# Modernizing Medium-/Heavy-Duty Fleets: A Feasibility Study on Operations and Strategic Planning

NCDOT Technical Assistance 2025-15
October 2025

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## FINAL REPORT

Submitted to:
North Carolina Department of Transportation
Office of Research
(Technical Assistance TA2025-15)

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October 2025

# Technical Report Documentation Page

1. Report No.
FHWA/NC/TA-2025-15

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Modernizing Medium-/Heavy-Duty Fleets: A Feasibility Study on Operations and Strategic Planning

5. Report Date
October 2025

6. Performing Organization Code

7. Author(s)
Leila Hajibabai, PhD; Jaliyah Chloe Anderson; Sarah Halsey; Hiruni Niwunhella

8. Performing Organization Report No.

9. Performing Organization Name and Address
North Carolina State University
915 Partners Way
Raleigh, North Carolina 27695

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
North Carolina Department of Transportation
Research and Development Unit
1549 Mail Service Center
Raleigh, North Carolina 276699-1549

13. Type of Report and Period Covered
August 2025 – October 2025

14. Sponsoring Agency Code
TA2025-15

15. Supplementary Notes

16. Abstract

This project aims to evaluate the feasibility of modernizing North Carolina's medium- and heavy-duty (MHD) fleets. Key challenges include understanding the costs of infrastructure investments, fleet operation, maintenance, and management, while optimizing service schedules, route design, and planning strategies. The infrastructure is particularly critical in this transition, which can create significant operational inefficiencies. Furthermore, managing the energy requirements for such a system poses a challenge, especially given North Carolina's varied landscape of power and utility providers. Coordinating between different power companies while ensuring reliable, efficient energy delivery to stations is crucial. There is a need to study how fleet operations, service schedules, and route design can be effectively planned to ensure reliable, resilient, and efficient fleet operations, and how fleet transition impacts public and individual travel patterns. This research provides a practical, evidence-based guidance for modernizing MHD fleets while maintaining cost control and operational reliability. The study synthesizes lessons learned from recent deployments and technical evaluations to identify the factors that most influence project budgets, schedules, and day-to-day operational performance. Findings show that early, site-specific planning decisions, particularly regarding depot power capacity, space and traffic flow, make-ready construction, and interconnection requirements, are the primary drivers of cost and timeline variability. Results also demonstrate that operational feasibility depends more on detailed duty-cycle characteristics and effective charger configuration than on rated charging capacity alone. Agencies that prioritize depot-based charging for initial deployment experience fewer schedule disruptions, lower capital costs, and reduced queuing, adding en-route charging only where it increases utilization or reduces the required spare ratio. The research concludes in a set of actionable best practices for planning, utility coordination, procurement, commissioning, and phased deployment, enabling NCDOT and statewide partners to make informed decisions and execute predictable, resilient fleet electrification strategies.

17. Keywords
Medium- and heavy-duty (MHD) fleets; Fleet modernization; Facility location; Site selection; Geographic information systems; Mathematical models; Life cycle cost analysis; Phased deployment; Route planning; Vehicle scheduling; Medium trucks; Heavy trucks; School buses; Transit buses; Reliability; Resilience; Demand management;

18. Distribution Statement

19. Security Classif. (of this report)
unclassified

20. Security Classif. (of this page)
unclassified

21. No. of Pages
40

22. Price

**Form DOT F 1700.7** (8-72) **Reproduction of completed page authorized**

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# ACKNOWLEDGEMENTS

This research was sponsored by the North Carolina Department of Transportation (NCDOT), Planning Division. The research team gratefully acknowledges the financial support and collaborative guidance provided by NCDOT throughout the project.

# EXECUTIVE SUMMARY

This report synthesizes current evidence on how agencies can modernize medium- and heavy-duty fleets while controlling costs and protecting operational reliability. The emphasis is on the mechanics that determine budgets and schedules -- site selection, make-ready construction, interconnection, commissioning, and day-to-day operations -- so planners can design deployments that are predictable and efficient.

Findings from recent programs and technical reports show that early, site-specific decisions dominate both costs and timelines. Vehicle pricing is relatively stable; the major variability comes from power availability, civil work, trenching, permitting, and how these activities are sequenced. Projects that validate depot power, space, traffic flow, and construction access up front encounter fewer change orders and avoid rework. Operational feasibility is most sensitive to duty-cycle details (e.g., block lengths, layover windows, grades, and climate loads) and to how those details align with charger placement, capacity, and uptime. Rated power is an imperfect proxy for actual performance; cable handling, stall layout, load sharing, thermal limits, and software controls determine energy delivered per charger per day and the plug-to-depart time during real operations.

The practice record reinforces these themes from an implementation lens. Programs with the lowest total cost tend to prioritize depot-based blocks/schedules before adding any en-route charging. Starting at the depot simplifies sizing, reduces queuing, and protects schedule integrity; en-route installations are added selectively where they measurably increase vehicle utilization or reduce the fleet spare factor/required spares. Consistent data practices -- standard templates for duty cycles, meter data, and charger telemetry -- improve coordination with utilities and compress interconnection timelines. Procurement language that sets clear performance metrics (e.g., uptime and energy delivered per charger per day), warranty terms, and site acceptance testing/commissioning steps reduces post-commission surprises in operations and maintenance.

The report closes with a concise set of actionable steps: Validate depot power and space/flow at the outset. Prepare standard utility scoping materials; include a load summary or projected demand letter and a single-line electrical diagram. Check schedule feasibility against dwell windows and effective charging performance, not just nominal ratings. Phase deployment: establish reliable depot operations first, then add targeted en-route charging only when it clearly improves utilization or reduces required spares.

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# Chapter 1. Introduction

## 1.1 Background

Fleet modernization efforts have largely centered on light-duty vehicles, yet the operational weight of medium- and heavy-duty (MHD) fleets (e.g., public transit, school transportation, public works, and freight support) makes them a priority for practical planning. Updating these fleets to newer powertrains and support systems introduces a different class of challenges than those seen in light-duty programs. The issues are less about vehicle availability and more about day-to-day feasibility: infrastructure readiness at depots and along routes, interconnection capacity and timelines, service schedule integrity, maintenance workflows, and the program management needed to keep costs predictable. MHD services run on tight blocks and fixed windows; any shortfall in fueling/energy replenishment capacity or site design can cascade into delays, missed trips, or added spare requirements. A clear synthesis of what the literature and current practice say about these constraints is therefore essential before committing to large capital programs.

A consistent theme in the literature is that infrastructure (not vehicles) drives schedule and budget risk. Studies and technical reports emphasize early decisions around site selection, make-ready construction, and utility coordination. Power availability, trenching and civil work, permitting, and commissioning steps contribute heavily to variance in both cost and timeline. Operational feasibility depends on matching real duty cycles to infrastructure capability: block lengths, layover windows, grades, climate loads, and depot circulation must align with charger/fueling placement, capacity, and uptime. Sources repeatedly caution that rated power is an imperfect indicator of actual performance; cable handling, stall layout, load sharing, thermal constraints, and software controls determine the energy delivered per charger per day and the practical plug-to-depart time. Literature on maintenance and facility planning highlights the importance of standardized parts, clear warranty terms, and diagnostic readiness to reduce downtime and protect service levels.

The state of practice echoes these findings from an implementation standpoint. Peer programs report that starting with depot-based blocks/schedules reduces risk by using predictable dwell windows and simplifying sizing. En-route installations are added selectively where they clearly increase vehicle utilization or reduce the fleet spare factor. Agencies that standardize data templates (e.g., duty-cycle profiles, meter data, and charger telemetry) tend to experience smoother interconnection processes and fewer change orders. Site designs tailored to large vehicles (e.g., pull-through lanes, adequate turning radii, cable reach, and canopy clearances) improve effective throughput and reduce labor losses during staging and plug-in. Programs also note that day-to-day operating cost is strongly influenced by load management and tariff structure; aligning charging windows and demand limits with schedules can materially affect monthly costs and reduce exposure to demand charges. Where power upgrades are required, early scoping with clear single-line diagrams and load summaries shortens timelines and clarifies phasing.

This report focuses on public MHD fleets because their structured operations, centralized management, and repeatable duty cycles make infrastructure planning more tractable and the lessons broadly transferable. The literature review consolidates cost and operational insights on infrastructure siting, interconnection capacity, commissioning practices, facility layout, and maintenance readiness. The state-of-practice review refines repeatable steps used by peer agencies, including utility coordination materials, site acceptance/commissioning procedures, data standards, and procurement language that clarifies performance metrics and service expectations.

The purpose of this report is to assemble the best available knowledge from recent literature and current practice into a concise foundation for planning, budgeting, and phased deployment of modernized MHD fleets.

## 1.2 Research Objective and Scope

The objective of this research is to synthesize what current evidence and practice offer about the costs, operational implications, and infrastructure requirements of modernizing MHD public fleets. The project focuses on the planning mechanics that drive budgets and schedules, e.g., depot readiness, interconnection capacity and timelines, make-ready construction, commissioning steps, and day-to-day operational feasibility (such as duty cycles, dwell windows, charger placement/capacity, and uptime). The intent is to clarify where cost and schedule risk typically arise and to identify repeatable steps agencies can use to reduce that risk. The project scope is limited to two activities: (i) a targeted literature review of technical reports, agency/utility guidance, and peer-reviewed sources related to MHD fleet infrastructure and operations; and (ii) a state-of-practice review that compiles procedures and materials used by peer programs (e.g., standard utility scoping materials, site acceptance/commissioning steps, data templates for duty cycles and meter/telemetry).

## 1.3 Research Approach

The research was structured around several interrelated components:

1. Review Literature and Identify Problem – This task aims to thoroughly review the current state of practice in electrified transportation, focusing on MHD fleet, with an emphasis on infrastructure and planning strategies. The research team conducted an extensive literature search to identify domestic and international studies, policies, and technical guidelines related to modernization challenges, operational needs, and infrastructure solutions, specifically for MHD fleets. The scope covers existing technical guidance from North Carolina, as well as other state DOTs, FHWA, AASHTO, TCRP, NCHRP, and key reports from universities and transportation research organizations such as the Transportation Research Board (TRB). The team reviewed existing published papers, technical reports, white papers, among other resources related to transitioning MHD fleets to modern vehicle technologies, planning needs, and other considerations. This review also incorporated cost-effective strategies for fleet modernization, along with the technological advancements

necessary for energy supply consideration. The outcome of this task was a synthesized body of knowledge, which will inform the planning of infrastructure investments and modernization strategies. This synthesis provides critical input for decision-makers and serves as the foundation for the technical and policy recommendations developed in later phases of the study. The literature review helps identify and understand actionable strategies to advance the modernization of the MHD fleet.

2. Review State of Practice – The team conducted a comprehensive review of best practices, policies, and guidelines that pertain to the modernization of MHD fleets. This review includes insights from existing models and case studies that highlight successful transitions to modern fleet technologies, with a focus on operational, fueling, and planning considerations. Specifically, the team reviewed national best practices and policies from NCDOT, FHWA, local government fleets, and, where available, private fleets. We conducted a comprehensive but not exhaustive process and policies review to capture the current state of MHD policies and practices. Specifically, the research investigated the following challenges, particularly in terms of infrastructure requirements:
   - Infrastructure: Medium-/Heavy-Duty (MHD) vehicles powered by alternative fuels require specialized refueling stations, which must be strategically located to support seamless operations. The number, placement, and fuel capacity of these stations need careful planning to prevent logistical inefficiencies.
   - Range and Refueling Time: Alternative fuel MHD vehicles may have operational limitations in terms of range and refueling time, which can impact long-haul routes and continuous fleet operations. Planning for fuel availability and optimizing schedules is critical.
   - Supply Chain and Energy Demand: The transition to alternative fuel fleets necessitates an evaluation of fuel availability, distribution networks, and supply chain resilience to ensure operational feasibility, particularly in high-demand areas.
   - Modernization Cost and Investment: The transition to alternative fuel-powered MHD fleets involves significant upfront costs for vehicles, infrastructure, and fuel supply chain adjustments. Financial feasibility depends on investment strategies, incentives, and partnerships.
   - Operational Adjustments: The adoption of alternative fuel technologies may require adjustments to fleet scheduling, refueling logistics, and vehicle deployment strategies to maintain operational efficiency.

