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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-
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.](image)

### Table 1

<table>
<thead>
<tr>
<th>Agency</th>
<th>Location</th>
<th>Year</th>
<th>Bus types</th>
</tr>
</thead>
<tbody>
<tr>
<td>New York City Transit (Barnitt and Chandler, 2006)</td>
<td>New York, NY</td>
<td>2004</td>
<td>Diesel, CNG, Hybrid</td>
</tr>
<tr>
<td>Alameda–Contra Costa Transit (Chandler and Eudy, 2008)</td>
<td>Oakland, CA</td>
<td>2006</td>
<td>Diesel, HFC</td>
</tr>
<tr>
<td>SunLine Transit Agency (Chandler and Eudy, 2009b)</td>
<td>Coachella Valley, CA</td>
<td>2008</td>
<td>HFC, CNG</td>
</tr>
<tr>
<td>Connecticut Transit (Chandler and Eudy, 2009a)</td>
<td>Hartford, CT</td>
<td>2008</td>
<td>Diesel, HFC</td>
</tr>
</tbody>
</table>

Data are from National Renewable Energy Laboratory transit bus demonstration projects.
HFC demonstration bus exceeds the others by an order of magnitude. Thus, we consider a subsidy. Operating costs for each bus type were calculated by adding operating expenses for fuel, labor, and maintenance. Maintenance and labor costs are reported by transit operators. Fuel costs were calculated by multiplying the inverse of the average fuel economy for each bus (diesel gallon equivalent/mile), the distance traveled (miles), and the 2008 equivalent average fuel price paid by the transit operators ($/gallon). Per-mile costs are presented in Table 2.

### 2.4. Calculation of life-cycle emissions

Our assessment of GHG emissions considers bus manufacturing and operating phases. We use a hybrid IO model to assess the manufacturing phase, and subsequently to assess the construction of support infrastructure for alternative fuel buses, i.e., depots and fueling stations for CNG and HFC buses. The IO approach to environmental LCA involves specifying the direct requirements, i.e., a bill of materials, of a product in terms of demand for economic sectors, e.g., transportation, construction, financial services, etc. This demand is (usually) expressed in monetary value, i.e., US dollars. The model, in turn, is used to compute the level of economic activity and environmental repercussions such as GHG emissions associated with satisfying the given demand for the product. Because all sectors represented in the economy are linked, there is no effective (and often subjective) boundary on the scope of the analysis. The flexibility, transparency and accuracy of the methodology explain its broad appeal in the scientific and engineering community, and its increasing use as a benchmark method for LCA.

Conducting any emissions LCA of bus manufacturing using such framework requires the specification of the direct requirements associated with manufacturing each of the bus types. In the US, the Department of Commerce generates tables that capture flows across nearly 600 economic sectors, and updates them approximately every 10 years. In spite of the scale and breadth, it is sometimes necessary to specify auxiliary economic sectors to obtain an adequate representation of specific activities, i.e., bus manufacturing for each bus type. The ensuing models are referred to as hybrid IO models.

We build a hybrid model with specifications of the manufacturing requirements for each of the bus types from the following economic sectors: Motor Vehicle Body Manufacturing (NAICS 336211) and Motor Vehicle Parts Manufacturing (NAICS sector 33631–336399). Each bus has the same economic activity assigned to Motor Vehicle Body Manufacturing, representing the bus chassis and similar parts. Additional costs for buses were assumed to be associated with increased component complexity, so the remaining activity was assigned to Motor Vehicles Parts Manufacturing. Batteries of the hybrid buses were charged using regenerative braking (Barnitt and Chandler, 2006).

A summary of results from the LCA appears in Table 3. Emissions from bus operations include both the tailpipe emissions, as well as emissions from the production and transportation of fuels, collectively referred to as “well-to-wheels” (WTW), and consisting of “well-to-tank” and “tank-to-wheels” emissions. WTW data on the per-mile emissions from diesel and alternative fuel buses are from Pont. Here, these values are updated to represent the reduced fuel consumption of the hybrid bus, include emissions from electricity used to charge the batteries of the HFC bus, and discounted over the 15 year life at a rate of 6%.

