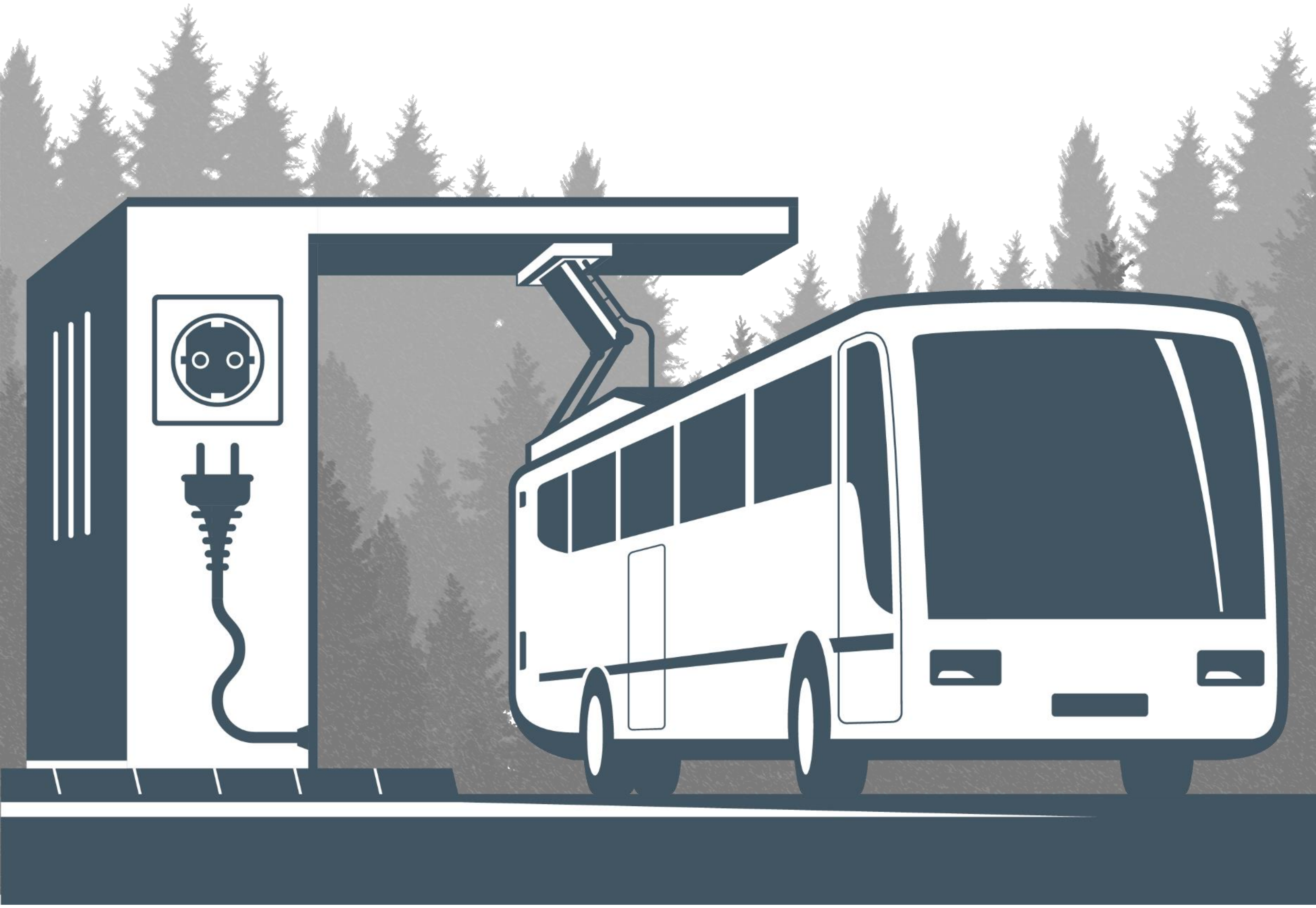
Transit Vehicle Electrification Best Practices

Revision 1



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Executive Summary

The state of Maine is currently making plans to reduce emissions to slow the effects of climate change. As part of these plans the Governor's office has developed a "Roadmap", encouraging Maine's transit agencies to transition their bus fleets to hybrid and battery electric vehicle technologies. While these technologies offer emission reduction benefits as well as potential improvements to operating costs and efficiency, they also present significant risk to agency operations. This report details lessons learned from other agencies that have transitioned to hybrid and battery electric vehicles in an effort to guide the agencies in Maine towards more successful fleet changes, and to mitigate the issues noted in past projects.