   Addressing these challenges requires coordinated planning, technological advancements, and public-private collaboration. Therefore, this task aims to understand such existing challenges and solutions at the local and national levels.

## 1.4 Report Organization

The organization of this final report reflects the structure of the research approach. Following this introduction, Section 2 presents a summary of the literature review, synthesizing existing research and methodologies. Section 3 describes the state of practice review. Sections 4 through 6 synthesize the study's findings, present policy and planning recommendations, and describe an implementation and technology transfer plan to support the practical application of this research.

# Chapter 2. Result of Literature Review

This chapter presents the literature review findings, focusing on relevant methodologies and processes. We reviewed publications related to the adoption of modern vehicle technologies, infrastructure investments, and modernization strategies for medium- and heavy-duty fleet electrification. The review covers practices, processes, and methodologies pertinent to infrastructure planning as well as technological, economic, and strategic aspects of the transition.

The findings are summarized in four categories:

- Technology and Vehicle Type Analysis
- Charging Infrastructure and Network Design
- Operations and Fleet Management
- Policy and Financial Incentives

## 2.1 Technology and Vehicle Type Analysis

This section summarizes the relevant research on evolving vehicle technology and alternative energy vehicles.

According to the literature, a common solution for transitioning to sustainable fleets is battery electric vehicles (BEVs). BEVs are becoming increasingly popular because they can be a cost-effective option for transitioning vehicles. Transit agencies that have implemented electric buses have shown them to be more economical than diesel buses, though this can fluctuate due to factors such as annual mileage, fossil fuel costs, and electricity tariffs (Blynn & Attanucci, 2019). For instance, Samet et al. (2024) highlight that battery electric trucks (BETs) are also competitively advantageous in urban trips with current technology based on a levelized cost of driving (LCOD) basis. The study presents a detailed review of how battery and charging technology improvements, combined with vehicle type and operational context, shape the cost competitiveness of medium- and heavy-duty BETs. The findings indicate that reductions in battery pack price, gains in gravimetric energy density, and extended cycle lifetimes are important in lowering the LCOD. Charging technology is equally significant, where the deployment of megawatt-scale fast chargers minimizes opportunity costs from downtime, particularly for heavy-duty, long-haul operations. Vehicle type and trip profile strongly affect results. Under current technology, BETs are already cost-competitive for urban applications, while medium-duty trucks under 40 tons gross vehicle weight are expected to become practical in regional and even long-haul contexts as battery performance improves. Nevertheless, for vehicles above 40 tons and in demanding long-haul scenarios, BET competitiveness is challenging without supportive measures such as policy incentives and widespread fast-charging infrastructure. The study also highlights the significance of optimal driving-range design, where battery sizing balances high upfront costs with operational efficiency. By comparison, fuel cell electric trucks (FCETs) have an advantage in long-haul freight due to lighter energy storage and faster refueling, despite higher fuel and infrastructure costs. BETs are better suited to urban and regional freight with their superior energy efficiency and lower near-term costs, while FCETs may be preferable in the heaviest and longest-haul applications. This suggests a future freight transport system where BETs lead cost-sensitive short- and medium-distance operations, while FCETs provide strategic solutions in long-haul logistics. Figure 1 depicts MHD vehicle market segmentation, considering three primary market segments: local and regional return-to-base, specialized vehicles and work trucks, and long-haul vehicles (U.S. Department of Energy; U.S. Environmental Protection Agency, 2024).

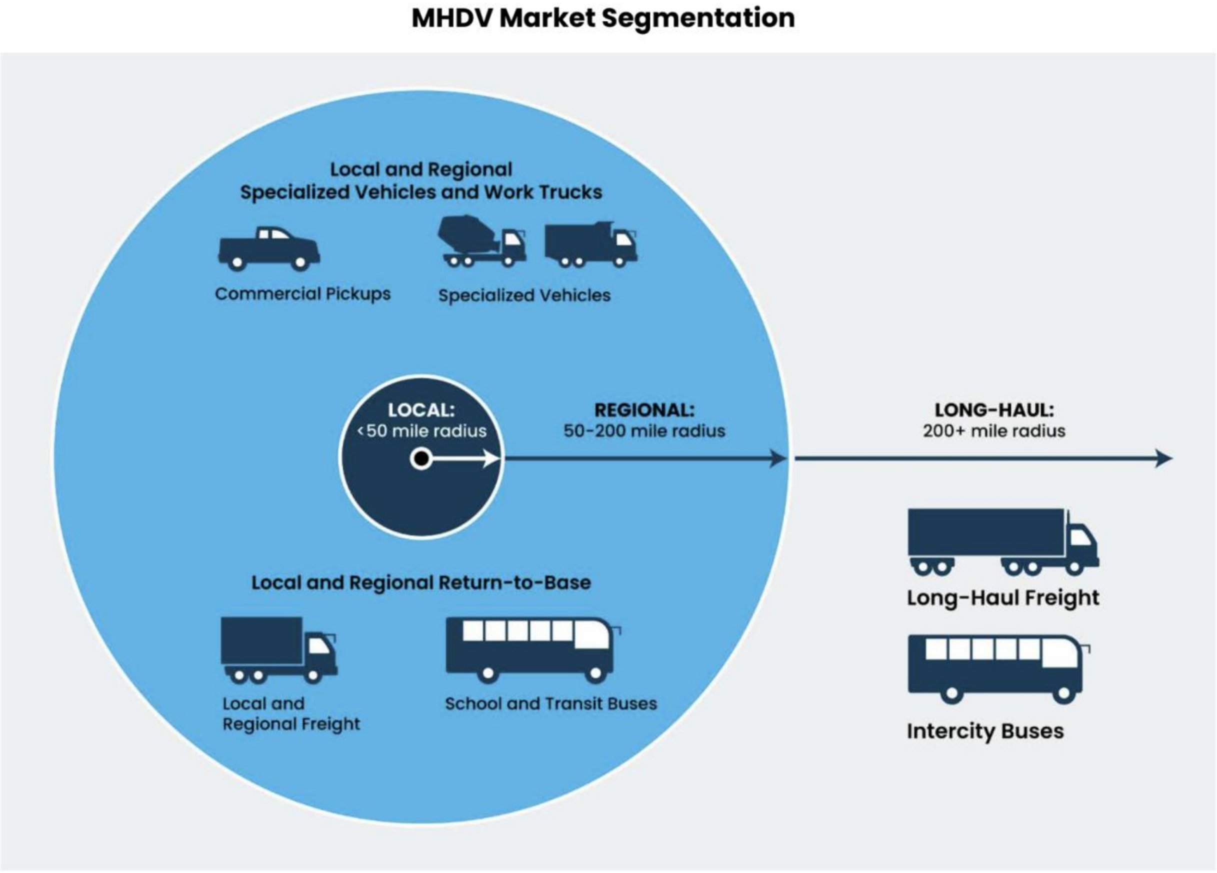


*Figure 1: MHD vehicle market segmentation [Source: U.S. Department of Energy; U.S. Environmental Protection Agency, 2024].*

LCOD and total cost of ownership (TCO) models have shown that BEVs will achieve TCO parity with diesel by 2030 in most cases and are more favorable for short-haul and urban segments due to lower fuel consumption and maintenance costs (Burke et al., 2023).

Another crucial technology that the literature identifies is hydrogen/fuel cell electric vehicles (FCEVs). FCEVs are critical in applications where BEVs fall short. Müller (2025) executes a multifaceted comparison of fuel cell heavy-duty trucks and battery electric heavy-duty trucks. Utilizing a socio-technical approach, he combines Rogers's Diffusion of Innovation theory with a Political, Economic, Social, Technological, Legal, Environmental analysis. His research synthesizes findings from literature reviews and 40 expert interviews, focusing on Upper Austria. The results indicate that battery electric heavy-duty trucks hold advantages in terms of political support, lower total cost of ownership, higher technological maturity, and greater public acceptance. On the other hand, fuel cell heavy-duty trucks demonstrate greater potential due to their longer range, faster refueling, higher payload, and better cold-weather performance. This indicates fuel cell heavy-duty trucks as more suitable for long-haul and heavy-duty operations (Müller, 2025). Research also indicates that, under favorable conditions, FCEVs can reach TCO parity with diesel vehicles in the long-haul division by the late 2030s (Burke et al., 2023).

Research by Burke et al. (2023) provides economic analyses of the future viability of zero-emission trucks and buses. They focus on battery-electric vehicles (BEVs) and fuel cell vehicles (FCVs) to showcase how costs look. As before, many costs are higher with electrifying trucks and buses, as they need batteries with higher charging capacity due to their size and responsibilities. Interestingly, they also indicate a need to examine climate and terrain before declaring what battery sizes are necessary. For FCVs, however, the high durability requirements and balance-of-plant components make these options more expensive than batteries. If done on a large-scale manufacturing level, though, costs would be reduced by more than half over two decades. These FCVs also need hydrogen storage and consumption. In the future, hydrogen production and delivery costs—specifically for "green" hydrogen—are expected to decline by 2040. By contrast, electricity prices have remained stable over the years, showing a favorable trajectory for the electrification of larger vehicles. In addition, maintenance costs further favor electrification, since BEVs are expected to achieve 30% lower costs than diesel by 2025, and FCVs will have 25% lower costs. Both BEVs and FCVs will benefit from current and future policies such as the Low Carbon Fuel Standard, which will eventually offset electricity and hydrogen costs. However, infrastructure questions and challenges remain a consistent hurdle in implementing wide-scale electrification of medium- and heavy-duty fleets. BEVs require costly charging upgrades and careful load management to avoid demand charges. FCVs are highly dependent on the current and future development of hydrogen refueling networks. The authors note that while upfront costs are high and daunting, the longevity associated with transitioning to full electrification will decrease with more support, planning, and adoption. Overall, BEVs seem to be making more headway than FCVs.

Additionally, the existing literature presents studies on hybrid vehicles and alternative fuels such as biodiesel and compressed natural gas (CNG). Sen et al. (2019) state that these alternative fuels offer a few advantages over traditional diesel engines in an optimal fleet context. This study shows how technology and vehicle type choices influence the sustainability and cost performance of heavy-duty truck fleets across U.S. economic sectors. Using a hybrid life-cycle assessment and robust Pareto-optimal modeling, the analysis compares diesel, biodiesel, CNG, hybrid, and battery-electric (BE) heavy-duty trucks. Results depict that diesel, hybrid, and BE trucks dominate optimal fleet mixes, while biodiesel and CNG trucks are omitted due to limited life-cycle benefits and higher external costs. BE heavy-duty trucks emerge as the cleanest option, with zero tailpipe emissions and substantially lower life-cycle air-pollution externality costs, about 70% lower than conventional diesel, making them socially advantageous despite higher upfront and infrastructure costs. Still, the study says that BE trucks are challenged by higher life-cycle costs (LCCs) and greenhouse-gas (GHG) emissions linked to electricity generation, which restrict their capacity to achieve deep emission reductions without cleaner power grids. Hybrid trucks serve as a transitional technology, providing modest improvements in fuel efficiency while maintaining competitive costs. Sector-specific analyses show that fleet composition is influenced by payload characteristics and the relative prioritization of economic versus environmental objectives. For instance, sectors with higher cost (such as beverages and household durables) lean toward hybrid and diesel mixes, while food products, oil and gas, and automotive sectors show higher incorporation of BE trucks. The findings highlight that advancing battery technology, lowering charging infrastructure costs, and decarbonizing electricity supply are crucial for BE trucks to lead future sustainable fleet configurations.

