A REPORT ON ACTIONS FOR MEDIUM- AND HEAVY-DUTY VEHICLE ENERGY AND EMISSIONS INNOVATION

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ABOUT THIS DOCUMENT

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TABLE OF CONTENTS

1. EXECUTIVE SUMMARY 1

1.1 Intent and Purpose 1

1.2 A Call to Action 1

1.3 Sector Today 3

1.4 Strategy to Reduce Emissions in the MHDV On-Road Sector for the Future 4

1.5 Energy Infrastructure Strategy 7

1.6 Increasing Efficient Freight Transportation 8

1.7 Job Creation and Workforce Development 8

1.8 Action Plan Moving Forward 10

1.9 Following Through with Action 11

2. INTRODUCTION AND CONTEXT 12

2.1 Commitment and Vision 12

2.2 The Role of MHDVs in the U.S. Transportation System 13

2.3 The Blueprint for Reducing MHDVs Emissions 15

2.4 Report Objectives And Organization 16

3. MHDV EMISSIONS ACCOUNTING 18

3.1 Sector and Emissions Accounting 18

3.1.1 Estimated GHG Emissions and Market Segmentation 19

3.1.2 Minimizing GHGs While Managing Criteria Pollutants 22

3.1.3 Methods and Limitations 24

4. MHDV DECARBONIZATION STRATEGY 26

4.1 Strategy Overview 26

4.2 Clean Fuels, Emerging Technologies, and Infrastructure 27

4.2.1 Technologies and Fuels 27

4.2.2 Current Market Status and Objectives 30

4.2.3 ZE-MHDV Technology Strategy 33

4.2.4 Energy Infrastructure and Corridors 49

4.2.5 Legacy Vehicles and Sustainable Liquid Fuels 75

4.3 Convenience and Efficiency 76
4.3.1 Strategies to Improve MHDV Convenience 76
4.3.2 Strategies to Improve MHDV Efficiency 78
5. CROSS-CUTTING STRATEGIES TO SUPPORT TRANSPORTATION DECARBONIZATION 83
5.1 Building Good Jobs and a Stronger MHDV Economy 83
5.2 Supply Chain and Manufacturing 84
5.3 Workforce Development and Transition 85
5.4 Community Impacts 87
5.5 Safety and Standards 90
5.6 International Coordination 94
6. NEXT STEPS – GETTING TO 2030 95
6.1 Core Strategic Plans and Milestones 95
6.2 Federal Actions Now Through 2030 97
6.3 Funding and Financing For Deployment 100
6.4 Policy and Regulatory Opportunities and Gaps 102
6.5 Research, Analysis, and Data Needs 103
6.6 Indicators of Progress 107
7. CONCLUSION 110
A Holistic, Comprehensive Approach 110
An Action Plan for Medium- and Heavy-Duty Vehicle Energy and Emissions Innovation 112
Call to Action 113
ACRONYM LIST 114
APPENDIX A: VEHICLE TYPES AND VOCATIONS 116
APPENDIX B: BIOFUELS' ROLE IN DECARBONIZING THE TRANSPORTATION SECTOR 118
APPENDIX C: MORE DETAIL ON SELECTED DECARBONIZATION ACTIONS 125
APPENDIX D: MARKET SEGMENTATION AND EMISSIONS ACCOUNTING 126
ACKNOWLEDGMENTS 129
REFERENCES 130

1. EXECUTIVE SUMMARY

1.1 Intent and Purpose

A Report on Actions for Medium – and Heavy-Duty Vehicle Energy and Emissions Innovation (the MHDV Plan) summarizes strategies and actions to substantially reduce emissions in the U.S. commercial on-road medium- and heavy-duty vehicle (MHDV) sector. This includes all on-road vehicles over 8,500 pounds used for commercial purposes. The intended audience of this report are industry and stakeholders who will take on the suite of actions needed to drive forward MHDV emissions reduction and decarbonization in a sustainable and economic way.

The transportation sector is now the largest source of GHG emissions in the United States and a contributor of harmful air pollutants that are negatively impacting the quality of life in cities, towns, and rural communities throughout America. In the United States, these effects disproportionately impact low-income communities. To address these challenges, we aim to dramatically reduce GHG and criteria emissions from each part of the transportation sector and implement a holistic strategy to achieve a future mobility system that is clean, safe, and accessible, and provides sustainable transportation options for all people and goods.

In 2023, the United States Department of Energy (DOE), the United States Department of Transportation (DOT), the United States Environmental Protection Agency (EPA), and the United States Department of Housing and Urban Development (HUD) released the U.S. National Blueprint for Transportation Decarbonization (Blueprint). The Blueprint provides the roadmap for how we can address these issues to provide better transportation options, expand affordable and accessible options to improve efficiency, and transition to zero-emission vehicles (ZEVs) and fuels.[a] This plan is built on five principles emphasized in the Blueprint that galvanize thought leadership to address transportation emissions:

1) Initiate bold action
2) Embrace creative solutions across the entire transportation system
3) Ensure safety, community benefits, and access
4) Increase collaboration
5) Establish U.S. global leadership.

The MHDV Plan is one of several action plans that cover each part of the transportation sector and build on the foundation presented in the Blueprint. Separately, individual sector action plans are also being developed to address rail, maritime, light-duty vehicles, and off-road vehicles. The Aviation Climate Action Plan was previously released, and action plans have also been developed to address the Blueprint's convenience and efficiency strategies.

1.2 A Call to Action

MHDVs contribute 21% of U.S. transportation GHG emissions, the second-highest transportation mode, despite making up a small proportion of vehicles on the road.[1] The vast majority of MHDVs today are fueled by diesel, which, in addition to emitting GHGs, contributes to poor air quality and associated negative health impacts, especially for communities located near truck routes and freight hubs. Communities near heavy truck traffic, and thereby pollution, are disproportionately burdened.[2] As such, decarbonizing the MHDV sector while minimizing criteria air pollutant (CAP)

[a] Zero-emission vehicles (ZEVs) is the term commonly used to refer to vehicles with zero tailpipe emissions. All analysis and support for the ***U.S. National Blueprint for Transportation Decarbonization*** (Blueprint) and this plan consider the full life cycle analysis (LCA) emissions, including, for example, the production of the energy to make electricity, hydrogen, or diesel. Other economic trends and technologies outside of the scope of this plan are leading to a substantial reduction in the emissions of other sectors, such as the electric sector.

emissions is a community concern. The strategies outlined in this plan address both GHG and criteria emissions that impact air quality.

Momentum is growing for MHDV decarbonization spurred by lower-cost innovations in technology. As of 2023, there have been nearly 35,000 zero-emission MHDV (ZE-MHDV) trucks and buses deployed, with more planned through future fleet and manufacturer commitments.[3, 4, 5] While growth has been rapid, today's deployments represent less than 1% of total MHDVs on the road today, necessitating continued innovation and substantial scale-up of vehicle deployments, clean fuels, and infrastructure.

This plan will support **implementation of the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles** (the "Global MOU") and, by 2030, support **30% of new commercial MHDV sales** as net zero tailpipe emission and work towards **100% sales by 2040** through public-private investments, research and demonstration, and vehicle and infrastructure incentives. The actions in this plan will advance commercialization for zero-emission solutions by 2030:

- Achieve competitive ZE-MHDV total cost of ownership
- Develop and demonstrate advanced ZEV technologies for long-haul and specialized vehicles
- Invest in manufacturing scale-up and workforce development for commercial ZE-MHDVs
- Invest in the deployment of ZE-MHDV charging and refueling infrastructure.

This plan lays out the path to achieve **cost parity by 2030 between new zero-emission long-haul heavy-duty trucks and existing internal combustion engine (ICE) long-haul trucks**, the largest source of GHG emissions in the sector. This will require extensive development of both battery-electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) coupled with investments in energy infrastructure at depots and regional hubs. Through DOE's SuperTruck Initiative and the 21st Century Truck Partnership, government and industry will collaborate to achieve these targets.

To achieve this transition to ZEVs, deploying charging/refueling infrastructure will be critical. This plan calls for the **implementation of the National Zero-Emission Freight Corridor Strategy (the "Corridor Strategy"),** which lays out an all-of-government approach to aligning investments and accelerating sustainable and scalable deployment of reliable ZE-MHDV infrastructure. Achieving this build-out will require close cooperation and coordination with industry, fleets, utilities, government, and community groups. This collaboration will inform ongoing improvements and implementation of infrastructure deployment through collaborative planning and public-private investments to realize **36%** completion of the National Highway Freight Network **by 2030** and close to **100%** by **2040**.

In 2024, the **United States announced a national goal for a zero-emission freight sector and announced the availability of $1.5 billion to transition MHDVs to ZE-MHDVs**. Also in 2024, EPA established multi-pollutant (GHG and air pollutant) emissions standards for light- and medium-duty vehicles (including Class 2b and 3 MHDVs) and, separately, GHG standards for heavy-duty (Class 4 and above[b]) on-road vehicles for model years 2027 through 2032. In addition, the National Highway Traffic Safety Administration recently announced the Heavy-Duty Pickup Trucks and Vans Fuel Efficiency Standards, covering Class 2B/3 trucks and vans for MYs 2030 to 2035. The MHDV Plan, developed with industry input, lays out the actions needed to help support realization of these important federal actions.

[b] This plan defines "Heavy-Duty" as Classes 7 and 8.

State-level rulemaking has set additional targets. California's Advanced Clean Fleets regulation requires a full transition to ZEVs between 2035 and 2042 for covered fleets, while California's Advanced Clean Trucks regulation specifies an increasing share of ZEV sales for MHDV trucks between MYs 2024 and 2035. The Advanced Clean Trucks rule has been proposed or adopted by 10 states as of July 2024. To achieve state and federal goals and bridge the gap between present-day deployments and future targets, bold and decisive actions are needed to address barriers, reduce market uncertainty, and signal a firm federal commitment to ZEV adoption.

1.3 Sector Today

The market for MHDVs is diverse. MHDVs play a central role in the U.S. freight system, providing local, regional, and long-haul freight transportation services. They are also used to move people short and long distances in school buses, shuttles, transit buses, and intercity buses. Finally, MHDVs are used in a wide range of commercial and municipal vocational applications that may involve specialized auxiliary equipment, such as utility trucks, refuse trucks, and street sweepers. This final category of vehicles is referred to as "specialized vehicles and work trucks" in this document.

U.S. On-Road Commercial MHDVs (Class 2B-8)

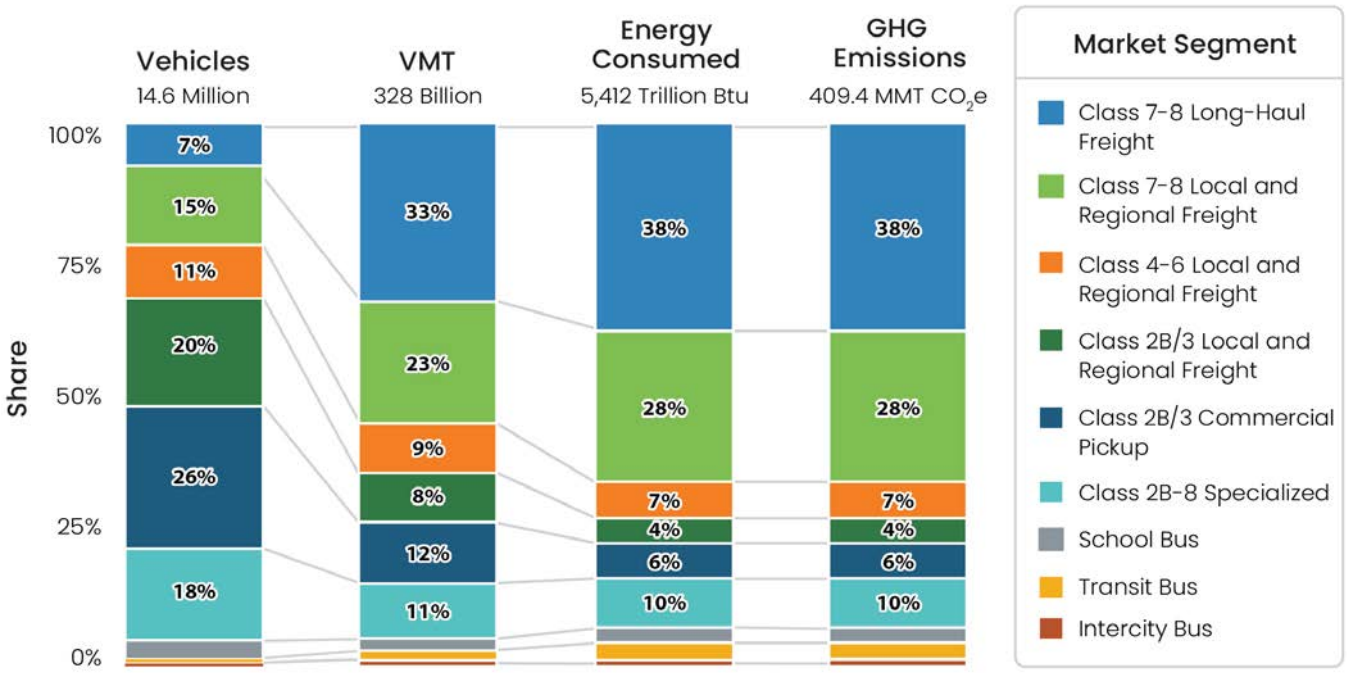


Figure ES-1. MHDV market segmentation by vehicle class—vehicles, vehicle-miles traveled (VMT), energy consumption, and GHG emissions. A small fraction of heavy-duty vehicles accounts for the majority of GHG emissions. Sources: National Renewable Energy Laboratory analysis using the Transportation Energy and Mobility Pathway Options (TEMPO) model based on data from the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI),[6] the Vehicle Inventory and Use Survey,[7] the National Transit Database,[8] the 2023 School Bus Fleet Fact Book,[9] and the American Bus Association.[10]

Figure ES-1 shows an overview of MHDV market segments in the United States and their relative contributions to vehicle population, activity (vehicle-miles traveled [VMT]), energy consumption, and GHG emissions. MHDV market segments were defined based on vehicle body type, type of operations (i.e., passenger, freight, or other commercial activities), and operational patterns, based on data from the 2021 Vehicle Inventory and Use Survey and other sources.

This plan breaks the segment into three subsegments with different strategies for decarbonization and timeframes for each. They include:

1) **Local and regional return-to-base, including local and regional freight trucks, school buses, and transit buses.** These market segments are characterized by relatively low mileage, daily returns to a home base, and relatively predictable routes. Local and regional return-to-base applications account for 49% of vehicles and 45% of energy consumption and GHG emissions (the majority of GHG emissions from Class 7–8 freight vehicles). These market segments offer early opportunities for transitions to ZEVs, particularly for BEVs in lighter vehicle classes driving shorter distances.

2) **Specialized vehicles and work trucks, including commercial pickups and specialized vehicles** serving vocations such as refuse transportation, snow removal, street sweeping, towing and hauling, equipment transportation, providing power to work sites, and powering auxiliary equipment. These market segments account for a high fraction of total vehicles and a relatively lower share of activity, energy, and GHG emissions. While a small number of ZEVs have been deployed to date (primarily refuse trucks), operational data collection and prototype development could be used to develop additional ZEV options for these segments.

3) **Long-haul**, including **Class 7–8 long-haul freight trucks** and **intercity buses**. These market segments are characterized by high mileage, few returns to central locations, and longer and more variable routes. Only 7% of vehicles are used for long-haul[c] operations, but their heavy weight and intensive utilization lead to disproportionate impacts: 39% of energy consumption and GHG emissions. Intercity buses are a smaller share of vehicles, VMT, and GHG emissions. Decarbonizing long-haul freight will offer the greatest returns in terms of reducing overall MHDV emissions, but further demonstrations of technology viability and supporting infrastructure are needed.

