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Relative economic competitiveness of light-duty battery electric and fuel cell electric vehicles

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ABSTRACT

This paper estimates battery electric (BEV) and hydrogen fuel cell electric vehicle (FCEV) costs from today through 2040 to explore the potential market size of each vehicle type. Two main tasks are performed. First, the total cost of ownership (TCO) – including vehicle purchase, fuel, maintenance, resale, and refueling inconvenience – is estimated for 77 light-duty vehicle (LDV) segments, defined by driving range and size class. Second, data on individual travel behavior is used to estimate the fraction of vehicle owners within each of the 77 segments. In 2020, BEVs are estimated to be the cheaper vehicle option in 79–97 percent of the LDV fleet and have a weighted average cost advantage of $0.41 per mile below FCEVs across all vehicle segments and drivers. However, costs of the two powertrains quickly converge between 2025 and 2030. By 2040, FCEVs are estimated to be less expensive than BEVs per mile in approximately 71–88 percent of the LDV fleet and have notable cost advantages within larger vehicle size classes and for drivers with longer daily driving ranges. This analysis demonstrates a competitive market space for both FCEVs and BEVs to meet the different needs of LDV consumers.

1. Introduction

Battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) are two promising all-electric powertrains that could help reduce emissions and petroleum use from on-road vehicles (National Research Council, 2013; Williams et al., 2015; Argonne National Laboratory, 2016a; Sims et al., 2014). A common notion among automakers is that BEVs will compete among smaller vehicle size classes with shorter driving ranges, and that FCEVs will compete among larger vehicle size classes with longer daily ranges (e.g., Eberle and von Helmolt, 2010).

A key factor that drives this assumed market segmentation is the difference in mass compounding. For BEVs, as the capacity of the battery pack increases, an ever-greater fraction of that capacity is used to move the mass of the batteries rather than the mass of vehicle, passengers, and cargo. This results in a nonlinear relationship between vehicle purchase cost and vehicle range. For FCEVs, after adding the basic components of the powertrain – i.e., the compressed gaseous storage tank, fuel cell, balance of plant components, and small battery – an increase in vehicle range requires only slightly larger components, which has a relatively small impact on vehicle mass and cost. Differences in mass compounding between BEVs and FCEVs may also be visible across vehicle size classes as the ratios of mass, stored energy, and range change.

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This paper advances the conceptual framework of mass compounding described above by examining costs of light-duty BEVs and FCEVs across a spectrum of vehicle driving ranges and size classes. Total cost of ownership (TCO) – including the time discounted vehicle purchase, operating, and maintenance cost – is estimated for FCEVs and BEVs for 77 market segments, defined by vehicle size class and vehicle effective range between refueling. Additionally, costs of range-related inconveniences are added to each vehicle segment. This segmentation helps elucidate the relative economic competitiveness of BEVs versus FCEVs into the future.

The paper is rooted in literature that examines costs, benefits, and consumer valuation of alternative fuel vehicles and refueling availability. The National Research Council (2013) uses a TCO vehicle model to conduct a sweeping comparison of four pathways to reduce light-duty vehicle (LDV) greenhouse gas (GHG) emissions out to 2050: (1) efficient internal combustion engine vehicles (ICEVs), (2) biofuels used in ICEVs, (3) BEVs, and (4) FCEVs. They find that none of the four pathways, by itself, is projected to achieve sufficient reductions in GHG emissions to meet deep decarbonization goals in 2050.

Other literature offers more focused examinations of a single factor that will determine the size of the future BEV market, such as vehicle use patterns (Pearre et al., 2011; Lin et al., 2012; Barter et al., 2015; Tamor et al., 2015; Tamor and Milacic, 2015) and household-level characteristics (Khan and Kockelman, 2012; Axsen and Kurani, 2012; Tal et al., 2013; Björnsson and Karlsson, 2017; Karlsson, 2017). Other studies examine the influence of incentives, vehicle characteristics, infrastructure availability, or other factors on early market BEV adoption (Sierzchula et al., 2014; Sheperd et al., 2012; Krause et al., 2016). Optimum BEV range is estimated by Lin (2014), while optimum introduction of BEVs into the market is estimated by Kontou et al. (2017). Earlier, Delucchi and Lipman (2001) identified the vehicle component cost and performance characteristics that must be met for BEVs to be competitive with incumbent technologies. Palmer et al. (2018) examine the historical link between TCO and market share for BEVs, hybrid, and plug-in hybrid electric vehicles.

