A Cost Benefit Analysis of a V2G-Capable Electric School Bus Compared to a Traditional Diesel School Bus

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Authors:

Lance Noel[1] (lnoel@udel.edu) (corresponding author) and Regina McCormack[1] (rmccorma@udel.edu)

[1]Center for Carbon-Free Power Integration, University of Delaware
ISE Lab, Newark, DE 19716

Abstract

Fuel expenses, diesel exhaust health externalities, and climate change are concerns that encourage the use of electric vehicles. Vehicle-to-grid (V2G) policies provide additional economic incentives. This analysis evaluates the costs and benefits associated with the use of electric vehicles and determines the cost effectiveness of using a V2G-capable electric school bus compared to a traditional diesel school bus. Several factors were analyzed, including fuel expense, electricity and battery costs, health externalities, and frequency regulation market price. The V2G-capable electric bus provides the school savings of $6,070 per seat in net present value and becomes a net present benefit after five years of operation. Without externalities, the net present benefit would be $5,700 per seat. If the entire school district's fleet switched to V2G-capable electric buses, the net present savings would be upwards of $38 million. A sensitivity analysis was conducted to determine how the factors influenced the costs and benefits. In all cases, purchasing an electric school bus is consistently a net present benefit. Policies could be set into place to incentivize public school adoption of electric buses, encourage more efficient batteries, and develop V2G capabilities.

Keywords: electric vehicle; V2G; cost-benefit analysis; school bus; climate change mitigation; diesel

1. Nomenclature

Variable	*Variable Definition*	*Value Used*
B_D	Cost of Diesel Bus	$110,000
B_E	Cost of the Electric Bus (Including Charger)	$260,000
B_R	Cost of Replacement Battery	$300/kWh
C_D	Seating Capacity of Diesel Bus	32
C_E	Seating Capacity of Electric Bus	24
C_{er}	Average Electricity Carbon Emission Rate	1.18 lbs/kWh
C_{dr}	Diesel Carbon Emission Rate	22.2 lbs/kWh
D	Miles Driven per year	8,850
D_C	Annual Cost of Diesel Fuel	$6,351*
D_D	Annual Diesel Demand	1,393 gallons
E_C	Annual Cost of Electricity	$714*
E_{CAP}	Capacity of the Charger	70 kW
E_D	Annual Diesel Externalities	$1,214
E_D	Annual Electricity Demand	6,613 kWh
E_E	Annual Electricity Externalities	$280
E_S	Battery Storage Capacity	80 kWh
f_1	V2G Adjustment Factor	0.1
f_2	Battery Capacity Factor	0.2
h_{dr}	Per-Mile Cost of Diesel Health Emissions	$0.08
h_{er}	Per-Mile Cost of Electricity Health Emissions	$0.0149
$H_{V2G/Y}$	Hours per Year Performing V2G	7,647.8
H_{V2G}	Hours per Day Performing V2G	18.25 (24)[†]
i_d	Diesel Inflation Rate	8.50%
i_e	Electricity Inflation Rate	1.90%
L_B	Estimated Life of the Battery	9 years
L_r	Labor Cost to Refuel	$225/year
M_D	Annual Maintenance Cost of Diesel Bus	$9,075
m_{dr}	Per-Mile Diesel Bus Maintenance Rate	$1
M_E	Annual Maintenance Cost of the Electric Bus	$1,770 ($25,770)[‡]
m_{er}	Per-Mile Electronic Bus Maintenance Rate	$0.20
N_{Cycle}	Rated Life Cycle of Battery	2,000
NPB	Calculated Net Present Benefit of Electric Bus	$6,070
P_D	Price of Diesel	$4.20/gal

Variable	***Variable Definition***	***Value Used***
P_E	Price of Electricity	\$0.106/kWh
P_R	Regulation Price for V2G Revenue	\$28/MWh
R	Range of Battery	100 miles
r_d	Discount Rate	3%
R_{V2G}	Annual V2G Revenue	\$15,274*
SCC	Social Cost of Carbon	\$36/MTCO$_2$e
Y	Year in the Model	N/A
μ_d	Diesel Engine Efficiency	6.35 mpg
μ_e	Battery Efficiency	747 Wh/mile

*These numbers represent the first year of the model and will change in ensuing years with inflation.

† Hours performing V2G on school day (Hours performing V2G on non-school day).

‡ Annual maintenance cost (Annual maintenance cost including battery replacement).

2. Introduction

Electric vehicles address several problems that traditional petroleum vehicles cause: health risks due to exhaust, dependency on foreign oil, and carbon emissions that perpetuate climate change. Diesel exhaust contains pollutants that cause respiratory irritation, heart disease, and lung cancer, posing substantial health risks for those frequently exposed to diesel exhaust [1]. Petroleum is the primary fuel for transportation, and transportation accounts for 28% of energy consumption in the U.S. [2]. While domestic resources provide 60% of U.S. oil demand, 40% is imported, with Canada providing the most imports, followed by Saudi Arabia, Mexico, and Venezuela, among other countries [3]. Climate change induced effects include global warming, sea-level rise, and extreme weather events that can displace people from their homes and wildlife habitat [4]. These concerns and innovative vehicle-to-grid technology (V2G) are the impetus of this cost benefit analysis of the choice to purchase a V2G-capable school bus versus a traditional diesel school bus.

Electric vehicles can provide services to the electric grid using V2G technology. Demand for electricity fluctuates continually depending on consumer actions. The frequency regulation market accounts for this fluctuation and enables the electric grid to match electricity generation to load. Combustion-based turbines, hydroelectric pumps, and flywheels are typically used for storage by the frequency regulation market, but electric vehicles offer novel storage capabilities that are more efficient. When electric vehicles are parked and connected to a charger, they can provide storage for the electric grid. In turn, vehicle owners can participate in the frequency regulation market and receive compensation for that service [5]. Revenue received for electric vehicle storage capability provides incentive for the adoption of electric vehicles. The literature has shown that V2G technology has been established as a potential revenue source as a participant on frequency regulation market [5] [6]. In addition, while many have detailed the economic toll of mitigating climate change and have investigated minimizing these costs [7] [8], there has been less of a focus on minimizing the costs of mitigating climate change effects due to transportation, especially with consideration of V2G technology.

