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Increasing the Range of Electric Shuttle Buses with Wireless Charging

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Abstract

The range of an electric shuttle bus has been increased from less than 50 miles on batteries alone to more than 120 miles by wireless charging during the period when passengers are normally boarding the bus. The Center for Energy, Transportation and the Environment at the University of Tennessee at Chattanooga in partnership with the Chattanooga Area Regional Transportation Authority (CARTA), EVAmerica, and Embedded Power Control (EMPCON) with support from the Federal Transit Administration (FTA) under Cooperative Agreement TN-26-7034, has demonstrated wireless charging for electric shuttle buses using Inductive Power Transfer (IPT) technology provided by Conductix Wampfler, AG. The system includes a track supply that provides power at 20 kHz to a coil embedded in the roadway. The power is transferred to the bus through an air gap to pick-up coils mounted on a mechanism under the bus that drops the coil into position 40 mm above the embedded coil. This short "opportunity" charge of three minutes duration at 60 kilowatts provides enough traction energy to power the bus for approximately three miles, thereby eliminating the normal range constraint that, until now, has required battery swapping during the day to cover the required daily route of 100 miles. Overall efficiency from the grid to the vehicle was found to be more than 90%, resulting in an energy cost per mile of less than $.10 while producing zero tailpipe emissions. Measurements of electromagnetic field strength at the edge of the coils near street level and at all locations inside the bus have been found to be well below draft international standards for exposure.
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Keywords: Range, Electric Shuttles, Inductive Power Transfer, Wireless Charging

1 Introduction

CARTA has been operating a fleet of electric shuttle buses since May 1, 1992. The decision to convert to electric buses was driven by a community effort to improve the air quality in Chattanooga and to comply with all provisions of the Clean Air Act. Anyone visiting Chattanooga today who has not been to Chattanooga lately would have difficulty recognizing the city because of the remarkable improvements in air quality that not only have put Chattanooga into a state of attainment with all EPA air quality regulations, but also has allowed for continued economic development such as the new Volkswagen assembly plant that is now in full production in Chattanooga, partly because of the strong community commitment to the environment. CARTA now carries approximately one million passengers each year on its electric shuttles. To remove the CARTA shuttles from Chattanooga today would be as unthinkable as removing the cable cars from San Francisco.
Over the years, CARTA experimented with virtually every new product that promised to extend the range of electric buses. This included various combinations of new battery chemistries, more efficient drive systems, and gas turbines running on diesel fuel or propane as range extenders that could recharge the batteries during operations.

Likewise, Santa Barbara Metropolitan Transportation District has been involved in testing and using electric buses since the 1980's [1-5]. In spite of much progress with batteries and drive systems, the range for electric buses remains limited. After almost 20 years of continuous operation of electric shuttles, the problem for CARTA can be stated as follows:

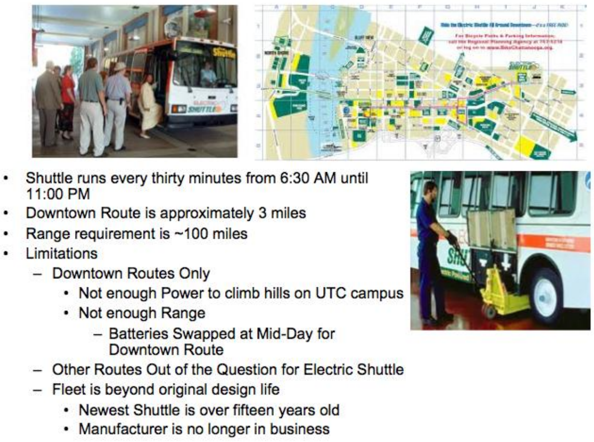

Figure 1 Statement of the Problem

1.1 History of wireless charging

The idea of roadway powered vehicles has also been considered since the 1980's [6,7] and at least one large scale demonstration of a Roadway Propelled Electric Vehicle (RPEV) that used IPT for buses was completed in 1994 at the University of California Richmond Field Station by the Institute for Transportation Studies under the California Partners for Advanced Transit and Highways (PATH) [8,9].

Field tests of opportunity charging with IPT were conducted in Europe, followed by deployment of wireless charging systems developed by Conductix Wampfler, AG for transit buses in Turin, Genoa and other cities. In addition to the work presented here, CETE has explored the use of ultracapacitors to complement inductive charging for buses[10].

Recent activity in the US [11,12], Japan [13,14] and Korea[15] confirms the growing international interest in wireless charging using IPT for buses.

1.2 The Advanced Vehicle Test Facility

This demonstration project was conducted at the Advanced Vehicle Test Facility (AVTF) which consists of a one-mile banked asphalt test track and a 9400 square foot research building located on 52 acres approximately six miles from the UTC campus in Chattanooga. An aerial photograph of the test track is shown in Figure 2.

Figure 2 Test Track in Chattanooga

The research building at the AVTF is shown in Figure 3.

Figure 3 AVTF Research Building

2 Preliminary Testing

2.1 Component Testing

All of the components for the wireless charging system were tested in the laboratory before installing them on the bus. Some of the components are shown in Figure 4.

Figure 4 Power Electronics Components

The equipment shown above includes the battery management system circuit board, the inductors and the communications module with wireless modem. The switch board on the right was used to simulate the controls that would be installed on the bus to allow the operator to initiate charging. Most of these components were designed and built by Embedded Power Control to specifications provided by Conductix Wampfler, AG.

