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

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***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.

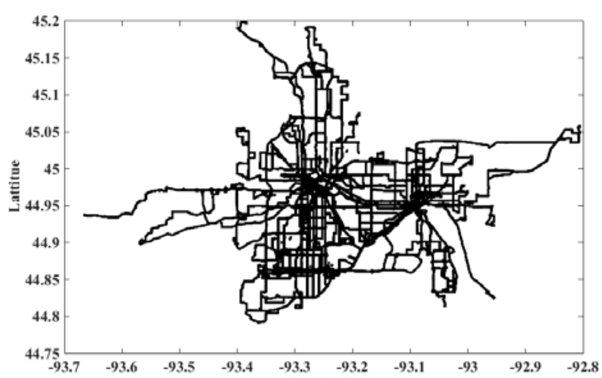

Fig. 1. Three hundred thirty-eight vehicle-days of transit bus routes

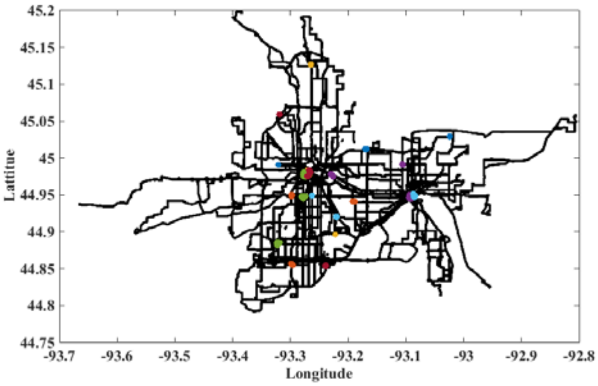

Fig. 2. Top thirty charging station locations selected using the total stop time-based approach

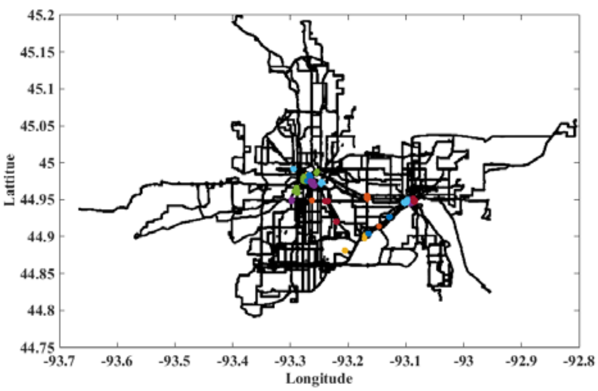

Fig. 3. Top thirty charging station locations selected using the stop frequency-based approach

B. *Economic Assumptions*

Table I summarizes the economic and input assumptions.

TABLE I. ASSUMPTIONS FOR PHEB COST-EFFECTIVENESS ANALYSIS

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

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.

$$anCBFC = serDay * aveCBDailyFC \quad (1)$$

where *anCBFC* is the annual fuel cost for a CB, *serDay* is 350 service days, and *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.

$$anHEBFC = serDay * (aveHEBDist / hevMPG) * dieselprice \quad (2)$$

where *anHEBFC* is the annual fuel cost for an HEB, *serDay* is 350 service days, *aveHEBDist* is the mean of 338 days drive distances, *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 *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:

$$battHEBCost = 10 * battHEBCost1 * markupFactor + 10 * battHEBCost2 * markupFactor \quad (3)$$

where *battHEBCost* is the cost of the HEB battery, *battHEBCost1* is the unit cost of the first HEB battery, *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

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:

$$anPHEBFC = serDay * avePHEBDailyFC \quad (4)$$

   where *anPHEBFC* is the annual fuel cost for a PHEB, *serDay* is 350 service days, and *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:

$$anElecCost = serDay * kwhDepot * elecprice \quad (5)$$

   where *anElecCost* is the annual electricity consumption cost for a PHEB, *serDay* is 350 service days, *kwhDepot* is the average daily electricity consumption for a PHEB at the depot, and *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:

$$anDmdCostDepot = charEnergy * dmdCostRate * 12 / charHour \quad (6)$$

   where *anDmdCostDepot* is the PHEB's annual electricity demand cost at the depot, *charEnergy* is the battery size, *dmdCostRate* is demand charge rate per month, and *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%.