Despite the advantages electric vehicles provide, electric vehicles face several limitations that prevent them from widespread implementation. Barriers include battery cost, vehicle range, and availability of charging stations [9] [10]. Hidrue et al. [9] found that battery cost discourages potential buyers. Likewise, Lemoine, et al., found that adoption of plug-in hybrid electric vehicles would not occur unless there were significant decreases to battery costs (or significant increases in gasoline prices) [11]. Also, batteries require several hours to fully charge and have driving ranges that are typically less than a petroleum vehicle's range. This requires electric vehicle drivers to adjust driving habits and refueling behavior [12]. Furthermore, charging stations are less abundant than gas stations, requiring drivers to plan their routes ahead of time.

The aforementioned limitations for electric vehicles are relevant particularly for private vehicle owners; however, this study analyzes the cost effectiveness of a V2G-capable, electric public fleet vehicle, as it is anticipated that public fleet vehicles will face less of these challenges. Compared to privately owned vehicles, public fleet vehicles may more successfully support V2G applications given they have predictable routes of limited range and are not in use for driving purposes for extended periods of time. After public fleet vehicles conduct their typical routes, they can be plugged in for the entirety of the time they are not in use, enabling them to collect revenues for V2G services for several hours per day. Though this analysis focuses on school buses, the analysis can be applied to other large public fleets such as city buses, garbage and recycling trucks, mail trucks, and other commercial fleets that fit within the same major assumptions of this paper.

Of all public fleet vehicles, school buses are of particular interest because they cause disproportionate health effects, especially on school children's health [13]. Health concerns arise because diesel buses release particulate matter and other harmful pollutants, and these emissions can be disproportionately higher within the cabin of the bus compared to ambient pollution levels [14]. In fact, it is estimated that up to 0.3% of in-cabin air comes from a bus's own exhaust [15]. School buses, for example, have a significant impact on local aerosol levels that could directly influence the health of children [16]. Such concern has been the impetus for several policies requiring the reduction of school bus exhaust pollution. For this reason, the cost-effectiveness of an electric school bus is analyzed because it avoids such health impacts.

While other studies have investigated the costs and benefits of electrifying privately owned vehicles [11], this analysis is novel for its focus on public fleet vehicles and V2G capabilities. For example, Al-Alawi and Bradley compared the costs and benefits of privately-owned conventional vehicles and plug-in hybrids, and found a payback period of 7 to 10 years [17], but did not include the possibility of V2G revenues, which the analysis found to be essential for cost-effectiveness. Feng and Figliozzi found that the electric commercial fleet vehicles were not competitive with conventional diesel commercial vehicles unless either battery costs decreased by 10 to 30% or both the diesel fuel economy was particularly low and vehicles were highly utilized [18]. However, this differs from this analysis in that it does not include V2G revenues and focuses on commercial rather than public fleet vehicles. Furthermore, articles that focus on buses tend not to focus on the costs and benefits, but rather the performance and fuel efficiency of differing types of buses. Hu et al. found that plug-in hybrid buses were more efficient than diesel buses from tank to wheel, and that increases in battery capacity further increased tank to wheel efficiency [19]. While the article determines the efficiencies of the buses, it does not account for any costs, and also does not include V2G capacity. In addition, Dawood and Emadi compared the different fuel efficiencies of differing types of buses, and found that parallel electric hybrid buses had the highest fuel economy and fastest acceleration [20]. Likewise, the article does not explore purely electric buses, V2G capacity, or account for any costs. Peterson et al. investigate the economics of using plug-in hybrid electric vehicle for V2G services, and found benefits of $10 to $120 per year [21] per vehicle. However this paper does not include frequency regulation participation, driving behavior, or purely electric vehicles with higher capacity as this analysis does.

The analysis investigates the cost-effectiveness of using a V2G-capable electric bus compared to a traditional diesel bus. Benefits were assessed such as reduced impacts on climate change, health externalities, and energy efficiency. Limitations were considered such as driving behavior, battery use, and infrastructure challenges. The analysis supports the adoption of V2G-capable vehicles for large fleets as a net benefit and provides implications for transportation policy.

3. Material and Methods

3.1 Bus Costs

The electric bus considered in this study is the Smith Newton eTrans electric school bus[1]. The eTrans costs $230,000 and can carry 24 adults plus two wheelchair accessible locations. The eTrans can be equipped with a battery pack ranging from 40 kWh to 120 kWh (Personal Communication, Brian Barrington, January 2013)[2]. For this analysis, the eTrans was fitted with an 80 kWh battery that has a range of 100 miles. The eTrans was compared to the counterfactual, a traditional diesel Type C school bus of comparable size and seating capacity. This bus carries 32 adults plus two wheelchair accessible locations [22][3]. The typical cost of a Type C diesel bus is $110,000 [23], and the average fuel economy is approximately 6.35 miles per gallon [24], including the effects of idling on efficiency.

[1] Model EN200DSFP900
[2] See http://www.transtechbus.com/
[3] Though the Type C diesel bus and the eTrans are nearly the same size, 12' by 7.5', the eTrans has a slightly roomier interior, seating fewer passengers. The Type C diesel bus is commonly named a 66-passenger bus because child passengers are smaller than adults and several more children can fit in the seats.

