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Life cycle ownership cost and environmental externality of alternative fuel options for transit buses

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ABSTRACT

This paper assesses alternative fuel options for transit buses. We consider the following options for a 40-foot and a 60-foot transit bus: a conventional bus powered by either diesel or a biodiesel blend (B20 or B100), a diesel hybrid-electric bus, a sparking-ignition bus powered by Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG), and a battery electric bus (BEB) (rapid or slow charging). We estimate life cycle ownership costs (for buses and infrastructure) and environmental externalities caused by greenhouse gases (GHGs) and criteria air pollutants (CAPs) emitted from the life cycle of bus operations. We find that all alternative fuel options lead to higher life cycle ownership and external costs than conventional diesel. When external funding is available to pay for 80% of vehicle purchase expenditures (which is usually the case for U.S. transit agencies), BEBs yield large reductions (17–23%) in terms of ownership and external costs compared to diesel. Furthermore, BEBs' advantages are robust to changes in operation and economic assumptions when external funding is available. BEBs are able to reduce CAP emissions significantly in Pittsburgh's hotspot areas, where existing bus fleets contribute to 1% of particulate matter emissions from mobile sources. We recognize that there are still practical barriers for BEBs, e.g. range limits, land to build the charging infrastructure, and coordination with utilities. However, favorable trends such as better battery performance and economics, cleaner electricity grid, improved technology maturity, and accumulated operation experience may favor use of BEBs where feasible.

1. Introduction

Transit buses provide short-distance public transportation service with multiple stops along fixed routes to serve citizens' mobility needs. Currently, there are 653 transit agencies operating in urbanized areas and 525 transit agencies in rural areas in the U.S. (Neff and Dickens, 2014). In 2013, these 1178 transit agencies operated a fleet of 65,950 active buses, which traveled 2.2 billion vehicle miles, and served 19.4 billion passenger miles (Davis et al., 2016). Altogether, transit buses consume 79 trillion Btu's of energy, or about 0.4% of energy consumed by on-road vehicles in the U.S. (Davis et al., 2016).

Alternative fuels and advanced technologies have the potential to reduce petroleum consumption and to mitigate unintended environmental consequences including climate change damages caused by greenhouse gases (GHGs) and health and environmental

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damages caused by criteria air pollutants (CAPs) by substituting for conventional vehicles powered by petroleum fuels. Transit agencies are more willing, compared to mainstream private vehicle owners, to adopt alternative fuel vehicles. This is not only because they face a different cost structure (fueling costs are more important due to high mileages), but also because they have higher awareness and sometimes obligations to funding agencies to pursue fuel diversity and/or environmental sustainability (Werpy et al., 2010). In the past two decades, there has been an increase in the penetration of alternative fuels in the transit bus market. American Public Transit Association (APTA) reported that 20% of U.S. transit buses were powered by compressed natural gas (CNG) and liquefied natural gas (LNG) and blends in 2013. In addition, 13% of transit buses were diesel hybrid electric buses (HEBs) and another 7% used biodiesel. The so-called "zero-emissions buses" (which have zero tailpipe emissions during normal operation), such as battery electric buses (BEBs) and fuel cell electric buses, have also emerged in some regional markets (notably, California), as encouraged by state-level environmental regulations and incentive programs (California Air Resources Board (CARB), 2016a).

There is a growing literature that assesses alternative fuel options for transit buses. Table 1 provides a summary of the scope and conclusions of selected U.S. studies. We find that existing studies estimated lifetime ownership costs of purchasing and operating diesel, diesel HEBs, CNG, B20 (a liquid blend of 20% biodiesel and 80% diesel), and BEBs. All of these studies considered capital investment and lifetime operation costs related to bus purchases and uses, and most studies included capital investment related to supporting infrastructure such as refueling stations and garage modifications. We find that in addition to these techno-economic assessments, a few studies also conducted separate environmental assessments to estimate life cycle GHG and CAP emissions (Bi et al., 2016; Clark et al., 2007; Ercan et al., 2015; Lowell, 2012), and two recent studies monetized the impacts of GHGs or CAPs (Bi et al., 2016; Ercan et al., 2015). Furthermore, as summarized in Tong et al. (2015), a number of studies examined solely life cycle GHG emissions for the same set of fuel options.

