Cape Cod Regional Transit Authority

Zero Emission Vehicle Transition Best Practices Report

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Date	**Rev.**	**Status**	**Prepared By**	**Checked By**	**Approved By**	**Approved By**
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ZEV Transition Best Practices

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1. Executive Summary

The Cape Cod Regional Transit Authority (CCRTA), in consultation with the Cape Cod Commission, has committed to transition its fossil fuel powered fleet to Zero Emissions Vehicle (ZEV) technology by 2030. The overarching goal of this transition is to decrease the Authority's carbon footprint by reducing greenhouse gas (GHG) emissions. Regional plans such as the Cape Regional Policy Plan (RPP), the Comprehensive Economic Development Strategy (CEDs), the Cape Cod Climate Action Plan, and the Regional Transportation Plan (RTP) all support steps required to expand ZEV access and use. In addition, the Massachusetts Clean Energy and Climate Plan for 2025 and 2030 calls for accelerating the electrification of fleet vehicles and investment in charging infrastructure.

The reason the region has made commitments to accelerate the deployment of ZEVs is due to the many benefits the technologies offer. For example, battery electric vehicles are approximately 70 to 90 percent more energy efficient than conventional transit vehicles. Battery electric vehicles also reduce lifecycle emissions by two to three times compared to that of diesel vehicles. In addition, electric powertrain technology has been proven in other applications such as light duty and rail vehicles to be far more reliable than diesel powertrains. ZEV technologies offer reductions in noise pollution, operational costs and maintenance costs as well.

Despite the many potential benefits of ZEV operations, transitioning CCRTA's fleet to these technologies is no small undertaking, and will require strategic planning, upfront capital, local and regional collaboration, and continued evaluation and monitoring. This report serves to provide details and lessons learned from other authorities that have transitioned to battery electric vehicles while touching on experience with hydrogen fuel cell vehicles in an effort to guide CCRTA towards a more successful fleet transition, and to mitigate issues noted in past projects.

Battery electric vehicles represent the likely long-term solution for many authorities, by offering the potential for the greatest energy efficiency, emissions reductions, and reliability. As a new technology, however, these vehicles have limitations that should be noted. First, the vehicles offer significantly shorter driving range than a diesel bus, especially in cold weather. Second, the vehicles require extensive supporting infrastructure such as charging equipment to operate. Finally, the vehicles and supporting infrastructure carry high capital costs to implement. As a result, best practices indicate that careful simulation, analysis, planning, and optimization is required to successfully operate the vehicles. Even with that work completed, however, the current limitations of the existing technology will likely render it infeasible to support all passenger service for CCRTA as currently operated.

Hydrogen fuel cell vehicles have also been deployed in the light duty and full size transit bus vehicle segments, demonstrating future potential. These demonstrations have shown that this technology offers longer range compared to current battery electric technology. Challenges associated with infrastructure costs, hydrogen fuel availability, and limited available performance data are some factors that currently limit the applicability of the technology to most transit operations. Furthermore, there currently are very few smaller transit vehicles (vans and cutaways) or trolleys commercially available that are powered by hydrogen fuel. As currently composed, CCRTA's fleet is predominantly made up of these smaller style transit vehicles limiting the short term possibility of implementation for the authority.

To offset the limitations of ZEVs, and still make progress towards emissions reductions, hybrid vehicles present a logical short to medium- term strategy. For CCRTA, shifting from diesel to hybrid represents a low-risk solution. Hybrid vehicles can usually function as a 1:1 drop-in replacement for current diesel vehicles. While hybrids carry a higher upfront cost than diesel vehicles, they offer the potential for authorities to save money over time through reduced fuel consumption while also reducing emissions.

Through review of the best practices associated with battery electric transit vehicles, it is evident that successful deployment is achievable. By following the lessons learned outlined in this report, and completing the necessary subsequent steps of analysis, planning, and optimization CCRTA can expect to reinvent their operations with more sustainable technologies. As these efforts progress, CCRTA should continue to evaluate industry trends and best practices and adjust their strategies and plans accordingly.

2. Vehicle Technology Options

CCRTA currently operates transit vehicles with Internal Combustion Engine (ICE) powertrains. CCRTA's fossil fuel powered fleet consists of various vehicle types including buses, mini buses (cutaways), mini vans, and trolleys. CCRTA commits to a 100% zero-emission powertrain technology vehicle transition by 2030; moving away from fossil fuel powered fleets to cleaner technology.

Figure 1 provides a high-level comparison of conventional diesel/gasoline, diesel/gasoline-hybrid, fuel cell hybrid, and battery electric propulsion technologies. Within the diesel/gasoline-hybrid category, there are two architectures: parallel hybrid and series hybrid.

- ICE vehicles use an engine to power auxiliary devices such as lighting and to propel the vehicle.

- Hybrid buses, on the other hand, are all equipped with electric motors and batteries. Hybrids are also always equipped with either an ICE or a hydrogen fuel cell to provide power to the battery and motor systems. The battery can also be recharged by harnessing the energy from braking or downhill coasting (regenerative braking). On the series hybrid architecture, the diesel engine's sole function is to help charge the battery. The electric motor is the only method of propulsion. This architecture is best suited for stop-start driving typical in urban environments. On the parallel hybrid architecture, the electric motor provides power during low-speed operation. The ICE is also mechanically linked with the wheels to provide propulsion during highway operation or when the batteries don't have sufficient charge. The efficiency of this design is higher with sustained high-speed driving. Hydrogen vehicles are very similar to ICE series hybrids, essentially replacing the ICE with a fuel cell. In these vehicles hydrogen passes through a fuel cell which generates electricity used to replenish the batteries.

- Finally, battery electric vehicles eliminate the use of engines entirely, and instead use bigger batteries and more powerful drive motors for propulsion and auxiliaries. The batteries are charged using energy from the grid and require dedicated infrastructure for charging (unlike the diesel-hybrid vehicles). Battery electric vehicles also recoup energy and recharge the batteries while braking and downhill coasting like the diesel-hybrid vehicles.

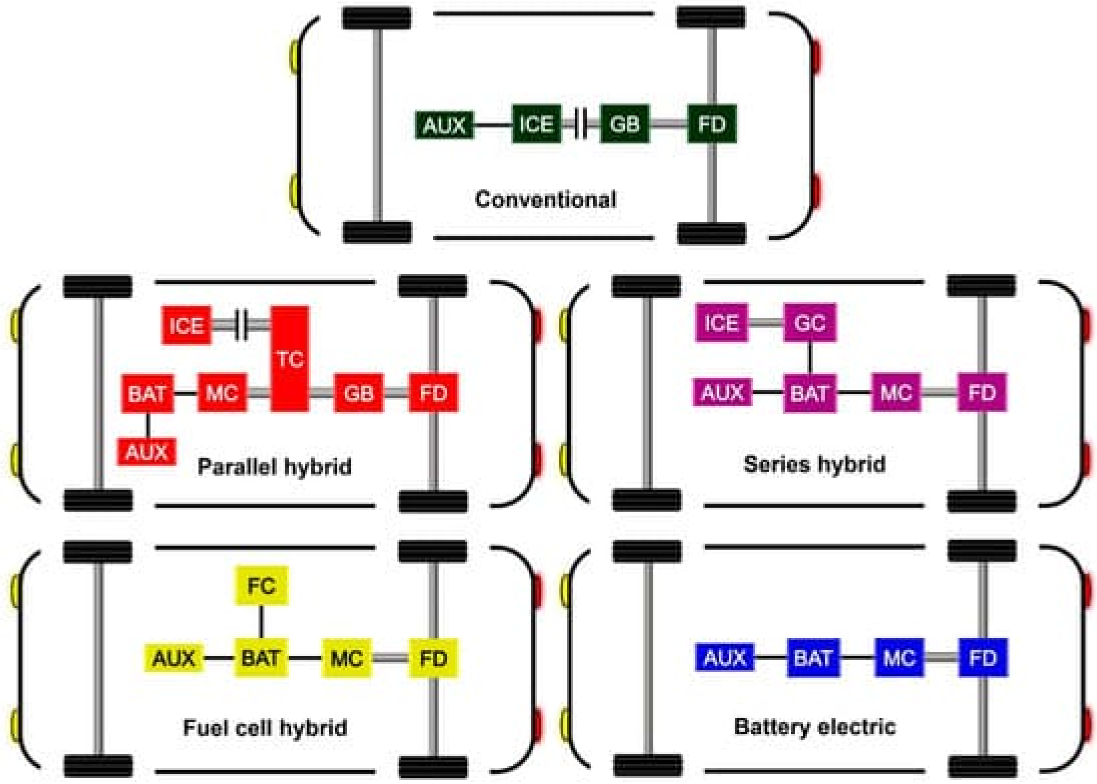

FIGURE 1-COMPARISON OF POWERTRAIN TYPES DISCUSSED IN THIS REPORT (SOURCE MDPI)

(AUX = auxiliary devices, BAT = battery, FC = fuel cell, FD = final drive, GB = gearbox, GC = generator and controller, MC = motor and controller, TC = torque coupler)

2.1 Battery Electric

From a technological perspective, battery electric vehicles offer multiple advantages over diesel vehicles. First, the energy efficiency of a battery electric vehicle is roughly three to four times higher than a diesel bus. Additionally, even when powered by electricity grids that use fossil fuels to produce electricity, operating battery electric vehicles reduces lifecycle emissions by two to three times compared to that of diesel vehicles. Finally, electric powertrain technology has been proven in other applications such as light duty and rail vehicles to be far more reliable than diesel powertrains.

Due to these benefits, battery electric transit bus usage has experienced rapid growth in recent years. In an effort to alleviate climate change concerns many countries have made the commitment to transition all transit vehicles to zero emissions technologies over the next few decades. Some countries have made more progress than others in these efforts, including China, where over 400,000 electric buses are currently in operation. In many other areas growth has been more measured. In Europe battery electric vehicles currently constitute 6% of new bus purchases, and in North America there are 3,533 battery electric vehicles either on order or in service (as of 2021), with the largest operator being the Toronto Transit Commission in Canada with 60 vehicles currently in service.

The US market is comparatively small, but expanding quickly, with a growth rate of 118% over the last three years. The demand has primarily been driven from California, where the California Air Resources Board (CARB) enacted regulations requiring all transit vehicles to be transitioned to zero emissions technologies by 2040. While not required through regulations, many major cities have committed to similar goals such as New York, Chicago, and Seattle. As starting points, however, most US deployments have been small scale pilot programs of around five vehicles. According to the American Public Transportation Association, the largest fleet of electric buses in operation is Denver RTD, which has 36 vehicles. Order and fleet sizes are expected to grow rapidly though in the next few years. Los Angeles Department of Transportation, for example, recently placed the largest order ever of electric buses in US history (130 buses).