The two stationary coils that are encased in concrete are shown in Figure 5 which also shows two yellow pick-up coils (one standing on edge) and the rectifiers (with cover removed) in the background.

Figure 5 Stationary Coils, Pick-Up Coils (yellow) and Rectifiers in Background (covers off)

2.2 Systems Integration

After component testing, duplicates of all the power electronics equipment shown in Figures 4 and 5 were installed on the bus by EVAmerica. The rectifiers and heat exchanger were installed in an open compartment on the side of the bus as shown in Figure 6.The output of each coil is connected to an associated rectifier module. The rectifier modules are configured in parallel for charging the batteries. The battery pack consists of 100 Amp-hour, Ni-CD, 6 Voltage modules. 25 modules are connected in series to form a string. Two pairs of parallel strings make up the 100 cell traction battery with a total nominal capacity of 200 A-hrs.

Figure 6 Rectifier Installation

The battery management system control board was installed inside the bus, behind the operator's seat as shown in Figure 7.

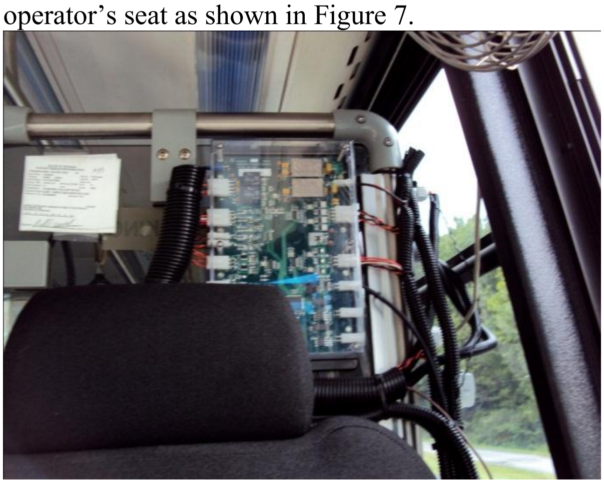

Figure 7 Battery Management System Control Board Mounted behind the Operator's seat

The communications equipment shown in Figure 8 was installed in the passenger compartment, directly behind the operator. The communications equipment includes an on-board wireless modem and antenna for communications with the stationary Track Supply.

Figure 8 Communications Equipment on the bus

In order to achieve the optimum air gap for charging, two pneumatically actuated mechanisms were designed and built by EVAmerica to lower the pickup coils into place. Figure 9 shows the pickup coils (yellow) being installed at the EVAmerica vehicle manufacturing plant in Ringgold, GA. The frame for the mechanism was made of aluminum to avoid interference with the electromagnetic field generated when charging.

Figure 9 Mechanisms for Lowering Pickup Coils

All of the power electronics equipment shown in Figures 4-8 were installed on the bus and integrated with on-board systems by EVAmerica at their plant in Ringgold, GA shown in Figure 10.

Figure 10 EVAmerica Assembly Line in Ringgold, GA

The fully integrated bus shown in Figure 11 was delivered by EVAmerica to UTC for testing in May, 2011.

Figure 11 Electric Shuttle with Wireless Charging

UTC students[16] designed and installed a guidance system outlined in Figure 12 to assist the operator in positioning the bus for charging.

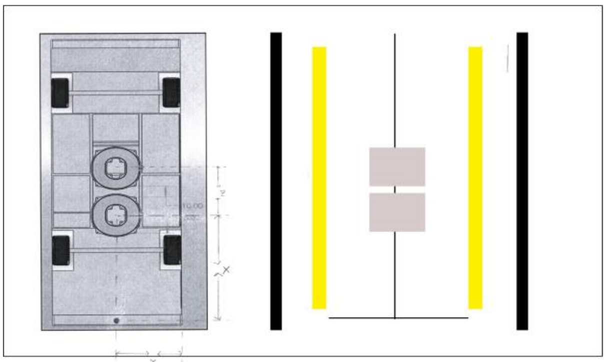

Figure 12 Worm's Eye View of Coils under the Bus and Bird's Eye View of the Alignment System

Components of the guidance system are shown in Figure 13.

Figure 13 Electronic Components of Guidance System

The camera was mounted inside the bus near the center of the windshield. The display was mounted on the dashboard as shown in Figure 14.

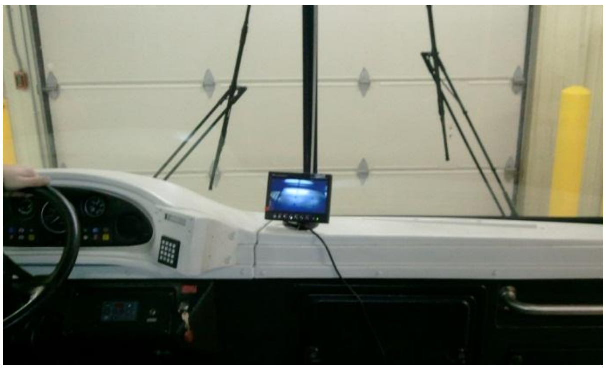

Figure 14 Display Used to Guide Horizontal Alignment

The white lane markers are used by the operator to get the bus started toward alignment as indicated in the photograph in Figure 15 below which shows the bus entering the charging area.

