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Testing energy efficiency and driving range of electric vehicles in relation to gear selection

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ABSTRACT

Electric vehicles (EVs) have the potential to be operated using a clean, renewable energy source. However, a major limitation is their relatively short vehicle driving range and the associated driver 'range anxiety'. This research investigates the effect of gearing on energy consumption and driving range efficiency on an EV-converted Ford Focus using a chassis dynamometer in a controlled test environment in accordance with international standards. Two designs of the Ford Focus were used in the tests; one with an automatic gear drive, and the other with a manual gear drive. The electricity consumption of the two cars driving under different gearing configurations was measured under identical drive cycles. The vehicle range tests showed that measuring energy consumption on just two consecutive drive cycles on a calibrated chassis dynamometer will lead to a small overestimation of the energy consumption due to a 'cold' drive train. The results also suggest greater attention needs to be paid to EV battery charger efficiency, particularly in terms of standby energy consumption, which can increase the total energy required for EV owners markedly.

1. Introduction

The International Energy Agency (IEA) states that transport accounts for about 25% of the total global CO_2 production [1]. Electric vehicles (EVs) are a viable alternative to internal combustion engine (ICE) vehicles and can contribute to reduction of energy security and supply risks, and mitigate carbon emissions and air pollution, provided the energy to run EVs is supplied from local renewable energy sources and is well-integrated with the electricity system [2–10]. Health issues and increased mortality from ICE vehicle air pollution is a consequence of increased exposure to exhaust gas emissions and particulates [2,5]. As a single example, an air quality study by Yim and Barret [11] found about 19,000 premature deaths in the UK per year due to combustion emissions generated in the UK and mainland Europe. This number far exceeds the annual road fatalities in the UK (1901 fatalities and 23,122 serious injuries in year 2011 [12]) or the estimated 7500 premature deaths from transport in general [11]. New and potentially cleaner transport technologies such as EVs, however, are not yet mainstream and their wider adoption has been hindered by several issues including high purchase costs, short vehicle driving ranges, limited recharging/refuelling stations, time-consuming recharging of batteries, vehicle safety, specialist vehicle applicability, and concerns of electricity infrastructure inadequacy in many regions [2,3,9,10,13–20].

The idea of the EV is not new; they first appeared in the mid-19th century when ICE vehicles required hand cranking to start [3]. Yet, after the invention of the electric starter motor for combustion engine vehicles, many EVs disappeared from the market and the ICE became the dominant vehicle propulsion technology. In 1997 Toyota developed the Prius, the first mainstream hybrid EV [21], primarily developed for improving fuel economy and more efficient urban driving [14]. Toyota reached a cumulative sale of two million Prius vehicles in 2010, making it the world's best-selling hybrid car, and in 2012 CNN claimed that by the end of that year most major car manufacturers will have a plug-in car available for sale [22]. Further trends towards large-scale manufacturing of EVs have become a political imperative, with President Obama's goal of one million EVs in the US by 2015, representing a milestone in the reduction of the dependency on foreign oil imports [23]. However,

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there is sparse refilling infrastructure available for EVs and they cannot be refuelled within a comparable time to liquid or gas ICEs [10,14]. The options for recharging EVs at present are limited to homes, some workplaces and a few official charging stations. Therefore, it is imperative that EV driving ranges are optimised, the cars are efficiently designed and the car is driven in an energy-efficient manner [24]. Nonetheless, many EV enthusiasts have not waited for buy-in from major car manufactures or widely available charging infrastructure [3]. In Australia, for example, an Electric Vehicle Organisation was founded in 1973 [25] and is still operational today, providing forums for social and technical communication to support the local car conversion industry, such as EV-Works in Landsdale, Perth, Western Australia [26], or Electric Vehicle Conversions in Balcatta, also in Perth, Western Australia [27]. These companies offer the conversion of a standard car into an EV. Fig. 1 shows one of the two Ford Focus vehicles tested for this study, both of which were standard factory motor vehicles that were converted by EV-Works into pure EVs [28]. Both vehicles had identical electric main drive motors, controllers and batteries (lithium-ion), with the only difference being the gearing.

2. EV testing and drive cycles

Measuring the performance and efficiency of EVs is a complex task when considering the effects of variable environmental factors, such as wind speed and direction, temperature, and ascending and descending slopes. All of these provide testing challenges and may significantly influence a vehicle's energy consumption and driving range testing results [4]. Many of these problems can be overcome by using a chassis dynamometer, a device capable of measuring forces on a car's wheels or engine. Some advanced chassis dynamometers are computer controlled and are capable of simulating driving under real road conditions.

Drive cycle testing was developed in the late 1960s for uniform emission testing on passenger cars with combustion engines [29,30]. A drive cycle represents a common driving pattern of motor vehicle users, and testing is usually performed on a calibrated chassis dynamometer to provide a stable, climate controlled and traffic-free environment. Drive cycles use predefined speed and acceleration profiles, and for a specific vehicle test, the (often human) test driver of the motor vehicle is required to follow the profile. To maintain the required profiles, a computerised driving aid supports the driver by indicating the rate of acceleration and deceleration of the vehicle, and vehicle operating conditions, to produce a valid test drive. Meeting these operating conditions is critical as the rate of acceleration, deceleration and vehicle speed influence vehicle emissions, energy consumption, etc., and heavily influence test results. Fig. 2 shows a typical computer driving aid used for this research and in industry for vehicle testing.

There are several international standards for chassis dynamometer drive cycle testing for combustion engine vehicles for different countries, and they all exhibit somewhat different drive cycle profiles and properties. The New European Driving Cycle (NEDC), introduced in 2000 [31], contains the European Union Urban Driving Cycle (UDC or ECE-15) and the Extra Urban Driving Cycle (EUDC), which is applied for Euro 3 standards and onwards emission testing. The first section represents the European Union Urban Driving Cycle from the Economic Commission for Europe (ECE) with a slow suburban test for 780 s. The second section represents a highway driving speed pattern for an additional 400 s at high speed with no stopping. In contrast, the US Federal city driving pattern for vehicle testing, which is also known as the FTP 75 (Federal Test Procedure) developed by the U.S. Environmental Protection Agency, exhibits a more 'aggressive' urban/city drive cycle than the ECE. The second section (highway driving) represents driving on a freeway with no stopping and little deceleration. The high dynamic variation in the FTP 75 city cycle is likely to represent a more 'real world' driving scenario than the ECE urban cycle with its 'flatter' shaped profile representing consistent and slow driving conditions. These drive cycle standards are also used for EV testing [32]. From an EV testing perspective, drive cycles provide a uniform testing procedure for range and energy consumption, and also for other performance testing including the evaluation of regenerative braking systems (RBS) and anti-lock braking systems (ABS). This research focusses on demonstrating efficiency and range characteristics using only gearing configurations without the benefits of RBS, which can vary considerably depending on vehicle and

Fig. 1. The licenced Ford Focus converted to an EV that was used in the research. Source: Ref. [37].

Fig. 2. Computerised driving aid for a human test driver to follow a predefined drive cycle used during the testing at Orbital's facility. The blue line in the centre of the track is the indication of required speed to be driven. The red lines show the driver the maximum allowed speed deviation for a valid test drive, and the crosshair is the present speed. The uncertainty of the results can be inferred by the difference between the speed reading on the dashboard (51 km/h), and the crosshair (~49 km/h) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.).