To meet growing demands, vans, cutaway buses, trolleys and transit buses between 30' and 60' in length are now available with battery electric powertrains. Manufacturers also offer a range of battery capacities on these vehicles to provide range flexibility to operators. Today battery capacity in an electric transit vehicle can range anywhere from 60 kWh to 738 kWh, which can provide an operating range of anywhere from 60 to 300 miles on a single charge depending on operating conditions. The results of battery electric vehicle testing have shown that typical range is commonly 150 miles or less in most transit operating environments.

Despite the growing prevalence of battery electric vehicles there are still major impediments to the technology becoming the primary powertrain configuration for transit authorities. The primary issues that must be considered when transitioning to battery electric vehicles relate to infrastructure, operations, and costs. While not as significant, there are also other issues to consider such as human factors and regulations.

Externalities like supply chain constraints and utilities limitations will also have an impact on the rate of adoption of the electric vehicles. The following subsections detail these issues, and present best practices for managing the risks.

2.2 Hydrogen Fuel Cell

Hydrogen vehicles offer both advantages and disadvantages when compared with battery electric vehicles. The first advantage of hydrogen vehicles is that they offer additional range, offering as much as 100 additional miles of operation to a battery electric bus. They also tend to experience less performance losses during cold weather, as the fuel cells produce heat as a byproduct of the chemical reaction process which can assist in the heating of the vehicles interior. Finally, fueling a hydrogen vehicle takes only a few minutes as opposed to several hours to fully charge a battery electric vehicle. The speed at which hydrogen vehicles can be fueled offers many operational benefits to transit operators.

The primary disadvantages of hydrogen fuel cells relate to sustainability. First, hydrogen fuel cell vehicles are less efficient than battery electric models. The efficiency of a battery electric vehicles ranges from 70-90%, whereas hydrogen fuel cell vehicles are only 25-35% efficient. This reduces the degree to which hydrogen vehicles can contribute to sustainability goals. Furthermore, hydrogen gas does not exist naturally and must be produced through one of many energy intensive processes. Most of these production processes involve the reformation of fossil fuels which create emissions. The most established form of "green" hydrogen production is hydrolysis, which extracts hydrogen gas from water molecules. This process requires a large amount of electrical energy, which if not produces sustainably, also reduces the sustainability of fuel cell operations. Hydrolysis also consumes a large amount of water which is another resource that should be conserved.

Other disadvantages of hydrogen fuel cell vehicles are related to the lack of commercialization of products. Hydrogen transit vehicles have been produced in far lower quantities. There are over 500,000 battery electric transit vehicles in operation globally, compared to less than 6,000 hydrogen vehicles. The market is almost non-existent for smaller transit vehicles, where hydrogen powered vans and cutaways are not commercially available. As CCRTA's fleet is predominantly made up of these smaller transit vehicles, it limits the applicability of the technology to the authority's operations. Also, unlike electric vehicles where charging infrastructure is rapidly being developed to support light duty and commercial vehicles, there are only 54 hydrogen fueling stations in operation in the US. Almost all of these fueling stations are located in California. This means that expensive fueling infrastructure typically has to be constructed on authority property, rather than being able to rely on commercial fueling as can be done with ICE vehicles.

3. ZEV, Equipment, and Resource Availability

As global demand for zero emission vehicles and infrastructure grows, a massive strain is being applied to supply chains that support manufacturers and operators. It is important for CCRTA to be cognizant of these constraints as it plans for its full transition to zero emission technologies.

3.1 Battery Electric Vehicle Resources

Although batteries have existed for centuries, the recent rapid growth in the electric vehicle market has strained the battery supply chain. Most battery types available today are produced with several key rare materials. Other electric vehicle components like propulsion motors are also produced using rare earth minerals. Although the mining industry is currently able to meet EV manufacturers' demand, the need for these rare-earth elements may become a constraint as EV demand continues to grow.

These challenges, combined with the impact of the COVID-19 pandemic, have resulted in long lead times for these vehicles. Batteries are the most critical component of these vehicles and, although manufacturers are working hard to secure the required minerals and scale up battery production, the availability of these critical minerals remains the biggest constraint on battery electric vehicle production. However, as the production capacity slowly ramps up and the impact of the pandemic wears off, the lead time for these vehicles should improve over the next few years.

The supply chain for electric vehicle supply equipment (EVSE) and upstream electrical equipment like transformers and switchgear continues to recover from the impact of COVID-19 pandemic. The lead times for the chargers are as high as 24 months with some manufacturers. However, this is temporary. The production capacity is not a concern with electrical equipment as, unlike the vehicles, it is not constrained by a single component production bottle neck. As the supply chain recovers over the next few months and years, the lead times for all these equipment should reduce to a more normal 16-24 weeks in the future.

Transit authorities should also be aware that spare parts and replacement batteries may prove difficult to acquire in the coming years. As more authorities transition to ZEVs and ZEBs, those vehicles and supporting infrastructure will require scheduled and emergency maintenance. An adequate supply of spare parts will be critical to authority operations and service.

To combat supply chain issues, one mitigation strategy identified by transit authorities is to evaluate multiple ZEV and supporting infrastructure manufacturers in smaller orders prior to moving to larger procurements. Secondly, strategic phasing for vehicle and infrastructure procurement to provide opportunity to evaluate real-time performance and better understand market changes is important. Transit authorities are encouraged to monitor the state of the battery market's supply chain and the development of any new battery chemistries that may require fewer, or different, rare-earth elements.

Finally, in order to support any ZEV transition, transit authorities must determine the robustness and capacity of the electrical grid in their region to determine whether or not the grid can support electric infrastructure. While not controlled by the transit agency, the utilities which provide power for charging the vehicles play an integral role in the transition to electric vehicles. Many authorities have found that sufficient power to support their electric vehicle operations is not currently available in the locations it is required (depots and on-route locations). As a result, utility upgrades may be required which can drastically alter the timeline and costs for transitioning to electric vehicles.

Other utility related issues that must be considered by authorities have to do with rate structures. Unlike with gasoline or diesel, the cost of electricity is not usually constant per unit used throughout the day. This variation takes two forms – demand charges, which are largely proportional to the peak demand drawn by the transit authority at any one time, and peaking charges, which vary the rate per kilowatt-hour by time of day.

Demand charges are most likely to affect a transit authority using fast chargers. Whether at a depot or external layover location, several vehicles drawing power from fast chargers at once may increase the peak demand rate. These can be significant; for example, the transit authority in Seneca, SC saved 40% on its power bill by negotiating an agreement with the local utility that did not include demand charges.

Peaking charges are most likely to affect transit authorities using on-route charging. As power rates are generally higher during the daytime and lower at night, a depot full of vehicles charging during the midnight hours will be drawing inexpensive power. However, a bus recharging at an outlying layover location before the evening rush hour, which is the usual time for peak power demand, will likely cost significantly more to recharge. Some authorities use a power management system at the depot, to optimize charging times for cost minimization.

For utility concerns, transit authorities are encouraged to collaborate with utilities at an early stage, as well as develop a charging management system to combat the risk of high charging rate structures.

3.2 Hydrogen Fuel Cell Vehicle Resources

Hydrogen fuel cell vehicles are less common in the US transit market; only two major vendors offer transit models today. Due to the small market, there are limited selections for vehicle sizing. Furthermore, there are only a few manufacturers of hydrogen fuel cells. This limits the ability of the supply chain to support the growing demand for these vehicles. Additionally, an increase in demand for precious metals used in fuel cells and electrolyzers is expected which could further strain the supply chain. Hydrogen fuel cell vehicles also include battery systems which are subject to the same supply chain constraints as were discussed in the previous subsection.

Unlike electricity, the availability of hydrogen is comparatively limited. Currently, hydrogen has a small number of commercial applications, such as fertilizer production, fossil fuel processing, and food refinement. These applications generally draw their hydrogen from dedicated sources that are located close to the point of use.

Transit authorities transitioning to hydrogen technology are typically located either in geographic regions where hydrogen facilities are in close proximity or where on-site hydrogen production facilities are feasible. A transit authority must operate a large fleet of vehicles to make the investment in on-site fueling infrastructure cost competitive with battery electric charging infrastructure. Even if fueling stations are commissioned, hydrogen generation and distribution facilities are likely to remain scarce, posing financial obstacles to widespread adoption of fuel cell vehicles. Identification of a reliable, nearby source of hydrogen would be necessary for authorities hoping for successful operation of FCEBs because of the high costs associated with transporting hydrogen over long distances.

4. ZEV Charging Infrastructure and Energy Storage Technology Options

The primary challenge with zero-emissions vehicle operation is successfully and economically sourcing energy at wayside locations and transferring it to the vehicle when required. Unlike fossil fuel vehicles for which large-scale distribution and storage systems are commonplace, both battery-electric and hydrogen fuel cell vehicles require delivery and storage methods with which transit authorities are unfamiliar. Proper energy management can have significant impacts on zero-emissions vehicle deployment feasibility.

4.1 Battery Electric Infrastructure

A major impediment to electric vehicle adoption is the considerable infrastructure modification required for vehicle operation. Electric vehicles require chargers as well as utility, facility, and management system upgrades for transit authorities to operate them. Further complicating these modifications is the range of available equipment and deployment strategies that authorities have implemented. The following subsections provide an overview of infrastructure modifications that are typically required to deploy battery electric vehicles, and the solutions that can be considered to meet those requirements.

4.1.1 Conductive vs. Inductive Charging

Battery-electric vehicles can either be charged via conduction or induction, as shown in FIGURE 2. Conductive charging is more common and involves a physical connection from the bus to the charger, either via a cable (similar to a plug-in car) or via a roof-top pantograph (similar to trolleybuses and streetcars). Inductive charging requires the bus to be stopped over a specially equipped section of road, which generates magnetic fields that are picked up by a receiver on the underside of the bus.

FIGURE 2-CONDUCTIVE (LEFT) AND INDUCTIVE (RIGHT) CHARGING. SOURCES: MTA AND MOMENTUM DYNAMICS

Each technology has its respective advantages and disadvantages. Conductive charging is a well-established, widespread technology, and the presence of a conductor provides maximum charging efficiency. The standards for conductive charging are very well established at this point. The SAE J1772 CCS Combo standard is a universally accepted standard by vehicle OEMs (for both consumer grade and heavy-duty vehicles) as well as charging equipment manufacturers. Similarly, J3105 (also sometimes known as OppCharge) is the widely adopted standard for overhead charging by all major commercial vehicle and charger OEMs. This technology is likely to continue enjoying widespread vendor support for the foreseeable future. However, conductors require plugging/unplugging (for corded chargers) or raising and lowering of the pantograph (for overhead chargers). This poses some risk for authority staff because of the exposed high-voltage conductors, and may increase maintenance requirements because of the number of moving parts and contact surfaces. In addition, conductive charging equipment presents spatial constraints. If plug-in chargers are used, then the charging stands will take up space. The exact amount will depend on the geometry of the depot and chargers, but an estimate between 5% (for ceiling-mounted chargers) and 25% (for ground-mounted ones) can be expected. Pantograph-type chargers, when mounted to a depot roof, do not require additional space, as all the hardware is located overhead, but this may require structural upgrades to the depot which can be costly. Finally, in cold climate the influence of snow and ice must be considered. Outdoor conductive chargers will require heaters and other mitigation measures for the chargers to function reliably in snowy and icy weather.

