City of Mankato

Zero-Emission Bus
Fleet Transition Study

Presented by Center for Transportation and the Environment

April 22, 2025

Table of Contents

List of Figures

List of Tables

List of Acronyms

A&E	Architecture and Engineering
APTA	American Public Transportation Association
BEB	Battery Electric Bus
BEV	Battery Electric Vehicle
CBPA	Clean Bus Planning Awards
CTE	Center for Transportation and the Environment
EoL	End of Life
ESS	Energy Storage System
EV	Electric Vehicle
FCEB	Fuel Cell Electric Bus
FCEV	Fuel Cell Electric Vehicles
FTA	Federal Transit Administration
GHG	Greenhouse Gas
HV	High Voltage
HVAC	Heating, Ventilation, and Air Conditioning
ICE	Internal Combustion Engine
kW	Kilowatt
kWh	Kilowatt Hour
kWh/mi	Kilowatt-hour/mile
LV	Low Voltage
MW	Megawatt
MWh	Megawatt-hours
OEM	Original Equipment Manufacturer
SOC	State of Charge
ZEB	Zero-Emission Bus
ZEBRA	Zero Emission Bus Resource Alliance

Executive Summary

Project Overview

This project is funded by the Joint Office of Energy and Transportation (Joint Office) through the Clean Bus Planning Awards Program (CBPA). The Joint Office provides free technical assistance on planning and implementation of zero-emission charging and fueling infrastructure as well as for zero-emission transit and school buses. The National Renewable Energy Laboratory (NREL) administers the program.

NREL engaged the Center for Transportation and the Environment (CTE) to develop a comprehensive plan to transition City of Mankato Transit System (Mankato) full fixed-route system of buses to zero-emission buses (ZEBs).

The results of the study will inform Mankato of the estimated costs, benefits, constraints, and risks of the transition to a zero-emission fleet and will guide future planning and decision-making.

Mankato Transition Scenarios

The City of Mankato indicated an openness to hydrogen buses where feasible in addition to battery electric, having cited that fleet colleagues in Minneapolis are having some negative battery electric bus experiences. As a result, CTE included both battery electric bus (BEB) and fuel cell electric bus (FCEB) scenarios in the transition plan assessments to best understand the agency's clean energy options. Mankato can likely take advantage of FCEB technology or use on route charging to increase feasibility for BEB replacements. Therefore, CTE incorporated BEB Depot Only, BEB Depot and On Route Charged, and FCEB Only in the ZEB scenario analysis.

Throughout the transition period (2024 – 2040), CTE lays out key points where Mankato will need to decide which fueling technology to invest in. Due to planned site upgrades at Mankato's garage, all transition to ZEBs was pushed to begin in 2028. As regional hydrogen projects and zero-emission technology grow, CTE recommends Mankato revisit this plan in late 2026 or early 2027.

Project Goals

The primary goals of this project were to assess the feasibility of transitioning the entirety of Mankato's fixed-route fleet to 100% zero-emission technology and to understand technology options, transition timelines, and relevant costs. Within the scope of the plan, CTE estimated capital and operational costs, planned project phases and timelines, and determined infrastructure requirements necessary to adopt ZEB fleet vehicles.

After discussions with Mankato's project team, CTE assumed a loose target of 100% ZEB by 2040.

Zero-Emission Transition Overview

The zero-emission technologies considered in this study include BEBs and FCEBs. These buses have similar electric drive systems that feature a traction motor powered by a battery. The primary differences between BEBs and FCEBs are the respective amount of battery storage and the method by which the batteries are recharged. The electric drive components and energy source for a diesel bus, BEB, and FCEB are illustrated in **Figure 1.**

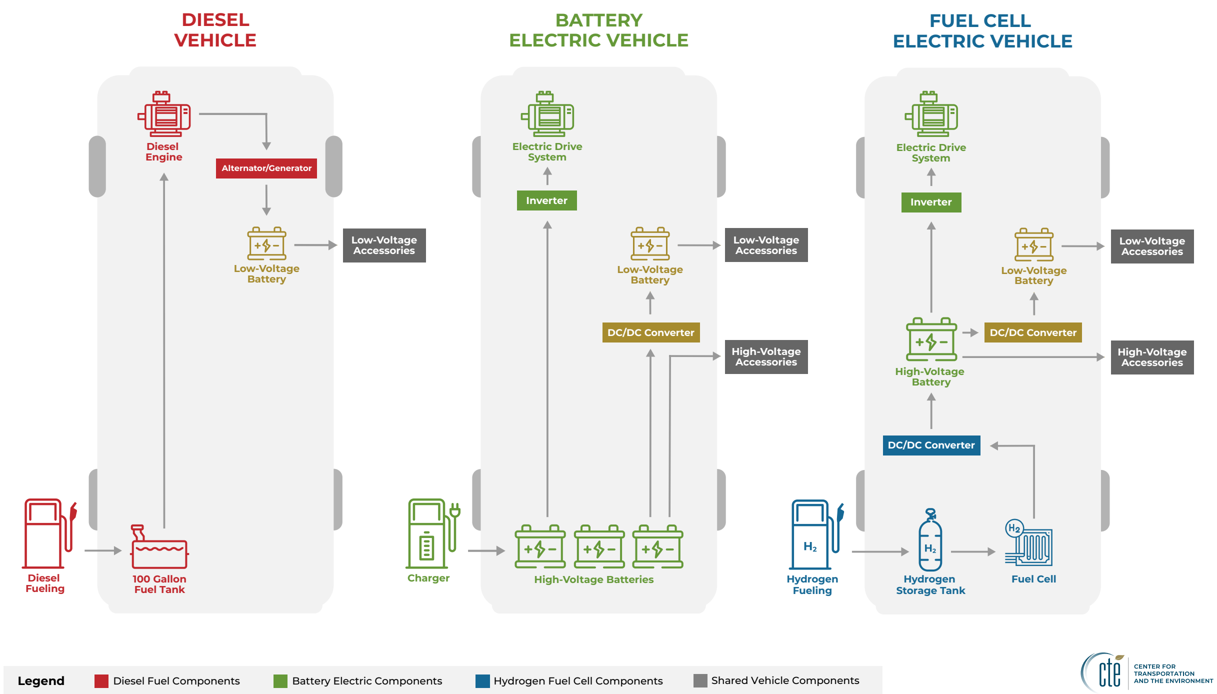


Figure 1 - Battery and Fuel Cell Electric Bus Schematic compared to Diesel

CTE worked closely with Mankato staff throughout the project to develop an approach, define assumptions, and confirm the results. The approach for the study is based on analysis of three ZEB technology scenarios compared to a baseline scenario:

0. Baseline (Current Fleet: Diesel Buses)
1. BEB Depot Charged Only
2. BEB Depot and On-Route Charged
3. FCEB Only

To accurately forecast service feasibility for each of these zero-emission technologies, CTE assessed the block feasibility of Mankato's current service schedules. A **block** is the series of trips assigned to a single bus from the time of garage pull-out to its return pull-in, including deadhead, in-service hours, and layover. **Block feasibility** is determined by comparing the estimated energy required to operate a BEB on a given block to the usable onboard energy storage capacity of the bus. If the block energy requirement exceeds the usable onboard storage capacity, the block is considered unachievable. If the block energy requirement does not exceed the usable onboard storage capacity, the block is considered achievable. To calculate the block feasibility of BEBs, CTE modeled a market representative vehicle, which had specifications that represent the average of the available vehicles in its class. Although not a zero-emission scenario, this study also includes a baseline scenario that is used to compare the cost of a ZEB transition to a "business-as-usual" case.

The **BEB Depot Charged Only Scenario** was developed to model an option with a fleet consisting entirely of battery electric buses that can meet existing service range requirements. Fleets consisting of depot-charged BEBs may not be able to meet the range requirements of present routes and would require additional time to return to the depot to mid-day charge or implement on-route charging. According to CTE's modeling, 0% of Mankato's blocks are achievable with BEB cutaways by 2040, 25% of Mankato's blocks are achievable with depot-charged 35' BEBs by 2040, and 75% of Mankato's blocks are achievable with depot-charged 40' BEBs by 2040. A shortcoming of a BEB only fleet is that it may be less resilient than a mixed fuel or internal combustion engine (ICE) fleet since interruptions to the power supply could jeopardize the operability of the fleet. This hurdle can be mitigated by installing back-up power supplies and planning contingencies.

The **BEB Depot and On Route Charged Scenario** was developed to mitigate the gaps in feasibility, as the Feasibility Assessment determined that the range of market average BEBs would not be sufficient to meet all Mankato's service requirements with just overnight, depot-charging. On-route charging allows Mankato to meet all their service needs under the following conditions:

- 1x cutaway block assigned to 30' vehicles would require an estimated **22 minutes** of on-route charging throughout the service day.
- 6 x 35ft blocks would require an estimated **4-27 minutes** of on-route charging throughout the service day.
- 1 x 40ft blocks would require an estimated **6 minutes** of on-route charging throughout the day.

The **FCEB Only Scenario** was developed to help identify benefits and mitigate challenges associated with switching the entire fleet to fuel cell technology. A FCEB fleet can replace diesel buses in a 1:1 ratio and avoids the need to install two types of fueling infrastructure that a mixed fleet scenario would require. Additionally, hydrogen fueling infrastructure is less expensive at scale compared to a large-scale fleet transition to BEBs. Though hydrogen is a more expensive fuel than electricity at current market prices, applying a sensitivity analysis to hydrogen costs shows that it will likely become more competitive compared to the cost of electricity by 2040. A FCEB Only fleet lacks the redundancy provided by having alternative technologies and fuel types in a mixed fleet, and current market prices for FCEBs are higher than BEBs.

The assessment follows CTE's **ZEB Transition Planning Methodology**, a complete set of analyses used to inform agencies planning the conversion of diesel fleets to zero-emission technologies. The methodology consists of data collection, analysis, and evaluation stages; these stages are sequential and build upon findings in previous phases. In the evaluation stage, CTE assesses energy efficiency and energy use by the buses to calculate the distance that a bus can travel on a single charge or hydrogen fill. CTE collected sample data from multiple Mankato routes. Using market representative ZEB battery capacity specifications for given bus lengths, CTE estimated range and energy consumption on Mankato routes and blocks under varying environmental and passenger load conditions. Once this information was established, CTE completed the following assessments to develop cost estimates for each of the scenarios.

Baseline Scenario

Mankato's Baseline fleet consists of thirty-two buses, fourteen of which are biodiesel and the other eighteen are gasoline. During the transition period, the total cost of ownership for the Baseline scenario is less than the other three scenarios analyzed at approximately $59.55 million. There are significant costs associated with infrastructure procurement for BEB charging and FCEB fueling, but because the infrastructure for the existing fleet is already in place, the Baseline scenario doesn't incur the same infrastructure costs. This scenario estimates a 0% ZEB fleet by 2040.

Battery Electric Bus (BEB) Depot Only Scenario

For a BEB fleet charged at only the depot location, ZEB transition costs are projected to be approximately $65.3 million where 19% of Mankato's fleet is replaced with BEBs by 2040 without adding buses. The difference in cost between the Baseline and BEB Depot Only scenario is the result of higher capital costs for battery electric buses compared to ICE buses and from the significant infrastructure investment necessary for charging infrastructure.

BEB Depot and On Route Charged

For an all-BEB fleet charged at both the depot location and on-route, ZEB transition costs are projected to be approximately $73.2 million over the length of the transition, from 2024 to 2040. This scenario estimates a 41% ZEB fleet by 2040 and is approximately $8 million more than the BEB Depot Only scenario to account for the increased infrastructure and fueling required to accommodate on-route charging.

Fuel Cell Electric Bus (FCEB) Only Scenario

In the FCEB Only scenario, ZEB transition costs are estimated at approximately $104.9 million and replace 100% of Mankato's fleet with FCEBs by 2040. Due to the limited deployment of FCEBs in service in the United States, capital costs for these buses and hydrogen fuel costs are expected to remain high in the near-term due to low market competition. This is expected to decrease in the long-term, although more data are needed to adequately forecast these cost decreases. As such, this study uses current FCEB and infrastructure pricing for the entirety of the ZEB transition period.

Given the necessary reliance on early-adoption maintenance data, FCEB maintenance cost data has a wider margin of error than BEB cost estimates. More concrete data will become available, and costs will likely fall, as a larger number of FCEBs and hydrogen infrastructure are deployed. Significant investments in hydrogen infrastructure may take years to materialize.

Transition Summary

Table 1 and **Figure 2** show the total costs from the assessments, by scenario and by assessment. The Baseline scenario is the lowest total cost option while the FCEB Only scenario is the highest cost option. Compared to the Baseline scenario, The BEB Depot Only Scenario is the next lowest cost option for total cost, fleet cost, fuel cost, and infrastructure cost. For maintenance costs, the BEB Depot Only Scenario is the lowest cost option across all scenarios.

The FCEB Only and BEB Depot and On Route Charged scenarios are the highest cost options as FCEB vehicles are the most expensive and on-route chargers require additional infrastructure and charging. The cost of hydrogen is likely to decrease over time and FCEBs function similarly to ICEs, so there are operational advantages outside of cost such as a 1:1 range equivalent and maintenance.

Table 1 - Total Cost of Ownership, Incremental Cost Compared to Baseline

Assessment	Baseline	ZEB Scenario 1 (BEB Depot)	ZEB Scenario 2 (BEB Depot & ORC)	ZEB Scenario 3 (FCEB Only)
Fleet	$45,665,000	$49,270,000	$53,934,000	$71,401,000
Fuel	$5,904,000	$5,930,000	$6,422,000	$15,521,000
Infrastructure	-	$2,228,000	$4,916,000	$8,200,000
Maintenance	$7,977,000	$7,823,000	$7,977,000	$9,824,000
Total	$59,546,000	$65,251,000	$73,250,000	$104,946,000
Compared to Baseline	-	+$5,705,000	+$13,703,000	+$45,400,000
% ZEB	**0%**	**19%**	**41%**	**100%**

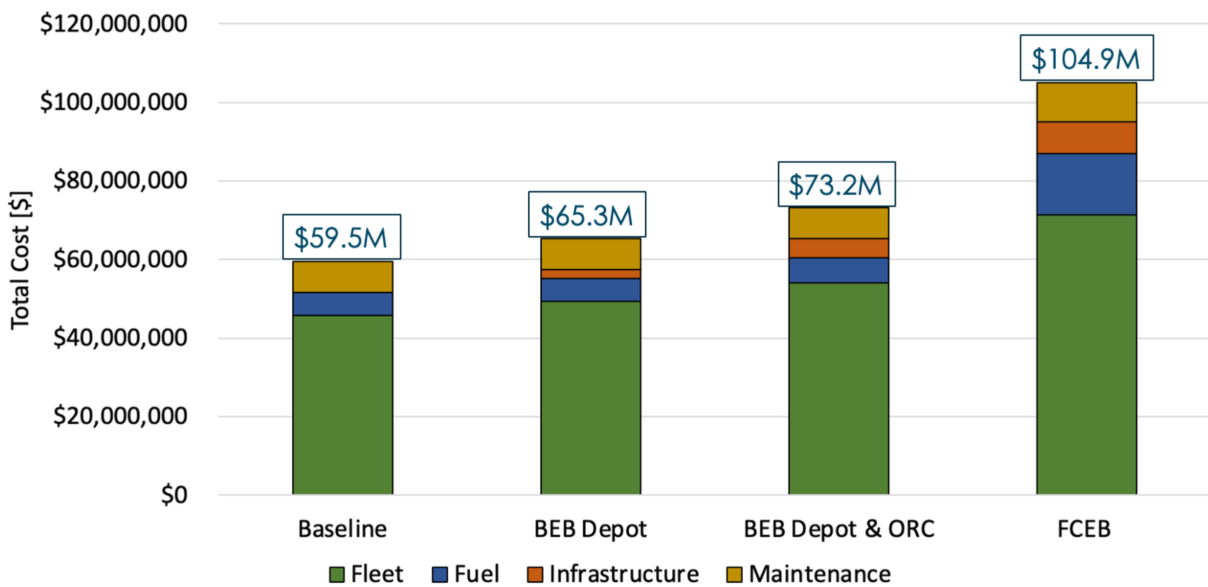


Figure 2 - Total Cost of Ownership, by Scenario

Project Risks

In addition to the uncertainty of technology improvements, there are other risks to consider in trying to estimate costs over the transition period. Although current BEB range limitations may be improved over time because of advancements in battery energy capacity and more efficient components, battery degradation may result in range limitations, which is a cost and performance risk to a BEB fleet over time. In emergency scenarios that require use of BEBs, agencies may face challenges performing emergency response roles expected of them in support of fire and police operations.

Furthermore, fleetwide energy service requirements, power redundancy, and resilience may be difficult to achieve at any given depot in a BEB scenario. Although FCEBs may not be subject to these same limitations, higher capital equipment costs and availability of hydrogen may constrain FCEB solutions. Mankato should evaluate the costs and benefits of various alternatives to mitigate the risks of power outages, hydrogen disruptions, and natural disaster impacts.

Project Benefits

Zero-emission buses offer a wide range of benefits not only for the agencies deploying them but also for the communities they serve. There are significant environmental benefits associated with the transition to ZEB technology. For agencies, the total cost of ownership for a ZEB fleet has the potential to be equal to or less than a fleet of ICE vehicles. ZEBs are also significantly quieter than traditional vehicles which can help with noise reduction.

Widespread adoption of zero-emission bus technology has the potential to significantly reduce greenhouse gas (GHG) emissions resulting from the transportation sector. Through the reduction of tailpipe emissions, ZEBs benefit the environment by delivering better air quality and health benefits to the passengers and neighboring areas which tend to be disproportionately low-income and historically disadvantaged communities. Mankato is committed to implementing environmentally friendly policies and reducing its carbon footprint.

Recommendations

Given these considerations, the recommendations for Mankato are as follows:

1) **Select a preferred scenario to refine and remain proactive with ZEB deployment grants:** This Transition Plan was developed to present Mankato with options for transitioning to a fully zero-emission fleet. The Plan will put forth Mankato's vision for a ZEB Transition and will act as a living document to help the agency plan grant funding requirements. As a greater proportion of Mankato's fleet converts to ZEB technology, auxiliary equipment, hardware, and software will be needed to ensure a successful fleet transition. Mankato should continue to remain proactive in the purchase and deployment of ZEBs and their associated systems by taking advantage of various grant and incentive programs.
2) **Monitor local and regional developments:** In the zero-emission technology sector, developments at the local level can have the ability to catapult the industry forward. When local bus OEMs or fuel providers enter the zero-emission market, it can spark technological innovation and cost reduction. Neighboring transit agencies can also work together through group purchasing agreements and lobbying efforts to reduce purchase costs or increase funding opportunities.
3) **Evaluate requirements for workforce and stakeholders:** Understand the impacts that the ZEB transition will have on key stakeholders and identify changes needed to accommodate workforce development. Evaluate the tradeoffs for various alternatives to reduce the risk for stakeholders of all levels from extreme weather events, power outages, equipment failure, and fuel disruptions, and allow Mankato to meet all first responder requirements.
4) **Match the individual bus technology to the individual route and blocks:** Mankato should consider the strengths of given ZEB technologies and focus those technologies on routes and blocks that take advantage of their efficiencies and minimize the impact of the constraints related to the respective technologies. These technologies cannot follow a one-size-fits-all approach from either a performance or cost perspective. Matching the present technology to the present service levels will be a critical best practice.

The transition to ZEB technologies represents a fundamental paradigm shift in bus procurement, operation, maintenance, and infrastructure. It is only through a continual process of deployment with specific goals for advancement that the industry can achieve the goal of economically sustainable, zero-emission public transit.

Introduction

City of Mankato Transit System (Mankato) is conducting a feasibility study which looks at converting its bus fleet to 100% zero-emission buses (ZEB) by 2040. To explore Mankato's options for meeting this fleet electrification target, this transition study presents three zero-emission fleet transition scenarios and uses Mankato's current fleet operations as a baseline to measure the effects of each transition scenario. For each scenario, this study assesses bus purchase costs, fuel costs, infrastructure investments, and maintenance costs. Additionally, this study also considers Mankato's local needs and conditions, namely considering resilience, redundancy, and emergency response adaptation options. By using real data provided by Mankato, its partners, and industry-reliable sources in the assessments, Mankato will be able to draw insights to select the optimal zero-emission transition scenario.

Transit Agency's Name: City of Mankato Transit System (Mankato)

Mailing Address:

10 Civic Center Plaza
Mankato, MN 56001

Contact Information

Schloesser, Shawn
City of Mankato Transit System
Associate Director- Transportation Planning Services
sschloesser@mankatomn.gov

Owens, Todd
City of Mankato Transit System
Transit Superintendent
towens@mankatomn.gov

Baird, Rick
City of Mankato
Environmental Sustainability Coordinator
rbaird@mankatomn.gov

Konz, Mark
City of Mankato
Director of Planning and Development Services

mkonz@mankatomn.gov

Sparks, Ben
City of Mankato
Central Garage Superintendent
bsparks@mankatomn.gov

Mike Jones
National Renewable Energy Lab (NREL)
Transportation Deployment Project Leader
mike.jones@nrel.gov

About the City of Mankato Transit System

History

City of Mankato's Transit System (Mankato) is the primary provider of mass transportation in the urbanized area which includes Mankato and North Mankato, Minnesota.

Service Area and Bus Service

The Mankato Transit System offers a range of bussing transportation options including their Fixed-Route, Kato Flex, Paratransit, and Summer Only: Kato Go Play service.

Mankato Transit System offers 15 fixed routes. Kato Flex is a shared ride, curb-to-curb service for individuals residing in areas where there is no fixed route bus service connecting neighborhoods to the Mankato Transit System network. The Paratransit/Mobility Bus Service of the Mankato Transit System is a shared ride, origin-to-destination complimentary service for eligible individuals with disabilities.

A map of Mankato's current system is shown in **Figure 3** and **Appendix A**.

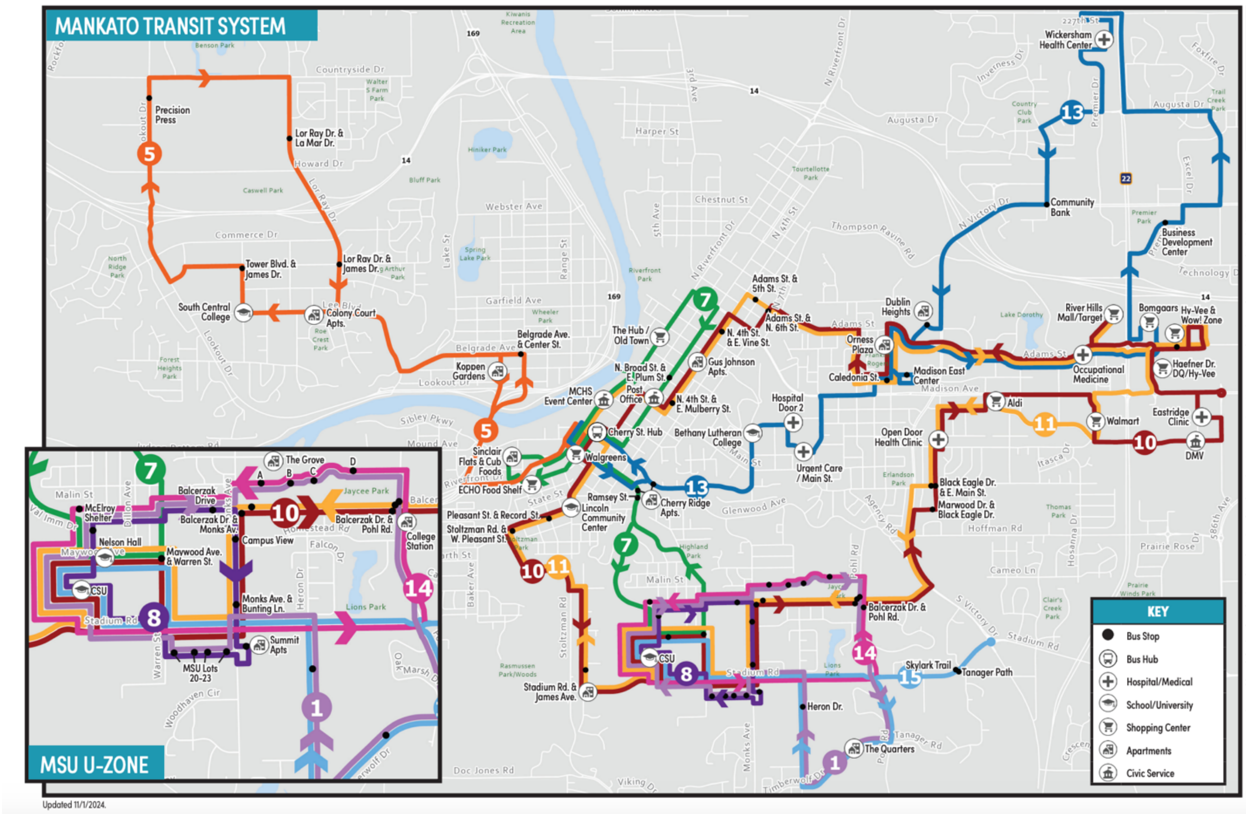


Figure 3 - Mankato Service Area

Emissions Reductions

Greenhouse gases (GHG) are the compounds primarily responsible for atmospheric warming and include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The effects of greenhouse gases are not localized to the immediate area where the emissions are produced. Regardless of their point of origin, greenhouse gases contribute to overall global warming and climate change.

Criteria pollutants include carbon monoxide (CO), nitrogen oxides (NOx), particulate matter under 10 and 2.5 microns (PM_{10} and $PM_{2.5}$), volatile organic compounds (VOC), and sulfur oxides (SO_X). These pollutants are considered harmful to human health because they are linked to cardiovascular issues, respiratory complications, or other adverse health effects.[1] These compounds are also commonly responsible for acid rain and smog. Criteria pollutants cause economic, environmental, and health effects locally where they are emitted.

By transitioning to ZEBs from ICE buses, Mankato's zero-emission fleet will produce fewer carbon emissions and fewer harmful pollutants from the vehicle tailpipes. Environmental impacts, both from climate change and from local pollutants, disproportionately affect transit riders. For instance, poor air quality from tailpipe emissions and extreme heat harm riders waiting for buses at roadside stops. The transition to zero-emission technology will benefit the region by reducing fine particulate pollution and improving overall air quality. In turn, the fleet transition will support better public health outcomes for residents in disadvantaged communities served by the selected routes.