5. Battery cost

   The battery cost was calculated by equation 7:

$$battCost = battSize * unitBattCost1 * markupFactor + battSize * unitBattCost2 * markupFactor \quad (7)$$

   where *battCost* is the battery cost, *battSize* is the battery size in kWh, *unitBattCost1* is the first battery cost ($/kWh), and *unitBattCost2* is the second battery cost ($/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.

- Lifetime cost calculation of PHEB with both depot and bus stop charging

  In addition to the costs for depot charging only, the costs of a PHEB with both depot and bus stop charging include two more parts.

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:

$$anDmdCost = charPwr * dmdCostRate * 12 * statAmount / busAmount \quad (8)$$

   where *anDmdCost* is the PHEB's annual electricity demand cost for bus stop charging, *charPwr* is the charging power, *dmdCostRate* is the demand charge rate per month, *statAmount* is the number of charging stations, and *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:

$$charStatCost = statCost * statAmount / totalBusAmount \quad (9)$$

   where *charStatCost* is the is the charging station infrastructure cost for each vehicle, *statCost* is the cost of each charging station, *statAmount* is the number of bus stop charging stations, and *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 II. Design of Experiments Matrix

Parameter	Low	High	Step
Battery energy (kWh)	30	80	10
Charging power (kW)	50	250	20
Charging station amount	5	30	1

B. Results for Charging at Both Charing Station Selection Approches

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.

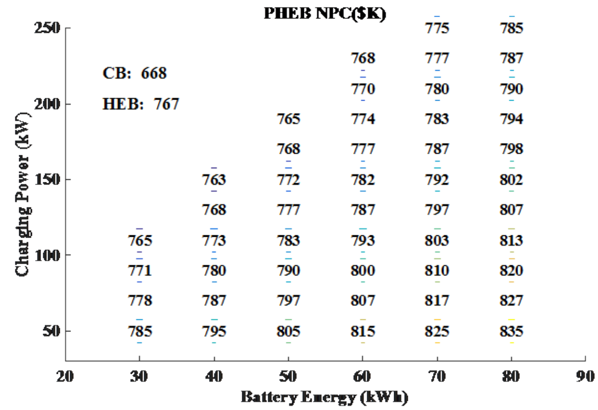

Fig. 4. NPC of total stop time-based approach

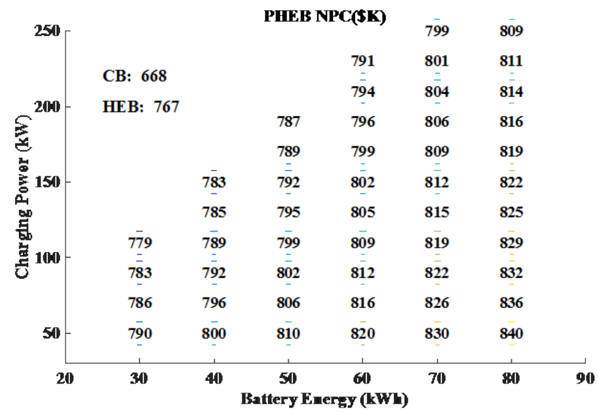

Fig. 5. NPC of stop frequency-based approach

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 insuffficient 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%.