Inductive charging, on the other hand, has no moving parts and no exposed conductors. This makes the charging process less vulnerable to damage of surfaces, snow/ice, and other contaminants. The convenience, however, presents a tradeoff with several drawbacks. First, inductive charging standards are still in the early stages of development. A universal standard (SAE J2954) was published in 2021, which only allows charging speeds of up to 11 kW. Faster wireless chargers (up to 500 kW) are available in the market based on proprietary technologies. There are two major manufacturers in the US that offers inductive charging solutions for commercial vehicles like transit vehicles. Both manufacturers require the vehicles to be outfitted with their respective proprietary receiver hardware on the vehicles along with the installation of the proprietary inductive chargers in the ground. This puts the fleet operator at risk of being locked with a vendor. The fleet operator might also find themselves with stranded assets if technical support, or the technology itself, are discontinued by the OEM. The SAE J2954 standard will very likely get updated to accommodate faster charging speeds in future iterations. However, it will take a very long time before OEMs start offering any solutions based on open standards. In addition, the added hardware also adds more weight to already heavy battery electric vehicles. Finally, inductive charging generates much more heat than conductive charging does, which decreases efficiency and requires active cooling of the bus's receiver during charging.

4.1.2 Fast vs. Slow Charging

Vehicle chargers are also available in two general groups of power levels, which broadly correspond to the two primary operating modes electric vehicles typically experience. "Slow" chargers, with power levels of approximately 50-120 kW, are most suited to overnight charging in the depot. As each slow charger takes two to eight hours to fully charge a vehicle, each one can usually only practically accommodate one bus during an overnight period. Therefore, the number of chargers must be approximately equal to the peak fleet requirement. This increases cost (and required depot space) compared to the fast charger option. Slow chargers are typically a standardized plug-in conductive format that is compatible between bus manufacturers.

"Fast" charging, at a level of approximately 450 kW, can usually fully recharge a vehicle in one to two hours. More commonly, however, fast chargers are used for on-route charging, to partially recharge batteries during layovers. Authorities can typically expect to add an additional mile of operating range for every minute a vehicle spends on an on-route fast charger. This strategy can also be used to minimize the number of chargers required in the depot. These chargers are typically pole mounted pantographs that come down to make contact with conductive strips on the top of the bus for charging. These pantograph style chargers are not typically compatible with the smaller style transit vehicles that make up the majority of CCRTA's fleet. Fast charging inductive and plug-in conductive chargers are now available, and could potentially be used to charge smaller vehicles on-route. One of the downsides of fast charging is that it is generally considered to reduce the lifespan of the battery. Another downside, when used for depot charging, is that vehicles must be moved on and off the chargers more frequently throughout the night. This increases operating cost. Finally, a Department of Energy study found the capital cost of fast charger purchase and installation to be approximately $700,000, compared with $70,000 for slow chargers. Figure 3 provides visual examples of slow and fast chargers.

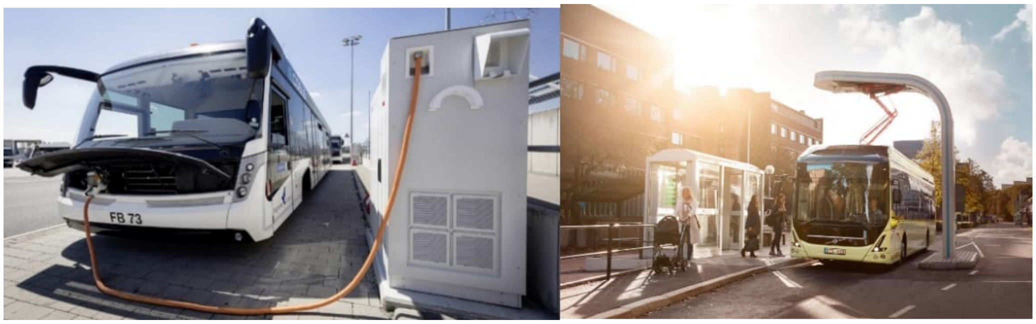

FIGURE 3 - PLUG IN SLOW CHARGER

(LEFT, SOURCE: SIEMENS) VS. PANTOGRAPH FAST CHARGER (RIGHT, SOURCE: OPPCHARGE)

One option to remove the charging time constraint altogether is to institute battery swapping. As the name suggests, this involves removing a drained battery from the bus and replacing it with a fresh, fully charged one. The vehicle can then resume its duties while the drained battery is gradually recharged. Although this technology has found applications in China, most electric vehicles in the US are designed with batteries in several tightly integrated parts that cannot be quickly removed from the vehicle. Therefore, battery swapping has not been instituted by any US transit authorities (or, for similar reasons, seen significant success in the consumer EV market) and is unlikely to gain significant adoption in the near future.

4.1.3 Centralized vs. De-Centralized Chargers

DC fast chargers typically come in two types of configurations: Centralized or De-centralized. A de-centralized charger is a self-contained unit that allows for the charging of one vehicle per charger. The charging dispenser is typically built into the charging cabinet. In contrast, in a centralized configuration, a single high-power charger can charge multiple vehicles through separate dispensers. The power is assigned to the dispensers dynamically based on the number of vehicles that are charging at the same time. The high-powered pantograph chargers are typically paired one-to-one with centralized charging cabinets to provide high speed charging. Examples of both configurations are shown in Figure 4.

FIGURE 4 – EXAMPLE CHARGING SYSTEMS (SOURCE: ABB)

LEFT – CHARGING CABINET (SYSTEM) AND THREE DISPENSERS (CHARGE BOXES)

RIGHT – OVERHEAD PANTOGRAPH CHARGER AND DE-CENTRALIZED CABINETS

4.1.4 Facility Modifications

Nearly any fleet conversion to electric vehicles will involve depot retrofits. In the congested environment of a legacy transit depot, this can be expensive. The primary required modifications are structural (charger locations and foundations, equipment relocation, and support structures), electrical (resiliency, switchgears, and cabling), and fire safety. Like the other factors that must be considered when transitioning to electric vehicles, many alternatives associated with depot design can have trade-offs that should be carefully considered.

As discussed previously, electric vehicles introduce several factors that may require additional space in the depot. Ground-mounted plug-in chargers, for example, will require additional space for the chargers themselves. Roof-mounted chargers, of either the plug-in or pantograph type, may require structural upgrades which can include additional columns impeding bus circulation. These structural upgrades can be significant, depending on the number of chargers and location of the power conversion units: the roof-mounted pantograph type weighs approximately 400 lb and the charging device itself weighs between 800 and 3,000 lb, depending on power level. The additional fire protection measures that electric vehicles typically warrant may also require additional space.

As part of structural and spatial analyses, decisions must be made as to whether chargers will be placed indoors or outdoors. Each approach has advantages and disadvantages. The primary advantage of indoor charging is isolation from the weather. Chargers perform best in a warm, dry place, such as the interior of a bus depot. The disadvantages of indoor charging primarily relate to the fixed infrastructure around which the chargers must be installed. Foundations, electrical conduits, and structural supports are typically more expensive to install in an existing indoor environment. In addition, an enclosed space such as a depot presents an increased fire hazard. Although the chance of a given battery catching fire while charging is very low, battery fires are notoriously difficult to put out once they ignite, and the potential for a chain-reaction (with one battery overheating, igniting, and causing other nearby batteries to overheat as well) presents a potential danger that must be mitigated.

Causes of, and mitigations for, this thermal runaway risk are still being researched. Some known risk factors are battery damage through mishandling, impacts such as crashes, and improper vibration isolation. The industry is also expanding its knowledge of battery fire warning signs, such as battery swelling, unusually high temperature, or overvoltage. Modern electric vehicles are equipped with sophisticated battery monitoring systems to keep track of key parameters that may indicate an impending thermal runaway event. This remains an area of active research, as fires still do sometimes occur. Recently, 25 buses caught fire at a bus depot in Germany, burning the entire bus depot to the ground, as shown in Figure 5.

Figure 5 – Electric Bus Fire in Stuttgart, Germany (Source: Sustainable Bus)

Late last year in Philadelphia, Pennsylvania, a battery power pack in a sidelined battery electric bus ignited at one of SEPTA's bus depots as shown in Figure 6; fire crews battled the blaze for hours. A similar event occurred in Connecticut with a CTDOT electric bus catching fire. Evidently, fire suppression and other safety systems are a critical element of electric bus infrastructure modifications. A detailed and comprehensive insurance policy is also paramount.

Figure 6 – Electric bus fire at bus depot in Philadelphia, PA

Cape Cod's humid climate and severe winters present a disadvantage for outdoor charging. Rain, snow, and ice can accelerate deterioration of charger components and present hazardous conditions for maintainers while recharging vehicles. Cold temperatures can also decrease battery capacity, and the energy spent on bringing the battery compartment and interior to an operating temperature at the beginning of the service day can reduce a vehicle's range. Although "pre-conditioning" (running the climate control system shortly before departure, while the vehicle is still connected to the charger) before departing the charger can mitigate this problem, allowing time for this to happen immediately prior to vehicle departure poses operational constraints.

From an electrical perspective, depot design is primarily influenced by resiliency and equipment requirements. With traditional fossil-fuel based operation, transit authorities were always reliant on external fuel suppliers to provide all energy for operations. With the conversion to electric power, this is no longer a given. Each transit authority can install solar panels or other local means of generation and storage to provide its own power supply. Even if this is impractical to supply the authority's full energy needs, a limited source of local generation or storage is still recommended to ensure continued operation during a grid disruption. This storage can also be used to reduce the authority's electricity costs by allowing "peak shaving" – recharging from low-cost power at night and feeding power back to the grid during daytime peak demand.

Other electrical modifications typically required at depots include transformer, switchgear and cabling improvements. Switchgears control, protect and isolate the power systems within a depot. Switchgears currently installed at depots which operate diesel vehicles are almost always undersized to handle the increased power demands of an electric bus operation. Therefore, careful analysis must be conducted to appropriately design and size a replacement switchgear. Transformers are designed to transfer energy between circuits at a bus depot, but often either need to be replaced or reconfigured for electric bus operations. Finally, cabling and conduit must be run throughout the depot area to power the required chargers. If an authority plans to transition to electric vehicles over a period of time, cabling and conduit should be laid out and run at one time to reduce recurring costs.

4.2 Hydrogen Infrastructure

Authorities considering hydrogen fuel cell vehicles have an infrastructure choice: produce hydrogen on-site, or have the fuel delivered to an on-site fueling station. Several transit authorities such as Sun Line Transit and Flint MTA have elected to build on-site hydrogen generation infrastructure to support their hydrogen bus operations. Most of these agencies have selected electrolysis, which converts water into hydrogen fuel, as the technology to produce hydrogen, as it has zero direct emissions. Once the production infrastructure is installed, hydrogen can be generated for as long as electricity and water are available. However, there is a high cost and electrical energy requirement for on-site.

