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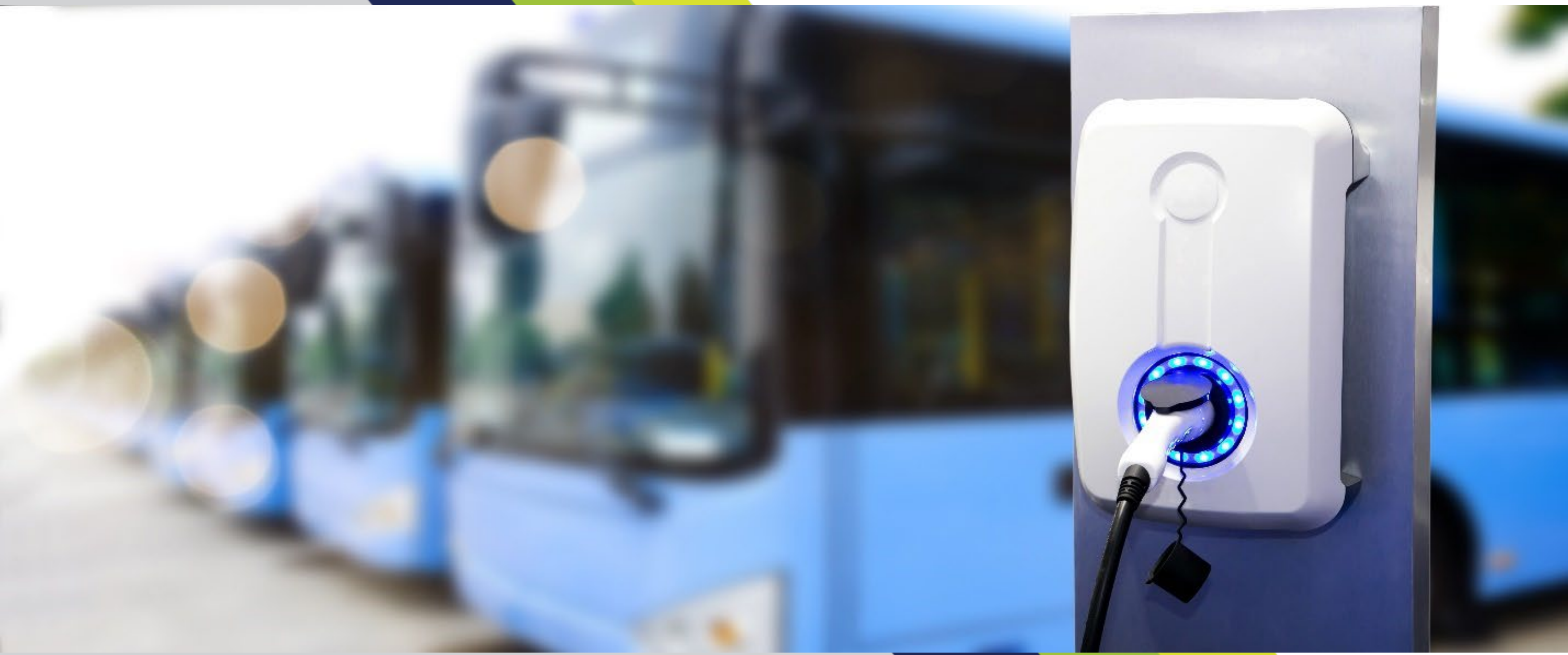

TRANSITIONING TO ZERO-EMISSION BUS OPERATIONS

Considerations for Greening Transit

MOMENTUM

U.S. Department of Transportation, Office of the Secretary
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NORTH AMERICAN PARTNERSHIP

The MOMENTUM "Transitioning to Zero-Emission Bus Operations: Considerations for Greening Transit" toolkit is a joint effort by the Governments of Canada, Mexico, and the United States. It furthers the aspirations of these countries' leaders at the 9th North American Leaders Summit (NALS) to "accelerate the transition to sustainable transportation, including more rapid deployment of electric vehicles," and fulfills the commitment made at the 10th NALS to "share information between our countries on best practices to electrify and decarbonize public buses through the cooperative development of a Joint Transit Decarbonization Toolkit."

This toolkit is a resource designed to help states/provinces, cities, and public transportation agencies both in North America and globally advance their efforts towards adding zero emission buses into their fleets. It shares practical experiences, lessons learned, and case studies that are relevant to transit operators at all stages of the transition to zero emission buses.

La boîte à outils « Transition vers des autobus à zéro émission : Considérations sur l'écologisation des transports en commun » de MOMENTUM est un effort conjoint des gouvernements du Canada, du Mexique et des États-Unis. Il promeut les aspirations des dirigeants de ces pays lors du 9e Sommet des leaders nord-américains (SLNA) d' « accélérer la transition vers des transports durables, y compris le déploiement plus rapide des véhicules électriques, » et répond à l'engagement pris lors du 10e SLNA de « partager, entre nos pays, l'information sur les meilleures pratiques pour électrifier et décarboner les autobus publics à travers le développement coopératif d'une boîte à outils commune pour la décarbonisation des transports en commun. »

Cette boîte à outils est une ressource conçue pour aider les états/provinces, les villes et les agences de transport public en Amérique du Nord et dans le monde à faire progresser leurs efforts visant à ajouter des autobus à zéro émission dans leur parc d'autobus. Elle partage des expériences pratiques, des leçons apprises et des études de cas pertinentes aux opérateurs de transport en commun à toutes les étapes de la transition vers des autobus à zéro émission.

El kit de herramientas MOMENTUM "Transición hacia Operaciones de Autobuses de Cero Emisiones: Consideraciones para la Sostenibilidad en el Transporte Público" es un esfuerzo conjunto de los Gobiernos de Canadá, México y Estados Unidos. Este kit promueve las aspiraciones de los líderes de estos países en la 9ª Cumbre de Líderes de América del Norte (CLAN) de "acelerar la transición hacia el transporte sostenible, incluida una implementación más rápida de vehículos eléctricos", y cumple con el compromiso hecho en la 10ª CLAN de "compartir información entre nuestros países sobre las mejores prácticas para electrificar los autobuses del autotransporte mediante el desarrollo cooperativo de un Kit de Herramientas Conjunto para la Descarbonización del Transporte Público".

Este kit de herramientas es un recurso diseñado para ayudar a estados/provincias, ciudades y agencias de transporte público, tanto en América del Norte como a nivel global, a avanzar en sus esfuerzos para incorporar autobuses de cero emisiones en sus flotas. Comparte experiencias prácticas, lecciones aprendidas y estudios de caso relevantes para los operadores de transporte público en todas las etapas de la transición hacia autobuses de cero emisiones.

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FOREWORD

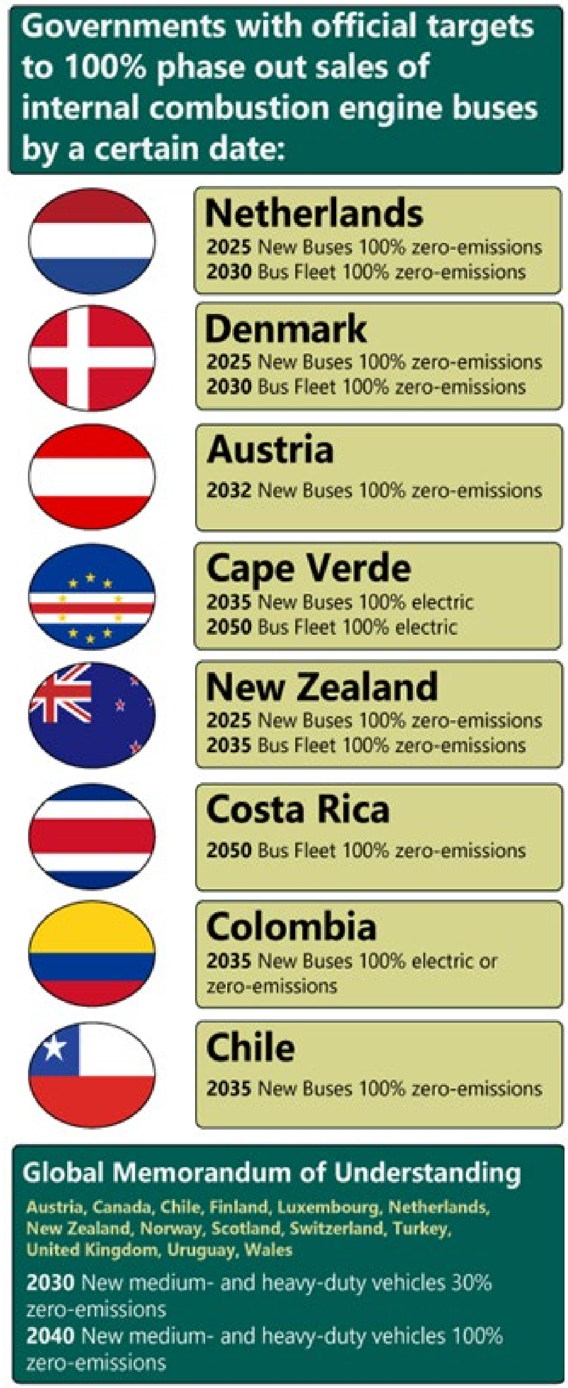
Zero-emission bus technology is emerging as a realistic procurement option for transit agencies looking to reduce greenhouse gases (GHGs) from their fleet. However, there are challenges with the adoption of zero-emission technology, including installing supporting infrastructure, identifying specific operational considerations related to deployment, and interdisciplinary planning. The purpose of this toolkit is to help transit agencies and related organizations understand the potential benefits of zero-emission buses and inform the early phases of decision-making related to the procurement of zero-emission buses. This document contains information about existing zero-emission bus technology, a transit planning questionnaire, and case studies on select existing zero-emission bus deployments.

HOW CAN AGENCIES ENCOURAGE THE TRANSITION OF PUBLIC TRANSIT BUS OPERATIONS TO ZERO-EMISSION VEHICLES?

In order to prevent the worst impacts of climate change, the world must reduce GHG emissions. Given that transportation accounts for approximately one quarter of worldwide emissions, transitioning public transit bus operations to zero-emission options presents an opportunity to achieve national emission-reduction goals, improve fleet performance and reduce operating costs, reduce local pollution from surface transportation vehicles, and provide a smoother and quieter ride experience for passengers and reduced noise in the communities they serve.