Disadvantaged communities are both socioeconomically disadvantaged and environmentally disadvantaged due to local air quality. Lower income neighborhoods are often exposed to greater vehicle pollution levels due to proximity to freeways and the ports, which puts these communities at greater risk of health issues associated with

[1] Institute of Medicine. Toward Environmental Justice: Research, Education, and Health Policy Needs. Washington, DC: National Academy Press, 1999; O'Neill MS, et al. Health, wealth, and air pollution: Advancing theory and methods. Environ Health Perspect. 2003; 111: 1861-1870; Finkelstein et al. Relation between income, air pollution and mortality: A cohort study. CMAJ. 2003; 169: 397-402; Zeka A, Zanobetti A, Schwartz J. Short term effects of particulate matter on cause specific mortality: effects of lags and modification by city characteristics. Occup Environ Med. 2006; 62: 718-725.

tailpipe emissions.[2] Communities disadvantaged by pollution served by Mankato's fleet will also directly benefit from the reduced tailpipe emissions of ZEBs compared to ICE buses.[3]

Purpose of Transition Planning

Developing a transition plan helps provide a holistic view of long-term fleet management, the availability of current and future infrastructure requirements, and the agency's workforce development goals. This not only supports identifying funding constraints for procurements over the entire transition period, but it also aids multi-year contracts with vehicle OEMs, fuel providers, and gives utilities the opportunity to plan ahead.

CTE ZEB Transition Planning Methodology

This study uses CTE's ZEB Transition Planning Methodology. The methodology, shown in **Figure 4**, encompasses ten key phases which are sequential and build upon findings in previous phases. The phases specific to this study are outlined below:

0. Planning & Initiation
1. Requirements & Data Collection
2. Service Assessment
3. Fleet Assessment
4. Fuel Assessment
5. Maintenance Assessment
6. Facilities Assessment
7. Workforce Development Assessment
8. Total Cost of Ownership Assessment
9. ZEB Transition Plan – Document Creation

---

[2] Reichmuth, David. 2019. Inequitable Exposure to Air Pollution from Vehicles in California. Cambridge, MA: Union of Concerned Scientists. https://www.ucsusa.org/resources/inequitable-exposure-air-pollution-vehicles-california-2019

[3] U.S. DOT 2022 Transportation Disadvantaged Census Tracts (Historically Disadvantaged Communities)

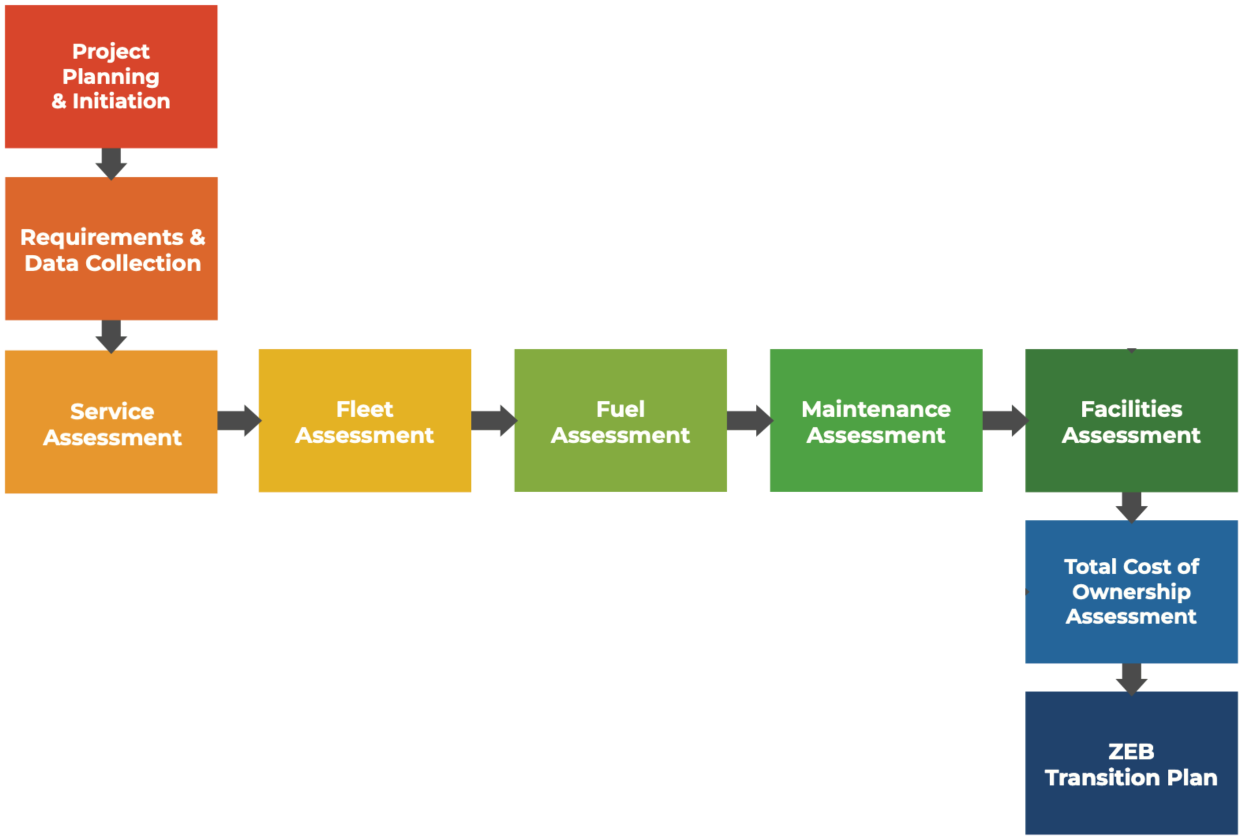


Figure 4 - CTE's ZEB Transition Study Methodology

The **Planning & Initiation** phase builds the administrative framework for the transition study. During this phase, the project team drafts the scope, approach, tasks, assignments and timeline for the project. CTE worked with Mankato staff to plan the overall project scope and all deliverables throughout the full life of the study.

For the **Requirements & Data Collection**, CTE collects GPS data on selected routes and uses software models to estimate ZEB performance. The results from this modeling are used to estimate feasibility of every block in Mankato's network using BEBs and FCEBs.

The **Service Assessment** phase initiates the technical analysis of the study. The results from the Service Assessment are used to guide ZEB procurements in the Fleet Assessment and to determine energy requirements (depot charging and/or hydrogen) in the Fuel Assessment. CTE met with Mankato to define assumptions and requirements used throughout the study and to collect operational data. This process was conducted for the fixed service blocks for buses.

The **Fleet Assessment** develops a projected timeline for replacement of ICE buses with ZEBs that is consistent with the agency's fleet replacement plan based on results from the Service Assessment. This analysis included an outline of the expected fleet structure and capital costs expected over the transition period for all scenarios explored and how they can be best optimized regarding any state mandates or to meet agency goals, such as minimizing cost or maximizing service levels.

The **Fuel Assessment** merges the results of the Service Assessment and Fleet Assessment to determine annual fuel requirements and associated costs. The Fuel Assessment calculates energy costs throughout the entire transition timeline for each scenario, including the agency's current ICE buses. As current technologies are phased out in later years of the transition, the Fuel Assessment calculates the increasing energy requirements for ZEBs. The Fuel Assessment also provides a total energy cost over the transition lifetime.

The **Facilities Assessment** determines the necessary infrastructure to support the projected zero-emission fleet based on results from the Fleet Assessment and Fuel Assessment. The Facilities Assessment is calculated for each scenario used in the Fleet and Fuel Assessments. The assessment determines the required hydrogen and battery electric infrastructure and calculates associated costs.

The **Workforce Development Assessment** develops a multi-phase process of training procedures and tools designed to assist the agency with transitioning skilled labor into ZEB proficiency in a manner consistent with the agency's fleet replacement plan. This assessment also includes an inventory of critical skills, training tools, and resources broken down by functional agency department. Furthermore, the report explores case studies and best practices from transit agencies on how to conduct training, what tools are most valuable, and the critical importance of the training relationship, including contractual considerations, with the ZEB OEM.

The **Maintenance Assessment** calculates all projected fleet maintenance costs over the life of the project. These costs include those related to existing ICE buses remaining in the fleet, as well as new BEBs and FCEBs, calculated for each scenario.

The **Total Cost of Ownership Assessment** compiles results from the previous assessments and provides a comprehensive view of all associated costs, organized by scenario, over the transition lifetime.

Assessment Assumptions

This transition study uses multiple assumptions to model Mankato's long-term fleet transition. The overarching assumptions are:

- Purchasing of ZEVs will take place following planned site upgrades in 2028
- Heavy-duty large buses have a normal service life of 12 years and cutaways have a normal service life of 5 years.[4]
    - This assumption follows the Federal Transit Administration's (FTA's) definition of vehicle useful life of 12 years as its retirement policy for standard bus sizes.
- BEBs are modeled to have a nameplate battery capacity of 450 kWh for 35' BEBs and 588 kWh for 40' BEBs in 2024. FCEBs capacity of 40kg (35' and 40').
    - These figures are based on the average of the bus manufacturers' specifications for the model compared with the Altoona Bus Testing and Research Center's bus report at the time of analysis.[5]
    - CTE estimates usable energy conservatively at 80% of nameplate, with an additional 3% loss of derated energy, based on validation testing from other deployments. Useable battery capacity and aging performance will vary across OEMs.
    - CTE estimates 69% of nameplate for battery degradation, used to estimate feasibility.
- A five percent improvement in battery capacity occurs every two years.[6]
- FCEB feasibility matches ICE feasibility; all blocks under 350 miles are assumed feasible
- FCEBs can more readily replace ICE buses one-for-one ratio due to operational ranges compared to BEBs.
    - Alameda-Contra Costa Transit District (AC Transit) and OCTA have reported operational ranges for FCEBs up to 350 miles.

---

[4] Federal Transit Administration, "Useful Life of Transit Buses and Vans". U.S. Department of Transportation. Retrieved on May 5, 2021, from https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/Useful_Life_of_Buses_Final_Report_4-26-07_rv1.pdf

[5] Altoona Bus Research and Testing Center, Bus Tests. Penn State College of Engineering. Retrieved on May 5, 2021, from https://www.altoonabustest.psu.edu/bus-tests/index.aspx

[6] BloombergNEF, "Hitting the EV Inflection Point". Bloomberg Finance L.P.2021. Retrieved on December 5, 2021, from https://www.transportenvironment.org/wp-content/uploads/2021/08/2021_05_05_Electric_vehicle_price_parity_and_adoption_in_Europe_Final.pdf

Requirements Analysis

Baseline Data Collection

Understanding the key elements of Mankato's service is essential to evaluating the costs of a complete transition to a zero-emission fleet. Mankato staff provided key data on Mankato's service including:

- Current fleet composition containing vehicle propulsion types and lengths
- Route and block information including distances and trip frequency
- Mileage and fuel consumption
- Maintenance costs and fuel costs

CTE prepared and distributed the Mankato Data Collection Template to the agency to begin the **Requirements Analysis & Data Collection** stage of the project.

Fleet Composition

Table 2 summarizes Mankato's 2024 fleet by vehicle size, fuel type, and bus length. The fleet currently consists of 20 cutaway vans, eight 35' transit buses and six 40' transit buses.

Table 2 - Fleet Summary by Fuel Type, Length, and Model Year

Bus Make	Bus Length	Model Year	Bus Quantity
Biodiesel	40'	2014	3
		2015	1
		2019	1
		2024	1
	35'	2012	1
		2013	1
		2023	3
		2023	3
	Cutaway	2015	1
Gasoline	Cutaway	2015	1
		2018	7
		2019	1
		2023	7
		2024	3
			Total: 34

Miles and Fuel Consumption

Data on Mankato's current fuel consumption is used to estimate energy costs throughout the transition period. **Table 3** provides the average annual fleet mileage and fuel use.

Table 3 - Average Annual Service Miles and Annual Fuel Consumption by Bus Length

Fuel Type / Length	Average Annual Mileage	Average Diesel/Gas Fuel Consumption
Biodiesel 40'	18,516	4,307
Biodiesel 35'	27,520	4,190
Biodiesel Cutaway	13,309	1,565
Gasoline Cutaway	26,953	46,003

CTE assumes the following known procurements in the analysis:

- 6 x 2026 Gasoline Arboc Cutaway (803-805, 827, 829, 831)
- 1 x 2027 Gasoline Arboc Cutaway (828)
- 1 x 2027 Biodiesel Gillig 35' (864)
- 1 x 2028 Gasoline Arboc Cutaway (832)

CTE assumes the following known disposals in the analysis:

- 1 x 2015 Gasoline Arboc (826) – final service year set to 2024
- 1 x 2015 Biodiesel Arboc (802) – final service year set to 2024

CTE assumes the following vehicles exceeding useful life in the analysis:

- 3 x 2010 35' Biodiesel – set to be replaced 2025

Service Assessment

The **SERVICE ASSESSMENT** analyzes the feasibility of maintaining Mankato's service with battery electric and hydrogen fuel cell electric buses. The key component of the Service Assessment is the **Block Analysis**, which analyzes bus range limitations to determine if ZEBs can meet the service requirements of the blocks within the transition period. The energy needed to complete a block is compared to the available energy for the prospective bus type that is planned for the block. If the prospective bus's available energy exceeds the block's required energy, then that block is considered feasible for that ZEB type. The Service Assessment also yields a timeline for when blocks become achievable for zero-emission buses as technology improves. This information is used to inform ZEB procurements in the Fleet Assessment.

Bus efficiency and range are primarily driven by bus specifications; however, both metrics can be impacted by a number of variables including the route profile (e.g., distance, dwell time, acceleration, sustained top speed over distance, average speed, traffic conditions, deadhead), topography (e.g., grades), climate (e.g., ambient temperature), driver behavior, and operational conditions (e.g., passenger loads and auxiliary loads). As such, the efficiency and range of a given ZEB model can vary dramatically from one agency to another. Therefore, it is critical to determine efficiency and range estimates that are based on an accurate representation of Mankato's operating conditions.

Modeling and Analysis Methodology

The first task in the Service Assessment is to develop route and bus models and run operating simulations for Mankato routes. The Service Assessment determines the percentage of the agency's blocks that will be achievable each year considering the energy demand of the blocks and the battery capacity of the buses (for 35' and 40') with an assumed battery capacity improvement factor of five percent every two years. This improvement in battery capacity increases the estimated range of the buses over time, which gradually increases the percentage of blocks that are achievable by 2040. This process was conducted for the fixed service blocks for buses. CTE modeled Mankato's route and the vehicle energy demand to predict which of Mankato's blocks can feasibly be transitioned to ZEB technology and the timeline of when the transition can occur.

ROUTE MODELING analyzes varying passenger loads, accessory loads, and battery degradation to estimate real-world bus performance, fuel efficiency, and range. The GPS data from routes and the specifications for each of the bus models are used to simulate operation on each type of route. The models were run under nominal and strenuous load conditions.

NOMINAL LOAD conditions assume average passenger loading and a moderate temperature over the course of the day, which places marginal demands on the motor and the heating, ventilation, and air conditioning (HVAC) system.

STRENUOUS LOAD conditions assume high or maximum passenger loading and near-maximum output of the HVAC system. These strenuous loading conditions represent a hypothetical and unlikely worst-case scenario, but one that is necessary to establish an outer bound for the analysis. This nominal/strenuous approach offers a range of operating efficiencies, measured in kilowatt-hour/mile (kWh/mi), to use for estimating average annual energy use (nominal) or planning maximum service demands (strenuous).

Figure 5 shows the range of remaining BEB battery energy (y-axis) on an example route. The blue and black areas show the range of estimated energy remaining between the nominal and strenuous load conditions for a new and an end-of-life (EoL) battery, respectively. The point at which these areas cross the x-axis is the point at which there is no battery energy remaining. These colored areas shown represent the spectrum of expected operating conditions throughout the bus life to aid in service planning. The triangles under the graph denote trips within a block.

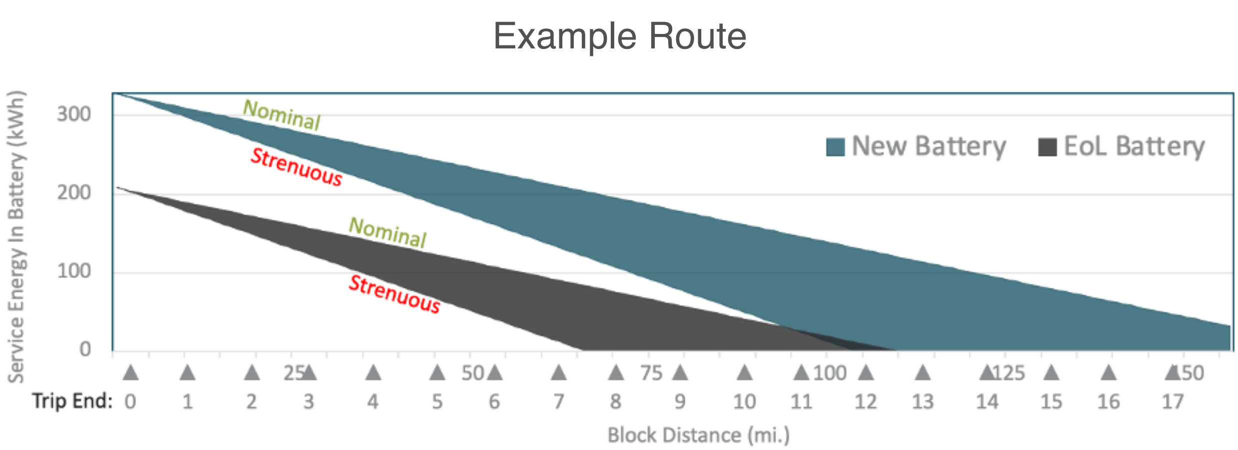


Figure 5 - Example Route Block Analysis

CTE employs a methodology, outlined in the **Figure 6** flow chart, to develop the analyses for the transition plan.

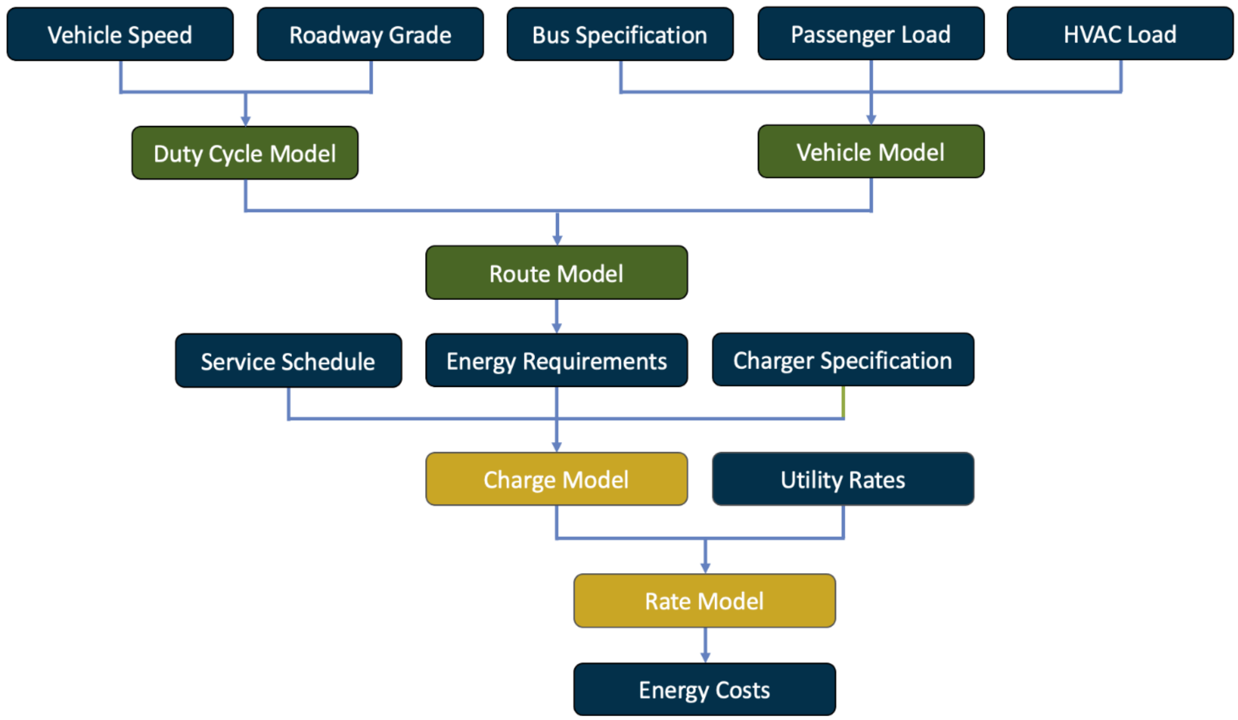


Figure 6 - CTE Modeling Methodology

Assumptions

CTE uses a set of assumptions related to battery capacity to guide the service assessment. The assumptions for the service assessment are as follows:

As of 2024, batteries for 40' battery electric buses have a nameplate capacity of 588 kWh with a usable capacity of 453 kWh. As of 2024, batteries for 35' battery electric buses have a nameplate capacity of 450 kWh with a usable capacity of 347 kWh. As of 2024, batteries for cutaway electric buses have a nameplate capacity of 120 kWh with a usable capacity of 92 kWh. The assumed usable battery capacity for BEBs is 80% of the nameplate capacity, which is the amount advertised by the original equipment manufacturer (OEM). CTE assumes a 69% nameplate capacity to estimate feasibility to account for battery degradation by the end of life. A five percent improvement in battery capacity is assumed to expand every two years. In addition, CTE assumed the use of an all-electric heater in 35',40', and cutaway efficiency estimates.

The BEB modeling was completed using strenuous conditions with HVAC loads designated at 17°F with estimated auxiliary loads between 12-18 kW. CTE assumed nominal conditions were represented by HVAC loads designated at 65°F with estimated auxiliary loads between 3-5 kW.

For this study, CTE assumes that Mankato will maintain service to similar destinations within the region and therefore the blocks maintain a similar distribution of distance, relative speeds, and elevation changes throughout the transition period. This core assumption affects energy use estimates and block feasibility in each year.

Block Feasibility Results by Bus Size

The **BLOCK ANALYSIS** uses the strenuous energy required to complete each block and compares it to bus energy storage capacities. It considers what length bus is assigned to each block, either cutaway, 35', or 40' buses. A detailed breakdown of Energy Needs by Mankato blocks can be found in **Appendix B**. Energy storage growth assumed five percent improvement in battery capacity or hydrogen storage capacity every two years which determines the timeline for when routes and blocks become achievable for BEBs and FCEBs. This information is used to inform ZEB procurement projections in the Fleet Assessment. Overall, the block analysis helps to determine when, or if, a full transition to ZEBs may be feasible and when there are requirements for supplemental energy solutions. Results from this analysis are also used to determine the specific energy requirements and develop the estimated costs to operate the ZEBs in the Fuel Assessment. **Table 4** provides the results from the block analysis for BEBs in selected years (every two years from 2024-2040) by bus size (cutaway vs. 35' vs. 40').

Table 4 - BEB Block Feasibility Percentage by Year

Bus Size [ft]	Block Quantity	Max. Block Distance (mi)	% Feasible in 2024	% Feasible in 2026	% Feasible in 2028	% Feasible in 2030	% Feasible in 2032	% Feasible in 2034	% Feasible in 2036	% Feasible in 2038	% Feasible in 2040
Cutaway	3	219	0%	0%	0%	0%	0%	0%	0%	0%	0%
35'	8	213	13%	13%	13%	13%	13%	13%	13%	25%	25%
40'	4	200	75%	75%	75%	75%	75%	75%	75%	75%	75%

Another factor affecting block feasibility is battery degradation. BEB range is negatively impacted by battery degradation over time. A BEB placed in service on a given block with beginning-of-life batteries may not be able to complete the entire block at some point during its life before the batteries reach end-of-life. End-of-life is typically defined as when batteries reach a certain percentage of available service energy remaining which is typically defined by the OEM. Conceptually, older buses can be moved to shorter, less demanding blocks and newer buses can be assigned to longer, more demanding blocks. Mankato can also rotate the fleet to meet service energy demand, assuming there is a steady procurement of electric buses to match service requirements.

Figure 7 and **Table 5** show the 35' BEB feasibility for existing blocks in the transition timeline. Blocks run with 35' buses are compared to today's 35' BEB energy storage capacities. The preliminary results show a 25% feasibility rate in 2040 with 2 out of 8 feasible blocks.

Figure 7 - 35' BEB Block Feasibility Projection

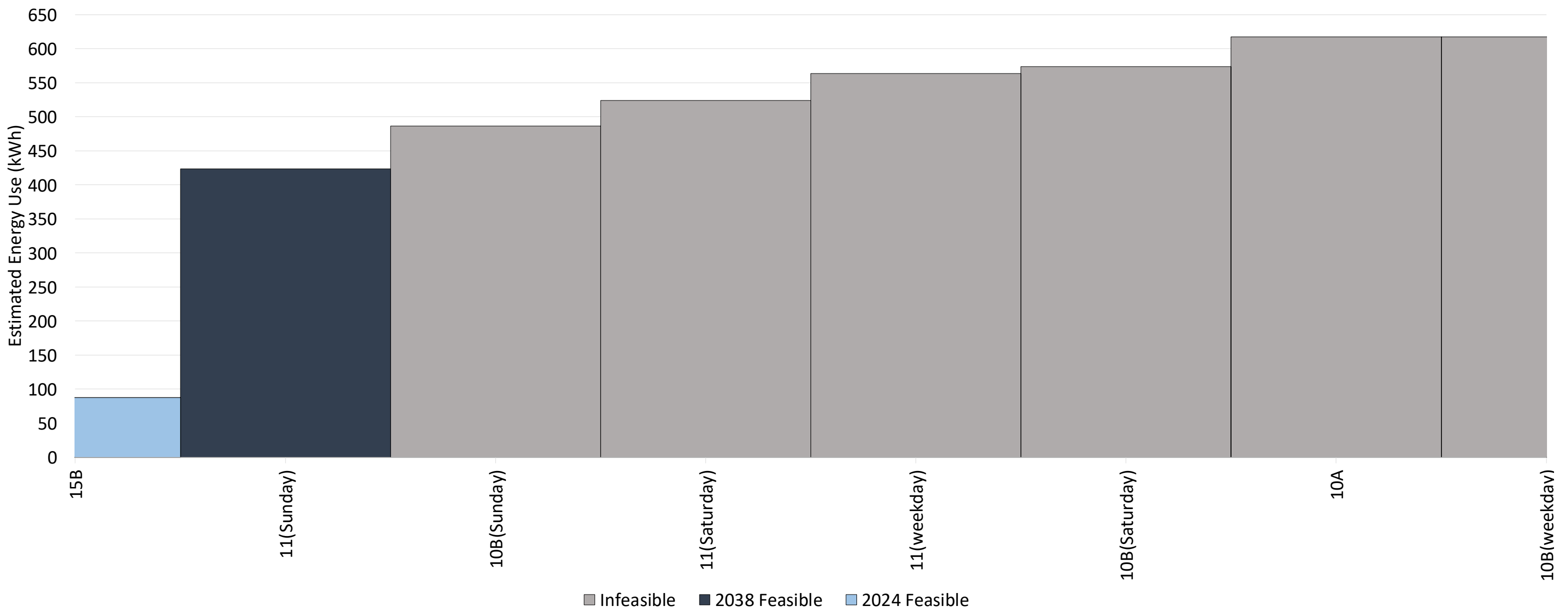


Table 5 - 35' BEB Block Feasibility Projection (2024-2040)

Bus Size [ft]	Block Quantity	Max Block Distance (mi)	% Feasible in 2024	% Feasible in 2026	% Feasible in 2028	% Feasible in 2030	% Feasible in 2032	% Feasible in 2034	% Feasible in 2036	% Feasible in 2038	% Feasible in 2040	Infeasible Blocks
35'	8	213	13%	13%	13%	13%	13%	13%	13%	25%	25%	6

Table 6 below shows the additional energy needs on 35' BEBs to make the 6 infeasible blocks feasible. 350kW is assumed for average BEB higher power opportunity charging power. Average charging power may vary depending on OEM and battery size.