The number of years a school system is allowed to use the buses is regulated by the states. This analysis considered the cost-effectiveness of an electric bus throughout the lifespan of a traditional diesel bus (14 years under Delaware law).[4]

Unlike a traditional diesel bus, the eTrans has additional costs because it requires charging infrastructure. It was assumed that a school bus operator would need to purchase a high capacity battery charger with the purchase of an eTrans. This analysis did not consider diesel infrastructure because it was assumed that bus operators would have access to diesel refueling stations. There are varieties of battery chargers, ranging from 3 kW up to over 70 kW. An on-board charger was instead used in the analysis, the EPiC 150 Automotive inverter, because it has a larger capacity. It can charge the battery at 70 kW continuously and discharge at a maximum of 140 kW for a minute, only requiring 208 V three phase plug [25]. The hypothetical cost of installing the EPiC 150 is approximately $30,000 (Personal Communication, Allen Abela, June 2013), assuming it was included in the design and construction stage of an eTrans. The overall cost of the eTrans in this paper includes both the actual cost of the bus, and also the charger, totaling $260,000.

3.2 Driving Behavior

Driving behavior was estimated based on data collected by the Red Clay School District in Delaware. The average bus route for the Red Clay School District is 50 miles a day and operates on the roads for 5.75 hours each day (Personal Communication, Ron Love, August 2012)[5]. It was assumed that each bus would operate only during the normal school year, which is 177 days, and that there would be no change in driving behavior. When a bus is not in operation, it would either be charging lost energy from driving or performing V2G services.

3.3 Energy Costs and Revenues

3.3.1 Diesel Costs

The cost of diesel was estimated to be approximately $4.20 per gallon, the average cost of diesel in the Central Atlantic region in 2012 [26]. However, diesel prices are highly volatile and change irrespective of the inflation rate. Though diesel prices have both dramatically increased and decreased, over the last two decades, the average annual price of diesel has increased by 8.5% [27]. The average inflation rate was chosen for this analysis.

3.3.2 Electricity Costs and Revenues

School buses are usually stored in a parking area, or a bus depot, which is where the eTrans would likely be stationed to connect to the grid and charge. Because they are neither

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[4] In adherence to the state of Delaware's 13 DE Reg 1086, after the fourteenth year, a school bus is required to be replaced for regular use but may be occasionally used as a spare. In addition, if the bus owner chooses, a bus can be replaced before fourteen years. If a bus has been driven 190,000 miles total, 130,000 miles in nine years, or more than ten years, a bus operator can elect to replace a bus. For the purpose of this cost benefit analysis, both buses are assumed to be in regular service for fourteen years.

[5] Ron Love is the Education Associate, Pupil Transportation for the Delaware Department of Education.

residential nor industrial, schools and their bus depots pay the commercial rate. The average commercial rate for electricity in Delaware is 10.6 cents per kWh [28].

An eTrans would participate in and gain revenues from the regulation market. Federal Energy Regulatory Commission (FERC) recently issued Order 755, finding that the current regulation payment structures were discriminatory towards actors like batteries. FERC required that regional transmission organizations like PJM, the regional transmission organization that operates in Delaware, to restructure payments to include not only capacity but also the amount of total energy charged and discharged and how accurately the regulation market participant reacted to the signal from the market [29]. Due to this order, batteries are paid more than the average regulation market participant because they are a more efficient frequency regulatory market participant. Batteries are more efficient because they can respond to a market change in a matter of seconds, whereas a traditional combustion-based regulation market participant responds in up to 10 minutes [30]. Because batteries respond quicker, batteries are able to charge and discharge more energy than traditional energy sources. Since the PJM's implementation of FERC Order 755, the effective overall market clearing price for regulation services has risen to approximately $28/MWh [31], which was the value used for the analysis.

The cost of electricity also varies widely from year to year, inflating and deflating at a rate independent of the normal inflation rate. Annual electricity inflation rates were calculated according the U.S. average retail price of electricity between 1990 and 2011 [32] . Electricity has fluctuated less dramatically than diesel fuel, ranging between -2% and 9%, per year. The average rate of 1.9% is used for this analysis.

3.4. Maintenance

3.4.1 Diesel Bus Maintenance Cost

Two factors were included in the maintenance cost. First, to estimate the costs of replacing and repairing parts of the diesel bus, the Federal Land Management Agencies cited a diesel bus maintenance cost of $1 per mile [23]. In this report, other studies were cited with significantly higher per mile maintenance costs, so this should be seen as a conservative estimate. The second factor included in the maintenance cost was the estimated costs of labor to refuel the bus. On average the operators refuel each bus 1.5 times a week, costing $225 annually [33]. It should be noted that the minimal time used to plug the eTrans into the charger was not included in the analysis because the labor requirements are negligible in comparison to the labor used to refuel the traditional diesel bus. The labor requirements of the bus driver for the eTrans would be simply plugging in the bus once it is parked.

3.4.2 Electric Bus Maintenance

The eTrans would require much less maintenance because the drive system is simple compared to a diesel bus with less moving parts. Due to this simplification, it is expected the maintenance cost for the electric bus would be significantly less than the traditional diesel bus.

Despite this expectation, there are no sources of data concerning average maintenance costs of electric vehicles, making it impossible to be certain of actual maintenance cost.

The major cost of electric vehicle maintenance is battery replacement, depending on the life of the battery and the cost of replacement. A key factor in the lifespan of a battery is the number of cycles of discharge and charge that the battery can withstand before it loses a certain percentage of nameplate capacity. The maximum cycle is estimated based on the depth of discharge in each cycle and the percentage capacity lost. There is not a uniform test for life cycle. For example, the test depth of discharge ranges from 80-100, where as in practice an eTrans would normally not approach this depth of discharge given that it only drives the average 50 miles a day. In addition, the percentage capacity lost before battery replacement can range from 70-90% of original capacity, depending on the standards of the battery manufacturer. As the range of an eTrans with original capacity is double the length of the average daily transit, battery capacity could deteriorate much less that 90% without affecting a bus's daily activities. The battery of an eTrans, an A123, is estimated to last approximately 2,000 cycles given 100% depth of discharge and 90% of original capacity, and more than 7,000 cycles given 100% depth of discharge and 80% of original capacity [34]. The input variable for the lifespan of the battery was 2,000 cycles and should be seen as a conservative estimate for the replacement time of the battery.