If hydrogen is not produced on-site, it must be transported to a fueling station from a remote production location. Because there are no hydrogen fueling stations in CCRTA's operating territory, this would require the Authority building hydrogen fueling infrastructure to store the fuel. Trucking is the most practical way to transport hydrogen to such a fueling station. If the hydrogen is transported in its gaseous state, it is generally compressed to 180 bar or higher, put in long cylinders, and placed on a flatbed (referred to as a tube trailer). The downside of this approach is that, even at high pressure, hydrogen has very low density. Therefore, large trucks and/or more frequent deliveries are required. Another option is to transport liquid hydrogen in heavily insulated, cryogenic tanker trucks. This is usually more economical than trucking gaseous hydrogen for long distance deliveries because liquid tankers can hold more hydrogen than tube trailers. Authorities can usually work with fuel suppliers to determine the frequency and volume of hydrogen delivery to match fuel cell fleet requirements.

Hydrogen storage is difficult due to its low volumetric energy density and its low boiling point. Currently there are two ways to store hydrogen: as a pressurized gas or as a liquid. Gaseous storage is perhaps the simplest because hydrogen is naturally a gas at room temperature. However, because of hydrogen's very low density, pressurization is used to keep storage tank sizes reasonable. Typical storage tanks use a pressure of 5,000-10,000 pounds per square inch (psi), which requires specialized tanks, pumping procedures, and safety regulations. Liquid storage avoids these challenges, but instead requires extensive cooling to keep the hydrogen below its boiling point (negative 423 degrees Fahrenheit). This cooling is highly energy intensive, reducing storage efficiency. However, because of the smaller tank size required compared to gaseous storage, liquid storage is the most common option available today, with multiple installations across the United States.

4.2.1 Hydrogen Dispensing

A fuel cell requires hydrogen in its gaseous form. To minimize onboard processing, it is also stored as a gas on the vehicles, pressurized to approximately 350 bar. So, unlike fossil fuels, hydrogen is dispensed from the fueling station in gaseous form. This introduces thermodynamic issues because, like all other gases, hydrogen expands as its temperature increases. The process of dispensing hydrogen into vehicles can cause its temperature to rise. If this problem is not mitigated, "false fills" – where the tank is filled with warmer gas that will then cool and condense (making the tank no longer full) – are likely. To avoid this issue, chillers are typically installed to cool the hydrogen before it is dispensed. This ensures that tank level is always measured at the correct hydrogen temperature.

As discussed in the previous section, hydrogen is typically delivered and stored in liquid form at the dispensing site. As a result, it needs to go through a liquid to gas conversion process, using a vaporizer, before it can be dispensed. FIGURE 7 below illustrates the process for dispensing the liquid stored hydrogen.

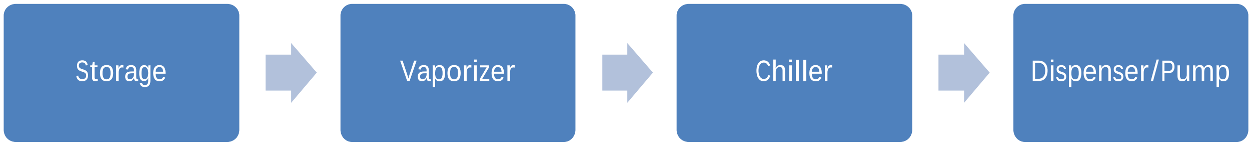

FIGURE 7 - HYDROGEN DISPENSING PROCESS FLOW DIAGRAM

4.2.2 Grey, Blue and Green Hydrogen

Hydrogen atoms naturally do not exist on their own – they are usually connected to oxygen and carbon atoms in chemical compounds such as water or methane. Energy is required to isolate the hydrogen atoms from these chemical compounds to produce pure hydrogen fuel. Depending on the way hydrogen atoms are separated from their original chemical compounds, the hydrogen is deemed either grey, blue, or green hydrogen, as further described in Figure 8.

Production of grey hydrogen involves the combustion of fossil fuels such as natural gas. Inevitably, this process produces significant carbon dioxide. Because of its simplicity and low cost, grey hydrogen production holds a dominant market share of nearly 95% of hydrogen gas produced. The disadvantage of this approach is the production of greenhouse gases, which diminishes the climate-positive impact of the hydrogen's intended use.

Blue hydrogen is like grey – it is also produced from non-renewable resources. However, with blue hydrogen, the carbon dioxide created during hydrogen generation is captured and stored, preventing most carbon emission. This process generally captures about 90% of emitted carbon dioxide. However, the challenges associated with the capture and storage process increase the cost of blue hydrogen significantly.

From a climate perspective, green hydrogen is ideal. It is usually produced using electrolysis, which requires large amounts of electricity and water as inputs and generates no greenhouse gases. However, the climate impact of green hydrogen production is heavily dependent on the grid's source of electrical power. If the electricity is provided by renewable sources such as wind turbines or solar panels, the production process can be truly considered zero-emissions. On the other hand, if non-renewable energy resources are used to power the electrolyzer, then even green hydrogen will have a carbon footprint.

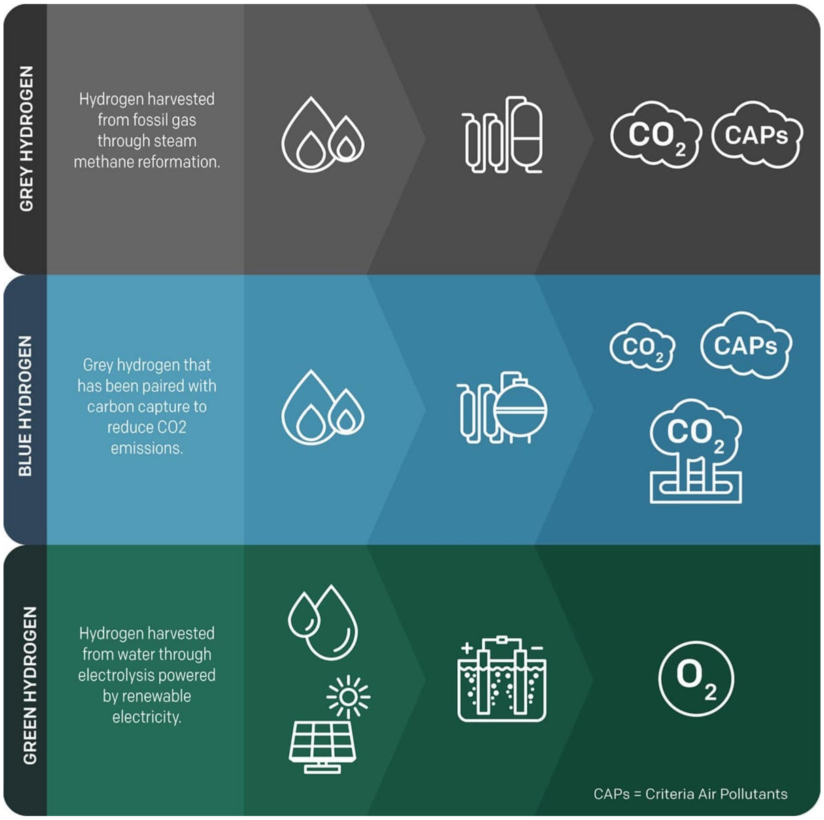

FIGURE 8 – HYDROGEN CLASSIFICATION BASED ON HYDROGEN ATOM ISOLATION METHODOLOGY

4.2.3 Mobile Fueling Stations

Hydrogen fueling stations – the infrastructure used to fill fuel cell vehicles with hydrogen – are available at a range of scales. Full-scale fueling stations involve significant construction and maintenance costs for the tanks, pumps, pressurizers, chillers, safety items, and other equipment. For small fleets, or conducting pilot studies, the construction cost of each of these elements may be prohibitive. One option to mitigate this cost is to use a mobile fueling station, which contains all the required equipment in a container approximately the same size as a truck trailer. Although the capacity of such a station is limited, and the operating cost higher than for a static station, the reduction in installation cost makes this a viable approach for authorities with few fuel-cell vehicles. Transit authorities such as Hawaii Mass Transit have elected to use mobile fueling stations to help experiment with the technology before building permanent fueling stations.

4.2.4 Facility Modifications

Hydrogen is a highly flammable gas that is hard to detect without special devices since it is invisible and odorless. It is also lighter than the air and in the event of a leak naturally rises and accumulates near the ceiling. These properties, which starkly contrast with other common propulsion fuels like diesel or gasoline, require special considerations for facilities where hydrogen fueled vehicles are parked, maintained, or otherwise stored for longer periods of time.

Proper ventilation is required to ensure that hydrogen gas does not accumulate in an enclosed facility in the event of a leak or accidental discharge. An active ventilation system, capable of six air changes per hour, is typically required to ensure that the hydrogen-air concentration does not exceed the flammable limit. The system should be designed to prevent recirculation of air inside the building under any circumstance. Additional exhaust fans might be required near the ceiling to ensure that any leaked gas that rises to the ceiling is properly exhausted. Finally, hydrogen sensing alarms that detect when a leak has occurred are required. The Hydrogen Technologies Code (NFPA 2) outlines specific ventilation requirements.

In addition to ensuring that flammable concentrations do not build up in a facility, it is of equal importance and required by code that any ignition sources are eliminated from the building. A typical transit maintenance facility contains various devices and equipment that could be a potential ignition source for hydrogen, including open flame heaters, exposed electrical wiring, and open light fixtures to name a few. NFPA 2 requires that all surfaces inside the facility stay below a threshold of 750 °F, providing a safety margin under hydrogen's 1,000 °F ignition temperature. Hence, for a facility to be safe for hydrogen fuel cell vehicles, all equipment must be replaced with alternatives that meet the surface temperature requirement and do not have a potential source of ignition (like sparking). Moreover, the building itself may require modification to allow for the energy of any potential ignition event to dissipate without compromising the building's structural integrity. This typically involves modification such as installing explosion relief panels on the building walls.

The following list of relevant codes and standards need to be considered for a facility where hydrogen fuel cell vehicles are parked and/or maintained:

- NFPA 2: Hydrogen Technologies Code
- NFPA 30A: Code for Motor Fuel Dispensing Facilities and Repair Garages
- NFPA 70: National Electric Code (NEC)
- NFPA 72: National Fire Alarm and Signaling Code
- NFPA 88A: Standard for Parking Structures
- NFPA 55: handling flammable gases
- International Building Code

5. ZEV Operational Considerations

Transit authorities provide key social services to residents in their region. A common mission is to provide reliable service, during adverse weather, power outages, and other difficult conditions. A transition to zero-emissions vehicles poses risks to the authority's operational robustness, due to both the increased reliance on electrical power and the uncertainty associated with comparatively new technology. These risks must be understood and mitigated to ensure reliable operation with the proposed vehicles.