1.4 Strategy to Reduce Emissions in the MHDV On-Road Sector for the Future

TECHNOLOGY STRATEGY

The MHDV Plan focuses on two primary technology pathways to reduce emissions from MHDVs, as well as additional transitional pathways. The primary pathways are BEVs and fuel cell electric vehicles (FCEVs). **BEVs** are ZEVs powered solely by electricity stored in an on-board battery. **FCEVs** are ZEVs that are powered by hydrogen and use fuel cells to convert hydrogen into electricity to power the vehicle. Both technologies have zero GHG or air pollutant emissions at the tailpipe. Coupled with an increasingly carbon-free upstream fuel supply, ZEVs offer a pathway to reduce emissions and greatly reduce local air pollution, addressing climate and public health goals.

Transitional pathways, such as sustainable liquid fuels—including biodiesel and renewable diesel—will play a role in reducing carbon emissions as the transition to ZEVs occurs. Other transitional technologies—including hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and

[c] Long-haul freight (which includes Class 7–8 combination trucks used for long-distance freight operations) is the single greatest contributor to emissions.

hydrogen internal combustion engines (H2ICE)—may also play a role in near-term transitions as ZEV technologies continue to develop.

Converting to sustainable solutions presents different tradeoffs and opportunities for BEVs and FCEVs across MHDV market segments and will require different vehicle and infrastructure solutions and investments. Figure ES-2 shows technology innovation pathways to transition to ZE-MHDVs across all MHDV market segments. BEVs will be the predominant technology option in low-mileage, **local return-to-base** applications, which are well suited to today's BEV capabilities. **Regional return-to-base** applications may require a mix of BEVs and FCEVs, with high-mileage applications and routes with shorter periods of inactivity favoring FCEVs. Applications such as drayage trucks—freight trucks operating out of ports—are priorities for these market segments. The MHDV Plan and the Corridor Strategy prioritize near-term deployment of ZEVs and charging/refueling infrastructure in critical freight hubs. **Specialized vehicles and work trucks** may use BEVs or FCEVs; as few models currently exist, near-term priorities include data collection to fully understand consumer needs and expectations, developing prototype vehicles, and demonstrating feasibility of ZEV powertrains.

Reducing emissions in the **long-haul** market segment will have the greatest impact on MHDV emissions. However, for this segment, ZEV technology and infrastructure solutions are still evolving, with substantial cost reductions anticipated. In the near term, further demonstrations and infrastructure deployment along corridors are needed to build confidence (including the ability to meet durability, range, recharging/refueling speed, and weight requirements) and spur investments. Given the uncertainties at this stage of market development, the MHDV Plan assumes that both BEVs and FCEVs may be deployed to support this segment, as both technologies offer benefits along with limitations. Sustainable liquid fuels may also support reducing emissions during the transition to ZEVs and might play a role in perpetuity for particularly challenging routes.

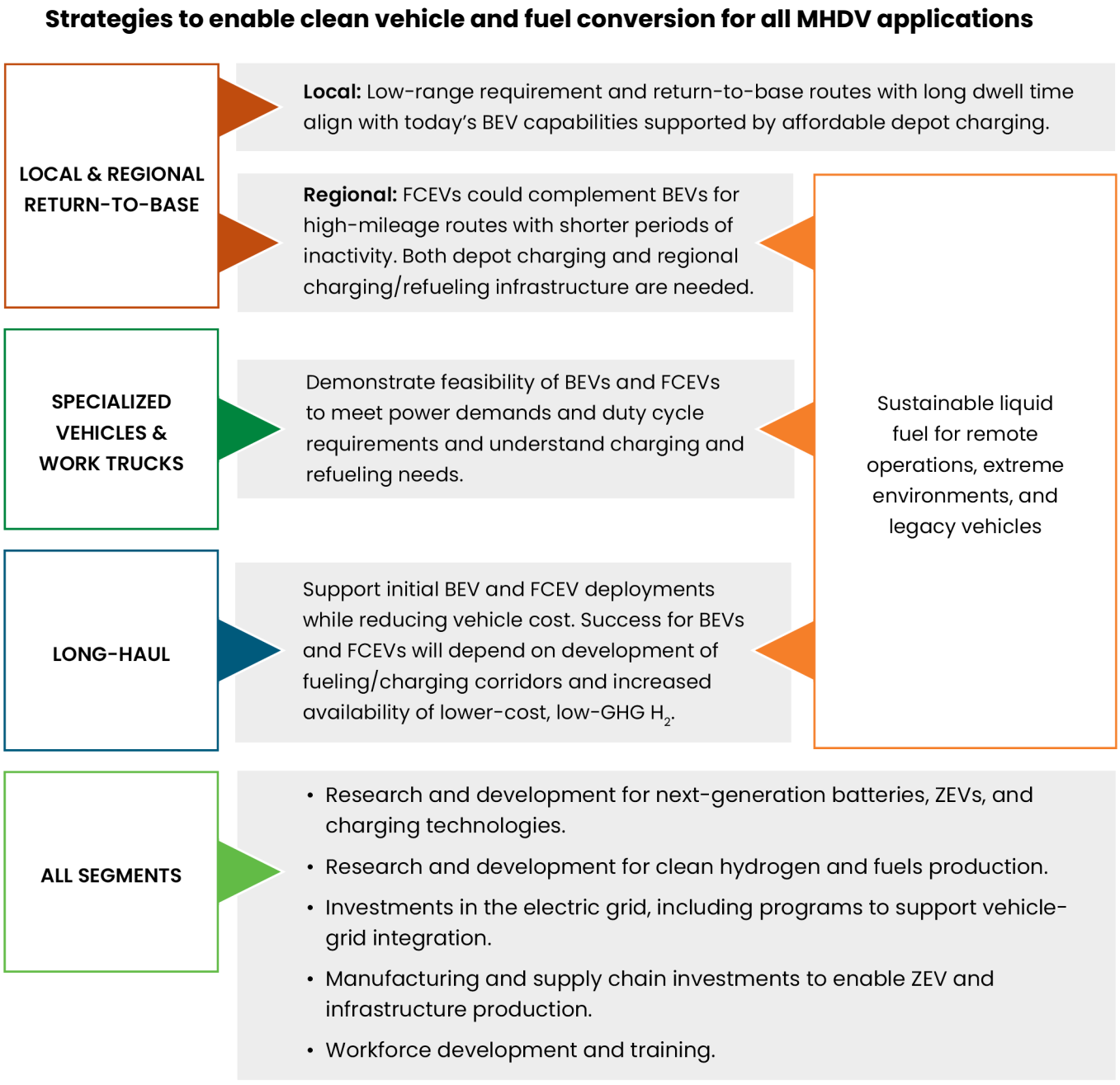


Figure ES-2. Strategies to enable clean vehicle and fuel conversion for all MHDV applications.

Key near-term strategies to enable ZEV technology transitions across all market segments include the following:

- **Support up-front cost reductions of ZEVs and total-cost-of-ownership competitiveness with internal combustion engine vehicles (ICEVs)** by leveraging existing incentive programs to support early ZEV adopters, implementing existing programs to scale manufacturing and supply chains, and supporting research on low-cost vehicle components and manufacturing processes. Funding programs and tax credits established by the 2021 Bipartisan Infrastructure Law (BIL) and the 2022 Inflation Reduction Act (IRA) provide historic levels of funding to pursue these aims.
- **Support innovative research, development, demonstration, and deployment** of ZEVs and component technologies to enable lowered costs, improved performance, and expanded ZEV model offerings in market segments such as specialized vehicles and work trucks and long-haul passenger and freight. DOE's SuperTruck 3 Initiative is one key example of a public-private partnership to achieve these aims.
- **Expand data collection efforts on ZEV operations** to enable prototype development and energy demand forecasting, particularly for market segments where data is sparse, such as specialized vehicles and work trucks. Partnerships between private actors and national laboratories can enable expanded analysis and data collection.
- **Key enablers** include continued **safety and standards development and education and workforce development** to ensure the development of robust manufacturing and maintenance workforces for ZEVs and infrastructure.
- Learning from deployment of freight vehicles, electric school buses, transit buses, and charging/refueling infrastructure in coordination with fleets and other stakeholders can be helpful to streamline future medium- and heavy-duty (MHD) vehicle and infrastructure deployments.
- **Charging/refueling infrastructure deployment** is also a key strategy and is discussed below.

1.5 Energy Infrastructure Strategy

Ensuring the timely deployment of ZEV charging/refueling infrastructure will be critical to enabling ZEV adoption. Different ZEVs will have different charging/refueling infrastructure needs, necessitating different priorities across market segments. Challenges include streamlining BEV charging infrastructure deployment timelines and coordination processes between fleets, utilities, regulatory agencies, and other stakeholders; developing low-cost clean hydrogen production and distribution networks; and developing a national charging/refueling network along key freight corridors. The following are key strategies to enable energy infrastructure deployment:

- **Streamline charging infrastructure deployment** through coordinated local, state, regional, and federal actions. Federal actions include providing **guidance** to streamline the energy infrastructure permitting process, promoting fleet-utility coordination and communication, and developing **forecasting tools** to help utilities better plan for future site energization demands. State and local actions can involve modernizing and streamlining the regulatory framework for grid planning and charging infrastructure deployment.
- **Support cost-competitive charging/refueling prices.** Cost-competitive electricity charging and hydrogen refueling prices are essential to enabling ZE-MHDV economic competitiveness. Actions include the following:
    - **Research and demonstrate MHDV vehicle-grid integration (VGI) approaches**, such as managed charging, that reduce costs and shorten energization

timelines while ensuring that MHDV fleet operators can meet or exceed operational needs with zero-emission solutions. These approaches will be most applicable to vehicles in the local and regional return-to-base and specialized vehicles and work trucks market segments.

  - **Invest in clean hydrogen production, distribution, and end-use networks** through DOE's Regional Clean Hydrogen Hubs Program.

- **Invest in phased deployment of charging/refueling infrastructure, including strategic and coordinated phased deployment of high-speed charging/refueling infrastructure along key freight corridors.** The Corridor Strategy lays out criteria for prioritizing charging/refueling infrastructure deployment, beginning in regional freight hubs and expanding along key freight corridors. Funding is available for station rollout through the National Electric Vehicle Infrastructure Formula Program, the Charging and Fueling Infrastructure Discretionary Grant Program, and the Regional Clean Hydrogen Hubs Program. Continued development of standards for high-speed charging/refueling, including the Megawatt Charging System and high-speed hydrogen dispensing, will also be needed.

1.6 Increasing Efficient Freight Transportation

Convenient and Efficient strategies will enable MHDV decarbonization by reducing the distance traveled between destinations and the energy intensity of each mile traveled while still meeting the needs of consumers. Actions to improve convenience will involve advanced freight movement-planning solutions, such as curbside demand management and off-peak deliveries. The federal government is currently developing technical assistance for state and local transportation agencies aimed at improving freight system convenience.

Actions to improve efficiency will involve vehicle-level innovations, including improved aerodynamics and component light-weighting; operational efficiency, including efforts to reduce vehicle idling and congestion; and system-wide efficiency measures, including investments in transit buses and investments to expand affordable access to efficient freight modes. Current programs include DOT's Mega, INFRA, Marine Highway, Port Infrastructure Development, and Consolidated Rail Infrastructure and Safety Improvements programs. DOT will designate a National Multimodal Freight Network that supports the use of lower carbon modes.

1.7 Job Creation and Workforce Development

A thoughtful, strategic approach to supporting the U.S. workforce and communities will be essential to ensure a strategic transition for all Americans.

Transitioning to a clean MHDV sector provides opportunities across a range of industries—including freight and passenger transportation, motor vehicle and parts manufacturing, vehicle and parts dealerships, and automotive and maintenance repair—which collectively employ more than 8 million people today.[11, 12, 13, 14, 15] Transitions will involve increased production and jobs in ZEVs, component technologies, fuels, and infrastructure.[16] Continued federal leadership is needed to ensure workforce development benefits all communities through actions such as policies and incentives to support high-quality job creation and retention and ongoing investments in domestic industries and supply chains and programs to facilitate worker training (including reskilling and upskilling).

Core strategy areas and supporting actions to promote MHDV Decarbonization

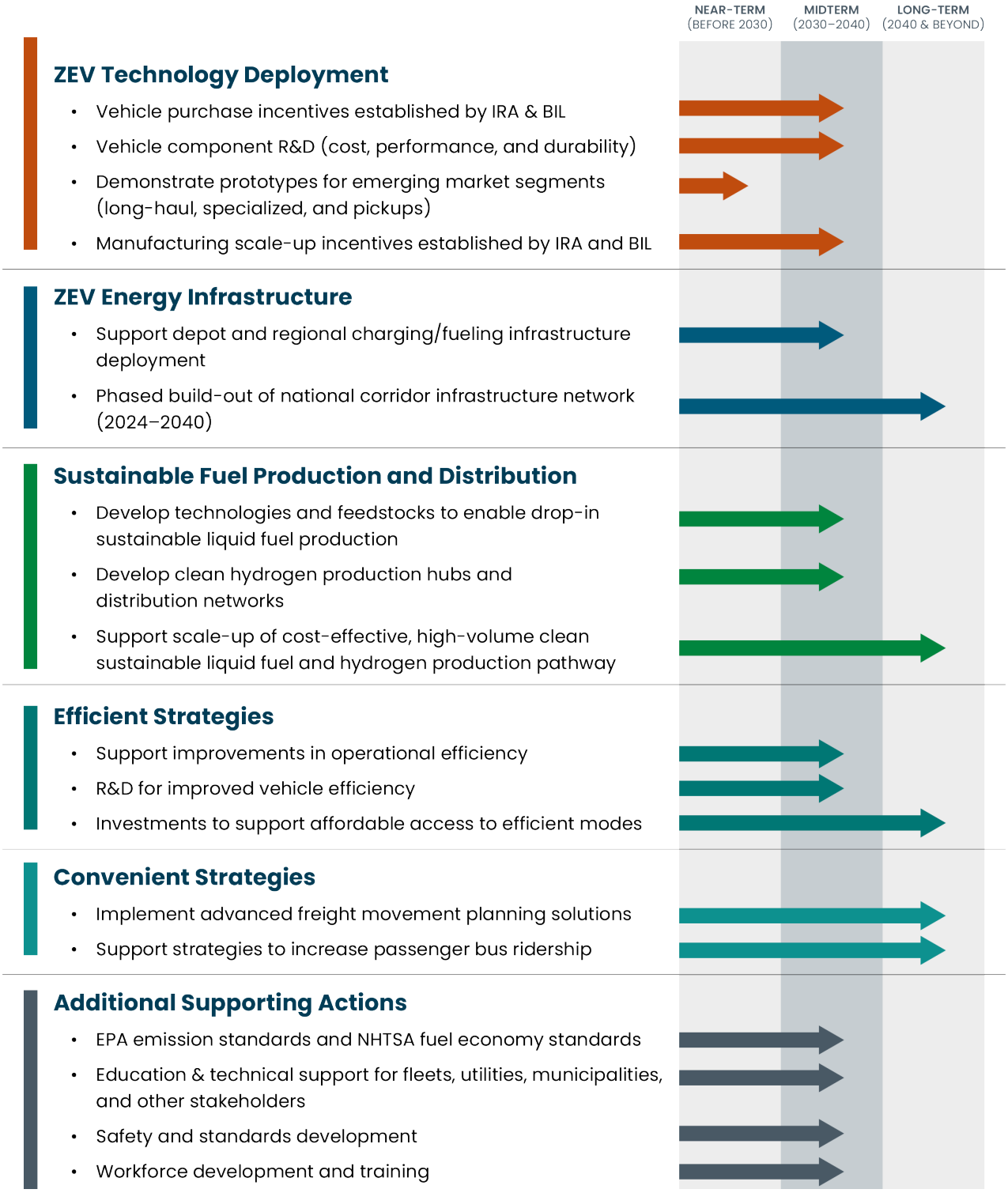


Figure ES-3. Core strategy areas and supporting actions to promote MHDV decarbonization.