A few studies have shown that heterogeneous fleet modeling outperforms homogeneous assumptions, with shorter turnover cycles enabling faster adoption of efficient vehicles. Guerrero de la Peña et al. (2019) utilized a system-of-systems engineering methodology to project the adoption of new technologies. They recognized that fleets are independent entities with varying characteristics such as size, budget, vehicle turnover cycle, and cargo demand. With this in mind, they developed a constrained mixed-integer linear programming (MILP) model that minimizes the total cost of ownership for individual fleets while accounting for their interactions on a shared highway network. The model also integrates vehicle performance, operational costs, freight demand, and traffic models. These integrations allow them to simulate how individual fleet purchasing decisions collectively lead to system-wide adoption trends over an 11-year period. The model's validity was calibrated and compared against historical adoption data ranging from 2005 to 2015 and achieved 90% accuracy by modeling fleet heterogeneity. From their analysis, they discovered that fleet-specific management parameters, like purchase cost, are more influential on adoption rates than broader factors like fuel price (Guerrero de la Peña et al., 2019).

## 2.2 Charging Infrastructure and Network Design

There are several studies that address the complexities of planning electric-vehicle charging infrastructure for large-scale MHD vehicle deployment. Multiple optimization and simulation models have been created and used to allocate vehicles and charging stations efficiently across freight routes and trip profiles.

One major approach is to formulate a flow refueling location model (FRLM), enhanced with capacity and queuing considerations, to identify optimal charging locations. For example, this approach was applied to a case study in Germany for battery electric trucks. The study found that well-positioned, large initial charging locations can already cover significant shares of battery-electric truck (BET) traffic. Capacity constraints, such as parking availability, would also increase the required number of stations compared to unconstrained models (Speth et al., 2025). The paper emphasizes that designing a robust charging infrastructure is vital for large-scale adoption of BETs in Germany. Unlike earlier models that often ignored physical and operational constraints, this study introduces a capacity-constrained FRLM that integrates real-world factors such as limited parking availability and grid-connection capacities. The results show that capacity constraints significantly increase infrastructure needs: while an unconstrained model identifies 42 stations in Germany, the capacity-constrained FRLM requires 124 stations with about 12,300 charging points to fully electrify national truck traffic. These facilities must support megawatt charging systems capable of delivering 720 kW on average and up to 1 MW per truck to recharge a typical 300-km driving range within a 45-minute rest period. Network design is shaped by traffic intensity and international flows, with large stations clustered along major freight corridors such as the A2 route linking Western ports to Eastern Europe. Utilization analysis reveals that stations operate at around 43% temporal capacity, highlighting both the efficiency of station placement and the challenge of balancing peak demand. The study also reflects early market phases: by 2030, with an assumed 15% BET share, about 2,000 charging points distributed across the same 124 locations would be sufficient, necessitating integration with existing medium-voltage substations. Overall, the study highlights that successful charging-network design must merge vehicle range, traffic flows, parking capacity, and grid limitations, ensuring both scalability and feasibility for long-haul freight electrification.

Similarly, GIS-based location-optimization frameworks provide another approach. Hurtado-Beltran et al. (2021) developed and applied a GIS-based methodology to evaluate the potential driving coverage provided by deploying direct-current fast-charging (DCFC) stations for battery electric trucks at existing truck-stop facilities along the U.S. Interstate Highway System. Using network analysis in ArcGIS, they calculated service areas for scenarios based on maximum driving distances of 25, 50, and 100 miles. Proximity to high-voltage electric transmission lines and truck-stop size were additional factors in their calculations. The results indicate that truck stops can provide substantial coverage (up to 99.5% of the interstate system) under a 100-mile service-area assumption with no electrical-proximity constraints. Another scenario -- truck stops with a 50-mile service area and within 5 miles of power lines -- demonstrated that 93.6% coverage could be achieved. This scenario was identified as a practical target for initial deployment. The study ultimately showed that the number of required stations could be reduced by over 70% while still maintaining similar coverage (Hurtado-Beltran et al., 2021).

## 2.3 Operations and Fleet Management

To improve system efficiency and charging logistics, modeling frameworks have been widely employed to address this concern. For instance, Wurtz et al. (2023) utilize flexible, constraint-based linear programming models and test their framework on a medium-sized city network in Germany. Their analysis indicates that depot-only charging is infeasible for complete electrification without diesel support. By contrast, opportunity charging combined with a small diesel fleet yields more cost-effective results. The study reveals that the transition to electric urban bus fleets fundamentally reshapes operations and fleet management by introducing new constraints on range, charging, and energy demand. Traditional diesel-based scheduling cannot simply be shifted to electric fleets, as operators must account for limited state-of-charge windows, dwell times adequate for opportunity charging, and battery-degradation considerations. Using big data (including GPS trajectories, telematics, passenger loads, and environmental factors), the study suggests a discrete optimization framework that integrates real-world operational details into fleet planning. This approach allows public transport operators to concurrently optimize vehicle choice, battery sizing, and charger placement while maintaining cost efficiency. Results from the case study show that mixed-fleet strategies, combining electric and diesel buses, initially provide the most cost-effective solutions, while full depot-charging strategies require excessively large batteries and still leave gaps in service coverage. By contrast, opportunity charging, enabled by strategically placed high-power chargers, supports smaller, cheaper batteries but demands precise alignment between route design and infrastructure. Significantly, the optimization framework complements existing driver schedules, lunch breaks, and rotation plans, ensuring feasibility in real-world operations. Visualizations of charger use and fleet composition also help public transport operators adapt incrementally, gradually reducing diesel reliance while stabilizing infrastructure investments. The paper shows that successful fleet management for electric buses depends on data-driven decision-making, flexible mixed-fleet operations in early phases, and robust optimization tools that balance energy constraints with service reliability.

Likewise, Gairola and Nezamuddin (2023) incorporate passenger waiting-time limitations at fast-charging terminals into their optimization model for battery electric bus (BEB) systems. Their model determines the optimal battery sizes for different bus routes and the design variables for charging infrastructure. These variables include location, size, number of depot slow chargers, and the number of terminal-based fast chargers. The objective of their study is to minimize total system costs. A key element is the integration of queuing theory into the model. Queuing theory is integrated as a C×M/M/1 system to ensure that expected waiting times at shared charging terminals do not exceed the available layover time. This essentially prevents trip delays. Gairola and Nezamuddin also extend their research to include the uncertainties of real-world energy consumption. As such, their deterministic model is expanded to a stochastic version that accounts for variable energy demands under different traffic and operational conditions. This is solved using a Lagrangian relaxation approach. Gairola and Nezamuddin then implement their models on a subnetwork in New Delhi, India. This subnetwork consists of 18 routes, 21 terminals, and 3 depots. The results of this case study demonstrate that considering stochastic energy demands leads to a more effective but costlier design, with a significant increase in fleet and charger costs. The trade-off is a slight decrease in electricity costs (Gairola & Nezamuddin, 2023).

A study on joint optimization of truck routing and charging is investigated and discussed by Bragin, Ye, and Yu (2024), addressing the challenges of implementing such infrastructure. Even though medium-heavy-duty vehicles represent 1% of all vehicles, they account for 25% of greenhouse gas emissions -- a factor many are concerned with. The electrification of this group has had longstanding difficulties due to limited charging infrastructure, high energy demand per mile, and operational complexity for vehicles in long-distance service. This study introduces a joint routing and charging formulation to combat these issues. Furthermore, medium-heavy-duty vehicles face more challenges for operational use compared to lighter EVs. Challenges such as higher energy consumption for larger vehicles, tighter charging-station capacity constraints, and more daily tasks with deadlines are among those considered. The authors' model aims to minimize total costs related to transportation, charging, and deadline penalties. They apply the Surrogate Level-Based Lagrangian relaxation model, which allows each truck's routing and charging plan to be optimized independently while still coordinating other fleet decisions. This is helpful as it gives a more thorough and personalized approach and result for each vehicle among a larger fleet. Through the model and analysis, medium-heavy-duty vehicles with larger battery capacities reduce costs, while higher charging power reduces the fleet size required to meet demand.

A related study on joint optimization of truck routing and charging leads to the development of an MILP model. It considers constraints such as vehicle energy consumption, route length, delivery deadlines, and charger availability (Bragin et al., 2024). The unified framework is tested on realistic freight-transportation scenarios and outperforms decoupled routing and charging methods.

Foda et al. (2025) introduce a framework for optimizing the infrastructure and operations of battery-electric bus (BEB) transit systems. Transit buses are strong candidates for electrification due to their fixed routes and schedules. However, prior studies often oversimplify electrification, causing limited and underwhelming results and analyses. By neglecting the variability in energy consumption caused by operational, vehicular, topographic, and environmental factors, previous results can lead to inefficient system designs. To make strides in better infrastructure design, the authors propose a model that integrates the Advanced Vehicle Simulator (ADVISOR) with a surrogate model-based space mapping (SMSM) approach. ADVISOR provides simulations aligned with current practices (e.g., trip-level energy consumption, vehicle load, speed profiles, route characteristics). While it is computationally intensive, the SMSM algorithm reduces complexity by using a linear model enhanced iteratively through input-space mapping. The model's objective, like others, is to minimize total costs. These costs consist of the number and power of chargers and operational costs. The constraints in this model address bus state of charge, charging-time limits, fleet schedules, and charger availability. A case study of a Canadian city's bus network is used with 11 buses on 9 routes. Two strategies are evaluated: flash charging, which entails smaller batteries, high-powered chargers, and frequent top-ups; and opportunity charging, with larger batteries and moderate charging power. Results show that, using SMSM, daily operating costs are lower by 4-5%. Comparing the two strategies, flash charging requires five chargers with total daily costs of $613, while opportunity charging requires seven chargers with $606 in daily costs. The SMSM algorithm also reduces peak charging demand and shifts charging away from high-cost periods.

Research by Zhao et al. (2025) combines machine learning (information gain), GIS analysis, and the best-worst method to identify high-demand zones near logistics hubs and heavily trafficked corridors. Their work focuses on optimal freight electric-vehicle charging station siting using spatial analysis, incorporating factors such as trajectory density, land use, traffic flow, and logistics access. These methods reveal that traffic flow is the most important factor after distance to the charging station. The study underlines how effective operations and fleet management of freight electric vehicles are linked to improved charging-station placement. Using GPS data from over 4,000 medium- and heavy-duty electric trucks in Suzhou, China, the authors determine that understanding freight-movement patterns is essential to designing infrastructure that supports consistent fleet operations. The study identifies high-priority nodes where charging demand is high by applying trajectory-density analysis, origin–destination flow mapping, and the PageRank algorithm. This approach allows fleet managers to minimize detours and downtime, improving vehicle utilization and operational efficiency. The inclusion of accessibility criteria (such as proximity to logistics hubs, road networks, and parking facilities) reflects the operational realities of freight fleets, where charging often overlaps with loading and unloading activities. The study employs an information-gain-based multi-criteria decision-making framework, which decreases subjectivity in weighing siting factors and ensures a more data-driven approach. Results show that distance to existing charging stations and traffic flow are the most crucial factors, followed by road accessibility and proximity to parking and logistics facilities. For fleet management, this means that charging-infrastructure expansion should prioritize areas that not only support vehicle range but also align with daily logistics operations. Suitability maps provide planners and operators with actionable insights to ensure charging networks are both resilient and efficient. The study highlights that aligning infrastructure planning with freight-vehicle operations is vital to reduce costs, mitigate range anxiety, and enhance the scalability of electric freight fleets.

