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Techno-economic and behavioural analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system in the UK

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ABSTRACT

This paper conducts a techno-economic study on hydrogen Fuel Cell Electric Vehicles (FCV), Battery Electric Vehicles (BEV) and hydrogen Fuel Cell plug-in Hybrid Electric Vehicles (FCHEV) in the UK using cost predictions for 2030. The study includes an analysis of data on distance currently travelled by private car users daily in the UK. Results show that there may be diminishing economic returns for Plug-in Hybrid Electric Vehicles (PHEV) with battery sizes above 20 kWh, and the optimum size for a PHEV battery is between 5 and 15 kWh. Differences in behaviour as a function of vehicle size are demonstrated, which decreases the percentage of miles that can be economically driven using electricity for a larger vehicle. Decreasing carbon dioxide emissions from electricity generation by 80% favours larger optimum battery sizes as long as carbon is priced, and will reduce emissions considerably. However, the model does not take into account reductions in carbon dioxide emissions from hydrogen generation, assuming hydrogen will still be produced from steam reforming methane in 2030.

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1. Introduction

Road transport today is responsible for a significant and growing share of global anthropogenic emissions of CO_2. Moreover, it is almost entirely dependent on oil-derived fuels and, therefore, highly vulnerable to possible oil price shocks and supply disruptions. Finally, using oil-derived fuels in internal combustion engines generates tailpipe emissions of pollutants such as PM_{10}, NO_X and VOCs which are harmful to human health.

Improving road transport requires all these issues to be addressed. Managing demand and promoting co-modality[1] can provide a partial solution, however, introducing alternative transport fuels and vehicles is also necessary in order to achieve the objectives of decarbonisation, energy security and urban air quality.

In this paper, two of the three alternative powertrain technologies considered by the International Energy Agency (IEA) as being capable of delivering a sustainable road transport system with near-zero emissions are addressed (IEA, 2008). The first is the Battery Electric Vehicle (BEV) and the second is the hydrogen Fuel Cell electric Vehicle (FCV). In this study, it was decided to focus exclusively on electric drive trains so the third option, biofuels, is not addressed.

Although the advantages and disadvantages of battery and hydrogen fuel cell technologies have been identified and discussed elsewhere (IEA, 2004; King, 2007; Bandivadekar, Bodek et al., 2008; Bandivadekar, Cheah et al., 2008; IEA, 2008; King, 2008; Tollefson, 2008; McKinsey, 2010) there is inadequate awareness of the strong synergies between them in road vehicle applications. Despite limited analysis comparing fuel cell and combustion engine range extenders for electric vehicles (Burke, 2007), BEVs and FCVs are still largely seen as mutually exclusive options. Moreover, the most recent high profile assessment of low carbon cars in the UK, the King Review (King, 2007), does acknowledge that a fuel mix including hydrogen and electricity is likely, but it implicitly assumes that this will be via different vehicle platforms, and not by a single vehicle with the capability to use both electricity and hydrogen. The Fuel Cell plug-in Hybrid (FCHEV) appears to have been mostly overlooked in the literature.

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[1] Co-modality can be defined as "the efficient use of different modes [of transport] on their own and in combination" so as to obtain "an optimal and sustainable utilisation of resources". Source: European Commission (2006). Communication from the Commission to the Council and the European Parliament. Keep Europe moving—Sustainable mobility for our continent. Mid-term review of the European Commission's 2001 Transport White Paper. Brussels, 22.06.2006. EC COM(2006) 314 final.

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Despite studies comparing conventional, hybrid, electric and hydrogen fuel cell vehicles (Granovskii, Dincer et al., 2006; Bandivadekar, Bodek et al., 2008; Bandivadekar, Cheah et al., 2008; McKinsey, 2010) there is limited literature on cost comparisons between fuel cell and fuel cell hybrids (Suppes, 2005; Van Mierlo and Maggetto, 2005; Suppes, 2006; Burke, 2007).

In response to this the authors demonstrated in a previous study (Offer, Howey et al., 2010) that a combination of electricity and hydrogen as a transport fuel could bring additional benefit to the end user in terms of both capital and running costs. A cost comparison of the lifecycle cost of BEV, FCV and FCHEV over 100,000 miles was undertaken, accounting for capital and fuel costs. A 2030 scenario was discussed and compared to a conventional gasoline-fuelled Internal Combustion Engine (ICE) powertrain. The sensitivity analysis showed that in 2030 FCVs could achieve lifecycle cost parity with conventional gasoline vehicles, but both the BEV and FCHEV had significantly lower lifecycle costs. All vehicle platforms exhibited the most significant cost sensitivity to powertrain capital cost, followed by hydrogen cost sensitivity and the lowest sensitivity to electricity cost. The key conclusion was that the best path for future development of FCVs is the FCHEV.

The results of the previous paper were also based on the assumptions that the plug-in FCHEV had a 6 kWh battery capacity and used electric power 50% of the time. These assumptions were somewhat arbitrary; in actual fact the optimum (minimum lifecycle cost) battery size of the vehicle is a strong function of the vehicle's specifications and driving pattern.