Figure 15 Bus entering the Wireless Charging Area

Secondary guidance for final alignment is accomplished by a camera mounted inside the windshield aimed at the yellow line down the center of the charging area. When the bus is properly positioned, the vertical yellow line representing the centerline of the charging pad and a horizontal line representing the correct stopping point will be aligned with cross hairs on the camera display, indicating to the operator that the bus is in the correct position for charging.

2.3 Site Preparation

In parallel to the design and integration work being done by EVAmerica, UTC installed all the stationary equipment on the grid side of the air gap at the AVTF. Beginning at the power grid, pull-down switches were installed to provide connection to a 100 KVA, 480V, three-phase circuit. A second switch was installed to allow power to be directed toward the inductive power transfer system or the direct chargers which were each equipped with individual disconnect switches that are necessary to comply with national and local electric codes.

Voltage transducers and current transformers were installed inside the main power switch to monitor grid voltage and current. These signals were fed through a data acquisition board into a PC that was equipped with Labview for data collection and analysis. Power from the grid was monitored by a voltage transformer. The photograph in Figure 16 shows the switch gear in the background, the data acquisition board in the upper left, the voltage transformer in the lower center, and the Labview data acquisition system in the lower left.

Figure 16 Switch Gear, Voltage Transformer and Data Acquisition System

The Labview screen for monitoring AC voltage and current is shown in Figure 17.

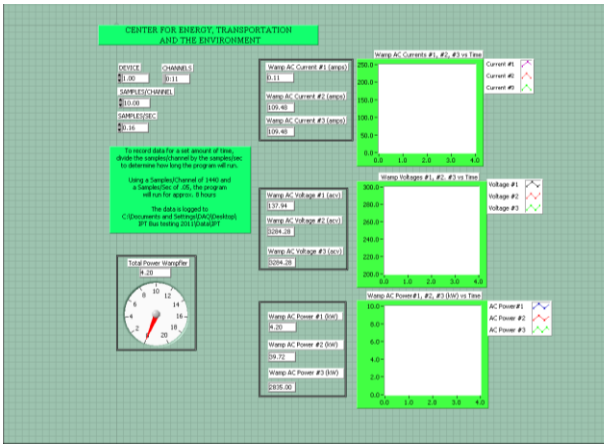

Figure 17 Labview Screen for Monitoring AC Power

The Track Supply shown in Figure 18 provides up to 60 kW of power at 20 kHz.

Figure 18 Track Supply

2.4 Tuning the System

A simplified circuit diagram16] for the system is shown in Figure 19.

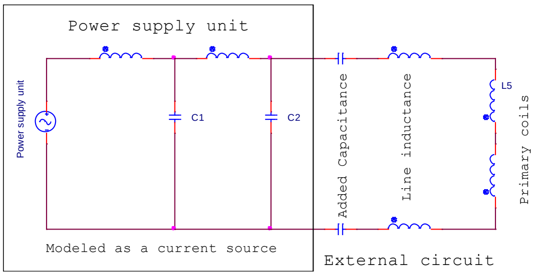

Figure 19 Simplified RLC Model for Primary Side of IPT Circuit

The resonant frequency for this circuit will be given by

$$Resonant\ frequency = \frac{1}{2\pi\sqrt{LC}}$$

The values of inductance and capacitance that will result in resonance at a given frequency could be derived from the above formula, and is given as

$$L = \frac{1}{4\pi^2 fr^2 C} \quad or \quad C = \frac{1}{4\pi^2 fr^2 L}$$

Since inductance is fixed as determined by the design of the IPT coils and the length and diameter of the Litz wires that connect the circuit, tuning is accomplished by insertion of capacitors to compensate for the inductance of the Litz cables. In this case, two capacitors were installed in series with the other components to tune the resonant frequency. Note that only finite values of capacitance can be used, so perfect tuning cannot be achieved without also changing the length of the Linz cables, which was not necessary for this installation.

Figure 20 shows the capacitor boxes with wires going into the conduit that leads to the outside IPT charging pad.

Figure 20 Capacitor Boxes used to Tune the Circuit

3 Experimental Results

3.1 Test Protocol

The CARTA downtown shuttle route, shown in Figure 21, consists of approximately three miles of relatively flat city streets with 20 stops.

Figure 21 Downtown Chattanooga Shuttle Route

The number of trips that can be made with the existing fleet of PbA battery powered shuttles depends upon number of passengers, traffic conditions, ambient temperature, and the driving habits of the operator. An overall range envelope for the existing shuttles is shown in Figure 22.

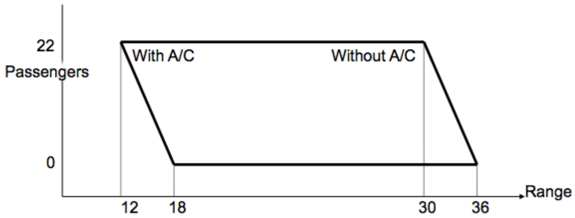

Figure 22 Range Envelope for Existing CARTA Shuttles with PbA Batteries

For testing purposes, it is recognized that the bus does not stop unless a passenger signals or someone is waiting for the bus. On average, the bus stops about nine times for each loop around the downtown route. Since the test track is a one mile oval, the test protocol adopted was to begin each test at the AVTF building with a full SOC, drive the bus for three laps around the track, stopping three times on each lap, to simulate a single trip of three miles with nine stops around the downtown shuttle route, ending back at the AVTF charging station.

