

Concept Paper

Costs and Benefits of Electrifying and Automating Bus Transit Fleets

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Received: 18 February 2020; Accepted: 9 May 2020; Published: 13 May 2020



Abstract: Diesel-powered, human-driven buses currently dominate public transit options in most U.S. cities, yet they 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, including the required charging infrastructure, will become lifecycle cost-competitive in or before the year 2030 at existing U.S. fuel prices (\$2.00/gallon), 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 \$3.30 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-2020, cumulative break-even (neglecting extrinsic benefits, such as respiratory health) occurs somewhere between 2030 and 2037 depending on the rate of battery cost decline and diesel-bus purchase prices. This range changes to 2028 if self-driving technology is available for simultaneous adoption on new electric bus purchases beginning in 2020. 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.

Keywords: self-driving bus; electric bus; transit costs; benefits of automation; benefits of electrification

1. 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 [1]. 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 [2]. 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 applications. Tzeng et al. [3] 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. Mahmoud et al. [4] provide a more recent analysis of six alternative technologies: diesel, hybrid (parallel and series), compressed natural gas (CNG), battery-electric, and hydrogen fuel cell. Their work focuses on a comparative analysis of emission, energy, and operation, but does not include cost estimation.

Lifecycle emission and cost assessments of electric buses, among other alternatives, is now receiving considerable academic attention. For example, Lajunen et al. [5] concluded that hybrid and battery electric buses are favored with respect to their lifecycle cost, operation, and environmental measures for transit application. Even when considering different charging methods, battery-electric technology is still favored [6]. A similar conclusion was reported by Christopher MacKechnie [7] in their comparison of the well-to-wheel energy and environmental assessment of electric buses. All lifecycle assessment models are context-sensitive, meaning that various significant factors vary across locations or cities, and over years. Given their dependency on the electricity grid and the associated carbon intensity, electric buses' environmental impacts vary significantly. In this respect, Kennedy [8] identified a carbon-intensity threshold (of 600 tCO₂e/GWh) in the power grid for electric buses and other electric vehicles to be environmentally competitive.

There remains an important research gap for lifecycle cost analysis of electric powertrains alongside autonomous driving capabilities. The co-implementation of both technologies is expected to create a synergetic impact beyond the independent impacts of each technology. Therefore, this study offers insights into the lifecycle impacts of the co-adoption of autonomous and electric buses in the transit context. Such co-adoption can reveal latent impacts that are currently not observed by the adoption of each technology independently.

To this end, this study considers alternative power sources and then analyzes the lifecycle cost implications of bus transit fleet electrification and automation, using Austin's Capital Metro bus system 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.

2. A Review of Bus Technologies

2.1. Alternative Powertrain Technologies

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 make 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 [9,10].

Natural gas is gaining popularity as a replacement for diesel in medium to heavy-duty vehicles, but its benefits are limited. Tong et al. [11] show liquified natural gas (LNG) to increase greenhouse gas (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 electric buses (FCEBs) have been used in pilot programs at transit agencies across the United States [12]. However, Lajunen et al. [5] pointed 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 the hydrogen produced in the United States is made from methane [13], the production of which creates carbon dioxide (a greenhouse gas) as a byproduct. Tong et al. [11] 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 buses (BEBs) are 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. [11] find BEBs to reduce emissions by 31% as 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 [14]. Hybrid-electric buses allow some use of recovered electric power, but rely largely on diesel fuel, with its attendant issues [5]. For the foreseeable future, BEBs appear most promising, and so are the focus of the power-source portions of this report.

Importantly, there is ongoing debate on the optimal configuration of BEBs [15]. There are two distinct configurations, emphasizing charging schedules: overnight versus en route. Each approach requires a different charging infrastructure system and impacts BEB lifecycle costs and benefits. Although several studies have been carried out to predict, estimate, and configure the required spatial and density of charging stations for passenger EVs [16,17], there are relatively few studies in the BEB research domain [18–21]. These studies' results suggest that BEBs' required charging infrastructure is very sensitive to each transit line's unique characteristics (e.g., route profile, timetables, geography, and weather), as well as to the adopted BEB technology (overnight and en route).

2.2. 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 [22–24].

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 [25], to a possibility of fleets of smaller autonomous buses, to an expectation that public transit will be strengthened by autonomous technology [26]. 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 [27,28] 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 the 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 [29] and small buses [30] 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.

3. 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.

