COSTS AND BENEFITS OF ELECTRIFYING AND AUTOMATING U.S. BUS FLEETS

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ABSTRACT

Diesel-powered, human-driven buses currently dominate public transit options in most U.S. cities, but produce health, environmental, and cost concerns. Emerging technologies may improve fleet operations by cost-effectively reducing emissions. This study analyzes both battery-electric buses and self-driving (autonomous) buses from both cost and qualitative perspectives, using the Capital Metropolitan Transportation Authority's bus fleet in Austin, Texas.

The study predicts battery-electric buses will become life-cycle cost-competitive in or before the year 2022 at existing fuel prices, with the specific year depending on the actual rate of cost decline and the diesel bus purchase prices. Rising diesel prices would result in immediate cost savings before reaching $3 per gallon. Self-driving buses will reduce or eliminate the need for human drivers, one of the highest current operating costs of transit agencies.

Finally, this study develops adoption schedules for these technologies. Recognizing bus lifespans and driver contracts, and assuming battery-electric bus adoption beginning in year-2017, cumulative break-even (neglecting extrinsic benefits, such as respiratory health) occurs somewhere between 2024 and 2035 depending on the rate of battery cost decline and diesel-bus purchase prices. This changes to 2023-2026 if self-driving technology is available for simultaneous adoption on new electric bus purchases beginning in 2017. The results inform fleet operators and manufacturers of the budgetary implications of converting a bus fleet to electric power, and what cost parameters allow electric buses to provide budgetary benefits over their diesel counterparts.

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INTRODUCTION

Transportation is on the cusp of technological shifts, with fully autonomous technology moving closer to reality, and alternative power sources experiencing technological advancement that is pushing them to challenge the status quo. Travel in the U.S. is dominated by personal automobiles, comprising 83% of U.S. passenger trips, with limited use of all other modes (Bureau of Transportation Statistics, 2018). Automobile dependence has resulted in sprawling development, significant traffic congestion, and limited public transportation options. Like many American cities, especially those in the south, Austin, Texas offers few rail travel options, with fixed-route buses accounting for 93% of the city's public transit trips (APTA, 2017). Reliance on diesel-powered transit buses for most of Austin's public transportation adds to the emissions produced on the region's roadways, and it limits the ability of Capital Metro and other transit agencies to broadly serve Austin's population. As a result, emerging technologies to reduce emissions and costs, and to attract more travelers to improved transit services should be considered.

Several research studies have been carried out to inform the implementation of alternative powertrains technologies for transit application. (Tzeng et al., 2005) conducted an analysis of alternative-fuel buses, which included battery-electric buses, and analyzed costs. The analysis is now outdated since battery and vehicle prices have changed considerably since its publication. The authors in (Mahmoud et al., 2016) and (Ferguson et al., 2019) provide a more recent analysis of six alternative technologies; diesel, hybrid, compressed natural gas (CNG), battery electric, and hydrogen fuel cell. Their work focuses on a comparative analysis of emission, energy, and operation, but does include cost estimation.

Recently, the life-cycle emission and cost assessment of electric buses, among other alternatives, is receiving considerable academic attention. For example, (Lajunen and Lipman, 2016) concluded that hybrid and battery electric buses are favored with respect to their life-cycle cost, operation, and environmental measures for transit application. Even when considering different charging methods, battery electric technology is still favored (Lajunen, 2018). Similar conclusion was reported by (Dreier et al., 2018), in their comparison of the well-to-wheel energy and environmental assessment of electric buses. Although all life-cycle assessment models are context sensitive, meaning that various significant factors vary across location and time. In addition, given their dependency on the electricity grid and the associated carbon intensity, the environmental impacts of electric buses vary significantly. In this respect, (Kennedy, 2015) identified a threshold (600 tCO2e/GWh) for carbon intensity in the electricity grid for electric buses/vehicles to be environmentally competitive.

However, an important observation from the literature is the lack of research efforts that jointly analyze the life-cycle cost of electric powertrains while considering autonomous driving capabilities. The co-implementation of both technologies is expected to create a synergetic impact beyond the independent impacts of each technology.

In this respect, this study considers alternative power sources, and then analyzes the life-cycle cost implications of bus transit fleet electrification and automation, using Austin's Capital Metro as a case study. Based on several likely cost assumption scenarios, adoption schedules are developed and evaluated. The results inform fleet operators and manufacturers of the budgetary implications of converting a bus fleet to electric power, and what cost parameters allow electric buses to provide budgetary benefits over their diesel counterparts.