Table 6 - Additional Energy Needs: 35' BEB

Blocks Infeasible with Overnight Charged BEB in 2035	Estimated Additional 2040 Energy Need (kWh)	Estimated Duration with 350kW Higher Power Opportunity Charging (h:mm)
10B (Sunday)	28	0:04
11 (Saturday)	65	0:11
11 (Weekday)	105	0:18
10B (Saturday)	115	0:19
10A	158	0:27
10B (Weekday)	158	0:27

Figure 8 and **Table 7** show the 40' BEB feasibility for existing blocks in the transition timeline. Blocks run with 40' buses are compared to today's 40' BEB energy storage capacities. The preliminary results show a 75% feasibility rate in 2040 with 3 out of 4 feasible blocks.

Figure 8 - 40' BEB Block Feasibility Projection

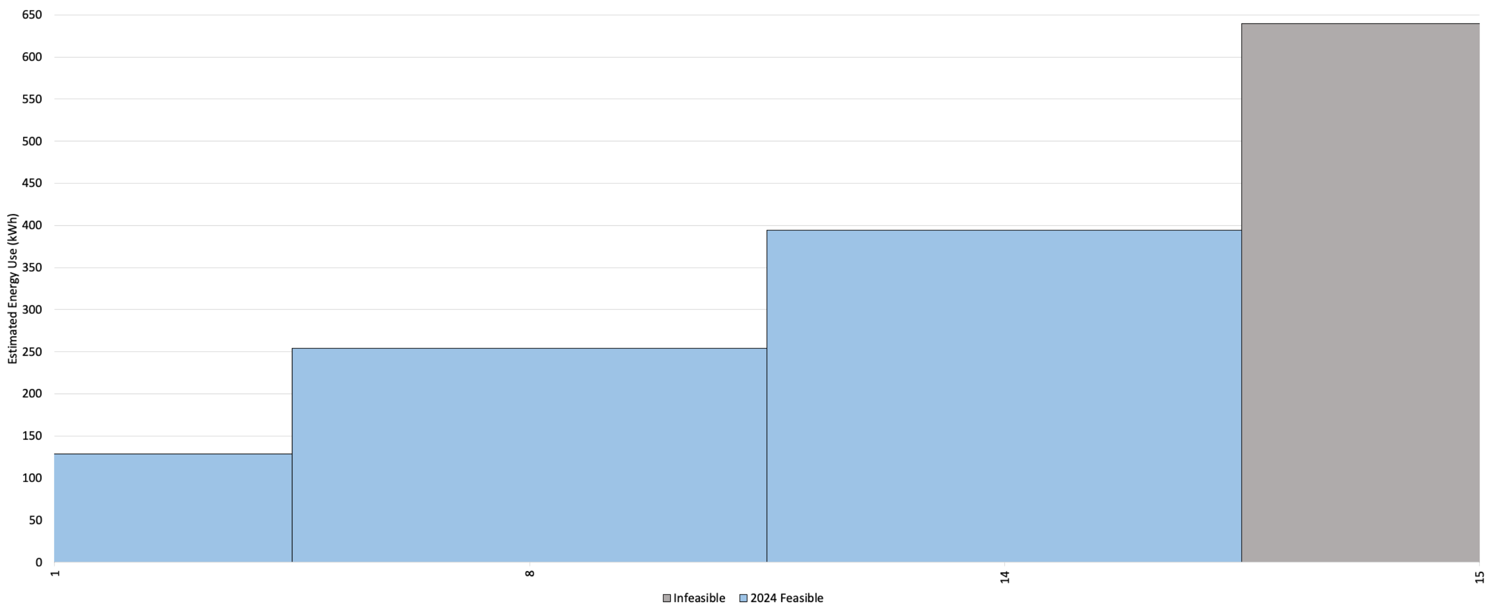


Table 7 - 40' BEB Block Feasibility Projection (2024-2040)

Bus Size [ft]	Block Quantity	Max Block Distance (mi)	% Feasible in 2024	% Feasible in 2026	% Feasible in 2028	% Feasible in 2030	% Feasible in 2032	% Feasible in 2034	% Feasible in 2036	% Feasible in 2038	% Feasible in 2040	Infeasible Blocks
40'	4	200	75%	75%	75%	75%	75%	75%	75%	75%	75%	1

Table 8 below shows the additional energy needs on 40’ BEBs to make the 1 infeasible block feasible. 350kW is assumed for average BEB higher power opportunity charging power. Average charging power may vary depending on OEM and battery size.

Table 8 - Additional Energy Needs: 40’ BEB

Blocks Infeasible with Overnight Charged BEB in 2035	Estimated Additional 2040 Energy Need (kWh)	Estimated Duration with 350kW Higher Power Opportunity Charging (h:mm)
15	40	0:06

CTE assumes that using on-route charging or transitioning to a fully FCEB fleet will fill in all projected feasibility gaps associated with the overnight depot charged block projections.

Error! Reference source not found. and Error! Reference source not found. showcase the feasibility projections over time for cutaways, 35’, and 40’ buses respectively.

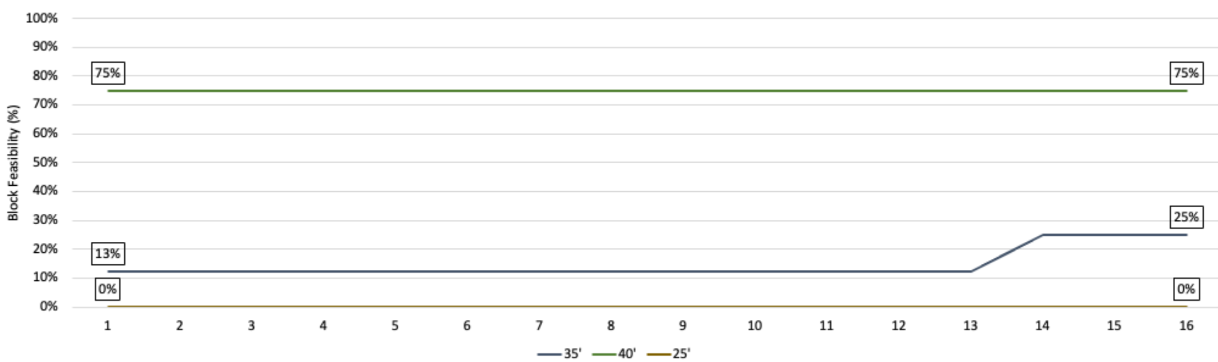


Figure 9 - Block Feasibility by Bus Size (2024-2040)

Table 9 - Block Feasibility by Bus Size (2024-2040)

Bus Size [ft]	Block Quantity	Max. Block Distance (mi)	% Feasible in 2024	% Feasible in 2026	% Feasible in 2028	% Feasible in 2030	% Feasible in 2032	% Feasible in 2034	% Feasible in 2036	% Feasible in 2038	% Feasible in 2040
Cutaway	3	219	0%	0%	0%	0%	0%	0%	0%	0%	0%
35’	8	213	13%	13%	13%	13%	13%	13%	13%	25%	25%
40’	4	200	75%	75%	75%	75%	75%	75%	75%	75%	75%

Fleet Assessment

The goal of the **FLEET ASSESSMENT** is to determine what type of ZEB technology solutions are required to transition an entire fleet to zero-emission vehicles. Results from the Service Assessment are integrated with Mankato's current fleet replacement plan and purchase schedule to produce two main outputs:

1) A projected bus replacement timeline through the end of the transition period, and

2) The total capital costs of those replacements.

Throughout the assessment, the projected bus procurement plan is referred to as the transition period.

For this effort, CTE used the Service Assessment to inform the percentage of buses that could be transitioned to BEBs or FCEBs each year during the transition. This analysis included an outline of the expected fleet structure and capital costs expected over the transition period for each scenarios explored.

Assumptions

CTE uses a set of assumptions related to vehicle prices to guide the fleet assessment. The assumptions for the fleet assessment are as follows:

- Purchasing of ZEVs will take place following planned site upgrades in 2028
- Procurement cost assumptions per vehicle type are shown in **Table 10** with the following assumptions applied:
  - Annual inflation of 4% applied through 2026, and 2% applied through the remainder of the period
  - Additional $50K was added to bus price for pantograph rails
  - Additional $75k was added to bus price for battery warranty
- Known Procurements:
  - 6 x 2026 Gasoline Arboc Cutaway (803-805, 827, 829, 831)
  - 1 x 2027 Gasoline Arboc Cutaway (828)
  - 1 x 2027 Biodiesel Gillig 35' (864)
  - 1 x 2028 Gasoline Arboc Cutaway (832)
- Known Disposals
  - 1 x 2015 Gasoline Arboc (826) – final service year set to 2024

    - 1 x 2015 Biodiesel Arboc (802) – final service year set to 2024
- Vehicles Exceeding Useful Life
    - 3 x 2010 35' Biodiesel – set to be replaced 2025
- Vehicle useable lifetime of 12 years for buses and 5 years for cutaways

Table 10 - Fleet Procurement Cost Assumptions

Vehicle	Cost	Source
Gasoline Cutaway	$369,200	Mankato 2026 Arboc Gasoline Purchase
Biodiesel Cutaway	$369,200	Mankato 2026 Arboc Biodiesel Purchase
Biodiesel 35'	$727,000	Mankato 2026 Gillig Biodiesel Purchase
Biodiesel 40'	$672,769	Mankato 2024 Gillig Biodiesel Purchase
Electric 35'	$1,028,187	20K reduction from 40ft
Electric 40'	$1,048,187	Average 40' Bus Cost - 4/1/24 State Contract
Fuel Cell Cutaway	$575,000	Estimate based off average market and upfitter
Fuel Cell 35'	$1,305,000	35' not available on the market, assuming same price as market 40'
Fuel Cell 40'	$1,305,000	Average 40' FCEB Bus Cost – 4/1/24 State Contract

**Although this study identifies biodiesel cutaways, Mankato noted that they no longer intend to procure these and will instead procure 29 foot GILLIG Class 700 (BRT) bio-diesel.*

Procurement Timeline

Figure 10, Figure 11, Figure 12, and Figure 13 show the overall procurement phase-in of buses during the transition period for each of the scenarios: Baseline, BEB Depot Only, BEB Depot and On-Route Charged, and FCEB Only. This timeline is inclusive of the vehicles that will need to be procured once they reach their end-of-life. The lifespan of a full-sized BEB and FCEB is approximately 12 years and 5 years for cutaways.

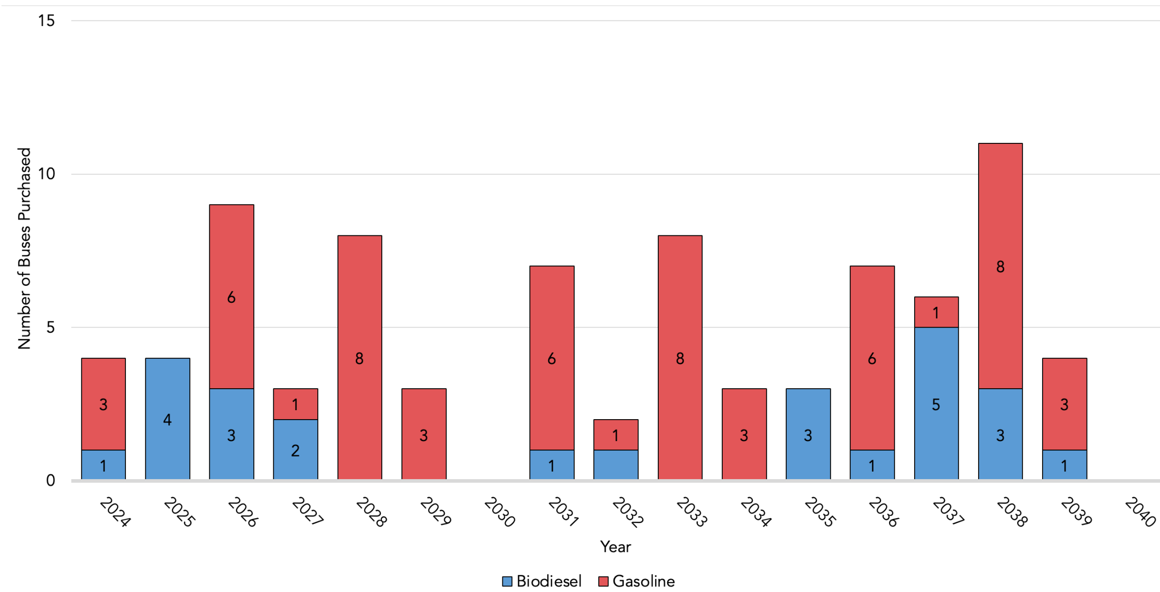


Figure 10 - Procurement Phase-In: Baseline Scenario

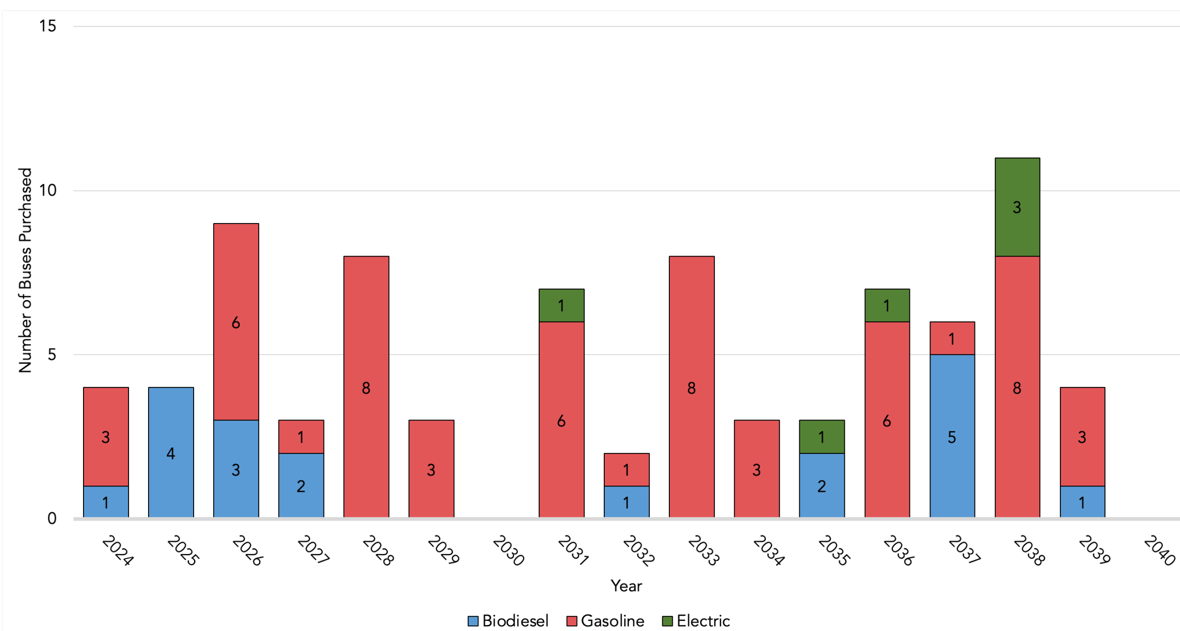


Figure 11 - Procurement Phase-In: BEB Depot Only Scenario

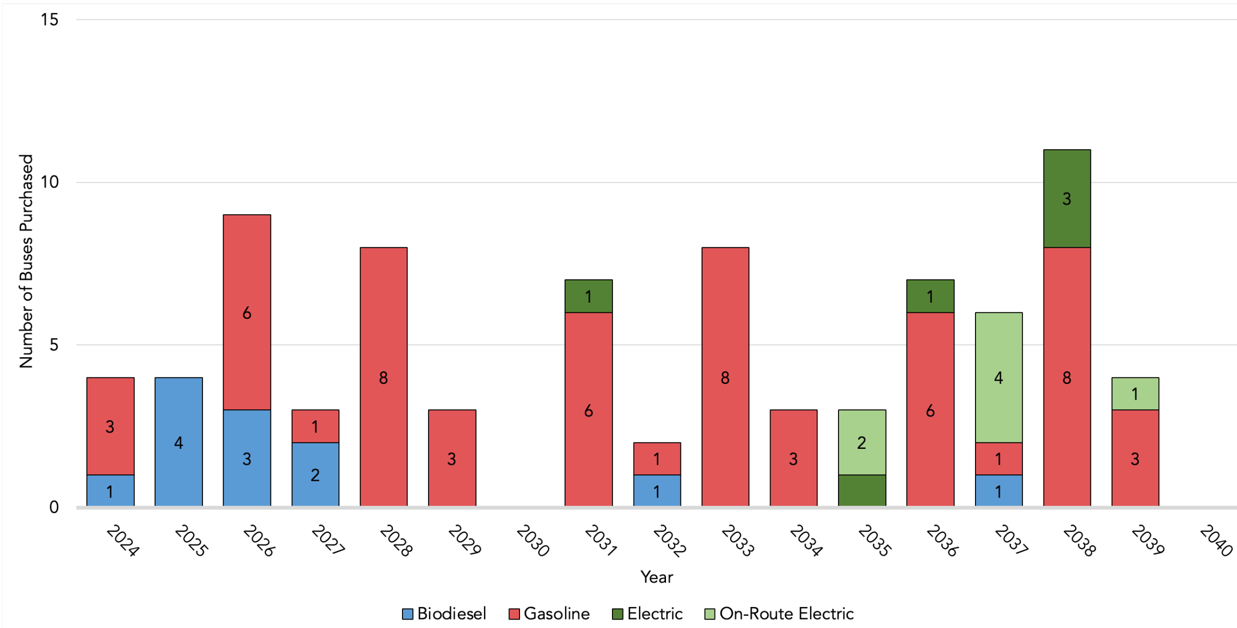


Figure 12 - Procurement Phase-In: BEB Depot and On-Route Charged Scenario

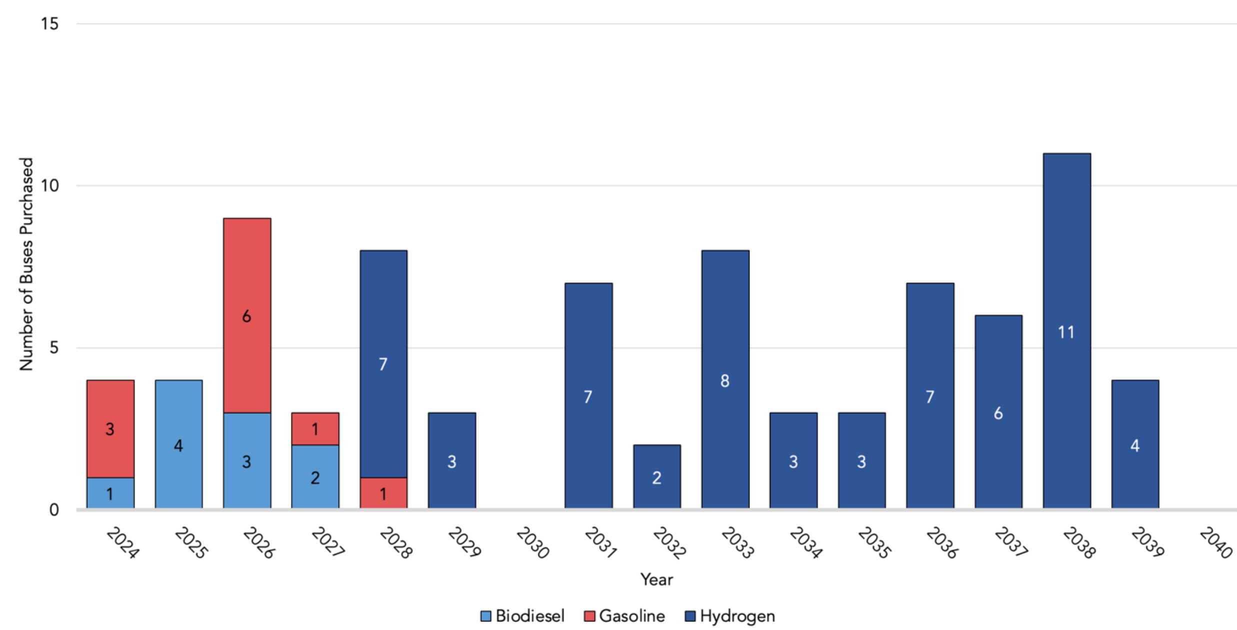


Figure 13 - Procurement Phase-In: FCEB Only Scenario

Vehicle Composition

Baseline

Figure 14 shows the vehicle composition of the Baseline scenario throughout the transition period. The Mankato fleet is 0% ZEB by 2040 with 14 biodiesel and 18 gasoline vehicles.

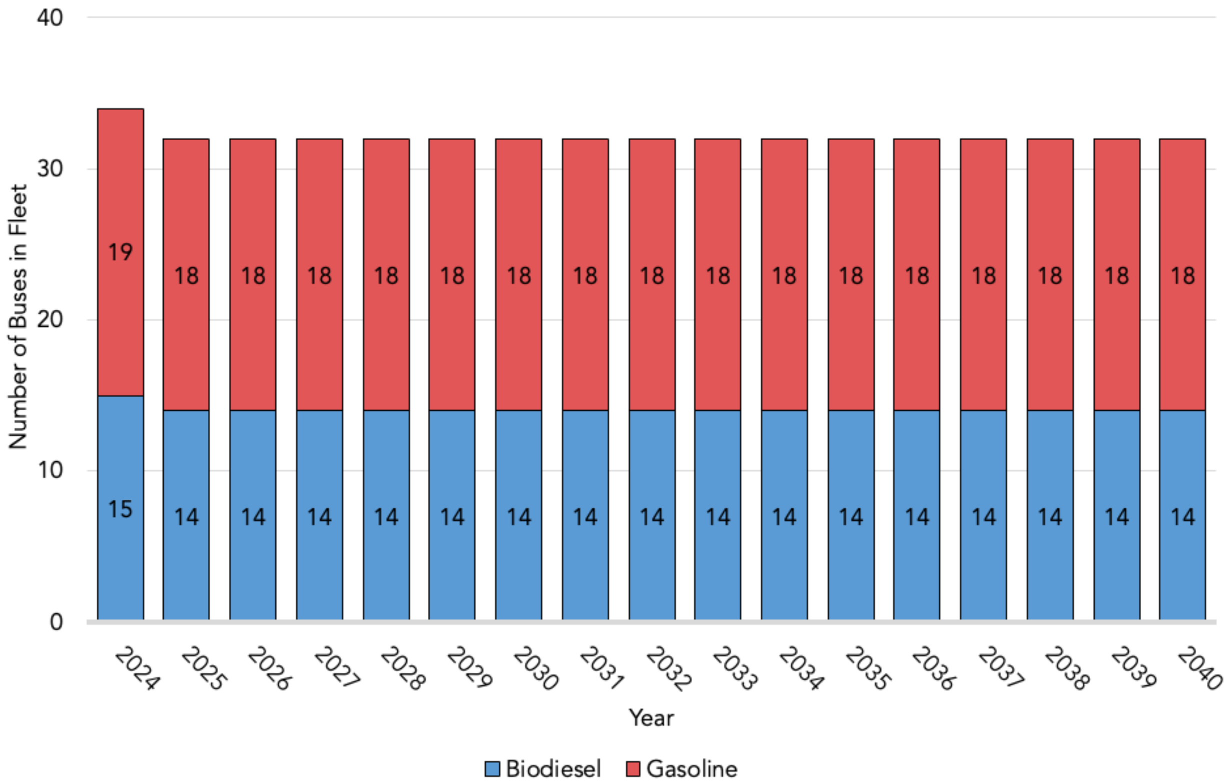


Figure 14 - Fleet Composition: Baseline Scenario

BEB Depot Only

Figure 15 shows the vehicle composition of the BEB Depot Only scenario throughout the transition period. The first BEB is introduced into the fleet in 2031. The Mankato fleet is 19% ZEB by 2040 and the transition to incorporate more ZEBs would continue until the fleet is fully composed of ZEBs.