5.1 Battery Electric

A major challenge for battery electric vehicle implementation is related to operations. Specifically, the operating range and required time to charge the vehicles can present significant operational restrictions. While electric vehicle manufacturers have advertised driving ranges of over 300 miles, these ranges have not been achievable by the authorities that have begun operating these vehicles. For example, Minneapolis Metro Transit found that in the winter the range of its vehicles was reduced to as low as 60 miles on a single charge. This constraint will likely ease over time as battery technology continues to progress, so a range limitation today will not necessarily constrain electric bus operations a decade from now.

In addition to range restrictions, the range can also vary depending on factors such as weather, speed, operator driving style, road gradient, and battery size. NYC Transit, for example, found their range to be between 50 and 120 miles depending on operating conditions, which is insufficient to operate on approximately one third of the authority's routes. This type of variability introduces uncertainty and risk into authority operations. However, conducting a prototype operation gives transit authorities a better understanding of their bespoke constraints and operating practices, helping narrow down this wide range to a more practical value. In addition, further developments in battery technology should help decrease this variability.

Charge time is the other major operational restriction for transit authorities associated with a transition to battery electric vehicles. As previously mentioned fully charging a transit bus can take as long as eight hours depending on the charger type being used and the battery capacity of the vehicle. In all instances, however, the charge time is significantly longer than the time required to fuel a diesel or hybrid bus, which alters operational flexibility.

As a result, the infrastructure changes explained in the previous sections should be designed to mitigate operational restrictions. Best practice established by the authorities who have begun their transition to electric vehicles is to conduct an operational simulation and optimization as part of a transition plan. These simulations should be conducted specific to each authority to accurately determine the effects that battery electric vehicles will have on operations, and to optimize vehicle and infrastructure design to support those operations. Specifically, route characteristics, weather, vehicle battery sizing, charger placement, and charge management need to be considered as part of the optimization effort. The following subsections provide an overview of best practices for conducting simulations and optimization studies and key operational considerations that must be considered.

5.1.1 Vehicle Performance

The most important operational details to be considered is vehicle performance which is determined by the route characteristics, specifically speed profiles and route topography. The necessary energy to complete a route is strongly dependent on the speed profile of the vehicle as it travels the route, known as the drive cycle. Identifying potential stopping locations and the speed limits on the bus route is necessary but insufficient for generating the drive cycle. Acceleration and deceleration must be determined from a database of similar real-world data to account for traffic conditions, driver behavior, traffic lights, etc. Other factors, such as road gradients, curvature, and weather-related adhesion must also be considered.

An example of the importance of simulating route characteristics was demonstrated during a recent study by NYC Transit on its B82 route. The study found that, although the route was only ten miles long, and therefore well within the range of electric vehicles, vehicles spend less than 50% of route time in motion. With 21% of time spent dwelling at stops and 29% of time spent waiting at traffic signals, an electric bus would spend significantly more energy on HVAC than an optimistic range estimate from the vendor may assume.

5.1.2 Seasonal Operations

The next major operational consideration that must be simulated relates to weather conditions, as high and low temperatures pose particular challenges for electric vehicles. Battery capacity decreases if the temperature is outside the battery's optimal range of approximately 59-86°F (15-30°C); in addition, the energy needed to climate control the interior of the bus imposes an additional energy draw on the battery. An example of actual vehicle efficiency variation based on temperature that was measured at four separate transit authorities is provided in Figure 9. Battery compartment temperature is typically controlled using a dedicated electric heater (or cooling system), which draws a small amount of energy. Using electric heating for the vehicle interior, however, is often impractical due to the major energy demand to condition the large volume. Duluth Transit, for example, has found that electric-only heating of the interior caused as much as a 60% reduction in range. To mitigate this issue many electric vehicles are equipped with stand-alone diesel heaters to avoid spending battery capacity on heating. Although this does introduce some emissions to an otherwise zero-emissions bus, the heater is much smaller and operates much less often than a propulsion engine, so emissions are minimal. However, even with these mitigations, winter weather may require a larger fleet size than the remainder of the year. These factors should be considered as part of the operational simulation and optimization effort.

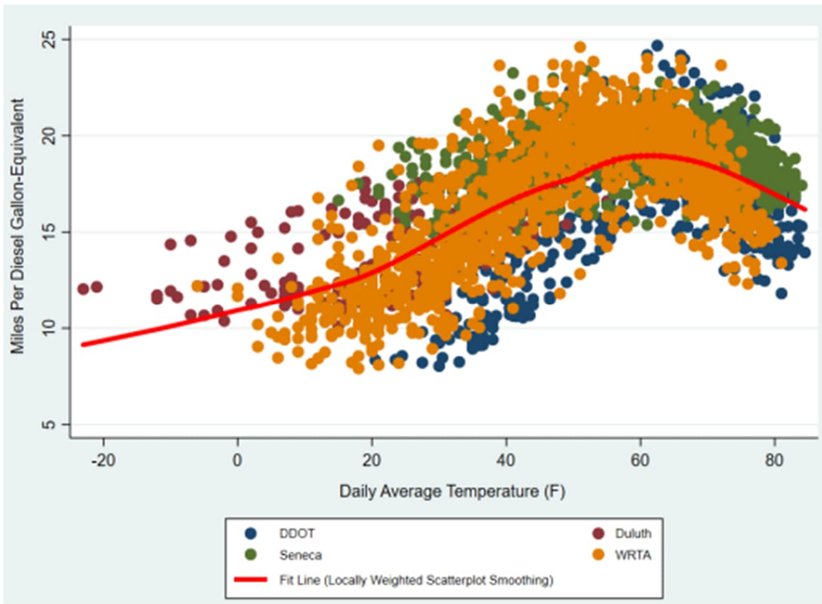

FIGURE 9 – THE RELATIONSHIP OF TEMPERATURE AND BUS EFFICIENCY (SOURCE: URBAN PUBLICATIONS)

5.1.3 On-route versus Depot Charging

As explained previously in the infrastructure section of this report, there are two different strategies for charging electric vehicles: depot charging and on-route charging, each with its respective pros and cons. During operational simulation these pros and cons can be considered in a trade-off analysis to optimize charging configuration.

Depot charging is typically easier and cheaper to deploy as the authority can avoid the land acquisition, utility connection, construction, and ongoing maintenance costs of chargers placed “in the field.” In addition, the maintenance and repair of chargers is easier as it is consolidated at the depot, and the presence of multiple chargers at the depot provides redundancy. However, restricting charging to only being performed at depots when vehicles are out of service poses a significant constraint on the length of the blocks that can be operated, as a bus’s batteries must have enough capacity to power it for the entire day, which is rarely possible with present technology. Instead, many authorities have found that some blocks / routes need reconfiguration or rescheduling to fall within the range of the vehicles. For example, one of Hatch’s previous clients, Portland Metro in Maine, found that electric vehicles could not operate the majority of its blocks for a full day, and that the blocks would need to be revised to allow conversion to electric vehicles.

Energy requirement analyses might find that some blocks can be operated by an electric bus throughout the service day, but others are too long for the range of the vehicles. This means that the authority must either install on-route chargers at layover locations, increase the number of blocks (and therefore fleet size) to accommodate reduced range, or maintain a backup of diesel/hybrid vehicles for the longer blocks until electric bus technology advances. On-route chargers allow opportunity charging during each layover, extending bus range during time already spent out of service. This can be used to create the “saw tooth” opportunity charging paradigm shown in Figure 10. This type of charging strategy can decrease fleet requirement and extend battery life, as batteries operate best with smaller fluctuations in charge level.

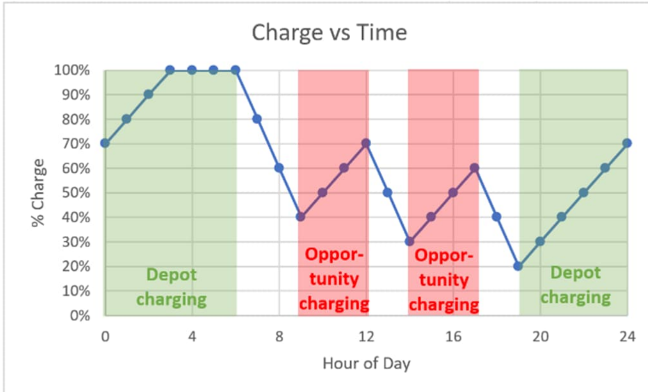

FIGURE 10 - ON-ROUTE CHARGING "SAW TOOTH " STATE OF CHARGE CURVE

There are additional costs and operating constraints associated with on-route chargers compared with depot charging, however. Some authorities with consistent road traffic volumes schedule fairly minimal layovers, which would leave insufficient time for charging. At each distinct location, land must be acquired, a utility connection must be built, and the infrastructure must be maintained. As on-route chargers must be fast chargers to be practical, they come at a significant cost premium (as discussed below). Once constructed, the on-route charger is likely to pose a significant constraint on any future route changes, as relocating or abandoning it is expensive. Finally, for terminals with only one charger, a backup procedure must be developed to ensure continued route operation in case of a charger breakdown. A central hub terminal with multiple chargers would help mitigate this single point of failure, assuming sufficient layover time is available.

Whether located at bus depots or on-route, charging infrastructure should be placed on curbs and protected by bollards, fencing, and other physical barriers to protect against vandalism. Vehicle Charging/fueling locations should be clearly marked via signage and paint. Some transit authorities have used options like grooved pavement, allowing the vehicle operator to correctly orient the vehicle in the charging area. Because on-route charging locations are determined based off simulation modeling, infrastructure design takes into account spatial constraints and operational restrictions such as passenger boarding/alighting, and bus circulation. Proper signage and preparation of charging locations are designed similar to that of fueling infrastructure locations. Dedicated lanes may be determined to negate standard operation interruption. The addition of caution lights may be programmed into the vehicle's charging process to alert personnel and bystanders of charging status.

5.1.4 Depot and Dispatch Management

Another aspect of operations that should be simulated and optimized is depot movement and dispatching. With diesel and hybrid vehicles, each bus can be refueled quickly in the depot and can thereafter be sent out for a full day's service. For electric vehicles, particularly ones that are charged slowly, this is more complex, as the operating pattern of each bus must be carefully balanced against the charge level of its battery. This complicates operations of unplanned services, cover for broken-down vehicles, and other unusual operations.

Translink in Vancouver, BC, for example, sometimes uses its regular bus fleet to provide replacement service during outages of the Skytrain rail system. As part of its fleet transition plan, the authority noted that the electric vehicles would not be able to fulfill the duty cycle currently required for Skytrain replacement service. The operating plan would therefore need to be reconfigured around available charging capacity, likely increasing the fleet requirement for these operations. The route operated would also need to be changed, as there is unlikely to be a charger in the right location, with sufficient availability between its scheduled routes, to accommodate high-volume bus flows from a rail replacement service. Although rail replacement service is less common on Cape Cod, other types of special event and contingency service must still be considered as part of the simulation efforts.