3.1. Lifecycle Cost of Electric Buses

Lifecycle costs reflect vehicle purchase price and fuel expenses over 12 years of operation since these are the costs most impacted by powertrain choice. Estimates of the purchase price of electric buses vary significantly. However, a recent average purchase price of electric buses is used for calculations and estimations. The cost of diesel buses and BEBs, including unit price, battery cost, and operational cost, are detailed in Table 1.

A standard diesel 40 ft transit bus costs about \$400,000–\$500,000 [31]. The cost varies due to additional equipment and electronics capabilities that are added to their vehicles. In this study we assume both a \$300,000 purchase price for diesel buses and a \$400,000 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.

With respect to BEBs, overnight BEB, as opposed to en route BEB, offers different operation profiles, which in turn impacts the required energy consumption, charging time, and refueling cost [32]. However, it is expected that a mix of both types of BEBs would be required to accommodate the varied transit operational demands and timetables [32,33]. Therefore, we utilize average BEB cost variables based on the rates of both technologies and assuming a BEB equipped with a 200 kWh battery pack.

The purchase price of BEB varies significantly in the literature, as well as from industry listing. This is mainly attributed to the sensitivity of BEB purchase price to the procurement process, leading to significantly varied discount rates associated with each procurement. For example, Blanco [34] reported a \$550,000-unit price (without battery) for a 40 ft Proterra bus. Bloomberg [35] reported \$570,000 and \$750,000 for 250 kWh and 350 kWh 40 ft BEBs, respectively. Mahmoud et al. [4] reported purchase price ranging from \$530,000 to \$590,000. Therefore, we adopted the approach of Pelletier et al. [36] and Blynn [37] by breaking down the cost of BEB into vehicle and battery. In this respect, the BEB unit price is assumed as \$550,000 following the recent Forbes report [34].

Similar to the cost of BEB, there are discrepancies in the cost of the unit kWh energy storage system [36]. Schmidt et al. [38] developed a comprehensive economic analysis of energy storage systems (ESS) and noted rapid decline rates of the cost of lithium-ion battery in transportation applications. Schmidt et al. [38] reported a value ranging from \$300–\$500 per kWh, while Blynn [37] reported \$150 kWh for electric vehicles. Therefore, in this study, we utilize a \$500 per kWh capacity [37] and assume a 200 kWh battery as average battery capacity for BEB. Overall, the BEB cost assumed in this study (\$650,000) is similar to the cost of BYD-BEB that was recently procured by LA Metro (approximately \$686,000 per bus) in 2017 [37].

Table 1. Costs of diesel and electric bus parameters [32,39–41]. BEB: battery-electric buses; MPG: miles per gallon; DC: direct-current.

Bus Capital and Infrastructure Costs (USD)	
Cost of new diesel bus (\$/bus)	\$300,000 and \$400,000 per bus
Cost of new BEB—Bus unit (\$/bus)	\$550,000 per bus
Cost of new BEB—Battery (\$/200 kWh)	\$100,000 per bus
Bus Operating Assumptions and Costs	
Fleet size (# of Buses)	360 buses
Replacement cycle (Years)	12 years
Procurement per year (# of Buses)	30 buses
Annual vehicle mile travelled (VMT)	54,403 mi/yr/bus
Diesel bus fuel consumption (MPG)	4.0 mi/gal (\approx 8.428 kWh/mi)
300 kWh BEB energy consumption (kWh/mile)	2.16 kWh/mi
Driver cost per bus (\$/bus)	\$271,500
BEB maintenance cost (\$/mile)	\$0.332/mi
Diesel maintenance cost (\$/mile)	\$0.631/mi
Cost of autonomous technology (\$/bus)	\$100,000
Overnight charger cost (\$/unit)	\$50,000
En route DC fast charger cost (\$/unit)	\$110,000
Diesel fuel cost (\$/gallon)—base case	\$2.00/gal
Electricity cost (\$/kWh)—base case	\$0.07/kWh

Maintenance and fueling infrastructure costs are also affected by powertrain choice, but these costs are not well documented due to the lack of agencies with large battery-electric bus fleets, or due to data availability. That said, for infrastructure cost, we utilize the cost parameters presented in [36] for charging infrastructure presented in Table 1. We assume that 70% of the BEB fleet will require overnight charger with 2:1 bus-to-charger ratio and 30% requires en route direct-current (DC) fast-charger (20:1). For the maintenance cost, Blynn [37] presented a detailed review of BEB reported maintenance cost. Based on their work, we utilize \$0.332/mile for BEB and \$0.631/mile for diesel buses. Energy consumption and electricity tariff are used in the analysis (2.16 kWh/mile, and \$0.07/kWh, respectively).

