1.0 EXECUTIVE SUMMARY

1.1 OVERVIEW OF STUDY

The Ann Arbor Area Transportation Authority (AAATA) Alternative Bus Propulsion Study was conducted to explore zero-emission bus (ZEB) propulsion technologies and assess the benefits and challenges of transitioning from a fossil fuel bus fleet to a ZEB fleet.

The move to ZEBs is primarily driven by an increasing regulatory push towards cleaner transportation, rapid advancements in bus and battery technologies, favorable fiscal incentives, new funding programs, and a maturing electric vehicle market providing lower costs and reduced technological risks. Although diesel buses have gotten cleaner, there are emerging ZEB technologies available today that will provide an even cleaner alternative.

The last several years have seen a rapid deployment of low-emission and ZEB technologies globally. As of 2021, 1,287 ZEBs have been deployed in the US, roughly 2% of the ~66,000 transit buses nationwide. In Michigan, a total of 15 BEBs and 2 FCEBs are currently in operation[1].

While Michigan has no state mandate for transit agencies to adopt ZEBs, the City of Ann Arbor has established targets to reduce climate change through the (non-binding) A^{2}ZERO Climate Action Plan. The A^{2}ZERO Plan estimated that AAATA's fleet emits ~10,700 tons of CO_2e annually, or about 0.5% of greenhouse gas (GHG) emissions throughout the region. Overall, the GHG emissions from AAATA's fleet is small and the cost to decarbonize is high.

The Alternative Bus Propulsion Study first considered a range of low emission and ZE technologies including: compressed natural gas, trolleybuses, battery-electric, and hydrogen fuel-cell electric buses. However, because natural gas buses are still carbon emitters and because trolleybuses would not be feasible due to environmental impacts related to tree-cutting required to install overhead wires, these technologies were not analyzed in depth.

The two technologies analyzed in detail in this study are hydrogen fuel cell-electric buses (FCEB) and battery-electric buses (BEB). Diesel and diesel hybrid-electric technologies were used for comparison to ZEBs and to create baseline scenarios.

BEBs and FCEBs are considered ZE technologies. Both use electricity to power their traction motors but require different fueling methods. BEBs use batteries to store electricity and typically require numerous charging stations and several hours to recharge. FCEBs use fuel cells to generate electricity by combining hydrogen and oxygen. They are fueled by filling a storage tank on the order of several minutes, and typically require only one fueling station.

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[1] https://calstart.org/wp-content/uploads/2022/01/2021-ZIO-ZEB-Final-Report_1.3.21.pdf

The study comprised of six main elements to evaluate the benefits, opportunities, challenges, risks, and costs of adopting different propulsion technologies:

1. Overview of current bus propulsion technologies
2. Assessment of AAATA's current bus operations
3. Battery-electric bus (BEB) technology assessment and modeling
4. Hydrogen fuel cell-electric bus (FCEB) technology assessment modeling
5. BEB and FCEB fleet transition financial analysis
6. BEB and FCEB emission reductions analysis

1.2 AAATA CURRENT CONDITIONS

AAATA currently operates a fleet of 103 heavy-duty transit buses for fixed-route service. AAATA operates both diesel and diesel hybrid-electric buses and typically completes bus refueling overnight in preparation for the next service day.

The agency's facility houses vehicle service, fueling, interior fleet parking, exterior employee parking, maintenance, administration, and operations. The facility meets AAATA's current operations and maintenance functions. Nevertheless, space is at a premium at AAATA's facility; the fleet size is currently housed in a facility designed for a fleet of about 100 buses, so any fleet expansion—whether for service growth and/or because of propulsion-related technology limitations—will need careful planning to minimize disruptions. In essence, AAATA's current facility may limit the ability of AAATA to fully transition to ZEBs or at the very least, to expand the fleet to increase service levels.