As of 2021, the International Council on Clean Transportation, seven countries, the state of California, and province of Quebec have committed to procuring 100 percent zero-emission vehicles for their public bus fleets. Similarly, some other countries (e.g., Pakistan) have adopted a National Electric Vehicle Policy to inform country-wide procurement regulations.[1] In August 2021, Canada announced the $2.75B Zero Emission Transit Fund to support the purchase of 5,000 zero-emission buses over a five-year period.[2]

Governments and transportation agencies now have several options to integrate zero-emission buses into their public transportation fleets. Historically, battery-powered vehicles have lacked the power, range, and efficiency to compete with the range provided by vehicles run on fossil fuels or required extensive supporting capital infrastructure, in the case of some trolley buses networks. Now, new zero-emission bus technologies are market viable and increasingly cost competitive when considering the life-cycle costs compared to buses that run on fossil fuels. Technology improvements have increased zero-



Source: International Council on Clean Transportation

[1] Pakistan's National Electric Vehicle Policy: Charging Towards the Future, The International Council on Clean Transportation

[2] Pakistan's National Electric Vehicle Policy: Charging Towards the Future, The International Council on Clean Transportation

emission vehicle ranges, making them able to run longer trips. It is estimated that over a 12-year life span, each zero-emission bus can eliminate 1,690 tons of carbon dioxide (CO_2) from the atmosphere.[3]

[3] Benefits of Zero-Emission Buses, U.S. Department of Transportation, Race to Zero Emissions

WHAT ARE THE DIFFERENT TYPES OF ZERO-EMISSION BUS TECHNOLOGIES?

As of May 2023, currently available zero-emission bus technologies include systems using hydrogen fuel cells, wired electric, and battery electric. Determining the best power source for a zero-emission fleet of transit buses will require transit agencies to analyze the different options that are available and feasible in their service area. They will need to coordinate with local planning agencies, maintenance and operations staff, local power utilities, alternative fuel providers, vehicle manufacturers, and community organizations to identify the most appropriate technology, or mix of technologies, to deploy zero-emission bus fleets.

Source: King County, WA

Case Study: Electric Bus Fleets in Mexico City

In 2021, Mexico City introduced a plan for country's capital city to make significant strides in transitioning the public transit bus fleets to battery electric vehicles. Mexico City, which has 21 million residents, currently operates bus, trolleybus, suburban railway, and light-rail services. The City procured ten 18-meter articulated buses with a range of 330 km for bus rapid transit routes and several new electric buses for the Metrobús transportation system. The vehicles will be supported by seven charging stations. The zero-emission buses are expecting to see up to a 30 percent cost reduction in operation versus their existing diesel-fueled models.

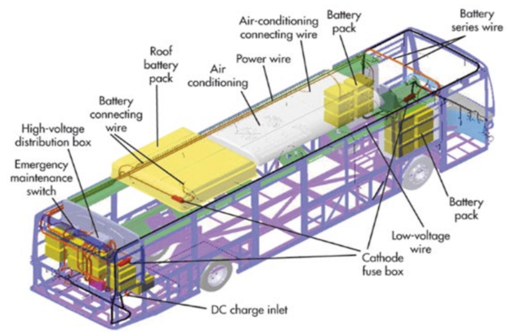
Source: Mexico News

Source: Electrifying Bus Routes: Insights from Mexico City's EJE 8 Sur Technology Assessment, Mexico Welcomes First-of-its-Kind Electric Buses

Battery Electric Buses

Battery electric buses use a fully electric propulsion and auxiliary system that delivers a smoother and quieter ride than buses that run on fossil fuels. Currently, battery electric buses are available in a variety of vehicle sizes, battery sizes, and charge types. Charge types available include on-route overhead charging and on-route pantograph charging, although most zero-emission bus deployments primarily utilize plug-in charging at the depot. Pantograph charging refers to charging bus at the depots or on-route through a mounted, inverted pantograph.

Charging is a key part of owning and operating a battery electric bus fleet – adequate charging infrastructure is necessary to meet service needs. Service schedules can vary widely across a transportation system, such as transit route length, route type (e.g., express, rapid, local, commuter), and route conditions (e.g., speed, curb heights, door openings, traffic patterns, gradient, surface type). Assessing the different types of batteries, charge types and feasible charging strategies can help agencies select the best battery electric vehicle type for their particular application.



Source: Electric Buses in India: Technology, Policy and Benefits

Lithium-ion batteries are the most common technology to power electric vehicles. Lithium-ion batteries can be a hazardous material and needs proper safekeeping and monitoring to maintain fire safety for all staff. Standard battery electric buses using lithium-ion batteries typically have a battery capacity of 250-600 kWh, which translates to a range of 160-320 km. Models with more onboard battery capacity and longer range are also emerging on the market. Many of the current battery electric 12.2-metre bus models, also known as 40-foot bus models, on the market can be fully charged in less than five hours with a plug-in charge.

Case Study: Antelope Valley Transit Authority All-Electric Buses

Source: AVTA

The Antelope Valley Transit Authority (AVTA) in southern California serves 450,000 residents in a 1,200 square mile service area. Recently, AVTA established the first all-electric bus transit agency in the U.S. The public transit agency laid out their plans to transit their diesel buses with a zero-emission bus fleet prior to the release of the California Innovative Clean Transit regulation in 2018. The California Air Resource Board (CARB) Innovative Clean Transit regulation instructs public transit agencies in the state to fully transition to zero-emission bus fleets.

AVTA began introducing battery electric buses into their fleet in 2017 and decommissioned its last diesel bus in 2020. The fleet currently consists of 87 all-electric vehicles including three different vehicle types: 57 buses, 10 vans, and 20 commuter coaches. The bus batteries are charged at the depot and via wireless charging pads located throughout the bus network. AVTA has estimated an annual saving of nearly $500,000, primarily in maintenance and operations costs, after their move from diesel to electric buses.

Sources: AVTA Becomes the First All-Electric Zero-Emission Transit Agency in North America, 4 Lessons From a California Transit Authority's Bus Electrification Rollout

For battery-powered vehicles, the highest and most efficient charge that a battery can hold is a function of both the battery management system and the type of power supply to the battery. Operators need to be familiar with how to observe battery charge and evaluate how that relates to the distance remaining to complete the route. Fleet owners and operators will also need to consider the decline of battery capacity over time. End of life of a battery is usually specified as a decrease of the battery's initial capacity by 20 percent. Agencies will have to navigate the maximum and minimum limits to determine the realistic battery capacity at the beginning, middle, and near the end of the battery's life. Agencies should discuss warranty provisions for batteries with the manufacturer, in order to ensure they maintain optimum capacity for the planned lifespan of the vehicle(s).

Driver behavior, operating temperature, bus storage in or out of sunlight, and whether the cab is pre-conditioned before leaving the depot can impact battery life and range of a vehicle. Driving behaviors, such as inefficient acceleration and braking, can drain the battery at faster rates. Fleet owners will need to incorporate driving training to help operators understand the difference in driving styles between a vehicle with a battery and electric motor versus one with a combustion engine.

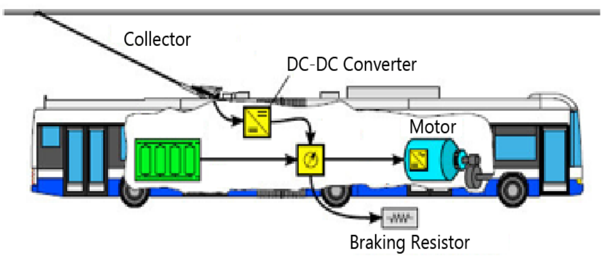
From a maintenance and operations perspective, operators may need to accommodate charging schedules by adjusting the number of buses serving a route, dividing the parts of scheduled routes among different buses (i.e., bus blocking), or adjusting layover times. However, the lower cost of electricity compared to diesel will help transit agencies generate cost savings. Transit agencies need to work with utilities to ensure that demand charges and time of use rates are designed to reflect transit battery electric bus requirements. Additional cost savings will likely be incurred from maintenance, since battery electric buses have fewer parts to maintain.

Wired Electric Buses

Wired electric buses, also known as trolleybuses, are electric buses powered by overhead cables running electricity directly to the vehicle. While their power systems are similar in look and design to streetcars, wired electric buses charge and operate on streets and fixed guideways. Wired electric buses can also use a battery, which can be charged through the wires, to operate for short distances off-wire. The size of battery in the wired electric bus will determine the distance the vehicle can operate off-wire before needing to reattach and recharge. Wired electric bus systems can be advantageous for service areas with hilly terrain or long, frequently run routes.

Source: TransLink

The TransLink fleet in Vancouver is the only wired electric bus system in Canada and the largest in North America. Trolleybuses have been a part of the city's transportation network for more than 70 years. For example, Vancouver has a trolleybus network of 262 buses and 315 km of two-way wiring along 13 routes.[4]



Source: Analysis of Limiting Factors of Battery-Assisted Trolleybuses

The implementation of a wired battery electric bus system requires fleets to either utilize an existing wire system or commit to building out wires and poles to power the buses. Additionally, the overhead line systems will ultimately determine where the bus routes are. Significant route adjustments require realigning or expanding the wire system.

Transit fleets will need to work with their local electric utilities to ensure the wire system is feeding from adequate power output sources, and potentially add substations to supplement. When building a new wire system for battery electric trolleybuses, they may have to contend with stakeholders and community members who may have opinions about the visibility and aesthetics of the overhead wired system through the main corridors. Fleet owners will need to work with maintenance and operations staff, along with a local utility, to determine how wiring issues will be addressed with minimal safety concerns and service disruptions.

Case Study: Trolleybus Network in Poland

One of the historic drawbacks of the trolleybus implementation is the constraint for the buses to only operate beneath the charging wire system. To provide flexibility, some trolleybuses in recent decades have been converted to hybrids, with diesel power generators installed to allow the buses to travel off wire to remote service areas temporarily. Newer iterations of trolleybus models are being outfitted with onboard batteries to supplement the overhead power supply.

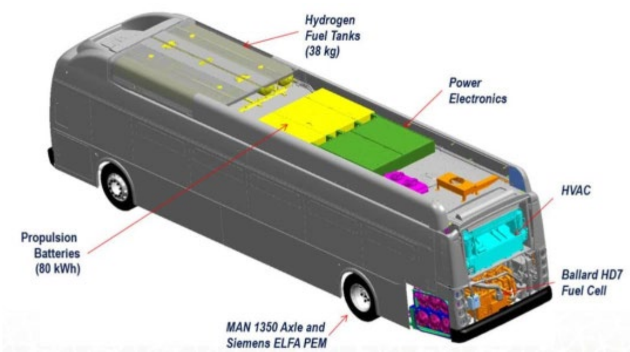
In September 2020, Gdynia, a city in northern Poland, purchased six trolleybuses with onboard batteries to service route sections without overhead lines. The system built seven new trolleybus lines between 2004 to 2020, and now have 15 lines served by trolleybus and one partially served by trolleybuses. Eight of the bus lines, in some sections, do not have overhead catenary wires, which requires fleet authorities to consider how to power the trolleybuses through the gaps in efficient and low-emissions ways. Some of the lines require the trolleybuses travel up to 10 km without overhead wires. These gaps are currently supplemented through battery power, though they previously utilized onboard diesel generators. Upfront costs and maintenance costs over time can be significant barriers for fleet owners to transit to zero-emission buses. Scenario mapping can help transportation planners and fleet owners determine what minimum battery size can adequately meet the service needs and allow flexibility for route changes or expansions in the long-term.
Source: Sustainable Use of the Catenary by Trolleybuses with Auxiliary Power Sources on the Example of Gdynia

[4] 15 Years of the Low Floor Trolleybus in Metro Vancouver, TransLink

Hydrogen Fuel Cell Buses

Source: Hydrogen Fuel Cell Bus Council

Hydrogen fuel cell buses use both hydrogen and oxygen to produce electricity and heat. Fuel cells differ from batteries by converting stored fuel, like liquid or gaseous hydrogen, into electricity to power an on-board motor and emit water vapor as a byproduct of using the hydrogen to fuel the vehicle. Hydrogen fuel cell buses require a hose and nozzle connected to a hydrogen storage tank, like some of the current equipment required to refuel buses that run on fossil fuels. A hydrogen fuel cell bus is equipped with a fuel cell, hydrogen storage tanks, and an electric motor. Hydrogen fuel cell buses have a longer range than battery electric buses and are more quickly returned to service, and as a result, could be more advantageous zero-emission vehicle option for transit services with lengthier routes.



