10 TRANSIT INFRASTRUCTURE AND ZERO-EMISSIONS TRANSITION CONSIDERATIONS

INTRODUCTION

This chapter reviews best practices for select transit infrastructure elements in the context of the ICATS and makes recommendations for agency implementation, where appropriate. The document is organized into four sections:

- **Introduction:** Introduces this chapter of the report.
- **Bus Stops:** Reviews best practices for bus stops, with special focuses on and recommendations for bus stop signage and the Pentacrest Downtown Interchange. This section also discusses best practice in stop spacing and opportunities for optimizing bus stop locations in the existing transit network.
- **Speed & Reliability:** Reviews context-specific best practices for speed and reliability improvements, making planning-level recommendations for select portions of the transit network.
- **Zero-Emissions Vehicles:** Discusses key considerations for the transition of a fossil fuel-based bus transit fleet to battery-electric or fuel cell-electric.

BUS STOPS

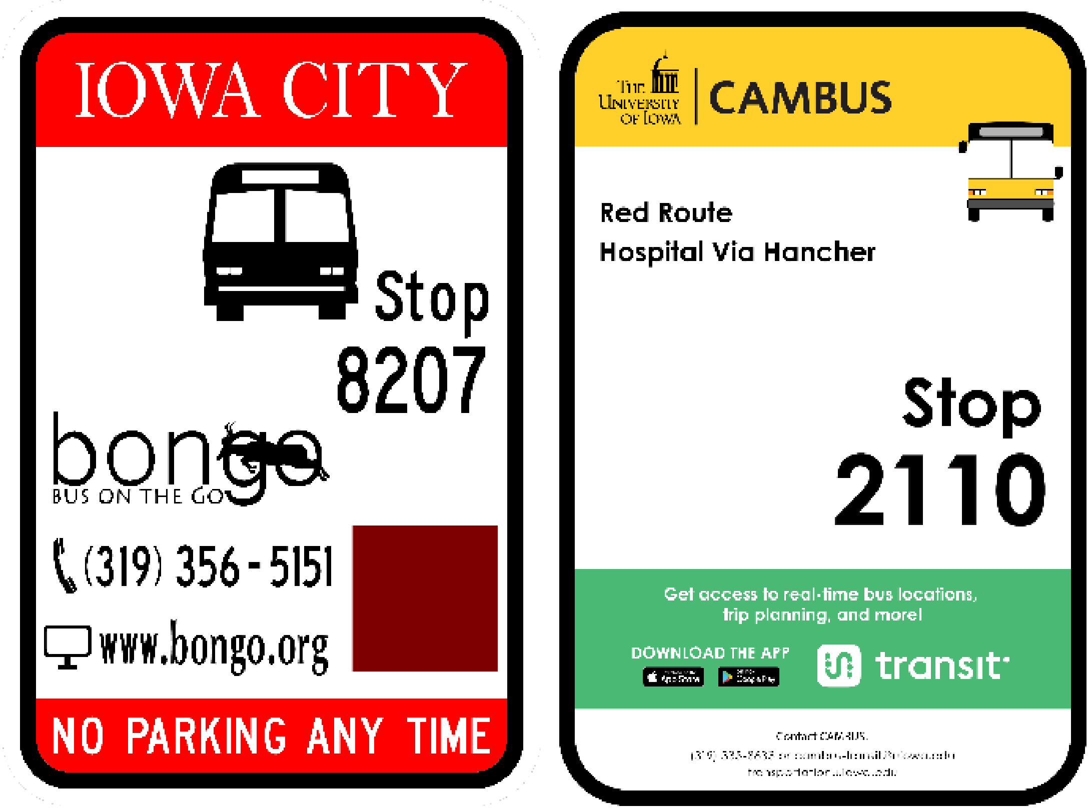
This section of the chapter reviews best practices in bus stop signage, making recommendations for future sign installation and replacement activities. It also discusses the current state of bus stop infrastructure at the Pentacrest Downtown Interchange, making recommendations to improve rider comfort. Stop location and optimization is also discussed.

Bus Stop Signage

Well-designed bus stop signage provides useful customer information while simultaneously marketing transit service. Current bus stop signage for CAMBUS, Coralville Transit, and Iowa City Transit could be improved to provide more information and better advertise the service.

Existing stop signs at ICATS agency stops include the agency name, stop ID, agency contact information, and information regarding real-time arrival information access. Iowa City Transit bus stops do not always include the routes serving the stop, and CAMBUS signs do not always include a no parking or standing notice. Stop signs for all three agencies display the stop ID more prominently than the names of the routes serving the stop.

Figure 10-1 CAMBUS and Iowa City Transit Bus Stop Sign Designs



Sources: Left to right, Iowa City Transit, CAMBUS

Bus stop signs are the single most important and cost-effective way to show where a bus operates, stops, and what destinations are served. Bus stop signs help new and potential riders learn the system and raise the visibility of the system in the community. Recommended changes to ICATS agency stop signs are to ensure the following information is included on every sign:

- Agency logo and colors (for all agencies serving the stop).
- Unique panels/stickers for each route serving the stop, with route number (if implemented) and name.
- Unique stop identification number (also called "stop ID"), which can be used to access schedule information via app or website. This information should be displayed less prominently than the names and numbers of routes serving the stop.
- Customer service phone number and website address.
- ADA-accessible symbol indicating that buses (not necessarily the stop) are accessible.

The placement of bus stop signage should be consistent for all stops. New signage should be installed on a free-standing pole and placed at the far end of the stop to mark the stopping point of the bus. Signage should ideally be installed three to five feet from the curb to maximize visibility.