1.8 Action Plan Moving Forward

Coordination across multiple federal agencies, as well as with state and local governments and private actors, will be needed to support MHDV decarbonization. Figure ES-3 outlines the sequencing of actions across core strategy areas: clean vehicles, fuels and infrastructure (including reducing ZEV costs, deploying ZEV infrastructure, and promoting sustainable fuel development), improving system-wide efficiency and convenience, and crosscutting measures. Three phases of action are envisioned, encompassing near-term (before 2030), medium-term (2030–2040), and long-term (2040 and beyond) actions.

Near-term actions (completed before 2030) will involve leveraging IRA and BIL **incentives** to support the deployment of ZEVs in early markets—including school buses, transit buses, and local and regional freight operations. This includes $5 billion in funding for EPA's Clean School Bus Program, $3 billion in funding for the Clean Ports Program, $1 billion in funding for the Clean Heavy-Duty Vehicles Grant Program, $2.5 billion for DOT's CFI Discretionary Grant Program, and numerous additional tax credits and incentives for ZEV purchases, clean fuel production, and manufacturing. **Manufacturing and fuel production scale-up** incentivized by IRA tax credits for critical vehicle components such as batteries and fuel cells, clean hydrogen production, and biofuel production will also begin in this period, with the goal of realizing medium-term cost reductions through economies of scale.

Energy infrastructure development—including deploying charging/refueling infrastructure at depots and local and regional networks—will also begin, with a particular focus on critical freight hubs. These three strategies will address both demand and supply barriers with the aim of stimulating medium-term market expansion of ZEVs. The following are near-term milestones for infrastructure and fuel production scale-up:

- By 2026: Finalize initial design for clean hydrogen production hubs and distribution networks through DOE's Regional Clean Hydrogen Hubs program
- By 2026: Host a ZE-MHDV infrastructure stakeholder workshop to promote collaboration across stakeholders
- By 2027: Complete Phase 1 of the Corridor Strategy, deploying charging at regional freight hubs
- By 2028: Meet clean hydrogen levelized cost target at the fueling station of $7/kg.

Simultaneously, a near-term **research, data collection, and outreach** agenda will lay the groundwork for future ZEV deployments in additional markets. This includes substantial stakeholder outreach and partnerships to collect data on vehicle duty cycles, develop education and training for fleets and workers, and evaluate ZEV safety and standards. In addition, core DOE research efforts will continue to focus on improved vehicle, fuel production, and infrastructure components, with the aim of reducing costs and improving performance and durability, as well as prototype development for expansion into additional market segments. Core milestones include:

- By 2026: Complete initial data collection on vehicle duty cycles, including nationally representative data on daily mileage, dwell times, and auxiliary power demands across all MHDV applications
- By 2027: Demonstrate long-haul ZEV operations and infrastructure on real-world freight corridor in partnership with industry and nonprofits; also demonstrate prototypes for specialized vehicles and commercial pickups.

Medium-term actions and milestones (2030 to 2040) will build on near-term programmatic efforts with the aim of expanding ZEV adoption from early-market to full-scale production, reducing production costs and improving performance of vehicle components and fuels, expanding ZEV adoption to new market segments, and further establishing regional and corridor

infrastructure networks. Investments will also build on prior research efforts, including in managed charging and VGI, multimodal investments, and strategies to improve convenience. Core medium-term milestones include the following:

- By 2030: Achieve cost parity for long-haul ZEVs with ICEVs, building on technology development, demonstrations, and manufacturing and fuel scale-up initiated in the near-term phase
- By 2030: Achieve 30% ZEV sales by 2030, aligned with the Global MOU
- By 2030: Connect key zero-emission freight hubs (Phase 2 of the Corridor Strategy)
- By 2031: Meet clean hydrogen levelized cost target at the fueling station of $4/kg
- By 2035: Expand corridor connections between critical freight hubs (Phase 3 of the Corridor Strategy).

Long-term actions and milestones (2040 and beyond) will be responsive to market developments in the near term and medium term. While many specific actions are in flux, key themes include expanding ZEV adoption to all market segments, achieving full build-out of corridor energy infrastructure, realizing cost reductions in ZEVs and fuels to reach levelized cost parity with ICEVs, and supporting sustainable liquid-fuel adoption for legacy vehicles. In addition, investments in transportation system efficiency and convenience will be realized on a long-term timescale. These actions will hinge on the success of previous efforts and related milestones—for example, build-outs of corridor energy infrastructure will hinge on proactive development of zero-emission fuels and efforts to modernize and streamline regulatory frameworks, as well as expanded ZEV adoption into long-haul market segments.

Key long-term milestones include the following:

- By 2040: Enable 100% ZE-MHDV sales across all market segments
- By 2040: Complete the national zero-emission freight corridor infrastructure network (Phase 4 of the Corridor Strategy)
- By 2050: Fully decarbonize the legacy fleet using sustainable liquid fuels and reach net-zero GHG emissions.

1.9 Following Through with Action

This MHDV Plan is envisioned as a living document, with progress on MHDV emissions reduction evaluated at regular intervals and future updates to this document made as needed. The path to significant MHDV emissions reduction will require innovative solutions across state and federal governments, industry, utilities, and other stakeholders. Ongoing and regular engagement, outreach, and partnership with industry, state and local government, utilities, and communities will be needed to support the transition and should be a priority for the implementation of all programs and strategies. Information sharing, exchange of lessons learned and best practices, support of technical assistance, and project development through partnership formation will be critical to the success of strategies outlined in this plan. With continued investments and technology progress, partnerships and collaborations, bold actions, and creative solutions, the future is bright for clean MHDV solutions.

2. INTRODUCTION AND CONTEXT

2.1 Commitment and Vision

To substantially reduce emissions, the United States has established a goal of achieving economy-wide net-zero greenhouse gas (GHG) emissions by 2050.[17] Reducing emissions in the transportation sector is critical to achieving this goal; at 33% of economy-wide emissions, it is the single greatest contributor to GHG emissions across all sectors.[18] To meet this challenge, four United States (U.S.) federal agencies—the U.S. Department of Energy (DOE), the U.S. Department of Transportation (DOT), the U.S. Environmental Protection Agency (EPA), and the U.S. Department of Housing and Urban Development (HUD)—released the U.S. National Blueprint for Transportation Decarbonization ("the Blueprint") in 2023, a whole-of-government strategy to significantly reduce emissions from all modes of transportation. The Blueprint calls for bold actions across all modes of transportation between now and 2030 to set the sector on a path toward achieving net-zero emissions by 2050.

Medium- and heavy-duty vehicles (MHDVs) account for 5% of on-road vehicles and 21% of sector-wide GHG emissions.[19, 20] Recent technological advancements in zero-emission vehicles (ZEVs)—vehicles with zero tailpipe emissions, which include battery-electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs)—have led to new optimism and the development of decarbonization targets at state, national, and international levels. In 2022, the United States signed the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (the Global MOU), a shared commitment by the United States and 32 other countries to identify pathways and implementation actions that enable zero-emission MHDVs (ZE-MHDVs) to reach 30% of new sales by 2030 and potentially 100% of new sales by 2040. In 2024, the United States announced a national goal for a zero-emission freight sector and announced the availability of $1.5 billion to transition MHDVs to ZE-MHDVs. In support of these aims, multiple U.S. federal and state policies have been developed to accelerate the deployment of ZE-MHDVs, which have zero tailpipe emissions and include technologies such as BEVs and hydrogen FCEVs, as well as other pathways to decarbonization, such as sustainable liquid fuels and measures to improve efficiency and convenience across the transportation sector. Notable federal policies are as follows:

- The 2021 Bipartisan Infrastructure Law (BIL) and the 2022 Inflation Reduction Act (IRA) each committed billions of dollars to decarbonization efforts across the transportation sector.
- Recently announced rulemaking by EPA establishes criteria air pollutant (CAP) and GHG emissions standards for light- and medium-duty vehicles and GHG emission standards for heavy-duty vehicles. These complement 2022 rulemaking aimed at reducing pollutants that create ozone and particulate matter (PM) from heavy-duty engines for model years (MYs) 2027 and later. Together, these three rulemakings form EPA's Clean Trucks Plan.

In addition to national ambitions, substantial state-level actions have occurred. California's Advanced Clean Trucks regulation specifies an increasing share of ZEV sales for MHDV trucks beginning in MY 2024. This rule has been proposed or adopted by 10 states as of June 2024. California's Advanced Clean Fleets regulation further requires a full transition to ZEVs between 2035 and 2042 for covered fleets. Finally, 17 U.S. states and the District of Columbia have joined the Multi-State Medium- and Heavy-Duty Zero Emission Vehicle Memorandum of Understanding, which commits to fostering a self-sustaining market for ZE-MHDVs, including striving to make 30% of MHDV sales ZE-MHDV by 2030 and 100% of sales ZE-MHDV by 2050. Beyond governments, major fleets—including Amazon, DHL, FedEx, and

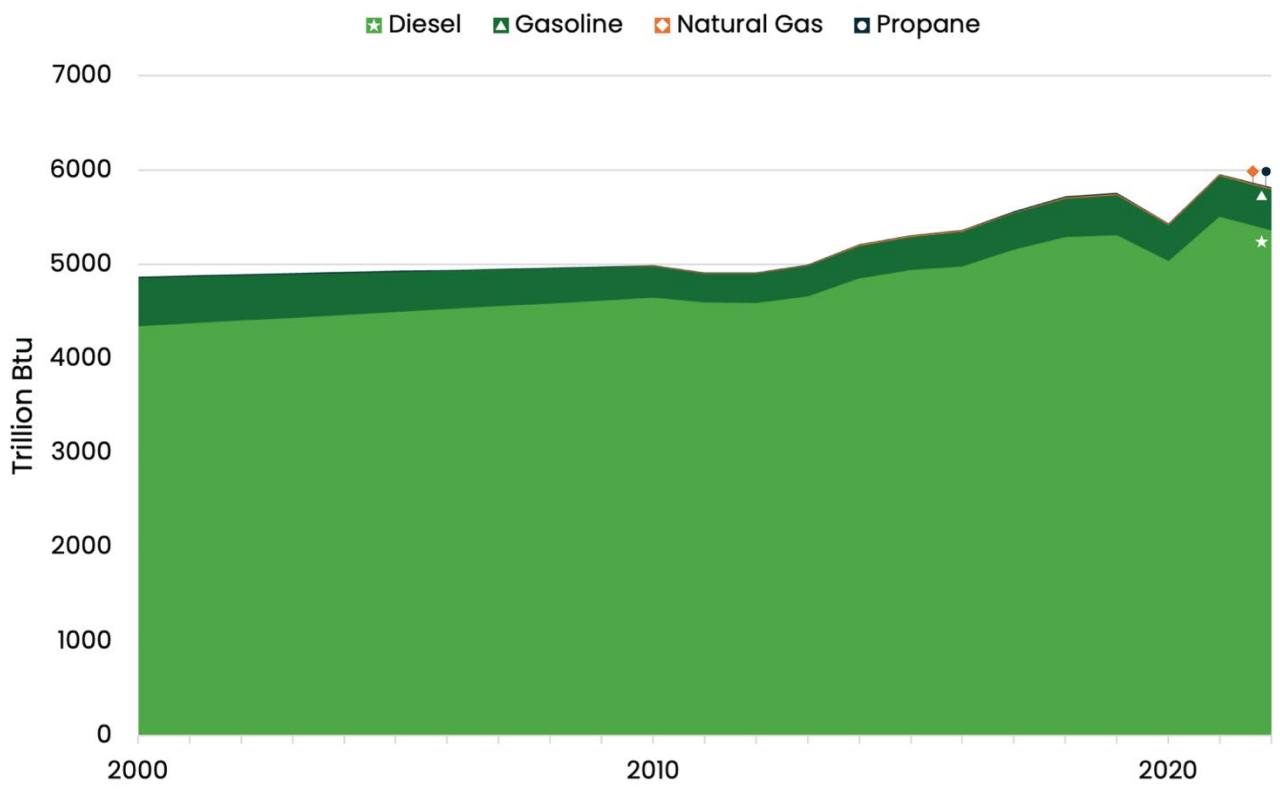
others—have also committed to significantly expanding their ZE-MHDV fleets. Simultaneously, major auto manufacturers and trade organizations have made commitments to decarbonization of their products sold through zero and net-zero solutions (see Table C1 for a list of manufacturer commitments).

With these ambitions and increasing commitments to ZEVs by fleets and industry, momentum is growing for MHDV decarbonization. This Report on Actions for Medium- and Heavy-Duty Vehicle Energy and Emissions Innovation (the MHDV Plan) builds upon the foundations established by the 2023 Blueprint by laying out near-term, medium-term, and long-term actions for the federal government to chart a path to MHDV decarbonization by 2050.

2.2 The Role of MHDVs in the U.S. Transportation System

MHDVs include all on-road vehicles with a gross vehicle weight rating (GVWR) greater than 8,500 pounds.[d] This MHDV Plan specifically considers commercial MHDVs—including all on-road vehicles with a GVWR over 14,000 pounds and a subset of on-road vehicles between 8,501 and 14,000 pounds used for commercial purposes.[e] Light-duty vehicles (all other on-road vehicles with a GVWR below 14,000 pounds) and off-road vehicles such as those used in mining and construction are not included in this scope but are addressed in additional mode-specific action plans.

Historical U.S. MHDV Energy Consumption Share by Fuel, 1990 to 2022



[d] GVWR and its relationship to vehicle class is further described in Appendix A, Table A1.

[e] We divide Class 2B and 3 vehicles (GVWR of 8,501 to 14,000 pounds) into personal and medium-duty commercial vehicles based on body characteristics and use. Commercial vehicles are accounted for in this plan, while personal vehicles will be accounted for in a Market and Technology Assessment for Light-Duty Vehicle Energy and Emissions Innovation.