Currently, the price of batteries has dropped significantly to $500 to $600 per kWh [35]. However, since the replacement of the battery will not occur until nine years in the future (See Equation 2), and considering that batteries will continue to decrease in the next nine years, this range was not used. Rather, the price used in this analysis is significantly less than current prices, estimated to be $300 per kWh, based on projected goals by the Department of Energy [36]. This is a conservative estimate considering other authors have estimated that prices will be less than that by 2020 [35]. Assuming that an eTrans is replaced with the same capacity battery, a new 80 kWh battery should cost approximately $24,000. While this should represent nearly all the maintenance costs for the electric vehicle, there could be other maintenance costs associated with an eTrans. A similar cost benefit analysis simply estimated that electric vehicles' maintenance costs would be approximately half of that of conventional vehicles [18]. This assumption was used as well for this analysis. Thus, the expected per mile cost of the eTrans should be approximately $0.50. Subtracting the per mile cost of future replacement of the battery, the remaining, miscellaneous cost is $0.20 per mile, the expected cost of all other maintenance.

3.5 Health and Environmental Externalities

3.5.1 Diesel Externalities

A traditional diesel bus has two externalities associated with the consumption of diesel fuel. First, carbon is emitted during the burning of diesel while driving the traditional diesel bus. The traditional diesel bus will directly emit approximately 22 pounds of carbon through its tailpipe for each gallon of diesel consumed [37]. For the analysis, monetization of the cost of carbon dioxide was based on an average of the social cost of carbon. Over the next decade, the average social cost of carbon is $36 per metric ton of carbon dioxide [38].

In addition to environmental externalities associated with carbon emissions, a diesel bus also emits conventional pollutants that affect public health. The combustion of diesel fuel releases particulate matter, ozone, sulfur dioxide, nitrous oxide, and other pollutants. Such pollutants cause heart disease, respiratory issues, and increased risk of cancer. Based on the weight of a Type C school bus [39], it is classified as a Class 7 Heavy Duty vehicle [40]. The estimated cost of health externalities for a Class 7 Heavy Duty diesel vehicle is $0.08 per mile [41].

3.5.2 Electric Externalities

Unlike a traditional diesel bus, an eTrans would have no direct emissions and have only indirect emissions generated by electricity production to charge the battery. The carbon emission rate depends on the generation mix of PJM Interconnection, which is currently dominated by coal, natural gas and nuclear power generation [42]. After multiplying carbon emission rates for each of the generation types [43] by the PJM generation mix, an average emission rate of 1.18 pounds of carbon per kWh was found. Thus, the total carbon emission associated with charging an eTrans' battery was calculated to be 3.56 metric tons a year. This figure is conservative given fuel switching that has already occurred since that study was undertaken (natural gas has been replacing coal and wind and solar energy has increased). Again using the social cost of carbon of $36 per metric ton of carbon dioxide, the yearly cost of carbon for the eTrans was estimated to be $130 a year.

Similar to the traditional diesel bus, pollutants that cause health risks are released via electricity production from fossil fuel sources such as coal, natural gas, and oil. The estimated cost for an electric vehicle is $0.0172 per mile in 2005 and projected to be $0.0149 by 2030 [41]. Because electric generation has changed drastically since 2005 and even since 2013, in that there has been a significant switch from coal to natural gas, and the increased penetration of renewable energy [44], $0.0149 is a more accurate estimate of the health externality associated with an eTran's electricity needs.

4. Theory/calculation

The cost benefit analysis was conducted by summing the costs and benefits of each of the respective buses over the fourteen year bus lifespan. Then, each sum was converted into the net present value, using a discount rate of 3%. Since a traditional diesel bus and an eTrans have different seating capacities, the net present value was divided by the capacity, converting the number into a net present value per seat. The traditional diesel bus's net present value per seat was subtracted from the eTrans's net present value per seat to yield the net present benefit of choosing the eTrans over the traditional diesel bus, as seen below.

Equation 1. Net present benefit calculation. Refer to the Nomenclature and Appendix sections for definitions and calculations of variables.

$$NPB = \frac{\sum \frac{R_{V2G} - (E_C + M_E + E_E + B_E)}{(1 + r_d)^y}}{C_E} - \frac{\sum \frac{D_C + M_D + E_D + B_D}{(1 + r_d)^y}}{C_D}$$

Annual V2G revenues were estimated by calculating the price of regulation per hour and the total hours performing V2G per the capacity of the charger. In addition, these revenues would be influenced by the electricity inflation rate. According to these calculations, annual V2G revenues could be approximately $15,000. Receiving this revenue every year greatly reduces the cost of ownership of an eTrans. Annual electricity costs are estimated at a little more than $700, dwarfed by the revenue from V2G, while also significantly less than the annual diesel cost, which was approximately $6,000 per year. The cost of electricity would increase year to year according to the electricity inflation rate as well. Likewise, the diesel cost would also fluctuate with the diesel inflation rate.

As previously mentioned, the annual electric bus maintenance cost was determined by the per-mile maintenance rate, the miles driven a year, and the cost of the battery. The estimated life of the battery was also calculated, according to the equation below.

Equation 2. Life of battery calculation. Refer to the Nomenclature and Appendix sections for definitions and calculations of variables.

$$L_B = \frac{N_{Cycle}}{\frac{d}{r} + f_1 \times H_{V2G/Y} \times f_2 \times \frac{E_{CAP}}{E_S}}$$