BUS TECHNOLOGIES

Power Sources

Diesel power currently dominates transit buses. Finite fossil fuel reserves and increasing global demand present uncertainties around the long-term availability of diesel and natural gas as fueling options. Additionally, climate change concerns and local emissions makes diesel power less attractive than alternatives in most settings. Furthermore, many travelers may dislike the noise and local air pollution (and engine and air conditioning heat released) while waiting for, boarding and alighting diesel buses. For such reasons, it is useful for transit agencies to explore non-petroleum power options (Mohamed et al., 2018).

Natural gas is gaining popularity as replacement for diesel in medium to heavy duty vehicles, but its benefits are limited. Tong et al. (2015) show liquified natural gas (LNG) to increase GHG emissions, and compressed natural gas (CNG) to offer at most a 2% reduction in emissions. Biofuels present an alternative bus fuel option with minimum apparent equipment and infrastructure disruption. However, since biofuels are burned similarly to diesel in a bus engine and emitted via tailpipe, many of the negatives of diesel power remain with biofuel-powered buses.

Hydrogen fuel cell buses have been used in pilot programs at transit agencies across the United States (Leslie Eudy et al., 2016). However, Lajunen and Lipman (2016) point out that the source of the hydrogen determines the total emissions generated from fuel cell vehicles. An economical or energy-efficient way of producing hydrogen from non-fossil fuel sources has not been developed, so 95% of hydrogen produced in the United States is made from methane (Nuttall and Bakenne, 2020), the production of which creates carbon dioxide (a greenhouse gas) as a byproduct. Tong et al. (2015) show hydrogen fuel cell-powered buses to increase emissions, compared to diesel power, when the hydrogen is produced from natural gas. Combined with a lack of existing delivery infrastructure for hydrogen fuel, this presents significant obstacles to the widespread adoption of hydrogen as a fuel source in most locations. Mechanical energy storage methods, such as flywheels or compressed air, have also shown potential for useful energy storage, but these technologies are not currently available as a primary power source.

Battery-electric power is another alternative, which can be free of fossil fuels if electricity generation comes from renewable sources (such as hydroelectric power, sun and/or wind). Even when powered by non-renewable natural gas electricity generation, Tong et al. (2015) find battery-electric transit buses to reduce emissions by 31% compared to petroleum-fueled buses. Electric vehicles are already in use, as both personal automobiles and transit buses, and this technology (and its costs) continue to improve (Nykvist and Nilsson, 2015). Hybrid-electric buses allow some use of recovered electric power, but rely largely on diesel fuel, with its attendant issues (Lajunen and Lipman, 2016). For the foreseeable future, battery-electric buses appear most promising and so are the focus of the power-source portions of this report.

Autonomous Technology

Tremendous advances are being made in the field of autonomous vehicle (AV) technology. Fully autonomous driving is expected to produce improvements in safety, roadway capacity, fuel consumption, and emissions (Fagnant and Kockelman, 2015; Fagnant and Kockelman, 2014; Gurumurthy et al., 2019). Though much of the focus has been on personal use of autonomous technology, public transit stands to be affected significantly, especially bus service, where lower vehicle capacities compared to rail modes currently result in higher per-passenger driver costs. Various levels of automation exist, but this report focuses on fully autonomous buses, which can operate without a human driver.

Speculation on how the introduction of fully autonomous vehicles will impact public transit varies among experts. Predictions range from a belief that shared AV fleets of personal-sized vehicles will effectively replace public transit (Shaheen and Cohen, 2018), to a possibility of fleets of smaller autonomous buses, to an expectation that public transit will be strengthened by autonomous technology (Shen et al., 2018). Eliminating or reducing mass public transit would be problematic, since replacing bus trips with personal vehicle trips would inevitably increase vehicle miles traveled, and therefore, congestion. Although some recent studies (Abe, 2019; Leich and Bischoff, 2019) indicate that replacing bus transit service with autonomous taxi might reduce the cost, the external cost of congestions and emissions are not fully considered.

Additionally, shared AVs may prove to be too expensive, depending on trip pattern, for many current bus users. With smaller fully autonomous buses, more vehicles would be needed to maintain current capacity. While this could be used to improve frequency, it may result in headways too close to maintain on some routes, and will limit the ability of the routes to cope with any added demand. Additionally, a shift to more vehicles with lower occupancy could contribute to worsening congestion. Full size transit buses alleviate some of the concerns associated with smaller vehicles, by maintaining current capacity without a need to add vehicles. In fact, since the human driver could be removed, it may be possible to make more capacity available for passengers. For these reasons, as well as ease of comparison, the autonomous technology portions of this study focus on the use of fully autonomous technology (level 5) in full-size transit buses.