#### Table 2
Operational costs, GHG emissions, and passenger capacity parameters for each bus type.

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Operating cost (per mile)</th>
<th>GHG (CO₂e, per mile)</th>
<th>Passenger capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel bus</td>
<td>$1.71</td>
<td>3287</td>
<td>86</td>
</tr>
<tr>
<td>Hybrid bus</td>
<td>$1.57</td>
<td>2453</td>
<td>70</td>
</tr>
<tr>
<td>CNG bus</td>
<td>$1.62</td>
<td>2540</td>
<td>66</td>
</tr>
<tr>
<td>HFC bus (R)</td>
<td>$1.58</td>
<td>2199</td>
<td>41</td>
</tr>
<tr>
<td>HFC bus (FF)</td>
<td>$1.58</td>
<td>4205</td>
<td>41</td>
</tr>
</tbody>
</table>

#### Table 3
Summary of LCA results for diesel and alternative fuel transit buses.

<table>
<thead>
<tr>
<th>Bus type</th>
<th>Manufacturing cost</th>
<th>Operational cost</th>
<th>Present value totals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cost ($1000)</td>
<td>GHG (CO₂e) (MT)</td>
<td>Cost ($1000)</td>
</tr>
<tr>
<td>Diesel</td>
<td>$347</td>
<td>149</td>
<td>$430</td>
</tr>
<tr>
<td>Hybrid</td>
<td>$460</td>
<td>207</td>
<td>$397</td>
</tr>
<tr>
<td>CNG</td>
<td>$383</td>
<td>165</td>
<td>$409</td>
</tr>
<tr>
<td>HFC (R)</td>
<td>$437</td>
<td>199</td>
<td>$399</td>
</tr>
<tr>
<td>HFC (FF)</td>
<td>$437</td>
<td>199</td>
<td>$399</td>
</tr>
</tbody>
</table>

Note: A 15 year service life and 6% discount rate is assumed.
Emissions from the HFC bus in particular can vary depending on the method for fuel production. Although it is possible to create hydrogen fuel using renewable energy sources, e.g., hydroelectric power, and a small amount is produced as by-products to manufacturing, most of the hydrogen production capacity in the US relies on fossil fuels, i.e., natural gas. We consider GHG emissions profiles for both scenarios, assuming equal costs for each. In terms of notation, HFC(R) refers to the case of hydrogen produced using renewable sources, while HFC(FF) hydrogen production using fossil fuels. Emissions for the hybrid bus were calculated by modifying the emissions from the diesel bus to reflect the reduced fuel consumption.

The emissions attributed to the fuel pathway can vary either because of technology or assumptions made in the analysis. To validate the assumptions, we depict a range of GHG emissions estimates from bus operations in Fig. 2. Large diamonds indicate values used. Comparison measures from five other studies are plotted (Cohen et al., 2003; Chui et al., 2006; Hesterberg et al., 2009; Chester and Horvath, 2009; Jaramillo et al., 2009). When a range of values was given in a particular study, we include both the best-case scenario (labeled as “Low”) and worst-case scenario (labeled as “High”) from a particular study. Fig. 2 shows that the GHG estimates used are in line with the results of previous studies.

Selecting a reporting metric for costs and GHG emissions is complex because it is necessary to make assumptions about the relative importance of GHG emissions that take place at different times. We follow Schapiro (2001), who suggests that GHG emissions should be discounted (at the same rate as costs), and thus, we report total discounted GHG emissions – measured in terms of mass of CO₂ equivalent units (CO₂e). Use of the 6% discount rate has the effect of weighing short-term repercussions more heavily than those occurring in the long-term. This is appropriate to account for uncertainties associated with the adoption of alternative fuel technologies, and leads to a conservative comparison that is skewed in favor of the conventional diesel buses. In any case, sensitivity analyses Croft McKenzie (2011) reveal that the comparison between the buses is only mildly sensitive to the discount rate.

3. Results

3.1. LCA of costs and GHG emissions

The results of the LCA appear in Table 3. The results include costs and GHG emissions associated with the manufacturing and operating phases.

Over a 15 year planning horizon, and in spite of the effect of discounting, emissions from the operating phase dominate, contributing between 74% and 85% of total emissions. This phase, however, only accounts for 35–58% of the cost, indicating a disconnect between costs and emissions. Specifically, diesel buses have the lowest capital cost, yet most of their emissions are incurred during operation. The HFC(FF) bus has a similar phase ratio of costs and emissions, and the highest overall emissions at 1260 MT. The HFC(R) bus has the lowest overall emissions, and less of these attributable to the operations phase (74%) than other buses. CNG buses outperform hybrid buses with respect to costs ($792 K) and emissions (807 MT); however, the hybrid bus has lower operational costs ($397 K versus $409 K) and emissions (619 MT versus 641 MT).