The life of the battery is dependent on the uses of the batteries, including driving, charging, and V2G services. The equation above is the life cycle rating of the battery, divided by the uses that impact the battery, resulting in the life of the battery in years. However, each of these uses has a different impact on the life of the battery and needs to be adjusted accordingly. The battery capacity factor, f_2, (also known as the dispatch to contract ratio) determines how the battery degrades according to normal operation and is dependent on several factors such as temperature and state of charge [45] [5]. The battery capacity factor was estimated to be approximately 0.2 [46], which would lead to a conservative estimate of battery life, as other sources have concluded that the battery capacity factor is lower at 0.08 [5]. Meanwhile, the V2G adjustment factor, f_1, or how much performing V2G impacts the life of the battery, is much more uncertain as the market for V2G is now just emerging. Since V2G occurs at a lower state-of-charge with fewer fluctuations, it will not have the same impact as driving. For small states of charges Kempton and Tomic calculated that using Saft batteries and a small fluctuation of state-of-charge (3% depth of discharge), f_1 would be approximately 1/10 of the impact as normal state-of-charge fluctuations [5]. Thus this analysis used an f_1 of 0.1. This factor should be considered conservative because others have found that the increased cycling due to V2G "poses no significant contribution to the overall aging of the battery" [45]. Using the stated equation, the 2,000 estimated life cycles would require a battery replacement in the ninth year. A123 estimates that their batteries will last approximately fifteen years [34], but this does not include potential wearing of the battery due to V2G. The assumption used here is a conservative estimate of battery life, since other sources have documented that using V2G can extend battery life by as much as sixty percent [45]. The authors concluded that the life of battery was extended since V2G services keep the battery at a medium state of charge, thus limiting the time that the battery is in a stressful high state of charge. The equation used in this analysis did not assume that V2G would extend the life of the battery and instead assumed that it would wear the battery, but if the authors' conclusions are true, it is possible that the battery would not need to be replaced at all.

Annual per-mile maintenance costs for each bus was calculated using the per-mile rate and the miles driven each year. Outside of the cost of the replacement battery, the average annual electric bus maintenance cost was calculated to be $1,770, a significant savings compared to the calculated annual diesel bus maintenance cost, $8,850. This leads to significant savings over the lifespan of the bus.

The electricity externalities were calculated based on the annual emission and health externality rates and electricity demand each year. An eTrans's annual externality costs totaled $241, while a diesel bus's totaled $1,060.

In conclusion, the annual fuel, maintenance, and externality costs all represented significant savings from the perspective of an eTrans, while an eTrans additionally provided an equally significant benefit in annual V2G revenues.

5. Results

The results are shown below as the net present value, per seat, of an eTrans minus the net present value, per seat, of a diesel bus. Choosing an eTrans rather than a diesel bus would save a school district $6,000 for every seat or approximately $230,000 per bus (although this does not account for different seating capacities) over the fourteen year lifespan of each bus. After the large initial investment of purchasing an eTrans, the school bus operator would begin to receive net positive gains from the eTrans in comparison to the traditional diesel bus after five years. If school districts purchase an eTrans, they could save a large amount of money while also shifting away from the consumption of diesel and enhancing school children's health.

5.1 Results Without Considering Externalities

While many are interested in the costs of the externalities, school bus operators that purchase buses would not normally include these considerations as a part of their budget. Even without considering the social cost of health and climate change externalities, the net present benefit per seat of selecting the eTrans is still significantly positive, at $5,700. Thus, selecting a V2G-capable electric bus could provide significant savings for the school bus operator, even when not including any externalities such as benefits for public health and abatement of climate change.

5.2 Results Without Considering V2G Revenue

It is clear that V2G revenues are essential to the cost effectiveness of the eTrans. While the net present benefit per seat of the V2G-capable eTrans is $6,070, without V2G capacity, the eTrans would be a have a net present cost per seat of $2,000 (or a net present benefit per seat of -$2,000). However, it makes little sense to pay for a charger with such a large capacity without participating on the regulation services. If one were to buy a simpler, cheaper 15kW charger, for an approximate price of $2,500[6], instead of the 70 kW inverter, the net present cost per seat for the eTrans is merely $115. Considering several other public health impacts that were not monetized (e.g. local health impacts to children on the bus), it is possible that the electric bus, without V2G capabilities, could be as cost effective as a traditional diesel bus. However, the school bus operator would be losing significant potential revenues.

5.3 Scaled Results

The Red Clay School District has 179 buses, which serve approximately 13,000 students. Normalized for the seating capacity, the net present benefit of switching their entire fleet could reach nearly $38 million dollars (in 2012$) or nearly $3,000 per student served. In addition, the carbon reductions of switching the entire fleet would be approximately 2,000 tons of carbon dioxide each year, or nearly 30,000 tons over the lifespan of the fleet. The total regulation capacity of this fleet would be about 18 MW, which would be approximately 3% of the overall regulation market capacity on an average hour in PJM. However this likely overestimates the benefits of the switching, since it is unlikely that 3% of all regulation capacity would be situated all in one place. Also the implementation of having 16 MW of capacity on the same local grid would be problematic and likely would require significant investments. Nevertheless, there would still be a clear significant benefit of switching the school bus fleet to V2G-capable eTrans.

5.4 Limitations of the Model

There are four key items that were not included in this cost benefit analysis. First, the eTrans would provide a benefit in that it would not pollute the cabin environment while idling, avoiding many health effects to children. Unfortunately, it was difficult to monetize this benefit due to lack of data regarding average idling and health costs.

Another important consideration is that batteries will continue to become more important in the future, especially with the large-scale implementation of renewables, namely wind and solar power. As a larger percentage of the electricity mix is derived from renewable sources, the more intermittent and unpredictable the load will be. This will increase the demand for regulation services and the demand for battery storage. As the grid becomes entirely renewable, there will be a need for large scale implementation of battery storage technology. Using current technology to participate on the frequency regulation market can be seen as a stepping stone to help phase in the large scale implementation of battery storage for the grid. Without these storage capabilities, the costs and reliability of

[6] The approximate cost of the 15kW charger used for V2G purposes at the University of Delaware.

large scale renewable energy could be doubted. The monetization of this benefit was not included in the cost benefit analysis but should be considered as a factor for policy makers.

It was assumed that the power electronics would not need to be replaced in the fourteen-year scope. The power electronics are an integral part of an electric bus's drive system, converting electric power into propulsion. While the power electronics should last longer than fourteen years, it could potentially require a replacement.