Source: Green Car Congress

Fleet operators that opt to procure fuel cell buses powered by hydrogen will need to consider fuel cell life and how to manage hydrogen fueling. Like a battery electric bus, the maximum output of a fuel cell can degrade over time. Agencies should discuss warranty provisions for fuel cell stacks with the manufacturer, to ensure they remain functional for the planned lifespan of the vehicle(s).

Agencies will need to evaluate their location's supply options in terms of access to hydrogen, source of hydrogen, and cost. If a fleet opts to produce hydrogen on-site, they should calculate the infrastructure installment costs as well as raw material provision costs, such as electricity, water, or natural gas to power the generation setup. Agencies opting to generate their own hydrogen can continue promoting their zero-emission priorities by producing hydrogen using renewable energy sources, known as "green hydrogen." "Grey hydrogen" is a term used to refer to hydrogen production powered by fossil fuel energy sources. Generating hydrogen onsite has the benefit of giving the operator greater control over the emissions generated by the hydrogen production.

Case Study: Clean Hydrogen in Aberdeen, United Kingdom

Source: Aberdeen Hydrogen FAQ

The Aberdeen City Council in Scotland is a leader establishing a hydrogen transportation infrastructure. The city has two publicly accessible hydrogen fueling stations to enable all types of vehicles to refuel. Aberdeen procured the world's first hydrogen fuel cell double-decker buses which first began service in early 2021, and now make up a fleet of 15. The city is home to Europe's largest fuel cell vehicle fleet. As of 2021, the city's fleet included 57 hydrogen vehicles, including road sweepers, vans, buses, and waste trucks, with plans to add 18 more vehicles by the end of 2022. To provide convenient and reliable local fuel supply and fueling infrastructure, the city also established Scotland's first hydrogen production facility. The city's zero-emissions vehicle procurements were funded in part by the European Union's Joint Initiatives for Hydrogen Vehicles Across Europe (JIVE).

Sources: H2 Aberdeen, Aberdeen City Region Hydrogen Strategy & Action Plan, The world's first hydrogen-powered double decker bus arrives in Aberdeen

Advantages and Disadvantages of Zero-Emission Bus Technologies

	Advantages	Disadvantages
Battery Electric 	• Several charging setups options available • Regenerative braking technology to extend vehicle range • Total Cost of Ownership has the potential to be lower than traditional diesel busses due to reduced operational costs associated with maintenance and fuel savings	• Upfront costs are more expensive than diesel buses (as of 2020) • Charging can be time intensive, depending on charging method • Have limited range on a single charge • Very high and very low external temperatures have a negative impact on battery aging and performance[5]

[5] Electrifying Transit: A Guidebook for Implementing Battery Electric Buses, 2021, Alana Aamodt, Karlynn Cory, and Kamyria Coney, National Renewable Energy Laboratory

	• Well-suited to local routes with more stop/starts	
Wired Electric 	• Do not need to recharge or refuel outside of the route • Well-suited for high-volume, longer, or hilly routes • Multiple buses can charge under the same wire • Regenerative braking technology can extend vehicle range	• When infrastructure does not currently exist, there are very large upfront capital costs i.e. installing extensive and costly overhead wire systems that can also have high maintenance costs. • Similar costs to battery electric buses due to limited options/supply chain (as of 2020) • Have little flexibility in route changes or require a battery to operate off wire
Hydrogen Fuel Cell 	• Scaling and expanding infrastructure less resource-intensive, depending on size of the bus fleet • Greater range than current Battery Electric technology and quickly refueled (between 321.9 and 482.8 kilometers) • More like a 1-for-1 fossil-fuel replacement kilometers • Regenerative braking technology to extend vehicle range	• Acquisition and maintenance of parts is currently challenging • Access to and cost of hydrogen fuel • More expensive than battery electric buses and buses that run on fossil fuels (as of 2020) • Operating costs are higher (e.g., producing, distributing, and storing hydrogen)

For more information:

- Foothill Transit Battery Electric Demonstration Results: Second Report, National Renewable Energy Laboratory
- A Zero-Emission Transition for the U.S. Transit Fleet, Center for Transportation and the Environment
- An Analysis of Transit Bus Axle Weight Issues, America Public Transportation Association
- Public Transportation's Role in Responding to Climate Change, Federal Transit Administration

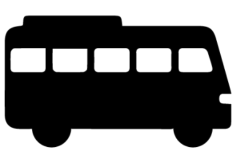
WHAT TYPES OF BUSES CAN USE ZERO-EMISSION TECHNOLOGIES?

Zero-emission buses can be found in several sizes, shapes, and capacities. The physical bus type will be a factor in how much power will be used to operate the vehicle – generally, larger vehicles require more power to operate, and smaller vehicles require less power. Fleets may have an existing bus type that works well with the needs of their service area, so they may be interested in similar-sized zero-emission buses. Others may be looking to incorporate alternative bus types to expand fleet functionality. Agencies must consider weight, capacity, and maneuverability when selecting among several available bus types. Common zero-emission bus types include:

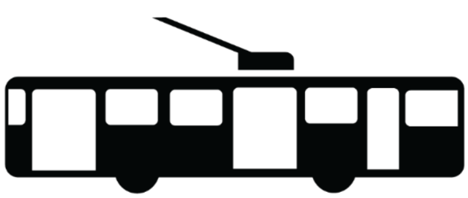
Standard Bus: Standard buses are typically between 10.7 and 13.7 meters long with a width of 2.4 to 3.8 meters. Conventional 40-foot buses can weigh up to 15,000 kg, or 20,000 kg when fully loaded with passengers. Standard buses have two axles and can carry 30 passengers sitting or up to 76 standing.

Double Decker Bus: A double-decker bus has two sections, one on top of the other, that both provide seating capacity. These buses often sit on three axles and are commonly 9.1 to 13.7 meters long and can carry up to 120 passengers.

Articulated Buses: An articulated bus is a single decker bus with two seating sections connected by a pivoting joint. These buses can carry up to 120 passengers and weigh between 17,237-22,680 kg empty, or up to 29,483 kg fully loaded and 18 meters long.



Cutaway or Mini-Bus: A cutaway is a smaller type of bus with seating capacity around 45 passengers. These buses are commonly around 7.3 meters long. These vehicles sit on a van chassis with a total weight between 6,350-11,793 kg.



Trolleybus: A trolleybus is a bus running on a catenary wire system, often with hybrid diesel and electric power systems. A catenary is a system of overheard wires used to supply electricity to a trolly, streetcar, or trolleybus. Conventional trolleybuses can hold up to 70 passengers and standard models have an empty weight of approximately 12,247 kg and length similar to a standard bus.

Three-Wheeled: Three-wheeled vehicles, referred to as rickshaws or tuk-tuks by some parts of the world, are outfitted with three wheels and sheet metal frame. These are common in several varieties but are often characterized by open or curtain sides and handlebar controls for the operator.

Case Study: Hydrogen-Powered Three-Wheeled Transit Vehicles

Source: DriveSpark

Research institutes and manufacturers in India and Canada are collaborating to establish a new version of the hydrogen-powered three-wheel transit vehicle. The project is funded by the Global Innovation & Technology Alliance (GITA) India-Canada Collaborative Industrial Research & Development Program. The Canada-India program was established to facilitate cooperative research activities geared toward innovative technologies, like zero-emissions vehicles. The new designs showcase an innovative low pressure and lower cost cylinder for storing hydrogen in smaller vehicles, like rickshaws. Hydrogen-powered rickshaws first hit the industry in 2012 in New Delhi with a fleet of 15 vehicles. The research and development projects for this new type of zero-emission transit vehicle was sponsored by the United Nations Industrial Development Organization International Centre for Hydrogen Energy Technologies (UNIDO ICHET).

Sources: Hydrogen in Motion Inc. Canada and H2E Power India to Develop a Hydrogen 3-Wheeeler for Indian Global Markets, World's first hydrogen-powered three-wheelers launched in New Delhi, India-Canada Collaborative Industrial Research & Development Programme 2019

WHAT SHOULD TRANSIT AGENCIES CONSIDER BEFORE TRANSITIONING TO ZERO-EMISSION BUSES?

While zero-emission bus technologies have advanced significantly over the last decade and come with long term-operational savings from fuel and maintenance, they come with many challenges to consider, including more limited ranges than traditional buses, higher initial costs, and a potential steep learning curve to implement at a wide scale. Implementing a zero-emission bus fleet can also require upgrades to fueling or electric charging infrastructure at bus depots. This toolkit provides an overview of the issues, challenges, considerations, and opportunities inherent in establishing or transitioning public transit fleets to zero-emission buses and provides resources to aid agencies with the process.

Before procuring a new zero-emission bus fleet, there are several considerations that should be taken into account. Agencies may lack resources or funding, have limited support from leadership, lack a clear plan to enable transition, or have regulatory constraints that could hinder fleet expansion or vehicle-type transition. Many fleets will need to pursue a phased-approach due to the continued high upfront costs and vehicle range (i.e., the distance the vehicles can run before needing to be recharged or refueled).

To accommodate for high upfront costs and infrastructure upgrades, agencies should explore available public and/or private funding incentives, rebates, and other supplemental funding options before establishing or transitioning bus fleets to zero-emission technologies. Beyond physical infrastructure and cost considerations, fleets will need to accommodate training bus operators and other key staff, emergency preparedness plan development, regular inspections of the fleet and charging/fueling infrastructure, and how to track and evaluate fleet performance.

When installing on-route charging systems, overhead wire networks, hydrogen fueling equipment, or making significant changes to the bus depot, agencies will also need to keep in mind the following to ensure efficient and collaborative infrastructure upgrades to accommodate zero-emission buses:

- Land Use and Zoning: Review local land codes to determine what review processes, constraints, and challenges might prevent infrastructure upgrades.
- Property Rights and Acquisition Processes: Work with local agencies and experts to understand the processes and procedures required to expand or develop infrastructure.
- Cable Routing on Public Roads: Work with safety, power utility, transportation planners, and public works officials to understand what restrictions and best practices exist for running an overhead cable network along public streets.
- Noise Guidelines: Be aware of the noise level restrictions in an area where infrastructure upgrades or development may be taking place.
- Bus Stop and Signage Design: Create methods for identifying and communicating charging equipment near public areas.
- Local utilities: Design and plan the power-infrastructure requirements.