To simulate passenger load, water barrels as shown in Figure 23 were placed along the centerline of the passenger compartment, representing the weight of approximately 22 passengers.

Figure 23 Water Barrels equivalent to 22 Passengers

3.2 Baseline Testing

After reconditioning the original Ni-Cd batteries, a range of more than 60 miles was recorded for travel around the test track at the AVTF with one stop after each mile. The measured performance envelope for the Ebus shuttle running on Ni-Cd batteries alone on the simulated downtown route (three miles with nine stops) is shown in Figure 24.

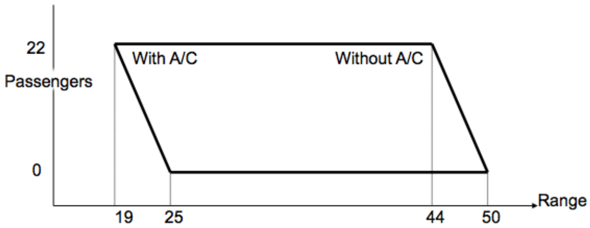

Figure 24 Baseline Range with Ni-Cd Batteries

It can be seen that the Ebus shuttle with Ni-Cd batteries alone significantly increased the range when compared with the existing shuttles that are powered with PbA batteries. However, the range is still not sufficient to cover the daily distance without swapping buses or changing batteries.

3.3 Range with Wireless Charging

Simulation suggested that a single charge at 60 kW for three minutes after each three mile trip would provide enough energy to extend the range to the required distance. Therefore, the Track Supply was programmed for a three minute charge and testing began, using three laps around the test track with three stops each lap.

The on-board data acquisition system was used to record State of Charge (SOC), battery voltage, energy consumed, and Amp hours consumed during each trip. Prior knowledge set the parameters for defining maximum range to be when the SOC dropped to 20% or the voltage dropped to 280 Volts.

Test results are given in Figures 25 and 26 that show changes in SOC and Voltage as a function of distance for the baseline bus and the bus with wireless charging.

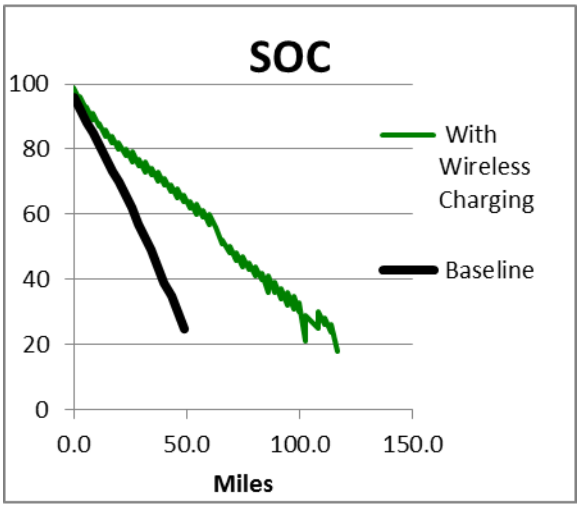

Figure 25 SOC as a Function of Distance

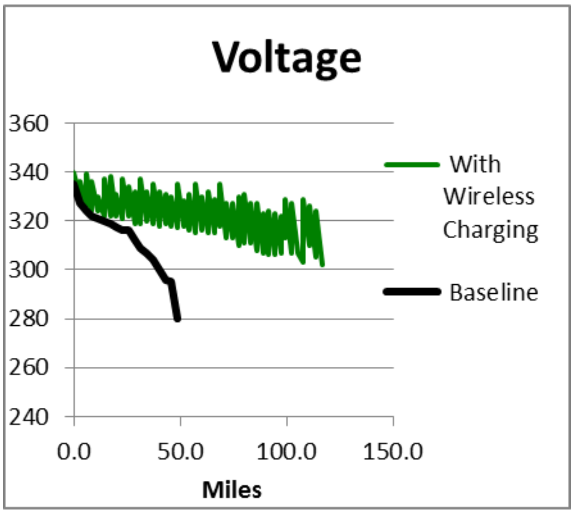

Figure 26 Battery Voltage as a Function of Distance

It can be seen that the range has been extended to more than 100 miles. Some of the irregularity in the plots is because the operator was not allowed to back the bus in order to achieve an acceptable position for charging. This is a safety rule. To compensate for a missed charging opportunity, the operator had the option of taking a double charge for six minutes duration at the next opportunity.

It can also be seen that the voltage collapses as the bus approaches the end of its range. SOC seems to be better behaved, but SOC is a derived number. Since a disabled bus with dead batteries in the middle of a trip would cause unacceptable inconvenience for passengers and a recovery operation by CARTA, it was decided that counting Amp hours (Coulombs) would be a better way of eliminating range anxiety for the operator. By starting with a full charge of 200 Amp hours and counting Amp hours consumed, the operator can know how many more trips can be made without losing power, which occurs when voltage collapse causes the current limiting features built into the drive system to reduce power as a means of protecting the batteries and on-board power electronics.