Again, while the cost per electric bus model would be similar, several calculations would be different if this analysis was scaled up to several V2G-capable electric buses. For example, unlike a single electric bus, a fleet of V2G electric buses would likely require infrastructure upgrades, including increasing the capacity of local distribution lines, which was not included in the results.

It was also assumed that the electric bus would charge separately from participating in the regulation market. In all likelihood it is possible that an eTrans could charge while performing V2G services, but forecasting of such a model is outside the scope of this analysis. As such, the estimate of hours spent a year participating in the regulation market is conservative.

6. Discussions

6.1 Sensitivity Analysis

To investigate the effects of individual variables on the net savings, several sensitivity analyses were executed around key variables, including regulation price, the regulation capacity, the electricity inflation rate, diesel inflation rate, miles driven per day, battery replacement cost, the social cost of carbon, and the percent of renewable energy on the grid. The possible range of values for each variable was tested for sensitivity while holding all other inputs constant as the original values used in the cost benefit analysis. The results can be seen in Graph 1.1. The different variables analyzed are discussed below.

The first variable that was analyzed was the regulation price. While the regulation price used in the analysis was \$28/MWh, the 8-month PJM average since implementing FERC Order 755, the actual price of regulation varies depending on the market each hour. The actual price that an eTrans will receive for its regulation services will be highly variable from day to day. In addition, the future of regulation prices is likely to increase with increasing presence of wind and solar on PJM's grid. These renewable electricity sources are incapable of tailoring their electricity production to demand, requiring more frequency regulation. A range from \$13/MWh, the regulation price in PJM before the implementation of FERC Order 755, to \$61/MWh, the 95th percentile of the regulation price in PJM since FERC Order 755 implementation, was examined. Regulation price has a very large effect on the net present benefit per seat of an electric bus, ranging from as little as \$1,700 to as much as \$15,500 per seat. For an eTrans and a diesel bus to be equally cost-effective, the price of regulation would have to be as low as \$6.95/MWh, nearly a quarter of the current average price. Thus, while the regulation price has a substantial effect on the net present value of the bus, it is not influential enough to reasonably cause an electric bus to be less cost-effective than a diesel bus.

Regulation capacity of an eTrans is more influential on the cost-benefit analysis. While 70 kW was used in the analysis for regulation capacity, there are many other potential charging options, and thus capacity options, for an eTrans. Chargers typically range from 3 kW at the lowest capacity, up to more than 70 kW. For the sensitivity analysis, a range of 3 kW to 105 kW was chosen to give a fuller picture of the impact of regulation capacity. While even 70 kW is relatively high on the scale, it is important to note that the EPiC 150, if allowed to bid asymmetrically, could average a regulation capacity of approximately 105 kW. The maximum regulation capacity of 105 kW would nearly double the net present value of the electric bus to $9,450. The increase of regulation capacity increases V2G revenues, which also increases the net present value of the bus. The minimum regulation capacity of 3 kW, assuming that the cost of the charger varies with capacity, decreases the net present benefit of the electric bus to $178. Thus, no matter the capacity chosen, the analysis shows that the eTrans would still be a net present benefit. It should be noted that it is unrealistic that an owner of an eTrans would select such a low level charge, but the analysis supports that the capacity of the charger is influential on the cost benefit analysis. The analysis stresses the importance of maximizing regulation capacity. The value of allowing asymmetrical bids is also highly significant, as changing this rule increases the net present value per seat of the bus by nearly $3,500.

The following variables were not as influential on the cost benefit analysis. The first of these variables, the battery replacement cost, is one such example. Because the future of battery costs is uncertain, the cost to replace the battery, expected in the ninth year, is indeterminate. Using a range from a low of $100 per kWh, a very generous expected future cost of batteries, to a high of $650 per kWh, which is slightly above today's average cost [35], the net present benefit per seat of the eTrans ranges from $6,600 to $5,200, respectively. Many may have expected the price of batteries to be a barrier to the widespread adoption of electric vehicles, but the cost of replacing the battery in nine years makes little difference in the cost effectiveness of the electric bus. This means that while much of the research and money is invested into the decreasing the cost of batteries, the analysis implies that it would be more effective if resources were invested into something else, like increasing the capacity of the charger. In addition, a sensitivity analysis was conducted on the miscellaneous maintenance rate, and even if the eTrans had the same maintenance cost as a diesel bus, there would still be a net present benefit of $4,000 per seat.

Prior to the analysis, it was assumed that the cost of diesel fuel and savings resulting from switching to electricity were major factors that would influence the rate of adoption of electric vehicles; however, the sensitivity analysis suggests otherwise. A sensitivity analysis of the diesel inflation rate was conducted ranging from 0% to 17%. The lower bound assumes that diesel prices stay the same for the next fourteen years, while the upper bound assumes that diesel prices increase at twice the rate than historically expected. If diesel prices stay stagnant, the net present benefit of the electric bus would still be $4,200 per seat.

Likewise, if the diesel inflation rate was twice the historical average, the net present benefit of the eTrans would increase up to $9,700 per seat. While it seems highly unlikely that either of these scenarios will indeed happen, it should be noted that for both scenarios, the eTrans is still cost effective. Similarly, the future of the cost of electricity does not change the intuition of the cost benefit analysis. Like the diesel inflation rates, the electricity inflation rates of the sensitivity analysis ranged from zero change in electricity costs to double the expected rate. If electricity rates do not increase, and thus the cost of refueling stays the same throughout the fourteen years, the eTrans will be slightly more beneficial, at a net present benefit of $6,110 per seat. If the cost of refueling the eTrans increased by twice the amount as expected, there would be a slight decrease of the net present benefit to $6,006 per seat. In addition, regardless of the combination of diesel and electricity inflation rates, the eTrans will remain cost effective as seen in Table 1.1 below. In the worst case where diesel prices do not increase at all, and electricity inflation is double the historical average, the eTrans is still a net present benefit of $4,200. On the other hand, if electricity prices do not increase and diesel inflation is double the historical average, then the eTran's net present benefit jumps to $9,800 per seat.