Schedule recovery is another factor that must be considered, particularly when using on-route chargers. A given length of layover time can be used to allow late vehicles to get back on schedule, or it can be used for recharging the bus's batteries, but not both. Although fast chargers can be used to maintain a satisfactory charge level using 15-20 minute opportunity charges at each terminal, this may extend the duration of some blocks just enough that another bus must be added to the route to maintain schedule. Bus bunching can also cause problems for routes with on-route chargers, because two vehicles arriving at a terminal at once will not be able to use the same charger. Therefore, on-time performance should be evaluated as part of the simulation to carefully plan around these issues.

5.1.5 Vehicle Battery Sizing

All the aforementioned operational considerations can be used to inform vehicle battery sizing. As previously discussed, commercially available vehicles are available with a range of battery capacities. Following the operational analysis, authorities can select battery sizing for future procurements having confidence that the sizing selected will support its operations. While it may seem logical to always purchase vehicles with the maximum battery capacity, these types of vehicles come with drawbacks. First and most importantly, batteries are one of the most expensive subcomponents of battery electric vehicles, and the largest battery sets come with high upfront, overhaul, and maintenance costs. Furthermore, large battery sets add significant weight to a bus. Battery electric vehicles are far heavier than diesel and gasoline vehicles due to batteries having a lower energy density than fossil fuels. The increased weight of batteries can result in civil penalties for damage to roadways, or even necessitate the upgrade of infrastructure such as bridges and in-depot maintenance lifts. Therefore, analysis should be done to optimize the battery sizing of the authority's bus fleet to ensure that excess capacity is not being procured.

5.1.6 Costs

Aside from operational and infrastructure impacts the last major obstacle to widespread adoption of electric vehicles is cost. Lifecycle costs associated with a transition to electric vehicles can primarily be grouped into four categories: infrastructure, vehicles, operating costs, and batteries. Upgrades such as depot fire safety, utility connection modifications, and land acquisition for on-route chargers have significant start-up and project oversight costs which are largely constant regardless of the number of electric vehicles in service. Some infrastructure elements – such as the number of chargers and specific size of the utility feeder ducts – are of course dependent on the number of vehicles, but this cost is relatively small compared to the fixed cost described above. This means that an authority looking to convert to electric vehicles will likely benefit from converting as large a portion of the fleet as possible, to take maximum advantage of the spending on fixed costs. It also means that potentially sharing depots or chargers with other nearby operators of vehicles (school buses, light duty vehicles, ferries, etc.) can offer great benefit. Therefore, the previously described operational analysis and a joint planning effort is required to project the costs that transit authorities should expect to incur as part of their transition.

Vehicle costs are the next major cost consideration for authorities to consider, but fortunately are much easier to project. The average cost of an electric transit bus ranges between $650,000 and $1,250,000 per bus. These costs are highly variable depending on the specific technologies and configurations selected, but in all cases are higher than the typical $500,000 purchase price for a diesel bus. One of the primary factors currently affecting the cost per vehicle for battery electric vehicles is the small order sizes being placed. As previously mentioned, most battery bus orders are for five vehicles or less. These small orders disrupt production flow within bus manufacturing operations, and do not allow bus vendors to purchase materials in bulk, driving up costs. To overcome these issues many operators are targeting larger order sizes.

LA DOT placed the largest US order ever for battery electric vehicles (130 vehicles) which resulted in a roughly $100,000 lower purchase cost per bus than their previous smaller orders. In Europe operators have formed "cluster procurements" where multiple authorities create joint procurements to buy zero emissions vehicles in bulk. This strategy has been successful in reducing the initial capital costs of the vehicles and could be deployed if a group of authorities partner together on electric bus purchases.

Operating costs are the next financial consideration for transit authorities looking to transition to electric vehicles. Reduction in operating costs are typically cited as an offset for the high upfront capital costs associated for vehicles and infrastructure. Bus manufacturers, for example, estimate annual cost savings in fuel and maintenance to range between $40,000 and $50,000 per year. While results have varied between authorities, some have begun to experience these benefits. For example, the transit authority in Seneca, South Carolina noted a decrease in fuel costs from 59¢ per mile for diesel to 28¢ of electricity costs per mile, and a decrease in maintenance cost from $1.53 to $0.55 per mile, after full conversion to electric vehicles.

The last cost consideration relates to batteries. The batteries are a critical, expensive, and comparatively short-lived component of an electric bus. Therefore, management of the battery as a standalone item, rather than an integral component of the bus, is warranted. A bus battery is generally estimated to last between six and eight years before its capacity becomes insufficient to stay in operation. As the lifetime of a typical transit bus is between twelve and fifteen years, a battery replacement at bus midlife is considered good operating practice. Depending on the battery capacity of the bus, these types of overhauls can cost hundreds of thousands of dollars.

To help mitigate this cost, battery leasing programs are available, where according to the manufacturers the up-front cost of the bus is similar to that of a diesel and recurring payments for the battery are made out of money that would otherwise have been spent on fuel and additional maintenance. Such programs may also allow the transit authority to avoid battery replacement costs at midlife, as the battery vendor guarantees performance for the full 12-year lifespan of the bus. Vendors have advertised a net savings of approximately 10% compared with the operating cost of a standard diesel bus using these leasing programs, but the specific terms and application should be carefully reviewed by each authority.

5.2 Hydrogen Fuel Cell

Operational challenges relating to hydrogen fuel cell vehicle transitions are less understood than those of battery electric vehicles. This is due in part to the limited US hydrogen fuel cell vehicle operators in the United States compared to battery electric vehicle operators and the associated monitoring data collected. However, since 2000, the National Renewable Energy Laboratory (NREL) has studied and evaluated hydrogen fuel cell transit bus performance, collecting data on fuel cell electric bus (FCEB) performance and costs. Similarly, Alameda-Contra Costa Transit District (AC Transit), US leaders in the zero emissions vehicle arena, conducted and published results of a zero emission transit bus technology analysis. This report concluded a two-year study analyzing five different bus technologies operated by the Authority. Five different technologies were compared, including two fuel cell electric systems, battery electric vehicles, diesel hybrid vehicles, and conventional diesel bus technologies. The data collected from these efforts provide key insights into hydrogen fuel cell vehicle operation for future ZEV transitions.

5.2.1 Vehicle Performance

Recent, small-scale studies show that vehicle service availability for hydrogen fuel cell technology is comparable to other zero emissions technology like battery electric. Availability issues have shown to be most often related to general bus-related problems with a small percentage related to fuel cell issues involving components in the power plant system; air blowers, compressors, sensors, and plumbing leaks have resulted in downtime for the vehicles. Although hydrogen fuel cell vehicles have demonstrated longer range than battery electric counterparts, some operators have reported range issues because of difficulties completely filling the hydrogen tanks. Vehicles have shown to run low on fuel before finishing scheduled routes because of tank pressure dropping due to hydrogen temperature changes. To avoid sending vehicles out with less fuel than is needed, some authorities top off the fuel tanks in the morning. This adds labor time, is more costly as more fuel is utilized, and overall deoptimizes typical transit operations.

Although the Department of Energy (DOE) set a performance target of four to six years for fuel cell propulsion system durability, fuel cell lifespan is still being researched as new FCEBs in operation have not accumulated enough data to determine actual lifetime. Some research shows that fuel cell lifespans equate to the approximate mid-life of diesel engines.

5.2.2 Seasonal Operations

Like battery electric vehicles, hydrogen fuel cell vehicles can be operationally limited based on seasonal weather patterns. Hydrogen fuel cell vehicles are, however, effected more by high summer temperatures than they are by colder winter climates. This is because fuel cells produce heat as a byproduct of the electrochemical process of using hydrogen to produce electrical energy. This heat can be used to supplement vehicle heating requirements, which helps to improve range in the winter. This also means that diesel heaters are not required to supplement heating in the winter, as is typical for battery electric vehicles. In the summer, however, hydrogen fuel cell vehicles can experience reduced efficiency. This is because the fuel cell can require cooling to perform optimally. Furthermore, the hydrogen gas in the storage tanks can expand allowing for reduced capacity which limits range. Sun Line Transit in California has tracked vehicle efficiency based on temperature and has demonstrated a clear correlation between temperature and reduced vehicle fuel economy, as shown in Figure 11.

Bus	Trip Mileage	Average Temperature	Average Speed	Fuel Economy (mi/kg)	Energy usage-Motor	Energy usage-HV Accessories (A/C)	Energy usage-LV Accessories	Total Regen Energy (kWh)
FC17	51	75.46	22.73	9.45	75%	15%	9%	26.90
FC14	114	77.11	18.45	8.54	72%	16%	12%	73.50
FC17	143	78.91	16.20	6.26	54%	28%	18%	116.60
FC14	148	79.64	18.04	8.68	70%	18%	12%	99.50
FC17	144	80.22	16.31	8.69	66%	21%	13%	96.60
FC17	143	82.90	16.33	8.21	66%	22%	12%	120.40
FC14	143	83.69	16.37	8.18	57%	26%	16%	100.10
FC14	142	84.34	16.51	8.55	62%	23%	15%	107.40
FC17	156	91.24	14.44	7.12	54%	30%	17%	119.00
FC17	156	98.19	14.78	6.06	52%	30%	18%	107.30
FC14	144	98.20	12.70	5.72	45%	34%	21%	101.80
FC17	143	98.58	16.67	4.76	52%	27%	22%	133.20
FC15	85	98.78	20.72	5.84	56%	24%	20%	46.70
FC16	133	99.28	15.65	4.91	49%	29%	22%	102.90
FC16	145	99.62	15.48	5.25	52%	26%	22%	95.10
FC15	138	101.85	14.29	4.56	50%	26%	24%	116.10
FC15	70	101.95	15.57	5.48	47%	30%	23%	48.80
FC17	130	101.96	15.19	4.09	46%	28%	26%	96.00
FC17	143	102.05	16.26	4.45	47%	28%	26%	108.80
FC14	80	102.13	18.25	5.63	52%	26%	21%	61.20
FC17	95	102.78	12.71	4.82	57%	19%	25%	79.60
FC17	129	103.33	12.43	5.06	44%	32%	23%	92.70
FC18	125	103.56	15.76	4.58	57%	28%	25%	98.70
FC15	104	104.34	13.28	5.52	18%	44%	38%	66.10
FC17	126	105.38	15.89	4.57	47%	28%	25%	112.30
FC14	72	109.30	16.40	4.81	44%	27%	29%	59.40

FIGURE 11 – CORRELATION BETWEEN TEMPERATURE AND REDUCED VEHICLE FUEL ECONOMY IN HYDROGEN FUEL CELL VEHICLES

5.2.3 Hydrogen Fueling

As mentioned earlier, hydrogen fueling remains one of the biggest operational challenges for this technology. Hydrogen is often difficult to access and expensive. Authorities have to determine whether constructing a fueling station and having fuel delivered, or constructing an on-site hydrogen production facility makes the most sense for authority needs.

