A Cost Effectiveness Analysis of Quasi-Static Wireless Power Transfer for Plug-In Hybrid Electric Transit Buses

Preprint

Lijuan Wang, Jeff Gonder, Evan Burton, Aaron Brooker, Andrew Meintz, and Arnaud Konan

Presented at the IEEE–Vehicular Power and Propulsion Conference 2015
Montreal, Quebec, Canada
October 19–22, 2015

© 2015 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC
This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Conference Paper
NREL/CP-5400-64089
November 2015

Contract No. DE-AC36-08GO28308
NOTICE

The submitted manuscript has been offered by an employee of the Alliance for Sustainable Energy, LLC (Alliance), a contractor of the US Government under Contract No. DE-AC36-08GO28308. Accordingly, the US Government and Alliance retain a nonexclusive royalty-free license to publish or reproduce the published form of this contribution, or allow others to do so, for US Government purposes.

This report was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or any agency thereof.

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Available electronically at SciTech Connect http://www.osti.gov/scitech

Available for a processing fee to U.S. Department of Energy and its contractors, in paper, from:

U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
OSTI http://www.osti.gov
Phone: 865.576.8401
Fax: 865.576.5728
Email: reports@osti.gov

Available for sale to the public, in paper, from:

U.S. Department of Commerce
National Technical Information Service
5301 Shawnee Road
Alexandria, VA 22312
NTIS http://www.ntis.gov
Phone: 800.553.6847 or 703.605.6000
Fax: 703.605.6900
Email: orders@ntis.gov

Cover Photos by Dennis Schroeder: (left to right) NREL 26173, NREL 18302, NREL 19758, NREL 29642, NREL 19795.

NREL prints on paper that contains recycled content.
A Cost Effectiveness Analysis of Quasi-Static Wireless Power Transfer for Plug-In Hybrid Electric Transit Buses

Lijuan Wang, Jeff Gonder, Evan Burton, Aaron Brooker, Andrew Meintz and Arnaud Konan
National Renewable Energy Laboratory
System Analysis & Integration Section
Golden, Colorado

Abstract—This study evaluates the costs and benefits associated with the use of a stationary-wireless-power-transfer-enabled plug-in hybrid electric bus and determines the cost effectiveness relative to a conventional bus and a hybrid electric bus. A sensitivity sweep was performed over many different battery sizes, charging power levels, and number/location of bus stop charging stations. The net present cost was calculated for each vehicle design and provided the basis for design evaluation. In all cases, given the assumed economic conditions, the conventional bus achieved the lowest net present cost while the optimal plug-in hybrid electric bus scenario beat out the hybrid electric comparison scenario. The study also performed parameter sensitivity analysis under favorable and high unfavorable market penetration assumptions. The analysis identifies fuel saving opportunities with plug-in hybrid electric bus scenarios at cumulative net present costs not too dissimilar from those for conventional buses.

Keywords—Quasi-static wireless power transfer, Conventional bus, Hybrid electric vehicle (HEV), Plug-in hybrid electric vehicle (PHEV), Hybrid electric bus (HEB), Plug-in hybrid electric bus (PHEB), Cost effectiveness analysis, Net present cost (NPC)

I. INTRODUCTION

In recent years, environmental concerns and high fuel prices have generated an increased interest in advanced propulsion systems for vehicles. Vehicle manufacturers also face demands to reduce harmful vehicle emissions in compliance with increasingly stringent regulations. Hybridization technologies have demonstrated their ability to significantly reduce the fuel cost for various vehicle applications. Plug-in hybrid electric vehicles (PHEVs) integrate large, grid-chargeable batteries that enable additional fuel displacement and potentially some amount of all-electric driving range. PHEV market penetration has been increasing, along with the range of technology options for vehicle charging. In the fairly near future, companies such as WiTricity, KAIST and WAVE hope to increase the convenience of garage and parking lot plug-in electric vehicle charging through the use of wireless power transfer [1-3]. A widely distributed network of public charging stations is important to provide the convenience and confidence required by PHEV drivers. Compared to personally owned vehicles, plug-in hybrid electric buses (PHEBs) may see even greater synergy with mid-route charging infrastructure, given that they normally operate on predictable routes of limited range.