Table 1.1

Net Present Benefit (2012 $) Per Seat		Electricity Inflation Rate (%)		
Diesel Inflation Rate (%)		*0*	*1.9*	*4*
	0	4,300	4,270	4,200
	8.5	6,110	6,070	6,000
	17	9,800	9,780	9,700

Two variables that had a negligible effect on the analysis are the social cost of carbon and the level of renewable energy supplying the electric grid. Varying the social cost of carbon from $10/MTCO_2e$ to $100/MTCO_2e$ only changed the net present benefit of an eTrans by approximately $300, less than 5% of the base case net present benefit. Varying the level of penetration of renewable energy penetration on the grid and the carbon emissions associated with the charging of the battery vary from zero to a hundred percent changed the net present benefit by less than 1%. This may mean that the benefits of climate change mitigation, when monetized, are unlikely to influence an economic analysis of electric vehicles; instead, other benefits of electric vehicles need to be considered.

A commonly held belief is that climate change mitigation could be achieved by implementation of a carbon tax [47] [48]. One of the implications of this analysis is that a potential carbon tax on its own would not incentivize the adoption of electric vehicles for fleets such as school buses. Even a strict carbon tax would have little impact on the cost effectiveness of electric vehicle adoption. If adoption of electric vehicles is required to mitigate climate change, other factors, such as potential V2G revenues, are better economic incentives.

The analysis also suggests that electric vehicle research can be better prioritized. Research should focus first and foremost on increasing the capacity of chargers to perform regulation services for the market. Maximizing potential revenues for regulation services would provide the highest economic incentive to utilize electric vehicles. Though increasing the price and value of regulation services is a key component, increasing the capacity of the charger would have greater effect. For heavy duty electric vehicles with limited daily range, research should be invested into the development of high kW capacity chargers rather than other factors, such as decreasing battery costs.

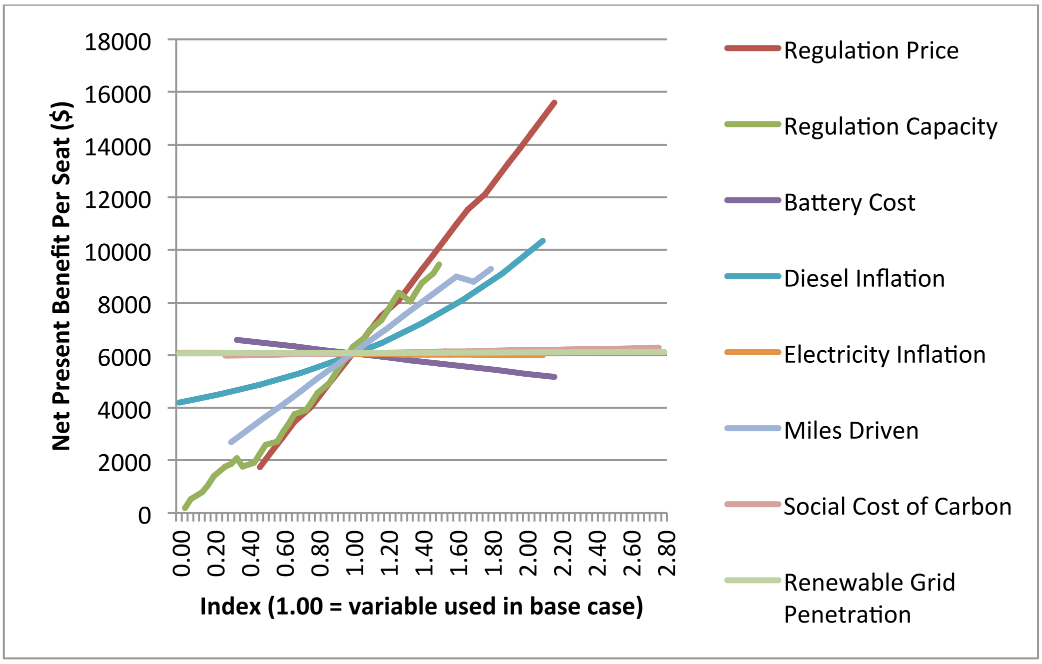
A simple way to increase capacity in chargers instantaneously is to allow asymmetrical bidding on the regulation market. Asymmetrical bidding would allow frequency regulation participants to bid different capacities for charging and discharging (regulation up and down, respectively). An eTrans equipped with existing technology such as the EPiC 150 inverter is capable of benefiting significantly from such a rule change, increasing the net present value of V2G revenues by 50%. Asymmetrical bidding also would incentivize the development of inverters that can provide even more benefits than the EPiC 150 can provide for electric heavy duty vehicles. Allowing asymmetrical bidding would require PJM to split its frequency regulation market into two separate markets, a regulation up (or charging) market, and a regulation down (or discharging) market, which would be complicated. Nevertheless, it would be important to consider the potential future of electric vehicles and how they could both benefit from and shape asymmetrical bidding in the regulation market.

Table 1.3

Variable	10% Δ in Variable Leads to X% Δ in NPB
Regulation Price	13.3%
Regulation Capacity	13%
Battery Replacement Cost	1.1%
Diesel Inflation Rate	3%
Electricity Inflation Rate	1.7%
Social Cost of Carbon	0.2%
Renewable Penetration	0.06%

It should be noted that regulation capacity has slightly less of an effect on net present value than regulation price given identical percentage change in values for each. However, regulation capacity has a much greater upside, with larger changes in regulation capacity much more likely to occur than regulation price. This supports the conclusion that regulation capacity is the most influential variable, but both capacity and price are essential to the analysis.