In theory, the range could also be extended by increasing the power level or increasing the frequency or duration of each opportunity charge. But C_5 = 0.3 is the maximum recommended charging rate for these batteries. From an operational standpoint, the wireless charging should meet, but not exceed, the level and duration needed to achieve the required range, allowing the batteries to reach a relatively low SOC at the end of the day, with slow overnight charging used to restore the batteries to a full SOC, while allowing the individual cell voltages to equalize, thereby increasing the life of the batteries.

DC Amp hours consumed and replaced over a 24 hour day is shown in Figure 27. It should be noted that regenerative braking provided some of the energy put back into the batteries during the day. It can also be seen that the direct charger used for overnight charging was programmed to restore automatically the batteries to a full charge of 200 Amp hours.

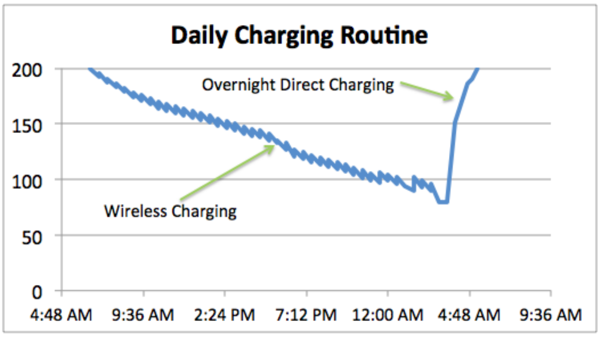

Figure 27 DC Amp Hours consumed and replaced over a 24 hour day

Labview was used to monitor AC voltage and current on each of the three phase lines connected to the power grid. Real AC power was calculated by applying a power factor of .95 for the Track Supply. Results for the driving phase of a 24 hour day are shown in Figure 28.

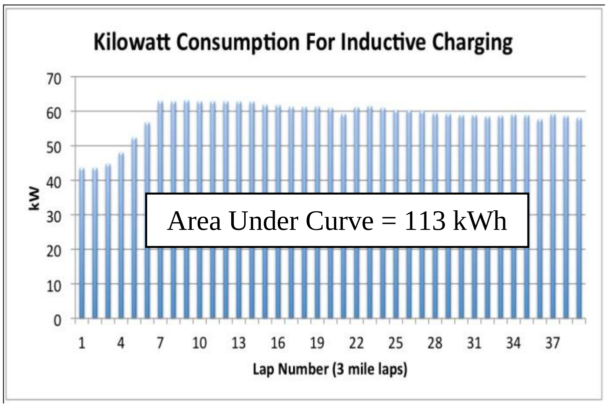

Figure 28 AC Power Consumed for a Day of Wireless Charging covering 39 trips (117 miles)

It can be seen that full charging does not occur until the seventh trip. Until the seventh trip, the SOC of the batteries is too high to accept a full charge. During this period, the wireless charging is truncated automatically. As a practical matter, wireless charging could be skipped until the SOC dropped to about 80 % at which time the batteries become more receptive to charging.

Two types of chargers were available for overnight charging. Both have been programmed to charge at their maximum charge rate until the SOC reaches 80%, followed by a lower rate of charge until the SOC reaches 95%, followed by a lower rate until SOC reaches 100%, followed by trickle charging until the SOC is slightly above 100%. The grid energy consumed by the Aerovironment 60 kW charger is shown in Figure 29. The area under the curve represents the kilowatts consumed. Analysis of the data confirmed that the automatic overnight charging not only restored the batteries to 100% SOC, but also replenished the Amp hours consumed during the previous day of driving.

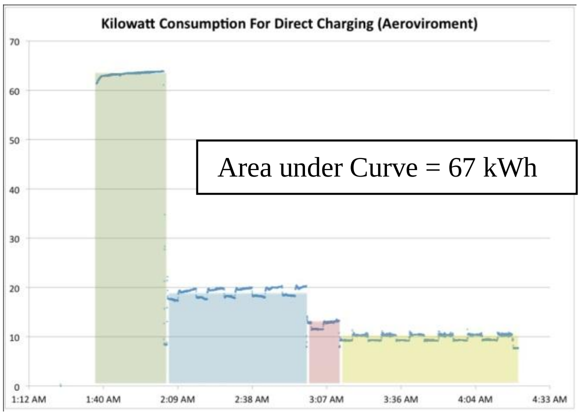

Figure 29 Power Consumed by Overnight Charging

The efficiency for direct charging depends upon the phase, with the most efficient operation occurring during the initial phase. During this phase, while the batteries were at a relatively low (<25%) SOC, the measured efficiency was more than 85%. Efficiency at other times was lower, but never below 80%.

The above data was recorded for an empty bus without air conditioning. The measured performance envelop for other operating conditions is shown in Figure 30. It can be seen that the range varies from 54 miles with a full load of passengers on a hot day to 120 miles with no passengers on a cool day. The climate in Chattanooga is mild enough most of the year that air conditioning has never been used on the CARTA electric shuttles. Should air conditioning be required, the charging profile could be modified or the operator could simply initiate double charges during the part of the day when air conditioning is needed.