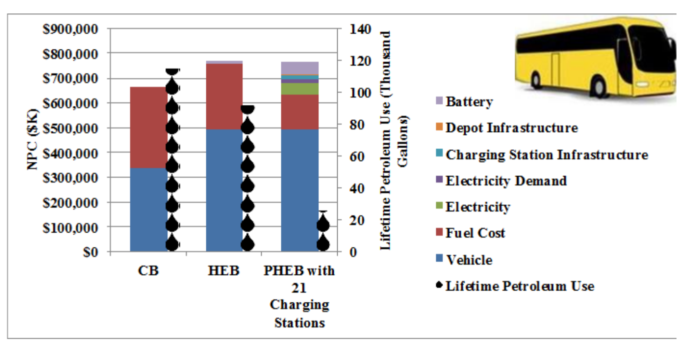

Fig. 6. Lifetime cost breakdown and fuel use

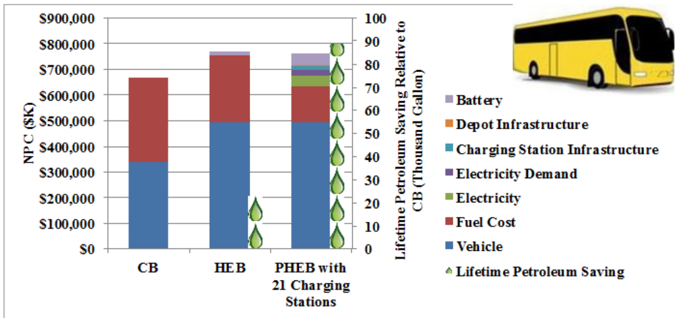

Fig. 7. Lifetime cost breakdown and fuel savings

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.

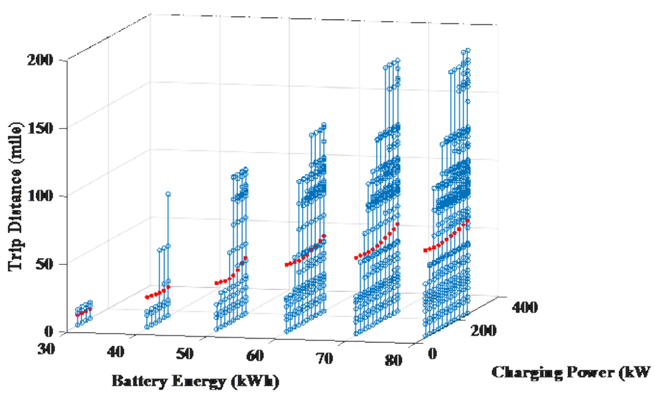

Fig. 8. Maximum (blue dots) and average (red dots) PHEB distance achieved in all-electric mode

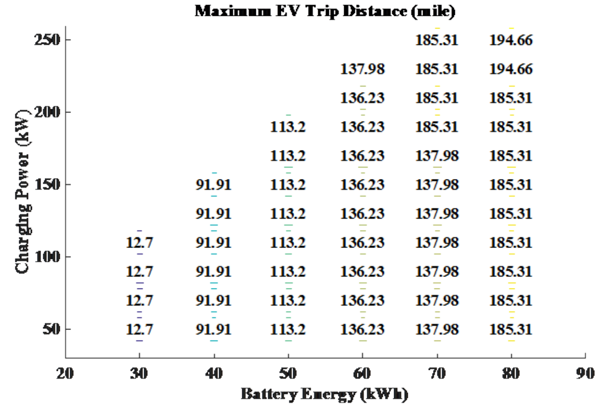

Fig. 9. Maximum PHEB distance achieved in all-electric mode

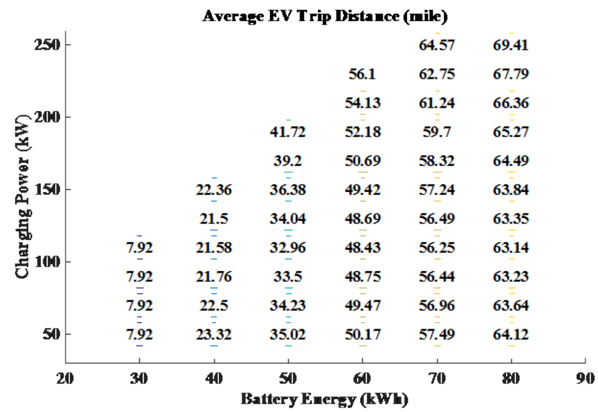

Fig. 10. Average PHEB distance achieved in all-electric mode

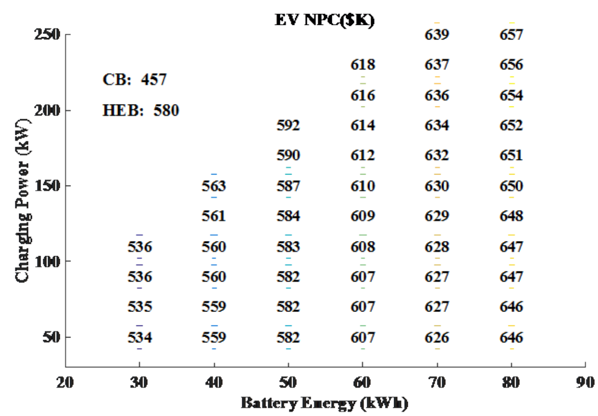

Fig. 11. NPC for vehicle-days that can be completed by the PHEB in all-electric mode