Displaying route-specific information on bus stop signs is key for communicating route information to potential riders. Information can be displayed directly on the sign, or on separate placards that can be updated as route alignments change, without needing to replace the entire sign.

Figure 10-2 Best Practice Single-Route Bus Stop Sign in Chicago

Source: Marc Heiden, licensed under CC BY-SA 3.0.

Downtown Interchange

The Pentacrest downtown interchange is served by CAMBUS, Coralville Transit, and Iowa City Transit, and is the primary transit interchange for the Iowa City metropolitan area. On an average weekday when University of Iowa is in session, over 3,600 riders begin bus trips at the interchange. This chapter addresses the lack of shelters and real-time information at the Pentacrest Downtown Interchange and provides examples of context-sensitive implementations elsewhere in the United States.

Shelters

Despite high ridership at the Pentacrest Downtown Interchange, there are no shelters for riders. This location is one of the few—if not the only—bus interchanges in the United States with over 3,500 average weekday boardings that does not have shelters. The recommended threshold for installing shelters in urban areas (50 to 100 boardings per day)[1] is well under the current boardings at the Pentacrest Downtown Interchange, and input gathered from the public, agency staff, and transit operators during the ICATS process included a clear desire from all parties for rider shelters at this location.

Figure 10-3 shows riders waiting for buses on E Jefferson Street at the Pentacrest Downtown Interchange without shelter. In inclement weather, the lack of shelters likely causes some riders to shift their trip mode away from transit. It also makes transfers between routes at this location much less attractive to existing and potential customers.

Figure 10-3 Riders Wait for Buses without Shelter at the Pentacrest

Source: Nelson\Nygaard

[1] Transit Cooperative Research Program. 1996. *Guidelines for the Location and Design of Bus Stops.* <http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_19-a.pdf> p. 66

Bus shelters are available in a variety of designs with different sizes, functionality, amenities, and aesthetics. Shelters can include benches, waste receptacles, HVAC equipment, lighting, green roofs, and artwork. In a downtown transit interchange context, a series of shelters or large pergola-type structures are frequently implemented to allow large numbers of riders protection from the elements. For installation in historically sensitive environments, shelters can be customized to include design elements that are compatible with surrounding architecture. Two examples of custom shelters are in Figure 10-4.

Figure 10-4 Bus Shelters in Historic Environments (left to right: Memphis, TN and Seattle, WA)

Sources: Left to right, Thomas R. Machnitzki, licensed under GNU Free Documentation License; Joe Mabel, licensed under GNU Free Documentation License

Real-Time Arrival Information

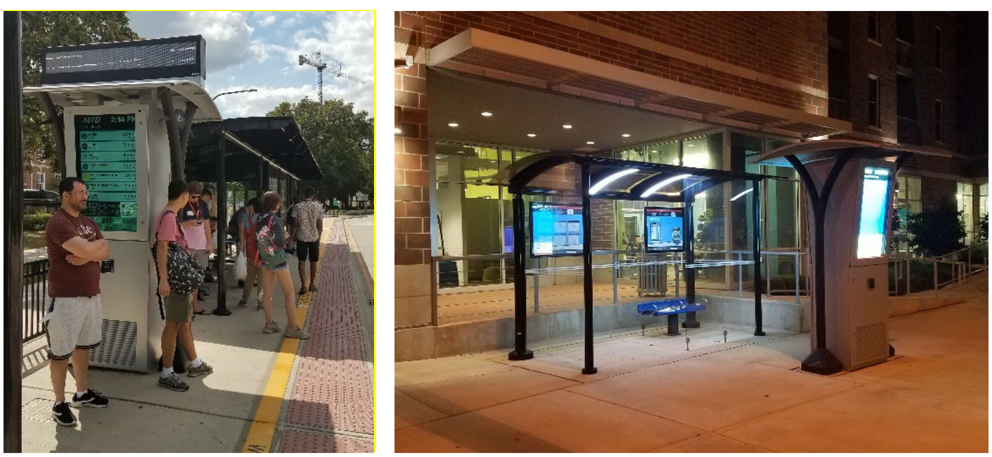
Improved real-time arrival information was an important desired improvement for riders and non-riders that engaged in ICATS public outreach. Access to more reliable on-time information was the third-most desired transit improvement for respondents taking the ICATS on-board survey,[2] and 39% of all online Design Your Own System respondents desired real-time information at stops.[3]

Real-time information increases riders' impressions of reliability and can allow them to better plan their trips. For some occasional or non-riders, real-time information provides just enough extra confidence in the reliability of the service to change their behavior and encourage them to ride more often. Real-time information displays also give riders without smartphones the ability to track approaching buses.

A significant portion of survey respondents complained about the reliability of the Bongo real-time bus tracker application used by ICATS agencies. These responses, however, were recorded before the introduction of Transit App to the Iowa City area. Transit App is, generally speaking, a higher-quality platform for real-time transit information, with improved user interface and experience and a trip-planning feature. The introduction of this app may have addressed many of the survey respondents' concerns and may generally improve access to real-time transit information for smartphone users in the Iowa City area.

In addition to supporting real-time bus tracking applications, many transit agencies install real-time information equipment at high-ridership stops using kiosks, televisions/monitors, or LED tickers. Examples of real-time displays in Urbana-Champaign, Illinois, are in Figure 10-5.