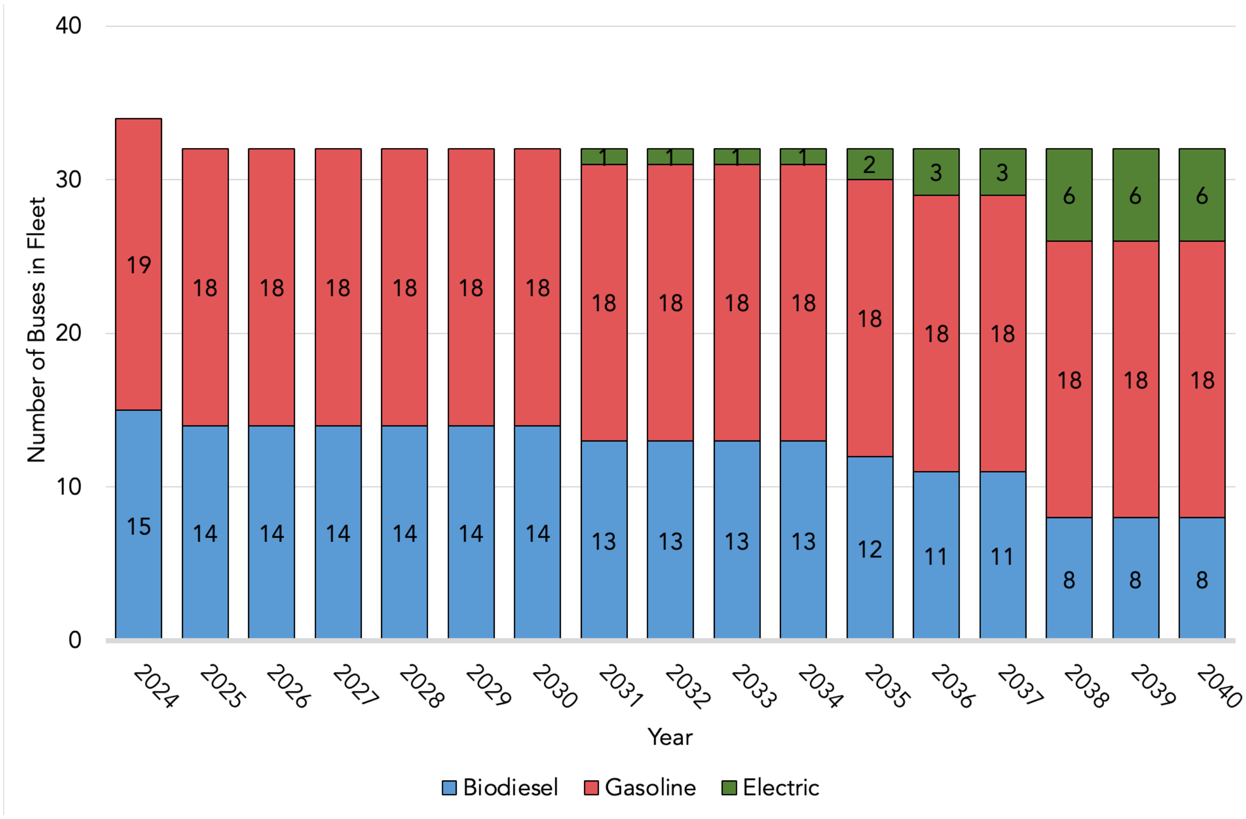


Figure 15 - Fleet Composition: BEB Depot Only Scenario

BEB Depot and On Route Charged

Figure 16 shows the vehicle composition of the BEB Depot and On Route Charged scenario throughout the transition period. The first BEBs are introduced into the fleet in 2031. The Mankato fleet is 41% ZEB by 2040 and the transition to incorporate more ZEBs would continue until the fleet is fully composed of ZEBs.

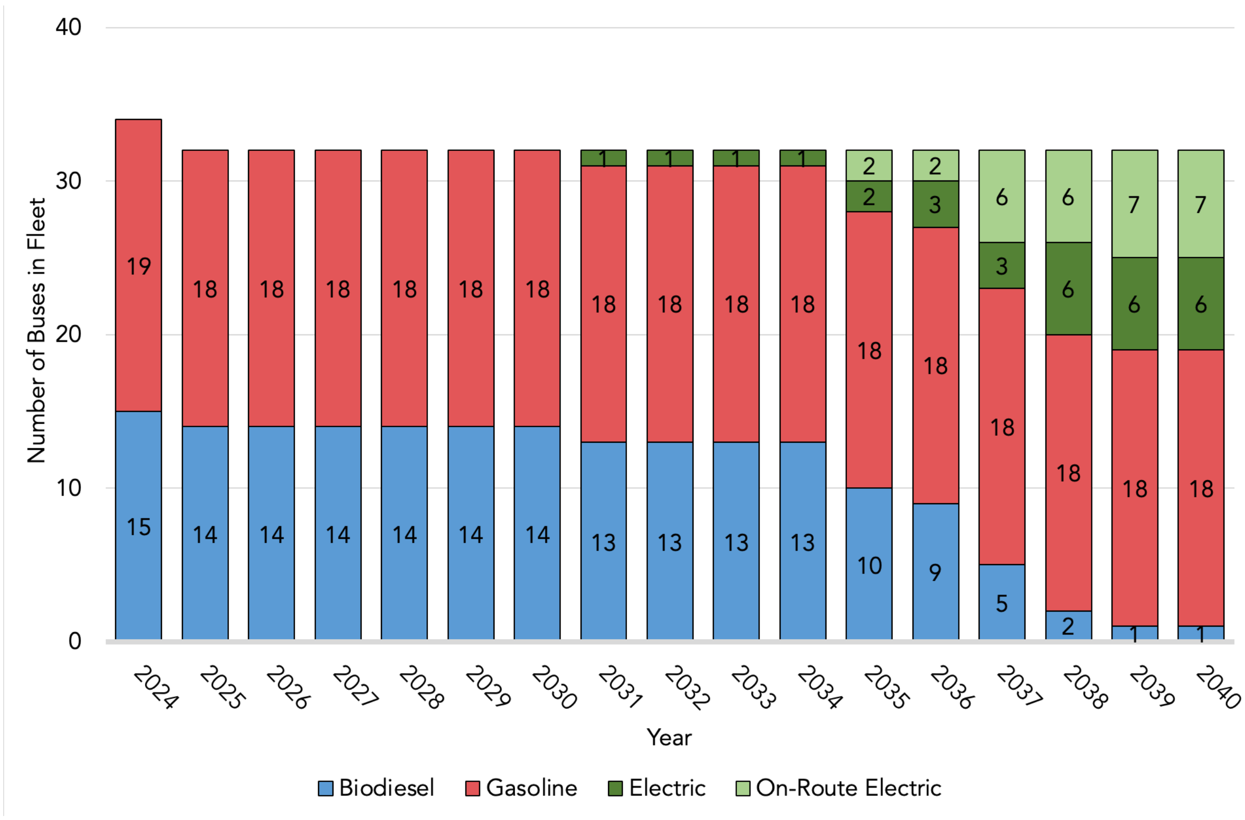


Figure 16 - Fleet Composition: BEB Depot and On Route Charged Scenario

FCEB Only

Figure 17 shows the vehicle composition of the FCEB Only scenario throughout the transition period. The first 25’ FCEBs are introduced into the fleet in 2028, the first 35’ FCEBs are introduced into the fleet in 2035, and the first 40’ FCEBs are introduced into the fleet in 2031. The Mankato fleet is free of gasoline buses by 2033, and the transition to a fully composed FCEB fleet is completed in 2039.

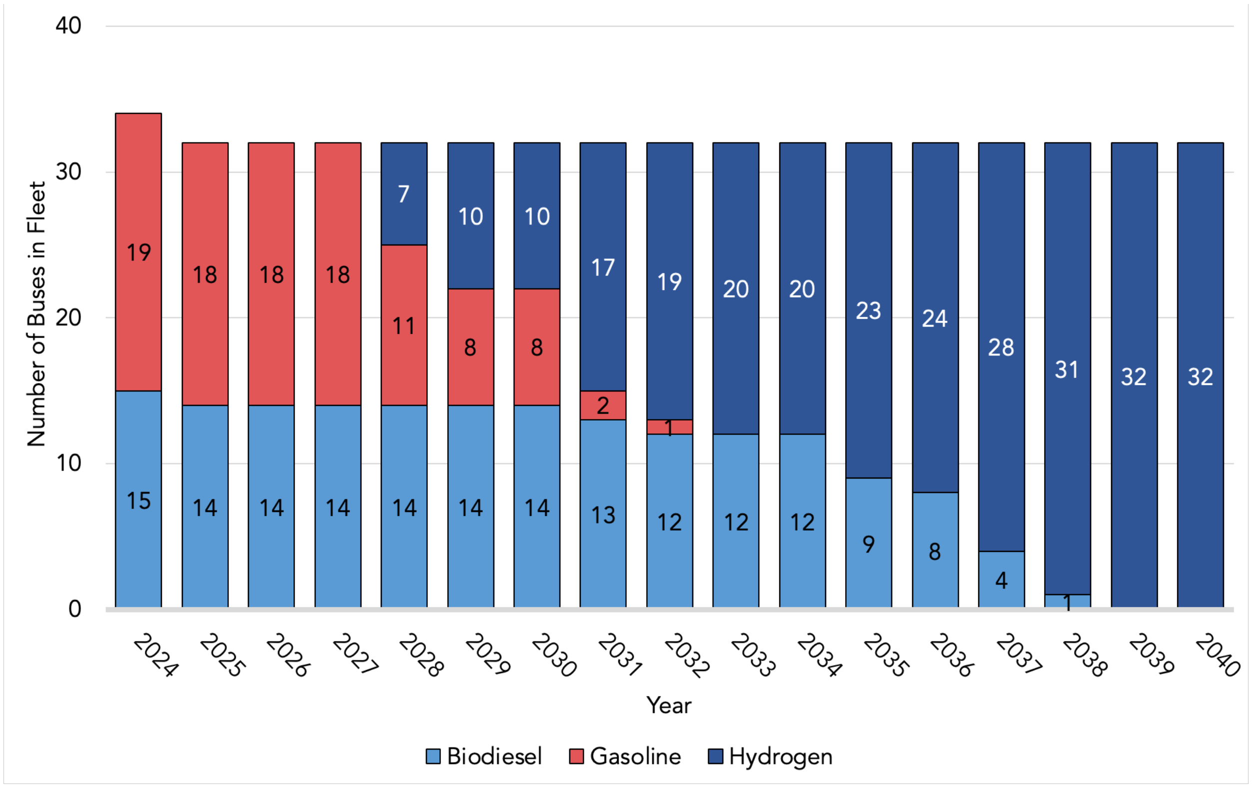


Figure 17 - Fleet Composition: FCEB Only Scenario

Annual Fleet Costs

Baseline

Figure 18 shows the annual fleet costs by fuel type in the Baseline scenario throughout the transition period. The total expenditures from 2024 to 2040 equals $45.7 million with $20 million coming from biodiesel vehicles and the remaining $25.7 million from gasoline vehicles.

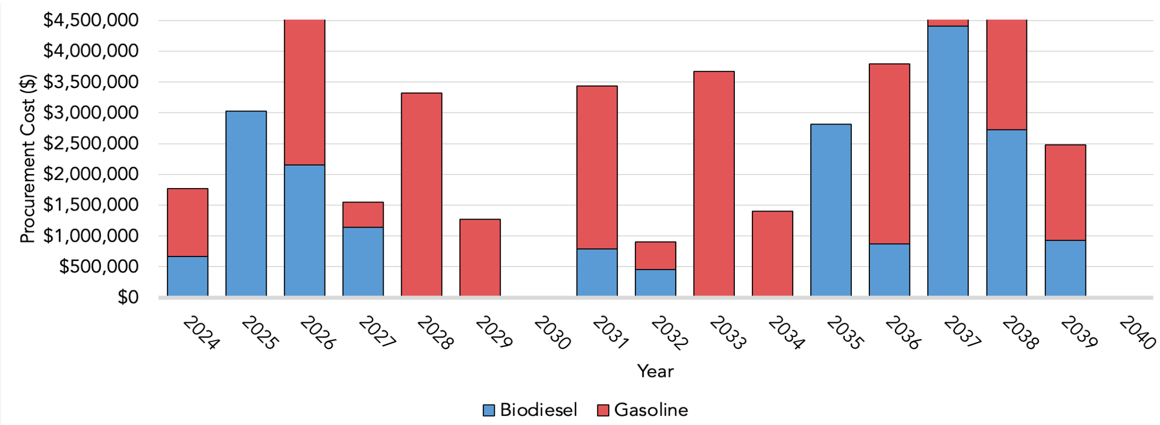


Figure 18 - Annual Fleet Costs: Baseline Scenario

BEB Depot Only

Figure 19 shows the annual fleet costs by fuel type in the Depot Only Charged scenario throughout the transition period. The total expenditures from 2024 to 2040 equals $49.3 million ($14.7 million from biodiesel vehicles, $25.7 million from gasoline vehicles, and $8.9 million from electric vehicles).

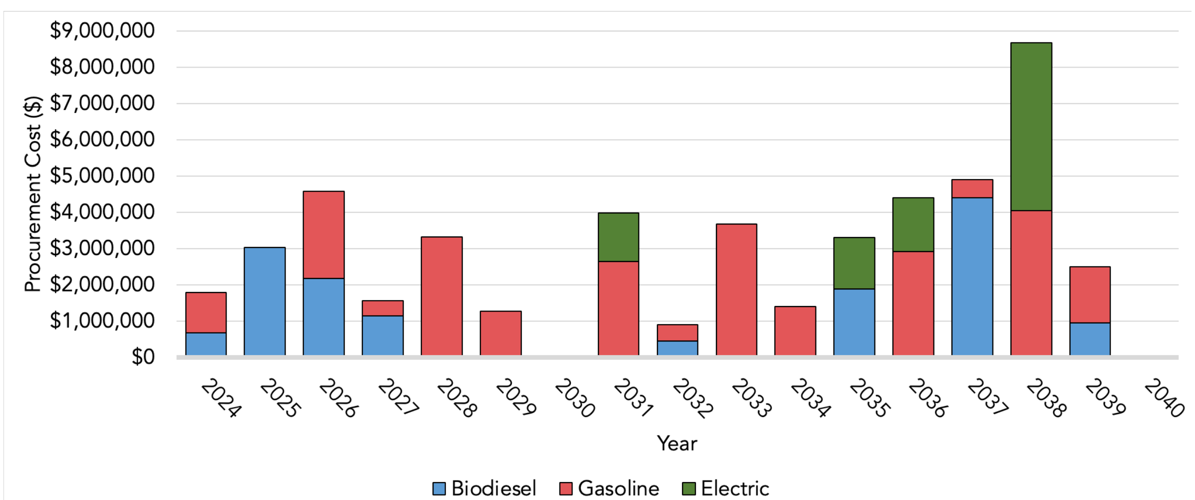


Figure 19 - Annual Fleet Costs: BEB Depot Only Scenario

BEB Depot and On Route Charged

Figure 20 shows the annual fleet costs by fuel type in the BEB Depot and On Route Charged scenario throughout the transition period. The total expenditures from 2024 to 2040 equals $53.9 million ($8 million from biodiesel vehicles, $25.7 million from gasoline vehicles, $8.9 million from the depot charged only electric fleet, and $11.4 million from on-route electric fleet costs).

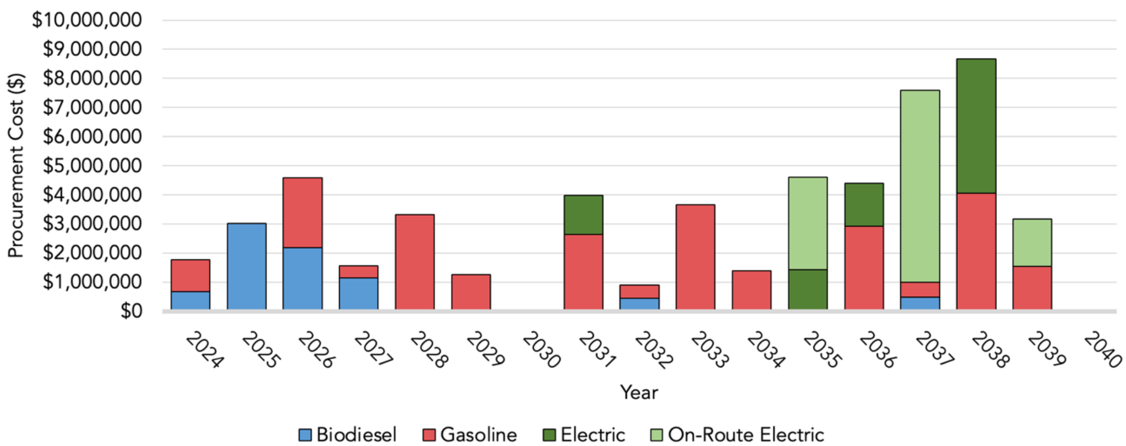


Figure 20 - Annual Fleet Costs: BEB Depot and On Route Charged Scenario

FCEB Only

Figure 21 shows the annual fleet costs by fuel type in FCEB Only scenario throughout the transition period. The total expenditures from 2024 to 2040 equals $71.4 million ($9.8 million from biodiesel vehicles, $4.3 million from gasoline vehicles, $57.3 million from hydrogen vehicles).

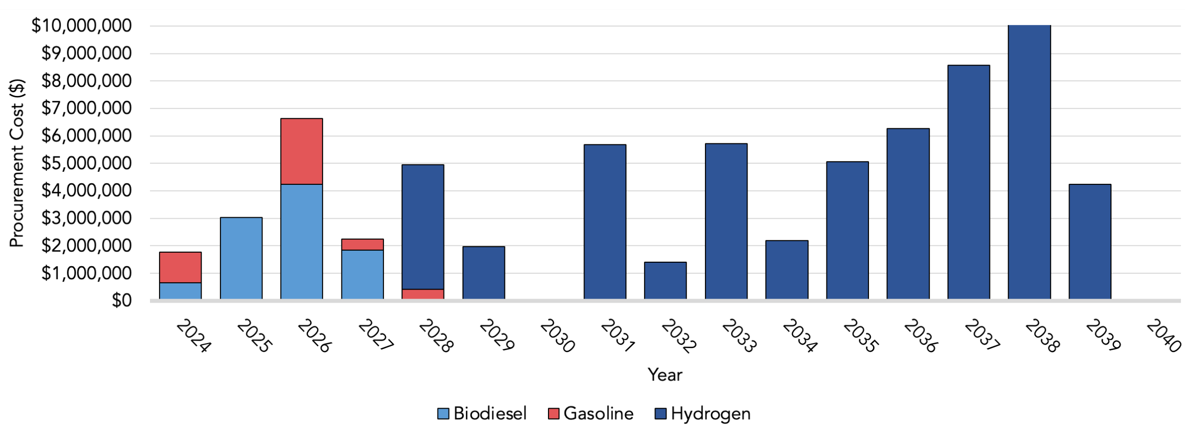


Figure 21 - Annual Fleet Costs: FCEB Only Fleet Scenario

Summary

Figure 22 and **Table 11** compare the cumulative costs and percentage of ZEBs in the fleet over the transition timeline of 2024-2040 for each scenario. The BEB Depot Only scenario is comprised of 19% ZEBs by 2040 and costs $49.3 million over the transition period compared to the baseline cost of $45.7 million. Mankato requires on-route charging or the transition to a FCEB fleet for ZEBs to be able to complete all Mankato blocks. Under the Depot and On Route Charged scenario, the Mankato fleet is comprised of 41% ZEBs by 2040 and costs $53.9 million over the transition period. Under the FCEB Only scenario, ICE vehicles are completely phased out by 2039 and costs $71.4 million over the transition period.

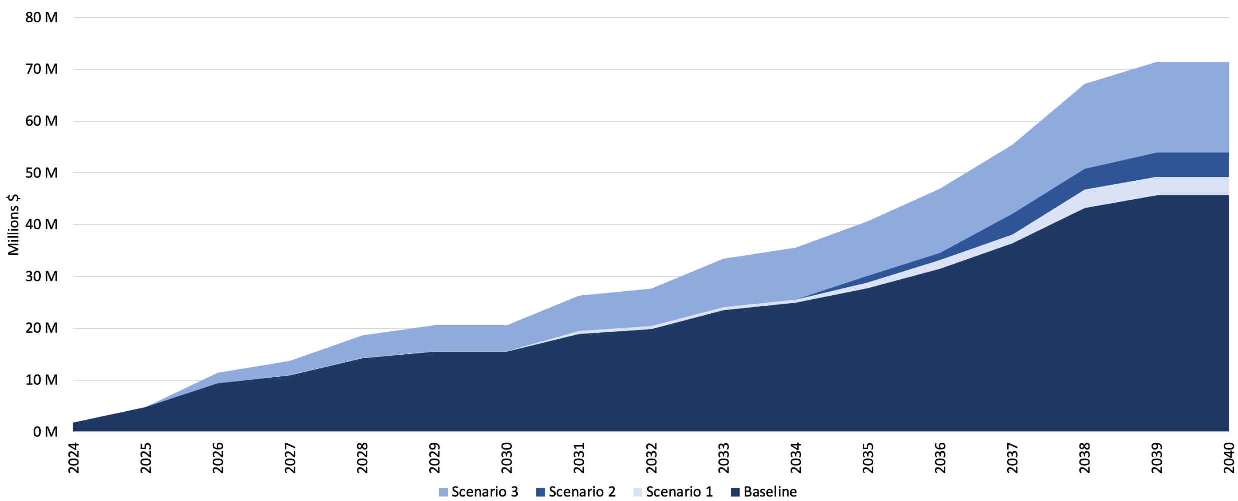


Figure 22 - Cumulative Fleet Cost by Scenario

Table 11 - Cumulative Fleet Costs by Scenario

Costs	Baseline	Scenario 1 (BEB Depot Only)	Scenario 2 (BEB Depot & On-Route)	Scenario 3 (FCEB Only)
Cumulative ($)	45.7M	49.3M	53.9M	71.4M
Incremental over Baseline ($)	-	3.6M	8.3M	25.7M
% ZEB Fleet by 2040	0%	19%	41%	100%

Fuel Assessment

The **FUEL ASSESSMENT** estimates fuel consumption and costs for each of the technologies: diesel, electric, and hydrogen studied in the relevant scenario. Using ZEB performance data from the route simulation, CTE analyzed expected bus performance on each block in Mankato's service catalog to calculate the daily fuel required for that block's completion. CTE completed this analysis for each of the three zero-emission fleet transition scenarios and the baseline scenario. The analysis produced estimates of the fuel costs for each projected fleet composition through the transition period.

Assumptions

The following assumptions have been made for vehicle fuel use and efficiency projections through 2040. Annual mileage and fuel use for all vehicles are expected to remain constant, as provided by Mankato.

For FCEBs, fuel use is calculated based on CTE's fuel efficiency assumptions, measured in miles per kilogram of hydrogen, with an additional 20% loss due to hydrogen venting and transportation inefficiencies. Boil-off is the result of evaporation of liquid hydrogen, primarily due to ambient heat. Different providers/infrastructure will have different thermal efficiencies. Using fuel at a high rate prevents continuous boil-off. Continuous boil-off can be a large expense and the market has introduced boil-off gas recapture systems which is something to consider for the FCEB Only scenario.

In the case of BEBs, fuel use is determined based on CTE's efficiency assumptions, measured in kilowatt-hours per mile, and assumes an 80% charger efficiency, reflecting typical losses during the charging process. These assumptions provide a basis for evaluating fuel consumption and vehicle efficiency over the projected period. **Table 12** and **Table 13** outline the assumptions used to estimate fuel cost. All fuel costs are escalated using EIA's 2022 Annual Energy Outlook 2024-2050 average annual change. The fuel assessment also includes charger maintenance costs to reflect total cost of charging operation. Depot charger maintenance is estimated at $3,000/yr/charger (2:1 vehicle: charger ratio) and pantograph charger maintenance cost is estimated at $7,500/yr/charger (4:1 vehicle: charger ratio). Demand is measured by maximum 15-minute average. Depot charging assumes all off-peak charging. On-Route Charging assumes all on-peak charging. Summer Charges apply in June-September, while Winter Chargers apply in October-May. General Service Time of Day is 9am – 9pm.

Table 12 - BEB Fuel Cost Assumptions- Utility Rate Schedule

Xcel Energy - General Service Time of Day		
Charge	**Cost**	**Unit**
Service Charge	$29.98	monthly
Summer Demand (On-Peak)	$16.49	kW
Winter Demand (On-Peak)	$11.90	kW
Demand (Off-Peak)	$3.35	kW
kWh On-Peak	$0.065280	kWh
kWh Off-Peak	$0.034410	kWh
Energy Charge Credit	$0.018250	kWh

Table 13 – Biodiesel, Gasoline, and FCEB Fuel Cost Assumptions

Fuel Type	Cost per Unit	Source
Biodiesel	$2.95	City of Mankato
Gasoline	$2.48	City of Mankato
FCEB	$9/kg	Average regional off-site trucked-in hydrogen costs

In addition, CTE assumed the following infrastructure needs based on each scenario:

Chargers

- Charging projects include purchase and installation of 180kW chargers and dispensers.
- Depot-Charging Ratio : 2 dispenser : 1 charger
- Permanent Station – 25,000 gallon storage – 2 lanes (1 lane: 32 bus ratio)

BEB Depot Only Infrastructure Costs include:

- Transformers, switchgear, DC chargers, plug-in dispensers for depot chargers (180kW)

FCEB Only Infrastructure Costs include:

- Hydrogen fueling station build (up to 64-Bus Incremental Design), including design, construction and equipment installation cost and “futureproofing” for additional dispensers in the future
- Infrastructure master planning and design in the year prior to construction at $200,000 per build-out of the H2 fueling station

Analysis Results

Baseline

Figure 23 shows the annual fuel cost by bus type over the course of the transition period for the Baseline scenario. The total expenditures from 2024-2040 equals $5.9M total ($3.8 million from biodiesel vehicles, $2.1 million from gasoline vehicles).

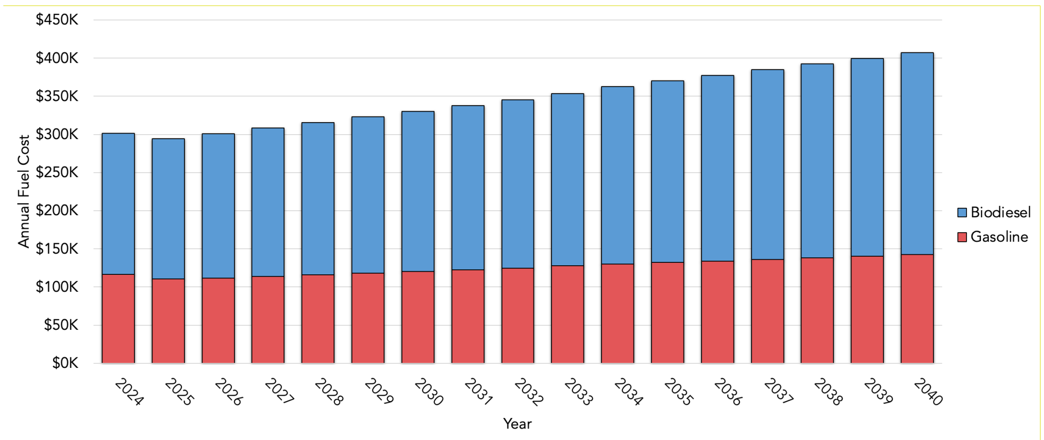


Figure 23 - Annual Fuel Cost: Baseline Scenario

BEB Depot Only

Figure 24 shows the annual fuel cost by bus type over the course of the transition period for the BEB Depot Only scenario. The total expenditures from 2024-2040 equals $5.9M total ($3.3 million from biodiesel vehicles, $2.3 million from gasoline vehicles, and $366.9K from electric vehicles).