Overall, electric vehicle technology is currently available, with multiple auto manufacturers selling fully electric models. High-level autonomous technology is likely still a few years away from widespread availability, though fully autonomous cars (Hesselgren et al., 2019) and small buses (Ayre, 2016) have begun carrying passengers in public testing scenarios. However, both may become commonplace in the future for public transportation. It is possible that both technologies will be adopted simultaneously by many transit agencies. For this reason, both technologies are analyzed individually in this report, as well as the possibility of simultaneous adoption.

IMPLEMENTATION COSTS AND IMPACTS

This section analyzes the costs of implementing each technology individually, including the potential for cost savings. Additionally, qualitative effects are discussed, as well as the co-implementation of both technologies.

Electric Buses

Lifecycle Cost

Life-cycle costs reflect vehicle purchase price and fuel expenses over 12 years of operation, since these are the costs most impacted by powertrain choice. Maintenance and fueling infrastructure costs are also affected by powertrain choice, but these costs are not well documented due to the lack of U.S. transit agencies with large battery-electric bus fleets, and therefore, are neglected in this analysis. Additionally, the lifespan of chagrining infrastructure is not well documented, largely due to the infancy of battery-electric bus use.

Estimates of the purchase price of electric buses vary significantly. However, a recent actual purchase price of electric buses is used for calculations and estimations. According to Gurciullo (2016), the battery-electric buses purchased in 2016 by the Chicago Transit Authority (CTA) carried a purchase price of $800,000 each, while others such as (Christopher MacKechnie, 2019) lists the typical purchase price of a diesel transit bus at $300,000. This means the current delta for a battery-electric bus is about $500,000 above the cost of a diesel bus.

Capital Metro’s recent diesel purchases cost about $450,000 each, due to additional equipment and electronics capabilities that are added to their vehicles that would mostly be expected to be included in electric buses due to their more electronically-dependent nature, which leaves a $350,000 delta in the purchase price between diesel and battery-electric buses for this transit agency. That said, the analysis in this study is repeated considering both a $300,000 purchase price for diesel buses and a $450,000 diesel purchase price. This is mainly to accommodate the fact that U.S. transit agencies may apply for Federal Transit Administration grants to help cover the additional capital costs, and other countries may have similar programs; but these funds are limited, so this analysis does not assume any additional assistance.

Furthermore, Becker et al. (2019) found that, while vehicle automation and electrification reduce production costs for various mode options, the cost-lowering effects are stronger for taxis than for buses. They predict that taxi prices will fall to the level of buses and trains, per passenger-mile traveled, so that those transit modes will be unable to compete without also lowering their own costs (and, ideally, becoming much more demand-responsive). Depot charging, as opposed to on-route charging, allows for much more flexibility and certainty in bus operations. The low power chargers used at a depot allow for much lower initial investment in charging infrastructure and peak demand electricity charge, as buses typically charge overnight (He et al., 2019). But depot charging has noticeable drawbacks as well, especially the lengthy recharge times and might require a relatively larger fleet size (Mohamed et al., 2017).

The largest opportunity for cost savings with electric vehicles is from fuel costs. Capital Metro's bus fleet consists of 438 vehicles with a 2017 budget showing annual diesel-bus fuel costs of $16.90 million (Capital Metro, 2015; Public Transportation Division, 2019), equating to $38,592 per bus. While electricity costs may vary widely by location and each transit agency's time-of-day charging pattern, Gurciullo (2016) estimates net annual fuel savings of $25,000 per electric bus, or $300,000 over a 12-year life of the bus, which the authors in (Leslie Eudy et al., 2016) note as a typical transit bus lifespan. Even using no discount rate, this alone is not enough to recoup the current premium for electric propulsion, leaving an added life-cycle cost of $200,000 (per bus) if diesel bus purchase prices are $300,000, or $50,000 if diesel buses cost $450,000 each. In total, this would increase Capital Metro's annual budget by $7.3 million or $1.835 million, respectively, if every new bus were electric and purchased at current prices. The agency's operating budget would enjoy lower fuel expenses, but the higher purchase prices would produce a larger increase in average annual capital expenses. Table 1 presents the life-cycle costs of each powertrain type.

Table 1: Costs of Diesel and Electric Buses at 2016 Prices.