Next, we examine the differences, relative to diesel, in alternative fuel technologies by considering the incremental costs and emissions reductions. Figs. 3 and 4 display incremental costs and emissions during the operational phase and over the
life cycle, respectively. The x-axis in the figures represents GHG emissions reductions. The y-axis represents savings to the transit operator. Quadrants to the right of the origin represent GHG reductions, while quadrants above the origin represent costs savings. The slope from the origin to each point is the marginal costs of emissions reduction, i.e., the additional cost (in dollars) per unit of emissions reduction (in MT) for each bus. Lines corresponding to costs of $100 = MT and/or $1000 = MT are presented in Figs. 3 and 4 for reference.

We observe that except for the HFC(FF) bus, the points representing the alternative fuel buses fall in the first quadrant in Fig. 3, meaning that they provide operational cost and emissions savings with respect to diesel buses. HFC(R) and hybrid buses are preferred to CNG buses because they provide greater cost savings and emissions reductions. The HFC(FF) bus also provides cost savings, but leads to increased GHG emissions compared to the diesel bus. Fig. 4 shows that the alternative fuel buses lead to higher life-cycle costs than the diesel bus. The CNG bus has the smallest marginal cost of just under $100 per MT CO$_2$e, and thus provides the greatest emissions reductions per unit of cost. Making conclusions based on Fig. 3 could lead to unintended consequences, and thus, underscores the importance of considering life-cycle costs and impacts.

3.2. Infrastructure for alternative fuel vehicles

In conducting the LCA, we have assumed that the infrastructure necessary to operate, maintain, and fuel the alternative buses was in place. However, when considering alternative fuel technologies, infrastructure, including changes to fuel distribution networks and storage and maintenance facilities, has to be considered. Even if capital costs are subsidized, construction of infrastructure can significantly affect the life-cycle emissions (Chester and Horvath, 2009). As examples, we examine two cases of additional infrastructure: depots and fueling stations for CNG, and similar structures for HFC buses. We update our IO model to calculate the emissions from the construction of the aforementioned facilities for CNG and hydrogen fuel-cell buses using NAICS sectors 23622 (Commercial and Institutional Building Construction) and 23712 (Gas Pipeline and Related Structures Construction). CNG infrastructure for a fleet of 50 buses costs $2.08 m and has additional emissions of 1270 MT of CO$_2$e. HFC infrastructure for the same size fleet costs $6.21 m and accrues an additional 3804 MT of GHG emissions. On a per-bus level, this increases the life-cycle costs and emissions for the CNG buses by $42 K (5\%) and 25 MT (3\%). Per-bus increases are somewhat more substantial for the HFC buses, at $124 K (15\%) and 76 MT (6–10\%).

As in our previous analysis, we calculate the incremental life-cycle costs and emissions, including infrastructure, for the alternative fuel buses in Fig. 5. The figure corresponds to costs and emissions allocated over 50 buses. Not surprisingly, we observe that when infrastructure is included in the analysis, the costs increases for the CNG and HFC buses, and that as a result marginal costs of GHG reductions increase by a factor of two for both alternatives. However, the additional costs and emissions from infrastructure for both types will be recouped in emissions savings in less than 5 years, if emissions are valued at $100 per MT or higher.

Note: Diesel bus is the baseline

Fig. 3. Additional per mile costs and GHG gas emissions from each bus type: operational phase.
4. Sensitivity analysis

4.1. Sensitivity to fuel price

Fuel price is often the driver of operational costs for a vehicle, and is especially important when technologies utilizing multiple fuel types are considered. The operational cost of a bus with a high fuel economy will vary somewhat with the price of fuel; the operational cost for a bus with a low fuel economy will depend greatly on fuel price. The HFC buses have the
highest fuel costs, balanced by a relatively high fuel economy. CNG buses have the lowest fuel economy but cheaper fuel prices. Costs for diesel and hybrid buses are somewhat balanced with moderate fuel prices, with the hybrid bus having a moderate advantage.

Fig. 6 shows the 2008 price of each of the three fuels plotted against projected changes in operating costs. The slope of the line indicates the sensitivity of each bus’s operating cost. We find that the operating cost of the CNG bus is most driven by fuel price, while the operating cost of the HFC bus is the least sensitive, even though the base fuel price is higher. Fig. 6 also shows the breakeven price points, e.g., the operating cost of the diesel bus will be the same as that of the HFC bus when the price per gallon of diesel is approximately 60% of the price per diesel gallon equivalent of hydrogen.

Because there is much uncertainty about long term prices of fossil and alternative fuels, Fig. 7 examines the additional costs of alternative fuel buses under low and high price scenarios. Specifically, the price of diesel fuel is held constant and the prices of CNG and hydrogen are increased by 50% in the “High Cost” scenario, and then dropped by 50% in the “Low Cost” scenario.