Battery electric buses represent the likely long-term solution for many agencies, by offering the potential for the greatest energy efficiency, emissions reductions, and reliability. As a new technology, however, these vehicles have limitations and issues. 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 operations in Maine. This does not mean that beginning the transition process is not advantageous, though; understanding each transit agency's requirements and constraints, and investing in infrastructure changes like depot upgrades that will need to occur regardless for an eventual transition, will position Maine's transit agencies for more successful adoption of battery electric buses even if the first generation of technology underperforms or if deployment is delayed.

To offset the limitations of battery electric vehicles, and still make progress towards emissions reductions, hybrid vehicles present a logical short to medium- term strategy. For transit agencies in Maine, shifting from diesel to hybrid represents a low-risk solution, albeit without all the fuel consumption and emissions benefits of a battery-electric bus. Hybrid buses can usually function as a 1:1 drop-in replacement for current diesel vehicles. While hybrids do carry a higher upfront cost than diesel vehicles, they offer the potential for agencies to save money over time through reduced fuel consumption while reducing emissions.

Through review of the best practices associated with hybrid and 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 simulation, analysis, planning, and optimization transit agencies in Maine can expect to reinvent their operations with more sustainable technologies. As these efforts progress, Maine agencies should continue to evaluate industry trends and best practices and adjust their strategies and plans accordingly.

Powertrains Considered

Currently transit agencies in Maine predominantly operate transit vehicles with Internal Combustion Engine (ICE) powertrains. In accordance with the Governor's Roadmap, Maine's transit agencies are encouraged to transition their transit fleets to powertrain technologies which assist in reducing the transportation sector's contributions to climate change. The two powertrain technologies currently being considered are diesel hybrid and battery electric. While there are shared technologies between the two powertrain types, there are also fundamental differences.

Figure 1 provides a high-level comparison of powertrains considered in this report: conventional ICE, parallel hybrid, series hybrid, and battery electric powertrain configurations. As previously stated, most transit vehicles operated in Maine currently use ICE powertrains. ICE vehicles use an engine to power auxiliary devices such as lighting and to propel the vehicle through the wheels. Hybrid buses are equipped with electric motors, fed by a battery. The battery is recharged by energy harnessed during braking or downhill coasting (regenerative braking). On some buses (series hybrids) the diesel engine's sole function is to help charge the battery. This is best suited for stop-start driving typical in urban environments. On other buses (parallel hybrids) the electric motor provides power during low-speed operation, but the diesel engine is still connected to the wheels and takes over propulsion during highway operation. The efficiency of this design is higher with sustained high-speed driving. Finally, battery electric vehicles eliminate the use of engines entirely, and instead use batteries to drive motors and auxiliaries.