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 that 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 III. HIGH/LOW MARKET POTENTIAL ASSUMPTIONS

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

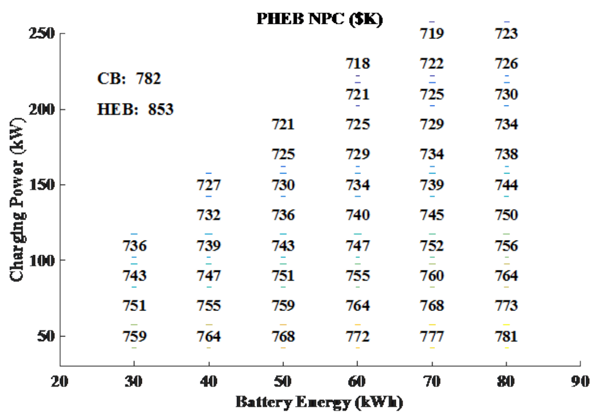

Fig. 12. NPC at favorable market potential assumptions

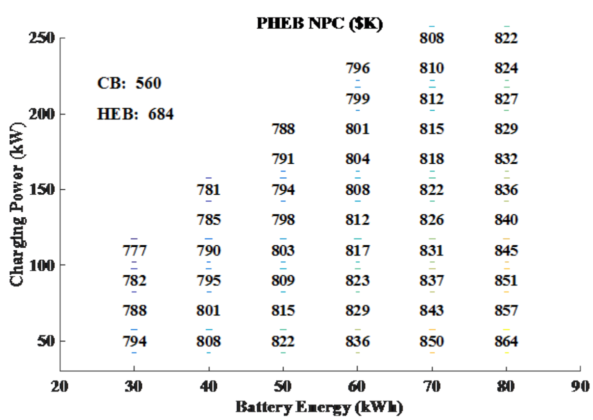

Fig. 13. NPC at unfavorable market potential assumptions

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

[1] WiTricity Automotive website, witricity.com/applications/automotive. Accessed September 24, 2014.

[2] Wireless Power Transimission Would Let EVs Draw Their Power from the Road, http://electricvehicle.ieee.org/advanced-charging/the-all-electric-car-you-never-plug-in/.

[3] WAVE Wireless Charing Electric Vehicles, http://www.waveipt.com/#!/

[4] U.S. Department Of Transportation, Federal Transit Administration, "Additional transit bus life cycle cost scenarios based on current and future fuel prices," Final Report, pp. 12, September 2008.

[5] Electric Schedule A-10 Medium General demand-metered service, Pacific Gas and Electric Company, San Francisco, California, U 39.

[6] U.S. Energy Information Administration (EIA) Website, http://www.eia.gov, Accessed on March 31, 2015.

[7] U.S. Department of Transportation, Federal Transit Administration, "Useful Life of Transit Buses and Vans," Report No. FTA VA-26-7229-07.1, pp. iv, April 2007.

[8] The EV Everywhere Challenge, http://energy.gov/sites/prod/files/2014/05/f15/APR13_Energy_Storage_c_II_EV_Everywhere_1.pdf, accesed on April 8, 2015

[9] A. Rogozhin, M. Gallaher, G. Helfand, and W. McManus, "Using indirect cost multipliers to estimate the total cost of adding new technology in the automobile industry," International Journal of Production Economics, vol. 124, iss. 2, pp. 360–368, April 2010.

[10] National Renewable Energy Laboratory, "Future Automotive System Technology Simulator," http://www.nrel.gov/transportation/fastsim.html

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