II. APPROACH

A. Charging Station Selection

Eighteen days of driving data were collected from 20 conventional transit buses (CBs) in the Minneapolis, Minnesota, transit bus fleet. After removing vehicle-days with less than one mile of driving, this study applied the remaining 338 vehicle-days of driving data to support the analysis. The vehicle speed, fuel rate, and driving location (longitude and latitude) were recorded for each second during the data collection. Fig. 1 shows the driving routes of the 338 vehicle-days from the collected data.

Two approaches were used when considering where to locate potential charging stations for use in the PHEB analysis scenarios: total stop time-based and stop frequency-based selections. The total stop time-based method was conducted by summing the total stop times at bus stops, and those stations with the longest stop times were selected to install the charging stations. For the frequency-based method, charging stations were located at those bus stops where the buses most frequently stopped. Figs. 2 and 3 show examples of the top 30 charging station locations from each method, mapped on the routes traversed by the 338 vehicle-day dataset.

Fig. 1. Three hundred thirty-eight vehicle-days of transit bus routes
C. Theory/Calculation

A cost-benefit analysis was conducted for four scenarios: CB, hybrid electric bus (HEB), PHEB with both nightly depot and bus stop charging and all-electric mode.

- **Lifetime cost calculation for a CB**
  
The CB lifetime cost was calculated by summing the capital CB cost and the lifetime fuel cost. The annual fuel cost was calculated using equation 1.

\[
an_{CBFC} = \text{serDay} \times \text{aveCBDailyFC}
\]  

where \(an_{CBFC}\) is the annual fuel cost for a CB, \(\text{serDay}\) is 350 service days, and \(\text{aveCBDailyFC}\) is the average daily fuel cost for a CB. The daily fuel cost was computed by multiplying the daily fuel consumption (in gallons) by the fuel price. The average daily fuel cost is the mean of 338 days daily fuel costs. The lifetime fuel cost was the sum of the CB fuel costs for 12 years, which was converted into the net present cost (NPC) using a discount rate of 4.2%.

- **Lifetime cost calculation for an HEB**
  
The lifetime HEB cost was the sum of the capital HEB cost without a battery, the lifetime fuel cost, and the battery cost (assuming a 10-kWh battery size in the HEB). The annual fuel cost was calculated using equation 2.

\[
an_{HEBFC} = \text{serDay} \times (\text{aveHEBDist} / \text{hevMPG}) \times \text{dieselprice}
\]

where \(an_{HEBFC}\) is the annual fuel cost for an HEB, \(\text{serDay}\) is 350 service days, \(\text{aveHEBDist}\) is the mean of 338 days drive distances, \(\text{hevMPG}\) is the fuel economy of an HEB, which was obtained by using the Future Automotive Systems Technology Simulator (FASTSim) [10] running an HEB model over a typical bus route, and \(\text{dieselprice}\) is the diesel price. The lifetime fuel cost for an HEB was the sum of the fuel costs for 12 years, which was converted into the NPC using a discount rate of 4.2%. Assuming the battery is replaced after 6 service years, the HEB 10-kWh battery cost calculation is given in equation 3:

\[
batt_{HEBCost} = 10 \times \text{battHEBCost1} \times \text{markupFactor} + 10 \times \text{battHEBCost2} \times \text{markupFactor}
\]

where \(batt_{HEBCost}\) is the cost of the HEB battery, \(\text{battHEBCost1}\) is the unit cost of the first HEB battery, \(\text{battHEBCost2}\) is the unit cost of the second HEB battery, and the markup factor is the sales markup factor, which can be found in Table I.

- **Lifetime cost calculation for a PHEB with depot charging only**

B. Economic Assumptions

Table I summarizes the economic and input assumptions.