Figure 10-5 Real-Time Bus Arrival Information at University of Illinois Urbana-Champaign



Source: Nelson\Nygaard

[2] Iowa City Area Transit Study. November 2019. *Survey Analysis*. p. 14

[3] Iowa City Area Transit Study. December 25, 2019. *ICATS "Design Your Own System" Survey Results*. p. 6

Stop Spacing

Optimal bus stop spacing requires a balance of customer convenience and operating efficiency. Closely spaced stops reduce the distance to and from customer origins and destinations but result in slower bus speeds and less reliable service. Stops spaced far apart result in faster, more reliable service but can significantly increase walking distance for riders.

Bus stop spacing varies in the ICATS area and is based on several factors, including population and employment densities, sidewalk availability, travel speeds, and past rider requests. In general, stops in the ICATS area are more closely-spaced than is ideal and—on some corridors—are spaced more than two times as closely as is ideal. In general, the recommended stop spacing for local bus service is between 1/5 and 1/3 of a mile, or a five-minute walk. This industry standard is supported by optimization research.[4]

Figure 10-6 Stops Spaced Approximately 500 Feet Apart on W Benton Street

Source: Nelson\Nygaard

In general, bus stops are recommended to be located in areas with good pedestrian access and safe crossings of nearby streets to and from major destinations. Stops are typically recommended to be located at the far side of signalized intersections. When possible, bus stops should be located close to the 'front door' area of major destinations, without requiring buses to deviate into driveways or parking lots.

[4] Peter Furth and Adam Rahbee, "Optimal Bus Stop Spacing Through Dynamic Programming and Geographic Modeling", Transportation Research Record 1731, Paper No. 00-0870 (2000)

Pedestrian infrastructure in the stop area is an important consideration; stops should be accessible via ADA-compliant sidewalks and should consider local topography and traffic patterns. Figure 10-7 shows Iowa City Transit Stop #8117, which lacks safe pedestrian access in winter conditions.

Figure 10-7 Bus Stop without Adequate Pedestrian Infrastructure on Oakcrest Street

Source: Nelson\Nygaard

Stop Optimization Recommendations

Eliminating stops that are too close together can improve schedule reliability and bus travel speeds while minimally impacting access to the route. However, stop spacing is not the only factor involved in bus stop optimization. Each stop's potential for transit demand, as well as its location relative to other streetscape elements, amenities, and pedestrian and wheelchair access are also important factors in optimizing a network of high-quality, appropriately spaced stops.

Guided by these considerations and using the industry standard 1/5- to 1/3-mile bus stop spacing, a bus stop optimization program in the ICATS area could consolidate up to 187 total stops. Stop optimization could also relocate up to 39 stops and add up to nine stops. Such a bus stop optimization program should also be guided by ADA accessibility requirements and should ensure that every bus stop is universally accessible. This includes—but is not limited to—paved sidewalks of the appropriate width and grade, satisfactory transit vehicle ramp deployment space, and tactile curb ramps at nearby curb cuts.

This level of opportunity for improvement to the bus stop network is significant. Consolidating 187 of 752 total bus stops (25% of stops) in the ICATS area would improve speed and reliability of nearly every route in the system, without increasing stop spacing beyond optimal distances, and without significant capital investment. Reducing the total of number of stops would also lower ICATS agencies' stop infrastructure maintenance and capital replacement costs.

SPEED & RELIABILITY

This section of the chapter highlights potential infrastructure upgrades to improve the speed and reliability of ICATS agency service in Iowa City, focusing on transit-only lanes and signal improvements.

Transit-Only Lanes

Providing transit vehicles with dedicated right-of-way is one of the most effective means of improving speed and reliability. Transit-dedicated right-of-way is most appropriate in select locations where transit carries high passenger volumes and consistent delays impact hundreds or thousands of riders per day. Successful implementations of transit-only lanes increase the total number of people moved on a road during congested periods and are a relatively low-cost strategy for decreasing travel times.

Jefferson Street Eastbound

The two eastbound general purpose lanes climbing the Jefferson Street hill between N Madison Street and N Clinton Street produce significant delay for transit, partially due to general purpose traffic interference and partially due to pedestrian crossings of Jefferson Street to and from University buildings (Figure 10-8). This location was highlighted by bus operators as problematic.

Figure 10-8 Buses in Mixed Traffic Climbing the Jefferson Street Hill at the Pentacrest

Source: Nelson\Nygaard

It is recommended that a transit-only lane be considered for the southern of the two general purpose lanes to provide transit priority for buses in this congested area. A transit-only lane in this location will also reduce rider frustration, as buses with high occupancy levels often climb the Jefferson Street hill more slowly than walking pace, and within eyesight of riders' destination.

A transit-only lane in this location would benefit 297 CAMBUS, 58 Coralville Transit, and 23 Iowa City Transit trips each weekday. At peak hours, this transit-only lane would serve a bus every one to two minutes.

It is likely that waiting times for general purpose traffic at the pedestrian crossing would increase with this treatment, but prioritizing transit will move more people faster through this area.

Newton Road

Newton Road, between S Riverside Drive and Elliott Drive, was also identified by agency staff and bus operators as an area with significant transit vehicle delay, particularly during peak commute periods. Future University of Iowa campus planning efforts are recommended to study limiting general purpose traffic through-access on Newton Road. These restrictions would dramatically improve the speed and reliability of the 286 CAMBUS, 68 Coralville Transit, and 88 Iowa City Transit weekday bus trips that currently use this road.

Signal and Intersection Improvements

There are several locations in the ICATS area where changes to signalization could improve bus flows with minimal impacts to other users. Each of these options should be studied further to confirm feasibility and more accurately quantify benefits.