Costs of Diesel and Electric Buses at $300K and $450K Diesel Purchase Prices			
	Purchase Price	Annual Fuel Expense	12-Year Life-cycle Cost
Diesel ($300K)	$300,000	$38,592	$763,107
Diesel ($450K)	$450,000	$38,592	$913,107
Electric	$800,000	$13,592	$963,107
Difference ($300K)	$500,000	($25,000)	$200,000
Difference ($450K)	$350,000	($25,000)	$50,000

Fuel Price Effects

The average fuel price for the Midwest region at the time of Gurciullo (2016) analysis was $2.023 per gallon, according to the U.S. Energy Information Administration (EIA, 2017). They also show that diesel hit a high of $4.705 in 2008, and are currently on the rise again. A $3.50 per gallon may be a reasonable estimation of future diesel prices, and average prices have been above this mark as recently as December 2014, according to the U.S Energy Information Administration (EIA, 2017).

If a diesel price of $3.50 per gallon is used, electric buses show an immediate 12-year life-cycle benefit of $138,116 and $288,116 per bus when considering a diesel bus purchase price of $300,000 and $450,000, respectively, before considering any effects on externalities. Cost competitiveness of electric buses at current purchase prices occurs when diesel is at $2.90 per gallon if the diesel bus purchase price is $300,000, or when diesel is at $2.24 per gallon if the diesel bus purchase price is $450,000. Gurciullo (2016) estimated the public health benefits of eliminating diesel buses' local emissions to be $55,000 per bus-year in Chicago, due to lower incidence of respiratory illnesses. Over the 12-year life of a bus, this implies $660,000 in human health savings per bus. Including this social cost savings suggests that each electric bus provides a net benefit of $460,000 or $610,000 over a 12-year lifespan, assuming a $300,000 or $450,000 diesel-bus purchase price, respectively. However, the public health benefits are experienced by the public, not directly by the transit agency, meaning additional funding would still be necessary to shift to electric propulsion at current prices.

External Costs

Additional costs would be incurred beyond what is analyzed in this study. Charging infrastructure would be needed, either at centralized locations "depot charging", en-route, or both (Feng et al., 2017; Mahmoud et al., 2016). The costs of such infrastructure are difficult to estimate, since they depend on the charging strategies and facilities an agency employs, as discussed in (Feng et al., 2017). This cost would be partially offset by reductions in diesel fueling facilities, especially once a bus fleet is fully converted to electric.

Lajunen and Lipman (2016) find that employing en-route charging is more cost-effective than using strictly overnight charging. However, other studies recommended a mix of en-route and depot charging to optimize the total cost of ownership. Additionally, electric buses are generally considered to have lower maintenance costs than their internal combustion counterparts, though actual numbers were not readily found for transit buses, likely owing to the infancy of the use of battery-electric buses (Mahmoud et al., 2016).

Future Cost Analysis

The cost of electric buses, and battery-electric vehicles in general, is falling. According to Gurciullo (2016), CTA paid $1 million per electric bus in 2014, so their 2016 purchase at $800,000 represents a 20% total price decrease in two years, or a 10.56% annual reduction. Nykvist and Nilsson (2015) reveal that electric vehicle battery pack costs are falling by 14% annually. Based on the two-year price reduction of $200,000 for an electric bus, this would indicate that the battery packs constitute $567,395 of an $800,000 electric bus. This means that the non-battery costs are $232,604, which is reasonable, since battery packs are the most significant portion of the cost of electric powertrains (Nykvist and Nilsson, 2015), especially in vehicles requiring significant battery capacity, like buses. Electric buses have been introduced to the market with a 320-200 mile range (BYD, 2020), which would be sufficient to provide full-day service on many routes, including 70% of Capital Metro's, though en-route charging could extend the range further.