Figure 1. Historical U.S. MHDV energy consumption share by fuel, 2000 to 2022. Data from the 2024 Inventory of U.S. Greenhouse Gases and Sinks.[21]

MHDV energy consumption and GHG emissions have grown substantially, increasing by 19% and 20% respectively between 2000 and 2022.[22] Today, the majority of MHDVs are powered by diesel (92%) or gasoline (7%) vehicles, with a small amount (around 1%) fueled by natural gas or propane. In addition to their contribution to GHG emissions, they are also a substantial source of local air pollution, accounting for roughly 29% of U.S. nitrogen oxide emissions from mobile sources and 17% of $PM_{2.5}$ emissions from mobile sources, in addition to other pollutants.[23] MHDVs play a central role in U.S. freight transportation, moving 65% of all U.S. freight by weight and 63% by value.[24] MHDV ton-miles of freight grew by 8% between 2000 and 2022, driven by economic growth and trends such as the rise of e-commerce (Figure 2).[25] This growth is greater than that of other competing modes; during the same period, rail ton-miles grew by 5%, while maritime ton-miles declined by 26%. In 2022, MHDVs accounted for 41% of all ton-miles of freight moved, compared to 29% for rail, 10% for marine, and 20% for pipelines. Growth is expected to continue in the future, with the Freight Analysis Framework projecting a 68% increase in ton-miles moved by MHDVs between 2022 and 2050.[26]

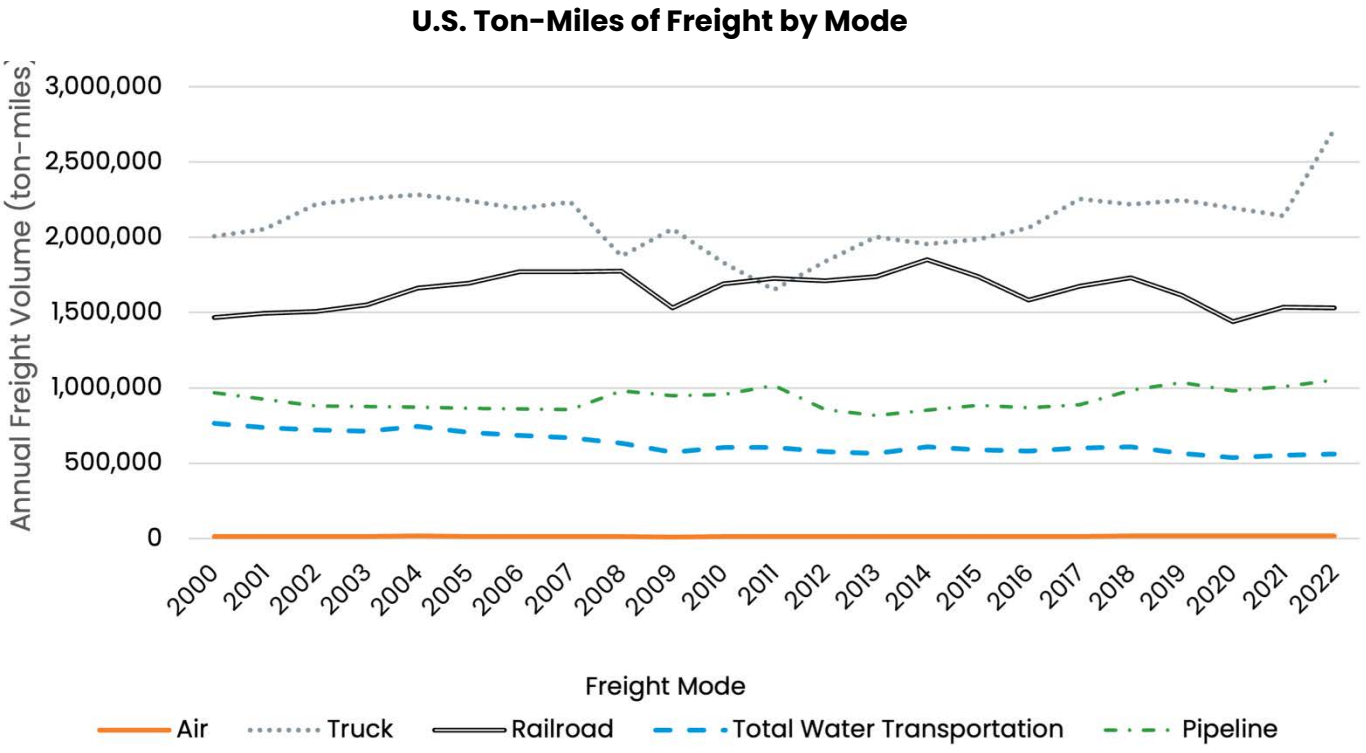


Figure 2. U.S. ton-miles of freight by mode. Source: Bureau of Transportation Statistics (BTS).[27]

Beyond transporting freight, MHDVs are used for many diverse applications, including transporting passengers over long and short distances (transit, school, and intercity buses), providing power to work sites, providing non-freight hauling services (such as pickups, tow trucks, and refuse trucks), and by powering auxiliary equipment such as cranes, cement mixers, lifts, and other specialized equipment types. Because of this diversity of uses, MHDVs are characterized by a range of body types, many of which are specialized for their application. Appendix A defines the primary vehicle body types considered in this report. This MHDV Plan divides the market for MHDVs into three primary market segments—local and regional return-to-base, specialized vehicles and work trucks, and long-distance passenger and freight vehicles—and several more subsegments, considering aspects such as vehicle weight class, distances driven, and the vehicles' purposes. All of these factors influence the GHG emissions rates of present-day vehicles and the strategies needed to decarbonize future market segments. This market segmentation is discussed further in Chapter 3.

2.3 The Blueprint for Reducing MHDVs Emissions

The 2023 Blueprint establishes a whole-of-government approach to decarbonizing the transportation sector, organized around three core strategies. "Convenient" strategies aim to reduce distances traveled between destinations by supporting community design and land-use planning at the local and regional levels. "Efficient" strategies aim to reduce the energy intensity of each mile by expanding affordable, accessible, efficient, and reliable options like public transportation and rail, as well as improving the efficiency of all vehicles. Finally, "Clean" strategies aim to reduce the carbon intensity (CI) of fuels by deploying zero-emission vehicles and fuels for cars, commercial trucks, transit, boats, airplanes, and more. Figure 3 summarizes these strategies and their areas of intersection.

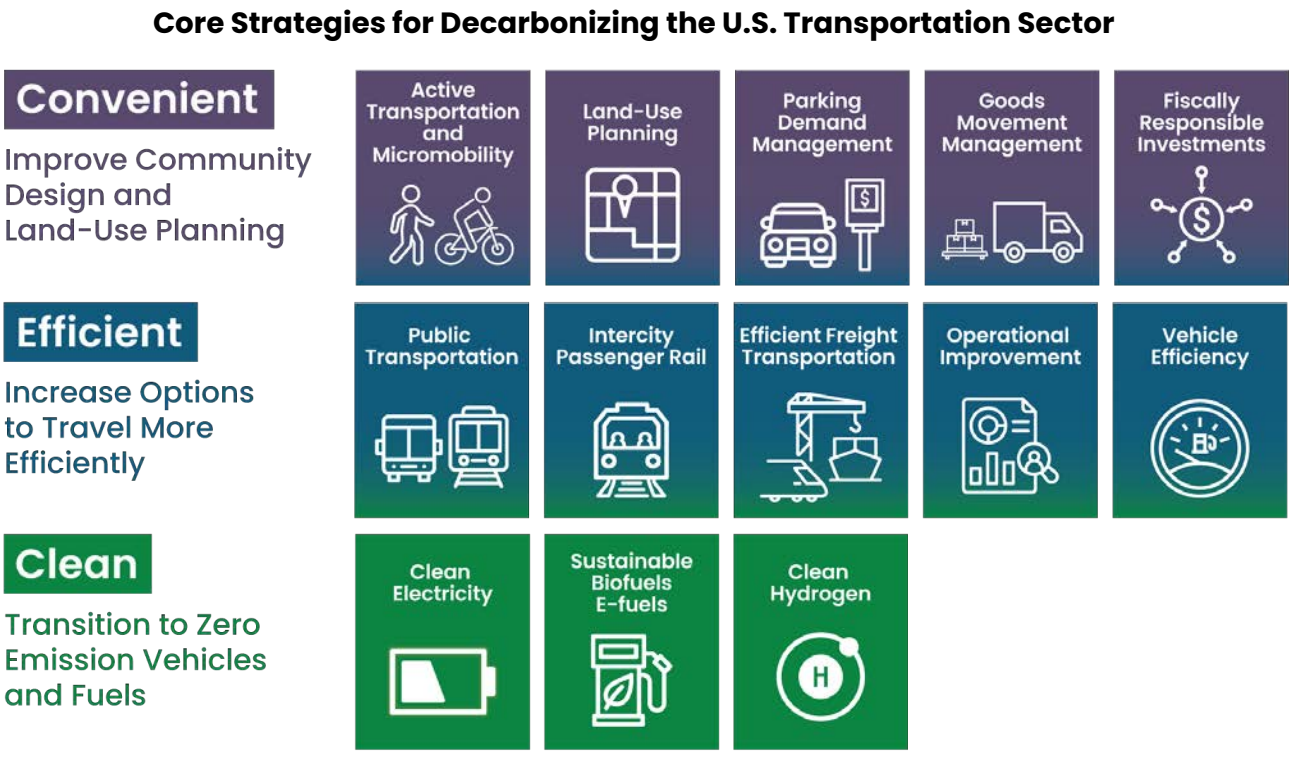


Figure 3. Core strategies for decarbonizing the U.S. transportation sector. Source: The U.S. National Blueprint for Transportation Decarbonization.

The Blueprint lays out three primary strategies that the federal government can take to accelerate MHDV decarbonization. These include the following:

1) Funding research and innovation to develop viable technologies low- to near zero-emission vehicles for all MHDV applications
2) Implementing policy and regulation to reduce new-vehicle GHG and criteria emissions and setting ambitious targets for transitioning to ZEVs on a timeline consistent with achieving economy-wide 2030 and 2050 emissions reduction goals
3) Investing in strategic demonstration and deployments to support the build-out of interoperable ZEV charging and refueling infrastructure through coordinated planning, policy, and funding opportunities.

The MHDV Plan builds on the strategies outlined in the Blueprint and dives deeper into specific opportunities and challenges to decarbonization across distinct MHDV market segments. A central component of the MHDV Plan is the adoption of commercial ZE-MHDVs (also referred to as ZEVs). Coupled with a carbon-free upstream fuel supply, ZEVs provide a concurrent solution to reducing both GHGs and local air pollution, addressing both climate and environmental goals.

A fully integrated economy-wide system approach will be necessary to reach net-zero goals, including transportation-specific strategies such as travel mode shift, land-use planning, and improved system-wide efficiency. Additional action plans (Convenient Transportation: An Action Plan for Energy and Emissions Innovation [the "Convenience Plan"] and Efficient Transportation: An Action Plan for Energy and Emissions Innovation [the "Efficiency Plan"]) detail strategies for these system-wide and multimodal emissions reductions. The MHDV Plan also incorporates these strategies at a technical level as they relate to freight and passenger MHDV and associated infrastructure. Full MHDV decarbonization will also depend on the decarbonization of upstream vehicle and fuel production processes, including decarbonization of electricity generation and the industrial sector. The United States has set ambitious targets for electricity and industrial sector decarbonization, with the goal of achieving 100% carbon-free electricity by 2035 and to reach net-zero industrial sector emissions by 2050.[28, 29] These targets will assist in decarbonizing full life cycle transportation sector emissions in the United States.

The MHDV Plan incorporates feedback from a range of stakeholders representing vehicle manufacturers, fleets, ports, infrastructure providers, community organizations, and other groups. The plan is envisioned as a living document that can be updated as technology and market conditions continue to evolve.

2.4 Report Objectives And Organization

The MHDV Plan has the following aims:

1. Identify key current and anticipated future barriers to deployment for zero-emission technologies and supporting infrastructure and propose solutions to address these barriers.
2. Chart a pathway to reduced emissions of the MHDV sector through the deployment of ZEV technologies and infrastructure, consistent with national ambitions and international commitments such as the Global MOU. This pathway will include the following elements:
    a. Strategies to reduce commercial ZE-MHDV costs, including demand-side incentives, manufacturing scaling, and research and development
    b. Strategies for deployment of critical infrastructure to enable ZE-MHDV adoption
    c. Strategies to support the most sustainable, cleanest fuels for year-2050 legacy internal combustion engines (ICEs), hybrids, and plug-in hybrids
    d. A plan to monitor progress toward near- and long-term decarbonization goals, including monitoring technology progress

and deployment of commercial ZE-MHDVs and infrastructure solutions and identifying data gaps and needs.

3. Identify Convenient and Efficient strategies that ease the transition to clean energy by optimizing operational efficiencies, investing in multiple freight modes (e.g., intermodal facilities, rail, and maritime), and integrating transportation and land-use planning to enable shorter or fewer trips.
4. Evaluate critical enablers to advancing commercial ZE-MHDVs, including incentives, policy drivers, technical assistance, and workforce development. As part of this action, identify gaps in current federal initiatives where additional guidance, coordination, regulation, research, data collection, and/or funding for demonstrations and deployments are necessary and propose actions to address these gaps.

The following sections of this report address each of these objectives. Chapter 3 begins with a summary of present-day MHDV emissions across all market segments. Chapter 4 then discusses the status of zero-emission technologies and fuels within individual MHDV market segments, current opportunities and barriers to further decarbonization, and key strategies that can be pursued for each market segment, including transitions to clean technologies and fuels, actions to deploy energy infrastructure, actions to improve convenience, and actions to improve vehicle and operational efficiency. Chapter 5 describes crosscutting solutions and key enablers, including ensuring good jobs and a stronger MHDV economy, actions to scale supply chains and manufacturing, actions to enable workforce development and transition, safety and standards, and international coordination. The report concludes with a roadmap of recommended actions between now and 2030, consistent with a pathway toward full modal decarbonization by 2050, including key indicators to track progress toward MHDV decarbonization and an accompanying strategy for ongoing monitoring and data collection.

3. MHDV EMISSIONS ACCOUNTING

3.1 Sector and Emissions Accounting

This plan uses 2022 tailpipe emissions for the baseline GHG estimates for the MHDV sector. These emissions correspond to the classification used in the Inventory of U.S. Greenhouse Gas Emissions and Sinks (GHGI).[30] Total 2022 MHDV emissions (all on-road vehicles with a GVWR of 8,501 pounds and above) are estimated at 439.4 million metric tons of carbon dioxide equivalent (MMT CO_2e), or 21% of U.S. transportation GHG emissions in 2022 (Figure 4). This estimate includes 0.1 MMT CO_2e of methane (CH_4), 3.3 MMT CO_2e of nitrogen dioxide (N_2O), and 6.3 MMT CO_2e of hydrofluorocarbons (HFCs). The Inventory's MHDV definition includes some Class 2B/3 vehicles used for personal use, whose emissions are accounted for under a Market and Technology Assessment for Light-Duty Vehicle Energy and Emissions Innovation. With these vehicles excluded, the total commercial MHDV emissions covered in this plan are estimated at 409.4 MMT CO_2e, or 19% of transportation emissions. This plan's baseline emissions data represents direct transportation emissions from the use phase of MHDVs, or "tailpipe" emissions, because upstream emissions from electric power, for example, are accounted for elsewhere in the national GHG emissions Inventory. Decarbonizing upstream sectors of our economy is the focus of other government-wide initiatives that complement this plan. Many transportation decarbonization solutions rely on electricity directly or indirectly, such as the production of hydrogen from water electrolysis or certain sustainable fuels. Achieving 100% clean electricity by 2035 is a critical co-strategy to support transportation decarbonization.

Total 2022 U.S. GHG emissions with transportation and mobile sources breakdown

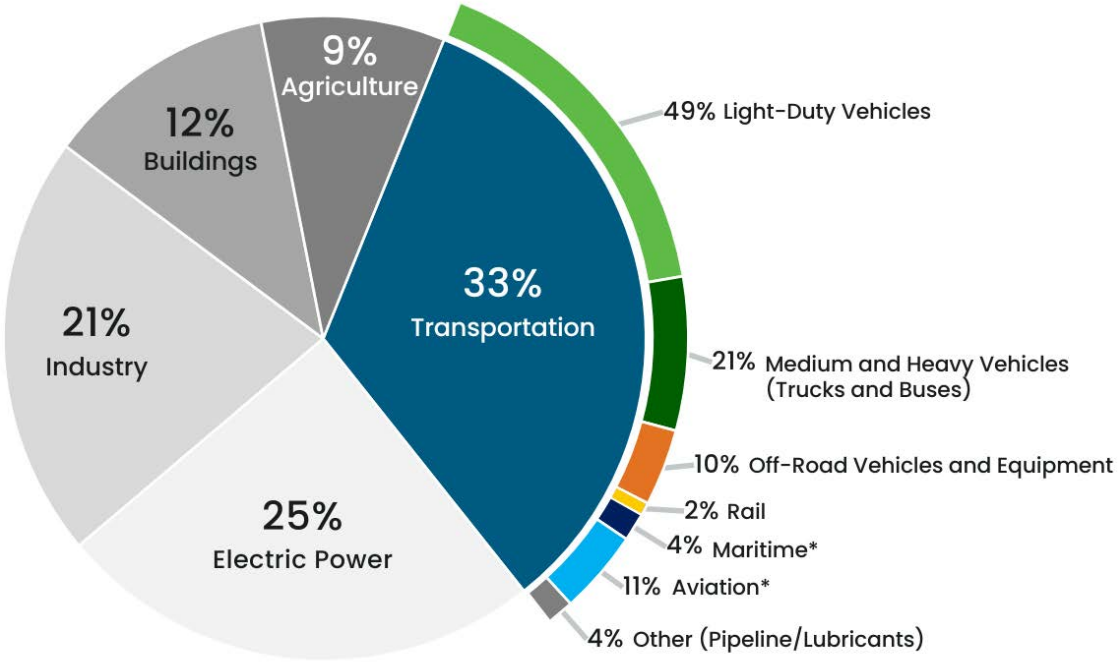


Figure 4. Total 2022 U.S. GHG emissions with transportation and mobile sources breakdown. Data derived from the EPA GHGI.