Table 2's values indicate how, without a discount rate, diesel fuel and maintenance cost savings are enough to recoup the current premium for electric propulsion, with an average lifecycle cost savings of \$72,907 (per bus) if diesel bus purchase prices are \$300,000. However, BEBs will recoup their initial cost and will lead a substantial lifecycle saving of \$172,907 if diesel buses cost \$400,000 each. Table 2 presents the lifecycle costs of each powertrain type.

Table 2. 12-Year lifecycle costs of diesel and electric buses.

Costs of Diesel and Electric Buses at \$300K and \$400K Diesel Purchas Prices *							
	Unit Price (USD)	Battery Price (USD)	Purchase Price (USD)	Average Annual VMT (Per Bus)	Annual Fuel Expense (Base Case)	Annual Maintenance Cost	12-Year Lifecycle Cost
Diesel (\$400K)	\$400,000		\$400,000	54,403	\$27,201.50	\$34,328.29	\$1,138,357.52
Diesel (\$300K)	\$300,000		\$300,000	54,403	\$27,201.50	\$34,328.29	\$1,038,357.52
BEB (300 kWh)	\$550,000	100,000	\$650,000	54,403	\$8225.73	\$18,061.80	\$965,450.36
Δ BEB-Diesel (\$400K)					(\$18,975.77)	(\$16,266.50)	(\$172,907.16)
Δ BEB-Diesel (\$300K)					(\$18,975.77)	(\$50,594.79)	(\$72,907.16)

* costs are based on data from Table 1 and does not include infrastructure cost.

3.1.1. Fuel Price Effects

The average fuel price for the Midwest region at the time of Gurciullo's [42] analysis was \$2.01 per gallon, according to the U.S. Energy Information Administration [43]. 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 [42]. In addition, the global average fuel price ranges between \$2.12 and \$2.85. However, given the volatility of fuel prices globally, a conservative value of \$2.00 per gallon is used here for BEB adoption decisions. This is to account for the varied fuel costs around the world.

If diesel fuel price rises by \$0.10 per gallon each year (starting from \$2.50 per gallon), BEBs are estimated to deliver an immediate 12-year lifecycle benefit of \$139,561 and \$239,561 per bus when considering diesel bus purchase prices of \$300,000 and \$400,000, respectively, before considering any emissions and noise benefits.

Cost competitiveness of electric buses at current purchase prices occurs when diesel is at \$3.30 per gallon if the diesel bus purchase price is \$300,000 or when diesel is \$2.14 per gallon if the diesel bus purchase price is \$450,000. This is assuming a 4.0 miles per gallon (MPG) for all diesel buses.

It should be noted that for BEBs charging infrastructure would be needed, either at centralized locations "depot charging", en route, or both [4,44]. The costs of such infrastructure are difficult to generalize since they depend on the charging strategies and facilities an agency employs, as discussed in [44]. Lajunen et al. [5] finds, however, that employing en route charging is more cost-effective than using strictly overnight charging. Other studies recommended a mix of en route and depot charging to optimize the total cost of ownership [32,45]. The recent work presented in [18,46] also highlights that the charging infrastructure and energy consumption are sensitive to electricity peak charge the time-of-use tariffs, and route topology, among other factors. Such papers also suggest that transit networks, in general, do not follow a universal network model (e.g., scale-free or random) [47]. Each network exhibits a unique set of features that impact charging network costs. Therefore, the cost of BEB's infrastructure utilized in this study should be carefully interpreted.

3.1.2. Future Cost Analysis

The cost of electric buses and battery-electric vehicles in general, is falling. According to the US Energy Information Administration (EIA) [42], Chicago Transit Authority (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 et al. [14] reveal that electric vehicle battery pack costs are falling by 14% annually. We utilize 5% and 10% annual discount rates for BEB batteries to project future cost analysis. Also, as mentioned previously, we use a \$500/kWh average cost for battery-based energy storage. Assuming an average battery capacity of 200 kWh (which represents a mix of depot and en route BEBs) delivers a BEB battery cost of \$100,000.