Prior to transitioning to zero-emission bus fleets, agencies should also consider the following:

- Financial Analysis
- Life-Cycle Analysis
- Procurement Considerations
- Planning Considerations

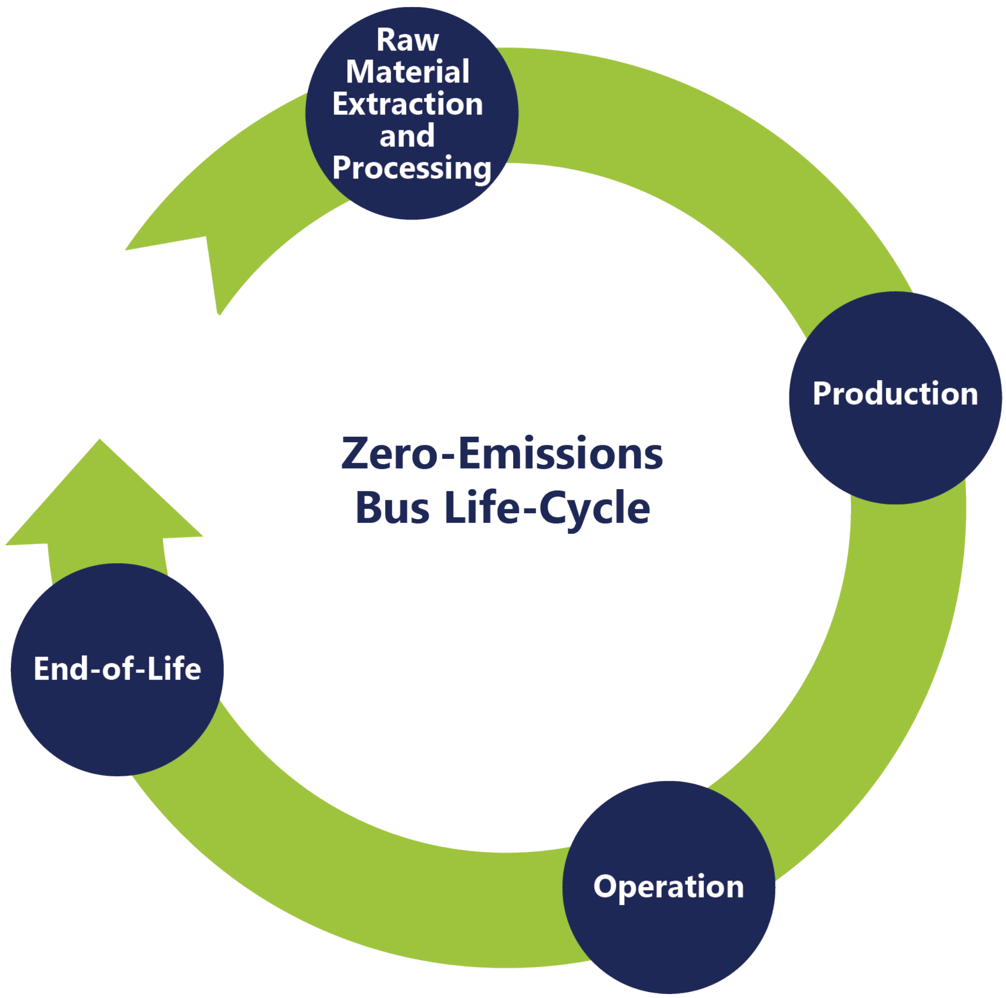
Financial Analysis

In assessing zero-emission bus options, it is important to conduct robust financial analysis that considers the purchase price of the asset, variable operating costs including energy and maintenance costs, refurbishment, depreciation, salvage values etc. once the asset has been depleted. This analysis should be compared to legacy diesel approaches and should also incorporate relevant carbon taxes applicable to a given jurisdiction. Agencies should develop plans to strategically deploy zero-emission vehicles to establish smaller-scale applications for early successes. These initial investments can help agencies determine how to financially and operationally scale up and create pathways for success.[6]

Life-Cycle Analysis

When transitioning to zero-emission buses, agencies should analyze the environmental impacts of the life-cycle of the vehicle, from raw materials extraction to end-of-life waste management. Life-cycle impacts of a product can include contributions to climate change, local and regional air pollution, public health concerns, air and water quality impacts, and resource consumption. Adequate and effective life-cycle analyses will depend on the transparency of the supply chain. Agencies should evaluate life-cycle impacts throughout the ownership of the fleet, not just when transitioning to zero-emissions buses. Decisions made in the maintenance, operations, and end-of-life phases of a zero-emissions bus will also have life-cycle impacts.

[6] The Beachhead Strategy: A Theory of Change for Medium- and Heavy-Duty Commercial Transportation, California Air Resources Board



Example of life-cycle considerations include:

- Raw Material Extraction and Processing:
  - Battery electric vehicles are powered by energy stored in a battery – likely with a lithium-ion chemistry.
  - Minerals used in battery electric vehicles include copper, iron, nickel, aluminum, graphite, lithium, and manganese.
- Production:
  - The size and type of the battery, the size of the bus, manufacturing efficiencies, and the electricity generation mix used during production are all factors affecting the impacts of battery electric bus production.
  - The battery manufacturing phase incurs the most energy used and emissions created during electric vehicle production, followed by the production of the electric motor.
- Operation:
  - The electricity generation mix used to power the batteries and produce hydrogen is the most significant determinant of the environmental effects of zero-emission buses. While zero-emission vehicles do not emit pollution, GHGs are emitted during the burning of fossil fuels, which is still the most commonly used fuel source for electricity and hydrogen production in many jurisdictions.

  - Some governments may have the option to work with their utility to power charging stations with low carbon-intensity renewable energy versus fossil fuels (e,g., hydro-electric power).
  - Regenerative braking is a way for zero-emission vehicles to increase energy efficiency during gradual deceleration and on hilly terrain. Training operators to optimize regenerative braking can conserve battery charge and extend battery life.
  - Electric buses use an electric motor rather than a combustion engine, and motors have fewer components. Therefore, less maintenance is required over time and mechanical failure rates are reduced as compared to buses powered by fossil fuels.
- End-of-Life:
  - From a procurement standpoint, agencies need to consider when their current fleet of buses will retire and their ability to secure funding for an acquisition of zero-emission buses.
  - Improper disposing or recycling of batteries can have negative environmental impacts through the release of toxic materials. Systems for recycling lithium-ion batteries are still in development, but the increasing electrification of the transportation sector has promoted growth in lithium-ion battery recycling research and development.

Procurement Considerations

As with any other transportation vehicle, agencies should consider how to minimize or eliminate some of the social and environmental impacts incurred during the life of a zero-emission bus. They can create or adopt procurement guidelines to reduce the environmental and social impacts of obtaining zero-emission vehicles. For example, agencies can opt to establish and enforce requirements around excavation and handling of waste materials during mining operations and promote and encourage the use of recycled materials.

When selecting and working with vendors, agencies will need to determine if they will procure the vehicles, charging/fueling equipment, and control systems from the same vendor, and if not, they will need to ensure interoperability across components. Agencies should also carefully review the warranty terms, especially with regards to the battery and battery capacity.

Agencies will need to consider charging and refueling as a part of procurement planning. First, agencies should estimate bus procurements based on service needs, and then work with the local utility providers early on to align procurement with electrical infrastructure upgrades/requirements. Local electric utilities can also provide a funding estimate based on the current or project rate structure, number of vehicles in the projected bus fleet, and the projected frequency of charging. Some utilities charge higher rates during peak electricity demand times, and fleets will want to coordinate with utilities to determine charging schedules to avoid peak demand rates. These conversations will also help forecast the future electricity costs for charging the vehicles.

Joint procurement approaches that involve numerous transit agencies, manufacturer partnerships and standardized specifications have the potential to reduce lead times for equipment deliveries, provide economies of scale for equipment producers and enable intra-jurisdictional interoperability for charging.

Planning Considerations

Capacity Assessment and Preparing the Depot

The deployment of zero-emission buses will rely on transportation planners to determine how current service routes and ridership rates align with the deployment of a vehicle type with alternative fueling and charging needs. Agencies will also need to work with relevant stakeholders to ensure the depots are equipped before the arrival of the new vehicles, and if the depot cannot fully support the charging needs, how to incorporate and install opportunity, or on-route, charging. Pilot tests can be designed to assess the capacity of the existing fleet and determine the scalability of employing zero-emission buses. Planners will then need to set an action and implementation plan for roll out and phased implementation. Fleets should make plans to invest in bus depot upgrades, energy storage equipment, facility energy management systems that incorporate smart-charging capability, data collection tools, skill development/workforce development, and charging and refueling equipment and infrastructure in both the short and long term to support the introduction of zero-emission buses.

Route Analysis

To determine how vehicle charging will align with route lengths and schedules, agencies should perform a route analysis. A route analysis considers service schedules, traffic patterns, topography, and in- and out-of-service times each day of the week. Agencies can use this analysis to better understand the charging needs for each route scenario in accordance with vehicle size, battery capacity, and refueling time required. Agencies may discover they need to increase their space ratio, change the percentage of unused vehicles, or redesign routes and service schedules to accommodate charging and refueling needs.

Charging Infrastructure

Agencies will also need to consider a systems approach to bus deployment that includes planning with local utilities and public works departments to make decisions about the charging or fueling infrastructure needed for zero-emission buses. The capacity to meet the needs of a new fleet of battery electric buses depends on the existing electricity grid capacity in the area. Agencies must determine whether the grid can accommodate the amount of electricity that a battery-electric bus fleet requires. Additionally, agencies should develop relationships with utilities early on in order to ensure electricity supply is sufficient and infrastructure upgrades are timed before the arrival of the battery electric bus fleet.

Charging Optimization

As previously mentioned, implementing a battery electric bus fleet will have impacts on the electric grid. Agencies should establish an operating profile and model routes to determine how to optimize the charging process, select the appropriate battery capacities, optimize the number of chargers/charging time needed, and any other requirements that might be needed for the new buses. Fleet operating profiles and route modelling includes information about the distance driven per day per vehicle, the number of stops, average and top speeds, climate conditions for routes, route topology, ridership dynamics milage requirements between charging and in-service, hours of operation per vehicle, and non-operating hours that are available to charge the batteries. This information is critical to better predict the actual performance of the fleet and optimize charging at the depot. Once an operating profile and models have been created, fleets can optimize charging through a couple different strategies:

- Installing high-powered chargers, either on-route or at the depot, to charge bus fleets more efficiently.
- Revising bus routes as needed to allow for staggered charging times and maximize charging time.

