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Energy consumption effects of speed and acceleration in electric vehicles: Laboratory case studies and implications for drivers and policymakers

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ABSTRACT

The number of electric vehicles in service throughout the world has increased from a few thousand in 2009 to some 740,000 in December 2014. These vehicles are often seen as a means of reducing climate and health damaging emissions, and their development is directly supported by some countries and endorsed by the EU. Aside from questions of rebound effects, embedded emissions and cleanness of electricity generation, there are unanswered questions about the energy performance of such cars under a range of driving conditions, and the results of existing studies are not easily interpretable by policymakers and drivers. This study uses the results of extensive dynamometer tests on eight commonly sold electric vehicles. It develops a multivariate model, with regression coefficients around 0.97, to map power demand and energy consumption for all likely combinations of speed and acceleration, producing accessible, easily interpretable displays. While electric vehicles are frequently marketed on the basis of their high acceleration, an important finding is that episodes of modest to high acceleration severely compromise their range and energy efficiency, regardless of speed. This also raises questions as to how well such vehicles perform in the erratic driving conditions of urban traffic.

1. Introduction

This paper develops user-friendly algorithms and graphical displays which offer reliable information on how moment-by-moment battery power demand and energy consumption vary as functions of speed and acceleration in eight different plug-in electric vehicles. Displays and results are also offered for total energy consumption over specific types of journeys. This information can be of use to both energy policy makers and the drivers of these vehicles. There are already existing studies intersecting with this area, but not for a representative range of electric vehicles in actual use. Further, the algorithms offered by existing studies are often of a more limited, technical nature suitable for specialists but not practitioners or members of non-automotive disciplines.

The last five years have seen a rapid increase in the numbers of these vehicles (called 'e-vehicles' in this paper), rising from a few thousand in 2009 to some 740,000 by the end of 2014 (CleanTechnica, 2015). The EU Commission has supported the development of e-vehicles since at least 2009 (EU Commission, 2009), and promoted their development and deployment as part of its policy on deployment of alternative fuels in 2014 (EU Commission, 2014). Some countries such as Norway

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subsidise e-vehicles through tax breaks and free or subsidised electrical charging, while others such as Germany encourage their development as a means of reducing climate damaging emissions and NOx and SO_2 emissions which have direct health impacts (Holtsmark and Skonhoft, 2014; Jochem et al., 2015).

There are moves at government level in the US to develop more sustainable transport (DOT, 2010), and electrification of passenger transport is seen as one of a number of ways to do this. It is argued that electric motors are inherently more efficient than ICE motors, there is already an electricity distribution network in place (compared to light biofuel infrastructure), and there are pressures on the electricity generating industry to reduce its own emissions (*op cit.* 6–7).

Recently a discussion has arisen as to whether e-vehicles do, in fact, reduce overall emissions (Arar, 2010; Jochem et al., 2015; Teufel et al., 2015). For countries generating electricity mostly through fossil fuels, much of the gain at the vehicle itself may be lost at the generating plant (Doucette and McCulloch, 2011; Duke et al., 2009). Even for countries which are moving rapidly towards renewable electricity generation, such as Germany, lifecycle analysis shows that emissions and wastes produced in the manufacture of e-vehicles and their batteries can negate most of the gains (Teufel et al., 2015). This raises the question of how and in what situations e-vehicles are more likely to meet emissions policy goals than internal combustion engine (ICE) or hybrid vehicles (Hawkins et al., 2012).

While these issues are central to discussion of the usefulness of e-vehicles in helping achieve emission reduction goals, a narrower but equally important issue is the power demand and energy consumption of e-vehicles on their journeys, particularly in relation to driving style. Given a country's mix of electricity generation types, emissions due to e-vehicle journeys will be proportional to their energy consumption. In a study on ICE and hybrid vehicles, Ahn et al. (2002) point to six types of variables that influence emission rates, which also apply to e-vehicles: travel-related, weather-related, vehicle-related, roadway-related, traffic-related and driver-related. This study focuses mostly on the driver-related factors of speed and acceleration. Distance traveled is a topic worth pursuing separately, from a behavioral point of view, as it may well be that the introduction of e-vehicles results in more journeys, or new types of car journeys that were previously made by public transport or bicycle or on foot, as Holtsmark and Skonhoft (2014) suggest for Norway.