If the 10% annual reduction in battery pack costs continues, electric bus purchase prices will fall, as shown in Figure 1. However, this would not make them competitive with diesel power from a premium cost perspective, even if diesel buses continue to carry a \$400,000 purchase price. However, as shown in Figure 2, if battery pack cost reduction for buses slow to the 5% rate assumed here, with \$2.00/gallon diesel fuel and \$0.07/kWh power pricing, BEBs will surpass the lifecycle competitiveness of diesel buses for diesel bus purchase price of \$400,000 and \$300,000. For both 5% and 10% annual reduction in battery costs, a BEB's lifecycle cost will beat the \$400,000 and 300K diesel buses at present (year 2020) as illustrated in Figure 2. Overall, with a conservative 5% annual reduction in battery costs, BEB will contribute a 12-year lifecycle savings of \$116,000 and \$216,000 for \$400,000, and \$300,000 diesel buses, respectively.

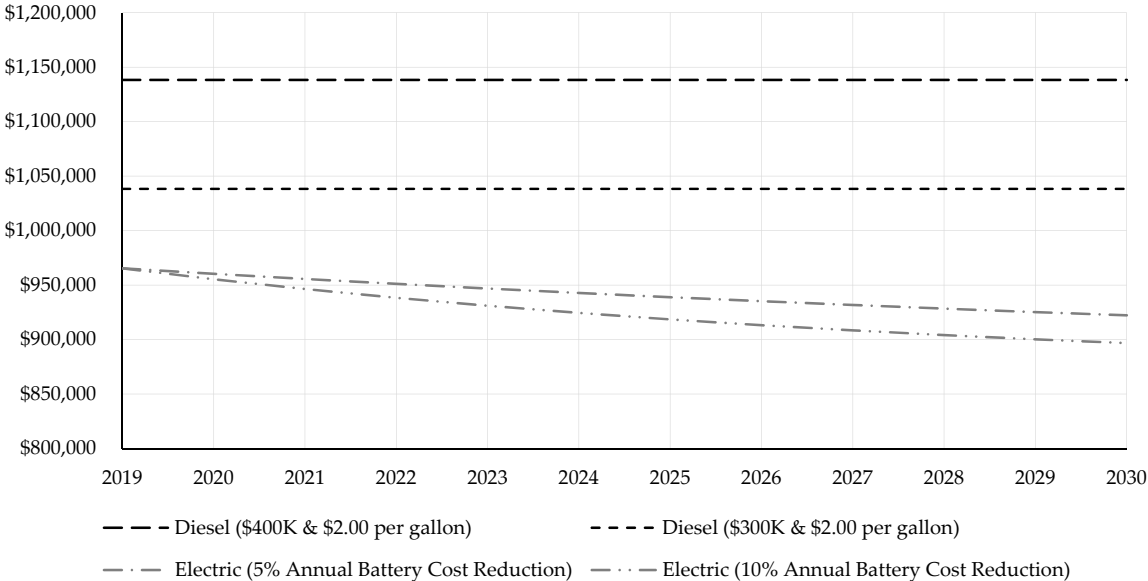


Figure 1. Purchase Cost of BEBs at 5% and 10% Annual Reduction of Battery Cost.