Pentacrest Downtown Interchange

General purpose vehicle and pedestrian traffic on roadways adjacent to the Pentacrest Downtown Interchange contribute significant delay to transit. Many transit trips serving the Pentacrest circumnavigate the Old Capitol megablock in the clockwise direction and incur the greatest delay when making right turns through high volumes of pedestrians in the E Jefferson Street, Clinton Street, and E Washington Street crosswalks. During periods of high pedestrian volume, only one or two buses can make a right turn per signal phase, as pedestrians continue to enter the intersection during the flashing "don't walk" phase.

To safely move more transit riders through these high-volume pedestrian crossings, many communities balancing pedestrian mobility and vehicular turning movements shorten conflicting pedestrian crossing "walk" times and add right-turn arrows to signals. In this type of signalization (technically called a lagging protected right turn phase), the pedestrian signal shows "Don't Walk," thus allowing right-turning vehicles to turn without pedestrian conflict. This improves pedestrian safety by reducing conflicts and reduces delay to turning vehicles. Figure 10-9 shows this type of signal improvement in Seattle, WA.

Figure 10-9 Lagging Protected Right Turn Phase in Seattle, WA

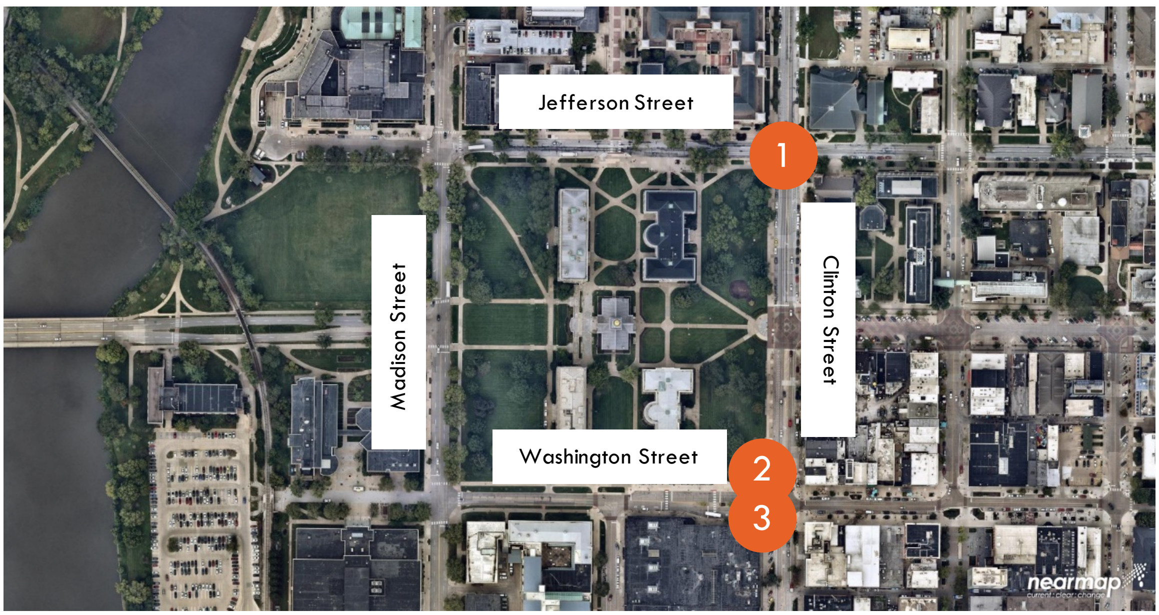
Source: Nelson\Nygaard

This lagging protected right turn phase approach could improve pedestrian safety and reduce vehicle delay at the following intersections, where 295 CAMBUS, 58 Coralville Transit, and 127 Iowa City Transit trips operate each weekday:

1. E Jefferson Street eastbound, turning on to N Clinton Street
2. S Clinton Street southbound, turning on to E Washington Street
3. E Washington Street eastbound, turning on to S Clinton Street

These three locations are shown as orange circles in Figure 10-10.

Figure 10-10 Pentacrest Downtown Interchange Potential Signal Improvement Locations



Source: Nearmap

Hawkins Road

The Hawkins Road corridor between Elliott Drive and Highway 6 was also identified by agency staff, riders, and bus operators as an area of severe transit delay, particularly northbound in the p.m. peak. Implementing a transit vehicle queue jump in the northbound direction on this roadway would likely produce significant savings for the 79 CAMBUS and 68 Coralville Transit weekday trips that currently conduct this turning movement in service.

A commonly applied transit priority treatment for this type of delay is the queue jump, which dedicates one lane approaching an intersection for transit vehicles, allowing them to advance to the front of a general purpose queue. This is typically implemented with an exclusive signal phase or leading interval for transit vehicles. A likely application of a queue jump to Hawkins Road at Highway 6 would involve rechannelization of Hawkins Road in both directions, converting the current northbound right-turn lane to transit-only, and extending it to Finkbine Commuter Drive. This lane addition may require widening the right-of-way or repurposing an eastbound lane, and would require changes in signalization at Highway 6 to allow transit vehicles to access Highway 6's two receiving lanes without conflict. Figure 10-11 identifies the general area of Hawkins Road that is recommended for further analysis of northbound queue jump lane placement.

