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Rebound effects from speed and acceleration in electric and internal combustion engine cars: An empirical and conceptual investigation

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HIGHLIGHTS

- Vehicle rebound effects have been investigated for distance but not speed.
- We investigate speed rebounds for an e- and an ICE-car in controlled lab tests.
- We develop a mathematical model to include these with distance rebound effects.
- The e-car shows 20% speed rebound comparing 1975 and modern driving styles.
- The ICE-car shows speed rebound due to lock-in from auto gear ratios.

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ABSTRACT

Rebound effect studies of road vehicle travel focus mostly on increases in distance traveled after increases in energy efficiency. Average journeying speed also increases with energy efficiency, but rebound studies avoid quantifying speed-related rebound effects. This may underestimate rebound effects by around 60%. This study offers a first attempt to show how increases in speed and acceleration contribute to rebound effects, and how these can be quantified. Its empirical data is dynamometer test results for a plug-in electric car and an internal combustion engine (ICE) pick-up van with automatic transmission, each on the WLTP and NEDC drive cycles, representing driving styles from today and 1975 respectively. Rebound effects are estimated by comparing the WLTP and NEDC results, using typical 1975 energy efficiencies for the NEDC. The electric car shows a 20.5% speed rebound effect, and a mathematical development sets out how speed rebound effects can be included in traditional rebound effect analyses. Results for the ICE-vehicle do not allow a direct rebound effect estimate due to wasteful engine revving on the NEDC and wrong gear ratios for sedate travel. However, this can be seen as a form of 'transformational' rebound effect, where vehicle design locks drivers into fast driving styles.

1. Introduction

This paper addresses the hitherto unexplored issue of 'speed and acceleration rebound effects' in light road vehicle travel.

The rebound effect is a name given to the phenomenon that reductions in fuel consumption as a result of an energy efficiency increase are frequently less than those predicted through engineering estimates [1–3]. This effect was first identified by Khazzoom [4] and Brookes [5], and has been extensively investigated and quantified in most energy-consuming sectors over the past 35 years [6–8]. There is broad consensus that consumers tend to increase their consumption of energy 'services' (e.g. distance traveled, number of rooms heated, extent and brightness of lighting, etc.) when an energy efficiency increase reduces the cost of these services. This compromises the amount of energy saved. Only a portion of the energy efficiency increase therefore goes to reducing energy consumption (e.g. 70%), while the remaining portion (e.g. 30%) is 'taken back' to increase the level of energy services. Such a case would represent rebound effect of 30% [9].

Calculating rebound effects is very important for energy policy planning, as rebound effects reduce the energy savings that ensue from mandated energy efficiency increases, thereby frustrating energy saving and CO_2 emission reduction goals [6,10]. This is especially so for road transport, due to the large energy consumption and CO_2 emissions of this sector worldwide [11]. Road transport is responsible for approximately 17.5% of energy consumption in the European Union [12] and 23% in the US [13], including 16.5% from light vehicles. World car production

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increased from 30.0 million in 1983 to 56.5 million in 2013, an average annual growth of 2% (*op cit.*).

There is therefore a long tradition of rebound effect studies in road transport, including studies on light vehicles, road freight transport and public transport. Rebound effects for light vehicle travel in OECD countries were typically found to be in the range 10–30% around the turn of this century [3,14–19]. This is compatible with findings of more recent studies, e.g. for Sweden [20], the US [21] and Norway [22], while results found for Germany are higher, at around 50–60% [23,24].

For passenger transport, Wang et al. [25] found rebound effects of 45% in Hong Kong in 1993–2009, falling to 35% in 2002–2009, while Zhang et al. [26] found rebound effects of around 26% for 30 provinces in China. Freight transport rebound effects appear to be at the high end of the range [27]. Wang and Lu [28] found freight transport rebound effects ranging from 52% to 84% across 31 provinces in China. This study is concerned with light vehicles only, though the theoretical concepts here developed should also apply to freight and public transport.

The large spread of rebound results from existing studies is partly due to the different countries or target groups within those countries, and different methodologies employed. One important cause of these differences, which has not yet been explored, is the effect of increases in speed and acceleration as a result of energy efficiency increases. In general it is possible to classify almost all road vehicle rebound effect studies into two types: those which use distance traveled as the dependent variable, and those which use fuel consumption as the dependent variable. Distance traveled is only one behavioral effect of energy efficiency increases, whereas drivers might also increase their speed and/or acceleration in response to the knowledge that their vehicle is now more fuel efficient, i.e. that driving is cheaper [29]. If this is the case, rebound studies which use fuel consumption as their dependent variable are likely to record higher rebound effects than those which use only distance traveled.