Operationally, buses are rotated through different bus assignments—known as blocks—each day, meaning the range of the propulsion system is sized for the requirement of the largest bus assignment. An analysis of bus assignments indicates that mileages typically do not exceed 300 miles per day, and about 70% of blocks are scheduled for 200 miles or fewer per day. As a point of reference, diesel buses can comfortably achieve 400 miles on a single tank, while BEBs can achieve about 100-250 miles, and FCEBs can achieve about 200-300 miles.

1.3 BEB AND FCEB GENERAL CONSIDERATIONS

When comparing BEB and FCEB technologies, several factors should be considered. Table 1 below provides a general comparison of BEBs and FCEBs on key factors.

Table 1: BEB and FCEB General Considerations

Factor	BEBs	FCEBs
Range	Shorter range (100-250 miles) of operation compared to fossil fuel buses (400+ miles)	Range of operation comparable to fossil fuel buses (200-300 miles vs. 400+ miles)

Factor	BEBs	FCEBs
Capital Cost	Vehicles are about double the capital cost of fossil fuel fleets As fleet size increases, so do incremental costs such as additional chargers and energy demand	Vehicles are about triple the capital cost of fossil fuel fleets Requires costly hydrogen fueling infrastructure
Operating and Maintenance Costs	Fuel costs likely to be lower than diesel because electricity rates are more stable and predictable, and BEBs are more fuel efficient compared to diesel buses Fewer parts to maintain, so cost savings can be incurred from maintenance	Hydrogen fuel costs are more expensive than electricity and diesel fuel, but costs are expected to come down in the future Fewer parts to maintain, so cost savings can be incurred from maintenance
Pros	Lower vehicle costs compared to hydrogen Lower maintenance costs Battery range expected to improve Lower fuel costs	Long operating range – can deliver over 90% of AAATA service in cold weather Minimal changes to servicing cycle (fueling, etc.) Lower maintenance costs More cost effective at scale
Cons	Range limited. Can deliver 62% of AAATA service in cold weather Space requirements for chargers and related infrastructure Electrical upgrades required Electricity rates more complex than diesel contracts Less cost effective at scale	Space requirements for on-site fueling infrastructure More expensive vehicles Significant building upgrades More expensive fuel compared to electricity – costs coming down

Scalability is also a crucial factor to take into consideration. With a small fleet, a BEB implementation is less expensive and simpler. However, a larger bus fleet will require more chargers and utility upgrades, increasing the price and complexity of the implementation. Conversely, FCEBs can be a more cost-effective option for larger fleets. The larger fixed cost of hydrogen fueling infrastructure becomes cheaper on a per bus basis (Figure 1).

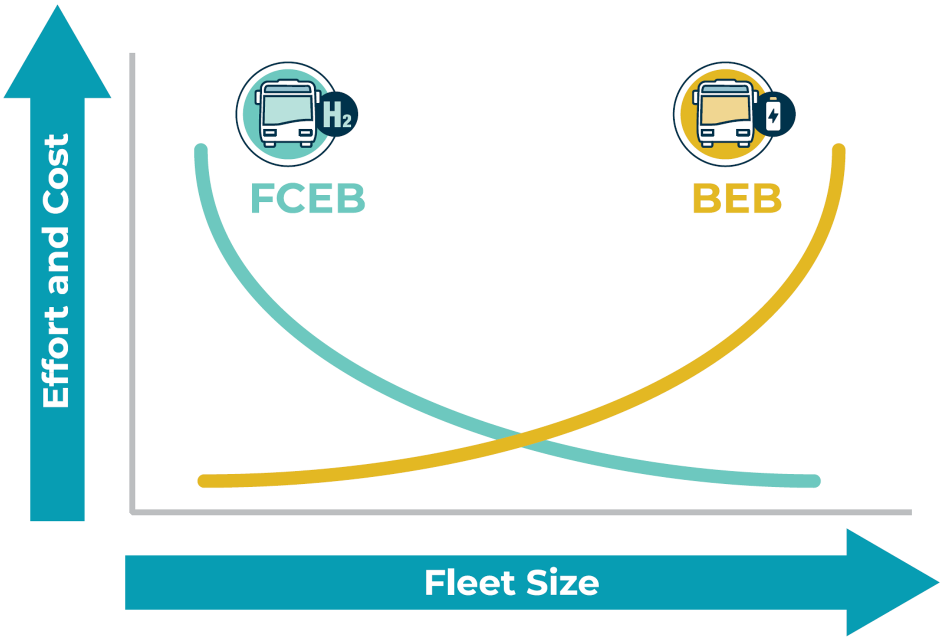

Figure 1: Scalability of FCEBs and BEBs (Source: TCRP, CTE)