Figure 10-11 Hawkins Road at Highway 6 Potential Queue Jump

Source: Nearmap

ZERO-EMISSIONS VEHICLES

This section of the chapter highlights the most important considerations for a transit agency considering converting fossil fuel-powered vehicles to battery-electric or fuel cell-electric alternatives. Key findings are:

- For battery-electric buses (BEBs), the type/number of vehicles and charging logistics are the primary considerations when building or upgrading a maintenance facility/bus depot.
- Maintenance facilities currently serving diesel buses should remain useful for BEB maintenance. As BEB technology matures, the reduction in BEB maintenance needs should free capacity in maintenance facilities.
- Handling, storage, and replacement of batteries is likely to have minor impacts on maintenance facilities. As greater numbers of BEB batteries in North America reach their midlife replacement date, more robust data on this subject will become available.
- Hydrogen fueling impacts the design of base facilities for fuel cell-electric buses (FCEBs). Even in small-scale applications, transit agencies must at least install storage tanks, compressors, and dispensers for a few buses.
- A large FCEB fleet will require a hydrogen generation facility, likely using methane reforming or water electrolysis.
- Because hydrogen is highly flammable, FCEB base operation involves regulations requiring leak sensors/alarms, fire extinguishing equipment, and other infrastructure construction guidelines.
- FCEB bases require larger footprints to accommodate equipment and meet regulations.

Battery-Electric Buses (BEB)

Battery-electric buses (BEBs) use an electric motor and electricity stored in an on-board battery pack. BEBs eliminate tailpipe emissions and are entirely zero-emissions when renewable energy sources (such as wind power) generate their electricity. Typically, BEBs are more energy-efficient than diesel buses, and have lower per-mile maintenance costs. Electric motors are more efficient than diesel internal combustion engines because they do not lose energy through heat dissipation, and require less maintenance because they have fewer moving parts.

Figure 10-12 summarizes major differences between BEB and diesel bus maintenance.[5] In general, maintenance components in the 'Other' category will not change in a transition to BEBs. Everyday activities, such as washes, tire inspection, and lighting tests will be the same. Checking suspension, steering, axles, and HVAC will use most of the same tools and equipment. Facilities at a depot for welding and sheet metal work will still support cab, frame, and body maintenance and repair.

In the 'Brakes' category, a regenerative system will likely reduce brake pad wear and extend their scheduled replacement. Although regenerative brakes will require more maintenance than traditional brakes, it is unlikely significant facility changes are needed to accommodate this work.

Some adjustments to maintenance facilities to service BEB propulsion system are expected. Although service of electric motor, transmission, and other elements will require staff training, only marginal facility adjustments are likely. Often, BEB manufacturers will assign a technician to work under warranty at a BEB base.[6] The BEB elements most likely to affect maintenance facility planning are managing battery pack capacity and installing charging infrastructure.

Planned **charging, parking, and shifting of buses inside a depot** is a critical consideration for building or adapting a BEB transit base. Instead of fueling (generally at an on-site diesel station) and then parking diesel buses, BEBs must either be charged for a long period of time while parked, or charged quickly and then driven to a parking location. Selection of one of these charging methods will impact base design, particularly yard or indoor bus storage space. If BEBs are to be charged for a long period of time using depot chargers, additional space will be required. If BEBs are to be rapidly charged and then moved to a parking stall, additional labor will be required.

Handling batteries and high-voltage electrical cables will require maintenance facilities to meet special fire protection construction standards established by the National Fire Protection Association (NFPA).[7] Battery storage and charging locations should be well ventilated to quickly evacuate gases released during charging, and facilities may need to upgrade smoke and heat detectors near charging areas, and/or install automatic shut-offs for chargers that may overheat.

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[5] BEB evaluations reviewed in this memo used these maintenance categories to highlight differences with diesel buses. Each category may contain preventive/scheduled maintenance, unscheduled maintenance, and other repairs.

[6] Zero-Emission Bus Evaluation Results: King County Metro Battery Electric Buses. (2018). Federal Transit Administration.

[7] Tracking Costs of Alternatively Fueled Buses in Florida. (2013). National Center for Transit Research, University of Florida.

Figure 10-12 Primary Differences in Maintenance between Diesel Buses and BEBs by System Category

Category	Components	BEB Differences vs. Diesel Buses	Overall Impact on Maintenance
Propulsion System	▪ Exhaust ▪ Engine ▪ Air intake system ▪ Cooling system ▪ Transmission	▪ BEB propulsion is simpler than internal combustion engines ▪ BEB motors do not require air intake and exhaust ▪ BEB motors do not need motor oil and oil filters	▪ Reduced scheduled maintenance to change oil and filters ▪ As electric technology matures, unscheduled repairs should also decrease in frequency
	▪ Battery pack	▪ BEBs must have a battery pack on board ▪ Because battery capacity degrades over time, a mid-life battery replacement is required ▪ Day-to-day operations require battery state-of-charge management	▪ Increased scheduled maintenance, particularly at bus mid-life for battery replacement ▪ Increased maintenance of systems tracking battery state-of-charge
	▪ Fueling/Charging	▪ Charging BEBs requires more time than diesel fueling ▪ More depot chargers are required than diesel pumps	▪ Increase maintenance (charging infrastructure is the most significant factor)
Brakes	▪ Brake pads ▪ Brake relines	▪ No significant difference in general braking components	▪ Reduced scheduled maintenance ▪ Less wear-and-tear, due to regenerative braking
	▪ Brake regenerative system	▪ When BEBs brake/decelerate, the motor reverses its field and generates electricity, which is stored in the battery	▪ Increased maintenance of regenerative system ▪ Extended life cycle of braking components
Other	▪ Cab and body ▪ Frame, steering, and suspension ▪ Heating, ventilation, and air conditioning (HVAC) ▪ Lighting ▪ Axles, wheels, and driveshaft ▪ Tires	▪ Most of these components are common to BEBs and diesel buses	▪ No major change expected to maintenance of these components

Sources: California Air Resources Board. (2016) Literature Review on Transit Bus Maintenance Cost.
Analysis of Electric Drive Technologies for Transit Applications. (2005) U.S. DOT.