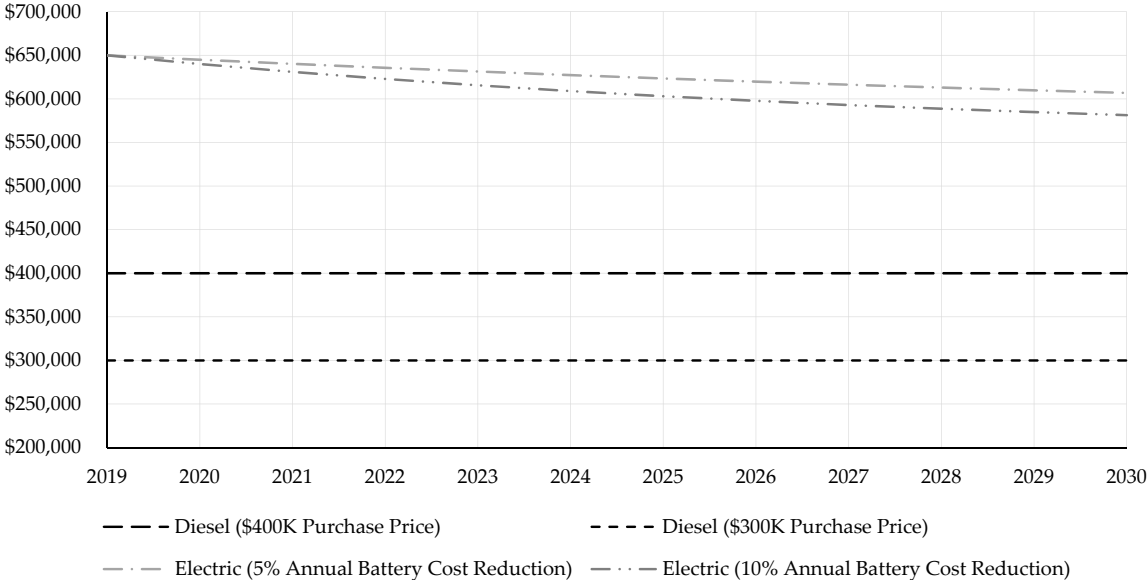


Figure 2. Total lifecycle cost (12 Years) for diesel and electric powertrains (assuming 5% and 10% annual battery cost reduction, \$500/kWh, and 200 kWh-BEB).

3.1.3. Qualitative Effects

Conversion to electric propulsion would have additional effects, which are not easily monetized by the information currently available. For example, Gurciullo [42] estimated the public health benefits of eliminating diesel buses’ local emissions to be \$55,000 per bus-year in Chicago, due to the lower incidence of respiratory illnesses. Over the 12-year life of a bus, this implies \$660,000 in human health savings per bus (without discounting). Including this social cost savings suggests that each BEB may provide closer to a net benefit of \$700,686 or \$600,687 over a 12-year lifespan, assuming \$300,000 and \$400,000 diesel-bus purchase prices, respectively. Those 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.

Furthermore, 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 et al. [5] 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 online, 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.

3.2. 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 the implementation of fully autonomous technology in buses. Qualitative effects of implementation are also discussed.

3.2.1. Driver Costs

The biggest financial benefit of fully autonomous buses to public transit agencies is the potential for a 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 [48]. This is 45% of the agency's operating budget and translates to an annual average of \$271,500 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 et al. [49] 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 study uses a conservative estimate of \$100,000 for the added cost of delivering a self-driving bus, which is twice that of a personal vehicle. With this estimate, the total lifecycle savings from implementing fully autonomous technology to completely replace human drivers would be \$3.6 million per 12-year (expected scrappage) age of a bus, which averages to \$300,000 per bus annually. With a shift to autonomous driving technologies, more technical support would likely be necessary to check

sensors and address technical issues on site. The extent and cost of such support are uncertain, but it will presumably be small compared to existing driver costs.

3.2.2. 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 [23]. 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.

It is estimated 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 [23,50].

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 [50], 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.

Dong et al.'s recent findings [51] suggest that the majority of transit users are willing to ride on self-driving buses if there is a transit employee monitoring and providing customer service onboard, while only small percentage (13%) are presently willing to ride such buses without a transit employee on board. Moreover, Wong and Zhao [52] and others [24,53] note how certain demographic groups are less likely to adopt AVs, at least in the near term. However, these factors are still unfolding as the technology is being developed and deployed, with public acceptance and use rates likely to grow rapidly once the technology is demonstrated to be safe and reliable.

4. Co-Implementation and Adoption Schedules: Methods and Assumptions

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 the electric bus scenario, autonomous bus scenario, and co-implementation scenario. The annual lifecycle cost is estimated as follows:

$$LC = \sum [(C_d \cdot N_d) + (C_e \cdot N_e) + (C_a \cdot N_a) + (C_{ae} \cdot N_{ae})] \quad (1)$$

$$C_e = [((BEB_u + BEB_b + D_c) \cdot N_b) + (VMT \times ((E_c \times E_r) + B_{bm})) + (\sum Ch_{xn} \times Ch_{xc})] \quad (2)$$

$$C_d = [((DIS_u + D_c) \cdot N_d) + \left(\frac{VMT}{MPG} \times D_r\right) + VMT \times B_{dm}] \quad (3)$$

$$C_a = [(DIS_u + AUT_c \cdot N_d) + \left(\frac{VMT}{MPG} \times D_r\right) + VMT \times B_{dm}] \quad (4)$$

$$C_{ae} = [(BEB_u + BEB_b + AUT_c) \cdot N_{ae}) + (VMT \times ((E_c \times E_r) + B_{bm})) + (\sum Ch_{xn} \times Ch_{xc})] \quad (5)$$