In addition, energy density is a key factor to consider. The energy density of a fuel directly impacts the range of the vehicle. Different types of fuels have different relative energy densities, and some require more storage space and are heavier. Gasoline and diesel require less storage space, are relatively light weight, and have a high energy content per unit volume. Batteries and hydrogen fall lower on these scales, as illustrated in Figure 2 below.

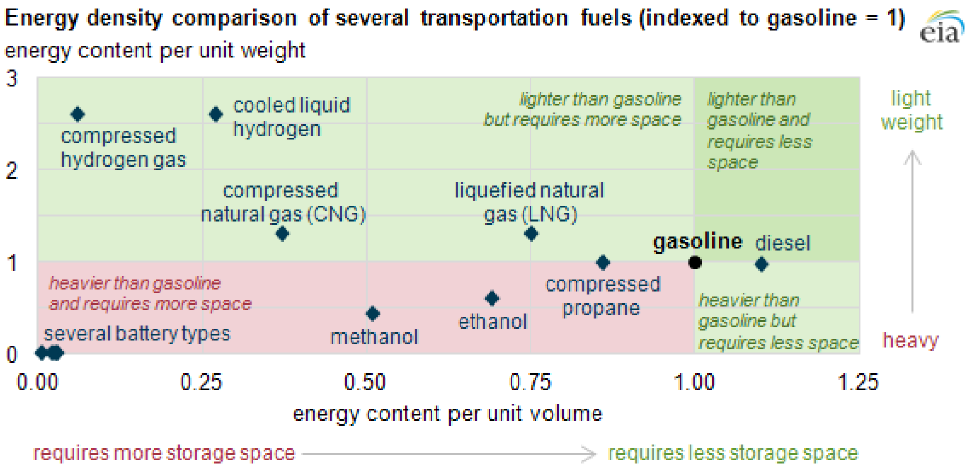

Figure 2: Energy density of transportation fuels. Source: EIA

Figure 2 illustrates how much more energy-rich fossil fuels like diesel tend are by volume. Furthermore, on the graph, diesel fuel sits to the right of batteries as a fuel, meaning that diesel fuel requires less storage space for a greater amount of energy per unit volume. Put another way, batteries need to be very large to carry the same amount of energy as diesel fuel. Heavy battery packs may in turn reduce fuel efficiency as well as limit potential route alignments based on weight restrictions for certain roadways like bridges or overpasses.

Similarly, compressed hydrogen gas is less energy dense than diesel, but slightly more than batteries. However, because compressed hydrogen gas is much lighter weight than diesel fuel, more of it can be stored onboard a bus without excessively increasing the weight compared to batteries. Overall, the notion of energy density helps explain some of the trade-offs associated with ZEBs and their operating range characteristics.

1.4 BATTERY-ELECTRIC BUS ASSESSMENT AND MODELING

AAATA and Stantec developed a preferred BEB concept based on workshops and conversations with AAATA staff, service analysis, and route modeling. The preferred concept is a BEB fleet with long-range batteries that will be charged in-depot. BEBs with 675 kWh batteries could successfully deliver 97% of service on mild days (59°F), but only 62% on cold days (10°F). Deploying on-route opportunity chargers at transit centers could elevate that cold day success rate to 87%, but may introduce other operational challenges, as well as increase capital and operating costs.