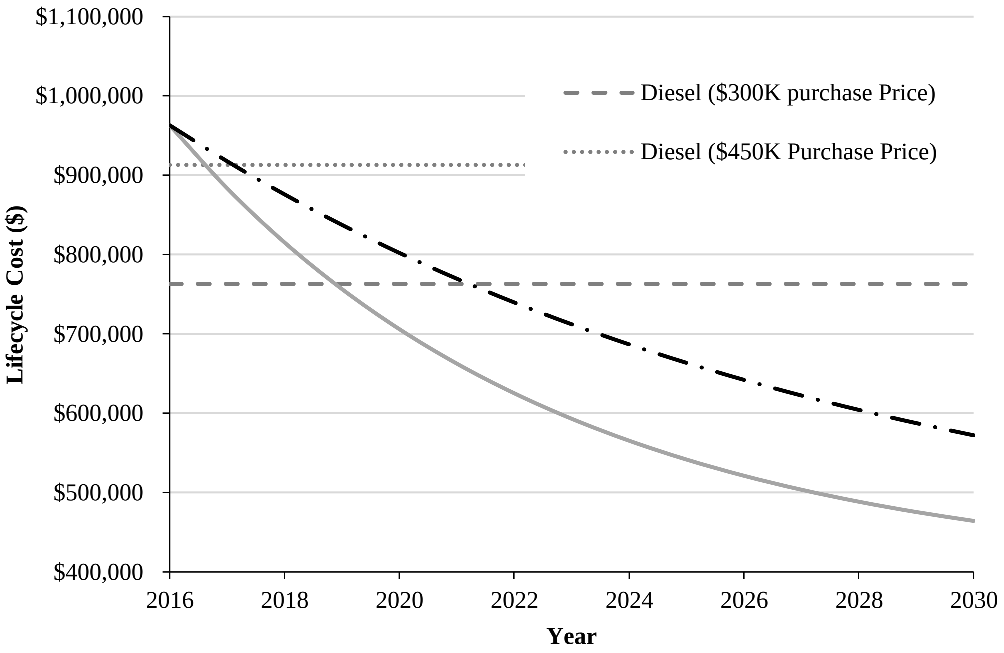

Figure 2: Total Life-cycle Cost vs. Purchase Year for Diesel and Electric Powertrains

If the 14% annual reduction in battery pack costs continues, electric bus purchase prices would fall an additional $206,500 by 2019, as shown in Figure 1. This would make them competitive with diesel power from a life-cycle cost perspective, assuming a $300,000 diesel bus purchase price. If diesel buses carry a $450,000 purchase price, this cost-competitiveness is reached in 2017. Nykvist and Nilsson (2015) indicate that the leading manufacturers of battery-electric cars are experiencing a lower rate of cost reduction for battery packs, about 8%. As Figure 2 shows, if battery pack cost reductions for buses slow to this rate, the $200,000 cost reduction would be surpassed, achieving life-cycle competitiveness with diesel power, by 2022 or 2018 for diesel bus purchase prices of $300,000 and $450,000, respectively. For comparison, Lajunen and Lipman (2016) estimate that electric buses may have lower total life-cycle costs than diesel by 2023 and could present a 20% life-cycle cost benefit over diesel buses by 2030, whereas the constant 8% annual battery cost reduction would yield a 25% life-cycle cost benefit in 2030 when using the more typical $300,000 purchase price for diesel buses.

Qualitative Effects

A conversion to electric propulsion would have additional effects, which are not easily monetized by the information currently available. Anticipated respiratory health benefits are discussed in the cost analysis section, since a monetized analysis has been performed. However, local emissions produced by diesel buses have wide ranging effects beyond respiratory health. These emissions are often expelled within a few feet of passengers alighting or waiting at bus stops, which can make the air unpleasant to breathe for these passengers and others in the area. Additionally, the diesel engine produces a considerable amount of noise and heat that can be unpleasant for the same people. These two factors may dissuade potential riders, especially those who may be sensitive to these factors, and may negatively influence the public opinion of bus service.

The burning of fossil fuels is widely known to contribute to climate change through the emission of greenhouse gases, and diesel buses contribute to this negative environmental impact. Though a fully loaded bus may provide some per-passenger greenhouse gas emission reduction compared to typical personal vehicles, the climate change impact of public transportation should not be ignored. Electric propulsion has the potential to significantly reduce the greenhouse gas emissions of transit buses, as well as overall air pollution emissions. Lajunen and Lipman (2016) conclude that electric buses could reduce emissions of the greenhouse gas carbon dioxide by 75%, though the amount of the benefit is dependent on the source of the electricity used to charge the buses.

Emissions from electric buses in Austin would depend on Austin's electricity sources. Austin Energy, the city's lone electric utility, maintains ownership stakes in power generation projects throughout Texas to cover its electricity demand, and makeup of the utility's generation included 20.68% renewable energy in 2013, more than double the ERCOT grid average. Austin Energy also has commitments to transition more of its electricity production to renewable sources, with 450 MW in solar energy scheduled to come on line, and a generation plan that calls for the installation of 950 MW of solar capacity by 2025. The utility has also committed to decommissioning its only coal plant, the Fayette Power Project, by 2022. Overall, Austin Energy plans to generate 55% of its electricity from renewable sources by 2025. This sharp increase in renewable power implies a significant reduction in greenhouse gas emissions and overall pollution emissions resulting from electricity consumed in Austin, including what would be used to power electric buses.

Autonomous Buses

Though fully autonomous vehicles are not yet widely available, predictions exist of potential price premiums for the technology. Estimates of the technology cost for buses are hard to find, but it is reasonable to expect that the large size of transit buses may necessitate the use of additional sensors, and therefore, higher cost than for personal vehicles. This section uses what estimates are available to analyze and discuss the costs associated with implementation of fully autonomous technology in buses. Qualitative effects of implementation are also discussed.