$$s.t F = \sum N \quad (6)$$

where

C_d	N_d	Cost and numbers of DBs	BEB_b	BEB unit cost	VMT	Vehicle Mile Traveled
C_e	N_e	Cost and nus oBEBs	BEB_u	BEB battery cost	E_c	BEB energy consumption
C_a	N_a	Cost and nuers of ABs	DIS_u	DB unit cost	E_r	Electricity rates
C_{ae}	N_{ae}	Cost and nuof AEBs	AUT_C	AB technology cost	D_r	Diesel rates
B_{dm}		Diesel Mainnance cost	D_c	Driver cost	MPG	Mile per gallon
B_{bm}		BEB Maintenance cost	Ch_{xi}	# of chargers in category x	Ch_{xc}	Cost of chargers in category x

In addition, the assumptions related to each scenario are detailed as follows.

4.1. Electric Bus Scenario

In this analysis, a 12-year life for each bus is used, which equates to Capital Metro replacing 30 buses in the average year. It is assumed that every new bus purchased is electric, beginning in 2020. The analysis is performed with two electric-bus adoption scenarios, one representing a 10% annual reduction in battery costs, and the other representing the more conservative 5% annual reduction in battery costs and repeated for both a \$300,000 and \$400,000 diesel bus purchase price. These estimates do not consider the change in diesel price. The cost of charging infrastructure follows the 30-bus annual adoption and terminates once all 360 buses have the required chargers.

4.2. 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, 5% 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.

In addition, it is expected that the presence of transit personnel on-board will still be required. Therefore, we assume that each autonomous bus will require a "trip attendant", with an average annual cost of \$67,500. Therefore, a fleet of 360 autonomous buses will require only 360 (180 × two shifts) trip attendants, costing approximately \$24.44 million annually.

4.3. 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. The analysis begins in 2020, which is unrealistic for the adoption of fully autonomous technology but demonstrates an adoption schedule for simultaneous adoption. Since battery costs will be higher in 2019 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.

5. 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 and presented in Figures 3 and 4 and Table 3.

As shown in Table 3, the cumulative costs for adoption (beginning in the year 2020) surpass a break-even point for the adoption of electric technology at a 5% annual battery cost reduction in the year 2032, assuming \$400,000 diesel bus purchase price. The break-even point for electric-only adoption at 10% annual battery cost reduction occurs in 2037 or 2030 for an equivalent diesel bus cost of \$300,000 and \$400,000, respectively.

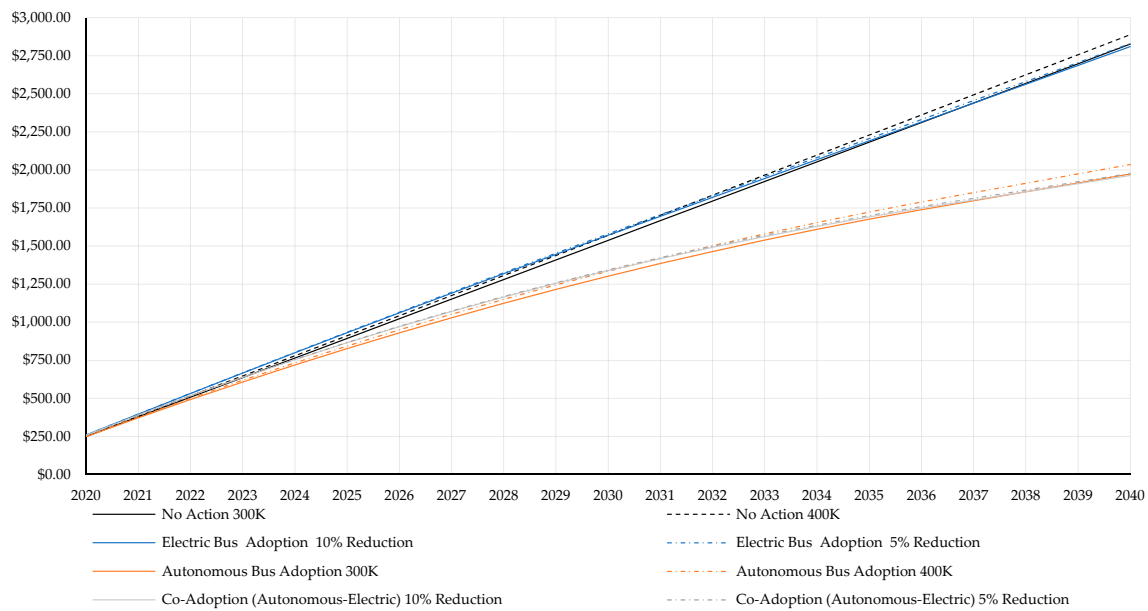


Figure 3. Cumulative expenses in millions for various adoption decisions (20 Years).