5.2.4 Costs

The expense of this technology remains the largest impediment to hydrogen fuel cell vehicle adoption. Because it is the newest of zero emission technology, the price of hydrogen fuel, and the price of the vehicles are higher than battery electric options. Also, constructing fueling or hydrogen production infrastructure is typically more expensive than installing charging infrastructure. Finally, purchasing hydrogen fuel is more expensive than electricity.

6. Other Factors

Outside of the infrastructure and operational considerations outlined previously in this report, there are several other factors that must be considered by authorities transitioning to zero-emission vehicles. The following subsections provide details on these issues.

6.1 Workforce Training

Although to the passenger they may appear similar to diesel vehicles, zero-emissions vehicles require specialized operating, inspection, and maintenance practices. A critical component of any fleet transition is getting workforce buy-in of the new technology and providing adequate training to expand existing employees' skillsets and recruit new employees.

In the case of electric vehicles, operators should be trained on specialized driving techniques. Acceleration and braking performance differs from that of diesel vehicles, particularly at lower speeds. Driving style is important, particularly to preserve range – electric vehicles are less forgiving of abrupt accelerations and decelerations as this drains the battery faster and decreases the efficiency of regeneration. As mentioned previously, there are also nuances regarding charging and depot operations that must be considered: for instance, pre-heating the interior of the bus before departing the charger at the beginning of the day can save significant energy and extend the range.

The primary changes from a staff perspective are on the maintenance side. Approximately 25% to 40% of maintenance tasks will change with the transition to electric vehicles, and staff will need to be given training for the new procedures. Some skillsets – such as maintenance of engines – will no longer be needed entirely, with the staff performing those diverted to the newly required tasks. All depot staff will need to undergo safety training related to the hazards electric vehicles introduce, such as high voltage equipment and battery fire risk. One strategy that other authorities have used effectively is shadowing – pairing a mechanic from the bus vendor with a mechanic from the authority during work shifts to ensure that the knowledge transfer can be hands-on and not merely classroom-based. Another strategy that has been used by agencies is to partner with local vocational schools and community colleges to develop training curriculum on these new technologies.

Staff will also need to be trained on safe charging of fueling procedures. Both overhead and plug-in chargers likely cannot be accommodated in the existing fueling lanes, and will likely need to be stationed near the depot parking areas. This means that operators and other depot employees will be walking around the parking area, which may have narrow confines and poor visibility, to plug/unplug chargers and move vehicles to and from the charging stations. For hydrogen, high pressure fueling systems can also present safety risks. Although these hazard can be mitigated through training and design, it should not be neglected during the transition process.

Transitioning to zero emission vehicles provides benefits for staff, as well. Electric vehicles are quieter and produce virtually no emissions, thereby providing a better working environment for the drivers and maintainers who are around them for their entire work shifts. Conveying these benefits to staff, and listening closely to any concerns they may voice, will ensure buy-in to the electrification initiative across the transit authority.

6.2 Risks

As a developing technology, battery-electric vehicles and infrastructure present technology risks to the transit authorities that adopt them. Many authorities have experienced quality and reliability issues during early adoption of electric vehicles. Authorities in Albuquerque and Philadelphia, for example, had to remove electric vehicles from service due to vehicle issues. Additionally, an authority in Minnesota had issues with its chargers overheating and improper communication with vehicles. These risks are amplified by the relatively small number of suppliers when compared to supply chains for diesel vehicles. Due to the relatively small size of the battery electric vehicle market and Buy America laws restricting the purchase of products not manufactured in the US, authorities may be forced to work through "infant mortality" of some unreliable equipment. However, with a carefully structured contract beginning these transitions now can be advantageous. Understanding each transit authority's specific requirements (with regards to route drive cycle, depot and utility upgrades, stakeholder involvement, and community considerations) is a substantial process, which will need to be performed regardless of the particular vendor and technology ultimately chosen. Starting the process will allow each transit authority to be more responsive to future advancements in the industry, with the initial ground work having already been done, and will allow each authority to understand its key requirements on a firsthand level.

6.3 Contractual Safeguards

It should be emphasized that zero-emission vehicle technology is developing, and the existing technology is not certain to be reliable, maintainable over vehicle lifetime, or ultimately the chosen technical option. There are several examples around the nation where initial pilots were unsuccessful. It is important to structure the procurement to minimize risk to the authority and maximize quality control, both from the technical and commercial perspectives. Production oversight at the vendor's factory is necessary to avoid quality lapses and subpar workmanship. The specifications' acceptance and quality criteria must be thought through carefully and adhered to strictly, to avoid quality lapses and subpar performance without imposing unduly strenuous (and therefore expensive) requirements. The overall contract should also be structured to minimize transit authority risk, as was done in Albuquerque, New Mexico. Although the vehicles and chargers were plagued with quality and safety issues, Albuquerque did not lose any money because the contract with the manufacturer included no payments until the vehicles passed inspections. At the end of the contract, Albuquerque forced the manufacturer to remove their vehicles and chargers from the city at no cost to the taxpayer. The city spent money on street reconfigurations for faster operation and bus depot modifications, but these changes are useful regardless of bus vendor and exact specifications.

6.4 Battery End of Life Management

Management of the battery packs at the end of its useful life is an important consideration for the environmental impact of the electric fleet operators like transit authorities. Authorities have a few options with regards to handling the expended battery pack in their vehicles. First option is to repurpose the batteries for stationary storage application. The batteries that are no longer suitable for mobility application, due to lowered charge holding capacity, can still be used for on-site stationary storage application for storing energy from renewable generation and/or for peak shaving. Commonly referred to by the industry as the second life, this option is in its early stages of development. Given the large number of batteries being produced it is very likely that options for will soon become available. Like the second life application, there will also be a market for used batteries soon. With this option, the authorities can salvage the value from the battery packs at the end of life if they don't have a use for the old batteries or do not want to take on the efforts required for repurposing batteries.

Once the batteries are no longer suitable for any application, they can be recycled to produce new batteries. As mentioned in the supply chain discussion earlier, the minerals required to produce the batteries are in short supply and expensive to mine. The industry predicts that most of the batteries from the vehicles will be recycled to harvest these precious metals. Companies like Li-Cycle and Redwood Materials already have the processes developed for recycling lithium batteries and have plans for scaling up their processing capacities as more and more battery packs retire. The recycling should help spread the environmental footprint associated with mining the original material over multiple product lifecycles thereby reducing the impact from each lifecycle.

Transit authorities can also consider the option of leasing the batteries instead of purchasing them. With the lease, authorities do not have to arrange for the disposal of the used batteries. The authority can simply return the packs at the end of the lifecycle. This option has added advantage for the authorities in the form of lower upfront capital costs as well as a guaranteed performance from the batteries during the lease period.

7. ZEV Information Technology Considerations

Performance monitoring and system data production are critical components to any zero-emissions transition strategy. Key performance indicators (KPIs) and the collection and reposit of transit assets and associated data into a centralized database allow authorities to monitor operational, financial, environmental, and societal impacts of the transition. As transit authorities and the communities they service transition further into the information age, the availability and ability to apply the data for betterment of service is necessary.

7.1 System Data Production

Although a positive feature to the conversion of an electric vehicle fleet is an overall lower maintenance demand to that of a fossil fuel equivalent, preventive maintenance is still required. Maintenance and operations management software will be a vital component to the system's short-term functionality and long-term reliability. Software solutions to efficiently schedule a fleet's preventive maintenance tasks and mitigate component failure are prevalent throughout the industry. These software solutions can also include charging infrastructure. In addition, operations and maintenance management software solutions provide automated scheduling and comprehensive costing and forecasting. The software can seamlessly link to the authority's pre-determined routes (established by Hatch's simulation modeling) and propose a vehicle's preventive maintenance schedule. The combination of vehicle telematics and fuel (hydrogen or electric) auditing provide real-time information on the overall system's status. Performance metrics are uploaded to a centralized data repository for extrapolation and analysis.

7.2 Mapping Applications

There are a number of dedicated electric vehicle charging applications currently available. The need for these applications are dependent on whether the transit authority's charging infrastructure configuration is public, shared, or private. These applications allow users to find charging infrastructure near them. In addition, there are network-specific charging applications and vehicle-specific applications that manufacturers and charging infrastructure companies have developed. Applications allow users to filter the data based on parameters such as plug type, charging speed, charging network, pricing, and more. There are functions allowing the user to plan routes based off of charging infrastructure locations, too.

8. ZEV Policy, Resources, and Legislative Impacts

CCRTA is not alone in recognizing the immediate need to reduce carbon emissions and pollution to ensure a healthier climate. Leaders at both the state and federal levels recognize the significance of zero-emissions vehicles and have implemented strong plans to achieve these goals. These plans include both timelines to achieve carbon emissions reductions and grant programs to provide the funding necessary for these reductions. CCRTA's decision to convert its fleet to zero-emissions vehicles aligns well with these policies and incentives.

The federal government provides several types of incentives for transit authorities to convert their fleets to zero-emissions vehicles, the most well-known of which is the Low or No Emission Grant Program (49 U.S.C. 5339 (c)), or the "Low-No" program. Through this program, which can allocate up to $1.6 billion annually for five years, the FTA provides matching funds for procurements of zero-emissions vehicles as well as for bus facility upgrades to support these vehicles. The Buses and Bus Facilities Competitive Program (49 U.S.C. 5339 (b)), though not limited to zero-emissions vehicles, can also provide federal funding for vehicle and infrastructure procurements. Other, more general funding options are also available. For example, US DOT's Public Transportation Innovation Program provides funding for research projects analyzing a wide range of new ideas, including zero-emissions vehicle technologies. The FHWA's Congestion Mitigation and Air Quality Improvement Program (CMAQ) provides over $2.5 billion a year for measures, including the adoption of zero-emissions vehicles, that will improve air quality and reduce pollution. Notably, each of these programs are competitive, so CCRTA is not guaranteed to receive funding. As the zero-emissions vehicle landscape expands and a greater number of authorities begin converting their fleets, availability of this funding is expected to become scarcer. Though less common, some formula (i.e. non-competitive) funding is also available, for example through the Formula

Grants for Rural Areas (49 U.S.C. 5311). This is generally more appropriate to fund operations rather than capital purchases.

The state of Massachusetts has also made clear the importance of zero-emission vehicle adoption. Table 1 provides a summary of current policies, resources and legislation that are relevant to CCRTA's ZEV fleet transition.