**TABLE I. ASSUMPTIONS FOR PHEB COST-EFFECTIVENESS ANALYSIS**

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB cost ($)</td>
<td>338,892 [4]</td>
</tr>
<tr>
<td>Hybrid electric bus (HEB) without battery cost ($)</td>
<td>491,951 [4]</td>
</tr>
<tr>
<td>Bus stop charging station cost ($)</td>
<td>500,000</td>
</tr>
<tr>
<td>Bus depot charging station cost for each vehicle ($)</td>
<td>5,000</td>
</tr>
<tr>
<td>Demand charge rate per month ($/kW)</td>
<td>12 [5]</td>
</tr>
<tr>
<td>Electricity cost ($/kWh)</td>
<td>0.10 [6]</td>
</tr>
<tr>
<td>Five-year average diesel price ($/gallon)</td>
<td>3.71 [6]</td>
</tr>
<tr>
<td>Vehicle life (years)</td>
<td>12 [7]</td>
</tr>
<tr>
<td>First battery cost ($/kWh)</td>
<td>500 [8]</td>
</tr>
<tr>
<td>Second battery cost (after 6 years) ($/kWh)</td>
<td>300</td>
</tr>
<tr>
<td>Battery markup factor</td>
<td>1.5 [9]</td>
</tr>
<tr>
<td>Bus service days (days/year)</td>
<td>350</td>
</tr>
<tr>
<td>Total buses in service</td>
<td>679</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.042</td>
</tr>
<tr>
<td>HEB average fuel economy (mpg)</td>
<td>6.65</td>
</tr>
<tr>
<td>CB average fuel economy (mpg)</td>
<td>5.29</td>
</tr>
<tr>
<td>PHEB efficiency in depleting mode (kWh/mi)</td>
<td>2.10</td>
</tr>
<tr>
<td>280 hp engine cost estimate ($)</td>
<td>30,000</td>
</tr>
</tbody>
</table>
The lifetime cost of PHEB with depot charging only includes the following six parts:

1. **PHEB capital cost**

2. **Fuel cost**
   
   The annual fuel cost for the PHEB was calculated by equation 4:
   
   \[ \text{anPHEBFC} = \text{serDay} \times \text{avePHEBDailyFC} \]  
   
   where \( \text{anPHEBFC} \) is the annual fuel cost for a PHEB, \( \text{serDay} \) is 350 service days, and \( \text{avePHEBDailyFC} \) is the simulated PHEB average daily fuel cost. The lifetime fuel cost is the sum of the PHEB fuel cost for 12 years, which was converted into the NPC using a discount rate of 4.2%.

3. **Electricity consumption cost at depot**
   
   Both consumption and demand charges are part of each electricity consumer’s bill. The annual electricity cost calculation is shown in equation 5:
   
   \[ \text{anElecCost} = \text{serDay} \times \text{kwhDepot} \times \text{elecprice} \]  
   
   where \( \text{anElecCost} \) is the annual electricity consumption cost for a PHEB, \( \text{serDay} \) is 350 service days, \( \text{kwhDepot} \) is the average daily electricity consumption for a PHEB at the depot, and \( \text{elecprice} \) is electricity price. The lifetime electricity consumption cost was the sum of the PHEB electricity consumption cost for 12 years, which was converted into the NPC using a discount rate of 4.2%.

4. **Electricity demand cost at depot**
   
   The electricity demand cost at the depot was given by equation 6:
   
   \[ \text{anDmdCostDepot} = \text{charEnergy} \times \text{dmdCostRate} \times \frac{12}{\text{charHour}} \]  
   
   where \( \text{anDmdCostDepot} \) is the PHEB’s annual electricity demand cost at the depot, \( \text{charEnergy} \) is the battery size, \( \text{dmdCostRate} \) is demand charge rate per month, and \( \text{charHour} \) is assumed to be 5 hours (for an overnight charge). The lifetime electricity demand cost at the depot was the sum of the PHEB electricity demand cost for 12 years, which was converted into the NPC using a discount rate of 4.2%. It should be noted that each station was assumed to have its own meter and thus the demand charge is calculated for each stop separately.

5. **Battery cost**
   
   The battery cost was calculated by equation 7:
   
   \[ \text{battCost} = \text{battSize} \times \text{unitBattCost1} \times \text{markupFactor} + \]  
   \[ \text{battSize} \times \text{unitBattCost2} \times \text{markupFactor} \]  
   
   where \( \text{battCost} \) is the battery cost, \( \text{battSize} \) is the battery size in kWh, \( \text{unitBattCost1} \) is the first battery cost ($/kWh), and \( \text{unitBattCost2} \) is the second battery cost ($/kWh) (after 6 years). Note that all values assume “usable” kWh.