In cold weather, indoor vehicle storage may be needed to preserve BEB battery charge. Even in temperatures above freezing, warming the inside of the bus at the start of service can take a considerable toll on battery energy, which limits vehicle range.[8] Recent research from AAA shows that using the HVAC system to heat the inside of an electric vehicle from 20°F to passenger-ready temperature reduces the driving range by 41% of nameplate estimates. To reduce the impacts of onboard heater energy consumption, many agencies operating BEBs in cold-weather climates have installed supplemental fossil fuel-powered heaters.

As transit agencies start moving from small-scale BEB implementations to medium- and large-scale deployments, they will require upgrades to the power infrastructure at their operating bases. Southeastern Pennsylvania Transportation Authority (SEPTA), for example, installed a two-megawatt substation at their maintenance facility to support the energy demands of its 25-BEB fleet.

It is common for BEBs to have components mounted on the roof of the bus, including the battery pack, HVAC equipment, and charging terminals or pantograph (in the case of overhead charging buses). Because of this, transit agencies should ensure they have appropriate lift and fall protection equipment for safe maintenance.

[8] New MBTA Bus Maintenance Facilities & Evolving Battery Electric Bus Technology. (2019). A Better City.

Charging Infrastructure

BEBs use three primary charging systems: plug-in charging, overhead inverted pantograph charging, and wireless induction charging. Of these three, only plug-in and inverted pantograph chargers are in widespread use. A summary table for each charger type, with pros and cons and images of each charger type, is in Figure 10-13. Figure 10-14 includes pictures of each charger type.

Figure 10-13 Charging Infrastructure Summary Table

Charger Type	Pros	Cons
Inverted Pantograph	▪ Can charge buses on-route ▪ Can charge buses faster ▪ Can provide buses with functionally unlimited range	▪ Typically costs more than other options ▪ Requires substantial supportive infrastructure ▪ Can incur demand charges ▪ Siting can be difficult ▪ Can restrict route adjustments
Plug-in	▪ Typically lower cost than other options ▪ Can charge more slowly to avoid demand charges	▪ Must be manually plugged in ▪ Typically cannot charge vehicles on-route ▪ Typically slower than other chargers
Wireless Induction	▪ Can charge buses on-route ▪ Relatively small footprint ▪ Siting can be easier than other options ▪ Very few moving parts	▪ Slightly less efficient than conductive charging ▪ Typically higher cost than other options ▪ Requires substantial supportive infrastructure ▪ Can incur demand charges ▪ Can restrict route adjustments

Figure 10-14 BEB Charging Methods

Left to right: Plug-in charger, overhead inverted pantograph charger, and wireless induction charger. Source: Nelson\Nygaard

Charger Types

Plug-in chargers are typically used in a depot or base setting. Drivers or mechanics must manually plug the charger in to the bus to charge batteries. The primary advantages of plug-in chargers are that they are relatively inexpensive and can be networked and programmed to manage charging costs. The primary disadvantages of the system are that they charge vehicles more slowly so require more time (multiple hours or an overnight period) and must be manually plugged into and removed from the vehicle.

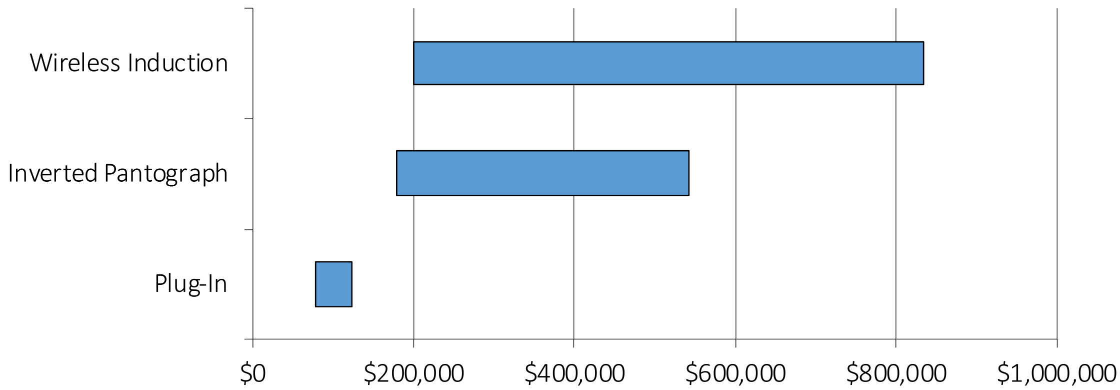
Overhead inverted pantograph chargers are used in both depot and on-route contexts, where they automatically extend and retract from an overhead system, making contact with a receiver on the roof of the bus for the conductive charging process (this can be as short a time period as a few minutes). This apparatus is closely related to the pantographs that have been used on trolleybuses, electric streetcars, and high-speed rail for decades, meaning that many aspects of the technology have fully matured. Inverted pantographs may or may not require workers to charge the vehicles, depending on base infrastructure.