TABLE 1 – POLICY AND RESOURCES AVAILABLE TO CCRTA

Policy	Details	Relevance to Agency Transition
The U.S. Department of Transportation's Public Transportation Innovation Program	Financial assistance is available to local, state, and federal government entities; public transportation providers; private and non-profit organizations; and higher education institutions for research, demonstration, and deployment projects involving low or zero emission public transportation vehicles. Eligible vehicles must be designated for public transportation use and significantly reduce energy consumption or harmful emissions compared to a comparable standard or low emission vehicle.	Can be used to fund electric vehicle deployments and research projects. (*Competitive funding)
The U.S. Department of Transportation's Low or No Emission Grant Program	Financial assistance is available to local and state government entities for the purchase or lease of low-emission or zero-emission transit buses, in addition to the acquisition, construction, or lease of supporting facilities. Eligible vehicles must be designated for public transportation use and significantly reduce energy consumption or harmful emissions compared to a comparable standard or low emission vehicle.	Can be used for the procurement of electric vehicles and infrastructure (*Competitive funding)
The U.S. Department of Transportation's Urbanized Area Formula Grants - 5307	The Urbanized Area Formula Funding program (49 U.S.C. 5307) makes federal resources available to urbanized areas and to governors for transit capital and operating assistance in urbanized areas and for transportation-related planning. An urbanized area is an incorporated area with a population of 50,000 or more that is designated as such by the U.S. Department of Commerce, Bureau of the Census.	This is one of the primary grant sources currently used by transit agencies to procure vehicles and to build/renovate facilities. (*Competitive funding)
The U.S. Department of Transportation's Grants for Buses and Bus Facilities Competitive Program (49 U.S.C. 5339(b))	This grant makes federal resources available to states and direct recipients to replace, rehabilitate and purchase buses and related equipment and to construct bus-related facilities, including technological changes or innovations to modify low or no emission vehicles or facilities. Funding is provided	This is one of the primary grant sources currently used by transit agencies to procure vehicles and to build/renovate facilities. (*Competitive funding)

Policy	Details	Relevance to Agency Transition
	through formula allocations and competitive grants.	
The U.S. Department of Energy (DOE) Title Battery Recycling and Second-Life Applications Grant Program	DOE will issue grants for research, development, and demonstration of electric vehicle (EV) battery recycling and second use application projects in the United States. Eligible activities will include second-life applications for EV batteries, and technologies and processes for final recycling and disposal of EV batteries.	Could be used to fund the conversion of electric vehicle batteries at end of life as on-site energy storage.
Energy Storage System Research, Development, and Deployment Program	The U.S. Department of Energy (DOE) must establish an Energy Storage System Research, Development, and Deployment Program. The initial program focus is to further the research, development, and deployment of short- and long-duration large-scale energy storage systems, including, but not limited to, distributed energy storage technologies and transportation energy storage technologies.	Can be used to fund energy storage systems for the agency.
The U.S. Economic Development Administration's Innovative Workforce Development Grant	The U.S. Economic Development Administration's (EDA) STEM Talent Challenge aims to build science, technology, engineering and mathematics (STEM) talent training systems to strengthen regional innovation economies through projects that use work-based learning models to expand regional STEM-capable workforce capacity and build the workforce of tomorrow. This program offers competitive grants to organizations that create and implement STEM talent development strategies to support opportunities in high-growth potential sectors in the United States.	Can be used to fund EV training programs.
Congestion Mitigation and Air Quality Improvement (CMAQ) Program	The U.S. Department of Transportation Federal Highway Administration's CMAQ Program provides funding to state departments of transportation, local governments, and transit agencies for projects and programs that help meet the requirements of the Clean Air Act by reducing mobile source emissions and regional congestion on transportation networks. Eligible activities for alternative fuel infrastructure and research include battery technologies for vehicles.	Can be used to fund capital requirements for the transition.

Policy	Details	Relevance to Agency Transition
Hazardous Materials Regulations	The U.S. Department of Transportation (DOT) regulates safe handling, transportation, and packaging of hazardous materials, including lithium batteries and cells. DOT may impose fines for violations, including air or ground transportation of lithium batteries that have not been tested or protected against short circuit; offering lithium or lead-acid batteries in unauthorized or misclassified packages; or failing to prepare batteries to prevent damage in transit. Lithium-metal cells and batteries are forbidden for transport aboard passenger-carrying aircraft.	Should be cited as a requirement in procurement specifications.
Volkswagen Environmental Mitigation Trust (Massachusetts Portion)	Under terms of court-approved partial settlements, Massachusetts is expected to receive more than $75 million to spend on environmental mitigation projects. Specifically, the second draft amendment proposes committing additional funding to regional transit authority electric buses and chargers.	Can be used to fund electric buses and charging infrastructure.
Public Access Electric Vehicle Charging Station Grants	The Public Access Charging Program provides grants to non-residential entities for 80% of the cost of Level 2 EV charging stations and installation, and a maximum of $50,000 per street address for hardware and installation costs. Installations at government property qualify for 100% of the cost, up to $50,000. Qualified EV charging stations must be available to the public at least 12 hours per day. This program is part of Massachusetts Electric Vehicle Incentive Program (MassEVIP) and is funded by Massachusetts' portion of the Volkswagen Environmental Mitigation Trust.	Can be used to offset hardware and installation costs for EV Level 1 and 2 charging stations.
Workplace and Fleet Electric Vehicle (EV) Charging Station Grants	The Massachusetts Electric Vehicle Incentive Program (MassEVIP) provides grants for 60% of the cost of Level 1 or Level 2 EV charging stations, up to $50,000 per street address. Eligible entities include private, public, or non-profit workplaces and fleets with 15 or more employees on site. The program is funded by Massachusetts' portion of the Volkswagen Environmental Mitigation Trust. Applications	Can be used to offset hardware and installation costs for EV Level 1 and 2 charging stations.

Policy	Details	Relevance to Agency Transition
	are accepted on a first-come, first-served basis until funds are exhausted.	
Electric Vehicle (EV) Charging Station Installation Incentive - Eversource	Eversource's Electric Vehicle Charging Station program provides make-ready installation costs for non-residential customers to install approved Level 2 or direct current fast charging (DCFC) stations at businesses, multi-unit dwellings, workplaces, and fleet facilities. To qualify, customers must own, lease, or operate a site where vehicles are typically parked for at least two hours. Eligible installation expenses include trenching, dedicated service meter, conduit, and wiring costs.	Can be used to fund Level 2 or DCFC EV charging stations.

9. Diesel Hybrid Vehicles

For all the reasons mentioned previously in this report, zero emission vehicles (at their present state of development) may not be feasible for all CCRTA operations. Therefore, the use of hybrid vehicles will likely serve as an appropriate vehicle type while the authority transitions towards the use of more zero emission vehicles, and while the technology and user experience advance.
Comparatively, hybrid technology is far more mature, has been deployed at larger scales, and has lower upfront costs. Hybrid vehicles also have several advantages over diesel and gasoline vehicles. Because the diesel engine primarily recharges the battery in a hybrid configuration, it can operate at a steadier speed, which improves lifespan and reduces maintenance requirements. Furthermore, series hybrid vehicles do not have transmissions which also reduces maintenance effort and costs to operate the vehicles. Regenerative braking also reduces wear and tear on the brakes and saves fuel by harnessing energy for future reuse. A study conducted by the Department of Energy and the National Renewable Energy Laboratory, showed for example, that hybrid vehicles travel roughly 3,000 miles longer on average between road calls than diesel vehicles. According to a series of 2013 tests at the Altoona test facility, these factors also yield fuel consumption savings of up to 44%, with greater savings on slower-speed urban-style routes. Emissions savings are more difficult to quantify, due to the specifics of each operation, but the Massachusetts Bay Transportation Authority (MBTA) and King County Metro have estimated reductions of approximately 20-40% compared to traditional diesel vehicles. Finally, there are few to no weather or range related constraints with hybrids, meaning they can replace diesel vehicles at a 1:1 conversion rate.

In addition, hybrids do not require significant infrastructure modifications for transit authorities. Most hybrid vehicles do not require or accept plug-ins, so there is no charging equipment required. The minor garage retrofits required to maintain the electric equipment include cranes and back shop equipment. (Some hybrid vehicles have roof-mounted batteries, which require overhead cranes for removal and maintenance.) Additionally, authorities will need "back shop" space allocated to maintaining electrical components that are not found on diesel vehicles such as motors and controllers.

Due to the advantages of hybrid vehicles over diesel vehicles and the minimal changes required to operate them, there has been a noticeable increase in national deployments of these vehicles, to the point where hybrid vehicles now constitute up to 40% of US transit vehicle purchases. Locally, however, the scale of deployment and the speed that agencies have transitioned to hybrids has varied. Some agencies, such as SEPTA in Philadelphia, have converted their bus fleets to 100% hybrid powertrains.

SEPTA operates one of the largest bus fleets in the country (over 1,400 vehicles), so this transition took roughly 15 years to complete. For smaller operations this conversion can be done more quickly. For example, Orlando LYNX converted its bus rapid transit line (LYMMO), with a fleet size of ten vehicles at that time, from fully diesel to fully hybrid between 2009 and 2014. Other agencies, like NYCT, have adopted a mixed fleet, continuing to order both diesel and hybrid vehicles.

To meet the growing demand, there are now a wide range of off-the-shelf hybrid products available from manufacturers, and vendor support is likely to continue for decades. Vehicles of all sizes are available as hybrids: transit vans, cutaway vehicles, trolleys, and full-sized transit buses can be purchased in this configuration, either directly from the vehicle manufacturer or from a third-party vendor.

The only other major drawback of hybrid vehicles when comparing them to diesels is the upfront capital costs. Hybrid vehicles have additional components – batteries, voltage converters, associated wiring, etc. – that must be maintained throughout the lifetime of the bus. Largely for the same reason, hybrid vehicles are more expensive than diesel vehicles. New York City Transit, for example, recently paid $870,000 for hybrid buses and $700,000 for diesel buses as part of concurrent procurements from the same manufacturers. Although this cost may be offset by savings on operating costs due to lower fuel and maintenance expenditures (of approximately 15% over the lifetime of the bus), the up-front cost may present an obstacle for budget-constrained transit authorities.

10. Conclusion

Zero emission vehicles are quickly becoming the future of the US transit industry. With proper transition planning, transit authorities are provided the opportunity to reduce their carbon footprint, develop and take ownership of sustainability initiatives, and lead regional and community efforts to combat climate change. These technologies offer near-zero emissions, decreased noise pollution, reduced maintenance requirements, and a variety of other benefits and advantages. However, conversion of an existing transit fleet to zero emission vehicles is intensive and carries risk due to the technology's immature state. At this time, battery-electric vehicles have relatively short ranges, long charge times, and substantial infrastructure upgrade requirements, such as chargers and depot fire mitigation. Similarly, hydrogen fuel cell vehicle considerations include infrastructure costs, hydrogen fuel availability, and limited available performance data. Limitations with both technologies have impacts on authority operations, maintenance, and budget. However, these downsides and risks can be mitigated using the techniques presented in this report. In addition, because the technology will continue to advance, the initial steps of a zero emission vehicle deployment (drive cycle generation, depot upgrades, prototype operation, stakeholder engagement) will be worthwhile even if the current generation of zero emission vehicles proves unsatisfactory. Although hybrid vehicles present an industry-proven alternative for short-term emissions reduction, in the medium to long term battery-electric vehicles will likely become the industry standard, with hydrogen fuel cell becoming more common, too. CCRTA can position themselves well for these advances by beginning the conversion process ahead of time.

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Attachment(s)/Enclosure