This study also touches on vehicle-related factors, paying attention to the differences in energy consumption, and therefore emissions, between different e-vehicle models.

While studies on ICE vehicles show energy consumption increasing with speed and acceleration (Ahn et al., 2002; Bakhit et al., 2015), there are currently very few studies relating driver-related factors to energy consumption in e-vehicles. Karabasoglu and Michalek (2013) compare journey energy consumption of one e-vehicle with that of an ICE and several hybrid vehicles, on laboratory driving test cycles based on city and highway driving. They find the e-vehicle does better compared to the ICE and hybrids in the lower speed, interrupted conditions of urban driving, but worse on the open highway. Knowles et al. (2012) made similar findings using actual journeys by one e-vehicle driven by different drivers in turn. The vehicle performed more efficiently on interrupted urban routes than on the highway. This is thought to be largely due to the 'regenerative braking system' (RBS) in these vehicles. As e-vehicles reduce speed, their motor acts as a dynamo, generating energy rather than consuming it, thus returning some of the vehicle's rolling energy to the battery (Xu et al., 2011). Nevertheless, Xu and colleagues found that energy consumption increased with the 'aggressiveness' (propensity to speed and rapidly accelerate and decelerate) of driving style, which in part contradicts this assumption. An important factor is how large the magnitude of energy recovery is on deceleration, compared to the magnitude of energy consumption upon acceleration. Since energy recovery is less than energy consumption, there must come a point where slower but erratic driving is less efficient than faster but steady driving. This issue does not seem to have been explored to date, and is included in this study.

A detailed and comprehensive study of energy consumption in an e-vehicle is offered by Wu et al. (2015). This used a conventional ICE utility van, refitted with an electric motor, drive train, etc. and monitoring equipment. The vehicle was driven a total of 169 journeys on 4 different routes from 'home' to 'work' and back. A physics-based algorithm was developed to model battery power demand and energy consumption, using the independent variables speed, acceleration and angle of road grade, together with fixed values of vehicle mass, aerodynamic rolling and grade resistances, and the electrical characteristics of the motor. Algorithms such as this are useful for vehicle design and for estimating energy consumption in commercially produced vehicles for which these factors are known.

However, as yet there is no study that offers algorithms for energy consumption with speed and acceleration in an e-vehicle that are accessible enough to be used by policymakers or drivers to obtain a working familiarity with a vehicle's energy performance, yet accurate enough to be reliable for most purposes. There is also a lack of graphical displays of the sort that can help drivers see, quite directly, how various combinations of speed and acceleration in their particular e-vehicle will influence battery power demand and journeying energy consumption. This study was designed to fill this gap.

The study uses the data outputs of laboratory dynamometer tests on eight commonly sold e-vehicles. These are the Nissan Leaf SV 2013, Kia Soul Electric 2015, Nissan Leaf 2012, BMW i3 BEV 2014, Ford focus Electric 2013, Mitsubishi I MiEV 2012, Chevrolet Spark EV 2015, and Smart EV 2014. These vehicles are not described in detail here as their features can be readily found on their manufacturers' websites, though their mass is given in Table 1. The dynamometer tests were run by the Argonne National Laboratory in the US, which tests vehicles in each of the categories Plug-In Hybrid Electric, Electric, Conventional, Conventional-Start-Stop and Alternative Fuel, and makes the test result data publicly available (Argonne, 2015).

Dynamometer tests simulate specific journeys for vehicles which remain stationary on rollers in a laboratory. Each test run, or 'driving cycle', is a set of starts, stops, accelerations, decelerations and steady speeds, ordered to represent a chosen