The preferred site concept uses an overhead pantograph charging arrangement while clustering charge cabinetry remotely. While pantograph chargers are more expensive than plug-in chargers, the space limitations at AAATA's facility requires an overhead approach to minimize the footprint and maximize space for vehicles. A BEB implementation will require electrical service upgrades because the existing electrical system is not adequate to serve the loads that will result from the full build out of BEB chargers.

With a BEB fleet, a portion of service will require restructuring of vehicle assignments that exceed the operating ranges of BEBs. Furthermore, AAATA can explore other options such as considering blocking range limitations for summer and winter weather, procuring BEBs with diesel-fired heaters, or deploying BEBs primarily on blocks within feasible ranges while keeping diesel buses assigned to the most challenging blocks. As battery technology improves, the operational alterations required are likely to diminish long-term. However, additional analysis is required to map out the scheduling of BEBs for AAATA's future service plans.

1.5 HYDROGEN FUEL CELL BUS ASSESSMENT

The preferred FCEB concept will replace diesel buses one-to-one. Route modeling demonstrated FCEBs can achieve 100% of AAATA blocks on mild days, and 91% of blocks on very cold days. Therefore, minor re-blocking will be required to achieve 100% service on very cold days. However, additional analysis is needed to consider the impacts of FCEB scheduling regarding AAATA's future service plans.

The preferred site concept requires site alterations to accommodate new hydrogen fueling infrastructure. If FCEBs are implemented, major HVAC system upgrades and a new gas detection system will be required. Additionally, building retrofits will be necessary to facilitate indoor hydrogen fueling.

1.6 FINANCIAL ANALYSIS

The financial analysis included a total cost of ownership (TCO) analysis and an evaluation of operating and capital budget impacts. This two-tiered approach is critical to ZEB planning for two primary reasons. First, it facilitates the ability to make final tweaks to the ZEB scenarios to ensure they are optimized for costs in addition to operational impacts, delivering maximum value for taxpayer dollars. Second, it provides valuable information for AAATA to facilitate future budgeting activities, grant applications, and more informed decision making.

Four different scenarios were financially modeled for the ZEB transitioning at AAATA. These scenarios included the following:

1. Transition to BEBs, procurement-based approach (8 buses per year, 13 years to complete)
2. Transition to BEBs, accelerated approach (14 buses per year, 7 years to complete)
3. Transition to FCEBs, procurement-based approach (8 buses per year, 13 years to complete)
4. Transition to FCEBs, accelerated approach (14 buses per year, 7 years to complete)

A “procurement-based approach”—applied to scenarios 1 and 3—involves the annual replacement of 8 diesel buses from 2024 through 2035, with 3 remaining buses replaced in 2036. This is in line with AAATA’s current procurement practices of replacing an average of 8 buses per year. Essentially, the procurement-based approach maximizes the value of AAATA’s existing fleet assets, and ZEBs are modeled to replace diesel buses only once the diesel buses have reached the end of their useful life.

The “accelerated approach” (scenarios 2 and 4), with the aim of converting AAATA’s entire fleet into ZEBs by the year 2030, was also analyzed. In the accelerated approach, 14 diesel buses are assumed to be replaced per year with ZEBs from 2024 through 2029, with the remaining 15 buses replaced in 2030.

The financial modeling, when completed over a 25-year forecast period, illustrates that scenario 1 (transition to BEBs, procurement-based approach) has the most favorable business case, with a TCO of $115M, compared to $138M, $130M, and $157M for scenarios 2, 3, and 4 respectively. This suggests that a ZEB replacement schedule that dovetails with AAATA’s current procurement schedule is ideal, and ensures that AAATA’s current diesel buses can continue to be utilized for their full 12-year lifecycle. Exploring a faster transition plan, for example full fleet conversion by 2030, or exploring different ZEB technologies such as FCEBs would make for a more complex transition, would necessitate additional costs, and would result in an underutilization of existing assets.