When natural gas and hydrogen fuel prices are low, CNG and HFC buses become less expensive over the life cycle than diesel buses. While the HFC(FF) bus does not provide emissions reductions; however, it does provide a cost savings if fuel prices are low. Conversely, a 50% increase in the price of hydrogen fuel doubles the marginal cost of the emissions reduction for the HFC bus, while a 50% increase for natural gas increases the marginal cost of emissions reductions for the CNG bus by a

![Fig. 6. Sensitivity of operating costs to fuel price for diesel and alternative fuel transit buses.](image)

![Fig. 7. Additional life-cycle costs and GHG emissions from each bus type with fuel price variation.](image)
factor of seven. In high cost fuel scenarios, hybrid technology becomes more valuable because of the higher fuel economy, whereas the opposite is true when fuel is inexpensive.

4.2. Sensitivity to passenger demand

Per passenger-mile (pax-mile) cost is an important metric for evaluation of transportation operations, as the efficiency and value of buses are dependent on the number of passengers that they are carrying. We convert results to a pax-mile metric by amortizing manufacturing costs and emissions to a per-mile basis, and adding them to the operating costs and emissions per-mile. Results are plotted against the load factor of each bus in Fig. 8. When the load factor reaches 100% capacity, another bus is added to carry additional passengers. Costs and emissions for a single passenger car are plotted as a benchmark. For reference, tailpipe emissions for a car are included, noting that life-cycle emissions from a car will be even higher.

The graphs in Fig. 8, show the costs in grams of CO₂e and dollar per pax-mile for different load factors. We find that the per pax-mile cost and emissions for each bus type is highly dependent on the pax-load factor, as well as the capacity of the bus. At low pax-load factors, the per pax-mile emissions are greatest for the diesel bus, however the higher capacity of this bus means that it has the lowest per pax-mile emissions at higher load factors. Similar trends are found for cost in the lower graph, but per-pax mile cost difference is not as pronounced as the emissions differences. Interestingly, at a pax-load factor of approximately 75, the costs and emissions for the CNG, HFC(R) and hybrid buses are similar.

4.3. Sensitivity to EIO-LCA sectors and manufacturing parameters

There is no specific sector in the Department of Commerce NAICS codes for transit bus manufacturing. In this paper, we divide the manufacturing activity for the buses between sectors 336211 and 36300. We tested the robustness of the LCA by first varying the percentage of activity assigned to each sector and secondly comparing to an alternative allocation used by Chester and Horvath (2009), who allocated all of the bus manufacturing activity to sector 336120 (Heavy Duty Truck Manufacturing).

We observe that the results are moderately sensitive to allocation of sector activity. Emissions vary from −11% to +18% as activity is divided between sectors 336211 and 36300. Assigning activity to sector 336120 as in Chester and Horvath (2009) results in an increase in emissions by 7%.

5. Conclusions

We use a hybrid IO analysis to estimate the greenhouse gas emissions associated with manufacturing and operating four types of buses that are being considered for adoption by various transit agencies in the US: ultra-low sulfur diesel, hybrid diesel-electric, compressed natural gas, and hydrogen fuel-cell. Much of the data are obtained from recent demonstration...
projects of buses used on actual transit routes in the US. A life-cycle approach allows examine the impacts in each phase and over the life cycle, as well illustrating crucial factors, such as the fuel distribution pathway.

The analysis indicates that the CNG and Hybrid buses have lower lifecycle GHG emissions than diesel buses, but these emissions savings come at an increase in costs, especially capital costs. The CNG bus has the lowest marginal cost of emissions reductions when compared to the diesel bus, at just under $100 per MT CO2e. HFC buses can provide an even higher level of GHG savings if hydrogen; especially when fuel can be produced using renewable energy sources. The additional costs of building infrastructure to store, fuel, and maintain CNG or HFC buses can be recovered within 5 years by emissions savings with only modest assumptions about a monetary price of emissions. Parameters such as price of fuel and passenger load factor can have significant impacts on the economic viability and emissions savings from alternative fuel technology.

Sensitivity analysis shows that changes in fuel price and passenger loadings affect bus types differently. HFC technology is the least sensitive to fuel price changes, which may translate to less variability and fluctuation in year to year operating costs. The higher fuel economy of the Hybrid bus can be especially valuable when fuel costs are high. Analysis of per pax-mile costs and GHG emissions shows that both costs and emissions savings vary with bus capacities and load factors. Since many buses in the US run at load factors that are much less than capacity, it is especially important to account for these relationships.

Acknowledgments

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References