For more information:

- Best Practices and Key Considerations for Transit Electrification and Charging Infrastructure Deployment to Deliver Predictable, Reliable and Cost-Effective Fleet Systems, Canadian Urban Transit Research Consortium (CUTRIC)
- Lifecycle costs and charging requirements of electric buses with different charging methods, Journal of Cleaner Production
- Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles, Congressional Research Service
- Standard Bus Procurement Request for Proposal (RFP), American Public Transportation Association
- Preparing to Plug In Your Bus Fleet, American Public Transportation Association
- Critical Minerals in Battery Electric Vehicles, Congressional Research Service
- Zero-Emission Bus Implementation Strategy, London Transit
- Federal LCA Commons Data Repository, U.S. Department of Agriculture

HOW CAN AGENCIES ENSURE THAT THE BENEFITS OF ZERO-EMISSION BUS TRANSITIONS ARE DISTRIBUTED EQUITABLY?

It is important to balance the distribution of benefits when deploying zero-emission buses to promote equity. The transportation sector is responsible for nearly a quarter of all global GHG emissions, in addition to the local pollution from combustion engines.[7] Residents of communities in densely populated areas are often exposed to high levels of air pollution. In the United States (U.S.), low-income communities are historically more reliant on public transportation options to travel to and from work and are often more exposed to transportation-related emissions.[8] Bus depots and maintenance facilities located in low-income neighborhoods can increase local air pollutants when these facilities serve traditional diesel buses.

There are multiple ways to integrate equity into zero-emissions bus deployments. Many fleet deployments will begin with a test area or a pilot program. Agencies can be intentional about selecting historically disadvantaged communities as the test area for deploying the initial set of zero-emission buses. This strategy ensures these communities gain early and consistent access to the new technologies and the reduced pollution and more enjoyable riding experience associated with zero-emission vehicles.[9] Similarly, determining which routes are assigned zero-emission vehicles should include an equity perspective to ensure newer, cleaner, and quieter transit vehicles are serving all communities, especially those most reliant on transit options.

Agencies can also consider workforce development opportunities for underserved populations when hiring drivers and operations and maintenance staff and building out fueling/charging infrastructure. Agencies should consider equity and impacts on low-income or marginalized populations when planning a buildout of charging and/or refueling infrastructure, such as potential environment hazards or power disruptions.

For more information:

- Battery Electric Buses – State of the Practice, Transit Cooperative Research Program
- Guidebook for Deploying Zero-Emission Transit Buses, Transportation Cooperative Research Board
- Electric trolley bus - Metro expands our Electric trolley bus fleet, King Country Metro
- A Guidebook for Implementing Battery Electric Buses, National Renewable Energy Laboratory
- Best Practices and Key Considerations for Transit Electrification and Charging Infrastructure Deployment to Deliver Predictable, Reliable, and Cost-Effective Fleet Systems, Canadian Urban Research Transit and Innovation Consortia

[7] Transport, United Nations Environment Programme
[8] Who Relies on Public Transportation in the U.S., Pew Research Center
[9] Guidebook for Deploying Zero-Emission Transit Buses, Transportation Research Board

- How Do Fuel Cell Electric Vehicles Work Using Hydrogen?, U.S. Department of Energy, Alternative Fuels Center
- 15 years of the low-floor trolleybus in Metro Vancouver, TransLink
- Public Transportation's Role in Responding to Climate Change, U.S. Department of Transportation, Federal Transit Administration
- Electric Buses: Clean Transportation for Healthier Neighborhoods and Cleaner Air, PennEnvironment Research & Policy Center

WHAT BENEFITS DOES TRANSITIONING TO ZERO-EMISSION BUS OPERATIONS PROVIDE?

Transitioning from bus fleets that run on fossil fuels to zero-emission bus fleets can provide many benefits. These benefits fall into three categories:

- Environmental Benefits
- Health Benefits
- Social Benefits

Environmental Benefits

A 2019 Swedish study compared the life-cycle environment impacts of diesel-powered and electric buses.[10] This study considered all aspects of the vehicle's life, including raw material extraction, emissions from operation, and end-of-life waste management. Researchers determined that outputs of CO_2 – in the Swedish, European Union, and U.S. contexts – were significantly lower for electric buses than diesel-powered buses, even when factoring in the emissions from the production of the vehicles. Electric buses were determined to have the greatest potential to reduce all-around emissions in the long-term, especially when using electricity produced by renewable energy sources.

Sub-national government, municipalities, and transportation agencies pursuing self-imposed goals to mitigate their climate change impacts can leverage the electrification of buses to reduce emissions. Promoting public transportation broadly lends itself to reducing GHG emissions by reducing the number of vehicles powered by fossil fuels on the road.

Life-Cycle Environmental Impacts of Zero-Emission Buses

Some could argue zero-emission buses are only considered "zero emissions" in a very narrow sense. Charging the batteries requires electricity, and most electricity grids throughout the world are still primarily powered by the burning of fossil fuels.

Governments will need to consider the life-cycle emissions in the production and operation of a zero-emission bus. Eliminating tailpipe emissions through the use of zero-emission buses is a major benefit of transitioning away from buses that run on fossil fuels, but zero-emission vehicles still participate in harmful resource extraction during production and fossil fuel burning to power the vehicles.

Health Benefits

Emissions from buses burning fossil fuels can significantly deteriorate local air quality. Exposures to pollutants such as particulate matter, carbon dioxide, and nitrogen oxides – commonly found in the exhaust from vehicles burning fossil fuels – can contribute to increased rates of lung disease, heart disease, and asthma, and can worsen the impacts of diseases like COVID-19. The U.S. Environmental Protection Agency has classified diesel exhaust as a likely carcinogen.

[10] Anders Nordelöf, Mia Romare, Johan Tivander, Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel, Transportation Research Part D: Transport and Environment, https://doi.org/10.1016/j.trd.2019.08.019.

A collection of research from China, Europe, and the U.S. studied the connection between local air pollutants and COVID-19. One study from Harvard University in 2020 determined that sources of local pollution, especially those emitting particulate matter (PM), can compound the effects of COVID-19.[11] Air pollution and COVID-19 both add respiratory stress to the body, and elevated respiratory stress can be dangerous, especially for people with pre-existing heart and lung conditions. The study also identified an association between long-term exposure to air pollution and higher mortality rates from COVID-19. Research also concludes that local pollution from buses contributes to higher rates and costs of respiratory illnesses like heart disease, lung disease, cancer, and asthma.

In May 2022, Delhi, India put 150 electric buses on the road for a study[12] aimed at forecasting the potential benefits of replacing all of Delhi's current bus fleet with zero-emission buses. These new buses are an addition to their existing fleet of compressed natural gas (CNG) buses. The study evaluated select traffic zones throughout 11 districts in Delhi to analyze existing pollution conditions with the emissions from the current CNG bus fleet.

Source: Current Science

Researchers noted a nearly 75 percent reduction in pollution emitted when moving to zero-emission buses or a reduction of nearly 44 tons of particulate matter of 2.5 microns kept from the air. The study concluded a transition to zero-emission buses is a pollution reduction strategy that researchers determined could result in 1,370 fewer deaths to air pollution and over 300 million USD in morbidity and mortality cost savings in Delhi.

Case Study: Electric Public Transportation Route Implemented in the Guadalajara Metropolitan Area, in Jalisco, Mexico

In 2021, the first all-electric bus route in Jalisco was integrated into the Public Transportation network, *Mi Transporte*. With a total of 38 buses, this route provides service with a 162 km route to the east of the Guadalajara metropolitan area, specifically to the municipality of Tonalá, an area historically lagging behind in both its urban infrastructure and its demand for quality public transportation.

The main objective of the electromobility route is to substantially renew mobility in the area by improving the connectivity of marginal neighborhoods adjacent to the Nuevo Periférico Oriente, such as Jalisco, Los Conejos, San Gaspar, Coyula, and Jauja. The route mainly benefits the student population that attends the University of Guadalajara's Centro Universitario de Tonalá, with a total of more than 9,000 passengers per day.

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[11] Coronavirus and Climate Change, Harvard T.H. Chan School of Public Health

[12] Anders Nordelöf, Mia Romare, Johan Tivander,Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel, Transportation Research Part D: Transport and Environment, https://doi.org/10.1016/j.trd.2019.08.019.

Mi Transporte Eléctrico is aligned with the objectives of the Metropolitan Climate Action Plan and the State Climate Change Action Program. The plan implementation contributes to the goal of net-zero GHG emissions by 2050. Reducing emissions will be achieved through an integrated, efficient, and quality metropolitan transportation system increasing infrastructure for mass and non-motorized mobility.

By 2030, the goal is to have 100 percent of public transportation vehicles be replaced with low-emission technology and operating under new, more efficient service schemes for users. On February 23, 2023, *Mi Transporte Eléctrico* route C98 completed 600 days of operation, during which it has traveled more than 5,349 kilometers and carried out 5.3 million user transfers. Since operations began in July 4, 2021, 6,546 tons of CO_2 and 1.66 tons Particulate Matter (PM10), a group of solid and liquid particles that cause respiratory diseases, have been kept out of the air.

In mid-October 2022, the route won the National Urban Transport and Mobility Award, granted by the Mexican Transport and Mobility Association in its 13th edition, competing against national and international projects.

Sources: Mi Transporte Eléctrico Celebra Primer Año de Operaciones

Zero-emission buses can have positive social impacts for the communities they serve. Typically, zero-emission buses are quieter than buses powered by fossil fuels, reducing noise pollution. A study in Germany determined the noise difference between diesel, hybrid electric, and hydrogen fuel cell buses.[13] Once the buses reach the speed of 50 km/h, the road noise created by each levels out to be about equal among all three. At slower speeds or when stationary, the diesel bus consistently operated at the highest decibel level, followed by the hybrid electric, and finally the hydrogen fuel cell bus.

[13] Modelling noise reductions using electric buses in urban traffic: A case study from Stuttgart, Germany, 2019, Transportation Research Procedia

A new fleet of zero-emission buses can also be an opportunity for fleet to re-market transportation options to residents. For example, CapMetro, the provider in Austin, Texas, is transforming their regional transportation system. Their Project Connect will reimagine their network connectivity, including a light-rail expansion and a zero-emission bus fleet. Their first electric buses were introduced in 2020 and were wrapped with artwork provided by students from Austin's Campbell Elementary School. To help residents and visitors become engaged with the new vehicles and to familiarize them with routes in the area, CapMetro created an on-demand area map titled the Electric Bus Tracker[14].

Deploying zero-emission bus fleets can enable agencies to shape the dialogue around a community's mobility strategy and GHG-reduction strategies. Community residents often perceive zero-emission bus service as an exciting and innovative transportation mode. Bus wrapping can be used to promote the benefits of zero-emission buses to local communities.