## 2.4 Policy and Financial Incentives

One of the biggest challenges with MHD vehicle fleet modernization is the economic aspect. A study on the modernization of public transport in the Philippines noted delays in the transition due to financial, operational, and political resistance. The study by Sunio et al. (2019) on bus modernization uses total TCO data and interviews to show that factors such as charging costs and operational costs can present significant barriers. The public utility vehicle modernization program in the Philippines reveals the vital role of policy and financial incentives in driving large-scale transport reform. The foundation of this program is strong state involvement, with the Department of Transportation and its agencies acting as institutional entrepreneurs by issuing the omnibus franchising guidelines, which mandate fleet modernization, route rationalization, and operator consolidation as prerequisites for franchise restitution. This regulatory framework disrupts the long-standing, fragmented jeepney regime and compels operators to transition into cooperatives or corporations. Financial incentives are equally critical to enable compliance. Through special loan programs from state-owned banks, operators can access financing covering up to 95% of new-vehicle costs, with a government equity subsidy of ₱80,000 per unit designed to meet the required 5% equity. These subsidies, combined with vehicle scrappage incentives, aim to lower barriers to fleet modernization. However, challenges persist; e.g., inflation has increased vehicle costs beyond original estimates, rendering the subsidy insufficient, and budget constraints limit its coverage. Social support measures provide livelihood training for displaced drivers, underlining the government's recognition of modernization's social impacts. Despite these incentives, resistance from operators, transport groups, and some legislators remains strong, with critics describing the program as anti-poor due to the financial burden on small operators. The results highlight that effective modernization requires not only regulatory compulsion and financial aid but also expanded, adaptive subsidies and stronger political strategies to overcome resistance and sustain reform.

Initial capital costs for electric vehicles are often high. He et al. (2025) present an analysis of the electrification of school-bus fleets in Richmond, Virginia. They also develop a mixed-integer linear programming model to optimize system designs, charging strategies, and costs. Using travel-itinerary data from 131 buses, operational patterns were identified: the buses traveled an average daily distance of 44.9 miles and spent about 6.2 hours midday and 15.2 hours overnight, dwelling at depots. These dwelling times were identified as key opportunities for charging. The model evaluates scenarios for full-fleet electrification and identifies the scenario with midday charging as the most cost-effective option compared with the scenario with no midday charging. Upfront costs are 28% lower with midday charging. The analysis also shows that optimized charging management that shifts energy use to off-peak hours could reduce annual electricity costs by 16-35% (He et al., 2025). Leveraging grants to cover the costs of BEBs, or creating low-cost financing programs and favorable electricity tariffs, are possible policies and strategies that can help with high upfront costs (Blynn & Attanucci, 2019).

Becker et al. (2019) use a case study from New Jersey to further explain why having MHD vehicles, specifically school buses, convert to electric is beneficial. Compared to diesel counterparts, electric vehicles reduce combustion-product emissions to zero and are mechanically simpler, leading to easier maintenance -- a positive for school districts with limited funding. Furthermore, diesel school buses have been linked to harming the environment and youth with their pollutants and exhaust emissions. Regarding cost for electric vehicles, even though maintenance costs are lower, charging stations and infrastructure add to costs, especially during peak hours, such as morning commutes. To combat these costs, it is possible to reduce energy and demand charges by implementing smart-charging controls and integrating distributed energy resources. This case study uses mixed-integer linear programming to optimize the size and dispatch of distributed energy resources using an objective function to minimize the life-cycle cost of energy. The initial analysis states that buses are parked when not driving and executing duties. More specifically, to reduce costs, school buses should be parked at the school rather than central depots for charging and maintenance. This is because, when investigating scenarios, the most cost-effective option is combining electric vehicles, distributed energy resources, and vehicle-to-building (VTB). VTBs allow school buses, when not in use, to discharge battery-pack energy back to the building load to further reduce energy and demand charges. In conclusion, it is most cost-effective, compared to diesel, to have school buses electrified with their own charging infrastructure.

Blynn et al. (2019) pose the question: What is needed to overcome barriers and increase electrification of transit buses? Rather than looking quantitatively, the authors investigate qualitative concerns by examining three states and agencies within them. These qualitative concerns are assessed through public-policy review, analysis of public statements, and interviews with agencies. The states include California, Kentucky, and Massachusetts, as these states are at various levels of transition toward the electrification of medium-heavy-duty vehicles. Through policies, most transit buses are procured with the Federal Transit Administration, which grants a fixed amount per metro for bus replacements. Furthermore, in California, the Low Carbon Fuel Standard creates a market for transit fleets operating with fuel vehicles. California is also updating the fleet rule for transit agencies, which would mandate zero-emission bus procurement. While Massachusetts has similar policies to California, they are on a lower scale with respect to programs and initiatives. To reduce costs, the Department of Public Utilities approved one investor-owned utility to invest in EV make-ready infrastructure. This would cap costs by ensuring that all installation and electrical-upgrade costs would be less than or equal to the value of the charging equipment itself. Interviews among agencies provide useful insights. Agencies identified factors as barriers or drivers for the implementation of electric MHD fleets. Many barriers are cost-related, such as upfront costs and infrastructure costs. Other concerns are more technical, like battery-performance uncertainty, manufacturer limitations, and added operational complexity. However, drivers are strong motivators, such as environmental benefits, maintenance-cost savings, equity benefits, and economic-development benefits -- factors continually considered as “pros” for increased electrification. Finally, many factors are universal across all agencies and can be seen as both barriers and drivers. Factors such as external pressure, electricity costs, and overall life-cycle costs fall into this category.

## 2.5 Lessons Learned

- BEVs/BETs are more cost-effective than diesel in many cases, especially in urban operations, due to fuel and maintenance savings.
- Optimizing FRLM variants helps solve complex charging-network design problems.
- FCEVs are better suited to long-distance operations given greater range, faster refueling, higher energy-storage potential, and strong cold-weather performance.
- While biodiesel and CNG have some operational advantages, mixed fleets generally outperform single-technology fleets.
- Depot-only charging is typically inadequate without diesel support; incorporating en-route charging is often necessary for cost efficiency.
- Methods such as machine learning with GIS, simulations, and surrogate modeling yield more accurate energy-use and charging-demand forecasts and highlight the importance of traffic flow.
- High capital costs remain a challenge across infrastructure strategies.

- Pairing fleets with distributed energy resources can improve cost effectiveness, and VTB approaches can create additional revenue.

The literature shows that cost-effective, reliable modernization of MHD fleets centers on coordinated, data-driven planning that integrates duty-cycle realities, infrastructure constraints, and utility coordination. This review identifies practical methods and recurring challenges that shape budgets, timelines, and service quality. These insights provide a clear foundation for agencies to structure pilots, procurement language, and phased deployments with predictable cost and operational outcomes.

# Chapter 3. Results of State of the Practice Review

Modernization in the MHD sector is rapidly growing, becoming a more common policy focus for local governments. Municipalities and other planning authorities may be interested in promoting and facilitating the required infrastructure for a variety of reasons, including better serving their communities, reducing dependence on imported oil, meeting environmental goals, and fostering economic development, to name a few. It is important to distinguish what types of vehicles are classified as MHD, especially since most research has focused on light-duty fleets. Figure 2 below shows the classification of MHD vehicles as displayed by the Maryland Department of Energy (2022).