These chargers can be used at transit maintenance or storage facilities to charge BEBs when they are out of service, and in an on-line context to 'top up' batteries and extend a vehicle's range. Because buses can charge more frequently throughout the day, BEBs using this type of charging usually have smaller battery packs (smaller batteries are lower cost, helping to offset the higher cost of overhead chargers). To be effective, this type of connection typically requires fast chargers that can deliver 175 kW of power or more, but at this rate a large number of buses charging simultaneously might require the installation of an electric substation at the depot. The main advantage of overhead charging is that it allows BEBs to be deployed in a similar fashion to conventional diesel buses. The main disadvantage is cost; overhead charging systems are expensive and high-speed charging requires high-voltage power, which can incur higher costs (especially during peak periods).

Induction chargers are a relatively new technology that wirelessly transmit electricity from a charger embedded in the ground to receivers on the bottom of a BEB. These chargers have few moving parts, which may drastically reduce their operating and maintenance costs. They also typically have fewer visual impacts. Early implementations of these chargers have been in layover zones.

The cost to purchase and install these charging systems ranges dramatically, depending on power or wattage of the charger, amount of electrical infrastructure required, general site conditions, and the extent to which indirect services and costs are required (e.g., consulting, engineering, and design). Figure 10-15 shows an approximate range of costs for each primary charger type, based on U.S. transit agency implementations.

Figure 10-15 Charging Infrastructure Element Approximate Cost Range



Sources: Various project engineering cost estimates, agency budgets, press releases, and agency interviews.

Note: Most costs in above cost ranges are fully installed but plug-in charger maximum and inverted pantograph minimum are unit only.

Additional potential costs that may be incorporated into a BEB charging system are in Figure 10-16. These costs vary dramatically, depending on the site chosen, charging needs, quantity of chargers installed, power of the chargers, quality of the goods and services, and labor market. Equipment and supportive infrastructure will influence maintenance facility configuration.

Figure 10-16 Charging Infrastructure Cost Variables

Equipment	Supportive Infrastructure	Labor
Transformers	Foundations	Architecture
Switchgear	Gantries	Electrical engineering
Power units	Cable trays	Consulting
Charging units	Cabling	Environmental engineering
Energy storage	Lighting	General contracting
	Grounding	Subcontracting
	Ductwork	Administrative

Source: Foothill Transit, 2019. In Depot Charging and Planning Study.

Fuel Cell-Electric Buses (FCEBs)

Fuel-cell electric buses (FCEBs)—like BEBs—are propelled by an electric motor. The difference between a FCEB and a BEB, however, is that FCEBs generate on-board power using hydrogen and a fuel cell. In other words, they do not need charging. The only tailpipe emission produced by this process is water vapor; if the hydrogen consumed by a FCEB is produced using renewable energy, then the upstream emissions are close to zero. FCEBs are still in development; only a handful of transit agencies are testing a small number of buses.

Since FCEBs have a similar electric-drive architecture to BEBs, the maintenance analysis presented in the BEB section above is also applicable to FCEBs, with the exceptions of the battery pack and charging infrastructure. FCEBs only need a small battery pack to store energy for the immediate use of the motor and auxiliary systems. As an FCEB operates, its battery will continuously obtain electricity from the fuel cell. In turn, the fuel cell can generate electricity as long as there is hydrogen, just as a conventional bus runs as long as there is diesel in the tank.

The implications of this difference are important. Because fueling buses with hydrogen can be as fast as with diesel, the disadvantages of lengthy electric charging periods (e.g., with BEBs) can also be eliminated, including the need to build charging infrastructure and optimize bus movements inside the depot. However, procuring hydrogen is challenging, and its production is energy-intensive. It also requires special handling and safety measures, given its high flammability and lighter-than-air weight. Because of this, transit agencies pursuing an FCEB fleet will need to invest considerable effort in building a hydrogen fueling station and adjusting maintenance facilities to applicable regulations.

The alternatives for hydrogen delivery/generation available to transit agencies are:[9]

- **Liquid or gaseous hydrogen delivery:** The hydrogen is generated at an off-site location (usually by an industrial gas firm) and delivered by truck to the transit agency's fueling facility. Hydrogen can be delivered in a liquid state and stored on-site cryogenically. It can also be transported in a gaseous form and put into on-site pressure tanks.
- **On-site reformation of methane:** accounts for 95% of hydrogen production in the U.S. This process uses natural gas,[10] water, and extreme heat to separate hydrogen from carbon in the natural gas. This process can be used at a smaller scale to produce hydrogen from pipeline natural gas at the fueling facility.
- **Pipeline delivery of hydrogen**: less common than vehicular hydrogen delivery or on-site generation, hydrogen is distributed through approximately 700 miles of hydrogen pipelines in the U.S. This mode is limited by the high cost and the need for fueling facilities to be near a pipeline.
- **On-site electrolysis of water:** this produces hydrogen by applying an electric current to water and splitting the oxygen from the hydrogen. This process requires water purification equipment and consumes high levels of electricity.

[9] Sokolsky, Steven, Jasna Tomic, and Jean-Baptiste Gallo. "Best practices in hydrogen fueling and maintenance facilities for transit agencies." World Electric Vehicle Journal 8, no. 2 (2016): 553-556.

[10] Natural gas is mainly composed of methane (carbon and hydrogen).

- **Mobile fueler:** these portable stations are relatively easy to move and feature on-board fuel storage in need of periodic replenishment. Because they incorporate both storage and dispensing capabilities into one unit, a mobile fueler is a solution for smaller fleets.