Graph 1.1



6.2 International Feasibility Analysis

While the analysis supports the use of grid integrated electric school buses in PJM, there are many other areas of the world that are encouraging the development of electric vehicles and renewable energy. Two similar cases to PJM are the Reseaux de Transports d'Electricte (RTE) of France and Energinet.dk of Denmark. It was assumed that all factors except diesel cost, electricity cost, and regulation price were the same as the United States in France and Denmark. The average price of regulation market for France and Denmark was \$23 per MW-h and \$25 per MW-h respectively [49]. The diesel price in France was calculated as \$7.68 per gallon, and the electricity price was \$0.10 per kWh [50]. The diesel cost in Denmark was calculated to be \$8.00 per gallon, and the electricity price was \$0.13 per kWh [50]. Due to significantly higher diesel prices, the cost-effectiveness of a V2G school bus in France was significantly higher, at a net-present benefit per seat of \$7,852. Likewise, Denmark's net present benefit was higher still, at \$8,617 per seat. Thus, the analysis highly encourages the development of V2G in fleet vehicles in Europe as well.

7. Conclusions

The cost benefit analysis first and foremost shows that with the inclusion of V2G capabilities, adoption of electric heavy duty vehicles is not only possible but imperative. Choosing an electric bus with V2G capabilities over a traditional diesel bus would save \$6,070 per seat. Without V2G revenues, an electric bus would not be cost effective, costing thousands of dollars per seat (\$2,000 per seat). Yet, the eTrans and the EPiC 150 inverter were both originally designed without consideration of V2G. Electric vehicles cannot afford to not include V2G capabilities in their designs, otherwise adoption of electric vehicles, especially in fleet operations, may be postponed until either the costs of electric vehicles significantly decrease or the costs of traditional vehicles drastically increase. Although making electric buses V2G-capable would require some alterations to the design, such as allowing the discharging of electricity while plugged into the grid, these changes would be comparatively small. Education and outreach thus have a large role to play in helping to ensure that electric vehicle manufacturers and consumers are cognizant of benefits of V2G and its potential to drastically reduce the lifetime cost of ownership of electric vehicles. As well, it is highly recommended that investment (private or government) be made in V2G to further encourage the adoption of electric vehicles.

One problem with the implementation of this model is that the initial costs of an eTrans, coupled with an EPiC 150 inverter may exceed the annual transportation budget of an average school bus operator or other similar fleet manager, as it requires an additional \$150,000 in capital costs than a traditional diesel bus. Despite an eTrans being an economically better choice over the lifespan of a bus, it is conceivable a school operator would be forced to choose the less economic traditional diesel bus simply due to budget restraints. Meanwhile, the net present value of the V2G services provided over the fourteen years is approximately \$190,000, which would significantly reduce the upfront cost of purchasing the electric vehicle. This situation is apt for a third party that has the capacity for large investments of capital with low risk return over long periods of time. A third party could pay the difference between the traditional diesel bus, making the eTrans just as costly as the traditional diesel bus for the school operator. Meanwhile, the third party could retain the revenues from V2G services performed by the eTrans and would profit a net present value of \$40,000, a return of investment about 27%. It is recommended that policies are put in place to encourage V2G and the development of methods for third parties to operate V2G-capable fleets.

Though vehicles that drive limited miles per year may not contribute as much to climate change on a per person-mile basis as other forms of transportation, such as an individually owned private vehicle, this analysis shows that significant contributors to climate change such as buses and other fleet vehicles can be readily replaced by electrified options. Limited range fleet vehicles face fewer obstacles to adoption than individually owned private vehicles, such as range anxiety and lack of charging infrastructure, making fleet operators key potential first adopters of electric vehicles. Inclusion of V2G could incentivize fleet operators to utilize electric vehicles and could be a stepping stone to an eventual widespread adoption of electric vehicles by individual owners. Similarly, the growth of V2G capacity through increased adoption of V2G-capable electric vehicles would encourage and potentially validate high penetration of intermittent renewable energy sources such as wind and solar energy. In conclusion, a V2G-capable electric school bus could save a school district thousands of dollars per seat over the lifespan of the bus, while avoiding health and environmental externalities, and encouraging the further adoption of electric vehicles and the growth of renewable energy.

Appendix

Refer to Nomenclature section for definitions of variables.

Equation A.1. Annual V2G revenue calculation.

$$R_{V2G} = \frac{P_R \times (1 + i_e)^y}{1000} \times H_{V2G} \times E_{CAP}$$

R_{V2G}	$15,274/Year
P_R	$28/MWh
i_e	1.9%
Y	N/A
$H_{V2G/Y}$	7,647.8
E_{CAP}	70 kW

Equation A.2. Annual electricity cost calculation.

$$E_C = \frac{P_E \times (1 + i_e)^y}{1000} \times \mu_e \times d$$

E_C	$714/Year
P_E	$0.106/kWh
i_e	1.9%
Y	N/A
μ_e	747 Wh/mile
D	8,850

Equation A.3. Annual electric bus maintenance calculation.

$$M_E = m_{er} \times d(+B_R)$$

M_E	$1,770 ($25,770)
m_{er}	$0.20
D	8,850
B_R	$300/kWh

Equation A.4. Annual electricity externalities calculation.

$$E_E = h_{er} \times d + E_D \times C_{er} \times SCC$$

E_E	$280
h_{er}	$0.015
D	8,850

E_D	6,613 kWh
C_{er}	1.18 lbs/kWg
SCC	$36/MTCO$_2$e

Equation A.5. Annual diesel fuel cost calculation.

$$D_C = \frac{d}{\mu_d} \times P_D \times (1 + i_d)^y$$

D_C	$6,351
D	8,850
μ_d	6.35 mpg
P_D	$4.20/gal
i_d	8.5%
Y	N/A

Equation A.6. Annual diesel bus maintenance cost calculation.

$$M_D = m_{dr} * d + L_r$$

M_D	$9,075
m_{dr}	$1
D	8,850
L_r	$225

Equation A.7. Annual diesel fuel externalities calculation.

$$E_D = h_{dr} \times d + D_D \times C_{dr} \times SCC$$

E_D	$1,214
h_{dr}	$0.08
D	8,850
D_D	1,393 gal
C_{dr}	22.2 lbs/kWh
SCC	$36/MTCO$_2$e

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