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Objective functions for plug-in hybrid electric vehicle battery range optimization and possible effects on the vehicle fleet

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ABSTRACT

This study analyzes how, in a possible electrification of the car fleet through plug-in hybrid electric vehicles (PHEV), the choice of objective function, which potentially reflects different stakeholders' interests, may influence the resulting optimal PHEV battery range, the PHEV share in the vehicle fleet, the fleet total cost of ownership (TCO) savings, and the fleet electric drive fraction under various economic conditions and policy options.

The optimal battery range can differ considerably among objective functions, especially between the objectives of maximizing the number of PHEVs and maximizing driving on electricity. Increased viability of the PHEV, for instance, through lower battery costs, higher running cost savings, or PHEV-promoting subsidies, will strengthen this effect. Therefore, a high share of viable PHEVs in the vehicle fleet does not necessarily result in a high share of electric driving. When designing policies to promote PHEVs, both the short- and long-term policy objectives and their potential effects need to be considered explicitly.

1. Introduction

While a hybrid electric vehicle (HEV) mainly runs on the same fuel as a conventional combustion engine, a plug-in hybrid electric vehicle (PHEV) has the potential to replace most of that fuel with electricity from the grid. Further, the driving-range limitations associated with a pure battery electric vehicle (BEV) do not apply to the PHEV. This makes the PHEV an interesting option for reducing greenhouse gas (GHG) emissions and local air pollutants as well as energy dependence, without sacrificing performance. However, how large fuel reduction that could be expected from PHEVs strongly depends on the battery range and driving and charging patterns (Björnsson and Karlsson, 2015). To maximize fuel reduction, battery capacity should be designed to reach a high share of electric driving. However, maximizing fuel reduction might not be the main objective for all stakeholders when optimizing battery range. Car owners could be more interested in reaching a low total cost of ownership (TCO), while manufacturers might focus on a battery range that suits as many potential buyers as possible. In this study, we analyze how the optimal battery range for the PHEV and the resulting vehicle fleet properties vary with the choice of objective function under various techno-economic conditions and policy options.

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1.1. Background

Driven to a large extent by the increasingly stricter regulations on fuel use and CO_2 emissions, (for example CAFE and GHG standards by National Highway Traffic Safety Administration, NHTSA and the U.S. Environmental Protection Agency, EPA[1] and mandatory emission reduction targets in the EU[2]) the on-going trend towards more fuel-efficient cars has led to various degrees of hybridization of the powertrain. Today, what should count as a "conventional" vehicle (CV) is somewhat ambiguous. A wide variety of models up to and including full hybrids are successfully marketed and sold[3], and most cars will soon have at least a stop/start system.

Also, PHEV technology varies. Manufacturers have introduced PHEV models that differ to varying degrees with respect to battery range, electric powertrain, and departure from the manufacturer's non-PHEV models. For example, Toyota's Prius PHEV builds on its original gasoline HEV-only Prius. The body design and fully integrated series/parallel hybrid powertrain are at large the same in the PHEV as in the HEV. The first version of the PHEV had a moderate electricity-only range of 20 km. The new version from late 2016 is offered with an all-electric range of approximately 35 km. The rest of the powertrain is kept intact with moderate electric power.

General Motors' Chevrolet Volt/Opel Ampera is a PHEV with greater electric range, about 85 km (first version about 60 km), with a reasonably small fuel engine as a range extender. The electrical components are therefore necessarily designed for electric drive and for meeting all the power requirements of the vehicle. The vehicle only exists as a PHEV with its own design, which differs from those of all other (hybrid and non-hybrid) vehicles in the GM family.

Thus, depending on the market perception of both how a PHEV should be designed and the requirement on its electric powertrain, as well as of what the alternative conventional/hybrid car looks like, it is possible that the transition from the fuel-efficient conventional/hybrid car to the PHEV may involve a small or a large change of the electric powertrain and its performance. This implies, besides the extra costs for a smaller or larger PHEV battery, a smaller or a larger initial powertrain cost corresponding to the level of technical change. Most studies have focused on the importance of battery cost. We have shown that the powertrain cost also can have a large influence on the viability of the PHEV, especially for short-range PHEVs (Björnsson and Karlsson, 2015). Axsen and Kurani (2013) preformed a survey to compare consumers' stated interest in conventional gasoline, hybrid, blended plug-in hybrid, all-electric plug-in hybrid and pure electric vehicles of varying designs and prices. They found that the low-powered and cheaper, blended PHEV more frequently was chosen than the more expensive all-electric PHEV.