Given that most transit agencies are only testing a few FCEBs, the most common method for procuring hydrogen is liquid delivery. If transit agencies are interested in deploying FCEBs on a larger scale, it will likely be necessary to construct a fueling station using reformation of methane or water electrolysis. Figure 10-17 shows the fueling characteristics of transit agencies currently testing FCEBs.

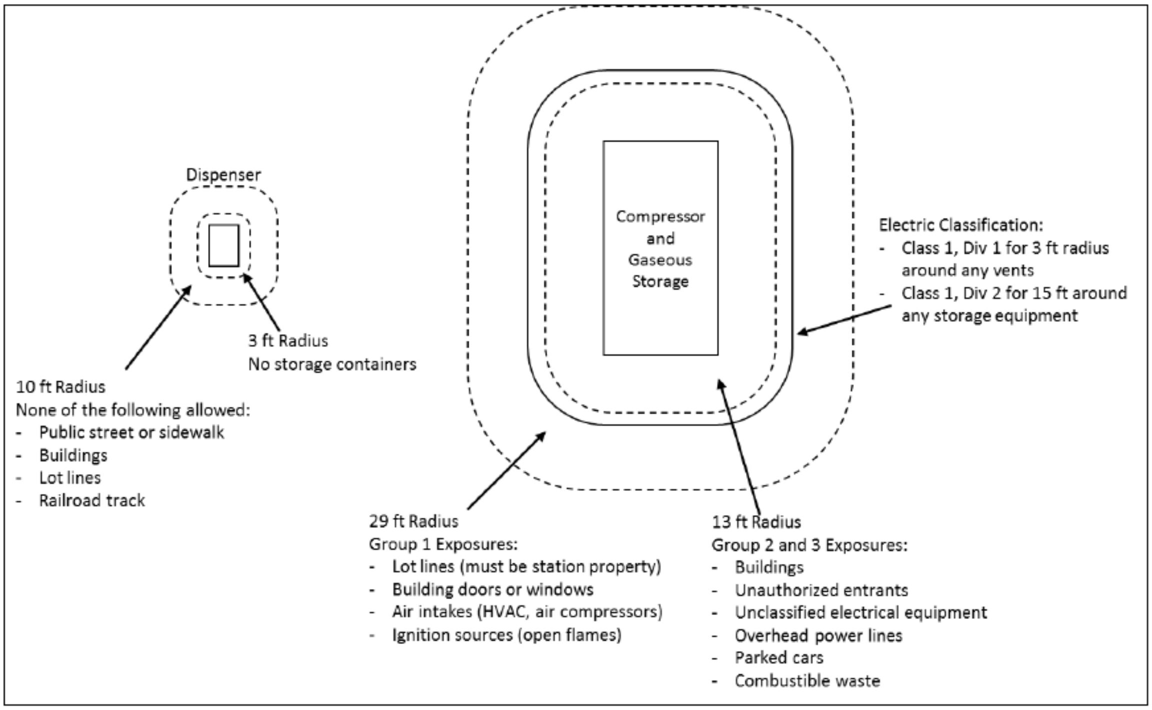
Figure 10-17 Select FCEB Fleet Fueling Station Characteristics

Transit agency	Hydrogen source	Station dispensing capacity (kg/day)	FCEBs in fleet	Public use available	Station capital cost
AC Transit (Bay Area, CA)	Liquid Delivery*	600	12	Yes	$10 million
SunLine (Riverside, CA)	Natural Gas Reformer	216	5	Planned	$750,000**
VTA (Santa Clara, CA)	Liquid Delivery	Not reported	3	No	$640,000
SARTA (Canton, OH)	Liquid Delivery	300	11	Planned	$2.2 million
CMRTA (Columbia, SC)	Gaseous Delivery	120	1	Yes	Not reported

Sources: Calstart (2016) Best practices in hydrogen fueling and maintenance facilities for transit agencies. MassDOT (2017) Zero-Emission Transit Bus and Refueling Technologies and Deployment Status. Sunline Transit Agency. https://www.sunline.org/hydrogen-cng-construction-project.
Notes: * AC transit also has an on-site electrolyzer with a capacity of 65kg/day. This production is only available for light-duty vehicles.
** SunLine is building a large electrolyzer that will be open to the public. Estimated cost is approximately $5 million.

After selecting a fueling station type, most transit facility conversion efforts are focused on reducing the risk of fire and explosion. Hydrogen stations must meet the minimum separation distance requirements set by the Hydrogen Technologies Code (NFPA 2). The separation distances depend on the pressure of the stored hydrogen and the size of the equipment's tubing. Figure 10-18 shows an example of required clearance for a compressor, storage, and dispenser.

Figure 10-18 Minimum Separation Distances Guidelines for Hydrogen Stations (NFPA 2)



Source: Calstart (2016) Best practices in hydrogen fueling and maintenance facilities for transit agencies. This example is based on a 3,000 - 7.000 pound-force per square inch (PSGI) hydrogen system and 0.288 inches of tubing diameter.

The NFPA 2 also sets requirements to minimize the risk of explosion in vehicle repair garages, as follows:

- Defueling is required for all work on the fuel system. Also, welding or open flame work cannot occur within 18 inches of the bus' hydrogen tanks.
- A gas detection system must be installed that activates the following if hydrogen levels exceed 25% of the lower flammability limit:
  - Initiation of audible and visual signals
  - Deactivation of heating systems
  - Activation of the exhaust system
- Facilities must remove all open-flame heaters or heating equipment with a temperature over 750°F in areas subject to ignitable concentrations of gas.