Some insights emerged from Table 1. First, the focus of alternative fuel options has changed from studies published a decade ago (where CNG and diesel HEB are the primary focuses) to more recent studies (where BEBs are included), which clearly reflects the changing technology landscape. Second, baseline assumptions, in particular, diesel prices, assumed in these studies have changed over time to reflect market dynamics. This in turn changes conclusions from these studies because diesel prices impact life cycle costs of conventional diesel buses significantly (see, for instance, Clark et al., 2007, 2008). Finally, we find that technology assessments on transit buses still largely focused on ownership costs from transit agencies' perspectives. No study has included externality or external costs caused by by-products of bus operation, such as GHGs and CAPs in addition to ownership costs to estimate full societal costs. In our literature review, only two recent studies (Bi et al., 2016; Ercan et al., 2015) assessed external costs, but their assessments are incomplete. Bi et al. (2016) only included climate change damages, but recent studies have showed that CAP-related health and environmental costs from electricity generation are significant (Jaramillo and Muller, 2016; Tong, 2016). Ercan et al. (2015) considered external costs of both CAPs and GHGs. However, they used national-average damage estimates of CAPs, which may be inaccurate because CAP impacts are local.

In this paper, we estimate both life cycle ownership costs as well as life cycle externality of GHGs and CAPs for alternative fuel options for transit buses. In addition to a complete estimate of life cycle external costs using up-to-date emissions inventories and state-of-art marginal damage estimates, contributions of this paper also include a comparison between two types of BEBs (slow-charging and rapid-charging) and separate assessments for 40-foot buses and 60-foot buses. We believe that our contributions can help transit agencies, bus manufacturers, and policymakers gain a better understanding of benefits and costs of alternative fuel options. In addition, we also estimate the contributions from transit buses to CAP emissions inventory in hotspot areas of Pittsburgh, PA to understand the environmental impacts of bus operations at a finer geographic scale.

2. Method

2.1. Scope

We model a 40-foot bus and a 60-foot articulated bus separately. We consider new transit buses in Model Year 2015 with the following fuel options: a conventional diesel bus, a diesel HEB, a sparking ignition natural gas bus powered by CNG, a sparking ignition natural gas bus powered by LNG, a conventional diesel bus with B20, a conventional diesel bus with B100, a BEB with slow charging in a garage, and a BEB with rapid charging along a bus route. The two types of BEBs differ in onboard batteries and the charging infrastructure.

Table 2 lists key assumptions used in this study. Assumptions regarding fuel economy, battery size, and battery replacement are taken from Tong et al. (2015). Vehicle purchase prices are collected from California Air Resources Board (CARB) (2015a), and METRO Magazine (2015). Fuel costs are taken from U.S. Department of Energy (DOE) (2016). Vehicle operation and maintenance (O & M) costs (except fuels) are taken from California Air Resources Board (CARB) (2016b, 2016c). Infrastructure costs are taken from California Air Resources Board (CARB) (2015) and Gladstein Neandross & Associates (GNA) (2012). Finally, we assume the number of buses that share the refueling or charging infrastructure (100 CNG or LNG buses for a refueling station and 10 rapid-charging BEBs for a charging station) to calculate the per-bus infrastructure cost.

The system boundary for ownership costs is not limited to a bus itself, but also includes refueling infrastructure and maintenance garages. This is because transit agencies use refueling stations located within their property. In deploying alternative fuel buses, transit agencies should co-optimize bus fleets and refueling infrastructure (even though it may be contracted and owned by a third party) to maximize investment return. We assume the end-of-life impacts of alternative fuel technologies are roughly the same due to lack of data on disposal of new alternatives. We note that further study may be needed to investigate the end-of-life impacts as recently deployed alternative fuel buses reach their lifetime. In any event, end-of-life disposal should be small relative to operating