6. **Depot charging infrastructure cost for each bus**
   
   The cost of depot charging infrastructure in this study is assumed to be $5,000 for each bus.

7. **Electricity cost at bus stop charging stations**
   
   which includes electricity consumption cost and electricity demand cost.
   
   The electricity consumption costs were calculated in a similar manner as equation 5 for the bus depot charging. The electricity demand cost assigned to each bus for bus stop charging was computed by equation 8:
   
   \[ \text{anDmdCost} = \text{charPwr} \times \text{dmdCostRate} \times \frac{12 \times \text{statAmount}}{\text{busAmount}} \]  
   
   where \( \text{anDmdCost} \) is the PHEB’s annual electricity demand cost for bus stop charging, \( \text{charPwr} \) is the charging power, \( \text{dmdCostRate} \) is the demand charge rate per month, \( \text{statAmount} \) is the number of charging stations, and \( \text{busAmount} \) is the number of PHEBs over which the charging station costs are spread. The lifetime electricity demand cost was the sum of the PHEB electricity demand cost at a bus stop for 12 years, which was converted into the NPC using a discount rate of 4.2%. It should be noted that each station was assumed to have its own meter and thus the demand charge is calculated for each stop separately.

8. **Charging station infrastructure cost**
   
   which was calculated by equation 9:
   
   \[ \text{charStatCost} = \text{statCost} \times \frac{\text{statAmount}}{\text{totalBusAmount}} \]  
   
   where \( \text{charStatCost} \) is the cost of each charging station, \( \text{statCost} \) is the cost of each charging station, \( \text{statAmount} \) is the
number of bus stop charging stations, and \textit{totalBusAmount} is the total number of buses benefiting from the stations over which the station costs are spread.

- Lifetime cost calculation of all-electric bus

The calculation of the lifetime cost of an all-electric bus is the same as that of the PHEB, except that the fuel cost is not included and the cost of the engine is subtracted.

III. ANALYSIS AND RESULTS

A. Design of Experiments

Table II shows a full factorial design over a number of different battery sizes, charging power levels, and number of charging stations. Following a complete simulation of the design matrix, all combinations of battery size, charging power, and number of charging stations were evaluated according to the assumptions in Table I. The NPC was calculated for each vehicle design and provided the basis for design evaluation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>High</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>Battery energy (kWh)</td>
<td>30</td>
<td>80</td>
<td>10</td>
</tr>
<tr>
<td>Charging power (kW)</td>
<td>50</td>
<td>250</td>
<td>20</td>
</tr>
<tr>
<td>Charging station amount</td>
<td>5</td>
<td>30</td>
<td>1</td>
</tr>
</tbody>
</table>

B. Results for Charging at Both Charging Station Selection Approaches

It was found that installing 21 charging stations was the most cost effective for the total stop time-based bus stop charger selection approach. The NPC is shown in Fig. 4, with battery size plotted on the horizontal axis and charging power plotted on the vertical axis. The two-dimensional space reflects 66 combinations investigated. Designs that would require battery charging at rates greater than four times the battery’s rated energy were excluded. For the charging stations selected using the stop frequency-based approach, installing 15 charging stations gave the lowest NPC, which is summarized in Fig. 5. It should be noted that both analyses assumed no changes to bus dwell time. It can be seen from comparing these two plots that the total idle time-based charging station selection approach was more cost effective. This may partially be due to the fact that the charging stations were more evenly distributed when applying the total stop time-based approach. Of the three powertrain vehicles, given the assumed economic conditions, the CB achieved the lowest NPC. The fuel savings for the optimal PHEB scenario (NPC = $763,000 at 40-kWh battery and 150-kW charging power) are insufficient to offset its upfront cost increment, resulting in a 14% higher cost for the PHEB relative to the $668,000 NPC for the CB. The optimal PHEB scenario achieved a 1% lower lifetime cost than the HEB.

Fig. 4. NPC of total stop time-based approach

Fig. 5. NPC of stop frequency-based approach

Fig. 6 shows the lifetime fuel use and cost breakdown for the CB, HEB and the optimal PHEB scenario, and Fig. 7 shows the same cost information alongside the lifetime fuel savings relative to the CB. Even though the PHEB savings are insufficient to totally offset its upfront cost increment, the PHEB reduces lifetime diesel fuel use by 78% relative to the 115,000-gallon lifetime consumption estimate for the CB, whereas the HEB scenario reduces fuel use relative to the CB by 20%.