MHDV Market Segmentation

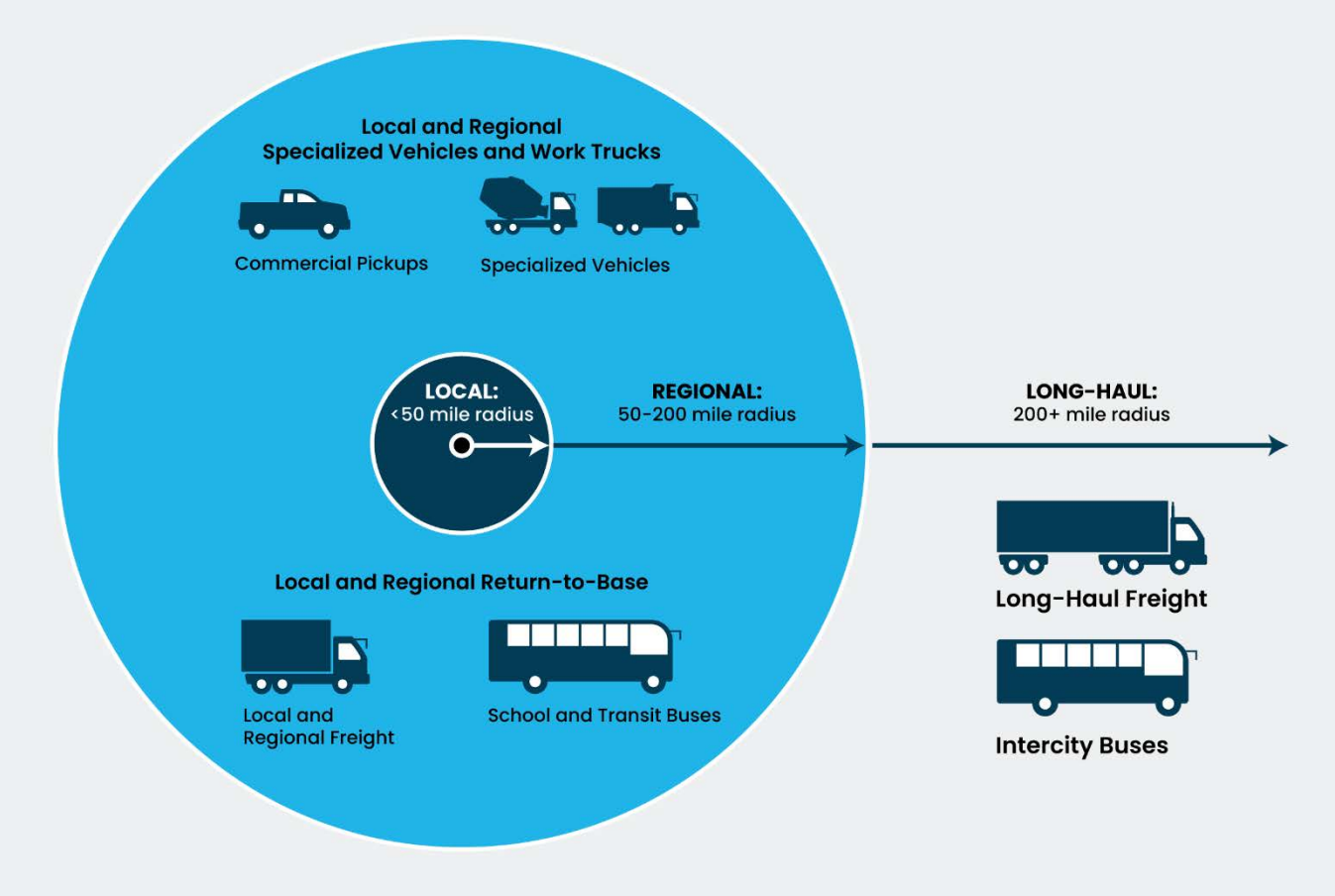


Figure 5. MHDV market segmentation. The MHDV Plan considers three primary market segments: Local and regional return-to-base, specialized vehicles and work trucks, and long-haul vehicles.

3.1.1 ESTIMATED GHG EMISSIONS AND MARKET SEGMENTATION

In 2022, there were an estimated 14.6 million Class 2B-8 commercial MHDVs driving 328 billion miles and consuming 5.4 quadrillion British thermal units (quadrillion Btu, or quads) of energy.[31, 32, 33, 34, 35] The MHDV Plan classifies these vehicles into three distinct market segments, which are grouped based on vehicle class, activity, and type of commercial use (Figure 5).

Different MHDV market segments have different contributions to energy and emissions. Due to differences in activity and fuel economy across vehicle classes, vehicle populations are not directly proportional to emissions shares. **MHDV energy consumption and emissions are highly skewed toward heavier and longer-haul vehicles**. Figure 6 shows the distribution of vehicles, activity, energy consumption, and emissions across all MHDV classes and market segments.

The local and regional return-to-base market segments include local and regional freight vehicles, school buses, and transit buses. These market segments are characterized by relatively low mileage, daily returns to a home base (with a maximum operating radius of 50 miles from a home base for local vehicles and 200 miles from a home base for regional vehicles), and relatively predictable routes. Examples of vehicles in these market segments include Class 2B/3 cargo vans, Class 4–6 step vans and box trucks, Class 7–8 day and sleeper cab tractor-trailers (aka "combination trucks") used in

local and regional freight operations, including drayage[f] activities, and transit and school buses of all classes. In 2022, a total of 7.2 million vehicles were categorized in this segment (50% of commercial MHDVs), which contributed to 44% of vehicle-miles traveled (VMT), 45% of energy consumption, and 45% of GHG emissions. The majority of GHG emissions were from Class 7–8 local and regional freight operations, which accounted for 15% of all commercial MHDVs and 28% of GHG emissions. Class 4–6 local and regional freight vehicles were the next-largest contributor, at 7% of commercial MHDV GHG emissions, while school buses, transit buses, and Class 2B-3 local and regional freight were smaller contributors. These market segments offer early opportunities for transitions to ZEVs, particularly for BEVs in lighter vehicle classes driving shorter distances. Substantial BEV deployment has already occurred—particularly for Class 2B/3 cargo vans (nearly than 26,000 BEVs),[36] school buses (nearly 4,000 BEVs),[37] and transit buses (more than 2,000 BEVs and nearly 100 FCEVs).[38]

The **specialized vehicles and work trucks** market segment includes Class 2B/3 commercial pickups and Class 2B–8 specialized vehicles serving vocations such as transporting refuse, snow removal, street sweeping, towing and hauling, transporting equipment, providing services for utilities ("utility service vehicles" or "bucket trucks"), providing power to work sites, and powering auxiliary equipment. Within this segment, Class 2B/3 commercial pickups composed the greatest share of vehicles in 2022 (3.8 million vehicles, or 26% of total MHDVs), while Class 2B–8 specialized vehicles were the remainder (2.6 million vehicles, or 18% of total MHDVs). These market segments account for a high fraction of total vehicles (44%) and a relatively lower share of activity (23%), energy (16%), and GHG emissions (16%). This is because a majority typically drive low mileage—less than 20,000 miles per year—and tend to be lighter and have lower energy consumption rates (a majority are Class 2B/3). However, it is important to note that these vehicles' towing and auxiliary load demands (i.e., from specialized equipment) are not reported in estimates of energy consumption, which consider only the mileage driven by the vehicle and could be a substantial source of additional demand. This is a key uncertainty of this market segment and will be important in developing future decarbonization options. Additional operational data collection and prototype development are needed to develop a greater number of ZEV options for these segments.

The **long-haul** market segment includes Class 7–8 long-haul freight trucks and intercity buses. These market segments are characterized by high mileage (85,000 miles per year on average for long-haul freight trucks), few returns to central locations (with an operating radius of 200 miles or greater from a home location), and longer and more variable routes. They account for 7% of vehicles, 34% of activity, and 39% of energy and GHG emissions. Long-haul freight trucks (which includes Class 7–8 combination trucks used for long-distance freight operations) are the single greatest contributor to emissions (7% of vehicles and 38% of MHDV GHG emissions), due to their high activity and high energy consumption rates (driving 6.8 miles per gallon of diesel on average).[39] The high loads that each vehicle carries are a substantial contributor to high energy consumption rates. Intercity buses are a smaller share of this segment, accounting for 1% or less of total MHDV vehicles, VMT, and GHG emissions.[40] Due to these characteristics, decarbonizing long-haul freight will offer the greatest emissions reductions per vehicle when reducing overall emissions. However, further demonstrations of technology viability and the development of national charging/refueling infrastructure networks are needed to ensure adoption in this market segment.

[f] "Drayage" trucks refer to trucks that transport shipping containers and bulk freights from ports to intermodal facilities, warehouses, and other near-port locations. Drayage trucks are highly relevant to air quality due to their high average age and operations near port communities. See Appendix A for more detail on vehicle body types.

The U.S. federal fleet encompasses more than 650,000 vehicles, of which roughly 150,000 are MHDVs (about 1% of total 2022 MHDV stock).[41] Executive Order (EO) 14057, issued in December 2021, requires 100% of federal fleet acquisitions to be zero-emission by 2035 (100% by 2027 for light-duty vehicles [LDVs]). We estimate that in 2022, the federal MHDV fleet consumed approximately 13 trillion Btu (less than 1% of 2022 MHDV energy consumption) and emitted roughly 1 MMT of GHGs (less than 1% of all MHDV GHG emissions).[9]

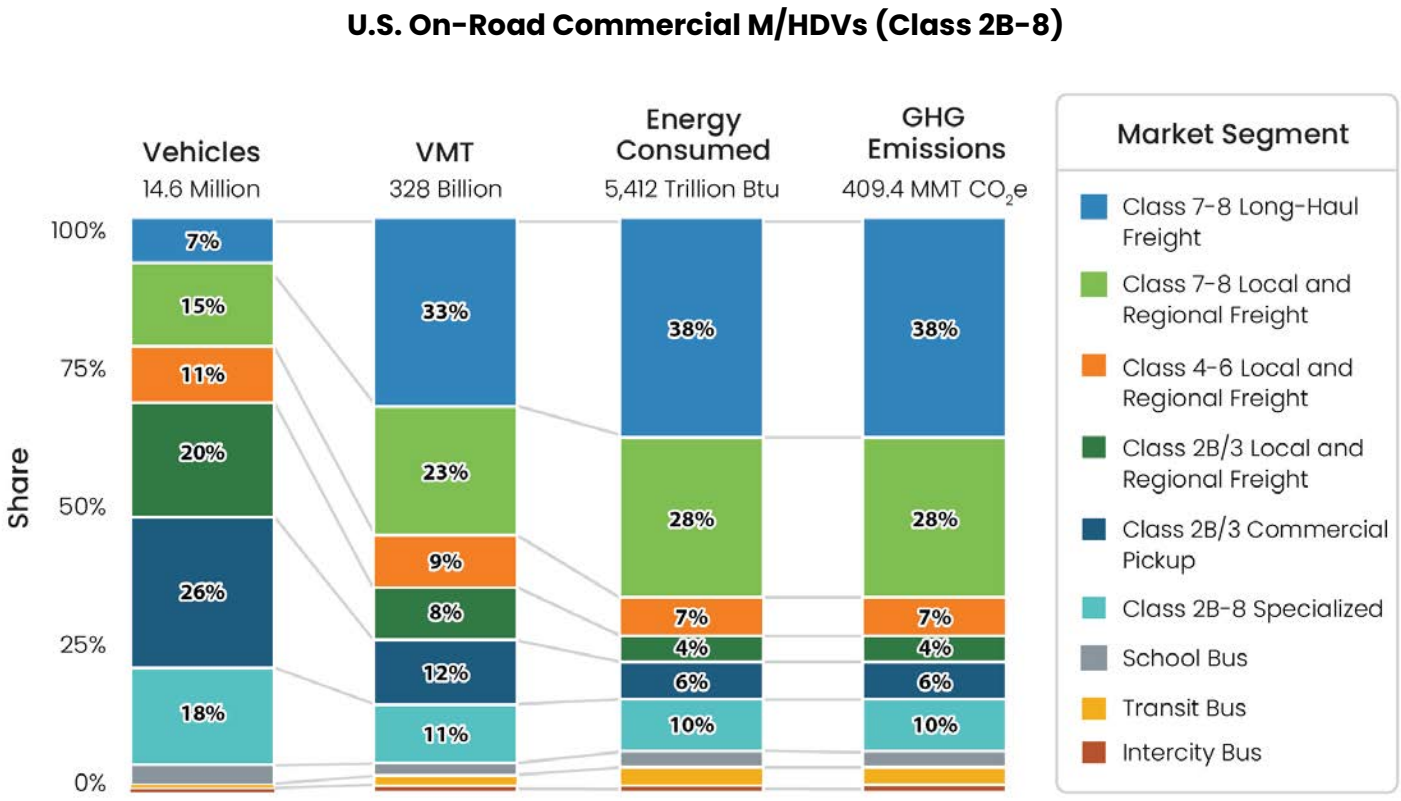


Figure 6. U.S. MHDV market segmentation by vehicle class—vehicles, VMT, energy consumption, and GHG emissions. A small fraction of heavy-duty vehicles accounts for the majority of GHG emissions. Sources: National Renewable Energy Laboratory (NREL) analysis using the TEMPO model based on data from the GHGI,[42] the Vehicle Inventory and Use Survey (VIUS),[43] the National Transit Database,[44] the 2023 School Bus Fleet Fact Book,[45] and the American Bus Association.[46]

[9] Federal fleet energy consumption and emissions were estimated from vehicle stock and activity data from reported federal fleet data, using fuel economy data from the Autonomie model and emission factors from the GREET model.

3.1.2 MINIMIZING GHGS WHILE MANAGING CRITERIA POLLUTANTS

Air pollution causes harm to human health and the environment. When decarbonizing MHDVs, it will be important to consider the impacts of new and existing technologies, fuels, and practices on both GHG emissions and air quality, including both at the tailpipe and upstream in the fuel or technology production process.

The National Emissions Inventory (NEI) developed by EPA reports air pollutant emissions from both stationary and mobile sources at three-year intervals, including six CAPs, criteria precursors, and other hazardous air pollutants. CAPs and their precursors have both direct air quality impacts and precursors to other pollutants such as PM and ozone[47] and have been proven to adversely impact public health.[48, 49, 50, 51, 52] MHDVs also contribute to other air pollutant emissions, including air toxics, which are compounds such as benzene and formaldehyde that are known or suspected to cause cancer or other serious health and environmental effects.[53] While most emissions from transportation are due to the combustion and evaporation of fuels, brake and tire wear are also significant sources of particulate emissions.[54]

The 2022 update of the 2020 NEI (the most recently released edition) shows that MHDVs are a major source of CAP and precursor emissions (Figure 7). These include:

- 29% of mobile and 13% of total U.S. nitrogen oxide (NO_X) emissions
- 4% of mobile and 1.4% of total U.S. CO emissions
- 17% of mobile and 0.4% of total $PM_{2.5}$ emissions
- 19% of mobile and 0.3% of total PM10 emissions
- 13% of mobile and 0.5% of total U.S. ammonia (NH_3) emissions
- Smaller contributions to sulfur dioxide (SO_2) and volatile organic compound (VOC) emissions.

