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The impact of daily and annual driving on fuel economy and CO_2 emissions of plug-in hybrid electric vehicles

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ABSTRACT

The potential of plug-in hybrid electric vehicles (PHEV) to reduce greenhouse gas emissions highly depends on vehicle usage and electricity source. The electric driving share, i.e. the share of kilometres driven electrically, is specific to PHEV and a key factor for its fuel economy. Altogether, a detailed understanding of all factors influencing PHEV fuel economy is missing, especially with regard to driving distances. We analyse the influence of driving behaviour on fuel economy and more precisely the influences on the electric driving share based on mobility data. We applied a regression with mobility data of 780 vehicles to identify the main factors explaining this variation. Our results indicate that real-world fuel economy of PHEV differs widely among users. The resulting factors that explain up to 80% of the fuel economy are the all-electric range, the annual mileage, the regularity of daily driving, and the likelihood of long-distance trips. In our empirical analysis, the average electric driving share of $N = 1{,}831$ Chevrolet Volt in real-world driving is 78%. When the electricity for charging comes from renewable energy sources the resulting real-world well-to-wheel CO_2 emissions of these PHEV are 37 gCO_2/km. However, even with the current US electricity mix, the annual CO_2 savings of all registered Chevrolet Volts in the U.S. amount to about 57 kt CO_2 in comparison to conventional cars. Furthermore, a full charge per day is necessary for high fuel economy and any necessary recharging during the day increases the share of electric driving and lowers the consumption of conventional fuel. Current test-cycle fuel economy ratings neglect these factors. Although fuel economy ratings are good estimates for average usage patterns, they fail to account for the high variation in individual driving behaviour. This should be taken into account by future test-cycles and policies should incentivise high electric driving shares.

1. Introduction

Plug-in hybrid electric vehicles (PHEV) use less energy than conventional internal combustion engine vehicles and can help to reduce greenhouse gas (GHG) emissions from the transport sector (e.g. Bradley and Frank, 2009, Arar, 2010; Vliet et al., 2010). However, their GHG emissions reduction potential strongly depends on their actual usage and the underlying electricity generation (Hawkins et al., 2012a, 2012b; Messagie et al., 2010; Lane, 2006). Presently, little is known empirically on the impact of various factors on PHEV fuel economy and GHG emissions.

PHEV combine an electric drive train with a conventional one. This hybrid drive train leads, in contrast to battery electric vehicles

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(BEV) on one hand and conventional vehicles (ICEV) on the other hand, to a more complex analysis of fuel economy. In a PHEV, both drive trains can be used for propulsion in parallel, in series or in a combination of the two (e.g. Bradley and Frank, 2009). We distinguish the following two operation modes: In charge-depleting mode, the electric engine is responsible for propulsion and the combustion engine is switched off. In charge sustaining mode (usually applied when the battery has been fully depleted), the combustion engine is (mainly) used to keep the battery state-of-charge within a small window. Even though there are several names for and variants of hybrid electric vehicles that combine combustion engine, electric motor, and on-board charger (e.g. range extended electric vehicle, REEV), we refer to all as PHEV in the following. The share of distance driven electrically in charge-depleting mode is denoted as electric driving share or utility factor (UF).

The official emission and fuel economy values of passenger vehicles are currently measured by standard test-cycles such as the New European Driving Cycle (NEDC) in Europe or the Federal Test Procedure (e.g. FTP-75) in the U.S. They are the basis for CO_2 emission targets or vehicle taxation and regulations have been extended to include PHEV (e.g. UNECE, 2014). For the calculation of total fuel consumption, the regulation assumes that PHEV are driven 25 km in addition to their electric driving range between two recharges. The UF of a PHEV thus results in $UF = L_e/(L_e + 25\text{km})$ with L_e denoting the all-electric driving range. However, recent studies show an increasing difference between test-cycle and empirical real-world fuel economy (Mock et al., 2014; Ligterink and Eijk, 2014). For PHEV, the differences are expected to be even higher due to the possibility of different operation shares of the two drive trains.