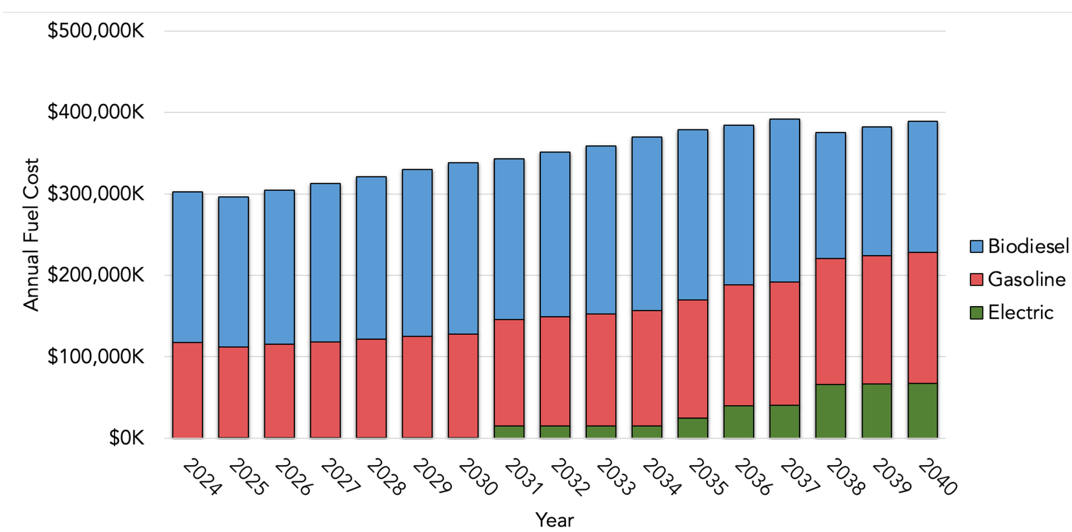


Figure 24 - Annual Fuel Cost: BEB Depot Only Scenario

BEB Depot and On Route Charged

Figure 25 shows the annual fuel cost by bus type over the course of the transition period for the BEB Depot and On-Route Charged scenario. The total expenditures from 2024-2040 equals $6.4M total ($2.8 million from biodiesel vehicles, $2.3 million from gasoline vehicles, $469.3K from electric vehicles, and an additional $891.2K for on-route charged electric vehicles).

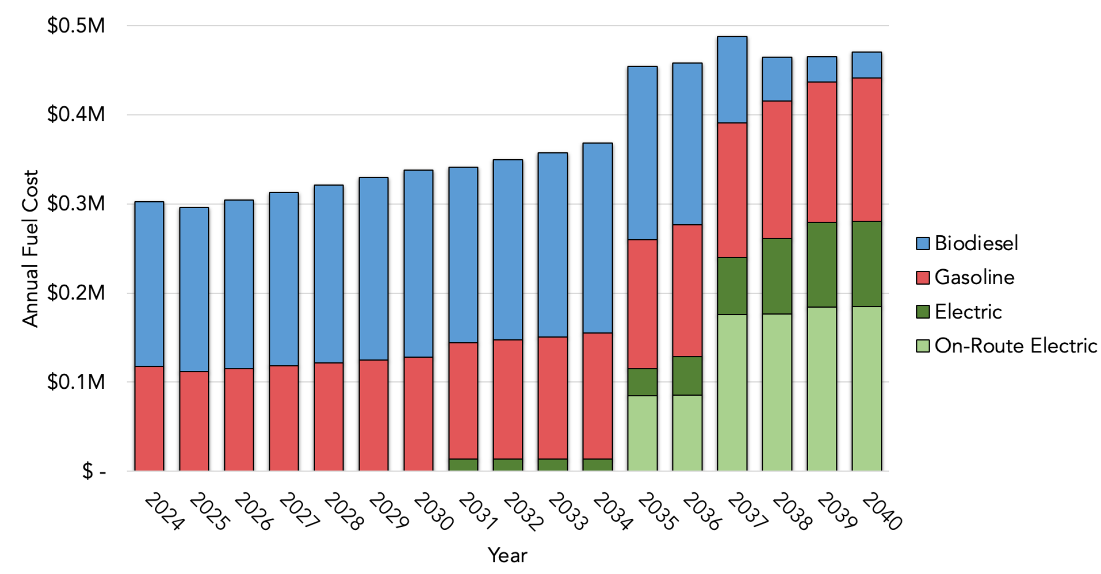


Figure 25 - Annual Fuel Cost: BEB and On-Route Charged Scenario

FCEB Only

Figure 26 shows the annual fuel cost by bus type over the course of the transition period for the FCEB Only scenario. The total expenditures from 2024-2040 equals $15.5M total ($2.5 million from biodiesel vehicles, $734K from gasoline vehicles, and $12.3 million for FCEBs).

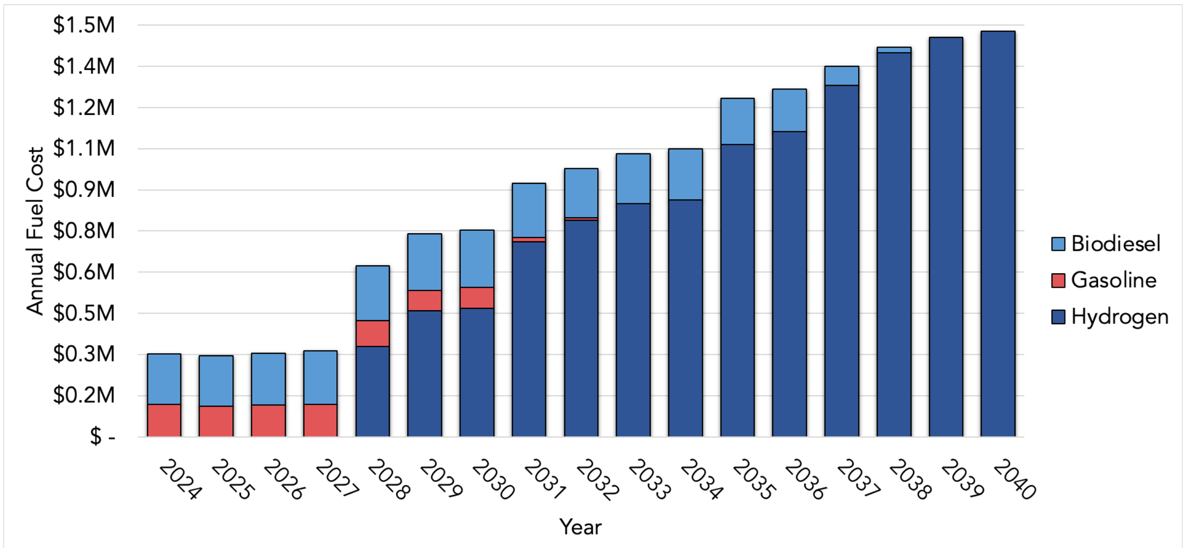


Figure 26 - Annual Fuel Cost: FCEB Only Scenario

Summary

When comparing vehicle options for fuel cost versus capabilities, there are a few tradeoffs to consider. Although FCEBs offer considerably more range capability than BEBs, the cost of hydrogen is still significantly higher than electricity. BEBs will ultimately require more depot infrastructure, and a BEB only fleet would require on-additional on route charging to reach 100% feasibility. **Figure 27** and **Table 14** - Cumulative Fuel Costs by Scenario show the cumulative fuel costs throughout the transition timeline by scenario. The Baseline scenario has a projected cumulative fuel cost of $5.9M, the BEB Depot Only scenario has a projected fuel cost of $5.9M, the BEB Depot and On-Route Charged scenario has a projected fuel cost of $6.4M, and the FCEB Only scenario has the highest projected fuel cost of $15.5M over the transition timeline.

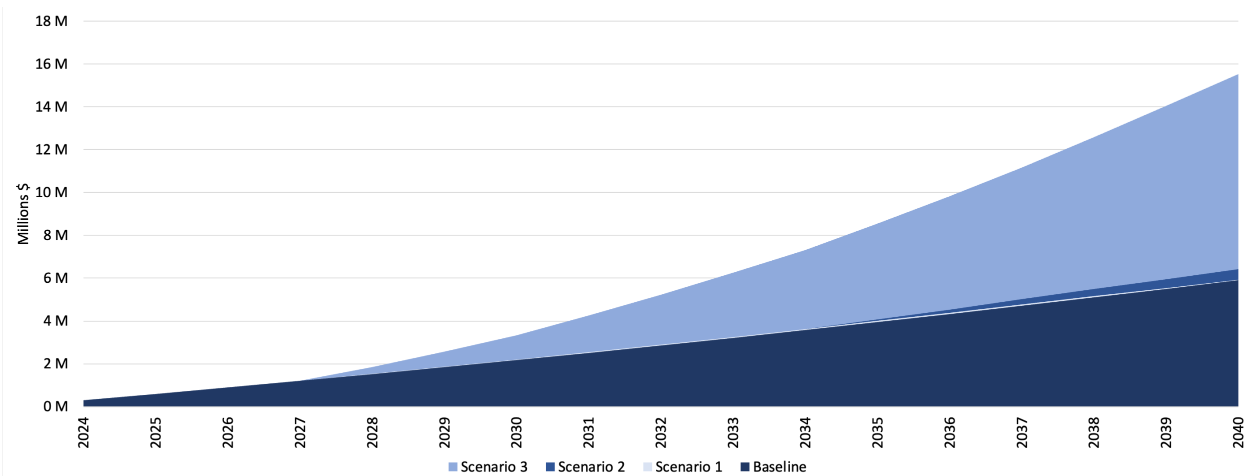


Figure 27 - Cumulative Fuel Costs by Scenario (2024-2040)

Table 14 - Cumulative Fuel Costs by Scenario

Costs	Baseline	Scenario 1 (BEB Depot Only)	Scenario 2 (BEB Depot & On-Route Charged)	Scenario 3 (FCEB Only)
Cumulative ($)	$5.9M	$5.9M	$6.4M	$15.5M
Incremental over Baseline ($)	-	+25.3K	+$517.5	+$9.6M
% ZEB Fleet by 2040	0%	19%	41%	100%

Maintenance Assessment

The **MAINTENANCE ASSESSMENT** examines the changes to fleet maintenance costs for each fleet composition scenario over the transition period. Since ICE and zero-emission vehicles have different maintenance requirements, they generally have different maintenance costs associated with them. For both BEB and FCEB maintenance cost estimates, CTE developed assumptions using real-world data from early adopters of ZEBs and applied them to Mankato's Maintenance Assessment. Taking on a conservative outlook of vehicle performance, CTE also included the cost impact of midlife overhauls for BEBs (where technicians look for signs of corrosion and install more durable parts) for components of the fleet. Cutaways are excluded from midlife overhaul costs due to short service life.

CTE used Mankato's reported costs for maintenance and average engine and transmission overhaul for the newest models of the existing ICE fleet. CTE also included the price of a midlife overhaul for FCEBs that covers the cost of a complete overhaul of the fuel cell system, which, if required, can be significant and may offset savings from traditional maintenance costs. The cost of a battery replacement for a BEB and the battery portion of FCEB's midlife maintenance costs is traditionally covered under the battery warranty. This is purchased in the procurement year and is therefore considered a capital cost versus an operational/maintenance cost.

Cost Assumptions

CTE's maintenance cost assessment includes labor, materials, and midlife overhaul costs. Only maintenance costs for fleet vehicles are included in the maintenance assessment; infrastructure maintenance is included as a part of the fuel assessment.

This assessment applied unit maintenance cost per mile by vehicle type with total costs based on average annual vehicle mileage as reported by Mankato. Total costs are based on the following assumptions:

- Maintenance costs for Biodiesel and Gasoline buses are based on data from Mankato's current fleet.
- Maintenance costs for BEBs are based on biodiesel equivalents from Mankato's current fleet.
    - Note that maintenance costs are hard to predict. Compared to conventional diesel and gasoline fueled vehicles, BEBs incur different maintenance needs that vary based on manufacturer and operating environment. In addition, many BEB components are covered by

warranty, so maintenance costs in the first few years are significantly lower than in the latter half of its service life.

- Maintenance costs for FCEBs were based on industry averages from NREL data.
  - Long-term FCEB maintenance costs for US manufactured buses are still to be determined and should be carefully considered as Mankato implements its transition plan.
- Midlife Overhaul Costs
  - Bio-Diesel Overhaul costs were estimated at $39,000 ($28,000 Engine + $11,000 Transmission)
  - Fuel Cell Overhaul costs were estimated at $40,000 per bus based on the average cost by OEM and fuel cell manufacturer over the life of the bus incurred at midlife.
  - Cutaways are excluded from midlife overhaul costs due to short service life.
- Inflation rate of 3% applied through 2040, based on historical CPI for labor.

Maintenance cost per mile is defined as the total labor costs plus the total material costs divided by the total number of miles. **Table 15** summarizes the estimated combined costs for scheduled and unscheduled labor and maintenance for each type of bus explored in this study.

Table 15 - Labor and Materials Cost Assumptions

Fuel Type	$/mi	Source
Bio-Diesel	$0.72	Mankato Maintenance Cost
Gasoline	$0.33	Mankato Maintenance Cost
Electric	$0.72	Equal to Bio-Diesel
Fuel Cell	$0.56	Industry Average

As a reminder, BEB maintenance cost does not include the battery warranty price which is purchased in the year of procurement and covers a single mid-life battery replacement. CTE included a $75,000 battery warranty cost to the fleet cost in the fleet assessment. FCEB maintenance cost does not include the extended warranty cost, which is purchased in the year of procurement.

Analysis Results

Baseline

Figure 28 shows the combined labor, materials, and midlife overhaul costs for the Baseline scenario for each year of the transition. The total maintenance cost associated with biodiesel vehicles is $4.3M and the total gasoline vehicle associated cost is $3.7M, for a total maintenance cost of $8M over the transition period.

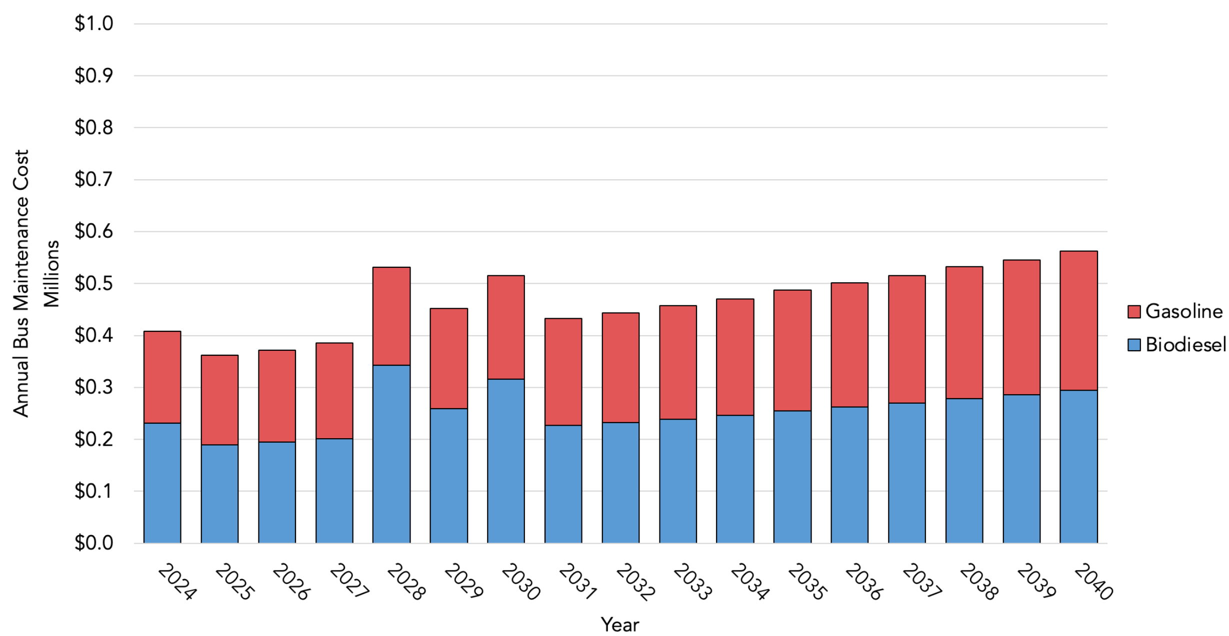


Figure 28 - Annual Fleet Maintenance Costs: Baseline Scenario

BEB Depot Only

Figure 29 shows the combined labor and materials for the BEB Depot Only scenario for each year of the transition. For the BEB Depot Only scenario, the cost of the battery warranty is used to reflect the midlife battery replacement. In the assessment, the warranty costs are incurred at the time of the bus purchase and were included in the capital costs seen in the Fleet Assessment. Thus, the warranty costs are not included in the maintenance costs. The spikes in maintenance costs for this scenario are scheduled to occur in the same years that large bus procurements take place. The total maintenance cost associated with BEBs is $557.5K, the total biodiesel vehicle associated cost is $3.7M, and the total gasoline vehicle associated cost is $3.5M for a total maintenance cost of $7.8M over the transition period.

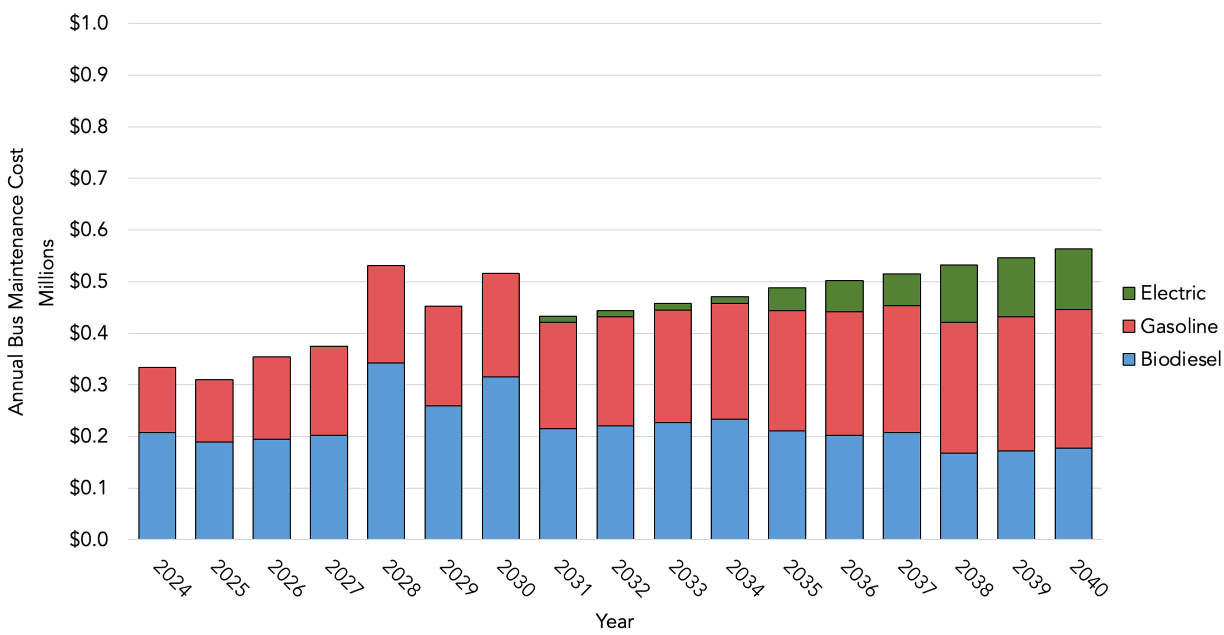


Figure 29 - Annual Fleet Maintenance Costs: BEB Depot Only Scenario

BEB Depot and On Route Charged

Figure 30 shows the combined labor, materials, and midlife overhaul costs for the BEB Depot and On Route Charged scenario for each year of the transition. Like the BEB Depot Only scenario, anticipated midlife battery replacements for ZEBs are covered in the extended battery warranty in the year of purchase and can be seen in the Fleet Assessment. The total maintenance cost associated with BEBs remains $557.5K, with an additional $687K for On-Route BEBs, and an additional $3.1M for biodiesels and $3.7M for gasoline vehicles, for a total maintenance cost of $7.9M over the transition period.

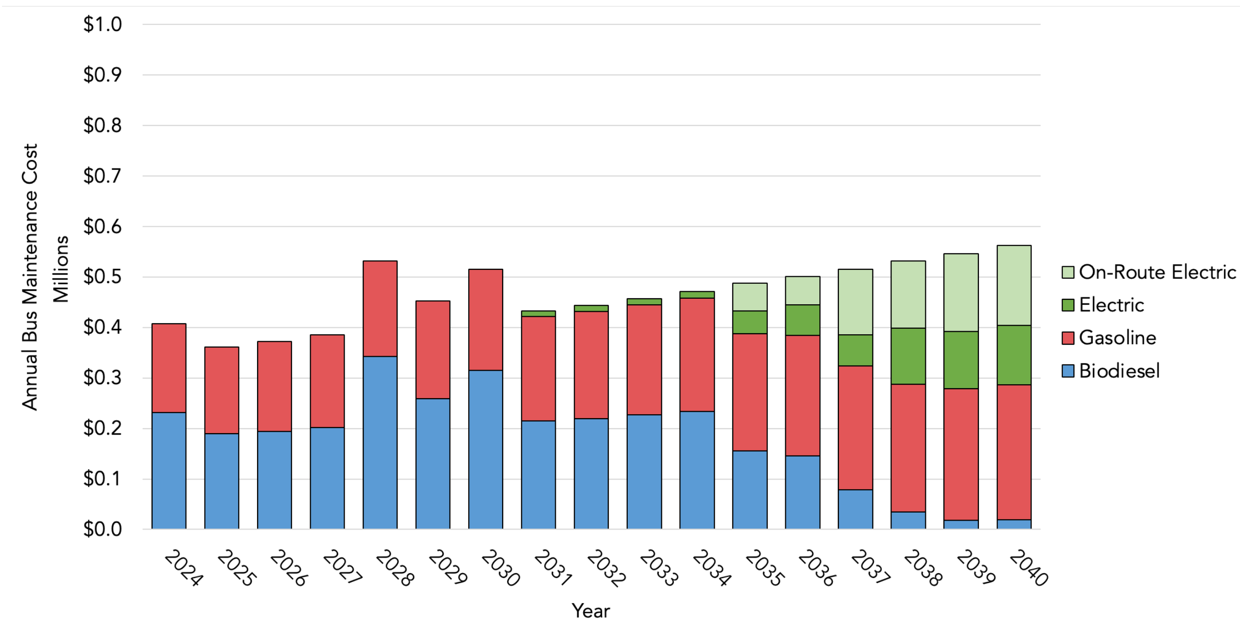


Figure 30 - Annual Fleet Maintenance Costs: BEB Depot and On Route Charged Scenario

FCEB Only

Figure 31 shows the combined labor, materials and midlife overhaul costs for the FCEB Only scenario for each year of the transition. Maintenance costs for fuel cells were calculated using industry-reported maintenance costs per mile and maintenance costs reported by NREL. The total maintenance cost associated with FCEBs is $5.9M, the total biodiesel associated cost is $2.9M, and the total gasoline associated cost is $987K for a total maintenance cost of $9.8M over the transition period.

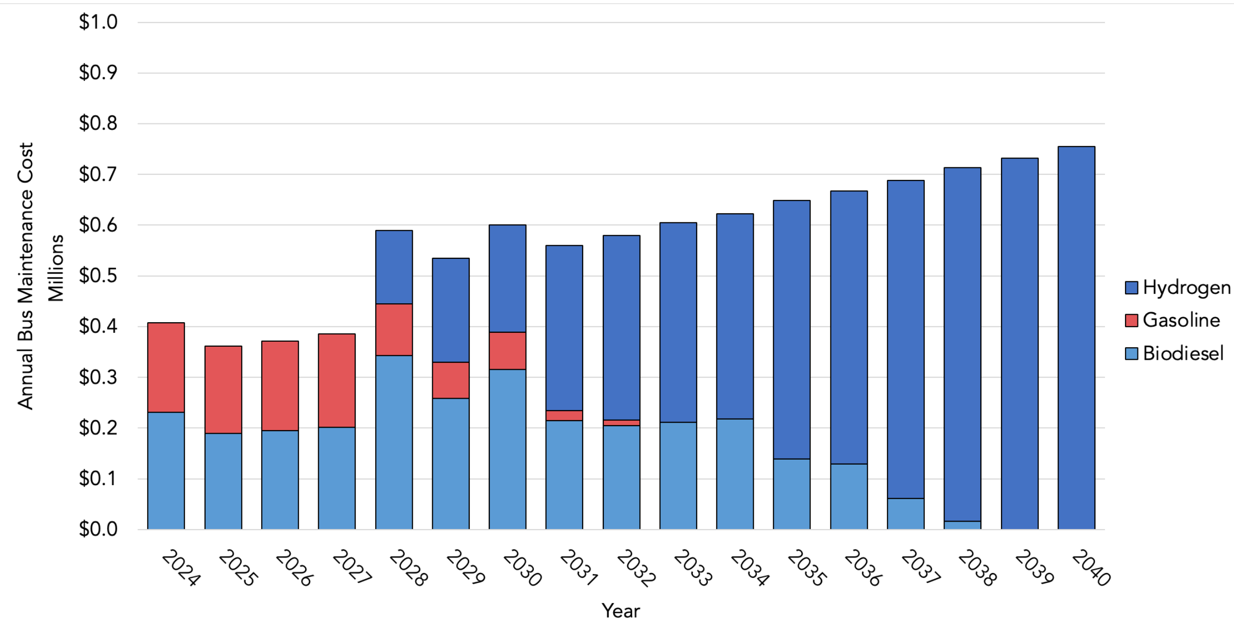


Figure 31 - Annual Fleet Maintenance Costs: FCEB Only Scenario

Summary

Figure 32 and **Table 16** shows the cumulative maintenance costs for each scenario. CTE's Maintenance Assessment estimates that by 2040, the FCEB scenario will incur the highest cumulative maintenance cost ($9.8M) while the BEB Depot Only and BEB Depot and On Route Charged scenarios will incur the least amount of maintenance costs (approximately $7.8M and $8M, respectively) each over the transition period. These compare to the cumulative maintenance cost of $8M for the Baseline scenario. Note that inflation is applied to show the cumulative costs.