Driver Costs

The biggest financial benefit of fully autonomous buses to public transit agencies is the potential for reduction in driver costs. To meet its current driving needs, Capital Metro contracts with two outside companies, which manage and provide drivers for all bus routes, at a total cost of $118.9 million annually (Capital Metro, 2015). This is 45% of the agency's operating budget, and translates to an annual average of $271,456 per bus in their fleet. Over a 12-year bus life, $3.26 million in driver expenses would be paid. There is ample room for cost savings if self-driving buses can replace the need for drivers. Though drivers may not be required to operate the bus, there may still be a need for roving attendants to create a sense of safety and check fares, though they would be needed in much smaller numbers than drivers currently are.

The cost of fully autonomous technology, as well as the cost for heavy duty vehicles like buses, is largely unknown since the technology is not yet on the market, and predictions vary widely. Bansal and Kockelman (2017) estimated the technology premium (i.e., added cost) in the early years of availability to be $40,000 for a passenger (light-duty) vehicle, based on expert opinions. This report uses a conservative estimate of $80,000 for the added cost of delivering a self-driving bus, which is twice that of a personal vehicle. With this estimate, the total life-cycle savings from implementing fully autonomous technology to completely replace human drivers would be $3.18 million per 12-year (expected scrappage) age of a CapMetro bus, which averages to $265K per bus annually, or $116 million in annual budget savings for an agency like CapMetro, with 438 buses. With a shift to autonomous driving technologies, more technical support would likely be necessary, to check sensors and address technology issues on site. The extent and cost of such support is uncertain, but it will presumably be small, compared to existing driver costs.

Additional Effects

Self-driving buses can provide benefits beyond a dramatic reduction in or elimination of driver costs. Autonomous technology is expected to improve safety (by employing many cameras, radar, mapping software, and Lidar in and around the vehicle), while smoother fully autonomous driving may improve fuel efficiency, emissions, and rider comfort. The autonomous technology currently being tested has a good safety record, and has the potential to be significantly safer than human drivers (Fagnant and Kockelman, 2015). Improving the safety record of transit buses would lower operation costs through lower insurance and crash expenses, in addition to the qualitative effects that improved safety can provide.

Silberg et al. (2017) estimate that fully autonomous technology can lower overall crash expenses for private vehicles by 40%. Transit buses may not see a reduction as extreme, since their drivers are trained professionals. The smoother driving provided by fully autonomous technology can reduce fuel consumption (Fagnant and Kockelman, 2015; Liu et al., 2017). With the use of electric power, this translates to lower energy consumption and increased range per charge. Regardless of power source, fuel or energy costs should fall. Lower fuel consumption, in addition to smoother acceleration, would also mean a reduction in harmful emissions, leading to a potential improvement in local air quality. Energy use and emissions may decrease 10% in light-duty vehicles (Liu et al., 2017), though the benefits may differ some for autonomous buses replacing experienced professional drivers. Smoother driving can also improve the ride comfort by reducing some of the jerking of the vehicle associated with human driving. If the cost savings of automation, are used partially to increase frequencies, transit service could become more attractive.

CO-IMPLEMENTATION AND ADOPTION SCHEDULES

Due to existing investments and commitments, there is a limited number of buses that would realistically be converted to electric power annually, since it is most agencies' interest to not retire large capital investments (like buses) early. Likewise, existing labor contracts with drivers must be honored. Here, an implementation schedule is developed for each technology, taking these factors into account. Overall, three implementation scenarios are developed, including electric bus scenario, autonomous bus scenario, and co-implementation scenario. Assumptions related to each scenario are detailed as follows:

Electric Bus Scenario

In this analysis, a 12-year life for each bus is used, which equates to Capital Metro replacing 36.5 buses in the average year. It is assumed that every new bus purchased is electric, beginning in 2017. The analysis is performed with two electric-bus adoption scenarios; one representing a 14% annual reduction in battery costs, and the other representing the more conservative 8% annual reduction in battery costs, and repeated for both a $300,000 and $450,000 diesel bus purchase price. These estimates do not consider the change in diesel price.

Autonomous Bus Scenario

Due to existing driver contracts and labor agreements, it is assumed that agencies, like Capital Metro, cannot lay off drivers at will. Since the terms and length of these contracts and the average driver's career duration are not known, it is assumed that a self-driving bus cannot be put into service until a driver retires. Assuming that each driver drives for 20 years, five percent of an agency's drivers may retire in the average year. In reality, some bus drivers have much longer careers, but after 20 years of not hiring new drivers, driver numbers may be low enough that the few who remain can be assigned to other duties, such as paratransit services, where humans may still be needed to assist customers with disabilities. The 12-year maximum bus life is still used though human-driven buses are allowed to be retired earlier in favor of fully autonomous buses if the driver retires, since the driver savings far outweigh the purchase price of the bus.