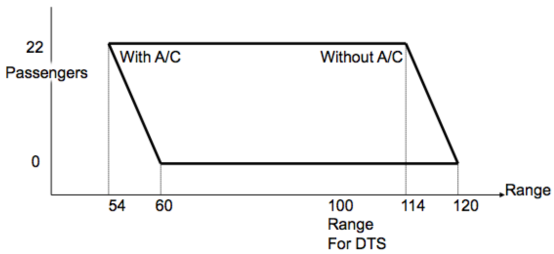

Figure 30 Range Envelope with Wireless Charging

4 Operating Cost Estimates

Overall energy consumption for traction and operation of auxiliary equipment can be estimated by summing the energy supplied from the grid during wireless and direct charging. Using the data from the above test, the total energy supplied was 113 kWh + 67 kWh for a total of 180 kWh during a day when the bus was driven 120 miles. This results in a specific energy consumption rate of 1.5 kWh per mile.

The present retail rate for electricity at the AVTF is 8.5 cents per kWh. However, large commercial customers like CARTA pay a lower rate. For a typical month, CARTA will pay 8.25 cents per kWh for the first 15,000 kWh and 3.43 cents per kWh for the balance of 21,000 kWh. This results in an average cost per kWh of 5.43 cents per kWh. The total cost of electricity used by the bus can be calculated as follows:

Daily Cost of Electricity = 180 x \$.0543

= \$9.77/Day

Cost/Mile = \$9.77/120 = \$0.08/Mile
(Empty, No A/C)

A fully loaded bus, operating on the same route on a hot day, with the air conditioning running continuously, will consume approximately 2.6 kWh per mile. This results in an estimated cost given by:

Cost/Mile = 2.6/1.5 x \$0.08 = \$0.14/Mile
(Full with A/C)

However, these conditions exist for only a few afternoons during the tourist season in Chattanooga. Furthermore, it should be noted that driving habits can have a significant impact on specific energy consumption. Taking all of these factors into account, it would be reasonable to conclude that one goal for this project has been met. Namely:

Average Cost/Mile < \$0.10/ Mile (Year Round)

This can be compared with the cost of fuel for a diesel bus that will average about 7 mpg. The present cost of diesel fuel for CARTA is \$3.23 per gallon. This yields the following estimates for a diesel bus:

Daily Cost for Diesel Fuel = 120/7 x $3.23

= $55.37/Day

Cost /mile for Diesel Bus =$3.23 / 7
= $0.46/Mile

A typical shuttle bus is designed for a useful life of seven years. Over that time, the bus will travel approximately 30,000 miles per year. Figure 31 shows a comparison of fuel costs for an electric shuttle and a comparable diesel shuttle at today's prices

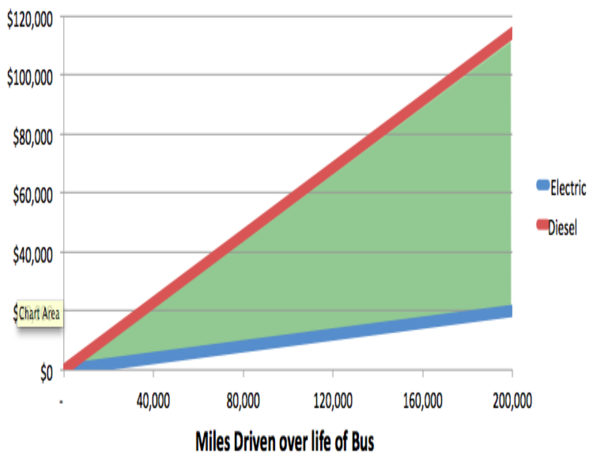

Figure 31 Comparison of Fuel Costs

It can be seen that an electric shuttle will save more than $100,000 on fuel costs over a seven year life.

Perhaps more importantly, elimination of the need to swap batteries or buses during the day has the potential to reduce the total number of buses needed from 13 to 5. It can also reduce the number of batteries since present operations require one set to be in the bus while a second set is being charged and a third set is cooling down. Also worth noting is a comparison of the changes in cost for electricity and diesel fuel over time. Since 1995 the cost of oil and the cost of electricity have both increased as shown if Figure 32.

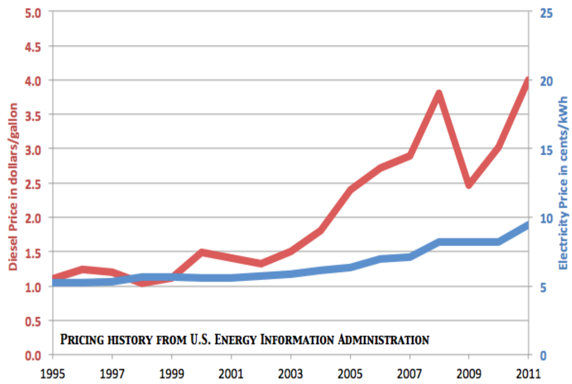

Figure 32 Cost of Diesel Fuel and Electricity

It can be seen that the cost of diesel fuel quadrupled over this period, while the cost of electricity doubled. It can also be seen that the price for diesel fuel has been much more volatile, making it difficult to budget for fuel costs. The impact of this volatility can be characterized by noting that a 10% increase in the price of diesel fuel would increase CARTA's annual fuel bill by more than $160,000.

5 Measurement of Efficiency

Since most of the wireless charging takes place after the batteries are able to accept a full charge, the most meaningful measurements of the rate of power transfer and the overall efficiency should be made during a charge cycle that occurs after the system has stabilized. The results given in the following table were measured during a wireless charging cycle that took place in the middle of the day after approximately 49 miles of service.