Two main approaches to analyse PHEV fuel economy and UF are present in the literature. The first approach simulates PHEV operations based on test-cycles or conventional vehicle driving data from mobility surveys (e.g. Elgowainy et al., 2009, Neubauer et al., 2013, Moawad et al., 2009, Axsen et al., 2011, Bradley and Quinn, 2010, Lin and Greene, 2011, Lin et al., 2012). Elgowainy et al. (2009) estimate electric driving shares based on the US National Household Transportation Survey (NHTS) and obtain an average UF of 23.2% for a PHEV with an all-electric range (AER) of 10 miles. For an AER of 20, 30, 40, and 60 miles they obtain an UF of 40.6%, 53.4%, 62.8%, and 74.9%, respectively. Neubauer et al. (2013) use GPS-data of a traffic choice study (398 profiles with 3 months observation period) to simulate the economics of different vehicle concepts. They calculate fuel savings of PHEV usage for different vehicle designs and charging scenarios that can be interpreted as UF and find 50% for 15 miles (60% if work charging is added) and 70% to 80% for 35 miles AER. Analogously, using over 100 one-day driving profiles from Kansas city, Moawad et al. (2009) find fuel savings to be 48% for a PHEV with a battery capacity of 4 kWh, 62% for 8 kWh and 88% for a 16 kWh battery. Axsen et al. (2011) on the other hand use driving reports of 877 car buyers in California and find an UF of PHEV with an AER of 20 miles to be 35% for home charging and 43% for home and additional work charging as well as an UF of 70% and 79% for an AER of 40 miles. The influence of the UF on PHEV's fuel economy has been further analysed by Bradley and Quinn (2010). They calculate the sensitivity of the average UF with respect to vehicle type, age, mileage and garage availability as well as charging behaviour. A PHEV with an AER of 42 miles was found to have an UF of 64% if fully charged once a day compared to 86% if fully charged before every trip.

A second approach in the literature is based on real-world data on PHEV usage and fuel economy. Plötz et al. (2017a and 2017b) give an overview of average UF in Germany and the US based on several sources. Their main finding are average UF for different AER and about 15,000 electric kilometres per year for long-ranged PHEV. Ligterink et al. (2013) and Ligterink and Eijk (2014) analyse Dutch refuelling data and find an UF of 24%, which includes an important group of business users who hardly charge. Excluding them, the UF raises to 33%. The Toyota Prius PHEV and Opel Ampera are found to have an effective fuel economy of about 4.5 l/100 km (52 MPG) compared to 5.3 l/100 km (44 MPG) for the Volvo V60 PHEV and 6.6 l/100 km (36 MPG) for the Mitsubishi Outlander PHEV (Ligterink et al., 2014). The corresponding UF were estimated from the fuel savings compared to a similar conventional vehicle and amount to 18% for the Toyota Prius PHEV, 30% for the Chevrolet Volt/Opel Ampera, 31% for the Mitsubishi Outlander, and 16% for the Volvo V60 PHEV. Davies and Kurani (2013) report results on 25 converted Toyota Prius and find fuel economy to be between 2.1 and 4.5 l/100 km (52–112 MPG) in charge depleting mode and between 4.3 and 6.5 l/100 km (36–55 MPG) in charge sustaining mode for an AER of 40–60 km. In a second step, using the obtained data to simulate different PHEV usage scenarios, they calculate an UF of 30% for a PHEV with an AER of 24 km for charging at home only, which rises to 50% if workplace charging is added.

The specific impact of travel patterns, i.e. daily and annual vehicle kilometres travelled (VKT) as well as day-to-day variation in VKT, on UF of PHEV has only been analysed by simulations so far. Lin et al. (2012) compare simulated PHEV energy use to estimates based on gamma distributed daily VKT. Lin and Greene (2011) highlight the importance on daily VKT variation on UF based on simulated UF. Wu et al. (2015) show the impact of additional recharging over day on top of the daily variation of VKT on simulated UF.

In summary, several studies have simulated UF of PHEV with different AER and some empirical data is available but a systematic understanding of the importance of driving patterns in terms of daily and annual driving distances is lacking. The aim of the present paper is to fill this gap. Here, we analyse the impact of daily driving and annual driving distances on PHEV fuel economy and the related CO_2 emissions with empirical data and simulations. We use vehicle usage data from about 1,800 Chevrolet Volt PHEV observed in North America over more than one year. This main data source is enriched and compared to data from several other PHEV with different electric driving ranges as well as numerical simulations of PHEV driving. In general, many factors impact vehicle fuel economy. We focus on factors that are specific to PHEV and related to direct vehicle usage. We discard factors such as aggressiveness of driving or the use of auxiliaries since these are also relevant for conventional vehicles even though potentially not in the same magnitude (Karabasoglu and Michalek, 2013). Instead our emphasis is on driving patterns taken from mobility data. We aim to analyse these points universally with the available data from the US and Germany.

The outline is as follows. We describe our data sources of PHEV and conventional vehicles in Section 2. The results on the impact