Co-Adoption Schedule Scenario

For the co-adoption scenario (of both automation and electrification, for each new bus), the same assumptions from the previous two sections are used. Analysis begins in 2017, which is unrealistic for adoption of fully autonomous technology, but demonstrates an adoption schedule for simultaneous adoption. Since battery costs will be higher in 2017 than in later years, this early start year provides the most conservative estimate of how long it will take to reach the break-even point in cumulative costs.

Adoption Results

For each scenario, bus purchase costs, driver costs, and fuel costs are tracked for each year for 20 years, and the accumulated totals are calculated. As shown in Table 2, the cumulative costs for adoption (beginning in year 2017) surpass a break-even point for the adoption of electric technology at a 14% annual battery cost reduction in year 2029 or 2024, assuming $300,000 and $450,000 diesel bus purchase price, respectively. The break-even point for electric-only adoption at 8% annual battery cost reduction occurs in 2035 or 2027 for an equivalent diesel bus cost of $300K and $450K, respectively.

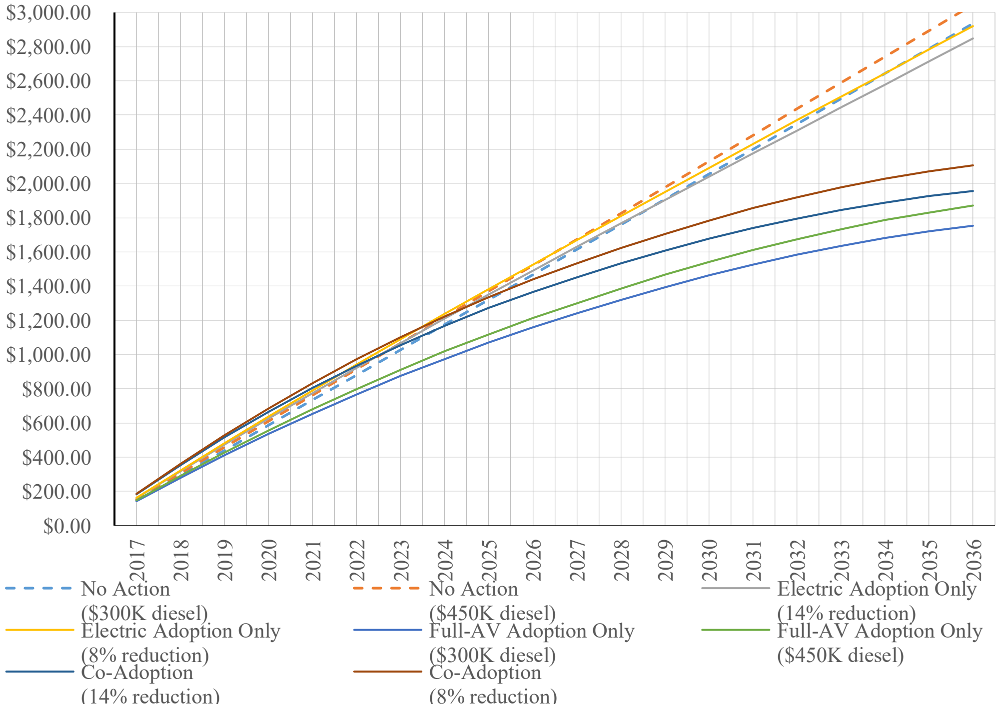

Table 2: Cumulative (Life-Cycle) Costs for 14% and 8% per-Year Battery Cost Reductions.