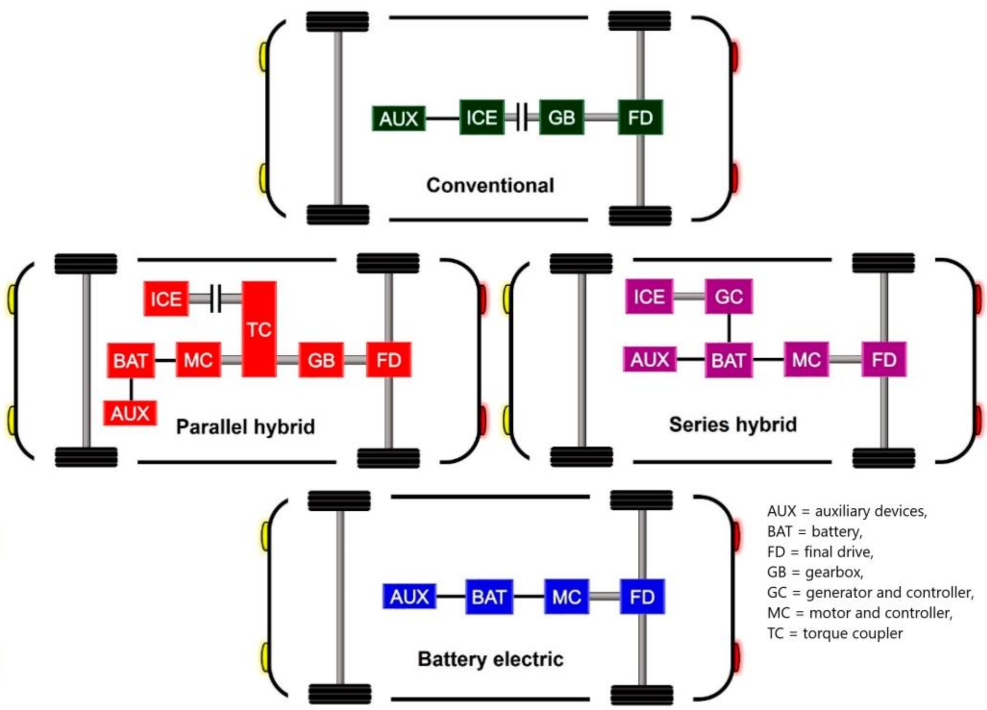

FIGURE 1 COMPARISON OF POWERTRAIN TYPES DISCUSSED IN THIS REPORT (SOURCE MDPI)

The following subsections provide background on the replacement powertrain technologies and provide lessons learned and best practices with respect to performance, operational restrictions, required supporting infrastructure, scalability, and organizational challenges associated with transitioning to alternative powertrain technologies.

Battery Electric Buses

From a technological perspective, battery electric buses offer multiple advantages over diesel buses. First, the energy efficiency of a battery electric bus 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 buses reduces lifecycle emissions by two to three times compared to that of diesel buses. 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 buses 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 buses currently constitute 6% of new bus purchases, and in North America there are 3,533 battery electric buses 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 buses 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, 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 675 kWh, which can provide an operating range of anywhere from 60 to 300 miles on a single charge depending on operating conditions.

Despite the growing prevalence of battery electric buses there are still major impediments to the technology becoming the primary powertrain configuration for transit agencies. The primary issues that must be considered when transitioning to battery electric buses relate to infrastructure, operations, and costs. While not as significant, there are also other issues to consider such as human factors and regulations. The following subsections detail these issues, and present best practices for mitigating them.

Infrastructure

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

Conductive vs Inductive Charging

Battery-electric buses 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 hybrid 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 technology is likely to enjoy 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 agency 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 geometric 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 a climate like Maine's the influence of snow and ice must be considered. Outdoor conductive chargers will require heaters and other mitigation measures to function reliably in snowy and icy weather, and indoor pantograph-style chargers must make contact with receivers on the bus rooftop which may have accumulated snow.

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, it offers a slower charging rate than conductive chargers, with the primary constraint being the size of the charge receiver on the bus. Second, inductive charging generates much more heat than conductive charging does, which decreases efficiency and requires active cooling of the bus's receiver during charging. Finally, inductive charging for buses is still in the early stages of development and is not currently available from a wide range of commercial suppliers. Currently only one manufacturer's buses can accept inductive charging, while all others require an after-market receiver retrofit.

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 buses generally experience. "Slow" chargers, with power levels of approximately 50-100 kW, are most suited to overnight charging in the depot. As each slow charger takes two to eight hours to fully charge a bus, 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 are compatible between bus manufacturers, although inductive products are available.