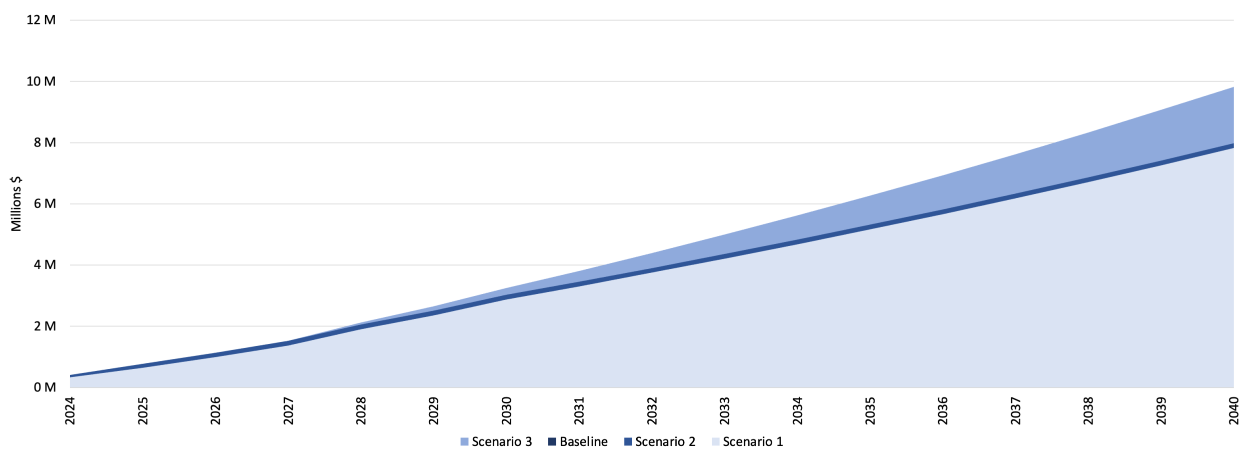


Figure 32 - Cumulative Maintenance Cost Comparison

Table 16 - Cumulative Maintenance Cost Comparison

Costs	Baseline	ZEB Scenario 1 (BEB Depot)	ZEB Scenario 2 (BEB Depot & ORC)	ZEB Scenario 3 (FCEB)
Cumulative ($)	$8M	$7.8M	$8M	$9.8M
Incremental over Baseline ($)	-	-$154K	-	+$1.8M
% ZEB Fleet by 2040	0%	19%	41%	100%

Facilities Assessment

The **FACILITIES ASSESSMENT** determines the scale of fueling infrastructure (charging stations for BEBs and hydrogen fueling stations for FCEBs) that is needed to meet the projected energy use for each scenario. It is informed by the Fleet and Fuel Assessments. Facilities costs are estimated based on the assessed infrastructure requirements for the given fleet and the selected fueling technology. The information in this section is organized according to the fueling technology explored in this transition plan: depot-charging, on-route charging, and hydrogen storage and fueling station. Diesel/gasoline fueling station build and installation costs are not included in this assessment as Mankato has already invested in the fueling infrastructure necessary to support the current fleet.

Assumptions

The following terms are used when discussing chargers and charging infrastructure:

- **Charging Station:** Self-contained unit that connects to grid, converts electricity from AC to DC, and outputs power to bus through dispenser.
- **Power Cabinet:** Structure to hold power conversion hardware. Connects to multiple dispensers.
- **Dispenser:** Cord that carries DC power from power conversion hardware to bus's charge inlet.

The charging infrastructure for the project will include the purchase and installation of 180kW chargers and dispensers. The depot-charging ratio is set at 2 dispensers for every 1 charger, while the pantograph-charging ratio will be 4 buses per 1 charger. Considering bus utilization, CTE assumed that 80% of buses will be used in daily operations and are assessed for infrastructure costs, with the remaining 20% considered a spare ratio. The permanent station will have a 25,000-gallon storage capacity and two lanes, with a bus-to-lane ratio of 32 buses per lane.

CTE also assumes a fixed cost for necessary service upgrades to accommodate the BEB scenarios. CTE assumes this upgrade will take place in 2025 to prepare for the BEB transition, however, this timeline can be adapted as needed.

For this assessment, CTE divided the ZEB infrastructure purchase needs by the three scenarios.

BEB Depot Only infrastructure costs include:

- Transformers, switchgear, DC chargers, and plug-in dispensers for depot chargers (180kW).

BEB Depot & On-Route Charging Infrastructure Costs include:

- Transformers, switchgear, DC chargers, and plug-in/pantograph dispensers for chargers (180 kW and 350kW).

FCEB Only Infrastructure Costs include:

- Hydrogen fueling station build (up to 64-Bus Incremental Design) including design, construction and equipment installation cost and “future-proofing” for additional dispensers in the future.
- Infrastructure master planning and design in the year prior to construction at $200,000 per build-out of the H2 fueling station.

Table 17 and **Table 18** provide the facilities cost assumptions associated with BEB infrastructure projects. These costs are based on industry averages. A contingency cost of 20% is applied to all project costs, and a design engineering fee of 6% is added to both the project costs and the contingency amount.

Table 17 - Facilities Cost Assumptions for BEB Power Upgrades

Power upgrade projects	Cost	Unit
Infrastructure Planning Cost	$ 200 K	Year before BEBs
Trench and Duct bank/Gantry	$ 15 K	per project
Switchboard & Pad (1 mW)	$ 300 K	mW
Switchboard & Pad (2 mW)	$ 300 K	mW
Switchboard & Pad (3 mW)	$ 300 K	mW
Switchboard & Pad (4 mW)	$ 300 K	mW
Switchboard & Pad (5 mW)	$ 300 K	mW

Table 18 - Facilities Cost Assumptions for BEB Charging Infrastructure

Charger + Dispenser projects	Cost	Unit
Chargers	$ 180 K	each
Charger Installation	$ 10 K	each
Depot/Pantograph Dispenser	$ 70 K	each
Dispenser Installation	$ 5 K	each

Table 19 provides the facilities cost assumptions associated with FCEB infrastructure projects. These costs are based on industry averages. A contingency cost of 20% is applied to all project costs, and a design engineering fee of 6% is added to both the project costs and the contingency amount. In addition, CTE assumes all fueling and maintenance bays will be upgraded. If bays are connected/open, they must be upgraded because H2 can move between bays without walls. Mankato appears to have 1 maintenance bay. The local jurisdiction may have additional requirements.

Table 19 - Facilities Cost Assumptions for FCEB Charging Infrastructure

H2 Projects	Cost	Unit
Infrastructure Planning Cost	$ 200,000	Year before FCEBS
Maintenance Bay Upgrade	$ 200,000	per bay (all at once)
25,000 Gallon Storage	$ 4.8M	~5,500kg useable tank and associated storage infrastructure (75+ bus capacity, 3-4 day storage)
Fueling lanes	$ 1.5M each, 3M total	Dispenser per Lane, including associated fueling equipment (pad, pre-chiller, etc.)

Analysis Results

BEB Depot Only

The BEB Depot Only scenario assumes a fleet of BEBs and plans a transition to an electric charging infrastructure. **Figure 33** shows the annual infrastructure costs associated with the BEB Depot Only scenario. This scenario does not consider on-route charging.

The infrastructure upgrades include comprehensive planning and the installation of chargers and dispensers. Analysis reflects an additional power upgrade planned for 2025. These enhancements are designed to improve access to modern, efficient charging solutions and ensure the infrastructure meets growing demand.

By the end of the transition period in 2040, Mankato's fleet and infrastructure will be composed of 6 BEBs, 26 ICEs; Mankato will have purchased 3 chargers and 6 dispensers throughout the transition period. The total infrastructure cost estimate for the BEB Depot Only scenario is $2.2M.

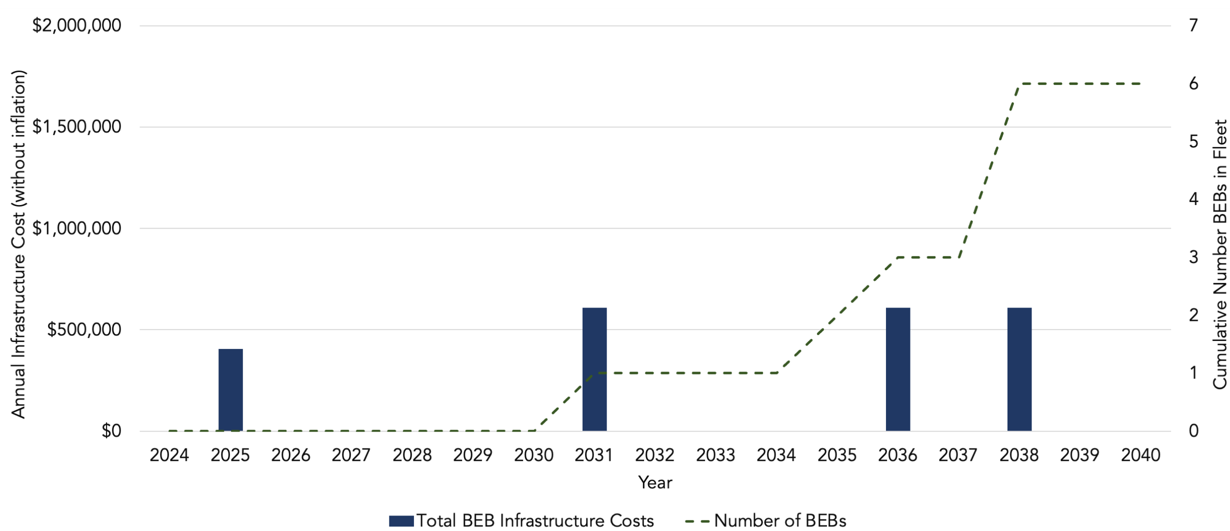


Figure 33 - Annual Infrastructure Costs: BEB Depot Only Scenario

BEB Depot and On Route Charged

Figure 34 shows the annual infrastructure costs associated with the BEB Depot and On Route Charged scenario.

The infrastructure upgrades include comprehensive planning and the installation of chargers and dispensers. Analysis reflects an additional power upgrade planned for 2025. These enhancements are designed to improve access to modern, efficient charging solutions and ensure the infrastructure meets growing demand.

By the end of the transition period in 2040, Mankato's fleet and infrastructure will be composed of 13 BEBs, 19 ICEs; Mankato will have purchased 7 depot chargers, 14 dispensers, and 2 pantograph chargers throughout the transition period. The total infrastructure cost estimate for the BEB Depot Only scenario is $4.9M.

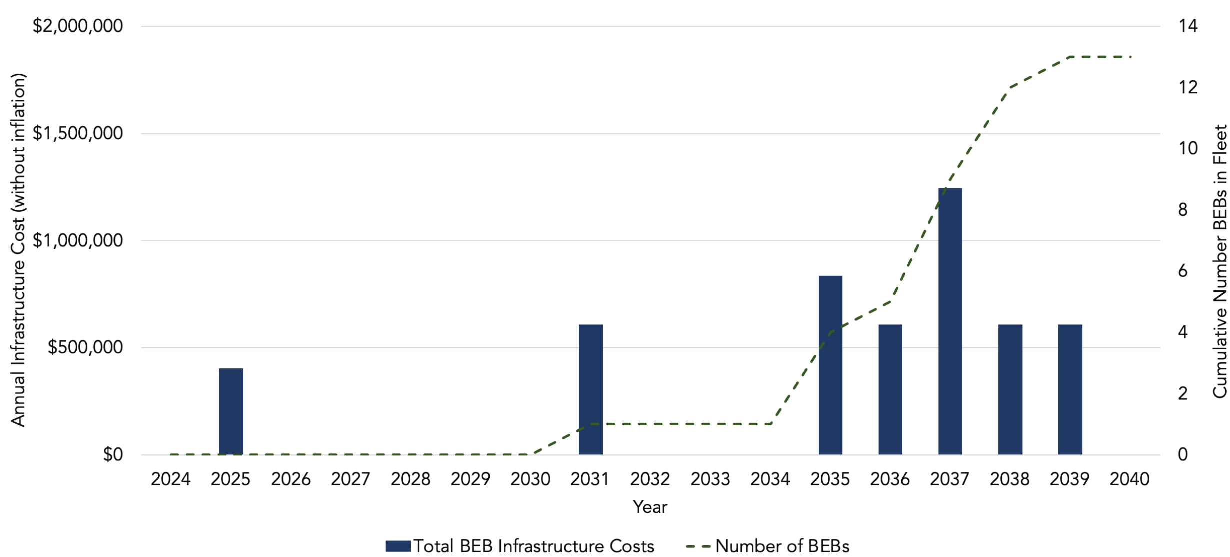


Figure 34 - Annual Infrastructure Costs: BEB Depot and On Route Charged Scenario

FCEB Only

Figure 35 shows the annual infrastructure costs associated with the FCEB Only scenario.

The infrastructure upgrades include planning and a maintenance bay upgrade in 2027 and the installation of a permanent station in 2028.

By the end of the transition period in 2040, Mankato's fleet and infrastructure will be composed of 32 FCEBS; Mankato will have purchased 1 permanent station in 2028 and upgraded their 1 bay. The total infrastructure cost estimate for the BEB Depot Only scenario is $8.2M.

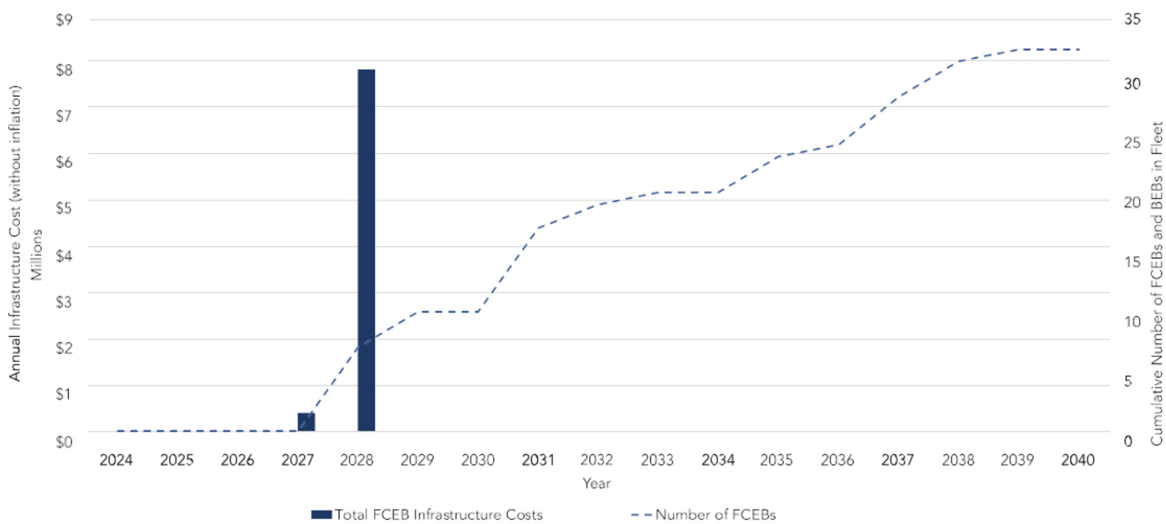


Figure 35 - Annual Infrastructure Costs: FCEB Only Scenario

Summary

The facilities assessment is intended to provide Mankato with insight regarding infrastructure costs associated with each scenario during the transition to zero-emission. **Figure 36** shows the total infrastructure investment cost by scenario during the transition period. The BEB Depot Only scenario has an estimated cost of $2.2M compared to the BEB Depot and On Route Charged scenario estimated cost of $4.9M, whereas the FCEB Only scenario has the highest associated infrastructure cost of $8.2M.

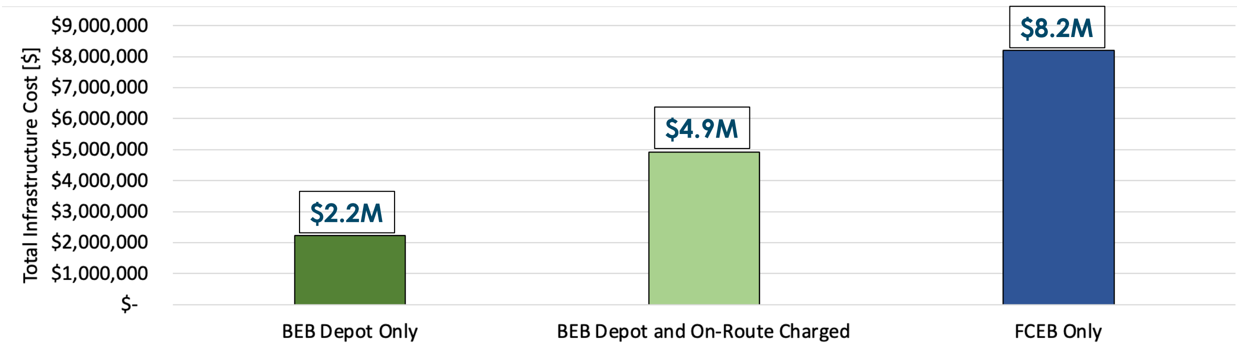


Figure 36 - Infrastructure Capital Costs by Scenario

Cost estimates for this assessment are constrained by a three percent annual inflation for both infrastructure hardware costs and for Architecture and Engineering (A&E) construction costs. The final site layout will ultimately determine the construction costs. The analysis assumes Mankato will maintain the current fleet size, electricity will be readily available at on-route charging sites, and the procurement follows the timelines discussed in the fleet assessment. FCEB facility costs vary by region and method of hydrogen delivery.

Total Cost of Ownership Assessment

Methodology

The Total Cost of Ownership Assessment compiles the cost results from the Fleet, Fuel, Facilities, and Maintenance Assessments to show cumulative and annual costs throughout the transition period for each scenario. The transition period is during the 16-year period between 2024-2040. It includes selected capital and operating costs of each fleet scenario over the transition timeline. Other costs may be incurred such as incremental operator and maintenance training during a fleet transition; however, these four assessment categories are the key drivers in ZEB transition decision-making.

This study assumes no cost escalation or any cost reduction due to economies of scale for ZEB technology because there is no historical basis for these assumptions. Future changes to Mankato's service level, depot locations, route alignments, block scheduling, or other operations were kept consistent. The analyses below provide best estimates using the information currently available and the assumptions detailed throughout this report.

Analysis Results

Figure 37 shows the total costs per scenario, broken down by assessment type.

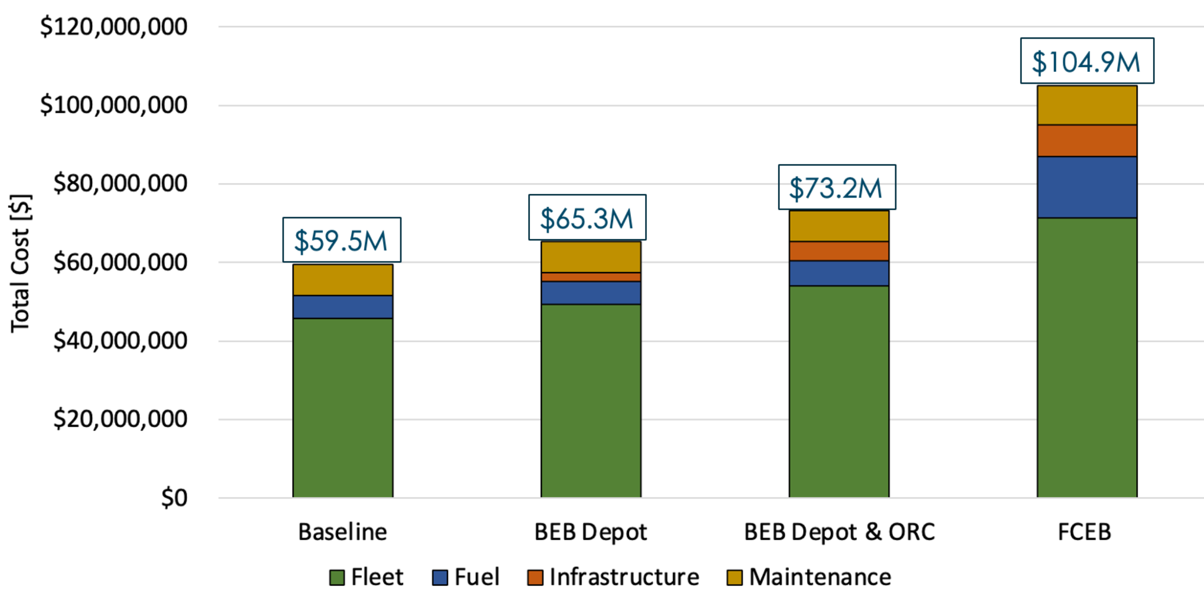


Figure 37 - Total Cost of Ownership

Figure 38 shows the costs by scenario over the transition timeline.

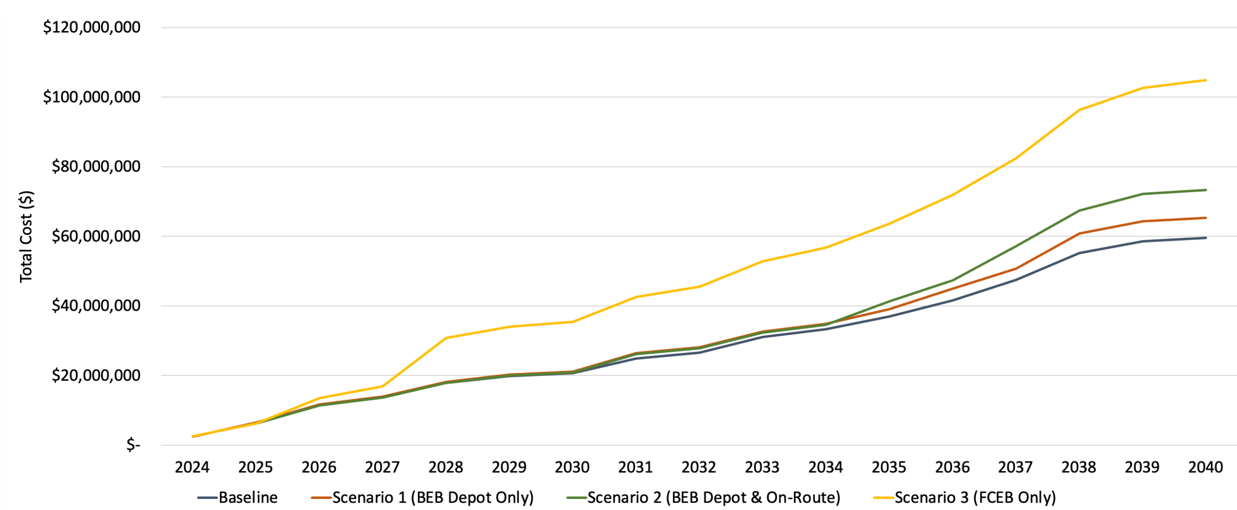


Figure 38 – Total Costs by Scenario 2024-2040

Baseline

The first bar in **Figure 37** shows the combined fleet, fuel, facilities, and maintenance costs for the Baseline scenario. Since bus capital costs represent the largest expense examined, at $45.7M, the fleet categories make up the largest portion of each bar on the graph. The predominance of fleet-related costs remains consistent across all scenarios. Fleet, Fuel, and Infrastructure costs for the baseline scenario are projected to be lower compared to the other scenarios. However, maintenance costs, of $7.98M, over the transition timeline are the same for the BEB Depot and On Route Charged Scenario. The total combined cost for the baseline scenario is approximately $59.5M from 2024 to 2040. This makes the Baseline scenario the most inexpensive option. However, this scenario estimates a 0% ZEB fleet by 2040.

BEB Depot Only

The second bar in **Figure 37** shows the combined fleet, fuel, facilities, and maintenance costs for the BEB Depot Only scenario. Fleet costs make up most of the transition costs at $49.3M. Fueling costs over the timeline are $5.9M, which is roughly the same as the Baseline scenario and significantly less than BEB Depot and On Route Charged and FCEB Only scenarios. Facility costs over the transition totals $2.2M. Maintenance costs for this scenario are also the lowest across all scenarios at $7.8M. The total combined cost is approximately $65.3M over the length of the transition, from 2024 to 2040. This scenario estimates a 19% ZEB fleet by 2040 and is approximately $5.7M more than the baseline scenario.

BEB Depot and On Route Charged

The third bar in **Figure 37** shows the combined fleet, fuel, facilities, and maintenance costs for the BEB Depot and On Route Charged scenario. Fleet costs make up most of the transition costs at $53.9M. Facility costs over the transition total $4.9M. Fueling costs over the timeline are $6.4M. Maintenance costs for this scenario are equivalent to the baseline at $7.9M. The total combined cost is approximately $73.2M over the length of the transition, from 2024 to 2040. This scenario estimates a 41% ZEB fleet by 2040 and is approximately $13.7M more than the baseline scenario.

FCEB Only

The fourth bar in **Figure 37** shows the combined fleet, fuel, facilities, and maintenance costs for the FCEB Only scenario. Across the scenarios, the FCEB scenario has the largest costs in each assessment category. Fleet costs over the transition total $71M, fuel costs total $15.5M, facilities costs total $8.2M, and maintenance costs are estimated at $9.8M. These costs are significantly larger compared to the other three scenarios. The total combined cost is approximately $104.9M over the length of the transition, from 2024 to 2040. This scenario estimates an 100% ZEB fleet by 2040 and is approximately $45.4M more than the baseline scenario.

Summary

Table 20 shows the total costs by scenario and assessment. The Baseline scenario is the lowest total cost option while the FCEB Only scenario is the highest cost option. Compared to the Baseline scenario, The BEB Depot Only Scenario is the next lowest cost option for total cost, fleet cost, fuel cost, and infrastructure cost. For maintenance costs, the BEB Depot Only Scenario is the lowest cost option across all scenarios.

The FCEB Only and BEB Depot and On Route Charged scenarios are the highest cost options as FCEB vehicles are the most expensive and on-route chargers require additional infrastructure and charging. The cost of hydrogen is likely to decrease over time and FCEBs function similarly to ICE vehicles, so there are operational advantages outside of cost such as a 1:1 range equivalent and maintenance involving compressed gas as a fuel.

Table 20 - Total Cost of Ownership, by Scenario and Assessment

Assessment	Baseline	ZEB Scenario 1 (BEB Depot)	ZEB Scenario 2 (BEB Depot & ORC)	ZEB Scenario 3 (FCEB Only)
Fleet	$45,665,000	$49,270,000	$53,934,000	$71,401,000
Fuel	$5,904,000	$5,930,000	$6,422,000	$15,521,000
Infrastructure	-	$2,228,000	$4,916,000	$8,200,000
Maintenance	$7,977,000	$7,823,000	$7,977,000	$9,824,000
Total	$59,546,000	$65,251,000	$73,250,000	$104,946,000
Compared to Baseline	-	+$5,705,000	+$13,703,000	+$45,400,000
% ZEB	**0%**	**19%**	**41%**	**100%**

* FCEB Only assumes $9/kg hydrogen

As noted previously, this analysis was completed based on the best available fleet data and procurement schedule available as of 2024.