The major cost drivers of a transition to BEBs include the capital cost of infrastructure (approximately $22M of incremental costs) and the capital cost of the vehicles (approximately $310,000 of incremental costs per bus, compared to diesel buses). However, there could be cost saving opportunities on the operating and maintenance side, with a “best guess” estimate at $101M in savings over the 25-year forecast period through the implementation of scenario 1. However, to achieve these cost savings, AAATA will require an additional $75M in capital funding throughout the forecast period, and an initial $7.7M investment in year 1 (2023). It is important to also appreciate that capital requirements may end up being larger than $75M in the event the transition to BEBs necessitates additional vehicle purchases, or in the event that unit costs do not decrease over time to the extent envisioned.

1.7 KEY CONSIDERATIONS

1.7.1 Benefits

Greenhouse Gas (GHG) Emissions Reduction

The chief benefit of transitioning to a ZEB fleet is the reduction of the region’s GHG emissions. Four scenarios were modeled over 12 years to understand how ZEB technologies will impact emissions. Based on the agency’s current diesel operations, the modeling estimated that AAATA’s existing fleet emits approximately 7,000 tons of CO_2 annually, slightly lower than the GHG emissions estimated by the A^2ZERO Plan (10,700 tons).

While ZEBs are zero emissions at the tailpipe, the electrical grid in Michigan isn’t 100% green, and hydrogen sources vary in their carbon neutrality. Assuming that AAATA will purchase green energy from DTE and green hydrogen produced through electrolysis, a 12-year period of ZEB replacement will result in:

- 41,000 tons of GHGs for BEBs
- 43,000 tons for FCEBs using electrolysis
- 61,000 tons for FCEBs using steam methane reforming methods of hydrogen production

Comparatively, continued operation of diesel buses will emit 82,000 tons of GHGs over the same time period. Emissions never reach zero in this timeframe due to emissions created by the continued operation of diesel buses during the transition to ZEBs. However, a fleet of entirely ZEBs with green electricity or green hydrogen would virtually eliminate the carbon footprint of AAATA’s fleet.