Case Study: Broad Benefits to Zero-Emission Buses

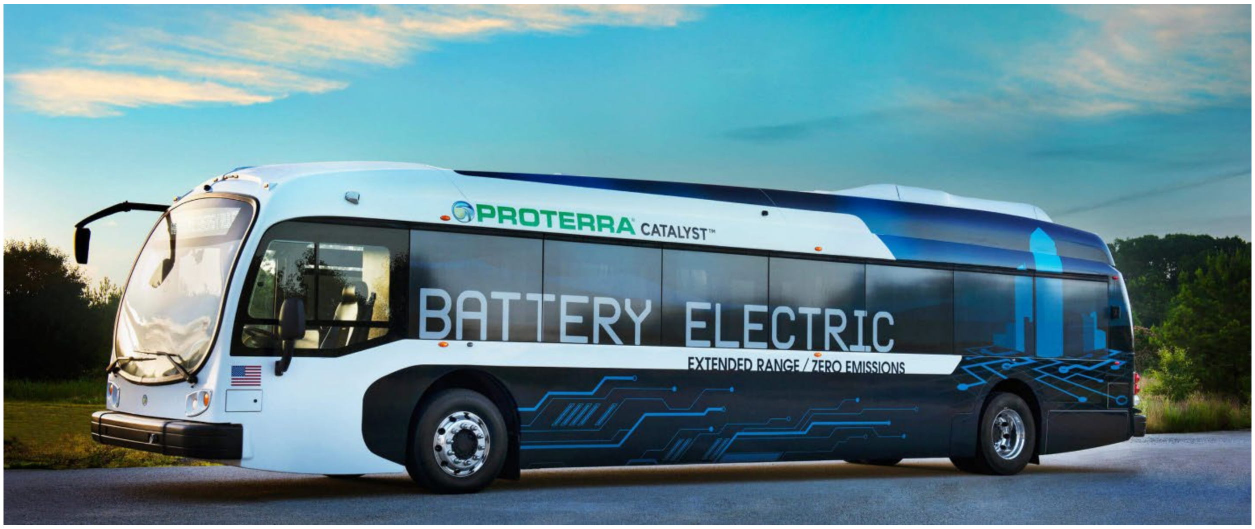
The Bangalore Metropolitan Transport Corporation (BMTC) investigated the potential for an electric bus fleet to help tackle local air pollution concerns. The BMTC ran a three-month trial program of both a battery electric bus and diesel bus serving a busy bus route in the city.

The bus powered by fossil fuels had greater seat capacity (the layout of an electric bus must accommodate for a large battery, reducing passenger capacity), but both generated similar fare revenues due to passenger enthusiasm for riding the electric buses. The fossil fuel-powered bus had longer range then the electric bus, as the electric bus was only able to be charged at night. The electric bus had zero tailpipe emissions. On top of improved air quality, researchers determined noise pollution was reduced due to the electric buses creating less sound and vibration.

Researchers determined replacing even one bus with an electric model could save approximately 25 tons of CO_2 from being emitted annually, even when factoring in the emissions for electricity produced for charging.

Source: Bangalore Metropolitan Transport Corporation (BMTC)

[14] Electric Fleet, CapMetro



Source: LakeTran

For more information:

- Coronavirus and Climate Change, Harvard T.H. Chan School of Public Health
- The Time Has Come to Electrify the Chicago Transit Authority Bus Fleet, Respiratory Health Association
- The impact of electric buses on urban life, International Association of Public Transport
- Electric buses' sustainability effects, noise, energy use, and costs, International Journal of Sustainable Transportation
- Increased e-buses in Delhi could reduce pollution-related mortality, morbidity: study, Mongabay
- Life cycle assessment of city buses powered by electricity, hydrogenated vegetable oil or diesel, Transportation Research Part D: Transport and Environment
- Quantifying the multiple environmental, health, and economic benefits from the electrification of the Delhi public transport bus fleet, estimating a district-wise near roadway avoided PM2.5 exposure, Journal of Environmental Management
- Air pollution and COVID-19 mortality in the United States: Strengths and limitations of an ecological regression analysis, Science Advances

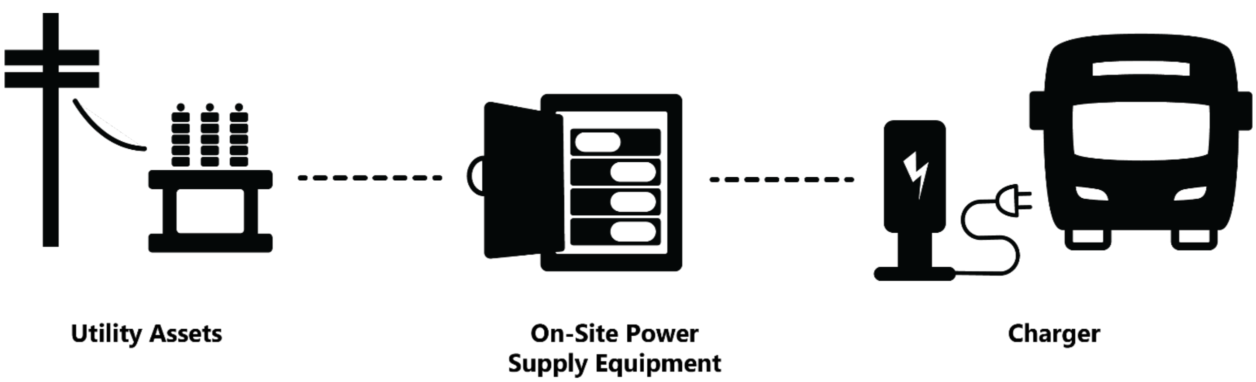
WHAT ARE THE INFRASTRUCTURE NEEDS OF ZERO-EMISSION BUSES?

Zero-emission buses are powered by an electric motor fueled by hydrogen or stored electricity, respectively. To support a transition from buses powered by fossil fuels to zero-emission bus fleets, agencies will need to rethink their vehicle fueling infrastructure. Adding new equipment for charging requires costs and considerations for engineering, design, materials, management, equipment, and construction. Agencies will want to stand up any needed charging or refueling infrastructure and associated maintenance procedures prior to acquiring the new buses.

Battery Electric Buses

Infrastructure Considerations at Bus Depots for Battery Electric Buses

Battery electric bus fleets require battery charging infrastructure to be installed upfront and over time to support an expanding fleet. Most battery electric buses will use high-powered direct current (DC) chargers. Fleet owners can maximize charging efficiency and reduce capital costs by procuring chargers with multiple plugs allowing multiple buses to charge from a single, high-powered DC source. For example, two to three buses could charge simultaneously, or sequentially, which could slow charging rates but requires the fleet staff to move the buses between chargers less often. Smaller vehicles, like vans or three-wheeled vehicles, can often be charged using lower-powered chargers.



Depot charging is currently the most common method for charging battery electric bus fleets. Several chargers will need to be installed on-site, depending on the size of the fleet. Agencies should work with their local electrical utility to determine the current level of electricity service and on-site electrical infrastructure already in place to identify additional equipment needs. Determining the right type and number of chargers will require agencies to consider space constraints, electricity rate structure, service needs, route variables (e.g., length, grade changes, surface type) and climate conditions. Additionally, the placement and layout of chargers should be planned to not inhibit other functions of the depot like cleaning, repairs, and parking.

Agencies should consider building out charging infrastructure that is flexible and adaptable to changing needs. They should first consider if the current footprint of the depot is sufficient to accommodate the required charging infrastructure, and if not, consider expanding the depot (if land use considerations allow) or opt for on-route charging. Agencies can also opt to store reserve power onsite using battery storage.

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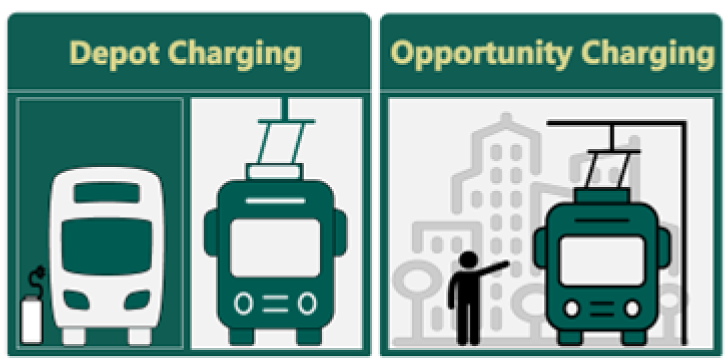
Energy Management Systems and software are also essential to optimize on-site/depot electricity assets, the performance of the buses and to minimize overall energy costs.

On-Route Charging Options

Agencies may consider implementing on-route charging of battery electric buses in place of – or in combination with – depot charging, especially for buses that travel longer routes. On-route charging, also known as opportunity charging, is a way to ensure battery electric buses have enough power to operate on long routes without the need to return to the depot to charge. On-route charging options include overhead or underground inductive wireless charging or wired/plug-in charging equipment along routes. These charging technologies are newer and can be more costly to build and to power than depot charging systems. They require fast, high-powered charger capabilities to enable bus batteries to be charged as quickly as possible, then continue on their routes. These charging applications can be strategically placed where multiple routes intersect to optimize the use and availability of charging.



In London, on-route pantographs provide additional charge to battery electric buses in less than 10 minutes. The amount of charge needed by an opportunistic charging system will depend on the size of the battery, length of the route, and the current of the power system. Pantograph setups can also be installed at terminals or depots for charging during the night or other off service times.

On-route plug-in charging equipment can enable multiple vehicle types to use the same charging infrastructure. As electric vehicles gain popularity, plug-in chargers can be found in parking lots and parking garages for use by battery electric cars, bicycles, and smaller battery powered transit vehicles, like vans and cutaway buses and rikshaws. On-route plug-in charging requires equipment that can sufficiently and quickly charge a bus battery and dedicated bus parking spaces, which can make it challenging to scale, especially for high-density areas. Increased on-route plug-in charging may be suitable for private or informal transportation.

On-route overhead charging allows bus batteries to be charged using pantograph or pin and socket dispensers. A pantograph is charging equipment mounted on the roof of the bus, or, in the inverted style, extends down to the roof of the bus from an overhead mast, that connects with the electrical system on the bus to charge the battery. This charging technology is often installed next to or as part of a bus stop or layover area.

Source: [Alliance for an Energy Efficient Economy]

Underground wireless charging allows buses to continuously be recharged through an inductive connection with copper coils installed underneath the road. The buses will need to have a special receiver mounted on the chassis. Underground wireless charging requires reconstruction of the roadways on which buses travel. This solution, like the overhead charging option, allows for buses to increase their range with smaller battery sizes. Because the buses are continuously charged along portions of their routes, this option can eliminate inactivity time that usually occurs while charging.

Underground inductive wireless charging most commonly takes place at a fixed location, like a layover point where the bus idles for 10 minutes or more. There are pilot projects, like the underground wireless charging system is being piloted on a two-kilometer bus route in Tel Aviv, Israel, that are demonstrating wirelessly charge vehicles that are in motion with wireless charging beneath the roadway.

Utility Considerations

Electricity production and distribution is closely matched with demand at any point in time. Historically, electricity demand is at its peak (and therefore rates can be more expensive) in the late afternoon and early evenings. Agencies can establish charging schedules that avoid peak demand times, such as charging overnight or in early morning hours. Depot stationary battery storage can also play a role in reducing peak energy demand. Agencies should work with their local power utilities to establish a back-up power plan in the event of power disruptions. Supplementary power supplies options include an on-site generator or secondary batteries. Agencies will also want to coordinate with their emergency management services to determine a fire safety for the vehicles, depot, and at any opportunity charging sites. Facilities can also consider supplementing the utility by self-generating power through solar panels or wind turbines.