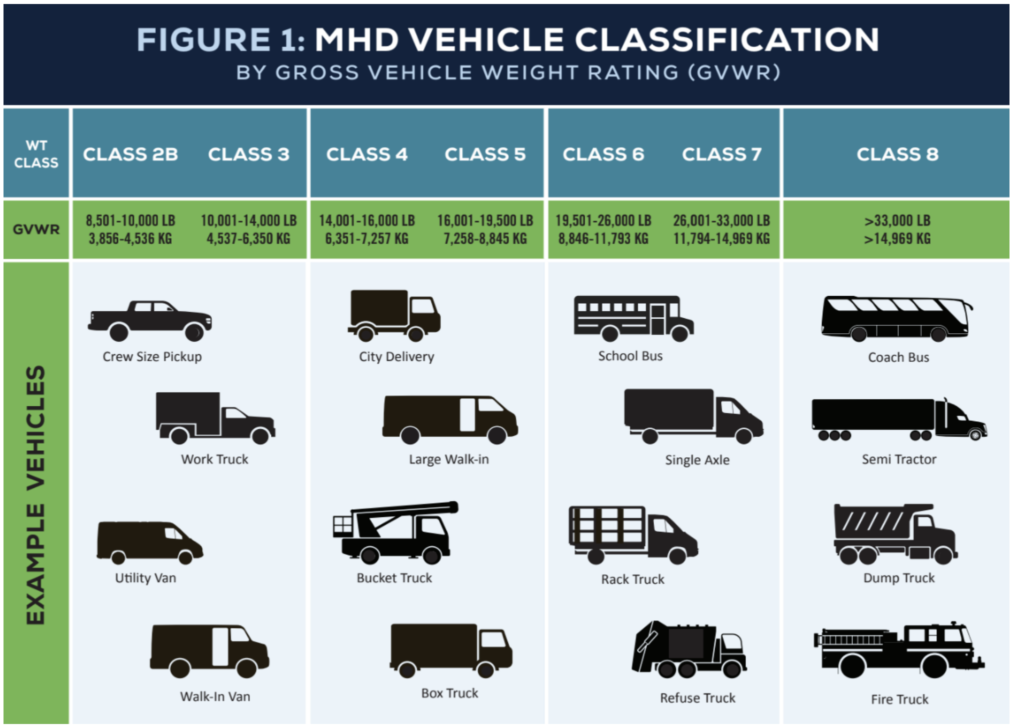


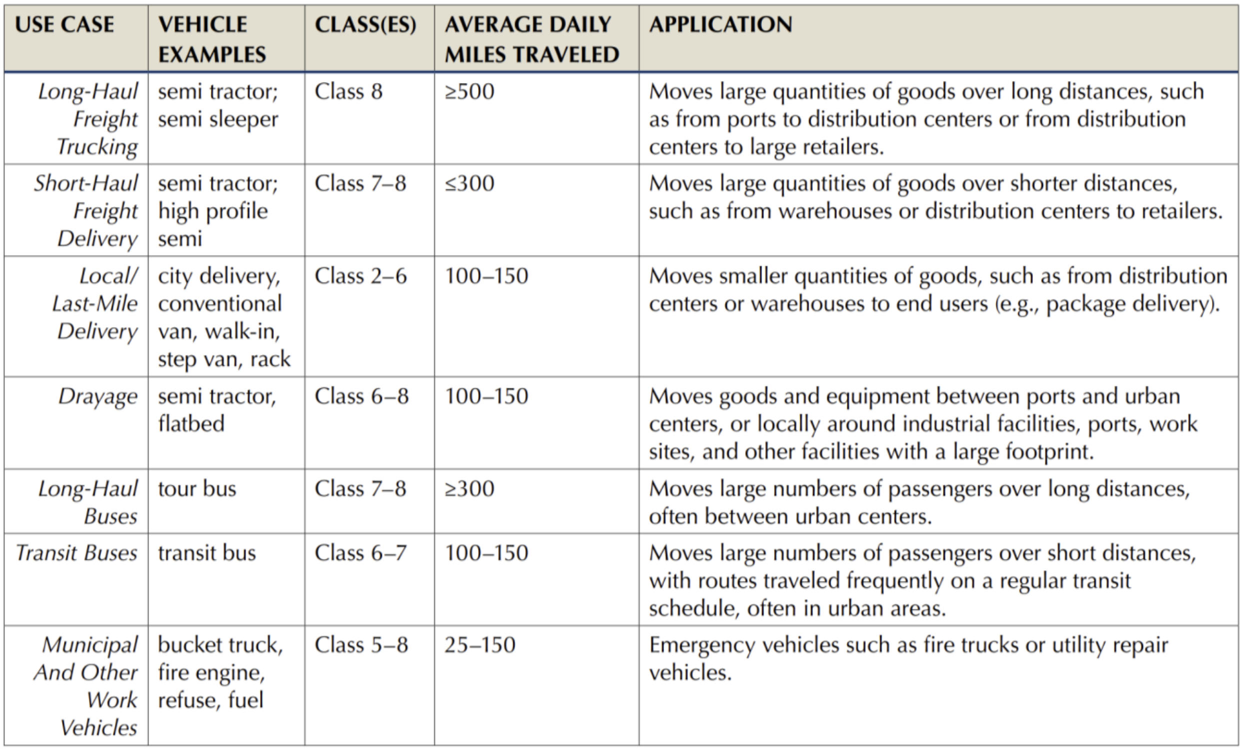
**FIGURE 1: MHD VEHICLE CLASSIFICATION**
BY GROSS VEHICLE WEIGHT RATING (GVWR)

| WT CLASS | CLASS 2B | CLASS 3 | CLASS 4 | CLASS 5 | CLASS 6 | CLASS 7 | CLASS 8 |
|---|---|---|---|---|---|---|---|
| GVWR | 8,501-10,000 LB<br>3,856-4,536 KG | 10,001-14,000 LB<br>4,537-6,350 KG | 14,001-16,000 LB<br>6,351-7,257 KG | 16,001-19,500 LB<br>7,258-8,845 KG | 19,501-26,000 LB<br>8,846-11,793 KG | 26,001-33,000 LB<br>11,794-14,969 KG | >33,000 LB<br>>14,969 KG |
| EXAMPLE VEHICLES | Crew Size Pickup<br>Work Truck<br>Utility Van<br>Walk-In Van | | City Delivery<br>Large Walk-in<br>Bucket Truck<br>Box Truck | | School Bus<br>Single Axle<br>Rack Truck<br>Refuse Truck | | Coach Bus<br>Semi Tractor<br>Dump Truck<br>Fire Truck |

*Figure 2: Classification of MHD vehicles [Source: Maryland Department of Energy, 2022].*

Table 1 depicts applications and use cases of MHD vehicles as analyzed by the Center for Climate and Energy Solutions (Gagnon, 2023). MHD vehicles include on-road vehicles with a gross vehicle weight rating greater than 8,000 pounds. Between 2020 and 2022, MHD energy consumption increased by 19%, signifying the rising emergence and importance of these vehicle types (U.S. Department of Energy; U.S. Environmental Protection Agency, 2024). Furthermore, 92% of MHD vehicles are powered by diesel and have contributed greatly to local air pollution (U.S. Department of Energy; U.S. Environmental Protection Agency, 2024). Gas emissions from MHD vehicles increased by 76% between 1990 and 2021 (Bruchon et al., 2024). Figure 3 shows historical U.S. MHD vehicle energy-consumption share by fuel, 1990 to 2022, for which data have been obtained from the 2024 Inventory of U.S. GHGs and Sinks (U.S. Department of Energy; U.S. Environmental Protection Agency, 2024).

*Table 1: Applications and use cases of MHD vehicles [Source: Center for Climate and Energy Solutions (Gagnon, 2023)].*



| USE CASE | VEHICLE EXAMPLES | CLASS(ES) | AVERAGE DAILY MILES TRAVELED | APPLICATION |
|---|---|---|---|---|
| *Long-Haul Freight Trucking* | semi tractor; semi sleeper | Class 8 | ≥500 | Moves large quantities of goods over long distances, such as from ports to distribution centers or from distribution centers to large retailers. |
| *Short-Haul Freight Delivery* | semi tractor; high profile semi | Class 7–8 | ≤300 | Moves large quantities of goods over shorter distances, such as from warehouses or distribution centers to retailers. |
| *Local/ Last-Mile Delivery* | city delivery, conventional van, walk-in, step van, rack | Class 2–6 | 100–150 | Moves smaller quantities of goods, such as from distribution centers or warehouses to end users (e.g., package delivery). |
| *Drayage* | semi tractor, flatbed | Class 6–8 | 100–150 | Moves goods and equipment between ports and urban centers, or locally around industrial facilities, ports, work sites, and other facilities with a large footprint. |
| *Long-Haul Buses* | tour bus | Class 7–8 | ≥300 | Moves large numbers of passengers over long distances, often between urban centers. |
| *Transit Buses* | transit bus | Class 6–7 | 100–150 | Moves large numbers of passengers over short distances, with routes traveled frequently on a regular transit schedule, often in urban areas. |
| *Municipal And Other Work Vehicles* | bucket truck, fire engine, refuse, fuel | Class 5–8 | 25–150 | Emergency vehicles such as fire trucks or utility repair vehicles. |

Figure 4, by Bruchon et al. (2024), shows the county-level transit-bus inventory in the U.S., highlighting the significant number of these MHD vehicles across the country, particularly in larger cities on the west and east coasts. This map, coupled with the rising air-pollution contribution from MHD vehicles, highlights the need for electrification of MHD fleets.

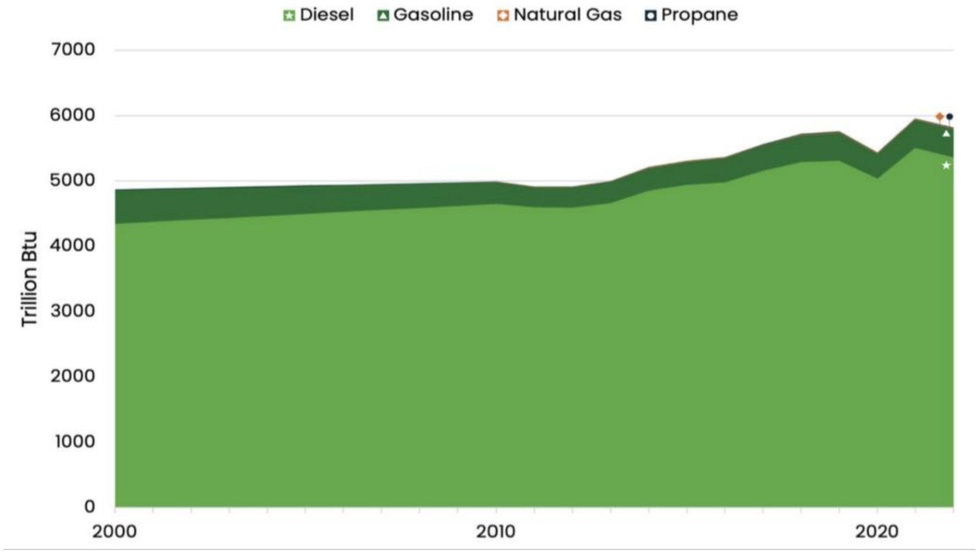


*Figure 3: Historical U.S. MHD vehicle energy consumption share by fuel, 1990 to 2022 [Source: U.S. Department of Energy; U.S. Environmental Protection Agency, 2024].*

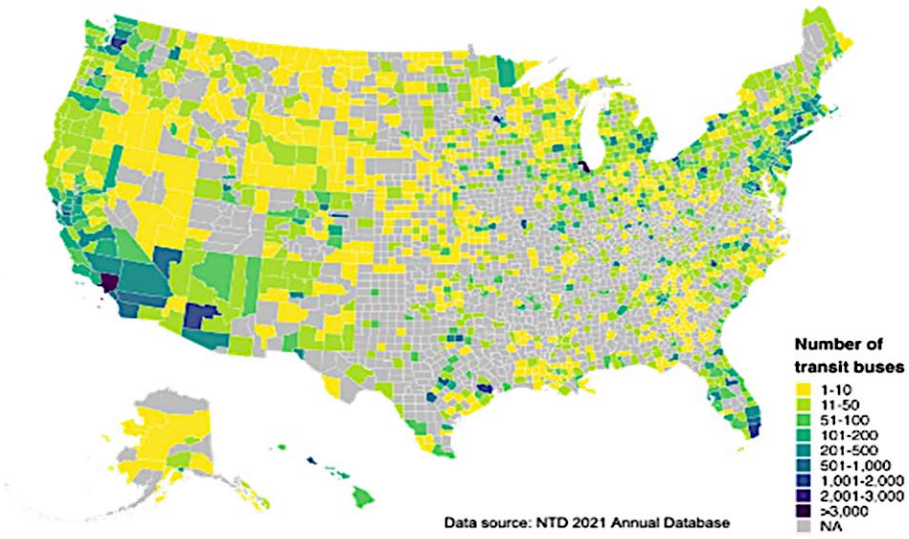


*Figure 4: Number of transit buses across the U.S. [Source: Bruchon et al. (2024)].*

This chapter captures national, state, and local government practices and policies for MHD fleet charging infrastructure to identify best practices, as well as potential opportunities, barriers, and policy disconnects in the following sections:

- Federal Plans, Programs, and Standards
- Regional and Local Planning Standards
- North Carolina Local Government EV Policies and Practices

## 3.1 Federal Plans, Programs, and Standards

The federal government has established multiple initiatives to support the transition to electric fleets, including several funding programs and tax credits. For example, the Inflation Reduction Act (IRA), the Advanced Technology Vehicles Manufacturing (ATVM) Loan Program, and the Charging and Fueling Infrastructure (CFI) Discretionary Grant Program provide financial support to ease the shift to cleaner, more efficient vehicles (The Joint Office of Energy and Transportation). All three offer some form of funding to help agencies and operators manage upfront costs.

The U.S. Environmental Protection Agency (EPA) has issued a final rule on greenhouse-gas emission standards for heavy-duty vehicles, with significantly stricter standards for model year 2027 and beyond. The standards are performance-based, allowing manufacturers to choose the emissions-control technologies that best fit their vehicles (Environmental Protection Agency, 2024). The Federal Highway Administration’s (FHWA) NEVI (National Electric Vehicle Infrastructure) Program provides funding for EV supply equipment (EVSE) installations but does not currently mandate site designs specific to MHD vehicles. Nevertheless, FHWA has encouraged states to consider pull-through layouts and circulation needs for larger vehicles. In parallel, the SAE J3271 Megawatt Charging System (MCS) standard is under development to support charging up to 3.75 MW for MHD fleets (Powell, Johnson, Yip, & Snelling, 2024).

Federal efforts also coordinate with standards bodies such as CharIN, which is developing a global high-power charging standard for commercial MHD vehicles (above 350 kW) (Walkowicz, Meintz, & Farrell, 2020). The federal government had set targets for MHD vehicles: 35% of total MHD vehicle sales to be zero-emission by 2030, and 100% zero-emission for a defined subset by 2040. Canada has likewise signed the Global Memorandum of Understanding on Zero-Emission MHD vehicles, aiming for 100% ZEV sales by 2040, aligning with broader net-zero pathways and emission-reduction plans (Electrifying Canada, 2022).