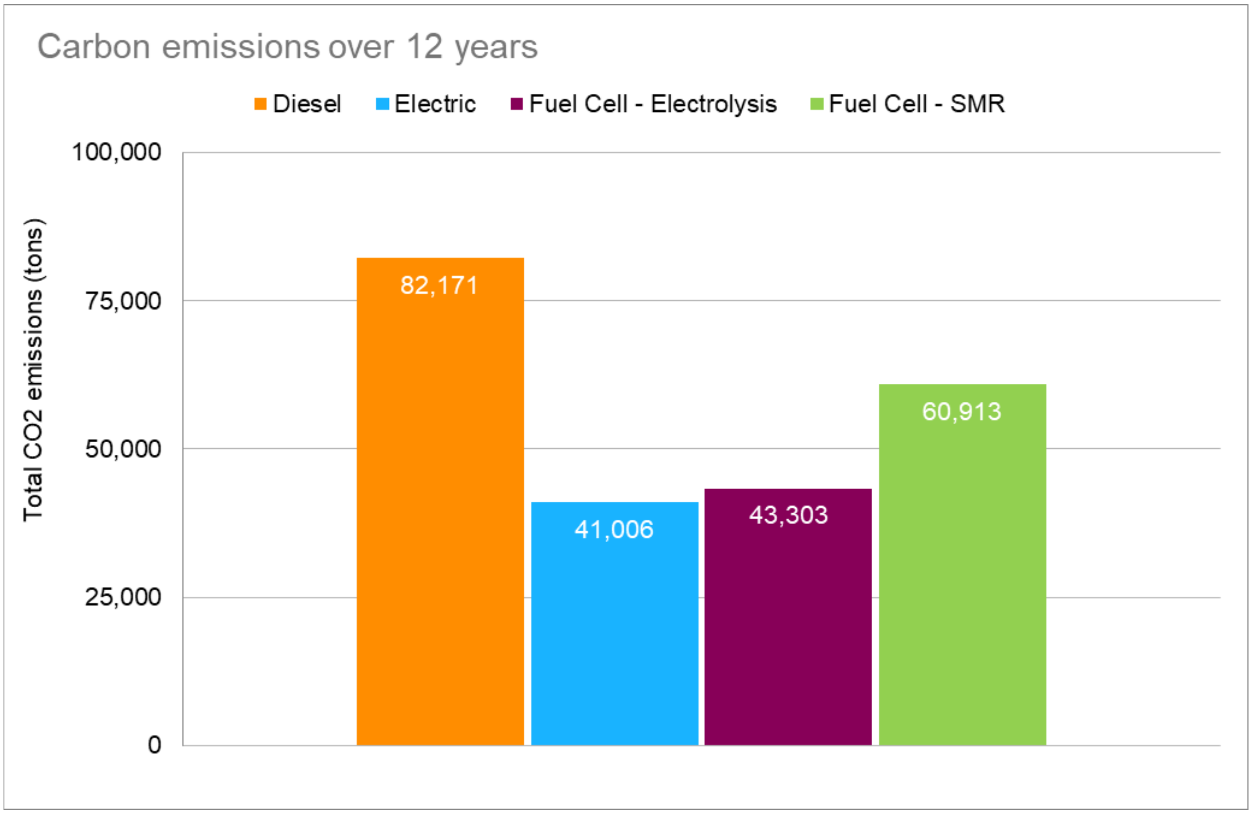

Figure 3: Total Carbon Emissions over 12 Years

Overall, adopting **ZEBs could reduce AAATA's fleet-based carbon footprint by 27-50% over a 12-year timeframe, which translates to a community-wide emissions reduction of less than 0.5%.** This aligns with the fact that the mileage AAATA's buses travel is also less than 1% of all vehicle miles traveled in the region. The Southeast Michigan Council of Governments (SEMCOG) estimates that in 2019, there were 3.95 billion total vehicle miles driven in Washtenaw County. AAATA's fixed-route buses traveled slightly more than 4 million miles that same year (0.1% of all vehicle miles traveled). Even if only half the total miles can be attributed to the Ann Arbor/Ypsilanti area, AAATA bus mileage would only be 0.2% of the total. Also in 2019, there were 173,441 vehicles registered in the cities of Ann Arbor and Ypsilanti, while AAATA had 103 buses (0.06%).

While AAATA is a small emitter, more localized benefits of ZEB conversion can help improve air quality where buses operate, particularly in communities with existing air quality issues, as well as at bus stops and at transit centers where buses generally idle while serving passengers. For example, diesel buses have been estimated to release between 2,700-3,500 grams of $CO2_e$ per mile along a corridor (depending on operating conditions like traffic, frequency, dwell times), and up to 300 grams of $CO2_e$ while at a bus stop[2]. And importantly, interior cabin air in ZEBs will also be cleaner and more healthful for

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[2] Alam, A. and M. Hatzopoulou. 2014. Reducing transit bus emissions: Alternative fuels or traffic operations? Atmospheric Environment, 89: 129-139; https://www.sciencedirect.com/science/article/pii/S1352231014001393

passengers and bus operators. It is unclear whether these levels are significant and further study may be warranted.

In addition, the conversion could also eliminate 16,000 kg of nitrous oxide (NOx) and 113 kg of particulate matter (PM) per year. Further greening of the electrical grid, as well as green hydrogen sources, together with a 100% ZEB fleet will reduce the carbon footprint even further.

Cost Savings

During the COVID-19 pandemic, diesel fuel prices were about $3 per gallon. As of August 2022, diesel fuel now hovers around $5 per gallon. The volatility of diesel fuel prices, coupled with the predictability and lower costs of electricity could translate to future cost savings with a BEB fleet. While hydrogen fuel is more expensive than electricity or diesel fuel, costs are expected to decrease over time to provide a cost savings compared to diesel fuel.

Additionally, the propulsion of systems of ZEBs involve fewer moving parts than a traditional diesel engine, which could result in reduced maintenance needs and cost savings. The learning curve for the new technologies will be steep and retraining of existing staff will be required for a ZEB fleet, but is expected to level off with technology maturation and increased experience from maintenance staff.