MHDV and Other Mobile Source Contributions to Three Criteria Air Pollutants

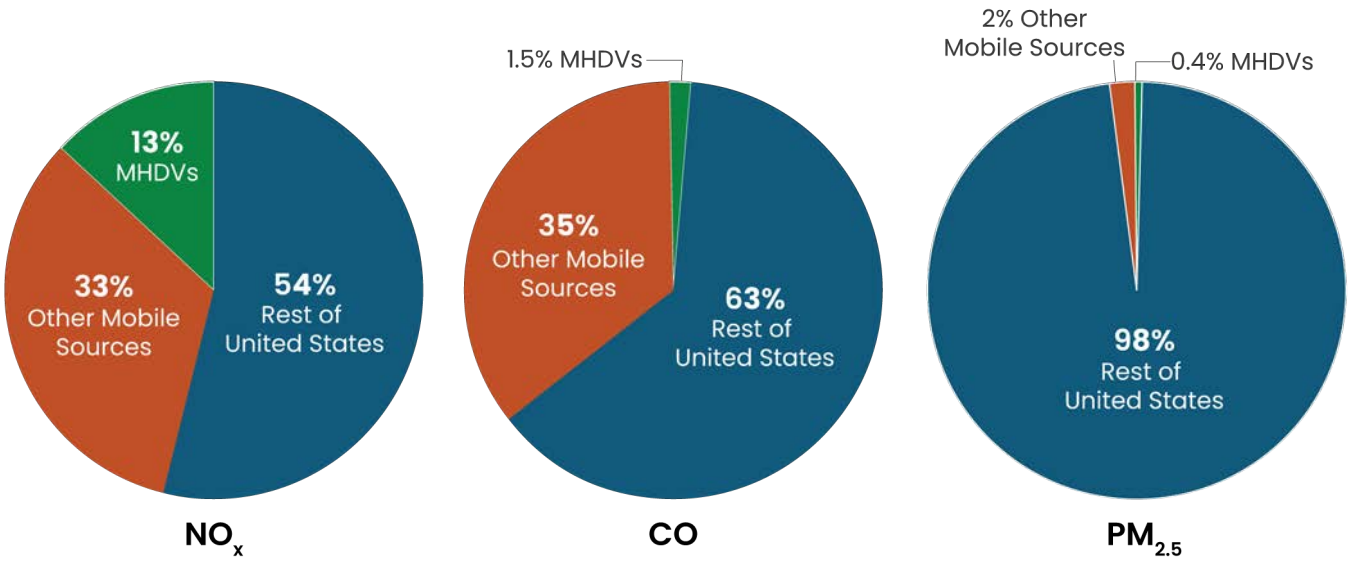


Figure 7. MHDV and other mobile source contributions to three CAPs. Source: 2020 National Emissions Inventory (2022v1 Emissions Modeling Platform).[55]

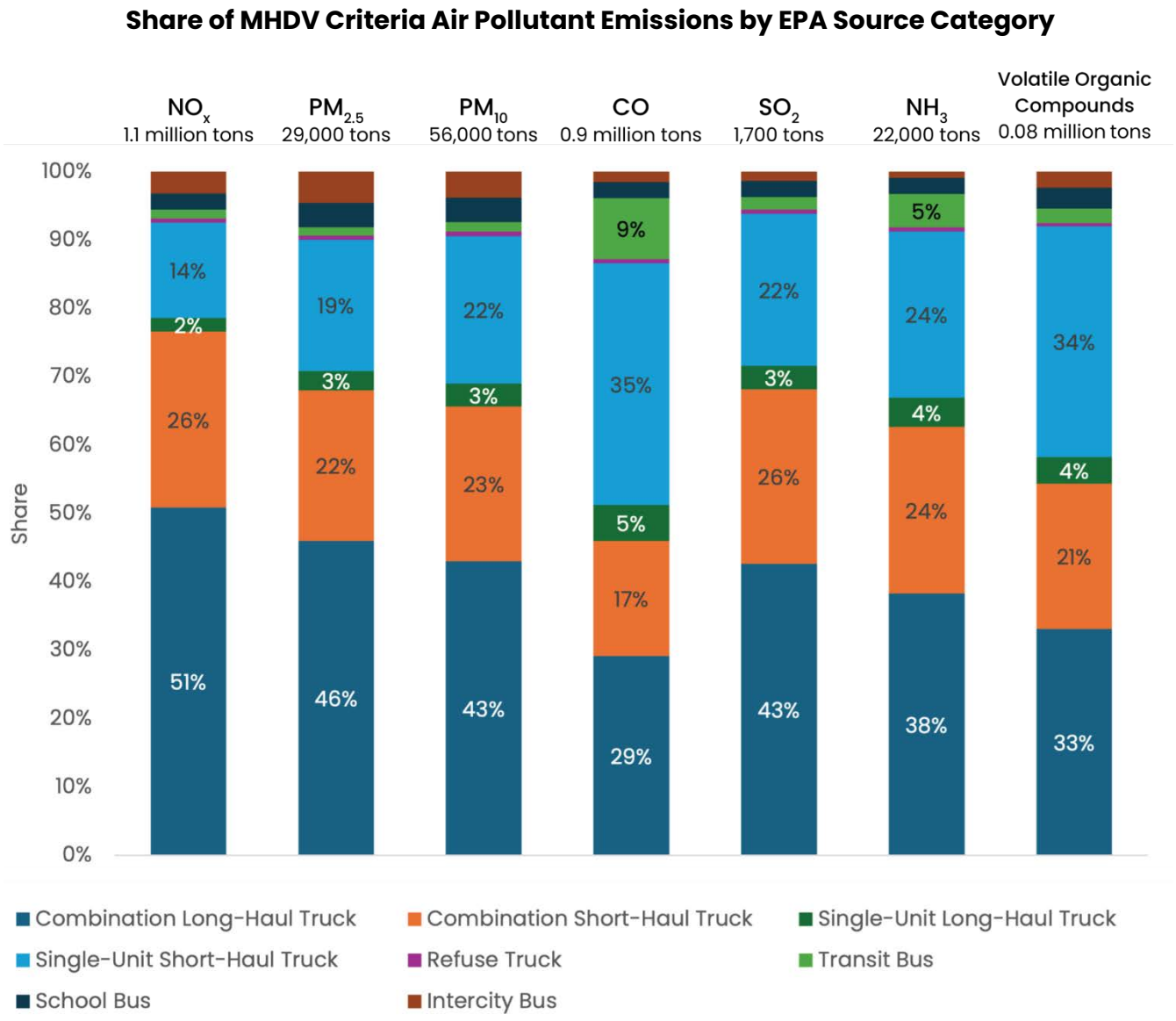


Figure 8. Share of MHDV CAP and precursor emissions by EPA source category. Source: National Emissions Inventory (2022v1 Emissions Modeling Platform).[56]

Figure 8 plots 2022 MHDV CAP and precursor emissions by source category. The greatest sources of MHDV emissions are Class 7–8 combination trucks (combination long-haul trucks and combination short-haul trucks). These are Class 7–8 vehicles primarily used for moving freight and are classified in this MHDV Plan as part of the local and regional return-to-base and long-haul market segments. Single-unit short-haul trucks, which are classified in the local and regional return-to-base market segment, are also significant contributors to emissions.

MHDV decarbonization efforts should consider local and regional impacts for public health. One of the benefits of transitioning to ZEVs is the lack of tailpipe pollutant emissions—including both GHGs and air pollutants—which has the potential to substantially improve public health. Beyond tailpipe emissions, emissions from upstream and downstream processes for the full life cycle of the vehicle and

infrastructure—including fuel production and distribution, vehicle manufacturing, infrastructure manufacturing and deployment, tire and road wear, and recycling and disposal—must also be considered, particularly with respect to impacts for communities with environmental concerns who may be disproportionately located near roadways and thereby exposed to pollution from on-road vehicles. The impacts of deploying ZEVs on air quality and public health will vary by geography, particularly for upstream fuel production processes. Screening tools and life cycle assessments must be used to fully assess the impacts of ZEVs, diesel-powered vehicles, and transitional technology deployments for local communities.

3.1.3 METHODS AND LIMITATIONS

To be consistent with the methodology used in the GHGI, we do not include life cycle emissions for our baseline estimates for commercial MHDV sector GHG emissions. However, the total emissions reduction potential of different technology pathways depends on their upstream emissions. For the purposes of this plan, we assume that by 2050,

Accounting for Life Cycle Emissions

The data reported in this action plan is direct emissions from the use phase of vehicles and transportation systems (i.e., tailpipe emissions). However, the strategies and recommendations in this action plan consider full life cycle GHG emissions, including the production and end-of-life phases of vehicles and fuels/energy sources. These life cycle emissions cover GHG emissions from fuel production and processing; vehicle manufacturing and disposal; and construction, maintenance, and disposal of transportation infrastructure. Inclusion of these life cycle emissions is important as the U.S. transportation sector evolves toward new power train systems with new fuels/energy sources. DOE has a long history of using life cycle analyses to assess energy technologies and inform how we can advance these systems and reduce their environmental footprint. For the transportation sector, the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET®) model is a suite of publicly available, best-in-class models used by the federal government and other stakeholders to assess the energy and environmental impacts of vehicles, fuels, chemicals, and materials across their life cycles. While the GREET model originated with a focus on transportation technologies, GREET currently covers the full life cycle, including manufacturing, industrial, and power sector impacts.

Reducing and ultimately eliminating life cycle emissions from these sectors is critical to achieving a fully sustainable transportation future and economy-wide decarbonization. While these modal plans are targeted to a given mode, related strategies and plans are subject to other government-wide initiatives that complement the Blueprint and these action plans. For example, a key long-term strategy of the United States is to decarbonize the electric power sector. Although outside the scope of this action plan, this co-strategy would greatly reduce the emissions associated with energy production that is used to power electric vehicles (EVs) and transportation systems. In summary, these action plans focus on the transportation use phase but acknowledge that a whole-of-government approach across multiple sectors and agencies is truly necessary to work to eliminate nearly all GHG emissions along every phase of the life cycle of the transportation system.

carbon-free electricity and clean hydrogen will be abundant, based on federal and private industry commitments and investments, such as the Hydrogen Shot and the commitment to a carbon-free electricity sector by 2035. In the interim, understanding the upstream emissions implications for different fuel types, operating profiles, and locations is important for prioritizing deployment of different equipment types. For example, replacing a highly utilized heavy-duty diesel long-haul MHDV in a location with access to clean electricity with an electric MHDV will lead to greater GHG emission reductions than replacing an infrequently used Class 2B cargo van in a location where the grid is still heavily reliant on coal.

For 2022 emissions, life cycle emissions track very closely with tailpipe emissions, as nearly all MHDVs rely on combusting conventional fuels. However, the total emissions reduction potential of different technology pathways depends in part on the upstream emissions. Currently, use-phase emissions make up the bulk of GHG emissions for conventional MHDVs. Recent life cycle analysis of multiple MHDV applications shows that BEVs are consistently lower emission than internal combustion engine vehicles (ICEVs), even with the present-day U.S. electric grid.[57] This analysis includes GHG emissions over the full vehicle cycle, including battery production for BEVs. FCEVs are also lower emission than ICEVs but have greater life cycle emissions than BEVs if hydrogen is produced from pathways such as steam methane reforming, which uses natural gas. Additional research is needed to comprehensively quantify full life cycle emissions for all MHDV market segments and technologies, including impacts on CAPs. Building out a data pipeline to estimate life cycle emissions for MHDVs is a near-term priority to analyze the near-term impacts of ZE-MHDV deployment across the full vehicle life cycle.

Available data on MHDVs comes from several sources. The 2021 Vehicle Inventory and Use Survey (VIUS) surveyed all commercial fleet activity in 2021 and includes data on vehicle populations, VMT, and fuel economy for freight and vocational vehicles. Limitations of this data include a lack of information on tons of freight moved by vehicle class, a lack of location granularity (vehicles are reported for the state they are registered in, but not necessarily where they are driven), and a lack of information on total fuel consumption inclusive of auxiliary loads. However, this source represents an important update to previous publicly available information on MHDVs. Continuing to update VIUS at regular (three-to-five-year) intervals should be a priority for monitoring MHDV decarbonization. Transit bus data comes from the National Transit Database (NTD), which provides annually updated and comprehensive data on transit bus operations at regional transit agencies. A limitation of this source is its reporting requirements: smaller transit agencies (fewer than 30 vehicles in peak operations) may have reduced reporting requirements and may be excluded from some metrics.[58] School bus and intercity bus data are compiled by industry associations (the School Bus Fleet Fact Book for school buses and the American Bus Association for intercity buses). Estimates of vehicle population, activity, and energy consumption represent aggregates from association members and may exclude other non-member operations. Additional data collection is needed to improve data quality for these modes.

4. MHDV DECARBONIZATION STRATEGY

4.1 Strategy Overview

A wide-ranging strategy is needed to decarbonize MHDVs, including clean technologies, sustainable fuels, and infrastructure; improvements in vehicle-level and system-wide efficiency; and improvements in convenience. The MHDV Plan is organized around the core strategy areas outlined in Table 1.

Deploying clean vehicles, fuels, and infrastructure is a central goal of the MHDV Plan. ZE-MHDVs will be needed to decarbonize new vehicles in line with the ambitions set out by the Global MOU. In addition, sustainable liquid fuels (including biodiesel and renewable diesel [RD]) will be needed to decarbonize legacy vehicles. Substantial scale-up of production and deployment of these solutions—and their supporting infrastructure—will be needed to reach near- and long-term goals.

Table 1. MHDV Plan Strategy Areas and Core Objectives

Strategy Area	Core Objectives
Clean Technologies, Fuels, and Infrastructure	1) Implement the **Global MOU on commercial ZE-MHDV sales**, including supporting **30% of new commercial MHDV sales** as zero-emission by 2030 and **100% by 2040** a. Achieve ZE-MHDV operational suitability in all commercial market segments through investments in research, development, demonstration, and deployment (RDD&D) b. Achieve competitive ZE-MHDV total cost of ownership (TCO) by implementing enablers to support the business case and reduction in costs for commercial ZEVs c. Deploy infrastructure to support commercial ZEVs, including a national charging and refueling infrastructure network, such as implementing the National Zero-Emission Freight Corridor Strategy 2) Support sustainable liquid-fuel deployment in legacy vehicles and remote and hard-to-decarbonize operations
Convenience	1) Support advanced freight movement planning solutions 2) Support the movement of people on public transit buses
Efficiency	1) Encourage the adoption of existing vehicle and fleet efficiency-improving measures 2) Support research and development to improve vehicle component and operational efficiency 3) Encourage system-wide efficiency improvements

Convenient and Efficient strategies will work in tandem with the deployment of clean technologies, fuels, and infrastructure to reduce the miles traveled by commercial MHDVs and the energy intensity of each mile. These strategies will encompass both vehicle-level and system-wide solutions, requiring research and development, investments, and implementation by actors at federal, state, and local levels. These strategies will also play a key role in enabling the clean strategy area by reducing the required scale-up of vehicles, fuels, and infrastructure needed to reach clean targets.