Relatively few studies examine the potential market size of FCEVs or attempt to segment the market into individual size classes. A simple method to segment vehicle markets is a "constraints analysis" in which one or more variables (e.g., access to at-home charging) constrains the maximum or minimum possible market size (Williams and Kurani, 2006). Another approach is to use a consumer choice model that captures vehicle purchase decisions at the individual level, then aggregates to an economy-wide level (e.g., Lin et al.'s (2013) *Market Acceptance of Advanced Automotive Technologies Model* (MA^{3}T)). Kast et al. (in press) use daily operational range to estimate the feasibility of converting 10 categories of medium and heavy truck classes to fuel electric trucks.

This paper provides a unique technology-behavioral cost perspective to estimate the competitive market size of LDV BEV and FCEV vehicle classes. BEVs and FCEVs are compared because they are two promising powertrains that can enable energy security via the reduction of U.S. oil imports in addition to deep greenhouse gas (ANL, 2016a) and air pollutant emissions reductions (Williams et al., 2015). Although this simplistic two-vehicle world ignores the many competing vehicle technologies (like hybrid electric vehicles), a clearer understanding about the potential size and relative costs of the two vehicle markets can help policy makers prioritize investment decisions.

Section 2 of the paper presents the methods for estimating the TCO and daily mileage requirements of U.S. drivers. Section 3 presents results comparing the TCO for 77 size class-range segments. Section 4 presents a sensitivity analysis for key assumptions. Section 5 discusses the results, and details how assumptions made by the authors to simplify the analysis might be affect the analysis conclusions. Finally, Section 6 offers the author's conclusions. The paper's goal is to examine the potential market sizes for BEVs and FCEVs, and to identify the size class/range segments most favorable to each powertrain, from today to the year 2040.

2. Methods

2.1. Total cost of ownership of BEVs and FCEVs

2.1.1. Estimating TCO from Autonomie

The non-linear relationship between vehicle mass, range, cost, and size class results in a complex vehicle design space. To depict this space, this paper uses the U.S. DOE's *Autonomie* model to project vehicle component-level costs of FCEVs and BEV-50 s through BEV-300s (at 50-mile increments) for the years 2020–2040. *Autonomie* is a forward-looking, vehicle simulation model that enables the comparison of vehicle powertrain configurations and component technologies on a consistent basis. *Autonomie* performs ground-up estimates of the size and type of components necessary to build a vehicle, from which it estimates a vehicle's fuel efficiency and cost. Further details can be found in ANL (2016b). Assumed component costs and fuel prices specific to this analysis are described below and given in greater detail in the Appendix. This paper's calculations assume a five-year lag between costs from *Autonomie* and real-world costs (i.e., *Autonomie* output for the year 2015 are assumed to be real-world costs in 2020), given the typical five-year lag time from initial vehicle R&D to retail sales. This five-year lag has been applied to *Autonomie* data in other analyses (see, e.g., ANL, 2016a).

Five post hoc calculations are performed on the output of *Autonomie,* as described below and in Sections 2.1.2–2.1.5. The first post hoc calculation is to calculate the net present value of TCO per mile for each vehicle range-size segment. This calculation methodology follows those used elsewhere (e.g. Lin, 2014; Kontou et al., 2017). A vehicle purchase payment is assumed to be made only once at the beginning of a vehicle's life, but fuel purchases are made regularly over the life of the vehicle. At the end of five years, the vehicles are sold on the used vehicle market for their depreciated price and the revenue is returned to the vehicle owner. The TCO in $ per mile is calculated as follows:

$$TCO = \left(\frac{1.5*V + F-R}{Mileage}\right) \tag{1}$$