It should also be noted that rebound effect studies may also be distinguished by their choice of independent variable: energy efficiency or fuel price. The most natural independent variable for rebound effect studies is energy efficiency, since the driver's response to a change in energy efficiency determines the rebound effect [1,30]. However, it is widely accepted that the inverse of fuel price change may be used as a substitute for a change in energy efficiency, since both are thought to result in the same proportionate change in the cost of travel [9]. But regardless of whether rebound studies use fuel price or energy efficiency as their independent variable, a clear distinction can be seen between those that map this to distance traveled, and those that map this to fuel consumed. The effect of this comes sharply into focus when we compare the results of these two types of studies.

Goodwin et al.'s [29] comprehensive review of vehicle fuel price elasticity studies maps changes in fuel price to changes in fuel consumption, vehicle fleet size, and traffic volume, which is used as a proxy for vehicle distance traveled. Goodwin and colleagues note that:

> *'The price elasticities for fuel consumption are higher than the elasticities for vehicle-km, i.e. when fuel price rises, people reduce their fuel consumption more than their mileage.'*
>
> [(op ct.: 284)]

They suggest this is because, when the price of fuel increases, drivers (a) reduce speed, acceleration and heavy braking, and (b) change to more fuel efficient vehicles in the longer term. They find average long-run fuel price elasticity post-1981 to be −0.43, but average elasticity of vehicle km −0.29. The gap of −0.14, which represents almost half the total elasticity, is caused by factors other than a change of driving distance. Since this is long-run elasticity, a portion will be due to upgrades to more energy efficient vehicles. However, the figures for short-run elasticity (changes within a year) are −0.16 and −0.10, where the gap is likely almost all due to reductions in speed and aggressiveness of driving. This suggests that some 38% (=6–16) of driver response to a change in the effective price of travel has to do with speed and acceleration, rather than distance. If that is the case, rebound effect studies which measure only distance might underestimate rebound effects by around 60% (=6–10).

A similar gap is found in Graham and Glaister's [31] review of vehicle fuel price elasticity studies. Here the average short-run fuel price elasticity of fuel consumption is −0.25, but that of km traveled is −0.15, a gap of the same proportions.

Most studies post-2004 also fall into these two categories. The rebound effect is defined in terms of distance only in Lindfeldt et al. [32] and Whitehead et al. [20] for Sweden; Greene [33], Hymel et al. [21], Simmons et al. [34] and Su [35] for the US; Frondel et al. [24] and Frondel and Vance [23] for Germany; Galvin [36] for the German state of North-Rhine-Westphalia; Zhang et al. [26] for China; and Odeck and Johansen [22] for Norway.

In contrast, fuel consumption is the dependent variable in studies by Schall and Mohnen [37] for Munich, Germany; Wang et al. [25] for Hong Kong; Wang and Lu [28] for China; Chitnis et al. [38] for the UK; and Dargay [39], Liu [40] and Wadud et al. [41] for the US.

Some studies use both fuel consumption and distance traveled in various types of multi-variate analyses, namely Sobrino and Monzon [42] for Spain; Whistance and Thompson [43] for the US; and Yu et al. [44] for Japan. Nevertheless there is no structured discussion in such studies as to the proportionate contributions that distance, speed, acceleration or other factors make to rebound effect results. This paper attempts to fill that gap by offering a structured account of how speed and acceleration contribute to rebound effects.

There are a few studies that note the effects of speed and acceleration on energy consumption, but these do not calculate rebound effects. Ericsson [45] finds the factors most influencing energy consumption are speed, aggressive acceleration and late upwards gear changing. Barth and Boriboonsomsin [46] investigate the influence of 'eco-driving' strategies on fuel consumption, finding that drivers who are prompted to moderate micro-features of their driving style in real time can reduce fuel consumption by 10–20% without increasing their journeying time. Van Mierlo et al. [47] find that a more 'fluent' and less 'sportive' driving style reduces energy consumption. Montag [48] notes that 'on-road fuel economy' is highly dependent on acceleration. MacKenzi and Heywood [11] find that an increase in vehicles' acceleration capability of around 1% leads to an increase in fuel consumption of around 0.44%. However, none of these studies relate their findings to rebound effects.

There is clearly a need for structured investigation of the influence of speed and acceleration on rebound effects, with clear demonstration of how results can be quantified. This paper offers a first attempt to break this new ground. Its main aim is not to produce a definitive figure for rebound effects due to speed and acceleration, but to explore how such rebound effects can be structured into a fairly standard, mainstream approach to rebound effects, worked through both theoretically and by way of two quite different empirical examples.

The paper continues as follows. Section 2 explores relevant theoretical and conceptual issues for average speed rebound effects. Section 3 gives details of the data sources and methodology. Section 4 presents the results, which are discussed in Section 5. Section 6 concludes.