"Fast" charging, at a level of approximately 450 kW, can usually fully recharge a bus in one to two hours. More commonly, however, fast chargers are used for en-route charging, to partially recharge batteries during layovers. Agencies can typically expect to add an additional mile of operating range for every minute a vehicle spends on an en-route fast charger. This strategy can also be used to minimize the number of chargers required in the depot. These chargers are typically use charger mounted pantographs that come down to make contact with conductive strips on the top of the bus for charging, although fast charging inductive and plug-in conductive chargers are now available too. 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 buses must be moved on and off the chargers more frequently throughout the night. This increases operating cost to maintain the vehicles. 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 bus can then resume its duties while the drained battery is gradually recharged. Although this technology has found applications in China, most electric buses 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 installed by any US transit agencies (or, for similar reasons, seen significant success in the consumer EV market) and is unlikely to gain significant adoption in the near future. Therefore, battery swapping is unlikely to be the best solution for electrifying Maine's transit bus fleet.

Depot Design

Nearly any fleet conversion to electric buses 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 buses, many alternatives associated with depot design can have tradeoffs that should be carefully considered.

As discussed previously, electric buses 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 buses 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, though 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 buses are equipped with sophisticated battery monitoring systems to keep track of these parameters. 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 4. Evidently, fire suppression and other safety systems are a critical element of electric bus infrastructure modifications.

FIGURE 4 ELECTRIC BUS FIRE IN STUTTGART, GERMANY (SOURCE: SUSTAINABLE BUS)

Maine'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 buses. 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 agencies 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 agency 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 agency'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 agency'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 buses 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 agency 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.

Utilities

While not controlled by the transit agency, the utilities which provide power for charging the buses play an integral role in the transition to electric vehicles. Best practices established from agencies who have begun their transition to electric vehicles indicate that contacting and working collaboratively with utilities from an early stage is crucial to successful implementation. Many agencies have found that sufficient power to support their electric bus operations is not currently available in the locations it is required (depots and en-route locations). As a result, utility upgrades may be required which can drastically alter the timeline for transitioning to electric vehicles.

Other utility related issues that must be considered by agencies 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 agency 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 agency using fast chargers. Whether at a depot or external layover location, several buses drawing power from fast chargers at once may increase the peak demand rate. These can be significant; for example, the transit agency 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 agencies using en-route charging. As power rates are generally higher during the daytime and lower at night, a depot full of buses 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 agencies use a power management system at the depot, to optimize charging times for cost minimization. These systems are also useful to minimize charge duration for any given bus, as the charging process itself consumes power (for example, for battery cooling). Even if a given bus is left connected to the charger for an entire weekend, stopping the battery charge at 8 hours or so can save significant energy.

Operations

The second major impediment to battery electric bus implementation is related to operations. Specifically, the operating range and required time to charge the vehicles can present significant operational restrictions. While manufacturers have advertised driving ranges of over 300 miles, these ranges have not been achievable by the agencies that have begun operating battery electric buses. For example, Minneapolis Metro Transit found that in the winter the range of its buses 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 agency's routes. This type of variability introduces uncertainty and risk into agency operations. However, conducting a prototype operation will give Maine's transit agencies 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 agencies 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 agencies who have begun their transition to electric buses is to conduct an operational simulation and optimization as part of a transition plan. These simulations should be conducted specific to each agency 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.

Route Characteristics

The most important operational details to be considered during simulation and optimization efforts are 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. If real-time location data is available this can be very helpful in developing a drive cycle; however, its granularity may be insufficient for small-scale acceleration and deceleration so some modeling will still be required.

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 buses, buses 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.

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 buses. 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 agencies is provided in Figure 5. 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 buses 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.