Case Study: Montgomery County, Maryland Microgrid Bus Depot

In October 2022, Montgomery County, Maryland's transportation system completed construction on the Brookville Smart Energy Depot. This depot is a leader in energy innovation and self-sufficiency, and the third of its kind in the U.S. to feature a solar array and 6.5 MW microgrid. The 1.6 MW of solar panels are mounted atop parking canopies that double as charging spots for the county's almost entirely electric bus fleet. The depot also features backup 3 MW of backup batteries to store the solar power. Providing power onsite will provide the county with cost savings through locked in electricity rates. The microgrid functions as a power generation source that can provide the area's riders with reliable bus service, even in the event of long-term power outages. The County has a goal to complete their 400-vehicle fleet's transition to zero-emission buses by 2035. The county government established a public-private partnership with AlphaStruxure in May 2021 to design, finance, own, and operate the fleet transition and depot build.

Source: Montgomery County Completes Nation's Largest Bus Microgrid and Charging Infrastructure Project in Silver Spring

Wired Electric Buses

Infrastructure Considerations for Overhead Wire Network

Zero-emission wired electric buses, or trolleybuses, come equipped trolley poles to connect with the overhead wires and batteries to provide supplementary power. The amount of overhead wires and charging time needed under the wires to support a trolleybus is dependent on the route conditions and length, the bus size, battery size, and vehicle speed. Agencies should work with their public works and planning agencies to determine the most economic and environmental conservation approach to establishing an overhead wire system throughout the service area. There will be a predetermined amount of power to be provided to the wires; agencies will need to consult with the local power utilities to determine if the location and capacity of substations is sufficient.

Hydrogen Fuel Cell

Infrastructure Considerations at Bus Depots

Supporting a fleet of hydrogen fuel cell buses requires installing refueling stations equipped with storage tanks, pumps, vaporizers, gaseous buffer storage, and dispensers. This infrastructure would replace existing diesel fueling infrastructure once the conversion of the full fleet is complete, but during the conversion process, both hydrogen and diesel fueling infrastructure will need to be operational. Additionally, hydrogen can be generated on-site or delivered from off-site; agencies should consider which approach would be more appropriate based resource availability and current infrastructure. Setting up hydrogen fueling stations and fuel supplies can be complex and costly, but once in place, few additional infrastructure upgrades are needed to support the hydrogen fuel cell bus fleet. Agencies should work with hydrogen fuel suppliers to establish contingency plans or establish back-up supply stores in the event of supply disruptions. Hydrogen, though well sealed at the depot and when carried in tanks on the bus, is still a highly flammable substance. Agencies should work with emergency management officials to put a fire safety plan in place both on at the depot and on-route.

Case Study: Green Hydrogen in Champaign-Urbana, Illinois

The Champaign-Urbana Mass Transit District (MTD) is the first transit agency in the United States utilizing on-site renewable energy to power their hydrogen fuel cell buses. To generate the hydrogen, MTD has installed an electrolyzer that splits water into hydrogen and oxygen using solar power. Currently, the onsite hydrogen production can accommodate 12-15 hydrogen fuel cell buses. The 5,500 solar power was installed in partnership with the Urbana-Champaign Sanitary District on land provided by the Champaign Public Works Department.

Source: Champaign-Urbana Mass Transit District

MTD first began their fleet transition in 2009 by procuring hybrid diesel-electric buses. In 2021, the fleet procured two 60 ft hydrogen fuel cell electric buses – their first truly zero-emission buses. By 2040, MTD plans for more than half of the fleet to be made up of hydrogen fuel cell buses powered by onsite solar power.

Source: MTD – Project: Zero Emissions Technology, MTD Zero Emission Transition Plan

For more information:

- Preparing to Plug In Your Bus Fleet, American Public Transportation Association
- A Zero-Emission Transition for the U.S. Transit Fleet, Center for Transportation and the Environment
- This Electric Road Charges an EV While You Drive, AutoEvolution
- Energy transition: The necessary evolution of bus depots to accommodate electric vehicles with Comeca, CCI France UAE
- The Impact of Electric buses on Urban Life, The International Association of Public Transport
- Infrastructure for In Motion Charging Trolleybus Systems, The International Association of Public Transport

HOW CAN TRANSPORTATION AGENCIES DETERMINE THE BEST ZERO-EMISSION BUS OPTION?

Since there are many options for zero-emission bus types and power sources, agencies must evaluate the different vehicle types and power sources to determine the most effective zero-emission technology to deploy for their needs. Agencies are encouraged to research and evaluate different buses against the current service needs in a variety of conditions to assess the bus performance throughout the duration of its life. Scenario planning can be useful to help weigh different options and predict operational issues. In addition to aligning the type or size of vehicle and the capacity of the power source with service needs, other considerations for selecting a zero-emission bus include:

- **Scalability:** Which zero-emission bus technologies align with existing resources and lend themselves to local or regional funding sources to grow the fleet in the short-term?
- **Safety:** Are there safety concerns specific to your region that might favor one zero-emission technology over another?
- **Length of Route:** How do bus route lengths align with the range of zero-emissions buses?
- **Location of Service Area:** Is the service area located in a location exposed to extreme temperature or topographical features that could impact zero-emission bus performance and range?
- **Configuration of Service Area:** How could the region's layout or street configuration impact the need for longer ranges in a zero-emission bus?
- **Life-Cycle Costs:** What are the upfront costs of implementing a particular zero-emission bus type? What are the life-cycle costs? How will the fleet fund upfront and life-cycle costs?
- **Common Systems Issues:** What are the most common issues when operating zero-emission vehicle technologies in the short-term? In the long-term?
- **Parts Supply:** Are there multiple manufacturing options to diversify the supply of vehicles and parts? Is there adequate access to qualified service technicians?
- **Reliable Access to Fuel/Electricity**: How readily available and accessible is the supply of hydrogen or electricity in the area? How volatile is the supply?
- **Cost of Fuel/Electricity:** What are local power and hydrogen rates? How are they likely to fluctuate in the coming years?
- **Accessibility:** How will accommodating batteries in the design of the bus effect passenger seat layout?

Case Study: Zero-Emission Buses and Winter Weather Conditions in Edmonton, Canada

Edmonton Transit Service (ETS), the transit agency in the City of Edmonton, Canada, has incorporated 60 electric buses into their transportation services. The majority of the electric buses operate out of the newly built Kathleen Andrew's Transit Garage, equipped with indoor bus parking with overhead pantograph chargers. ETS aims to operate an emissions-neutral public transportation fleet by 2050. Extremely cold temperatures, like those experienced during Edmonton winters, can impact the range and battery capacity of battery electric vehicles. Colder temperatures can slow chemical reactions, which can slow charging, and in some vehicles the climate control pulls power directly from the battery. Depending on the design and configuration of the bus heating system, colder weather also may result in electric buses additional battery power to heat the interior of the bus, which can affect battery range. Prior to the current electric bus deployment, ETS conducted a trial of two different battery electric buses to determine if electric buses could meet the needs of the ETS service area, especially in winter weather conditions. According to the Feasibility Study report released in 2016, the battery electric buses would be able to perform as reliably as the diesel bus fleet with appropriate planning and training, noting that the trial took place during an unseasonably warm winter in Edmonton. There were no observed issues relating energy usage issues and colder outdoor temperatures, but the trial did show that the use of electric heaters could decrease range by 15-25percent.

Sources: ETS Electric Bus Feasibility Study, Electric Buses: Edmonton is a Canadian Leader

For more information:

- Guidebook for Deploying Zero-Emissions Transit Buses, Transportation Cooperative Research Board
- Zero-Emission Fleet Transition Plan – Element 6: Workforce Evaluation Tool, Federal Transit Administration

HOW SHOULD TRANSPORTATION AGENCIES ENGAGE STAKEHOLDERS IN A TRANSITION TO ZERO-EMISSION BUS FLEETS?

Agencies should create a collaborative, effective, and equitable process for planning to a public transportation system using zero-emission buses. Stakeholders, including the communities that will be served by the service, vehicle and equipment manufacturers, first responders and emergency services, and transit agency staff, will need to be involved throughout the process for their input, technical expertise, user experiences, and more.

Community

- Prior to deployment and during the planning process, agencies should pursue opportunities to gauge public perception about a possible zero-emission bus fleet, establish platforms for two-communicate with concerned stakeholders, and address concerns as they arise.
- Agencies should engage the community to gather input on transit needs and the benefits and challenges of different zero-emission bus types and technologies.
- Agencies should communicate early and often with populations that are expected to use transit to set expectations about the changes that zero-emission bus fleets will bring and any related service disruptions.

Vehicle and Equipment Manufacturers

- Agencies should work with manufacturers early in the process to estimate costs and procurement timelines to confirm they can meet the anticipated needs.
- Agencies should work with manufacturer representatives for training and oversight during the installation and initial deployment to ensure optimal vehicle operation and performance.

First Responders and Emergency Services

- Agencies should coordinate with first responders and emergency management officials to incorporate safety and emergency response training.
- Agencies should establish plans and procedures, in coordination with local emergency services, to respond to the case of accidents at the depot or on-route.
- Representatives from your local power utility or bus manufacturer can be called upon to train staff in high-voltage systems safety when utilizing battery electric and wired electric buses.

Transit Agency Staff

- Transit staff should work with operators and planners to establish baseline weather conditions, traffic conditions, driving habits, route topography for modeling different bus types and service scheduling.
- Staff interacting with the buses and equipment in the depot or on-route need to have some degree of training managing a high-voltage charging system and responding to potential fire safety incidents.
- Zero-emission bus deployments will have different operational characteristics from conventionally fueled vehicles, and agencies should invest in trainings, workshops, and other capacity-building opportunities to support implementing zero-emission vehicle technologies and remaining resilient as technologies evolve.

- For battery electric buses, transportation agencies will need to manage the sharing of on-route chargers and continually engage operators to determine the necessary schedule changes to accommodate range limits.

Case Study: Toronto Transit Commission (TTC) – Electric Bus Trial

The Toronto Transit Commission (TTC) services over 600,000 passengers a day on over 150 bus routes, 9 streetcar routes, 3 subway lines, and 1 rapid transit line. As part of TTC's Green Fleet Program, the transit agency has committed to be 50 percent zero emissions by 2028-2032 and 100 percent zero emissions by 2040.

To date, TTC has deployed 60 all-electric buses from three different manufacturers TTC has engaged with the National Research Council of Canada, Transport Canada, and Environment and Climate Change Canada to evaluate the performance of this deployment over multiple years of in-service operations. This study includes the collection of data from in-use operations along with an assessment of the reliability, maintainability, and operability of the electric buses. The resulting reports will detail the data, analytical methods, and findings of electric vehicle performance throughout various seasons. The evaluation also included three sets of head-to-head tests where one bus from each manufacturer was tested in a controlled manner on selected routes.

