating the impact of technology switching from technical energy efficiency. The global push to diversify the fuel mix for passenger carss, including electric and hydrogen vehicles[12] strengthens the argument for raising the importance of quantifying the impacting of inter-fuel substitution. A full decomposition analysis with as much disaggregation as possible is required to determine the best policy levers to control the energy consumption and associated emission of a passenger car stock.

This paper quantitatively confirms, at the level of national energy statistics, that vehicle fuel economy figures (obtained from the legislative requirement for vehicle manufacturers to provide the result of fuel economy tests in controlled laboratories for vehicle performance labels) are not a reliable indicator of efficiency improvement in passenger cars transport consumption. For the Irish test case, ex-post analysis suggests that the diesel passenger-car fleet is just over 40% higher than the vehicle manufacturer labels suggest. Similarly, the on-road factor is 30% higher than vehicle manufacturer labels. This corroboration significantly diminishes the value of relying on a single indicator to monitor energy efficiency trends in passenger cars fleets and reinforces the conclusion that monitoring more factors is an imperative.

The contribution of this paper is to expand the discussion of energy efficiency in passenger cars beyond a single indicator of technical efficiency improvement only, to examine the influence of a number of factors, including technology or fuel switching, on-road energy consumption and associated emissions. The impacts of indicator choice and decomposition analysis methodology, the setup of the analysis (fixed or rolling base year) and the level of model disaggregation on quantification of energy efficiency in transport are evaluated.

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[12] Electric vehicles can be measured in energy terms as kilowatt-hour per kilometre (kWh/km), however more frequently an ‘equivalent l/100km or mpg’ is quoted. An equivalent metric is most often similarly quoted for hydrogen vehicles.

The analysis concludes that understanding the savings potential and monitoring the impact of technology and behavioural changes on passenger car energy and emissions requires a more detailed and holistic analysis than is currently commonplace. When transport energy and emissions are analysed using as a full decomposition analysis - as in this paper - the results highlight that activity is the biggest driver of transport energy consumption and emissions.

The findings in this paper reinforce the rationale for an Avoid-Shift-Improve approach to transport energy policies (Schipper, L & Marie-Lilliu, C., 1999). The ranking of the impact of the factors suggests that addressing vehicle ownership is the powerful policy lever. Policy measures which target vehicle ownership and usage could have a powerful impact on passenger car energy consumption, especially in conjunction with technology changes. This policy advice is particularly relevant for developing economies, where most of the future growth in transport demand and associated emissions are anticipated and may still have the opportunity to influence land use and urban planning a critical early intervention to avoid transport demand.

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