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Environmental life-cycle assessment of transit buses with alternative fuel technology

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ABSTRACT

The paper presents a life-cycle assessment of costs and greenhouse gas emissions for transit buses deploying a hybrid input–output model to compare ultra-low sulfur diesel to hybrid diesel-electric, compressed natural gas, and hydrogen fuel-cell. We estimate the costs of emissions reductions from alternative fuel vehicles over the life cycle and examine the sensitivity of the results to changes in fuel prices, passenger demand, and to technological characteristics influencing performance and emissions. We find that the alternative fuel buses reduce operating costs and emissions, but increase life-cycle costs. The infrastructure requirement to deploy and operate alternative fuel buses is critical in the comparison of life-cycle emissions. Additionally, efficient bus choice is sensitive to passenger demand, but only moderately sensitive to technological characteristics, and that the relative efficiency of compressed natural gas buses is more sensitive to changes in fuel prices than that of the other bus types.

1. Introduction

Because they generally produce less tailpipe emissions than diesel, alternative fuels are arguably necessary to address environmental concerns. As described in Schimek (2001) and in Transit Cooperative Research Program (2010), public policies aimed at fostering a switch to alternative fuels require careful analysis of the life-cycle impacts, including those from indirect sources. Reducing tailpipe emissions can lead to unintended and disproportionate emissions increase from transportation, energy generation, and other sectors.

Here we present a life-cycle assessment (LCA) transit buses fueled by, diesel, compressed natural gas (CNG), diesel-electric hybrid (Hybrid), and hydrogen fuel-cell (HFC). We use an input–output (IO) model to estimate and compare the costs and GHG emissions associated with bus manufacturing and operations. The analysis includes both direct and indirect/derived impacts, which, for example, leads us to consider emissions from different energy sources to produce hydrogen for HFC buses, as well as the life-cycle costs and emissions associated with the construction of support infrastructure, i.e., depots and fueling stations, for CNG and HFC buses. We use the results to estimate and compare the implied costs of emissions reductions, and we also examine the sensitivity of the results to changes in fuel prices, passenger demand, and to technological characteristics impacting performance/emissions.

2. Methodology

2.1. Life-cycle assessment scope

We use the framework depicted in Fig. 1 to analyze LCA to estimate the costs and GHG emissions associated with the manufacturing and operating phases of four types transit buses: diesel, compressed natural gas (CNG), diesel-electric hybrid (Hy-

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brid), and hydrogen fuel-cell (HFC). The figure is adapted from MacLean and Lave (2003), who review LCAs of vehicle fuel and propulsion systems. The clear boxes in the figure represent processes and inputs within our scope. These include indirect inputs from the supply-chain, e.g., raw materials extraction, the fuel pathway, and energy generation for each of the bus types. Shaded boxes are inputs excluded from the analysis. This includes the end-of-life phase, which has been shown to have a minor yet complex effect on emissions (Chester and Horvath, 2009). In part, the decision to exclude this phase was based on preliminary analysis showing that it had little bearing on the comparison between the different bus types considered herein, with perhaps the most significant difference related to the disposal of the hybrid bus's lead acid batteries.

2.2. Data sources

Data on bus specifications and use come from a series of demonstration studies on alternative fuel buses conducted by the National Renewable Energy Laboratory (NREL). The data sources are summarized in Table 1. In these studies, the transit agencies purchased, operated, and evaluated the performance of alternative fuel buses on existing transit routes from 2003 to 2009. The data include operational, performance, and maintenance statistics, as well as detailed cost breakdowns for each bus. These studies were selected due to their transparency, data availability, and the representation of different regions. The method and reporting metrics between the studies are consistent, an issue limiting the comparability of results between many studies on vehicle performance (Jaramillo et al., 2009). Supplementary data from a "well-to-wheels" study on transit buses are used to calculate emissions from bus operations (Pont, 2007).

Detailed specifications of the transit buses appear in Croft McKenzie (2011). In summary, all of the buses, except the Orion V, are 40 ft buses. As a baseline, buses are assumed to travel 26,000 miles per year, to remain in service for 15 years, and to travel in urban areas with speeds averaging 7–15 mph on non-express routes. Passenger carrying capacity as given by the manufacturer's specifications is shown in Table 2. A discount rate of 6% is used for both costs and emissions.

2.3. Calculation of life-cycle costs

The costs for each of the buses are summarized in Table 3. Capital costs for Diesel, CNG, and Hybrid buses come from the purchase prices reported by the transit agencies in Table 1. All values are converted to 2008 dollars. The purchase price of the

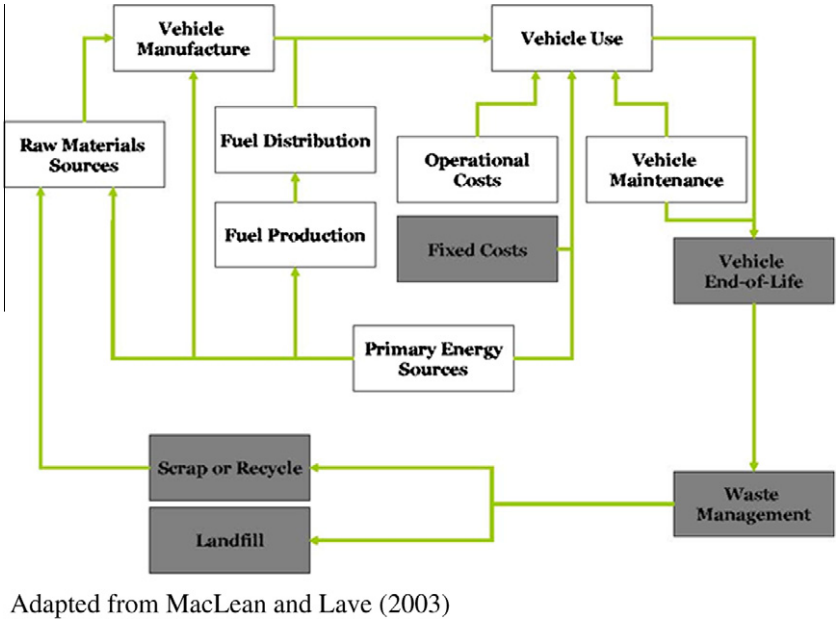

Fig. 1. Life-cycle phases of a transit bus.

Table 1
Data are from National Renewable Energy Laboratory transit bus demonstration projects.

Agency	Location	Year	Bus types
New York City Transit (Barnitt and Chandler, 2006)	New York, NY	2004	Diesel, CNG, Hybrid
Washington Metro Transit Agency (Chandler and Eberts, 2006)	Washington, DC	2004	Diesel, CNG
Alameda–Contra Costa Transit (Chandler and Eudy, 2008)	Oakland, CA	2006	Diesel, HFC
SunLine Transit Agency (Chandler and Eudy, 2009b)	Coachella Valley, CA	2008	HFC, CNG
Connecticut Transit (Chandler and Eudy, 2009a)	Hartford, CT	2008	Diesel, HFC