A Cost Effectiveness Analysis of Quasi-In-Motion Wireless Power Transfer for Plug-In Hybrid Electric Transit Buses from Fleet Perspective

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I. Motivation:

A. Wireless power transfer charging technology has made it possible to wirelessly charge a parked vehicle’s battery.

B. Transit buses provide an early quasi-in-motion application opportunity.

II. Objective:

A. Perform a cost comparison of plug-in hybrid electric bus (PHEB), hybrid electric bus (HEB), and conventional bus (CB) scenarios.

B. Explore the fuel displacement opportunity.

C. Provide incremental rollout solutions for charging stations and PHEBs.
Outline

I. Charging Station Location Selection

II. Economic Assumptions and Design of the Simulation Matrix

III. Cost Comparison of Various Scenarios
   A. Sweep analysis from a PHEB perspective
   B. Charging station incremental rollout
   C. PHEB incremental rollout
   D. More scenarios

IV. Sensitivity Analysis

V. Summary
338 Vehicle-Days of Driving
Charging Station Location Selection

*The overlapped charging stations are considered one

20 Charging Stations Mapped with 338 Day-Trips
# Model Input Assumptions and Design of Experiments Matrix

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB cost ($)</td>
<td>338,892 [2]</td>
</tr>
<tr>
<td>HEB without battery cost ($)</td>
<td>491,951 [2]</td>
</tr>
<tr>
<td>Bus stop quasi-static charging station cost ($)</td>
<td>500,000</td>
</tr>
<tr>
<td>Bus depot static charging station cost for each bus ($)</td>
<td>5000</td>
</tr>
<tr>
<td>Demand charge rate per month ($/kW)</td>
<td>12 [3]</td>
</tr>
<tr>
<td>Electricity cost ($/kWh)</td>
<td>0.10 [4]</td>
</tr>
<tr>
<td>Five years average diesel price ($/gallon)</td>
<td>3.71 [4]</td>
</tr>
<tr>
<td>Vehicle life (year)</td>
<td>12 [5]</td>
</tr>
<tr>
<td>First battery cost ($/kWh)</td>
<td>500 [6]</td>
</tr>
<tr>
<td>Second battery cost (after 6 years) ($/kWh)</td>
<td>300</td>
</tr>
<tr>
<td>Battery markup factor</td>
<td>1.5 [7]</td>
</tr>
<tr>
<td>Bus service day (days/year)</td>
<td>218</td>
</tr>
<tr>
<td>Discount rate</td>
<td>0.042</td>
</tr>
<tr>
<td>HEB fuel economy (FE) (mpg)</td>
<td>6.65</td>
</tr>
<tr>
<td>CB average FE (mpg)</td>
<td>5.29</td>
</tr>
<tr>
<td>PHEB efficiency in depleting mode (kWh/mi)</td>
<td>2.10</td>
</tr>
<tr>
<td>280 hp engine cost estimation ($)</td>
<td>30,000</td>
</tr>
</tbody>
</table>

<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>
Sweep Analysis Results from A PHEB Perspective

PHEB NPC($K)

<table>
<thead>
<tr>
<th>Charging Power (kW)</th>
<th>Battery Energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB: 668</td>
<td></td>
</tr>
<tr>
<td>HEB: 767</td>
<td></td>
</tr>
<tr>
<td>Optimal PHEB NPC</td>
<td></td>
</tr>
</tbody>
</table>

NPC= Net Present Cost
All PHEBs with Charging Station Incremental Rollout

- **PHEB comparable to HEB cost with triple the fuel savings**

Optimal PHEB design

$\text{CS} =$ charging station

- Fuel Cost
- Depot Infrastructure
- Charging Station Infrastructure
- Electricity Demand
- Electricity
- Battery
- Vehicle
- Fleet Lifetime Diesel Use