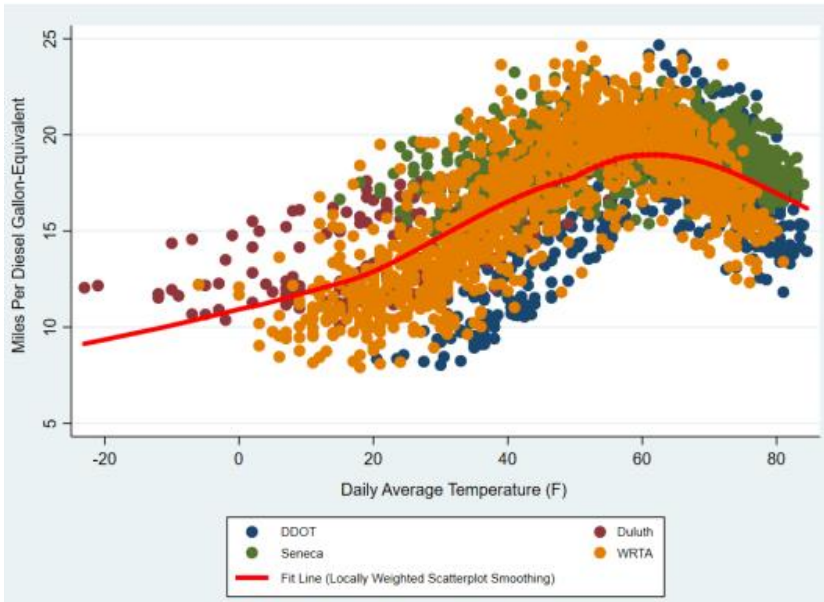

FIGURE 5 THE RELATIONSHIP OF TEMPERATURE AND BUS EFFICIENCY (SOURCE: URBAN PUBLICATIONS)

En-route vs Depot Charging

Once drive cycles are developed and weather-related constraints are understood, energy profiles for each one-way trip can be calculated and operating range can be simulated. The required energy for each trip in a block is then summed and compared against weather related efficiency to determine the optimal type of charging for the network. Generally, these analyses have found that some blocks can be operated by an electric bus throughout the service day, but others are too long for the range of the buses. This means that the agency must either install en-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 buses for the longer blocks until electric bus technology advances.

As explained previously in the Infrastructure section of this report, there are two different strategies for charging electric buses: depot charging and en-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 specific to each agency.

Depot charging is typically easier and cheaper to deploy as the agency 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 buses 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 agencies have found that some blocks / routes need reconfiguration or rescheduling to fall within the range of the buses. For example, one of Hatch LTK's previous clients, Redwood Coast Transit Authority (RCTA) in California, found that electric buses could not operate even a single round-trip of their longest route, and that the route would need to be split to allow conversion to electric buses.

More commonly, agencies have found that they must charge their buses throughout the day to support operations. Where depots are located near a central hub, "opportunity charging" (shown in Figure 6) is sometimes possible, where buses pull in for a brief charge before resuming service. The general strategy with opportunity charging, as deployed by agencies, is to create a "saw tooth" state of charge pattern. While the overall state of charge for the vehicle declines throughout the day, repeated opportunity charges add enough energy to keep the vehicle in service throughout peak operating periods. In other cases, this cannot be feasibly accommodated by the schedule and the fleet size increases as a single block for diesel buses is split into two or more for electric buses. RCTA, for instance, found that the majority of its blocks would need to be divided into two to fall within the available range. As a rural agency, its vehicle fleet comprised only cutaway buses (which have lower battery capacity), so this principle might not apply to all of Maine's agencies. However, it serves as a useful example, demonstrating that depot-only charging may not be practical if current fleet sizes are maintained.

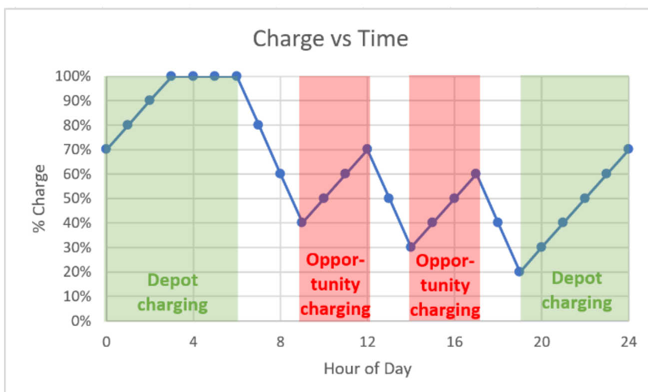

FIGURE 6 EN-ROUTE CHARGING "SAW TOOTH" STATE OF CHARGE CURVE.