This paper further explores this issue by including car driving behavioural aspects in the analysis. Analysing data from the most recent UK National Travel Survey (DfT, 2008a,b) a nationwide distribution of distances currently travelled by private cars each day was generated, both aggregated for all car types and specific for main car types in turn. From this distribution, the percentage of total all-electric miles driven can be determined as a function of battery capacity; this percentage is also referred to in the literature as utility factor (Kromer and Heywood, 2008; Bradley and Quinn, 2010). This was then included in the model to determine how the electric only range and battery capacity affect the capital and fuel costs for different degrees of hybridisation. A combustion engine vehicle is included in the study for comparison purposes. Although we consider future efficiency improvements in combustion engine powertrains, the main focus of this paper remains the comparison between different electric powertrains based on batteries and fuel cells; hence a complete assessment of the future role of internal combustion engine powertrains also comprising plug-in hybrid architectures is beyond the scope of the present paper.

In addition, in the present paper, the CO_2 emissions from each option are included, and the effect that this has on the costs is discussed based upon a range of extended assumptions relative to the previous paper.

2. Driver behaviour analysis

In order to determine the correct sizes of the battery, the fuel cell and the hydrogen tank in a FCHEV, (i.e.: the optimum battery size assuming that the fuel cell installed power remains constant[2]), it is necessary to consider the distribution of daily driving distances over the lifetime of the vehicle. Optimum battery size is defined as delivering the lowest lifecycle costs.

Assuming batteries are only recharged at night,[3] it is the total distance travelled in a typical day and not the length of the single trip that matters. A trip is defined as "a one-way course of travel with a single main purpose" (Anderson et al., 2009), and several trips are possible in one day.

Both the total distance driven over the lifetime of the vehicle and the distribution of daily distances driven can be regarded as behavioural variables; the type and size of car that people purchase is also a behavioural aspect. These depend on choices that are made by the car user, who in turn is influenced by a number of factors, such as personal/household income, the cost of motoring relative to other transport modes, the relative convenience of the various available transport modes, just to name a few.

Trends in personal transport by car have been observed in the last few decades, and they illustrate both the important role that the car plays in personal mobility in the UK, and how usage patterns can change over time. Between 1980 and the early 1990s the average miles travelled per person per year by all modes of transport in the UK grew roughly in line with GDP. Since then, however, some decoupling has been observed and the growth of average miles travelled has been slowing down (DfT, 2005). Since 2005 the average distance travelled per person per year remained roughly constant, but the fraction of the distance travelled by car has kept increasing. In 2008, trips by car accounted for 63% of all trips made and almost 80% of distance travelled (DfT, 2009).

Since 1980, the number of cars per household in the UK has been steadily growing, with the fraction of households having access to one or more cars going from 59% in 1980 to 74% in 2002. As a result, during the 1990s the annual distance travelled by car drivers rose by 15%, while the distance travelled by passengers remained roughly constant (DfT, 2005), therefore, car occupancy rates have fallen. Since around 2000, there have been more households with at least two cars than households with no car. However, since 2005 car availability per household has reached a plateau (DfT, 2009). During the 1990s, as result of increased car use, the average annual distance walked fell by 20% and the distance travelled by bus fell by 11%; in general a shift away from public transport and towards car transport is evident, and this is also related to the fact that between 1980 and 2003 bus and rail fares have risen in real terms by over a third, while the cost of motoring has remained at or below its 1980 level (DfT, 2005).

Therefore, the car in 2010 is the prevalent mode of transport for short to medium length trips in the UK, with rail and plane only taking up a significant fraction of trips longer than 350 miles; as shown in Fig. 1.

It is also interesting to note that travel varies considerably with car availability. On average in 2008, members of car owning households made 41% more trips than people living in non-car owning households, and travelled over two and a half times as far per year (DfT, 2009). Car access and income are closely related. Hence, both the average number of trips and the distance travelled per person per year are strongly influenced by income level, as shown in Fig. 2.

In light of these trends, it is clear that car travel patterns do change significantly over time, and even within the same household; in fact changes in income level and car availability of an individual are bound to change his or her travel behaviour. Patterns also change as a result of policy. If the domestic transport system is to become more sustainable, the current trend towards an increasingly dominant role of the car in private transport needs to be countered by efforts aimed at promoting co-modality

[2] The power of the fuel cell range extender is defined here by the power needed to propel the vehicle at constant cruising speed on a motorway, and is thus independent from the size of the battery. The fuel cell may be downsized even further to reduce costs, such that the battery is depleted at cruising speed, however, this has not been considered here.

[3] This is a conservative assumption justified by the fact that fast-charging poses significant technical and infrastructural challenges, whereas fully recharging a vehicle battery using domestic power sockets (230 V AC, 13 A) typically requires several hours and, therefore, is likely to occur overnight.

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