Fig. 6. Lifetime cost breakdown and fuel use

Fig. 7. Lifetime fuel savings
C. Results for All-Electric Bus

The results also indicated that 1,231 out of 22,308 simulation cases (the combination of 6 battery sizes, 11 charging power levels, and 338 vehicle-days) could run in all-electric mode for the entire driving day. The distances in electric battery mode are variously depicted in Figs. 8 through 10 with battery size plotted on the horizontal axis and charging power plotted on the vertical axis. The three-dimensional plot (Fig. 8) visually demonstrates the maximum (blue dots) and average (red dots) distance with different combination of battery size and charging power. Fig. 9 and Fig. 10 explicitly provide the respective maximum and average EV trip distances achieved over the design space. Fig. 9 shows that the drive range can reach 195 miles in scenarios with an 80-kWh battery, 230-kW charging power, and 21 charging stations. Fig. 11 shows the EB NPC calculated based on the daily average travel distance assumption in Fig. 10. It indicates that NPC for the EB is higher than for the HEV when the average driving range is greater than 34 miles.

D. Sensitivity Analysis

To investigate the effects on cost effectiveness, sensitivity analyses were executed under two alternate sets of economic assumptions:

- Unfavorable conditions for PHEB market penetration: Low fuel price and high battery, electricity, and charging station infrastructure cost
- Favorable conditions for PHEB market penetration: High fuel price and low battery, electricity, and charging station infrastructure cost
The two sets of assumptions are listed in Table III, and the NPCs under each scenario are illustrated in Figs. 12 and 13. The analysis indicated NPC is highly sensitive to assumptions about economic climate. Fig. 12 shows that the NPC of the PHEB scenario is lower than that of the CB scenario under the favorable PHEB economic conditions set of assumptions, whereas Fig. 13 shows that the unfavorable PHEB economic conditions set of assumptions causes the PHEB to be the least cost effective.

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Favorable Market Potential Scenario</th>
<th>Unfavorable Market Potential Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bus stop charging station cost ($)</td>
<td>300,000</td>
<td>700,000</td>
</tr>
<tr>
<td>Depot charging station cost for each vehicle ($)</td>
<td>3000</td>
<td>7000</td>
</tr>
<tr>
<td>Electricity cost ($/kWh)</td>
<td>0.08</td>
<td>0.12</td>
</tr>
<tr>
<td>Demand charge ($/kW/month)</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Diesel cost ($/gallon)</td>
<td>5.00</td>
<td>2.50</td>
</tr>
<tr>
<td>First battery cost ($/kWh)</td>
<td>500</td>
<td>600</td>
</tr>
<tr>
<td>Second battery cost (after 6 years) ($/kWh)</td>
<td>0 (no battery replacement)</td>
<td>400</td>
</tr>
</tbody>
</table>

Fig. 12. NPC at favorable market potential assumptions

Fig. 13. NPC at unfavorable market potential assumptions

IV. CONCLUSION

This analysis has examined two charging station selection approaches and concluded that the total stop time-based method achieved more favorable benefits. Real-world vocational data and multiple sets of economic assumptions have been employed for the cost effectiveness analysis. Given the baseline set of economic assumptions, the optimized PHEB scenarios were unable to outpace the NPC of the CB. However, the PHEB reduces lifetime diesel fuel use by 78% relative to the 115,000-gallon lifetime consumption estimate for the CB, whereas the HEB scenario achieves a 20% reduction relative to the CB.

Future work in the related area will include cost effectiveness analysis from the fleet (rather than average individual vehicle) perspective. Additional research will investigate incremental rollout of PHEBs and chargers, beginning with the most favorable route and bus stop locations.

REFERENCES


V. ACKNOWLEDGMENTS

This work was supported by the U.S. Department of Energy under Contract No. DE-AC36-08GO28308 with the National Renewable Energy Laboratory. Funding was provided U.S. DOE Office of Energy Efficiency and Renewable Energy Vehicle Technologies Office.

The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.