As also explained previously, another strategy for charging the vehicles throughout the day is through the use of en-route chargers. En-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 6. This type of charging strategy can decrease fleet requirement and extend battery life, as batteries operate best with smaller fluctuations in charge level.

En-route chargers do, however, come with additional costs and operating constraints compared to opportunity charging. Some agencies 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 en-route chargers must be fast chargers to be practical, they come at a significant cost premium (as discussed below). Once constructed, the en-route charger is likely to pose a significant constraint on any future route changes, as relocating or abandoning it is expensive. Finally, for outlying 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 as found at many smaller agencies would help mitigate this single point of failure, but the pulse-transfer schedules commonly operated at such hubs afford minimal charging time.

Depot and Dispatch Management

Another aspect of operations that should be simulated and optimized is depot movement and dispatching. With diesel and hybrid buses, each bus can be refueled quickly in the depot and can thereafter be sent out for a full day's service. For electric buses, 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 buses, 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 agency noted that the electric buses 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 in Maine, 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 en-route chargers. A given length of layover time can be used to allow late buses 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 en-route chargers, because two buses 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.

Vehicle Battery Sizing

All of the aforementioned operational considerations can be used to inform vehicle battery sizing. As previously discussed, commercially available buses are available with a range of battery capacity. Following the operational simulation and optimization, agencies 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 buses, and the largest battery sets come with high upfront, overhaul, and maintenance costs. Furthermore, large battery sets add significant weight to a bus. Battery buses 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, simulation should be used to optimize the battery sizing of each agencies bus fleet to ensure that excess capacity is not being procured.

Costs

Aside from operational and infrastructure impacts the last major obstacle to widespread adoption of electric buses is cost. Lifecycle costs associated with a transition to electric buses can primarily be grouped into four categories: infrastructure, vehicles, operating costs, and batteries. For smaller agencies like those in Maine, the majority of infrastructure costs are constant regardless of the size of the bus fleet deployed. Upgrades such as depot fire safety, utility connection modifications, and land acquisition for en-route chargers have significant startup and project oversight costs which are largely constant regardless of the number of electric buses 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 buses, but this cost is relatively small compared to the fixed cost described above. This means that an agency looking to convert to electric buses will likely benefit from converting as large a portion of the fleet as possible, to take maximum advantage of the spending on fixed costs, and from sharing depots or chargers with other nearby operators of transit buses, school buses, etc. if possible. Therefore, the previously described operational analysis and a joint planning effort is required to project the costs that Maine transit agencies should expect to incur as part of their transition.

Vehicle costs are the next major cost consideration for agencies 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 attributing to the cost per vehicle for battery buses is the small order sizes being placed. As previously mentioned, most battery bus orders are for five buses 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.

As discussed earlier, LA DOT placed the largest US order ever for battery electric buses (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 agencies 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 within Maine if agencies partner together on electric bus purchases.

Operating costs are the next financial consideration for transit agencies looking to transition to electric buses. 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 agencies, some have begun to experience these benefits. For example, the transit agency in Seneca, South Carolina noted a decrease in fuel costs from 59¢ per mile 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 buses.

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 tens 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 agency 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 agency.

Other Factors

Outside of the Infrastructure and Operational considerations outlined previously in this report, there are several other factors that must be considered by agencies transitioning to battery electric vehicles. These factors include training, regulations and standards, contractual safeguards, and technology risks. The following subsections provide details on these issues.

Training

Although to the passenger they may appear similar to diesel buses, electric buses 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.