This chapter describes the objectives and key actions needed to enact each of the MHDV Plan's core strategy areas. Section 4.2 begins by describing technologies and fuels that can enable decarbonization, current ZE-MHDV market status, and actions needed to achieve clean strategy objectives, including ZE-MHDV deployment, energy infrastructure deployment, and investments in sustainable liquid fuels. This section also describes current federal regulatory actions that can enable this transition, including recently enacted emissions and fuel economy standards. Section 4.3 describes strategies and actions to achieve MHDV convenience and efficiency objectives. Finally, critical enablers—such as education and workforce development initiatives; investments in domestic vehicle component, fuel production, and infrastructure manufacturing and supply chains; and continued development of safety and standards for vehicles infrastructure and fuels—are discussed in Chapter 5.

4.2 Clean Fuels, Emerging Technologies, and Infrastructure

4.2.1 TECHNOLOGIES AND FUELS

Continued development of zero-emission and net-zero vehicle technologies and fuels is central to reaching MHDV decarbonization goals. In the long term, the primary technologies to decarbonize MHDVs will be ZEVs—including BEVs and FCEVs—which can address both decarbonization goals and substantially reduce CAP emissions, a core priority for public health aims. Transitional low-emissions technologies and sustainable liquid fuels may also play a role, particularly in market segments where ZEVs are slower to emerge. Near- and long-term technologies to decarbonize MHDVs are described below.

BEVs are ZEVs powered solely by electricity stored in an on-board battery. Key BEV components include the traction battery, which stores and delivers power to the vehicle and accounts for the majority of vehicle cost and weight; the electric traction motor, which propels the vehicle using power from the battery; and the power electronics, which control the power delivered by the battery to the electric motor.[59] BEVs can be highly energy efficient, with efficiencies two to four times greater than diesel counterparts, and they have been shown in early deployments to have lower maintenance costs than ICEVs due to fewer moving parts.[60, 61] However, in some applications, BEVs face challenges due to misalignment between charging power and fleet duty cycles, range limitations (currently available vehicles have typical ranges between 125 and 300 miles),[62] and heavier weight.[63, 64] Further improvements in BEV technologies—particularly batteries—are still needed to improve vehicle range, charging speed, specific energy (the energy stored per unit of weight), and other performance attributes. DOE's Vehicle Technologies Office (VTO) has prioritized the following battery research agenda:[65, 66]

- Reduce battery pack costs—reaching $100/kWh by 2025 and $75/kWh by 2030 for LDVs. Today's MHDV battery pack costs may be higher than current LDV pack costs on a per-kWh basis due to lower production volumes and lack of standardization.
- Improve fast-charging performance of lithium-ion batteries—including with respect to battery degradation and cycle life.
- Improve low-temperature performance.

- Improve the recycling of critical minerals—such as lithium, cobalt, manganese, nickel, and graphite.[67]
- Investigate next-generation battery technologies—including those using silicon and nickel-manganese-cobalt composites and lithium metal chemistries, which have the potential to deliver lower costs and improved specific energy for future vehicles.

Other cost and performance targets for BEVs—including batteries and other components—can be found in MHDV-specific technology roadmaps supported by DOE, such as the agenda laid out by the 21st Century Truck Partnership. Vehicle component research is ongoing through partnerships such as the United States Advanced Battery Consortium and other DOE-funded programs.

FCEVs are ZEVs that are powered by hydrogen. FCEVs typically generate energy using polymer electrolyte membrane (PEM) fuel cells, which generate electricity to power the vehicle by splitting hydrogen into protons and electrons using a catalyst. This reaction also generates water, which is the only tailpipe emission of an FCEV. Key FCEV components include the fuel cell stack, where power is produced from this hydrogen reaction; onboard hydrogen storage tanks, which store hydrogen on the vehicle; the electric traction motor, which, like in a BEV, is used to propel the vehicle; the battery pack, which provides supplemental power to the motor and is smaller than a BEV's battery; and the power electronics, which manage power delivered from the fuel cell and battery to the motor.[68] FCEVs can refuel rapidly (in under 20 minutes for Class 8 vehicles),[69, 70, 71] have longer ranges (typically between 300 and 500 miles),[72] and are lighter than BEVs,[73, 74] making them of great interest for heavy-duty and long-distance MHDV applications with high uptime. However, they face key challenges surrounding the cost, production, and distribution of hydrogen, which will be crucial to overcome to achieve widespread adoption.[75] DOE's Hydrogen and Fuel Cell Technologies Office (HFTO) administers a wide-ranging research agenda focused on hydrogen production, infrastructure, and fuel cells. For FCEVs, this includes the following research aims:

- Improve fuel cell stack costs—with targets of $80/kW by 2030 and an ultimate target of $60/kW for a 275-kW PEM fuel cell
- Improve fuel cell lifetime to 25,000 hours (with an ultimate target of 30,000 hours), consistent with a million-mile lifetime
- Improve fuel cell peak efficiency to 68% in 2030 and 72% ultimately
- Conduct research on reuse and recycling, particularly for platinum group metal components.

Additional details and targets can be found in HFTO's 2024 Multi-Year Program Plan, which also includes details on clean hydrogen production cost targets—aiming to reach $2/kg by 2026 and $1/kg by 2031 as part of the Hydrogen Shot™ program.

Sustainable liquid fuels are another alternative proposed for MHDV decarbonization. Sustainable liquid fuels include fuels that are produced through renewable, non-petroleum feedstocks such as biomass and waste oils,[76] which can have low or net-zero carbon emissions when considered on a well-to-wheels life cycle basis[77] and can be used in vehicles designed to operate on conventional fuels leveraging existing fueling infrastructure.[78] RD and biodiesel are two such fuels that are suitable for use in MHDV diesel engines, while renewable natural gas can substitute for conventionally produced natural gas in compressed natural gas (CNG) and liquified natural gas (LNG) engines. The adoption of sustainable liquid fuels will depend on future availability, land use, and cost.

In 2023, production of RD and biodiesel was 5.1 billion gallons per year.[79] DOE's Bioenergy Technologies Office (BETO) released the 2023 Billion-Ton Study, which identifies ways in which the United States can sustainably produce between 1.1 and 1.5 billion tons of biomass per year, translating to more than 60 billion gallons of sustainable liquid fuels per year available for use

in transportation or other sectors.[80] However, **more research is needed** on sustainable liquid fuel demands across multiple transportation modes and economic sectors, including on feedstocks, conversion technologies, emissions intensity, and costs of meeting these demands. The Clean Fuels & Products Shot™ and other projects under BETO's R&D portfolio aim to develop strategies to sustainably and cost-effectively increase the supply of net-zero carbon fuels to meet these needs.[81, 82]

Other hybrid and low-emission transitional technology solutions have also been proposed. These include hybrid electric vehicles (HEVs), which are powered by an ICE and have an onboard battery that cannot be charged from an external source.[83] and PHEVs, which are powered by both a chargeable battery pack and an ICE.[84] HEVs and PHEVs have been proposed as partial solutions for some MHDV market segments where ZEV technologies are not fully developed in order to offset some portion of GHG and air pollutant emissions.[85] Electric power takeoff (ePTO) technologies may also be used in conjunction with either conventional vehicles or ZEVs to power auxiliary functions on a vehicle using an onboard battery.[86]

Another proposed technology is the hydrogen internal combustion engine (H2ICE), which uses hydrogen to power an ICE. This technology has not yet been deployed but has gained interest because it requires lower purity (and therefore less expensive) hydrogen than FCEVs and few modifications to a traditional combustion engine, potentially allowing it to be deployed more rapidly than FCEVs. H2ICE has been suggested as an interim solution to enable the development of hydrogen production, distribution, and refueling networks.[87] H2ICE produces some NO_x emissions, though these can be minimized (but not eliminated) with emission control technologies. EPA rulemaking requires manufacturers to demonstrate that H2ICE complies with criteria pollutant emissions standards, including through the use of emission control technologies where necessary.[88, 89] H2ICEs have received interest from U.S. automakers for heavy-duty and off-road applications, with some models slated to enter production as early as 2025.[90, 91] Research by automakers is ongoing into durability, fuel efficiency, and emission control technologies to minimize NO_x and CO_2 emissions at competitive costs. DOE has also awarded $10.5 million to advance research into H2ICEs.

Finally, natural gas-powered vehicles, including CNG vehicles and LNG vehicles, are deployed in low numbers today and have 15% lower tailpipe GHG emissions compared to diesel.[92] While only ZEVs have zero tailpipe GHG and CAP emissions in line with long-term goals, transitional technologies offer near-term alternatives for fleets to achieve compliance with emission standards.[93] Acknowledging that the demands of MHDVs are diverse and that ZEV technologies remain in their

infancy in some market segments, the MHDV Plan considers ZEV, hybrid, and alternative-fuel ICE technologies to be viable transition options in the near term (MYs 2025 to 2032) while setting a long-term goal of a full ZEV transition across all market segments by 2040, consistent with the Global MOU.

4.2.2 CURRENT MARKET STATUS AND OBJECTIVES

Since 2019, the market for commercial ZE-MHDVs has rapidly expanded, with a cumulative estimate of around 34,700 vehicles deployed as of December 2023 (around 34,600 BEVs and 100 FCEVs) (see figure 9).[94, 95, 96] Most deployments have been Class 2B/3 BEVs used in local and regional return-to-base operations such as last-mile deliveries and e-commerce. Heavier BEVs and FCEVs have been deployed in lower numbers, including school buses, transit buses, and local and regional freight operations. Tables D3 and D4 provide further information on cumulative annual deployments, model availability, and additional characteristics of ZEVs on the market as of 2023.

Simultaneously, ZEV technologies have rapidly progressed. Between 2008 and 2022, lithium-ion battery pack costs declined by 89% (in real 2022 dollars), falling to a low of $157/kWh.[97] In 2023, battery pack costs further declined to $133/kWh across all applications and $128/kWh for BEVs (including LDVs).[98] Meanwhile, volumetric energy density has also substantially improved, increasing eightfold between 2008 and 2020 to 450 Wh per liter.[99] Fuel cell system costs and performance have also rapidly improved. DOE estimates show that LDV fuel cell system costs have declined by almost 70% since 2008.[100] While MHDV fuel cells and BEVs have different technical requirements from LDVs—including increased performance and lifetime requirements that make them more costly for an equivalent system[101]—improvements in LDV component technologies and production capacity will also benefit MHDV components. DOE has set ambitious targets to further improve present-day and next-generation battery and fuel cell technologies along measures of cost, durability, performance, and lifetime.

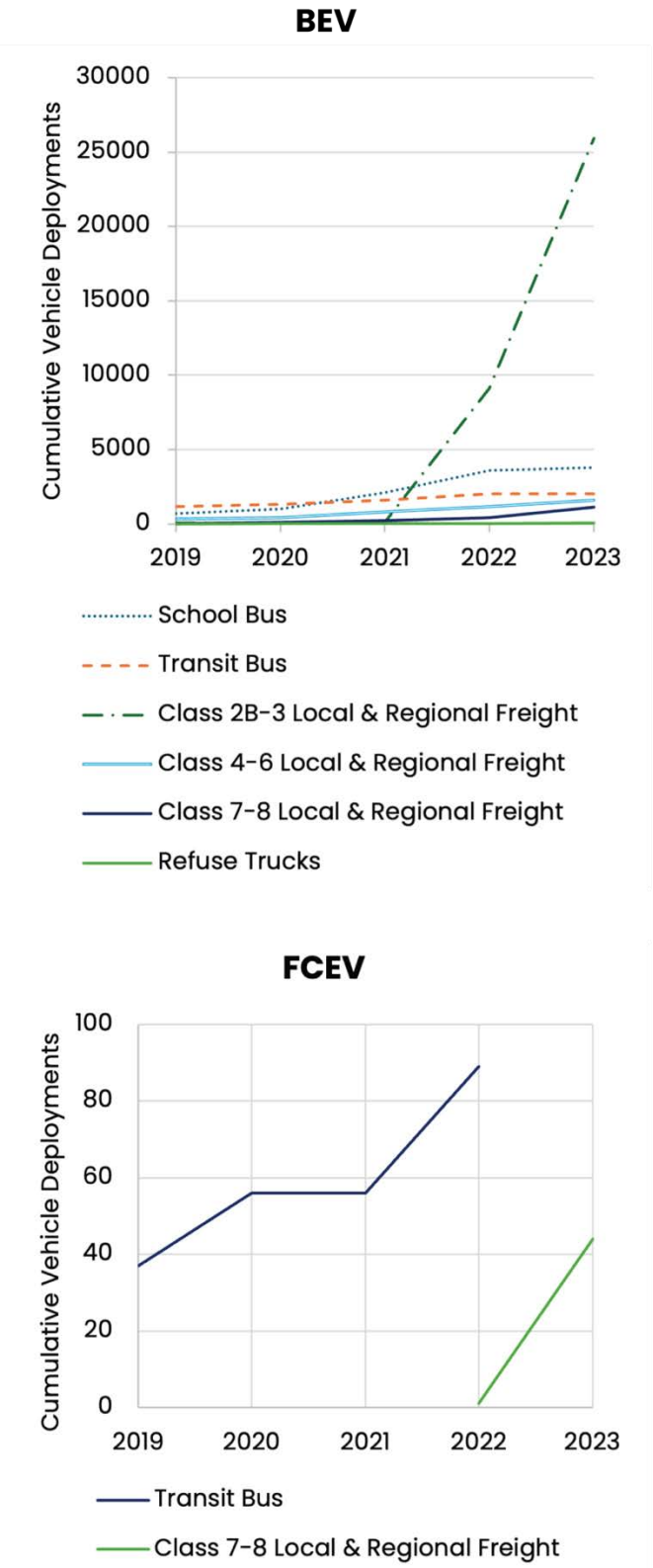
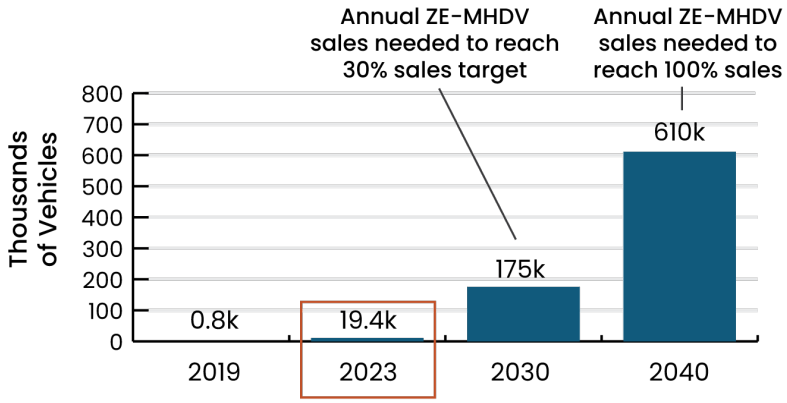


Figure 9. Cumulative ZE-MHDV deployments, 2019 to 2023. The number of ZE-MHDVs has grown rapidly, particularly for local and regional Class 2B/3 BEVs. Sources: CALSTART,[102] NTD,[103] World Resources Institute.[104]

Further progress is still needed. The Global MOU sets a target of 30% new ZE-MHDV sales by 2030 and 100% by 2040. Assuming growth in this sector is consistent with projections from the 2023 *Annual Energy Outlook* (AEO),[105] these targets imply that 177,000 new ZE-MHDVs will need to be sold in 2030 and 610,000 in 2040 (Figure 9). New ZE-MHDV deliveries have grown by more than twentyfold between 2019 and 2023, from under 1,000 vehicles per year to nearly 20,000,[106, 107] but reaching 2030 goals will require further scale-up—including rapid expansion of ZEV manufacturing capacity, such as manufacturing of batteries, fuel cells, and other vehicle components; scale-up of charging and refueling infrastructure stations; expansion of clean hydrogen production; and investments in the electric grid.[h]

Annual New ZE-MHDV Deployments, 2019 and 2023 AND Projected Deployments Needed to Reach Global MOU Targets



Vehicle Type	2019	2023
School Bus BEV	411	1,266
Transit Bus BEV	315	53
Transit Bus FCEV	10	0
Class 2B-3 Local & Regional Freight BEV	17	16,828
Class 4-6 Local & Regional Freight BEV	33	455
Class 7-8 Local & Regional Freight BEV	16	706
Class 7-8 Local & Regional Freight FCEV	0	30
BEV Refuse Trucks	2	20

Number of Vehicles

Figure 10. Annual new ZE-MHDV Sales, 2019 and 2023, compared to projected sales needed to reach Global MOU targets. Substantial scale-up of vehicles, infrastructure, and fuels will be needed to reach targets. Sales projections are based on base-year data from VIUS,[108] the NTD,[109] and bus industry sources,[110, 111] and scaled using growth rates from the AEO, 2023 edition.[112] Current ZEV sales estimates are from the NTD,[113] the World Resources Institute,[114] and CALSTART.[115] Sources include only delivered and operating vehicles within the calendar year and exclude vehicles committed or ordered but not delivered.