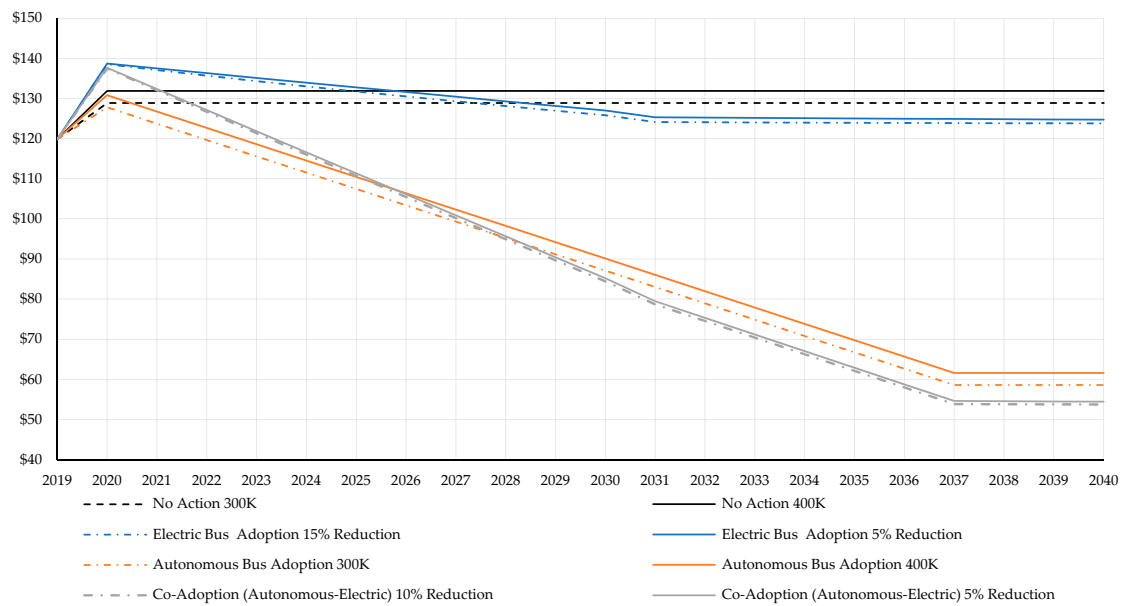


Figure 4. Annual expenses in millions for various adoption decisions (20 Years).

For the autonomous technology adoption, the results suggest significant savings over the 20-Years projection, as highlighted in Figure 3. The cost savings are mainly associated with reducing driving costs and once all drivers retire the system annual expenditure drops to \$58.59 M and \$61.59 M for an equivalent diesel bus cost of \$300,000 and \$400,000, respectively.

Results of the co-adoption scenario show very promising lifecycle savings for transit operation. As compared to autonomous buses only, co-adoption requires higher starting costs. However, it is estimated to surpass the autonomous bus adoption scenario savings in the year 2038, assuming a diesel bus cost of \$300,000 with 10% annual battery cost reductions, or in the year 2030 assuming a bus cost of \$400,000 and battery cost reductions of 5% per year.

Overall, the results suggest that use of autonomous-electric technology in bus-transit systems will deliver substantial lifecycle savings of over each bus’s 12-years lifetime. For electric buses, and despite the higher initial cost and the required infrastructure, the lifecycle savings could be realized in a short period of time, even when assuming a very conservative 5% battery cost reduction. While,

for autonomous and co-adoption scenarios, the lifecycle savings are very sensitive to the significantly reducing the driver's or operator's cost for each adopted autonomous-electric bus.

Table 3. Cumulative lifecycle) costs in millions for all adoption scenarios.