Conclusions and Recommendations

Zero-emission buses offer a wide range of benefits not only for the agencies deploying them but also for the communities they serve. There are significant environmental benefits associated with the transition to ZEB technology. Widespread adoption of zero-emission bus technology has the potential to greatly reduce greenhouse gas (GHG) emissions resulting from the transportation sector. Through the reduction of tailpipe emissions, ZEBs benefit the environment by delivering better air quality and health benefits to the passengers and neighboring areas which tend to be disproportionately low-income and historically disadvantaged communities. Additionally, the total cost of ownership for a ZEB fleet has the potential to be equal to or less than a fleet of ICE vehicles. ZEBs are also significantly quieter than traditional vehicles which can help with noise reduction.

Mankato is a great example of an agency motivated to move to ZEBs without any mandates or staff well-versed in ZEB technology. To get a better understanding of the obstacles and requirements involved with the switch to zero-emission, Mankato has proactively worked to develop a ZEB transition plan to act as a blueprint for ZEB long-term fleet and facilities management.

ZEB technologies are in a period of rapid development. While the technologies have been proven in many pilot deployments, they are not yet matured to the point where they can easily replace current ICE technologies on a large scale. BEBs require significant investment in facilities and infrastructure and may require changes to service and operations to manage their range constraints. FCEBs can provide an operational equivalent to ICE buses, but the cost of buses, fueling infrastructure, and fuel remain a significant barrier to mass adoption. Despite the challenges associated with ZEB technology, Mankato has the opportunity to implement environmentally friendly policies and reduce its carbon footprint.

Summary of Scenario Options

The approach for this transition plan is based on the analysis of three ZEB technology scenarios compared to a baseline scenario. The baseline scenario is reflective of Mankato's current diesel bus fleet. The three potential transition scenarios include a BEB Depot Only scenario of battery electric buses charged at the depot, a BEB Depot and On Route Charged scenario of battery electric buses charged at the depot and on route, and a FCEB Only scenario of fuel cell electric buses.

Total transitional costs under the BEB Depot Only scenario is an estimated $65,251,000. The difference in cost between this scenario and the Baseline is largely the result of the price difference between ICE buses and BEBs as well as up-front capital costs for new fueling infrastructure. This scenario is projected to cost approximately $5,705,000 more than the baseline over the transition period.

Total cost the BEB Depot and On Route Charged Scenario is estimated at $53,934,000. The difference in cost between this scenario and the BEB Depot Only scenario is largely the result of the additional infrastructure and fueling to support on-route charging. This scenario is projected to cost approximately $13,703,000 more than the BEB Depot Only scenario over the transition period.

Total cost for the FCEB Only scenario is estimated at $104,946,000 and results in an entirely FCEB fleet by 2040. While only accommodating a single technology, the FCEB Only scenario has a larger total cost due to higher bus capital, maintenance, and fuel cost as compared to ICEs or BEBs. A primary assumption for the FCEB analysis is that FCEBs are already available for all bus types and lengths during the transition period. Due to the current lack of market diversity of FCEBs and hydrogen availability in the United States, fuel costs and bus capital costs remain high. These costs are largely expected to decrease in the future as more buses are deployed; however, more data are needed to understand how much cost may decrease.

Additionally, data for FCEB maintenance costs reflect higher costs than what might be expected as agencies become more familiar with the technology. As such, there are more unknowns associated with costs for the FCEB Only scenario, and costs are more subject to change. This scenario is projected to cost approximately $ 45,400,000 more than the baseline over the transition period assuming a fuel cost of $9/kg H_2.

Recommendations

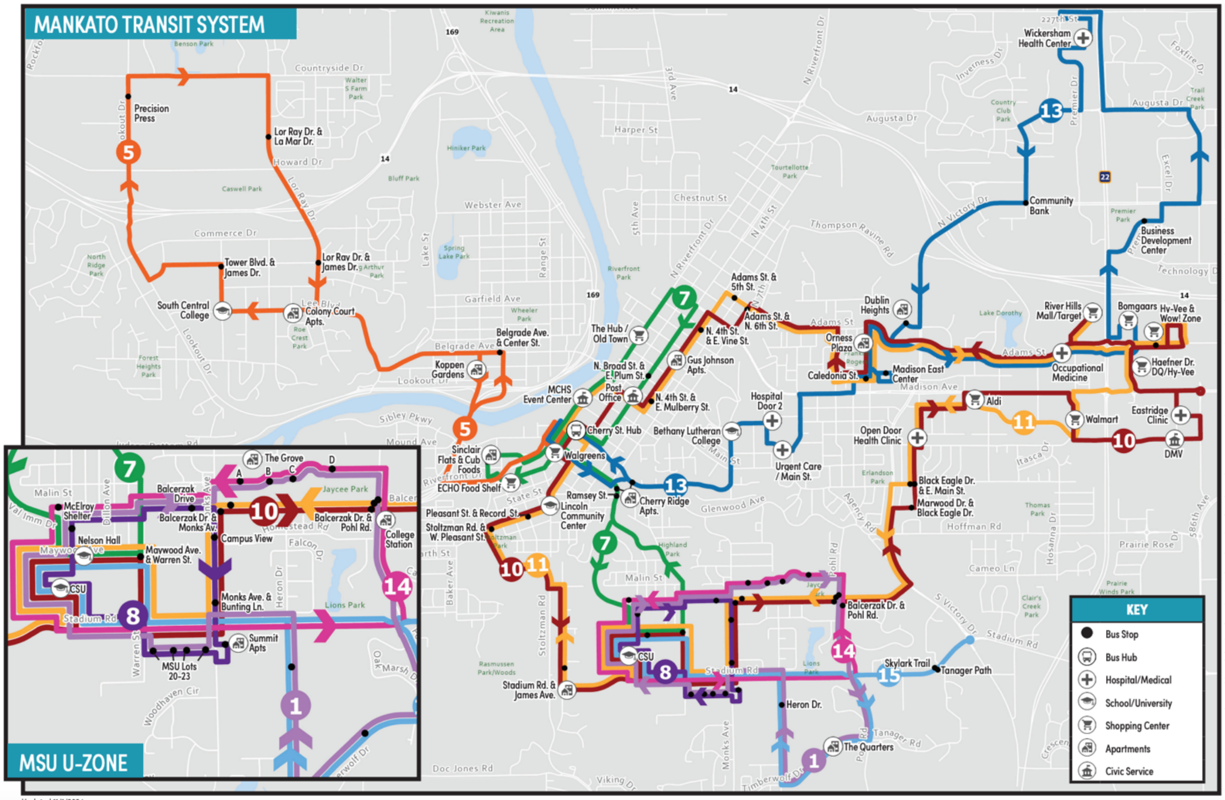
Given these considerations, the recommendations for Mankato are as follows:

1) **Select a preferred scenario to refine and remain proactive with ZEB deployment grants:** This Transition Plan was developed to present Mankato with options for transitioning to a fully zero-emission fleet. The Plan will put forth Mankato's vision for a ZEB Transition and will act as a living document to help the agency plan out grant funding requirements. As a greater proportion of Mankato's fleet converts to ZEB technology, auxiliary equipment, hardware, and software will be needed to ensure a successful fleet transition. Mankato should continue to remain proactive in the purchase and deployment of ZEBs and their associated systems by taking advantage of various grant and incentive programs.
2) **Monitor local and regional developments:** In the zero-emission technology sector, developments at the local level can have the ability to catapult the industry forward. When local bus OEMs or fuel providers enter the zero-emission market, it can spark technological innovation and cost reduction. Neighboring transit agencies can also work together through group purchasing agreements and lobbying efforts to reduce purchase costs or increase funding opportunities.
3) **Evaluate requirements for workforce and stakeholders:** Understand the impacts that the ZEB transition will have on key stakeholders and changes to accommodate workforce development. Evaluate the tradeoffs for various alternatives to reduce the risk for stakeholders at all levels for hurricanes, tropical storms, power outages, equipment failure, and fuel disruptions, and allow Mankato to meet all first responder requirements.
4) **Match the individual bus technology to the individual route and blocks:** Mankato should consider the strengths of given ZEB technologies and focus those technologies on routes and blocks that take advantage of their efficiencies and minimize the impact of the constraints related to the

respective technologies. These technologies cannot follow a one-size-fits-all approach from either a performance or cost perspective. Matching the present technology to the present service levels will be a critical best practice.

The transition to ZEB technologies represents a fundamental paradigm shift in bus procurement, operation, maintenance, and infrastructure. It is only through a continual process of deployment with specific goals for advancement that the industry can achieve the goal of economically sustainable, zero-emission public transit.

Appendix A - Mankato Current System Map



Updated 11/1/2024.

Appendix B – Mankato Block Energy Needs by Bus Size

Block*	Vehicle Class	Distance (mi)	Duration (h:mm)	Strenuous Energy (kWh)
5	Cutaway	219	11:30	328
7	Cutaway	157	12:20	235
13	Cutaway	156	11:20	234
1	40’	40	4:15	129
8	40’	79	11:15	254
10A	35’	213	12:30	617
10B(weekday)	35’	213	14:30	574
10B(Saturday)	35’	198	12:30	487
10B(Sunday)	35’	168	12:30	617
11(weekday)	35’	194	14:30	524
11(Saturday)	35’	181	11:30	424
11(Sunday)	35’	146	9:30	564
14	40’	123	11:15	394
15	40’	200	11:45	639
15B	35’	30	5:30	88

Appendix C – Stakeholder Analysis

Stakeholder Analysis

A successful ZEB deployment will require input from staff from across your transit agency and from external organizations. Engage with representatives from these different departments or groups early to ensure that you have the information you need to make informed decisions. Early interaction with stakeholders will help you determine their level of support and identify the information they will require throughout the project.

Key Stakeholder Considerations

Project Managers

By engaging key stakeholders, conducting thorough cost analyses, aligning technology with agency needs, and maintaining strong relationships with utilities and OEMs, project managers can help guide their agencies through a successful ZEB deployment. The list below outlines essential steps and best practices for project managers:

- Executives from all departments should participate in characterization of your transit agency's short- and long-term ZEB needs and priorities. Ask for support in engaging leaders and making project planning a priority.
- Research available technologies as well as capital, construction, and operational costs prior to your leadership discussion. Talk with OEMs, experienced consultants, and other ZEB operators to help guide your discussion and educate leadership on the advantages, disadvantages, and costs of each deployment option.
- Base technology selection on modeling results and specific agency requirements, as bus performance can vary greatly based on temperature, topography, and driving habits.
- Ensure route modeling efforts do not simply rely on OEM-provided range or energy efficiency estimates as those are typically based on ideal operating conditions and may not reflect your transit service demands. If BEB technology is selected, consider charge and utility rate modeling to identify your constraints for charging windows, suitable blocks or routes, flexibility in planning for equipment, and costs.
- Coordinate with your operations and maintenance staff to develop a clear technical and performance specifications for your bus and fueling infrastructure
- Ensure all expectations are clearly defined in your procurement documents and final contracts.
- Complete bus and infrastructure cost analyses before each deployment. OEMs or transit agencies that have deployed the technology may be able to provide cost

estimates for equipment or lessons learned. However, you should conduct an analysis specific to your deployment.
- Factor all future plans for ZEB deployments into your cost analysis to ensure infrastructure investments made today have long-term usefulness. Balance this analysis with an understanding that technology advancements may alter your plan in the future.
- Research funding opportunities to support your ZEB deployments. Funding availability can significantly offset capital costs. Coordinate with procurement on funding requirements and deadlines.
- Establish or maintain a strong relationship with your electric utility throughout the ZEB deployment process to discuss service and infrastructure needs as utility upgrades might be needed, changes to your electricity rate schedule after ZEB deployment, and methods to lower electricity costs through demand management.
- Develop an electricity rate model to estimate electricity costs based on BEB charging procedures, considering the duty cycle, schedule, battery capacity, and useable charger power.
- Work with the utility and operations staff to identify ways to optimize the charging approach to limit demand charges, weighing service and operational constraints (e.g., % state of charge [SOC] needed for morning pullout, limiting demand charges, minimizing overall costs).
- Ensure infrastructure deployment and upgrades to maintenance facilities are completed prior to bus acceptance for proper testing and validation of the buses.
- Create a realistic project timeline, allowing for the continued coordination of stakeholders, a formal bidding process, facility and power supply upgrades, design and construction, and commissioning of the station prior to bus delivery.
- Conduct a kick-off meeting with key stakeholders, including designers, equipment manufacturers, power utility representatives, facility managers, maintenance and operation managers, and health and safety personnel.
- Select a vehicle inspector either from your agency's staff or a third-party vendor that is familiar with electric drive vehicles and high voltage system build practices.
- Schedule a review on-site at the OEM with your agency's ZEB deployment team prior to the first vehicle being approved for shipment.
- Coordinate with transit agency staff to develop an acceptance and validation testing plan. Some tests will require the participation of staff from the operations, maintenance, and facilities departments (e.g., road tests, testing the bus under various loads, identifying challenging locations in the service area).
- Utilize the results of validation testing to update model assumptions for future deployment analyses.
- Engage operations staff when developing a deployment plan. For your first deployment, consider starting vehicles on less challenging blocks to accommodate a learning curve on technology nuances.
- Inform decision makers on the validated range in your service area at the conclusion of testing to set realistic expectations of vehicle performance.

- Coordinate with the OEM prior to delivery of the buses to schedule all required training and ensure that you retain a copy of any materials.
- Coordinate with first responders to conduct training on potential hazards and response procedures.
- Develop a plan to determine what portion of your drivers and maintenance staff should be trained on the ZEB; a smaller deployment may allow you to train fewer staff initially. Additionally, if your agency has a union, negotiations might be required.
- Establish a plan to provide recurrent training for staff if the size of your ZEB fleet provides limited exposure opportunities.
- Consider incentives to influence efficient driving behaviors as operators can significantly impact energy efficiency. Safety and schedule demands should be key considerations for any incentive program.
- Ensure operations and maintenance departments are briefed on battery degradation and potential service impacts for BEBs. Identify useful blocks that your BEB fleet can complete throughout its entire service life.
- Establish a method to measure the battery capacity at time of delivery, and a schedule to periodically measure battery health at least once per year. Track battery degradation and any impacts on service.
- Monitor operator efficiency throughout the deployment.
- Facilitate coordination of OEM and maintenance staff to create a spare parts inventory and a catalog of ZEB components and lead times.
- Develop reports, as requested from executive leadership and agency staff, and as required by Federal, State, or Local funding sources used to support the ZEB deployment.
- Coordinate with bus and infrastructure OEMs, electric utility providers, and operations and maintenance staff to establish data collection procedures for ongoing reporting.
- Stay on top of industry news to be able to speak to new advancements with OEMs, and to know what your options are for future procurements.
- Your agency may be the first to pilot new technology. Plan for adequate testing of the new features if this is the case.
- Engage with transit industry colleagues and stakeholders to share deployment data and lessons learned. Two industry leaders for consideration include the American Public Transportation Association (APTA) and the Zero Emission Bus Resource Alliance (ZEBRA).
- Remain informed of new standards and mandates that will impact your agency's requirements for deploying ZEBs.

Operations, Maintenance, and Facilities

The successful operation and maintenance of a ZEB fleet requires close coordination between operations, maintenance, and facilities teams. This transition to new technologies impacts not only how buses are deployed and maintained but also how service is delivered to customers. Thoughtful planning is necessary to ensure that service modifications, such as route adjustments or changes in schedules, do not negatively affect customer satisfaction. Facilities need to be prepared for the specific space, power, and safety requirements associated with fueling infrastructure—whether for BEBs or FCEBs—and must be involved early in the planning process to ensure that necessary maintenance bay and other facility upgrades are completed in time for deployment. Training for both operators and maintenance staff is crucial, as ZEBs differ significantly from conventional buses in terms of components, controls, and performance. This includes understanding charging infrastructure, maintenance needs, and safety protocols for high-voltage systems or hydrogen use. Effective charge management and fleet optimization will also be key to minimizing costs while ensuring reliable service. As the deployment progresses, regular data collection and collaboration with OEMs and other transit agencies will help ensure smooth operations, share lessons learned, and prepare for future advancements in technology and operations. The list below outlines essential steps and best practices for operations, maintenance, and facilities staff:

- Service changes should be carefully considered when deploying ZEB technology as they can impact customer satisfaction and complicate support for your ZEB fleet. While service designed especially for ZEBs can reduce range anxiety, technology solutions may exist that can help avoid route changes. For unavoidable changes, ensure current and future ZEB plans are considered.
- Route distances and dwell times (for on-route charging) will be relevant in determining what service modifications may be needed.
- Facility managers should understand space and power requirements of fueling infrastructure and be ready to advise on installation options for your transit agency.
- Participate in route modeling discussions, as schedule accommodations may be required due to range limitations for BEBs.
- Based on expected battery warranty conditions, evaluate how battery degradation may impact service planning over the life of the bus.
- Operation and maintenance of the bus will affect performance. Ensure adequate training requirements are included in contracts.
- Review maintenance requirements for your ZEB technology to understand required facility upgrades/equipment and training needs.
- Review power requirements for BEB charging to understand facility upgrade needs.

- Meet with your electric utility early in the planning process to discuss infrastructure needs for the fueling infrastructure deployments.
- Ensure that roles, responsibilities, and timing for bus fueling are clear, either at the hydrogen fueling stations for FCEBs or at the bus yard for depot-charged BEBs.
- Identify service and operational constraints that would impact charge management optimization (e.g., %SOC needed for morning pullout, timing and flexibility of electric bus assignment, limiting demand charges, minimizing overall costs).
- For BEB deployments, consider placement of charging infrastructure that accommodates safe and efficient charging while allowing adequate egress.
- Ensure that the selected fueling approach does not disrupt the operations of the facility, which may be challenging with larger ZEB fleets.
- For FCEB deployments, ensure maintenance facility upgrades meet ventilation and gas detection standards and are coupled with alarm systems for safety.
- For BEB deployments, identify a charging solution for maintenance facilities.
- Ensure charging infrastructure has been installed prior to vehicle acceptance.
- Coordinate training on conducting post-delivery inspections with the OEM in advance of bus arrival, to ensure that you have the information needed to conduct a thorough inspection of new components.
- Conduct post-delivery inspections and coordinate with the OEM to confirm that all repairs are completed prior to acceptance.
- Coordinate with bus and fueling equipment OEMs to commission the buses with the chargers after the first bus arrives.
- Identify possible service blocks for deployment, and work with the project manager to develop a deployment plan.
- ZEBs have different components and controls than conventional buses. Bus performance also differs. Train drivers on the differences and efficient operation of the buses. Emergency procedure recurrent training should be provided.
- Maintenance staff need to be trained to service and troubleshoot all-electric propulsion and auxiliary systems, how to work with the on-board diagnostic systems, and be trained in safe work practices for high voltage and, if applicable, hydrogen.
- Operations staff should be briefed on any expected range or endurance limitations (including seasonal variations) of the ZEBs as well as expected fueling and charging times.
- Safety training is critical for all staff involved in supporting ZEB deployments.
- Consider incentivizing efficient driver behaviors to optimize ZEB use.
- Coordinate with OEMs and component manufacturers to create spare parts inventories and understand lead times for ZEB components.
- Ensure procedures are in place for capturing ZEB mileage, block assignments, service data, and daily availability.
- Develop availability metrics to distinguish issue causes.
- Track ZEB maintenance activities and costs for the duration of ownership (both during and after warranty periods).

- Support the data collection and analysis efforts to share your agency's experiences with transit industry colleagues and stakeholders. Review available deployment data from other transit agencies located in a similar climate or that provide similar service as your agency.
- Future advancements may include tools that provide decision-support to dispatch, providing more detailed insight into bus performance and available range.
- Future advancements may include charge management solutions for large fleets of ZEBs, which may improve or streamline current charge management strategies

Procurement

Procurement requires careful alignment of budget, regulatory compliance, and vendor selection. Agencies must assess the balance between operating and capital funds to determine the timing of ZEB deployments and the technology choice. Understanding long- and short-term priorities, as well as relevant state and federal regulations, is key to guiding the procurement process. Choosing the right procurement method and collaborating with other stakeholders ensures that technical specifications are met without vendor bias. Contracts should include clear inspection plans, testing requirements, and adherence to industry standards. Additionally, engineering design services may be needed for fueling infrastructure, and external expertise may be required for cost estimates. Funding opportunities, utility rate analysis, and research into hydrogen delivery options must also be considered. Competitive bidding processes for fueling station design and construction, along with clear contractor responsibilities, are essential. Finally, ensuring contracts cover data access, spare parts procurement, and compliance with safety and regulatory standards will support the long-term success of the ZEB deployment. The list below outlines essential steps and best practices for stakeholders involved in the procurement process:

- Provide insight into your transit agency's balance between available operating and capital funds, which may influence the timing of ZEB deployments, and the type of technology selected.
- Understand long and short-term agency priorities for ZEBs.
- Review relevant State and Federal regulations that require your agency's compliance.
- Determine the best type of procurement approach for your bus and infrastructure selections (e.g., IFB, RFP, RFI).
- Coordinate with the Project Manager, Operations, and Maintenance to ensure procurement documents include the required technical and performance specifications without unintentionally creating vendor bias.

- Ensure final contracts include the same specifications, as well your inspection plan, acceptance testing requirements, and adequate time for testing.
- Consult APTA guidelines for ZEB procurements to understand existing industry standards.
- Engineering design services may be needed to fully understand the required facility modifications and cost of fuel equipment installation. If expertise is not available in-house, a third-party could provide a cost estimate.
- Funding opportunities will often require grant applications or rebate filings. Review applicable terms, deadlines, and filing requirements to ensure compliance.
- Coordinate with agency staff to understand estimated monthly fuel costs.
- Work with your electric utility provider to review and identify the most favorable rate schedules for your deployment strategy.
- For hydrogen delivery deployments, research production facilities and delivery options to determine the combination that best satisfies service demand.
- Prepare for RPFs. Design and construction of the fueling station will likely require at least one competitive bidding process, potentially two (one for design, one for construction).
- Ensure General Contractor scope of work clearly delineates contractor responsibilities and requires coordination with the OEMs for equipment delivery and installation instructions.
- Coordinate with key stakeholders to ensure solicitations and contracts include the necessary responsibilities.
- Ensure your RFP requires specific knowledge of ZEBs and demonstration of qualifications, if utilizing a third-party vendor for inspection.
- Ensure contracts for ZEB bus and fueling technology require adherence to all applicable codes, regulations, and industry standards to ensure proper safety techniques and systems are included.
- Coordinate spare parts procurements needed for ongoing ZEB maintenance.
- Review contracts to ensure access and rights to the desired bus and fueling infrastructure data.
- For FCEB deployments, notify project managers upon renewal of hydrogen fuel contract pricing.
- Ensure contract terms address appropriate procedures to test and understand new features that your agency may be piloting.
- Industry standards for cost principles may impact how capital, maintenance, and operations costs are tracked.
- New mandates for ZEB requirements may impact your agency’s fleet composition and procurement requirements.

External Stakeholders

Coordination with external partners is also essential for ongoing maintenance, data collection, and knowledge sharing to optimize ZEB performance and improve future deployments. The list below outlines essential steps and best practices for external stakeholders, such as electric utilities, OEMs, labor unions, third-party consultants, and other relevant entities:

- Electric utilities should be consulted early to plan short- and long-term electrical infrastructure needs, review available rate schedules, and discuss possible incentives or pilot programs supporting the design, purchase, or installation of fueling infrastructure.
- ZEB consultants may be required to assist with project planning, modeling, and fleet transition planning.
- Existing ZEB OEMs, including bus and fueling station providers, should be consulted before each deployment to ensure the latest technology options are analyzed.
- Agencies who have already deployed ZEB technology are valuable resources, especially those with similar climate, topography, and service needs.
- Consult any impacted labor unions to ensure needed accommodations can be implemented in your ZEB deployment plan.
- Selected OEM(s) should be engaged quickly to finalize clear contractual specifications and requirements. Be sure all expectations are defined, measurable, and understood by all parties.
- Bus and fueling infrastructure OEMs should be consulted on current technology options and costs prior to any ZEB deployment.
- Electric utilities should be consulted early in the planning process to discuss funding opportunities or potential partnerships for sharing in capital costs of infrastructure or energy storage systems.
- Third party consultants can be useful in identifying funding opportunities or helping build business cases for deployment.
- Electric utility providers should be engaged throughout the ZEB deployment process to discuss service and infrastructure needs, changes to your electricity rate schedule, and methods to lower electricity costs through demand management. The utility may be able to offer pilot rates or programs to support the ZEB deployment or infrastructure operation.
- Hydrogen production facilities and delivery companies, when applicable, should be engaged to discuss hydrogen costs, estimated demand, and delivery schedules.
- Labor unions may need to be engaged if staff are assigned new job responsibilities to operate a hydrogen fueling station or plug in depot-charged buses.
- Third party vendors provide software solutions to support data monitoring and smart charging capabilities.

- Electric utility providers should be engaged early to discuss the required upgrades to meet the increased electricity demand; scalability for future ZEB deployments, and possible incentive programs for infrastructure purchase or installation.
- An engineering design firm should be engaged to support site selection and infrastructure design.
- Local permitting authorities will be required throughout the planning and construction process.
- A general contractor will likely be needed for construction and installation of infrastructure, unless the OEM provides a turnkey solution.
- The bus OEM and fueling equipment providers should be consulted throughout the design process and should be on-site for equipment commissioning.
- All stakeholders should be available during the entire infrastructure deployment process to address any unanticipated issues or changes.
- Third party vendors may be utilized to conduct vehicle inspections. Establish procedures for reporting the results of inspections.
- OEMs will provide training to your transit agency, per the requirements identified in your contract.
- First responders and the local emergency response community should participate in training on potential hazards and response procedures.
- Schedule and test towing training with the contractor who will ultimately tow the vehicle, as required.
- Centers of excellence focused on ZEB technology may be good resources for additional training.
- Depending on the service required, licensed technicians or OEM-provided technicians may be needed for some maintenance activities.
- OEMs should provide suggested spare part inventories and indicate driver behaviors that can increase efficiencies.
- Third party data monitoring services or OEM technicians may be required to measure battery health.
- Bus and fueling infrastructure OEMs should be notified of data needs and access requirements prior to bus deployment.
- Share deployment data and lessons learned with other transit agencies through trade associations, conferences, or direct contact.
- Reach out to bus and fueling infrastructure OEMs to learn more about new components and features

Appendix D - Workforce Impact Analysis

Workforce Impact Analysis

Background

As Mankato transitions from an ICE fleet to zero-emission buses (ZEBs), three critical workforce areas require attention to ensure a smooth and successful shift; The WORKFORCE IMPACT ANALYSIS is comprised of three interrelated concepts:

1. Recruitment of new employees,
2. Retention of existing employees, and
3. Training needs associated with continuously improving employee skills and abilities.