Social

There are also social benefits to transitioning to a ZEB fleet through the reduction of negative externalities like health impacts related to GHG reduction. The US Department of Transportation estimates a monetized value of the social costs of carbon emissions at $53 per ton. Therefore, removing 7,000 tons of CO_2 annually represents a potential social benefit of approximately $371,000 per year.

Other

Other factors, such as improved cabin air quality and near-silent operations, make riding the bus safer and more pleasant for both operators and passengers. In addition, the cachet of ZEBs could be leveraged as a marketing tool to grow ridership by offering green transit.

1.7.2 Risks and Challenges

There are several risks associated with ZEB technologies related to planning/scheduling, operations maintenance, cost, safety, and human resources. The risks with the highest likelihood and impact include:

- Service changes and the impacts on fleet size and scheduling
- Uncertainties in bus and battery performance and life
- Availability of resources for unexpected maintenance/repair requirements
- ZEB life cycle is not fully proven out
- Unknown long-term commodity prices for fuel (electricity, hydrogen, etc.)

Alam, A., E, Diab, A. El-Geneidy, M. Hatzopoulou. 2014. A simulation of transit bus emissions along an urban corridor: Evaluating changes across several years and under various service improvement strategies. Transportation Research Part D, 31: 189-198. http://tram.mcgill.ca/Research/Publications/Bus_emissions.pdf

- Battery replacement costs
- Bus and battery residual value
- Hydrogen fuel cell replacement/ refurbishment costs
- Workforce training and retention
- Execution and deployment of ZEBs
- Balancing competing capital needs for AAATA

AAATA will encounter agency-specific challenges while transitioning to ZEB technologies. AAATA's current operating base and maintenance facility lack the space needed for future growth and for ZE charging and fueling infrastructure. This will require facility upgrades that are carefully planned and phased to not impact the agency's day-to-day operations.

If BEBs are implemented, substantial electrical upgrades will be required to meet power demand. Charging equipment for buses will also need to be installed inside the building. If FCEBs are implemented, major HVAC system upgrades will be required to provide sufficient exhaust and make-up air to the maintenance and bus storage areas of the building.

There are also several industry-wide challenges common to ZE fleet transitions. Short term, the global supply chain is driving up the costs of vehicles and manufacturing, while also increasing lead time for parts and vehicles. In addition, agencies will need to retrain staff, particularly maintenance technicians and operators, on ZEB technologies and sufficient lead time is required for training and workforce development. Maintenance can also be challenging once maintenance activities shift from the manufacturer to the agency. Lastly, ZEB and infrastructure procurement requires a large capital outlay. Although the Federal Transit Administration (FTA) has demonstrated its support for ZEB transition by doubling funding for bus acquisitions, future funding levels may not be sufficient to support industry-wide transition to ZEBs. Funding at the state and local level will be required for matching funds to unlock federal grants.

1.8 NEXT STEPS

With a preliminary understanding of ZEB technologies and the potential transition, necessary next steps include:

1. Determine the preferred alternative propulsion technology for AAATA. In the interim, AAATA will continue to procure the newest and cleanest diesel buses to minimize emissions.
2. Determine necessary modifications to the current facility, or if a new facility will be used
3. Conduct further analysis of future service plans to determine potential implications on the conversion to ZEBs.
4. Determine the relative priority of propulsion compared to other needs like transit center and customer-facing projects. This will affect grant applications and the timeline of the transition to a ZEB fleet.
5. Develop a phasing plan that outlines the transition to a ZEB fleet.
6. Determine if additional consulting work is needed to reach decisions about the transition.
7. Take steps towards filling grant applications such as the FTA Low-No program.

8. Assess staffing requirements to oversee and manage a successful transition and ensure adequate resources. Workforce training should also be considered.
9. Begin planning for future garage modifications that take into consideration the specific requirements of the ZEB technology.