Table 1 Voltage and Current during Wireless Charging

AC Voltage	AC Current	Apparent Power (KVA)	Battery	Utility Load	Battery + Utility
272.9	74.1	20.2	382 V	325 V	-
272.8	73.2	20.0	137 A	-7A	-
272.6	74.6	20.3	-	-	-
Total	-	60.5	52.3	2.3	54.6

It can be seen that the total power being delivered across the air gap, including the utility load on the bus, was 55 kW when the grid was supplying apparent power of 60.5 kVA. A true indication of overall electrical efficiency would be the ratio of real power delivered to the bus divided by the real power provided by the grid. By definition, real power is the product of apparent power and power factor which takes into account both phase displacement and harmonic distortion. A Fourier series representation of the current input to the rectifier yields a theoretical value [17] for power factor of $3/\pi = 0.955$.

This would yield the following estimate for theoretical efficiency:

Theoretical Efficiency = 54.6/ (60.5x0.955) = 94.5%

6 Magnetic Flux Emissions

Public safety must be paramount in all transit operations. Documentation [18,19]. provided with the equipment suggested the electromagnetic field strength around the charging coils would be safe for human exposure. However, since the actual field strength depends upon the installation, Dr. John Boys was retained to measure electromagnetic flux to ensure public safety. The following section of this report was written by Dr. Boys:

Flux measurements were taken while the vehicle was on charge at maximum power. There is in fact a rather small window in which to get the measurements made and after this short time the charging current reduces quite significantly. The measurements were made with a Narda Safety Test Solutions ELT, Model ELT-400, P/N 2304/01, S/N M-0282. The instrument was equipped with a B field Probe P/N 2300/90 10, S/N M-0301. This instrument has been specifically designed for this type of measurement and is ideally set up for it. It was manufactured in Germany before the ICNIRP guidelines were revised upwards so the scales based on ICNIRP measurements were not used here. The measurements were all taken using the probe directly under the edge of the vehicle as shown in the Figure 33.

Figure 33 Dr. John Boys Measuring EMF

Variations in the flux density in any particular site occur at different positions along the site, and depending on how close to the ground the probe is. The flux on the side of the vehicle above the air-gap is a lot smaller than the flux in the air-gap and does not contribute to the ICNIRP measurement. The range of measurements covers the available movement possible with the 100 cm^2 probe. Results are shown in Table 2.

Inside the vehicle it was expected that the flux levels would be very small. However it was observed that there were scattered pockets of flux up to 8.8 µT very close to the floor of the vehicle. All of these measurements were well under the ICNIRP guidelines but there are still points of interest.

Table 2 EMF Measurements

Position	**Flux Range**
A Forward of front wheels	<0.5 µT
B Driver's Side, between wheels	2.3-7.2µT
C Door side, Between wheels	7.2-7.5 µT
D Behind the rear wheels	<0.5 µT

(This ends the section written by Dr. Boys)

It is important to avoid use of ferrous materials in the vicinity of the induction coils. In Figure 33 you will note the presence of a steel plate used to cover the access tunnel to the embedded primary induction coils. Dr. Boys recommended replacement of this steel plate. When the steel plate was replaced with an aluminum plate, the measured EMF was reduced as shown in Table 3.

Table 3 EMF Measurements after replacing Steel Plate with Aluminum Plate

Position	Flux Range
Background	0.13 µT
Inside Bus at Floor Level above Coils	4.1µT
Inside Bus 3 feet above Floor	0.41µT
Inside Bus 6 feet above Floor	0.21µT

7 Environmental Considerations

7.1 Compliance with Clean Air Act

Elimination of tailpipe emissions makes electric shuttle buses particular friendly to the environment. When the electric shuttles were introduced in Chattanooga, the primary driving force was to assist Chattanooga to attain compliance with the Clean Air Act. This meant significant reductions in all the emissions normally associated with diesel buses, including hydrocarbons (NHOG, NMHC, or THC), Oxides of Nitrogen (NO_x), particulate matter (PM), Carbon Monoxide (CO), and Formaldehyde (HCHO). Today, Chattanooga has not only attained full compliance with the Clean Air Act, but has also created enough “headroom” to accommodate economic development projects such as the new automobile manufacturing plant recently built in Chattanooga.

7.2 Reduction in Green House Gases

In addition to reducing SMOG, there will also be a corresponding reduction in Green House Gases (GHG). Using the method recommended by the American Bus Association[20], it can be estimated that combustion of a gallon of diesel fuel will produce 10,274 grams of CO_2 while the US average for production of 1 kWh of electricity is 600 grams. A diesel bus will average 7 mpg. An electric bus will consume approximately 1.5 kWh per mile for traction. Using these values, an electric bus will reduce CO_2 emissions by approximately 567 grams per mile. Reductions over the design life of an electric shuttle are shown in Figure 33.