Bus operators should be trained on the specialized techniques of driving an electric vehicle. Acceleration and braking performance differs from that of diesel buses, particularly at lower speeds. Driving style is important, particularly to preserve range – electric buses 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 buses, and staff will need to be given training for the new procedures. Some skillsets – such as maintenance of transmissions – 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 buses introduce, such as high voltage equipment and battery fire risk. One strategy that other agencies have used effectively is shadowing – pairing a mechanic from the bus vendor with a mechanic from the agency during work shifts to ensure that the knowledge transfer can be hands-on and not merely classroom-based.

Staff will also need to be trained on safe charging 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 buses to and from the charging stations. Although this hazard can be mitigated through training and design, it should not be neglected during the transition process.

Electrifying the fleet provides benefits for staff, as well. Electric buses 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 agency.

Technology Risks

As a developing technology, battery-electric buses and infrastructure present technology risks to the transit agencies that adopt them. Many agencies have experienced quality and reliability issues during early adoption of electric vehicles. Agencies in Albuquerque and Philadelphia, for example, had to remove electric buses from service due to vehicle issues. Additionally, an agency in Minnesota had issues with its chargers overheating and not communicating properly 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, agencies may be forced to work through "infant mortality" of some unreliable equipment. However, with a carefully structured contract (as discussed below) beginning these transitions now can be advantageous. Understanding each transit agency's requirements (with regards to route drive cycle, depot and utility upgrades, and stakeholder involvement) 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 agency to be more responsive to future advancements in the industry, with the initial ground work having already been done, and will allow each agency to understand its key requirements on a firsthand level.

Contractual Safeguards

As mentioned above, electric bus 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 agency 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 agency risk, as was done in Albuquerque, New Mexico. Although the buses 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 buses passed inspections. At the end of the contract, Albuquerque forced the manufacturer to remove their buses 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.

Diesel Hybrid Buses

For all the reasons mentioned previously in this report, battery electric buses (at their present state of development) may not be feasible for all operations in Maine. Therefore, the use of hybrid vehicles will likely serve as an appropriate vehicle type while agencies transition towards the use of more battery electric vehicles, and while the technology and agency experience advance.

Compared to battery electric vehicles, hybrid technology is far more mature, has been deployed at larger scales, and has lower upfront costs. Hybrid buses also have several advantages over diesel and gasoline vehicles which Maine transit agencies currently operate. 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 buses 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 buses travel roughly 3,000 miles longer on average between road calls than diesel buses. 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 MBTA and King County Metro have estimated reductions of approximately 20-40% compared to traditional diesel buses. Finally, there are few to no weather or range related constraints with hybrids, meaning they can replace diesel buses at a 1:1 conversion rate.

Hybrids also do not require significant infrastructure modifications for transit agencies. 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 buses have roof-mounted batteries, which require overhead cranes for removal and maintenance.) Additionally, agencies will need “back shop” space allocated to maintaining electrical components that are not found on diesel buses such as motors and controllers.

Due to the advantages of hybrid vehicles over diesel buses and the minimal changes required to operate them, there has been a noticeable increase in national deployments of these buses, to the point where hybrid buses now constitute up to 40% of US transit bus 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 buses), 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 buses 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 buses.

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 buses, 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 buses when comparing them to diesels is the upfront capital costs. Hybrid buses 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 buses are more expensive than diesel buses. 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 agencies.

Conclusion

Battery-electric buses are almost certainly the future of the US public transit industry. They have near-zero emissions, lower noise, reduced maintenance requirements, and a variety of other benefits and advantages. However, conversion of an existing transit fleet to battery-electric buses is capital-intensive and, due to the technology's immature state, carries risk. Currently operating battery-electric buses have relatively short ranges, long charge times, and substantial requirements for upgrades such as chargers and depot fire mitigation. These limitations have impacts on agency operations, maintenance, and budgets. 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 battery-electric bus deployment (drive cycle generation, depot upgrades, prototype operation, stakeholder engagement) will be worthwhile even if the current generation of electric buses proves unsatisfactory. Although hybrid buses present an industry-proven alternative for short-term emissions reduction, in the medium to long term battery-electric vehicles will become the industry standard. Maine's transit agencies can position themselves well for these advances by beginning the conversion process ahead of time.