To date, the trial has saved 879,765L of diesel fuel, amounting to over a $200,000 difference in cost between diesel fuel and the cost of charging. TTC has greenlit the procurement of 300 more all-electric buses that will be delivered between 2024 and 2026.

Sources: TTC Green Initiatives, TTC to Discuss Next Steps for Fleet Electrification at Upcoming Board Meeting, TTC to Discuss Next Steps for Fleet Electrification at Upcoming Board Meeting

For more information:

- Stakeholder Collaboration Models for Public Transport Procurement of Electric Bus Systems, International Journal of Sustainability Policy and Practice
- Guidebook for Deploying Zero-Emission Vehicles, Transportation Cooperative Research Program

HOW CAN TRANSPORTATION AGENCIES GET THE MOST OUT OF THEIR NEW ZERO-EMISSION BUS FLEETS?

There are several things fleets can do to maximize the benefits of their zero-emission bus fleets. These include:

- Inspections and testing
- Personnel training
- Data collection and monitoring

Inspections and Testing

Once an agency has thoroughly evaluated the viability of deploying a zero-emission bus fleet for their transit needs and purchased a preferred bus type and technology, they must undergo inspections and testing prior to full revenue service. These are especially crucial steps for vehicles that are housing newer technology. Some fleet owners may have in-house inspection services, while other may contract with a third-party inspection service. Inspections should be comprehensive to ensure that the technology and vehicles were manufactured properly and fit the context in which they will operate. Testing should be conducted to determine expected versus actual performance, safety features, range, maneuverability, battery power (if battery electric), passenger capacity, and charger/fueling equipment compatibility. On-route testing can also help determine how the new vehicle operational performance aligns with the service area characteristics. Running the bus through scenarios with a combination of travelers of different ages and mobilities and routes with varying curbs heights and gradients can assess potential deficiencies in ease of access for different kinds of riders.

Personnel Training

Zero-emission buses and their associated charging and fueling equipment will include elements and functions that will be unfamiliar to your operations, maintenance, and facilities staff. Ensuring adequate training for all staff who interact with the buses will help ensure efficient, effective, and safe operations. Continuous educational opportunities should be provided to ensure personnel stay informed as zero-emission technologies emerge and evolve.

Data Collection and Monitoring

Data collection and monitoring can help agencies assess the performance of their zero-emission bus fleet. Performance metrics can also be used to leverage local or regional funding opportunities for alternative vehicles. Agencies should establish key performance indicators (KPIs) to evaluate the costs and benefits to operating a new zero-emission bus fleet. Relevant KPIs for zero-emission buses include:

- Fuel cost per distance travelled
- Energy economy/performance
- Ridership (comparing between existing fleet and zero-emission fleet)
- Life-cycle costs

- Emission reductions
- Availability and utilization
- Battery state of health (for zero-emission buses with batteries)
- Downtime/uptime for buses and infrastructure

Strategies in Action Case Study

Large-Scale Electric Bus Deployment in Santiago, Chile

In Santiago, Chile, the public transportation system is replacing its current bus fleet with zero-emission vehicles. Santiago is home to the largest bus system outside of China and is one of the most populous cities in South America. The country established a national electromobility strategy to guide the phasing-out of all vehicles run by fossil fuels by 2045, including a goal to transition all public transportation vehicles to electric models by 2040. The city's system currently has 776 electric buses in operation in Santiago, with the long-term goal for a total number of 17,000 electric buses by 2035. This project is set to be the largest fleet conversion to zero-emission vehicles in Latin America.

The project was a joint effort by the private bus fleet operator (Metbus), RED, the public transport agency for the Santiago Metropolitan Region, the Chilean Ministry of Transport, a private contractor and owner of the charging infrastructure and buses, the bus manufacturer, and the financial agency who manages fare collection and operator payments. The separation of ownership and operation of the buses allowed the government to best navigate the costs of procuring the buses upfront and managing the operational needs of a large-scale electric bus deployment. To rollout a large scale zero-emission bus fleet, the governments and their partners took on a phased approach starting in 2017:

- In 2017, the project kicked off a year-long pilot project with two standard electric buses.
- From 2018-2020, they procured 433 electric standard buses.
- In 2019, they conducted a two-month pilot program with an articulated electric bus.

After the pilot and establishing a large-scale fleet operating profile, operators concluded no route changes were needed to accommodate the charging needs of the buses. All buses are charged fully overnight on one of 218 chargers at the depot. Additionally, all bus routes go through the Avenida Grecia, which is a collection of five 100 percent electric bus terminals to do partial charging during the day.

IS YOUR TRANSPORTATION SYSTEM A GOOD FIT FOR ZERO-EMISSIONS BUSES?

- Shorter Route Lengths
- Smaller Vehicle/Paratransit Fleets
- High Share of Renewable Energy in Power Supply Mix
- Service Areas with Flat Terrain
- Established Leadership Interest and Buy-in

For more information:

- Guidebook for Deploying Zero-Emission Transit Buses, Transit Cooperative Research Program
- Can Chile Ditch Combustion Buses and Cars by 2035?, Diálogo Chino
- Estrategia Nacional de Electro-Movilidad, Gobierno de Chile
- Metbus Pioneering E-Bus Deployments in Santiago, C40 Knowledge Hub
- From Pilots to Scale: Lessons from Electric Bus Deployments in Santiago de Chile, Center for Mathematical Modeling - University of Chile
- Latin America Clean Bus in LAC Lessons from Chile's Experience with E-Mobility, The World Bank
- ZEBRA (2020) Santiago Metbus E-Bus Deployments Case Study, C40 Knowledge Hub

GLOSSARY

Carbon dioxide (CO_2): A naturally occurring gas, CO_2 is also a by-product of burning fossil fuels (such as oil, gas and coal), of burning biomass, of land-use changes (LUC) and of industrial processes (e.g., cement production). It is the principal anthropogenic GHG that affects the Earth's radiative balance. It is the reference gas against which other GHGs are measured and therefore has a global warming potential (GWP) of 1. See also Greenhouse gases (GHG).

Climate change: Climate change refers to a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use. Note that the Framework Convention on Climate Change (UNFCCC), in its Article 1, defines climate change as: 'a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.' The UNFCCC thus makes a distinction between climate change attributable to human activities altering the atmospheric composition and climate variability attributable to natural causes.

Depot: Maintenance facility where mechanics and other maintenance department personnel provide basic readiness inspection (e.g., tire pressure, oil/fluid levels, etc.) and light repair (e.g., mirror replacement) or service (e.g., sweeping) on revenue vehicles. Revenue vehicles may be stored here overnight or between being placed into revenue service.

Fossil fuels: Carbon-based fuels from fossil hydrocarbon deposits, including coal, oil, and natural gas.

Global warming: The estimated increase in global mean surface temperature (GMST) averaged over a 30-year period, or the 30-year period centered on a particular year or decade, expressed relative to pre-industrial levels unless otherwise specified. For 30-year periods that span past and future years, the current multi-decadal warming trend is assumed to continue.

Greenhouse gases (GHG): Greenhouse gases are those gaseous constituents of the atmosphere, both natural and anthropogenic, that absorb and emit radiation at specific wavelengths within the spectrum of terrestrial radiation emitted by the Earth's surface, the atmosphere itself and by clouds. This property causes the greenhouse effect. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary GHGs in the Earth's atmosphere. Moreover, there are a number of entirely human-made GHGs in the atmosphere, such as the halocarbons and other chlorine- and bromine-containing substances, dealt with under the Montreal Protocol. Beside CO_2, N_2O and CH_4, the Kyoto Protocol deals with the GHGs sulfur hexafluoride (SF_6), hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs).

Hydrogen: Hydrogen is a clean fuel that, when consumed in a fuel cell, produces only water. Hydrogen can be produced from a variety of domestic resources, such as natural gas, nuclear power, biomass, and renewable power like solar and wind. These qualities make it an attractive fuel option for transportation and electricity generation applications. It can be used in cars, in houses, for portable power, and in many more applications.

Impacts (consequences, outcomes): The consequences of realized risks on natural and human systems, where risks result from the interactions of climate-related hazards (including extreme weather and climate events), exposure, and vulnerability. Impacts generally refer to effects on lives; livelihoods; health and well-being; ecosystems and species; economic, social and cultural assets; services (including Annex I Glossary AI 552 ecosystem services); and infrastructure. Impacts may be referred to as consequences or outcomes, and can be adverse or beneficial.

Infrastructure: Includes, at a minimum, the structures, facilities, and equipment for, roads, highways, and bridges; public transportation; dams, ports, harbors, and other maritime facilities; intercity passenger and freight railroads; freight and intermodal facilities; airports; water systems, including drinking water and wastewater systems; electrical transmission facilities and systems; utilities; broadband infrastructure; and buildings and real property. Infrastructure includes facilities that generate, transport, and distribute energy.

Life-cycle: Evolution of a system, product, service, project or other human-made entity from conception through retirement.

Particulate Matter (PM): A mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. Particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Particulate matter contains microscopic solids or liquid droplets that are so small that they can be inhaled and cause serious health problems.

Resilience: The capacity of social, economic and environmental systems to cope with a hazardous event or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure while also maintaining the capacity for adaptation, learning and transformation. This definition builds from the definition used by Arctic Council (2013).

Public Transportation: Transportation by a conveyance that provides regular and continuing general or special transportation to the public.

Transportation Sector: A sector that consists of all vehicles whose primary purpose is transporting people and/or goods from one physical location to another.

Zero-Emission: A vehicle that produces no tailpipe criteria pollutants, toxic air contaminants, or GHG emissions.

SELF-ASSESSMENT QUESTIONS

Take some time to think through transportation and infrastructure in your country, and how it could best support a zero-emission fleet. Consider the following questions:

- **Does the leadership in your organization support the transition to a zero-emission bus fleet?**
- **What sources of funding are available for the purchase and deployment of a zero-emission bus fleet?**
- **How does the transportation sector in your community currently procure vehicle fleets?**
  - How often does your community currently retire and replace buses?
- **How many buses would your community transition to zero-emissions?**
- **What public transportation bus size is most common in your community?**
- **What bus size would best suit the common routes, conditions, and passenger capacities?**
- **What vehicle range would best suit the common routes, conditions, and passenger capacities of your transit operations?**
- **What supplemental infrastructure would be needed to enable zero-emission buses?**
- **What infrastructure changes would need to be made to accommodate transitioning the current bus fleet and allow for future expansion?**
- **What grid upgrades may be necessary?**
  - What conditions are prevalent in your country that might influence the placement of charging infrastructure and supplementary equipment in safe and reliable locations (e.g., weather hazards, high traffic areas, wildlife populations, etc.)
- **How do major electric utilities price electricity, and how would that impact vehicle charging schedules?**
- **How is workforce development integrated into the existing transportation system?**
  - Is there workforce development capacity to support the training and skills development associated with zero-emission buses?
  - How does your government plan to address those challenges?

For more information about Zero Emission Buses, or to learn more about partnering with Momentum, please contact us at momentum@dot.gov