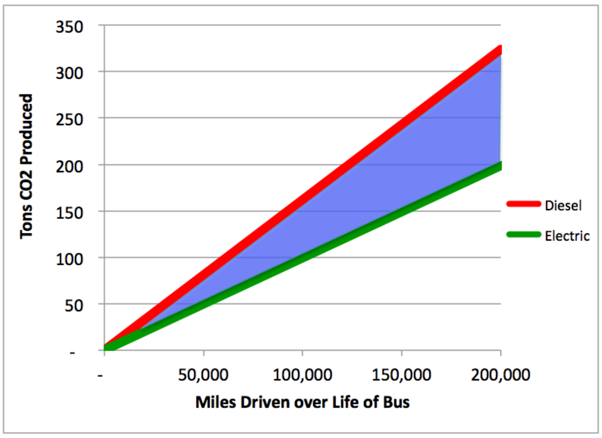

Figure 33 Comparison of CO_2 Emissions for Diesel and Electric Shuttle Bus (22 foot)

It can be seen that an electric shuttle will reduce CO_2 emissions by at least 125 tons. Total GHG emissions would be higher for diesel buses because of emitted hydrocarbons and particulate matter. It should also be noted that electric buses are virtually silent, thereby reducing noise pollution that can be particularly annoying in those areas normally served by transit buses.

8 Summary

A comparison of the goals and results for this project are given in Table 4

Table 4 Summary of Results

Objective	Goal	Results
Charge Time	**One Minute**	**One Minute**
Distance per Charge	**One Mile**	**One Mile**
Cost per Mile	**$0.10**	**$0.08**
Range w/o Charging	**100 Miles**	**120 Miles**
Tail Pipe Emissions	**Zero**	**Zero**

While there was no specific goal for efficiency, it was found that the overall grid to vehicle efficiency was greater than 90%. It was also demonstrated that electromagnetic flux emissions were well below ICNIRP standards for all locations.

9 Conclusions

It can be seen that the goals of this project have been met. It has been shown that wireless charging using IPT technology can “bend the curve” for net energy consumption, thereby eliminating the limited range constraint that has restricted use of electric buses to relatively flat circulator routes that can support battery and/or bus swapping. Furthermore, it has been shown that this can be done in a safe, cost effective, operationally sound and environmentally friendly manner.

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11 References

1. Santa Barbara Electric Bus Project, Phase 3A Final Report, Systems Control Technology, Inc. September 1983
2. Santa Barbara Electric Bus Project, Prototype Development and Testing Program Phase 3B Final Report, Systems Control Technology, Inc. September 1984
3. Santa Barbara Electric Bus Project, Test Facilities Development and Testing Program Static Test, Systems Control Technology, Inc. June 1985
4. Santa Barbara Electric Bus Project, Prototype Development and Testing Program, Phase 3G-Final Report, Systems Control Technology, Inc. May 1986
5. Lashkari, K., Shladover, S.E., and Lechner, E.H., "Inductive Power transfer to an Electric Vehicle," Proceedings of Eighth International Electric Vehicle Symposium, Washington, DC October 1986
6. Lechner, E.H. and Shladover, S.E., "The Roadway Powered Electric Vehicle-An All-Electric Hybrid Systems," Eighth International Electric Vehicle Symposium, Washington, DC October 1986
7. Shladover, S.E, "Systems Engineering of the Roadway Powered Electric Vehicle Technology," Proceedings of Ninth International Electric Vehicle Symposium, Toronto, Ontario
8. Roadway Powered Electric Vehicle Project Track Construction and Testing Program Phase 3D, Institute of Transportation Studies, California partners for Advanced Transit and Highways (PATH) 1994
9. Ross, Howard R., Roadway-Powered Electric Vehicle System Having Onboard Power Metering and Communications Channel Features US Patent No 5,573,090 November 12,
10. Griffith, Paul, Bailey, J. Ronald, Simpson, Dan, "Inductive Charging of Ultracapacitor Electric Bus", World Electric Vehicle Journal, Volume 2, Issue 1 September 2008
11. Ross, Howard, R., Roadway-powered Electric Vehicle System having Automatic Guidance and Demand-based Dispatch Features, US Patent No 6,879,889 issued April 12, 2005
12. Bailey, J. Ronald, Hairr, Mark, Dugan, Thomas, Curtis, Albert, and Booth, Dick, "Wireless Charging of Shuttle Buses", Conference on Electric Roads and Vehicles, Park City, Utah February, 2012
13. Kamiya, Yushi, Daisho, Yasuhiro, Kuwabara, Fumio, Takahashi, Shunsuke, and Narusawa, Kazuyuki, "Development and Performance Evaluation of An Advanced Electric Micro Bus Transportation System, EVS 22, Yokohama, Japan, October 2006
14. Kamiya, Yushi, Nakamura, Toru, Sato, Takeshi, Kusaka, Jin, Daisho, Yasuhiro, Takahasi, Shunsuke, Narusawa, Kazuyui, "Development and Performance Evaluation of Advanced Micro Bus Equipped with Non-contact Inductive Rapid-Charging System, EVS23, California 2008
15. "On Line Electric Vehicle (OLEV) project, announced by Korean Advanced Institute of Science and Technology (KASTI), February 2009
16. Bush, Corey, Joseph, Vipin, Williams, Mike, Ashmore, James, "Inductive Power Transfer Final Report for ENGR 485 April 2011
17. Boys, John, "Note on Power Factor" to J.R. Bailey, September 2011

18. Wampfler IPT Facts: “Evidence that IPT Does Not resent a Health Hazard”, Wampfler, AG, January 2000

19. Wampfler IPT Charge Facts: Magnetic Flux Densities of the IPT Charge System, Wampfler AG, November 2000

20. Bradley, M.J. & Associates, “Comparison of Energy Use & CO_2 Emissions From Different Transportation Modes, May 2007

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