## 3.2 Regional and Local Planning Standards

Jurisdictions in the U.S. have committed to making 100% of new medium- and heavy-duty vehicles zero-emission by 2050 through the Multi-State MHD Zero-Emission Vehicle Memorandum of Understanding (MOU) (ZEV Task Force, 2022). Figure 5 depicts zero-emission MHD vehicle model availability in the United States and Canada, as analyzed by Global Commercial Vehicle Drive to Zero's "ZETI Data Explorer" (Gagnon, 2023).

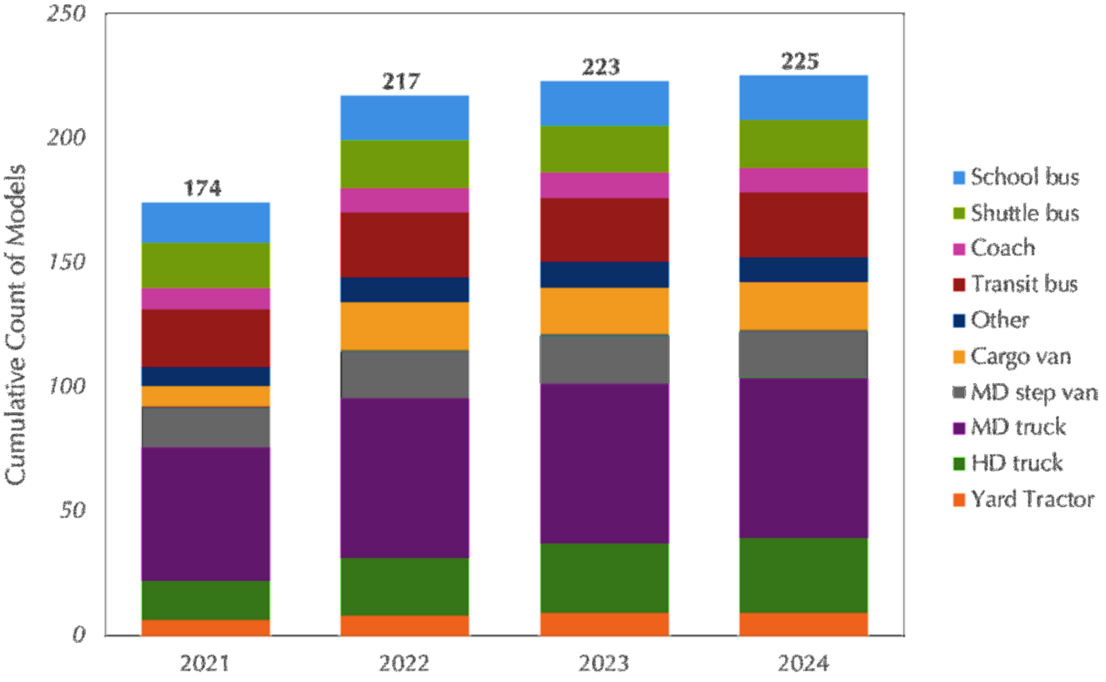


*Figure 5: Zero-emission MHD vehicle model availability in the U.S. and Canada [Source: Gagnon, 2023].*

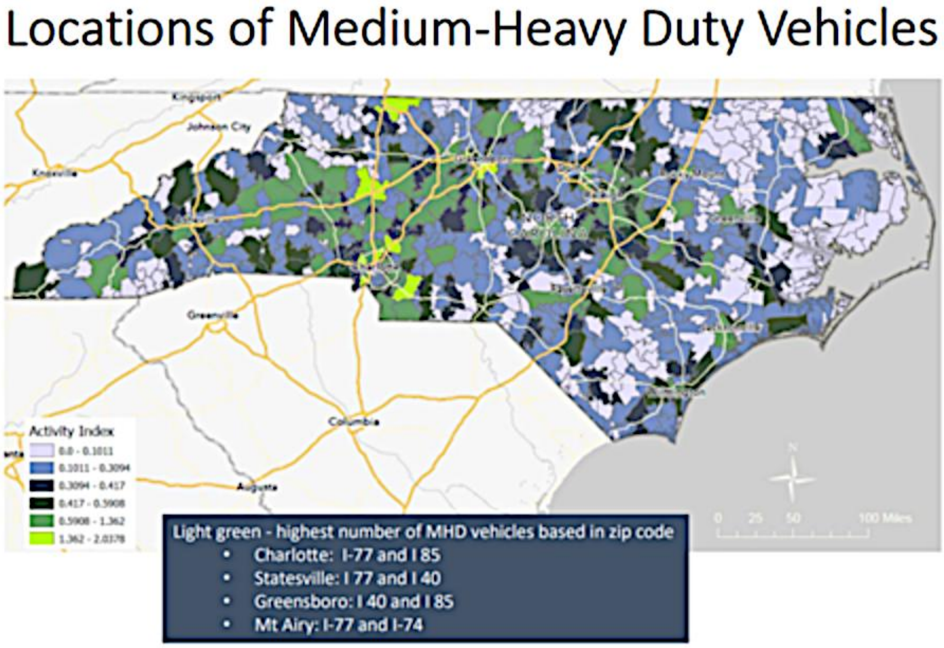
Some state EV deployment plans have looked beyond NEVI requirements. For example, Louisiana includes scoring criteria favoring projects that serve oversized/commercial trucks, and Illinois considered adopting MHD-specific requirements but has not done so due to site-feasibility and cost concerns (Powell, Johnson, Yip, & Snelling, 2024). Walkowicz, Meintz, and Farrell (2020), in R&D insights for extreme fast charging of MHD vehicles: insights from the NREL commercial vehicles and extreme fast charging research needs workshop, note challenges in permitting and interconnection processes that vary by jurisdiction and utility. They highlight cases from California and Hawaii, where streamlined permitting and interconnection task forces have reduced delays. Regional differences in billing requirements, regulations, and hosting capacity strongly influence feasibility.

Some provinces are developing their own standards. British Columbia’s CleanBC roadmap commits to new MHD vehicle standards, whereas Quebec’s Green Economy Plan outlines an MHD vehicle target. Both reference California’s Advanced Clean Truck (ACT) regulation as a model, which mandates increasing percentages of ZEV sales over time (Electrifying Canada, 2022).

In addition to federal standards, California has ZEV regulations. Under the Clean Air Act, California obtained a waiver to implement vehicle-emission standards that are stricter than federal standards. ZEV regulations encourage manufacturers to produce more electric vehicles by imposing monetary penalties for noncompliance (National Academies of Sciences, Engineering, and Medicine, 2020).

## 3.3 North Carolina Local Government EV Policies and Practices

While previous research has produced procedures and models for light-duty fleets in North Carolina, the state also has a substantial presence of MHD vehicles. Figure 6, from Advanced Energy (2023), shows an activity index indicating where MHD vehicles are concentrated.



Locations of Medium-Heavy Duty Vehicles

Light green - highest number of MHD vehicles based in zip code

- Charlotte: I-77 and I 85
- Statesville: I 77 and I 40
- Greensboro: I 40 and I 85
- Mt Airy: I-77 and I-74

*Figure 6: Location of MHD vehicles [Source: Advanced Energy, 2023].*

Areas shaded light green have the highest numbers of MHD vehicles. It is unsurprising that higher-population ZIP codes and cities connected by major highways record more MHD activity.

North Carolina has been actively engaged in fleet modernization at both the state and local levels. The North Carolina Department of Environmental Quality's Executive Order 271 proposes adopting the Advanced Clean Trucks (ACT) Program (U.S. Department of Energy). The program would require automakers to sell an increasing percentage of zero-emission trucks over time. The state also has goals for at least 30% of new MHD sales to be zero-emission by 2030 and 100% by 2050 (Cooper, 2022).

### 3.3.1 Costs

While producing a procedure for any fleet electrification, cost is a primary issue (National Academies of Sciences, Engineering, and Medicine, 2021). The report details specific challenges that arise when attempting to account for costs. Identifying all relevant costs is one of the more challenging requirements because there is minimal guidance on what should be included in calculations. Furthermore, costs vary over the lifespan of equipment, and different time periods carry different cost profiles. As with many vehicles, equipment used for electrification depreciates over time, with owning costs increasing due to wear. Figure 7, from the National Academies of Sciences, Engineering, and Medicine (2020), shows how costs change throughout the lifespan.

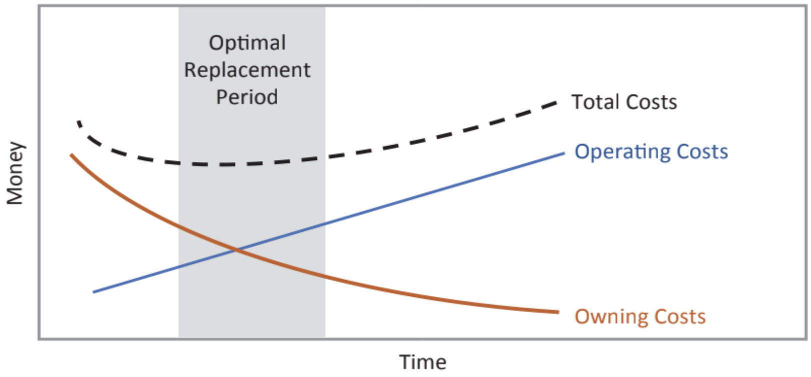


*Figure 7: Financial lifespan of vehicles [Source: National Academies of Sciences, Engineering, and Medicine, 2020].*

According to Walkowicz, Meintz, and Farrell (2020), high upfront capital costs, long payback times, and uncertainty in total operational costs are major barriers. Demand charges from utilities significantly affect station economics, especially at low utilization. Fleets emphasized the need for total TCO models that capture infrastructure, battery life, maintenance, and salvage values. Battery recycling currently adds a negative residual value of $4,000–$5,000 per vehicle.

Modernizing MHD Fleets highlights that while upfront investment in EVs is higher, MHD fleets often benefit from lower lifetime operational costs. The report notes that financing is emerging as a key tool, with turnkey electrification services bundling vehicles, charging infrastructure, and financing to mitigate upfront-cost challenges (Electrifying Canada, 2022).

According to Pacific Gas and Electric Company (2019), strategies such as shifting charging to off-peak periods or using on-site energy storage help lower maximum demand, reduce utility bills, and manage demand charges. Furthermore, utilities may provide credits to offset the cost of expanding service for EVSE.

### 3.3.2 Building & Site Design Requirements

FHWA encourages, but does not mandate, MHD design considerations, and states may add their own. Key site-design elements include pull-through charging stations, adequate canopy heights, and sufficient circulation space for larger vehicles. Only 0.6% of tracked U.S. stations are accessible by MDVs and 0.2% by HDVs, underscoring the need for better site planning (Powell, Johnson, Yip, & Snelling, 2024).

Site configuration and cable management are critical, since connector durability, cord length, and charge-port placement can create issues. Facilities must also account for “behind-the-fence” charging design, limited yard space, and power sharing with buildings. Real-estate availability, land use, and modular site-design approaches are emphasized, along with planning for scalable expansion and resilience (Walkowicz, Meintz, & Farrell, 2020).

Fleet depots may require building-level or substation-level upgrades to handle increased energy demand. Utilities and operators should plan depot infrastructure, charging stations, and energy-management systems in tandem. Turnkey solutions (e.g., Ontario Power Generation’s PowerON) cover infrastructure from grid connection to chargers, including on-site generation and storage (Electrifying Canada, 2022).