**Ratio of Incremental Cost to Fuel Saved**

- All HEB
- All PHEB, 5 CS
- All PHEB, 11 CS
- All PHEB, 15 CS

**NPC ($M)**

- $0
- $50
- $100
- $150
- $200
- $250
- $300

**Lifetime Diesel Use (Million Gallons)**

- 0
- 5
- 10
- 15
- 20
- 25
- 30
- 35
- 40
- 45

Optimal PHEB design

CS = charging station
PHEB Incremental Rollout

Lifetime Diesel Use (Million Gallons)

NPC ($M)

Fuel Cost
Depot Infrastructure
Charging Station Infrastructure
Electricity Demand
Electricity
Battery
Vehicle
Fleet Lifetime Diesel Use

Fuel savings increase with more PHEBs.

20 PHEB with 1 CS gives the lowest incremental cost/gallon saved.
Fleet Lifetime Cost and Fuel Consumption for More Scenarios

- Depot charging only is not as cost effective.

DC = Depot Charging
CS = Charging Station

Ratio of Incremental Cost to Fuel Saved

- $\text{Ratio} = \frac{\text{Incremental Cost}}{\text{Fuel Saved}}$

NPC (SM) vs. Lifetime Diesel Use (Million Gallons)

- Fuel Cost
- Depot Infrastructure
- Charging Station Infrastructure
- Electricity Demand
- Electricity
- Battery
- Vehicle Cost
- Fleet Lifetime Diesel Use
# High/Low Market Potential Assumptions

<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 ($)</td>
<td>300,000</td>
<td>700,000</td>
</tr>
<tr>
<td>Depot charging station cost for each bus ($)</td>
<td>3,000</td>
<td>7,000</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>
All PHEBs with Charging Station Rollout with Favorable Market Potential Assumptions

- All PHEB scenarios cost effective with large fuel saving.
All PHEB scenario has lowest cost and largest fuel savings.
More Scenarios with Favorable Market Potential Assumptions

Depot charging only is again not as cost effective.
All PHEB with Charging Station Rollout with Unfavorable Market Potential Assumptions

- PHEV unsurprising less cost effective with unfavorable market
- The NPC is higher with more CS, but the dollar per gallon saving is lower.
PHEB Incremental Rollout with Unfavorable Market Potential Assumptions

- 20 PHEBs give comparable NPC and lowest incremental cost per gallon saved.
More Scenarios with Unfavorable Market Potential Assumptions

- Depot charging only is again not as cost effective.

Ratio of Incremental Cost to Fuel Saved

- $\text{Dollar/Gallon}$

- 20 PHEB, DC Only
- 20 PHEB, 1 CS
- All PHEB, DC Only
- All PHEB, 3 CS

NPC ($M$) vs Lifetime Diesel Use (Million Gallons)

- Fuel Cost
- Depot Infrastructure
- Charging Station Infrastructure
- Electricity Demand
- Electricity
- Battery
- Vehicle Cost
- Fleet Lifetime Diesel Use

- All CB
- 20 PHEB, DC Only
- 20 PHEB, 1 CS, 30kWh, 250kW
- All PHEB, DC Only
- All PHEB, 3 CS, 30kWh, 250kW
Conclusion

I. Comparison results of various scenarios:
   A. Given current economic assumptions, the optimized PHEB scenarios were unable to outpace the NPC of the CB. However, PHEBs could achieve comparable lifetime costs as HEBs but tripled the fuel savings realized relative to CB.
   B. The simulation results suggested the incremental rollout should start from 20 PHEB and 1 charging station.

II. Sensitivity analysis:
   A. For favorable market conditions, each of the PHEB scenarios have a lower NPC than the CB, and the best fuel and cost savings occurs when all the CBs are replaced by PHEBs.
   B. The unfavorable PHEB market potential assumptions unsurprisingly caused the PHEBs to have the highest NPC, but relative to the HEB and the PHEB with depot charging only the PHEBs with charging stations achieved the lowest incremental cost per gallon of fuel saved.
Questions?
References


Acknowledgments

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