1.1.1. Subsidies

There are today a number of countries and regions with policies in place to enable an earlier introduction of electrified vehicles. While most subsidies for PHEVs and BEVs are indifferent to battery range or capacity, U.S. federal tax credits are a prominent exception, which start at $2500 for 4 kWh and gradually increase with each additional kWh up to $7500. The Nissan Leaf and the Chevrolet Volt are both eligible for the full tax credit, while the Toyota Prius PHEV receives $2500 (IRS, 2013). Additional subsidies exist in some states: e.g., in California, PHEVs are eligible for a rebate of $1500, while BEVs receive up to $2500 depending on range (California EPA, 2012)[4]. In Sweden, a BEV qualify for a rebate of $5000, while a PHEV with emissions below 50 g CO_2/km qualify for a rebate of about $2500 (Transportstyrelsen, 2017). In France, any vehicle with CO_2-emissions under 20 g CO_2/km receives a rebate of $6300, which is gradually reduced for higher CO_2 emissions (ACEA, 2015). In the UK, BEVs and PHEVs with CO_2 emissions below 75 g/km are eligible for a grant of up to $7200 and partitioned in three categories: vehicles with CO_2 emissions below 50 g/km and a zero-emission range of at least either 70 or 10–69 miles, or CO_2 emission between 50 and 75 g/km and a zero-emission range of at least 20 miles (ACEA, 2015). China offers a flat subsidy of about $5400 (Mock and Yang, 2014).

Besides subsidies, there are several other possibilities to through policies facilitate an earlier introduction of PHEVs. In Sweden for example, PHEVs used as company cars for private driving have a lower fringe benefit tax than conventional cars (Skatteverket, 2017). For vehicle manufacturers, PHEVs are considered low emission vehicles that receive super-credits to meet the corporate average emissions and fuel economy standards in the U.S. and emission reduction targets in Europe (EPA, 2010b; European commission 2015).

1.2. Literature review

A number of studies have analyzed optimal driving ranges for PHEVs (Björnsson and Karlsson, 2015, 2017; Shiau and Michalek, 2011; Shiau et al., 2009, 2010; Smith et al., 2011; Lin, 2012; Özdemir and Hartmann, 2012; Hou et al., 2014; Redelbach et al., 2014; Meinrenken and Lackner, 2014; Kontou et al., 2015). Some have investigated optimality through minimizing TCO (Björnsson and Karlsson, 2015; Smith et al., 2011; Lin, 2012; Hou et al., 2014; Redelbach et al., 2014). Others have compared the tradeoffs between minimizing TCO versus minimizing GHG emissions or fuel use (Shiau and Michalek, 2011; Shiau et al., 2009, 2010; Özdemir and

[1] The EPA has established national GHG emissions standards under the Clean Air Act, and the NHTSA has established Corporate Average Fuel Economy (CAFE) standards under the Energy Policy and Conservation Act. EPA's standards are projected to result in an average industry fleet wide level of 155 g of CO_2 per km (250 g per mile) in model year 2016 (EPA, 2010a). The program was extended for the period 2017 to 2025 with the projection to result in an average industry fleet wide level of 101 g CO_2 per km (163 g per km) in model year 2025 (EPA, 2012).

[2] EU legislation sets mandatory emission reduction targets for new cars, where the target for average emission levels of new cars sold in the EU after 2015 should be under 130 g of CO_2 per km. From 2020 and onwards the target is set at 95 g per km (European Parliament, 2009).

[3] Today 15 million microhybrids are sold yearly; one vehicle battery market forecaster claims 35 million will be sold in 2020 (Pillot, 2016).

[4] Recently, an income cap for high-income users was introduced (Clean Vehicle Rebate Project, 2015).