Cumulative Purchase, Fuel, and Driver Costs (in $1 Million) for Capital Metro's Fleet								
Year	**No Action**		**Electric Adoption Only**		**Full-AV Adoption Only**		**Co-Adoption**	
	$300K diesel	*$450K diesel*	*14% reduction*	*8% reduction*	*$300K diesel*	*$450K diesel*	*14% reduction*	*8% reduction*
2017	$146.8 M	$152.2 M	$161.2 M	$162.4 M	$142.6 M	$148.0 M	$183.3 M	$185.8 M
2018	$293.5	$304.5	$319.0	$322.4	$279.2	$290.1	$354.8	$361.7
2019	$440.3	$456.7	$473.7	$480.1	$409.8	$426.3	$515.1	$527.9
2020	$587.0	$608.9	$625.7	$635.6	$534.6	$556.5	$664.8	$684.7
2021	$733.8	$761.1	$775.1	$789.0	$653.3	$680.7	$804.6	$832.2
2022	$880.5	$913.4	$922.3	$940.3	$766.2	$799.0	$934.7	$970.7
2023	$1,027	$1,066	$1,067	$1,090	$873.1	$911.4	$1,056	$1,100
2024	$1,174	$1,218	$1,211	$1,237	$974.0	$1,018	$1,168	$1,221
2025	$1,321	$1,370	$1,352	$1,383	$1,069	$1,118	$1,271	$1,334
2026	$1,468	$1,522	$1,492	$1,527	$1,158	$1,213	$1,366	$1,438
2027	$1,614	$1,674	$1,630	**$1,670**	$1,241	$1,301	$1,453	$1,533
2028	$1,761	$1,827	$1,767	$1,811	$1,318	$1,384	$1,532	$1,621
2029	$1,908	$1,979	$1,903	$1,951	$1,394	$1,466	$1,608	$1,706
2030	$2,055	$2,131	$2,039	$2,091	$1,463	$1,542	$1,678	$1,784
2031	$2,201	$2,283	$2,174	$2,230	$1,526	$1,611	$1,740	$1,855
2032	$2,348	$2,436	$2,310.	$2,369	$1,583	$1,675	$1,796	$1,919
2033	$2,495	$2,588	$2,444	$2,507	$1,635	$1,733	$1,846	$1,976
2034	$2,642	$2,740	$2,579	$2,645	$1,680	$1,785	$1,889	$2,026
2035	$2,788	$2,892	$2,714	$2,783	$1,720	$1,831	$1,926	$2,069
2036	$2,935	$3,045	$2,848	$2,920	$1,753	$1,871	$1,956	$2,106

CONCLUSIONS

Based on analysis of direct costs, battery-electric buses are not yet cost-competitive with diesel-powered buses, while fully-automated buses (without a driver or full-time attendant) should be cost-competitive immediately. However, electric bus purchase prices are falling, primarily due to falling battery prices, and this should make electric buses life-cycle cost-competitive within the next few years. Electric buses can also provide various social benefits that do not appear in an agency's budget, via improved service quality, public health and other environmental benefits, and public perceptions. Battery-electric buses should be thoughtfully evaluated by all U.S. agencies for coming purchases. Some transit agencies may be currently paying much more or less for diesel buses than the prices used in the present study. Austin's Capital Metro adds options to diesel buses that increase their price significantly, and European and other transit agencies may experience much higher diesel prices than U.S. agencies do, potentially making battery-electric buses more attractive than diesel counterparts in many settings.

Though their technology premium remains uncertain (and the use of en-route bus attendants remains uncertain), fully autonomous buses will almost certainly exhibit a life-cycle savings over their human-driven counterparts. Transit agencies generally have contracts with their drivers, but the anticipated savings from adoption of self-driving buses are significant enough that transit agencies could afford to offer significant contract buyouts to accelerate adoption, and still realize substantial savings. Professional (bus and truck) drivers may become operators and attendants, with new and different responsibilities, like monitoring the CAV systems and sensors, to ensure they are functioning properly, performing interior maintenance, directly assisting those with mobility or other impairments, and/or performing administrative and logistics work for their employers en route/remotely, as discussed in (Clements and Kockelman, 2017). In terms of mitigating unemployment issues, the U.S. Center for Global Policy Solutions (2017) recommends unemployment insurance reform and driver retraining programs.

In addition to lower costs, self-driving buses offer the potential to improve the quality of service (possibly including through smaller buses, offering at higher frequency, for example), reduce fuel consumption and emissions, and operate more safely than their human-driven counterparts. Further, the budget improvements afforded by fully autonomous technology could be used to expand or otherwise improve transit-system service and provide the funds for adoption of electric (self-driving) buses. Fully autonomous vehicles appear to be the way of the future, and it is important that transit agencies begin planning for their use, along with electrified buses.

The results of the co-adoption alternative are auspicious for transit agencies. Although the initial cost of the co-adoption is higher than the autonomous bus alternative, in the long term, the co-adoption is more economically feasible. The higher initial cost is attributed mainly to the fact that the fleet replacement process includes both autonomous and electric buses, with a higher premium for electric buses.

Overall, the study demonstrates the feasibility of replacing diesel transit buses with new alternative technologies, including electric and autonomous technologies. The results provide transit agencies with clear directions and schedules for the lifetime cost of adopting different powertrain technologies. However, the present study is limited with respect to accounting for the external benefits associated with the reduction in GHG emissions and off-peak electricity demand charges. Both elements should be considered in future research activities.

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