Pacific Gas and Electric Company (2019) emphasizes designing charging sites that balance functionality, compliance, and cost efficiency. For space utilization, layouts should support current fleet operations while leaving room for future expansion. Electrical design must address breaker sizing and continuous-load limits to meet code requirements. The guidance also notes charging-interface options: plug-in (most common, lower capital cost), overhead pantographs (used for transit fleets requiring higher power), and wireless charging (emerging, higher cost, alignment-sensitive). Infrastructure and construction needs include trenching, cable management, and reliable connectivity for networked chargers.

### 3.3.3 Power Supply Requirements

MHD vehicles consume roughly 2.4 kWh/mile—about 8× more than light-duty vehicles. Fleet depots may require several megawatts of power, often necessitating costly grid upgrades. The Megawatt Charging System (MCS; SAE J3271) will provide up to 3.75 MW per port. To mitigate peak demand and grid strain, smart charging and distributed energy resources, such as solar and battery storage, are emphasized (Powell, Johnson, Yip, & Snelling, 2024).

Extreme fast charging for MHD vehicles will likely need megawatt-scale power per port. Utilities often cap interconnections at ~2.5 MW per point due to transformer limits, requiring upgrades or dedicated feeders. Strategies discussed include behind-the-meter storage, distributed energy resources integration, and DC-as-a-Service. High-voltage DC (350-1,500 V) is emerging as the standard, though safety and interoperability remain concerns (Walkowicz, Meintz, & Farrell, 2020).

Utilities must proactively plan for increased fleet-charging demand, assess local substation capacity, and prepare for megawatt-scale highway charging for long-haul trucks. The integration of smart charging and load-management tools is also highlighted by Electrifying Canada (2022).

Pacific Gas and Electric Company (2019) focuses on matching fleet energy demand with grid and site capabilities. This includes developing load profiles and calculating daily and per-vehicle energy needs to size charging systems appropriately. Aligning charging speed with available dwell time can reduce peak demand and better fit charging windows. For utility connections, agencies can install dedicated meters, dual-meter setups, or submetering to track EV-specific energy use. On-site batteries or generation can supply backup power, shave demand peaks, and improve resilience.

### 3.3.4 Charging Practices

While gasoline vehicles need refueling every certain number of miles to remain in service, electric vehicles and fleets require charging to maintain use. Most vehicles do not have battery packs large enough to run continuously for days. However, larger electric vehicles, such as buses and vans, need larger batteries with longer storage capacities (Zhang, 2022). This requires longer charging times. Yet many buses are used for public transportation and require constant availability and movement. These two requirements, i.e., longer charging times and constant service, create logistical challenges.

Depot charging (overnight, AC Level 2 or DCFC) is expected to supply 75–97% of MHD charging needs by 2030-2035. Residential charging applies to ~11-20% of medium-duty vehicles and ~5-13% of heavy-duty vehicles parked at homes. En-route charging is mostly needed for long-haul tractors, whereas opportunity charging can occur during loading/unloading or at rest stops, and destination charging may supplement depot models for delivery fleets (Powell, Johnson, Yip, & Snelling, 2024).

Fleets use private depot charging to ensure reliability, while public truck-stop charging is critical for smaller fleets and long-haul trips. Operational practices include integrating charging into logistics systems, managing demand charges, and coordinating with driver hours and break times. Options explored include overnight low-power charging, opportunity charging, battery swapping, and potential bidirectional (vehicle-to-grid) services in specific use cases like school buses (Walkowicz, Meintz, & Farrell, 2020).

Electrifying Canada (2022) notes that charging constraints remain a barrier and that fleets rely mainly on depot charging, but some require public charging networks -- especially for long-distance routes. The report highlights uncertainty over responsibility for deploying public MHD vehicle charging and the importance of time-shifting tools such as smart charging to manage peak demand.

Pacific Gas and Electric Company (2019) provides the following best practices and strategies for day-to-day fleet charging:

- Charge during off-peak hours to minimize costs through deliberate scheduling.
- Use software and networked EVSE to balance charging across multiple vehicles and avoid demand spikes.
- Leverage utility programs that reward fleets for reducing load during high-demand periods.
- Employ cloud-based networking for real-time monitoring, reporting, and integration with grant or program requirements.
- Develop backup charging strategies for outages via storage (emergency management), redundant utility feeds, or planned temporary reductions in operational capacity.

## 3.4 Lessons Learned

- MHD vehicles are a major source of emissions and energy use. From 2020 to 2022, energy consumption rose 19%, and 92% of vehicles still run on diesel.
- Federal support for MHD electrification is expanding through programs like the Inflation Reduction Act, Advanced Technology Vehicles Manufacturing Loan Program, and CFI Grants. New EPA standards for 2027 impose stricter performance-based requirements, while the development of SAE J3271 Megawatt Charging System will enable high-capacity fleet charging.
- States and provinces are setting zero-emission goals that often exceed federal targets. The Multi-State ZEV Memorandum of Understanding commits to 100% zero-emission MHD vehicle sales by 2050, while California and Canadian provinces such as British Columbia and Quebec are implementing stricter standards modeled after California's ACT program.
- North Carolina is moving forward with Executive Order 271, which proposes adopting the Advanced Clean Trucks program. The state has set goals of 30% zero-emission MHD vehicle sales by 2030 and 100% by 2050, focusing infrastructure efforts on high-traffic urban and highway areas.
- High costs remain the biggest restriction to fleet electrification. Project costs are driven by high upfront investment, long payback periods, and negative residual values from battery recycling. Off-peak charging, on-site storage, and bundled financing solutions are being introduced to address these challenges.
- Current infrastructure and site design are insufficient for many MHD fleets, with only 0.6% of U.S. stations accessible to medium-duty vehicles and 0.2% to heavy-duty vehicles. MHD fleets require more robust infrastructure than smaller fleets, including wider charging lanes, increased canopy heights, durable cables, and major electrical upgrades.
- Depot charging is the most common practice and is expected to meet up to 97% of fleet needs by 2035. Other approaches, e.g., en-route and opportunity charging, support long-haul and delivery fleets.

- Electrifying MHD fleets is a growing priority supported by strong policy momentum; progress depends on overcoming barriers related to cost, infrastructure, and operational constraints.

Table 2 maps topic areas across the literature and state-of-practice sources; it presents the findings that follow in the next chapter.

*Table 2. Evidence map linking literature categories to contributors.*

| **Categories** **Contributors** | Becker, et al. (2019) | Blynn, K., Attanucci, J. (2019) | Bragin, et al. (2024) | Burke, et al. (2023) | Foda, et al. (2023) | Gairola, P., Nezamuddin, N. (2023) | Guerrero de la Pena, et al. (2019) | He, et al. (2025) | Hurtado-Beltran, et al. (2021) | Muller, C. (2025) | Samet, et al. (2024) | Sen, et al. (2019) | Speth, et al. (2025) | Sunio, et al. (2019) | Wurtz, et al. (2023) | Zhao, et al. (2025) | Aamodt, et al. (2021) | Bruchon, et al. (2024) | Cooper, R. (2022) | Powell, et al. (2024) | Zhang, Y. (2022) | Walkowicz, et al. (2020) | Electrification Coalition. (2024) | Electrifying Canada. (2022) | Environmental Protection Agency. (2024) | Georgetown Climate Center. (2012) | National Academies of Sciences, Engineering, and Medicine. (2019) | National Academies of Sciences, Engineering, and Medicine. (2020) | National Academies of Sciences, Engineering, and Medicine. (2021) | Pacific Gas and Electric Company. (2019) | The Joint Office of Energy and Transportation. (n.d.) | U.S Department of Energy, U.S Environmental Protection Agency. (2024) | U.S Department of Energy. (n.d.) | ZEV Task Force. (2022) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Modeling & Simulation | | | | | X | x | | | | | | | | | | | | | | | X | | | | | | X | | | | | | | |
| Economic and Total Cost of Ownership Analysis | X | X | X | X | X | X | X | X | | X | X | | | | | X | X | | | | | | | | | | | X | | | | | | |
| Charge Scheduling | X | | X | | X | X | | | | | X | | | | | | X | X | | | | | | | | | | | | | | | | |
| Power Distribution Network Analysis | X | | | | | | | | | | | | | | | | | | | X | | | | | | | | | | X | | | | |
| Bus Electrification | X | X | | X | X | X | | X | | | | | | | X | | X | | | | X | | | | | | | | X | | | | | |
| Battery Electric Vehicles | X | X | | | X | X | | X | | X | X | | X | | | | X | | | | | | | X | | | | | | | | | | |
| Public Transportation | | X | | X | X | X | | | | | | | | X | X | | X | | | | | | | | | | | | | | | | | |
| Sustainability | | X | | | X | X | X | X | | X | | X | | X | | | | | X | | | | | X | X | | X | | | | | X | | X |
| Big Data Analytics & Machine Learning | | | | | | | | | | | | | | | X | X | | X | | | | | | | | | | | | | | | | |
| Fleet Electrifications | X | X | X | X | X | X | X | X | | | | | | | | X | | | | | | | | X | | | | | X | X | | | | |
| Optimization Methodologies | X | | X | X | X | X | X | | X | | | X | X | | X | | | | | | X | | | | | | | | | | | | | |
| Electric Trucks | | | X | | | | | | X | | | | X | | | X | | | | | | | | | | | | | | | | | | |
| Alternative Fuel | | | | | | | | | | X | | | | | | | | | | | | | | X | | | | | | | | | | |
| Zero Emission Truck | | | | | | | X | | | X | | | | | | | | | | | | | | | X | | X | | X | | | X | | X |
| Network Deisgn | | | | | | | | | X | | | | | X | | | | | | X | | | | | | X | | | | | | | | |
| Heavy-Duty Vehicles | | | X | | | | X | | X | X | X | X | X | | | X | | X | | X | | X | | X | X | | | | | | | X | | X |
| Technology Adoption | | | | | | | X | | | X | X | | | | | | | | X | | | | | | | | | | | | | X | | |
| Medium-Duty Vehicles | | | | | | | | | | | X | | | | | | | X | | X | | X | | X | | | | | | | | | | X |
| Mixed-Integer Programming | X | | X | X | | | | | | | | | X | | | | | | | | X | | | X | | | | | | | | | | |
| Hybrid Fleets | | X | | | | | X | | | X | | X | | X | | | | | | | | | | | | | | | | | | | | |
| Policy, Regulation, and Strategy | | X | | | | | X | X | | X | | | | X | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X | X |
| Charging Infrastructure | | | X | | X | X | X | | X | X | | | X | | | X | | | | X | X | | | | | X | | | X | X | | | | X |
| Charging Technology & Strategy | X | | X | | X | X | | | | | | | X | | | X | X | X | | X | | X | | | | | | | | | | | | |
| Fleet Operations & Routing | X | | X | X | X | X | | | | | | | | X | X | | | | | | | | | | | | | | | | | | | |
| Grid Impact & Stability | X | | X | | X | | | | | | | | | | | | | | | | | X | | | | | | | | X | | | | |
| Battery Technology | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | X | | |
| Battery Degradation & Lifespan | X | | | | | X | | | | | X | | | | | X | | | | | | X | | | | | | | | | | | | |
| Hydrogen & Fuel Cell Vehicles | | | | | | | | | | X | | | | | | | | | | | | | | X | | | | | | | | X | | |
| Lifecycle Assesment | | | | | | | | | | X | X | X | | | | | | | | | | | | | | | X | X | X | | | | | |
| Implementation & Case Studies | X | X | X | X | X | X | X | X | | | | | X | X | | | X | | | | | | | X | | | | | X | | | | | |
| Infrasture Cost and Financing | | | | | | | | | | X | | | | | | | X | | | | | | X | | | | | | | X | X | | X | X |
| Transition Planning & Pathways | | | | | | | X | | | X | | | | | | | X | | | | X | X | X | X | X | X | X | X | X | X | X | X | X | X |

# Chapter 4. Findings and Conclusions

This project synthesized evidence from both the literature review and the state-of-practice review to isolate what most strongly affects costs, operations, and infrastructure when modernizing MHD fleets. The evidence map that combines both reviews shows dense coverage in total cost of ownership analyses, bus electrification case studies, battery-electric technology, charge-scheduling methods, and optimization/modeling tools. It also surfaces thinner treatment in MHD-specific site design standards, power-distribution and interconnection practices at depots, and performance specifications that tie procurement to delivered energy and uptime. Taken together, the clearest finding is that early, site-specific decisions -- not vehicle procurement -- drive most schedule risk and cost variance. Power availability at depots, make-ready scope, interconnection timelines, and yard circulation determine whether programs proceed on time and within budget. Vehicle pricing is comparatively predictable; trenching, civil work, switchgear, and utility upgrades are not, and they remain uncertain until each site is thoroughly scoped.