While all are important in a comprehensive workforce plan, in the context of this report, the most significant focus in this analysis will be on **training needs**. This emphasis arises because the training process is most directly impacted by the shift to zero-emission technology and requires specialized attention to maintain operational efficiency and workforce confidence.

The transition to ZEB technology involves complex changes to operations, maintenance, and safety protocols. To ensure a successful shift, Mankato must account for several critical training considerations, which are inherently tied to the specific differences between operating diesel fleets and ZEBs. CTE has identified a series of four distinct phases between the beginning of a ZEB transition and the completed transition where specific training processes are necessary to assure confidence with the new technology. The primary goals of this analysis, accordingly, will be to:

1. Outline the phases of the transition in the context of the training process,
2. Identify the various process elements of each phase,
3. Identify a library of ZEB specific workforce skills,
4. Map those skills to existing Mankato department training logs/records and;
5. Provide best practices for transition training via transit agency case study briefings.

Methodology

Embedded in this report are considerations for the long-term workforce development needs of Mankato, especially as it concerns the speed and reliability of the agency at large.

The phases can be modified based on the technology adoption, pushing out the timeline in the case of FCEB adoption. The skills library and matrices are based on research by CTE staff into various technical sources, which will be referenced in the resource library provided in this report. In general, they comprise training syllabi from other transit agencies, FTA recommendations, and other transit industry training materials. It is important to note that different OEMs have distinct training and tool elements that are specific to their brands and vary considerably. This element has implications for utilization of certain training materials, especially in the Phase 1: Pre-Deployment.

Special consideration has been given for the three fuel type scenarios in the transition plan. Each fuel option has implications for the Transition Training period that Mankato should take into consideration when making a selection, as different technologies (FCEB vs BEB) have distinctive types of training requirements. These potential areas of deliberation are discussed in more detail below.

Considerations Beyond Training

One note on the topic of recruitment vs. retention in this section: overwhelmingly, institutional knowledge favors training and retention of skilled labor over attempts to recruit that labor with the skills in place. Given the emerging nature of ZEB technologies and a relatively limited series of training providers the market for skilled labor is exceptionally tight. It is cost effective to retain staff members who have been trained in these specialized skills, making appropriate designation and documentation of these skills even more critical.

Finally, in preparing for training with any of the various partners and resources identified in the appendices, it is important to note that the training itself is not the only element requiring procurement. However, many of the specific items required for the training element are OEM specific and require direct consultation with the provider for identification.

Those items include, but are not limited to:

- Personal Protective Equipment
- Training simulation materials, including virtual and hands-on options.
- OEM machine tools specific to the make and model of vehicle.
- Facilities elements (e.g., chargers, lifts, space requirements, etc.)

Focus Area: Training

To provide a comprehensive walkthrough of the Transition Training process phases, a brief definition of terms is necessary.

- **ZEB Champion**: Identified staff that will pioneer the new technology; they will be first to learn new skills, and act as a resource and a technology advocate for the rest of the staff.
- **ZEB Specialist**: Hands-on staff that have developed a level of technical competency on ZEB technology to act as an internal resource for troubleshooting, training and other ZEB specific tasks.
- **Hands-On Staff**: Staff that interact directly with the ZEBs as a regular part of their job (e.g., maintenance, operators, facilities).
- **ZEB Support Staff**: Staff outside of hands-on departments that will be impacted by the ZEB transition (e.g., IT, finance, planning, etc.).

Process: Training Considerations Per Deployment Phase

CTE recommends pursuing workforce development in four phases: pre-deployment, early deployment, normalized deployment, and refresher/retraining. These phases are determined based on the procurement timeline and the ZEB percentage of the fleet. For each department, the expectation is that the staff will develop introductory skills during the planning phases, then build on those skills, from technical to advanced, through phases two and three; by phase four, ZEBs will have become a normalized part of Mankato's operation, and all staff should have developed the skills appropriate for their job requirements. The phases and training required is outlined in **Figure 39 and is contingent upon Mankato's transition timeline**.

Figure 39 - Workforce Development Training and Phases

Phase 1: Pre-Deployment

The pre-deployment phase is before any ZEBs have entered service. The pre-deployment phase carries the heavy lifting on the planning side, including planning for workforce training. During this window, it is a best practice to have Knowledge Champions of zero-emission buses in the departments that will have the most direct contact: fleet, facilities, and operations. These Knowledge Champions can be reservoirs of knowledge while the full staff is learning the new technology. They are also responsible for learning the new material first; this will require substantial knowledge acquisition in phase one before the buses arrive.

In Phase 1, understanding the upcoming relationship with the OEM and the variations in products in the ZEB market is critical. The transit agencies leading the way on workforce development rely heavily on OEM training offered alongside a bus purchase. Those trainings will have the most up-to-date information on the specific buses Mankato has procured. Many agencies send all staff to these OEM trainings to minimize training costs. Agencies must consider a holistic viewpoint of the vehicles when determining procurement for training tools at this stage, as each OEM has specific mechanical functions across the entire vehicle that can vary substantially. It is crucial to engage with the OEM as soon as possible after selection to ensure that the agency has access to a comprehensive list of tools needed to take full advantage of direct, specialized OEM training in Phase 2. It is recommended to cross reference the skills and tools outlined in the gap analysis of this report with OEM supplied materials to ensure complete coverage.

As described later in the Case Studies section, peer agencies also recommend prioritizing safety training for hands-on staff before the buses arrive; this will help staff feel comfortable with the vehicles once they are on site. A best practice recommended is to explicitly include safety training for the entire agency staff in the initial vehicle procurement contract.

For ZEB support departments, Phase 1 brings the opportunity to start building knowledge on the job components that will change and start planning for those transitions. For example, the finance team may need to begin to plan for how cost analysis will change with the new technology, and put systems in place to integrate new types of data; IT will need to understand new software, and can begin to plan for that software's arrival; and facilities staff may want to understand the building's existing electrical usage patterns as a baseline to compare against once the buses arrive. Each deployment phase presents unique challenges and opportunities, which are outlined below in **Table 21**.

Table 21 - Phase One Opportunities and Challenges

Phase 1: Pre-Deployment	
Opportunities	Challenges
● Instilling basic technology familiarity across the agency to fully utilize OEM training in Phase 2. ● Building ZEB leadership internally across most affected departments. ● Flexibility in learning timeline. ● Skill development partnerships can be built with other training partners external to organization (e.g., consultants, technical colleges).	● Extremely limited opportunities for hands-on training before buses arrive. ● Timeline could be compressed or expedited depending on bus delivery timeline and the availability of training partners. ● Tool identification and procurement is OEM-specific. Acquisition of this information should be prioritized during Phase 1 of the Supplier engagement.

Phase 2: Early-Deployment

In the early deployment days, with less than twenty-five percent of the fleet transitioned to ZEBs, access to vehicles to work on is a challenge. Since the ZEBs will constitute a small percentage of the fleet, the buses rotation through maintenance will be infrequent, and all staff may not have hands-on experience on a regular basis. In this training window, it is helpful to have the ZEB Knowledge Champions lead the hands-on work on the buses, and work alongside staff that are still building up their zero-emission experience. Similarly, when possible, it is a best practice to have Mankato staff work alongside any OEM staff when they perform on-site maintenance while the buses are still under warranty. This on-the-job refresher is invaluable for allowing staff access to experts and seeing best practices at work.

Phase 2 is the most likely period in which direct, hands-on training with the OEM over the details of the ZEBs of choice is to occur. Planning for the most efficient use of this time is crucial. As discussions and scheduling with the OEM occur during Phase 2, the agency should acquire specific training documentation to support foundational training work. By Phase 2, that information should be on hand and the necessary procurement engaged to mitigate potential delays. In the Gap Analysis, a list of tools has been identified that are pertinent to this procurement effort. CTE suggests cross referencing this list with the OEM's guidelines during Phase 1 for maximum efficiency. In the early deployment, hands-on staff will build on their introductory knowledge base and begin building their technical baseline of the ZEBs. Over the course of this phase, all staff will need to build this technical baseline. Given the small number of buses in service, staff will need to be intentionally scheduled to make sure all staff get the opportunity to re-enforce any classroom learning with hands-on experience. Some peer agencies opt to run ZEBs on training only shifts initially before starting passenger service to allow staff to become accustomed to the new buses.

During the early stages of Phase 2, when advanced knowledge is still limited, it is crucial to distribute ZEB expertise among multiple staff members. This prevents agencies from relying solely on one individual, ensuring ZEB service is not disrupted if that person is unavailable. Additional opportunities and challenges are outlined in **Table 22**.

For ZEB support departments, phase two marks the shift from "theoretical" to "actual," and will require departments to incorporate ZEB information into operations. These departments will now have access to ZEB data as required by each department.

Table 22 - Phase Two Opportunities and Challenges

Phase 2: Early Deployment	
Opportunities	Challenges
• ZEB Knowledge Champions develop and refine their skills while establishing and implementing a train-the-trainer program. • OEM field technician contract options allow for on-site training during the first year of deployment, if negotiated in the contract.	• Limited ZEBs in the fleet will limit opportunities for hands-on knowledge internalization. • Intentional scheduling may be required to make sure appropriate skills are available on each shift. • Pressure to meet daily needs may impact availability for staff to work alongside and learn from field-techs.

Phase 3: Normalized Deployment

Once ZEBs constitute over twenty-five percent of the total fleet, all staff can expect to have hands-on experience with the buses on a regular basis and will need to know how to work on the vehicles. At this point, some hands-on staff will need to move beyond their technical baseline and begin building advanced ZEB skills. The ZEB Knowledge Champions can also begin developing a train-the-trainer program to ensure that knowledge continues to be passed to all staff.

The normalized deployment phase is also well-suited to the development of an apprenticeship program to bring additional staff up to speed or into leadership positions on the new vehicles. Mankato's ZEB procurement timeline ramps up quickly, and, if training capacity is desired in-house, this window will allow both trainers and trainees immediate maintenance access to vehicles. Additional opportunities and challenges are outlined in **Table 23**.

Table 23 - Phase Three Opportunities and Challenges

Phase 3: Normalized Deployment	
Opportunities	Challenges
• Train-the-trainer program will have ample opportunities for practice and can fine-tune the approach. • Larger portion of staff will have growing experience in ZEBs.	• Limited number of buses in service may still require intentional cycling of staff to keep skills fresh. • All staff will need to come up to speed on ZEBs which may be a challenge for staff that are less interested in new technology.

FCEB Introduction:

If Mankato chooses to pursue FCEBs, the FCEB process will mimic the BEB process, with the ZEB Knowledge Champion initially captaining FCEB learning, then involving more staff at additional levels of leadership as the number of FCEBs increases.

Phase 4: Ongoing Normalized Deployment

After several years working with a twenty-five percent ZEB fleet in Phase 3, all staff are expected to be fully trained on ZEBs and have gained regular hands-on experience with the buses. The goal of the ongoing normalized deployment phase will be similar to the status-quo of diesel operation: make sure staff stay up-to-date on their skills, allow space for advancements in knowledge, and manage knowledge transfer with any staff transitions (e.g., new staff, retirements, etc.). CTE recommends regular refresher training either through OEM trainings or through an established train-the-trainer program. **Table 24** outlines the remaining opportunities and challenges for ongoing deployment.

Table 24 - Phase Four Opportunities and Challenges

Phase 4: Ongoing	
Opportunities	Challenges
• In house experts available for training • Staff transitions (e.g., hiring, retirement, promotions) will provide opportunities for continued leadership growth in ZEB expertise.	• Aging ZEBs from initial procurements may require new types of maintenance to which the staff haven't yet been exposed to (e.g., battery replacement)

Skills Gap Analysis

CTE has conducted extensive research to identify a comprehensive list of skills necessary to successfully bridge the gap between having zero ZEB experience and a completed skill transition. The skill analysis covers the development of the ZEB Specialist role. While CTE has differentiated maintenance skills by the ZEB progression (ZEB Intro, ZEB Basic, ZEB Advanced, ZEB Expert), the skill matrix is meant to be a fluid, working document. Mankato may elect to train its staff on certain skills before or after the recommended progression. CTE has provided summaries of those breakdowns.

Maintenance

While ZEBs will present many new and exciting challenges for maintenance staff, there are several transferable maintenance skills between ICE vehicles and ZEB vehicles that will ease the transition training burden. The type of fuel selected in the final transition scenario is a noteworthy factor impacting variable levels of skill crossovers available to Mankato. This section provides a brief comparison of bus subsystem changes and the implications on maintenance.

Energy Storage System (ESS) and Battery Management

Existing low voltage battery handling skills will be directly applicable to low voltage (LV) battery work in ZEB's; however, ZEB Basic staff will need to have high voltage (HV) awareness training and understand how to safely disable HV systems to work on the LV systems on a ZEB. A critical example of a LV skill that will require HV awareness, but not necessarily HV training, is starting the bus with jumper cables. The component responsible for activating and deactivating HV systems is called a battery contactor and is powered by LV batteries. In the instance that the LV batteries are depleted before the HV system can recharge them, the bus would need to be jumped like a traditional ICE bus would be jumped. BEBs and FCEBs also have larger battery packs requiring specialized high voltage training (most OEM's can provide), and specialized battery handling skills. Staff must be trained on OEM lock-out tag-out procedures before working on primary battery packs. ZEB Advanced staff will dig deeper into the ESS and understand how to diagnose HV system issues on the ZEB.

The most critical non-safety skill for both BEBs and FCEBs, as it pertains to the ESS, will be selecting staff members who will become experts with the OEM ESS fault diagnostic software and interface tool (exact tool varies by OEM). This will allow specialized staff to diagnose, confirm, and apply corrective action to faulty components within the battery packs or the batteries themselves.

Electrical / Multiplexing

Existing basic electrical and multiplexing skills will be crucial for all ZEB service staff, with select staff becoming multiplexing experts. Staff will still need to repair fuses, identify shorts, and effectively use a voltmeter (among other skills). With ZEBs there will be high voltage circuits and risks will be much higher. All staff should be able to identify high voltage components of the bus (batteries, high voltage junction box, DC-DC inverter, traction motor, power steering, HVAC, air compressor, fuel cell, thermal battery management system). In addition, suspension systems, friction-based braking systems, HVAC, power steering, axels, grounding, doors, and ADA will not be different from a tradition ICE bus. The major change is that every component will be powered either by high voltage power directly from the ESS or LV power that has been passed through a DC-DC inverter.

Propulsion, Transmission, Braking

As opposed to diesel bus technology, ZEBs are propelled forward by an electric motor. Electric motors work by leveraging a fundamental electromagnetic principle: alternating electric power flow induces a magnetic field, and correspondingly alternating magnetic fields induce electric power flow. An electric motor generates propulsion from electrical energy by surrounding an electromagnet with a permanent magnet and switching the direction of the current flow such that the electromagnet reverses polarity. ZEB intro staff should be able to describe the power flow from the DC battery to three-phase AC motor. The starter motor is the same as the main motor in ZEBs as electric motors can provide powerful, near instantons torque. In addition, ZEBs do not have an alternator nor a static converter. Friction-based brakes will see less wear and tear due to regenerative braking reducing some of the braking burden.

Regenerative braking works because internal processes within an electric motor are reversible, whereas internal combustion is a chemical process that cannot be reversed. Instead of power flowing from a HV battery through a complicated circuit and switch schematic to create a strong electromagnet, the physical work done by wheels physically moves the permanent magnet such that it creates electric energy to power the battery. Because of this, regenerative braking does not have special maintenance requirements outside of regular requirements of the engine, Controller Area Network (CAN), and (potentially) transmission (ZEBs can also be direct drive).

The most critical non-safety skill for both BEBs and FCEBs, as it pertains to the propulsion system, will be selecting staff members who will become experts with the OEM fault diagnostic software and interface tool (exact tool varies by OEM). This will allow specialized staff to diagnose, confirm, and apply corrective action to faulty components within the motor and its accompanying components.

HVAC

High voltage batteries power the electric HVAC system, as opposed to traditional electric HVAC technology powered by an alternator with a static converter. The electric HVAC system itself is the same across bus types, so service staff will only need to be fully aware of HV safety requirements to understand HVAC maintenance. It is important to note that while the maintenance is similar, the ESS and or fuel cell are more sensitive to temperature than an ICE, so HVAC upkeep will be particularly important to the overall success of a ZEB rollout.

Charging

In a ZEB, LV batteries are charged using HV power that is converted through a DC-DC inverter. HV batteries are recharged by a fuel cell or from direct plug-in external power. ZEB intro staff must understand the difference between AC and DC fast charging and how charging types impacts the flow of power into the vehicle. The most common bus-side charger malfunction is related to bus-charger communications and the bus CAN. It will be critical to assign a staff responsible for coordinating software updates between charger OEM and bus OEM, as they might not be the same entity.

Fuel Cell System

Fuel cells work by generating electricity through an electrochemical reaction, not combustion. Fuel cells intake hydrogen and then split the hydrogen molecules into electrons and protons (H+) using a highly specialized catalyst. The protons pass through a porous electrolyte membrane while the electrons are directed toward a nearby circuit. On the other side of the electrolyte membrane, the protons, electrons, and newly added oxygen combine to produce water. The flow of electrons from the positively charged side of the fuel cell (anode) to the negatively charged side of the fuel cell (cathode) generates electricity, which will either directly power the electric motor or recharge battery packs that will power into the electric motor.

Any work on the fuel cell and accompanying HV components require HV training. It is important to consider that FCEB training encompasses BEB training in terms of skill sets but is also more expensive given the extent of the training required. In the past, other transit agencies such as AC Transit have chosen to train all staff on FCEBs to ensure every ZEB tech can work on every type of ZEB. Due to the infancy of the hydrogen-fueled transit-bus economy, there is a dearth of information on maintaining FCEBs. The progression of fuel cell skills in the skills matrix may vary once buses are deployed and beginning OEM-specific preventive maintenance programs.

Summary of "Black-Box" ZEB Maintenance Modules

The most complex components of the new technology will likely not be serviced by Mankato staff. Even a ZEB Expert would not be expected to open an inverter and repair a circuit board, but service staff should understand how each of the following components work to be able to better diagnose faults. A list of modules within a ZEB that technicians will need to rely on the OEM to service can be found below:

- Battery Cells (Battery packs are serviceable)
- Traction Inverter
- Electric Motor (Drive unit may have serviceable parts; the actual motor does not)
- Auxiliary Power Module (HV-LV DC-DC converter)
- Fuel Cell

Operators

Vehicle operations are where some notable skill changes take place between ICE and ZEB vehicles, especially as it relates to the actual experience of driving the bus. Unlike service staff which can have tiers or levels of skills, bus operator training is binary in a sense that a driver is either fully trained to drive a bus or not. It is imperative that a driver is not partially trained and operating a ZEB alone.

Table 25 - Operators Skill Matrix

Operators	ZEB Education and Safety	• Zero-emission technology overview • Awareness of high voltage systems • High voltage exposure warning emergency response procedure
	Bus Operation	• Regenerative braking and friction-based braking overview • HVAC Significance • Remaining operating time • Technological limitations (fuel cell output vs input) • Turn off12/24VDC battery disconnect for the bus and apply a multi-lockout device • Fueling a FCEB • Driving feel under various levels of regenerative braking • Optimal driving habits to maximize regenerative braking • Bus docking for on-route charging (BEB only) • Start-up / shut-down procedures (including inspections) • Decreased noise implications on shut off procedures and pedestrians

Vehicle operators will need to have a heightened understanding of the high voltage exposure warning emergency response procedure. This warning alerts the driver that something is very wrong with the bus (perhaps from an accident) and that they need to follow a series of OEM-specific safety procedures. In addition, operators will need to understand remaining operating time and technological limitations. If they are driving a full fuel cell bus on a hot day at high speeds down the freeway, the power demand might exceed the power output by the fuel cell to charge the on-board battery pack. This is a rare instance, but certainty one to be aware of, especially if Mankato has city or county emergency response commitments in the event of an evacuation. In most other cases, the battery state of charge of a fuel cell bus should remain relatively high if the bus is fully fueled with hydrogen. Operators will need to know how to charge or fuel the bus, and any pre and post charging/fueling inspection procedures that will accompany the process (OEM specific). Additionally, the extremely quiet nature of the vehicles requires a mental shift in the perceptions of the driver. Noise related lessons learned from other operators have indicated repeated concerns around pedestrian safety and unknowingly leaving the bus on at the end of the shift. Properly training bus operators to turn the bus off can alleviate any risks of leaving the bus on overnight.

Finally, and perhaps most significantly, regenerative braking will significantly change how it feels to drive a ZEB. While the regenerative braking process is described in detail in the previous section outlining ZEB skills for service staff, it is crucial for operators to understand what the reversibility of the technology means for them. When an operator approaches a stop, they can choose to apply the friction-based traditional braking system still present with ZEBs, or coast and let the torque created by the regenerative braking system bring them to a halt. The more the operator relies on regenerative braking, the more efficient the bus will use its onboard energy. Additionally, the “strength” of regenerative braking can be adjusted and subsequently change how it feels to drive the bus. Some OEMs automatically increase the regenerative braking strength when the battery state of charge drops below a certain level. Without proper training, this could confuse and concern operators who are not expecting it.

Service Development

Service development staff will need to develop ZEB skills to plan and support hands-on staff driving and servicing the vehicles. The necessary skills include, but are not limited to, writing bus procurement and infrastructure development RFP’s to specifically include training, planning dispatch so that operators do not run out of fuel under strenuous and nominal conditions, carefully selecting ZEB Knowledge Champions and promoting a ZEB-forward culture from organizational leadership, and completing high voltage awareness training and/or learning hydrogen safety fundamentals.

First Responders

First responders are of critical importance to keeping staff and the local community safe. The local Fire Department will need to have high voltage training, and in the instance of FCEBs they will need high-pressure gas handling training and to understand the basic chemical properties of hydrogen. While hydrogen dissipates into the atmosphere much quicker than petroleum-based fuels, hydrogen fires are not visible during the day and first responders will need to know when they might be encountering a hydrogen fire. One of the best practices is to explicitly include first responder and safety training into the OEM training contract.

Tools

Many of the tools integral to the ZEB maintenance process are proprietary designs and highly specified to the make and model of vehicle. Based on the skills identified above, CTE has provided a list of fundamental maintenance and safety tools below. High voltage electricity refers to electrical potential large enough to cause injury or damage. While many of the tools needed to service ZEBs are OEM-Specific; these safety tools will be required regardless of OEM or fleet transition scenario.

- Class 0 High Voltage Rubber Gloves (ASTM D120), inspected biannually to ASTM F1236
- High Voltage Safety Footwear (ASTM F2413-05) or High Voltage Overshoes (ASTM F1117)
- Eyeglasses (no conductive frames)
- CAT III 1000V Digital Multimeter
- CAT III 1000V Test Clips
- CAT III 1000V Test probes
- CAT III two-pole tester (provides voltage reading even with an empty battery)
- Hot Stick (ASTM F-711)
- Insulated tool set
- Insulated torque wrench
- Arc Flash Suit (ATSM 1506) when working on HV batteries, HV disconnect panel, HV switch, etc.
- Gas detector calibrated for hydrogen (FCEB only)
- Defibrillator
- Fire extinguisher (CO2)
- Steering wheel danger sign
- Safety fence
- HV signage
- Man-harness and lanyards
- Safety caged exterior ladders
- Scissor lifts
- Insulated pallets (up to 1000V) for HV batteries
- Insulated cover

Below is a sampling of tools that will be required to work on a ZEB. Please note that the OEM will provide additional information on necessary and required maintenance tooling.

- CAT III 1000V Digital Multimeter – measure voltage, current, and resistance
- Current Clamps – Measure electrical current
- Ohmmeter – Measure electrical resistance
- Refractometer – measure refractive index / coolant conductivity
- Megohmmeter – determine the condition of insulation on wires
- Oscilloscope – Measure voltage waves and display electrical signals
- Hydrogen venting tool (FCEB only)

Case Studies and Best Practices

CTE conducted informational interviews with two agencies across their ZEB transition to gather lessons learned and best practices for the transition process, specifically as it regards training. Additional best practices from CTE's knowledge database are provided as well.

Case Study 1: Champaign-Urbana Mass Transit District

The Champaign-Urbana Mass Transit District (CUMTD), located in the Illinois college town of the same name, serves an annual ridership of roughly 5.5 million. Their ongoing transition from diesel vehicles to FCEBs accompanied by hybrid buses is still in relatively early stages, giving us direct insight into Phase 1 struggles. Specifically, CUMTD's largest takeaways come in recommendations about the utility of certain training methods.

MTD's leadership emphasized hands-on training was the most effective form, especially when conducted in direct consultation with OEMs. This has implications for the periods both before and after the direct interactions with the OEM trainers. In advance, doing as much fundamental and theory training as possible allows for maximum utilization of specialist's time, Once OEM training is completed, rapidly developing an in-house, formal training system was a strong recommendation on the part of CUMTD. Their creation of a Fuel Cell Training Center has paid off in dividends, allowing for specialized knowledge to remain among staff.

Case Study 2: Alameda-Contra Costa Transit District

Alameda-Contra Costa Transit District (AC Transit), located in Oakland, California, has been a leader in ZEB adoption in the transit industry for over 20 years. In an effort to meet state standards of a fully zero-emission fleet by 2040, AC Transit has been rapidly replacing its existing diesel fleet with ZEBs, but with over 640 vehicles in service (592 diesel-powered), the transition is still in early stages. AC Transit emphasized that this change represents a total paradigm shift for an agency which, according to AC Transit's leadership, has been and can continue to be improved through the use of "ZEB Champion" roles. Having staff members take ownership of the culture change inherent in the transition is crucial.

AC Transit's additional feedback echoed much of what CUMTD recommended regarding training methodology: hands-on training, focus on effective use of OEM time, and building formal in-house knowledge transfer systems. Their largest additional item relates to vertical integration, (i.e., involving as many levels of staff in the process as early as possible). By limiting the cultural shift to only hands-on staff, comfort with the new technologies does not effectively reach all departments, stifling transition.