Cumulative Purchase, Fuel, maintenance, Infrastructure, and Driver Costs (in \$1 Million)								
Year	No Action		Electric Bus Adoption		Autonomous Bus Adoption		Co-Adoption	
	300K	400K	10% Reduction	5% Reduction	300K	400K	10% Reduction	5% Reduction
2019	\$119.89	\$119.89	\$119.89	\$119.89	\$119.89	\$119.89	\$119.89	\$119.89
2020	\$248.78	\$251.78	\$258.45	\$258.60	\$247.71	\$250.71	\$257.38	\$257.53
2021	\$377.67	\$383.67	\$395.55	\$396.11	\$371.45	\$377.45	\$389.46	\$389.89
2022	\$506.56	\$515.56	\$531.24	\$532.42	\$491.13	\$500.13	\$516.18	\$516.99
2023	\$635.45	\$647.45	\$665.58	\$667.55	\$606.73	\$618.73	\$637.54	\$638.83
2024	\$764.34	\$779.34	\$798.62	\$801.50	\$718.26	\$733.26	\$753.58	\$755.42
2025	\$893.24	\$911.24	\$930.39	\$934.28	\$825.71	\$843.71	\$864.31	\$866.76
2026	\$1022.13	\$1043.13	\$1060.93	\$1065.89	\$929.10	\$950.10	\$969.75	\$972.86
2027	\$1151.02	\$1175.02	\$1190.25	\$1196.34	\$1028.41	\$1052.41	\$1069.92	\$1073.73
2028	\$1279.91	\$1306.91	\$1318.39	\$1325.63	\$1123.64	\$1150.64	\$1164.83	\$1169.37
2029	\$1408.80	\$1438.80	\$1445.35	\$1453.77	\$1214.81	\$1244.81	\$1254.50	\$1259.78
2030	\$1537.69	\$1570.69	\$1571.17	\$1580.76	\$1301.90	\$1334.90	\$1338.93	\$1344.98
2031	\$1666.58	\$1702.58	\$1695.33	\$1706.09	\$1384.92	\$1420.92	\$1417.61	\$1424.43
2032	\$1795.47	\$1834.47	\$1819.41	\$1831.33	\$1463.87	\$1502.87	\$1492.13	\$1499.73
2033	\$1924.36	\$1966.36	\$1943.44	\$1956.50	\$1538.75	\$1580.75	\$1562.51	\$1570.88
2034	\$2053.25	\$2098.25	\$2067.43	\$2081.59	\$1609.55	\$1654.55	\$1628.74	\$1637.89
2035	\$2182.14	\$2230.14	\$2191.37	\$2206.61	\$1676.28	\$1724.28	\$1690.84	\$1700.75
2036	\$2311.03	\$2362.03	\$2315.27	\$2331.57	\$1738.94	\$1789.94	\$1748.81	\$1759.48
2037	\$2439.92	\$2493.92	\$2439.14	\$2456.47	\$1797.53	\$1851.53	\$1802.66	\$1814.07
2038	\$2568.81	\$2625.81	\$2562.99	\$2581.30	\$1856.11	\$1913.11	\$1856.46	\$1868.60
2039	\$2697.71	\$2757.71	\$2686.82	\$2706.08	\$1914.70	\$1974.70	\$1910.23	\$1923.07
2040	\$2826.60	\$2889.60	\$2810.63	\$2830.81	\$1973.28	\$2036.28	\$1963.95	\$1977.49

6. Conclusions

Based on the analysis of direct costs, BEBs 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 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 transit 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. While this study uses Austin's Capital Metro fleet data, the results are likely to apply across various contexts – with even better BEB adoption savings in settings with higher diesel-fuel costs.

Though their technology premium remains uncertain (and the use of en route bus attendants remains uncertain or trip attendants), fully autonomous buses will almost certainly exhibit lifecycle savings over their human-driven counterparts. Transit agencies generally have contracts with their drivers, but the anticipated savings from the 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 et al. [54]. In terms of mitigating unemployment issues, the U.S. Center for Global Policy Solutions [55] 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 a 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 the 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 and their infrastructure.

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.

Author Contributions: The authors confirm the contribution to the paper as follows: study conception and design: N.Q. and K.M.K.; Data analysis and interpretation of results: N.Q. and M.M. Draft manuscript preparation: N.Q., K.M.K., and M.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Science Foundation (NSF) Sustainability Research Networks Competition (SRN), grant number 1444745. Additional support, was provided (for the third author) by the Natural Sciences and Engineering Research Council of Canada: Grant Number RGPIN-2018-05994.

Conflicts of Interest: The authors declare no conflict of interest.

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