Operational feasibility across sources depends on aligning real duty cycles with effective, not nominal, charging performance. Rated power is an imperfect indicator of delivered energy per charger per day; cable reach, stall layout, power sharing, thermal behavior, and software limits govern actual plug-to-depart times. Programs that validated schedules against dwell windows and measured throughput avoided schedule creep and spare-factor inflation seen when plans relied on ratings alone. Consistently, a depot-first sequence is the most reliable: back-to-base blocks can be served with predictable charging windows, while en-route assets are added only when they demonstrably increase vehicle utilization or reduce required spares. The matrix of sources also confirms that mixed-fleet strategies and opportunity charging can be cost-effective in early phases, while long-haul use cases are where fuel-cell options appear most operationally advantageous.

This project’s evidence shows that modernization succeeds when agencies combine clear operational assumptions with purpose-built planning and simulation tools. Early, site-specific decisions (e.g., available depot power, make-ready scope, interconnection timelines, and yard circulation) still drive most schedule risk and cost variance, not vehicle procurement. Rated charger power alone does not capture actual throughput; effective “plug-to-depart” times depend on stall layout, power-sharing logic, and charging windows within real schedules. A depot-first sequence remains the most reliable path, with en-route assets added only where they demonstrably raise utilization or lower required spares.

The state of practice shows that standardized inputs shorten timelines and reduce change orders. Agencies using a concise load summary or projected demand letter, a single-line electrical diagram, and a phased load profile received faster, clearer utility responses. Where hosting capacity was constrained, staged commissioning -- initial caps on site power paired with later upgrades -- combined with smart charging and, in some cases, on-site storage, allowed projects to begin operations without overruns. Site design choices specific to larger vehicles (e.g., pull-through geometry, canopy height, turning radii, cable management, safe pedestrian flows) proved crucial for throughput and labor efficiency, yet are unevenly addressed in current codes and guidance, a gap reflected in the evidence map.

The synthesis also points to a concrete next step: establish short- and long-term planning frameworks that use modeling to evaluate strategic and tactical scenarios for alternative-fuel infrastructure. In the near term, the framework should optimize current operations for public MHD fleets (such as school buses, refuse trucks, transit vehicles, and municipal fleets) by identifying immediate depot needs, sizing refueling/charging systems to match duty cycles, and managing site energy demand across diverse regions. Over the longer horizon, the same framework should test expansion scenarios that reflect increasing adoption, evolving route plans, and potential advances in storage, charging, and distribution technologies. Scenario results should indicate where to phase depot upgrades, when to introduce targeted en-route capability, and how to maintain service levels while controlling costs.

An optimization-based approach is well-suited to these questions. Models can represent depot constraints, route and block structures under energy limits, refueling requirements, and placement of depots relative to rest areas, parking, and logistics hubs. They can also compare tariff options and managed-charging strategies, quantify the impact of staged interconnection caps, and reveal the spare-factor and labor implications of alternative site layouts. By structuring sensitivity tests around grades and schedule padding, the framework separates items that merit contingency from those that do not, yielding plans that are both practical and defensible.

Since public agencies operate on defined schedules and service commitments, focusing the framework on these fleets will produce immediately actionable guidance for planning, deployment, and resource allocation. Coordination with ongoing departmental programs and prior analytic efforts will keep assumptions consistent and streamline implementation. To make the methodology usable, the project should deliver a tool that encapsulates the planning and simulation logic, allowing staff to screen sites, compare phasing options, and generate inputs for procurement and utility engagement.

In conclusion, the conclusions point toward disciplined planning supported by modeling: start at the depot, size and phase infrastructure against real operating patterns, and use scenario analysis to decide where and when to add capability. This approach provides a clearer path to predictable budgets, reliable service, and scalable infrastructure.

# Chapter 5. Recommendations

The following recommendations synthesize findings from the literature review and the state-of-practice review, with a focus on cost, operations, and infrastructure.

## 5.1 Evidence-Based Recommendations

The electrification of MHD vehicles is technologically viable and increasingly cost-competitive, with battery-electric and fuel-cell options emerging as the primary pathways. Due to lower fuel and maintenance costs, BETs and buses have been successfully implemented in urban areas and on short-haul routes, albeit gradually. As battery prices decline and energy density improves, BETs will become more attractive to cities seeking to electrify MHD fleets. Battery-electric MHDs should be prioritized for expansion in city freight operations and public transit systems. Newer programs (such as vehicle-to-grid and vehicle-to-building applications) should be explored further to support future electrification. However, for long-haul and heavy-duty operations, fuel-cell electric trucks are advantageous due to faster refueling, lighter energy storage, and better cold-weather performance. Investments in hydrogen refueling corridors and industry partnerships will be critical to position fuel cells as a complement to batteries for long-distance freight, despite higher costs.

Infrastructure expansion is one of the most important issues, requiring careful planning and significant investment. Capacity-constrained flow-refueling location models and GIS-based optimization frameworks show that charging networks can be designed around freight flows, grid access, and parking capacity to maximize coverage while minimizing costs. Governments and agencies should work in tandem to locate charger depots and truck stops where demand is highest, typically along major freight corridors and near logistics hubs.

A phased transition strategy is recommended. These strategies should combine battery, fuel-cell, and hybrid vehicles, since relying only on depot charging has proven difficult without diesel backup. Opportunity charging and mixed-fleet operations allow operators to maintain service reliability while preparing for a fully electric future. Upfront costs (i.e., vehicle purchases and infrastructure) remain a significant challenge across technologies. To address this barrier, grants, low-interest loans, and subsidies from governments and agencies should be expanded.

Modernization strategies that bundle vehicles, chargers, and maintenance services can reduce uncertainty for operators. To manage demand charges and improve long-term economics, incentives that reward fleets integrating distributed energy resources and smart-charging technologies should be utilized. Government and agency policies should reflect real-world operational and cost realities. Research on MHD fleet modernization and school-bus electrification shows the need for stronger subsidies as costs rise, as well as for charging during idle periods (e.g., when school buses are waiting at the school) to reduce energy expenses. Connecting stakeholders and initial projects with planners and operators will help ensure that policies reflect operational needs and gain broad acceptance.

Research and simulations show that energy use and charging demand can be forecast with higher accuracy when real-world factors (e.g., traffic flows, logistics-hub activity, and charging-station constraints) are incorporated. Governments and agencies should encourage adoption of these methods at both fleet and regional-planning levels to ensure that charging networks are resilient, cost-effective, and scalable.

In summary, a dual-technology approach is feasible for MHD electrification: battery-electric vehicles for urban and regional freight, and fuel cells for long-haul operations. Governments and industry can accelerate adoption by expanding financing, planning infrastructure precisely, enacting phased-adoption strategies, and establishing standardized policy frameworks.

## 5.2 Practice-Based Recommendations

The modernization of MHD vehicles is important for supporting economic development along with reducing emissions and improving public health. However, constraints in the process include cost, infrastructure, and operational logistics. Governments and agencies can play a major role in reducing the impact of these barriers through expanded funding opportunities, development of standards, and coordinated infrastructure planning. Reducing upfront investment costs through federal and state financial support will allow more progress in the electrification process.

Highlighting the importance of standards assists the overall development of electrifying MHD fleets, as they create guidelines for all to follow. Design requirements such as pull-through lanes, canopy height, and connector durability should be standardized across jurisdictions to ease planning and lower costs. To reduce the risk of overwhelming power grids, collaboration with utilities will be important. With government support, grid modernization will further enable the efforts.

Cost-reducing strategies should be advanced to make modernization a realistic option for MHD fleets. Regional and local governments should play a proactive role by adopting clean-truck regulations and integrating electrification into transportation planning. States such as North Carolina and California have demonstrated how proactive local action can drive progress by setting aggressive targets and providing clear regulatory direction.

Transportation agencies and governments can encourage progress in charging practices by supporting en-route charging, battery swapping, and vehicle-to-grid services. Establishing roles for public charging infrastructure will ensure equitable access and accelerate adoption across all fleet sizes. Actions such as expanding funding, initiating standards, modernizing the grid, and mitigating costs will allow governments and agencies to combat barriers and enable a maintainable transition in the MHD vehicle sector.

# Chapter 6. Implementation and Technology Transfer Plan

Given the focused scope of this project, i.e., synthesizing the literature review and the state-of-practice review, the technology transfer approach is intentionally lean and centered on the report itself. The goal is to make the synthesis easy to reference in day-to-day decisions without creating new programs, trainings, or companion toolkits. Implementation therefore, relies on clear organization, explicit cross-walks, and concise language that can be cited directly in planning memos, scoping notes, and internal reviews.

Chapter summaries, the combined evidence map table, and the consolidated "Findings and Conclusions" chapter are written to stand alone and be quoted verbatim in scoping documents and decision briefs. The evidence map links topic areas (e.g., cost and TCO analyses, bus electrification cases, charge scheduling, optimization methods, site and interconnection practices) to key sources, allowing staff to trace each recommendation to its references quickly.

In practice, agencies and partners can use this synthesis in three common moments without additional materials. First, at project initiation, the report provides the rationale for sequencing work "depot-first," emphasizing site readiness, make-ready scope, and interconnection timelines as the primary drivers of budget and schedule risk. Second, during concept and preliminary design, the discussion of effective, not nominal, charging performance supports right-sizing decisions about stall layout, power sharing, and "plug-to-depart" expectations. Third, as projects approach procurement and commissioning, the report's conclusions on site design for larger vehicles, staged upgrades where hosting capacity is tight, and acceptance steps help align expectations across teams.

The synthesis is written to slot into current scoping, concept design, and utility-coordination steps rather than to introduce new ones. For example, the discussion of concise utility submittals (i.e., load summary/projection and one-line diagram) is framed as support for the materials agencies already prepare, not as a new template to develop. Likewise, the conclusions on phasing (i.e., reliable depot operations first, targeted en-route capability only when justified) are structured to inform existing programming decisions and not to prescribe new procedures.

Looking ahead, the report also identifies logical next steps that could be pursued in a subsequent phase if desired, such as short- and long-term planning frameworks to test depot expansions, interconnection caps, and route changes. Those items are intentionally presented as future opportunities rather than as current commitments. For this project, technology transfer is achieved by making the synthesis itself easy to cite, easy to navigate, and directly usable within existing workflows, so agencies can apply the conclusions immediately while retaining the option to deepen the work in later phases.

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