[h] Rapid expansions are currently underway for battery production and other vehicle components. Analysis by Gohlke et al. suggests that annual domestic battery manufacturing capacity in the United States could be as high as 1,200 GWh by 2030. Current (as of July 2024) announced battery cell factories are estimated to be sufficient to supply 10 million electric vehicles per year. Section 5.2 contains a more detailed discussion of U.S. manufacturing scale-up efforts.

To reach ZE-MHDV deployment goals, the following conditions must be met:

1) **Achieve ZE-MHDV operational suitability** in all market segments. While ZEVs are operationally suitable in many market segments today, RDD&D can help improve vehicle performance and market confidence in market segments such as long-haul and specialized vehicles.
2) **Achieve competitive ZE-MHDV TCO** (a metric that encompasses up-front cost, fuel and maintenance costs, and other operating costs). Several strategies and critical enablers—including encouraging ZE-MHDV purchase through existing incentive programs; supporting manufacturing scale-up; and additional R&D into advanced vehicles, fuels, and infrastructure—can help achieve these aims.
3) **Deploy infrastructure to support commercial ZEVs,** including associated investments in clean fuel production and distribution processes (for hydrogen) and grid transmission and distribution upgrades (for electricity).

To meet these challenges, the MHDV Plan lays out the following near-term ambitions:

- **Achieve cost parity by 2030 between new zero-emission, long-haul, heavy-duty trucks and existing ICE long-haul trucks.** Long-haul trucks are the largest source of GHG emissions in the sector and are thought to have the greatest technical challenges to ZEV adoption.[116] Achieving this goal will require extensive development of both BEVs and FCEVs coupled with investments in energy infrastructure at depots and regional hubs. Government and industry partnerships present a pathway to achieve these targets.
- **Implement the National Zero-Emission Freight Corridor Strategy** through collaborative planning and public-private investments to realize **36%** completion of the National Highway Freight Network (NHFN) **by 2030** and close to **100%** by **2040**. Achieving this build-out will require close cooperation and coordination with industry, fleets, utilities, government, and community groups.

Multiple levers will be needed to enact these strategies, many of which are already being implemented in a diverse array of research partnerships and funding programs. Subsequent sections describe the actions needed to reach these targets in each ZE-MHDV market segment.

4.2.3 ZE-MHDV TECHNOLOGY STRATEGY

4.2.3.1 Economic and Operational Criteria

Commercial MHDV fleets make decisions based on economics. To achieve widespread adoption, MHDV decarbonization solutions, including ZEVs and sustainable liquid fuels, must both be **economically competitive** and meet or exceed **operational needs** in the market segments for which they are deployed. A third criterion, having **sufficient energy infrastructure** (i.e., charging/refueling infrastructure), is also an essential prerequisite for adoption and is further discussed in section 4.2.4.

Economic competitiveness refers to the cost of owning a vehicle—including up-front cost, fuel and maintenance cost, resale value, and other factors—which must be competitive with ICEs. Economic competitiveness is typically measured using **TCO**, which computes the value of initial and recurring costs for a period (typically the fleet's ownership period for a vehicle). TCO considers vehicle purchase cost, resale value, fuel and maintenance costs, financing costs, driver wages, insurance, taxes and incentives, and tolls (using a discount rate to represent the value of future expenditures). Operational factors such as penalties for cargo limitation and charging time delays may also be included in measures of TCO. Other more simplified metrics, such as total cost of driving or levelized cost of driving, may also be used in lieu of TCO in analyses of vehicles' economic competitiveness. These metrics include at minimum vehicle purchase costs and fuel costs, but may exclude other costs such as driver wages, insurance, and taxes.[117, 118]

Figure 10 shows the projected cost of driving for a range of diesel-powered MHDVs in 2025. For most vehicles, labor is the greatest driver of costs and is unlikely to differ for ZEVs. Fuel and maintenance costs are frequently the second- or third-largest cost drivers for many vehicles. In the near term, ZEVs with higher up-front costs must be able to realize cost savings in these areas to be economically competitive. A key uncertainty for ZEVs today is their lifetime and, relatedly, their value on the used vehicle market. Further research is needed on these factors to provide confidence for fleets that ZEVs will retain their value over time. BEVs may also be able to capture residual value at their end of life through battery second-life applications, such as stationary storage.[119]

Operational suitability refers to the performance of the vehicle. Decarbonization solutions must be able to complete the same vehicle duty cycles as ICEs (including range, cargo load, and power requirements).

MHDVs have different technical requirements from LDVs. Many vehicles have more challenging duty cycles, including greater power and torque demands, higher durability needs, and longer lifespans. At its most demanding, a Class 8 tractor may require a propulsion system that delivers four times the torque of an LDV, can power a vehicle with a GVWR of up to 80,000 pounds, and lasts for an average of 14 years and 1 million miles.[120]

Many studies of ZEV competitiveness operate under the assumption that ZEVs must replace ICEV operations on a one-to-one basis to achieve market acceptance.[121] While this may not always hold in the future—for example, some case studies suggest that fleets are beginning to adapt operational patterns to accommodate BEVs with shorter ranges[122]—this assumption is used to evaluate ZEV readiness in this MHDV Plan.

Criteria that are commonly considered when evaluating ZEV technology suitability include the following factors:

- Ability to meet power demands, including from driving (with and without cargo) and auxiliary loads
- Vehicle range
- The time needed for en route charging/refueling
- Vehicle weight, including payload restrictions from weight limitations.[123]

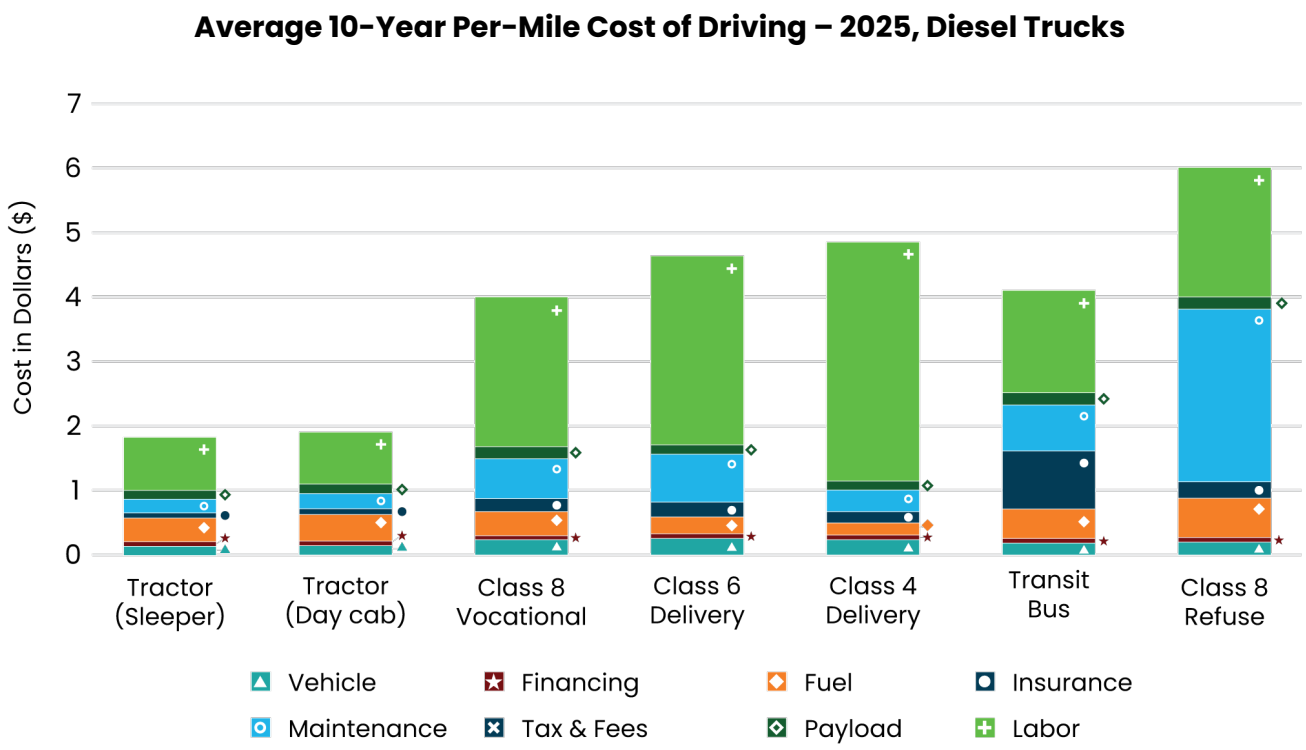


Figure 11. Projected cost of driving for diesel-powered vehicles in 2025. From Gohlke, 2021.[124]

Factors such as road grade, route variability, and temperature can impact the technical requirements needed for operationally suitable ZEVs. Various ZEV solutions will need to meet the extremely diverse demands in the MHD transportation segment. Early adopters are already using BEVs in some of their daily routes. FCEVs can complement BEVs by catering to the use cases that require longer driving ranges.

Operational suitability and economic criteria often overlap, as different vehicles may have different design requirements that in turn impact cost. A study conducted by Argonne National Laboratory (ANL) showed that, based on TCO, the optimum technology choice between BEV and FCEV will vary based on the vehicle design criteria, technology cost assumptions, and fuel and energy prices.[125] If the technology targets set by DOE are met, both BEVs and FCEVs will have lower cost of ownership than the diesel counterparts. FCEVs will tend to have a lower cost of ownership for longer-range vehicle designs, and BEVs will likely have lower ownership costs for shorter-range vehicles. The exact trade-offs depend on assumed future vehicle component costs, such as battery pack and fuel cell costs.

Figure 12 shows the design range where BEVs and FCEVs are economically attractive for several MHDV applications from a TCO point of view, overlaid with vehicle usage data from VIUS for different MHDV applications. For many applications, short-range BEVs may reach 50th- or up to 80th-percentile mileage needs, while for a smaller share of routes FCEVs may be more economically beneficial. These considerations influence the technology strategies chosen for the MHDV market segment.

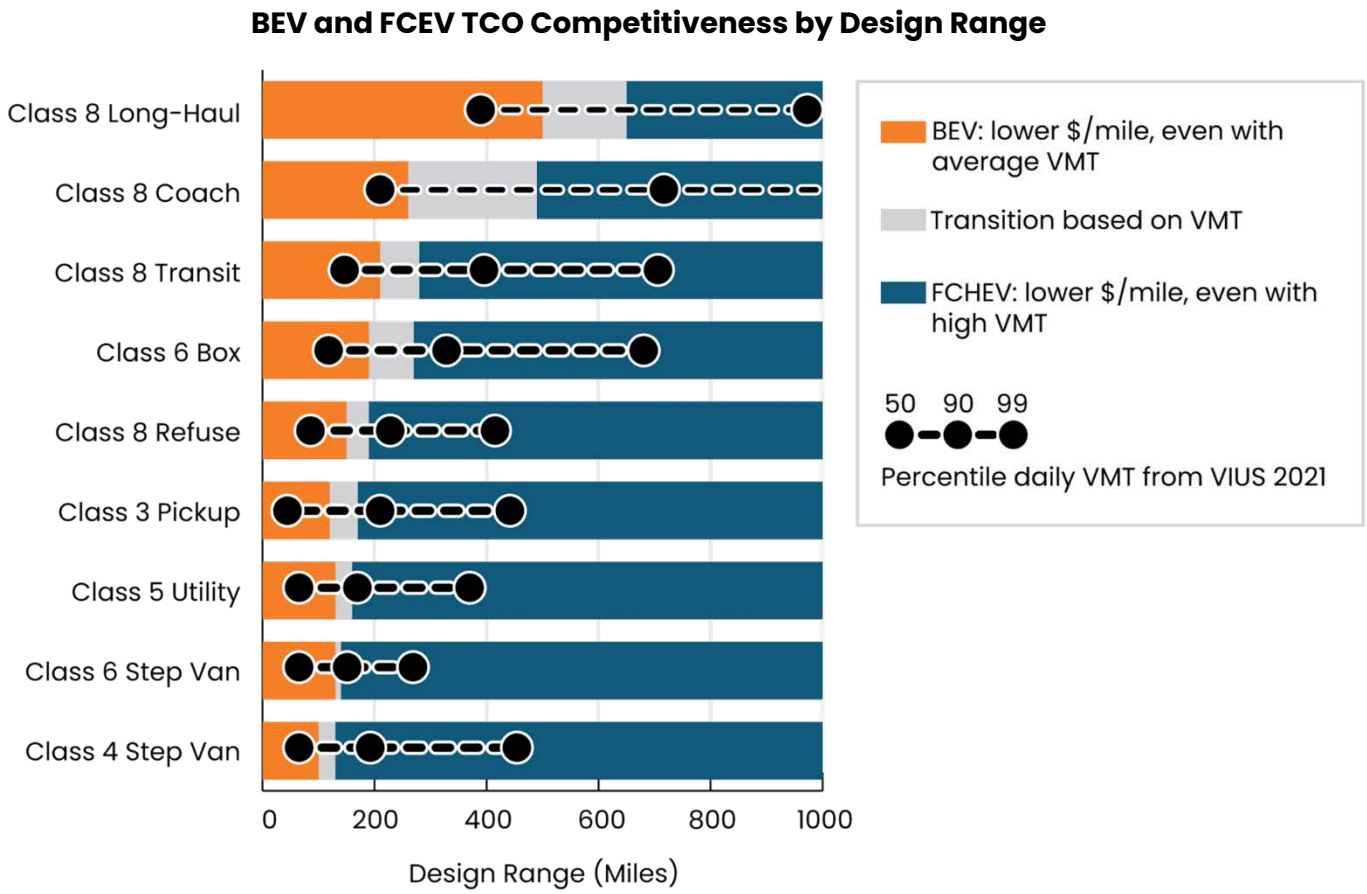


Figure 12. BEV and FCEV TCO competitiveness by design range. BEVs have lower TCO for shorter-range designs for all MHD applications. FCEVs have lower TCO for longer-range designs. VIUS 2021 data shows that both types of vehicles are needed to meet the needs of the consumers. Results assume 2030 fuel costs of $4/kg hydrogen and $0.15/kWh electricity. Source: Vijayagopal.[126]

4.2.3.2 Technology Strategies by Market Segment

Converting MHDVs to clean solutions presents different tradeoffs and opportunities for BEVs and FCEVs across MHDV market segments and will require different vehicle and infrastructure solutions and investments. Coordination will be needed across all levels of government, including federal, state, and local policy development, as well as collaborations with nongovernment actors in the vehicle and energy infrastructure industries, with fleet operators, community organizations, research institutions, and more. Figure 13 summarizes strategies to transition to ZE-MHDVs across all MHDV market segments.

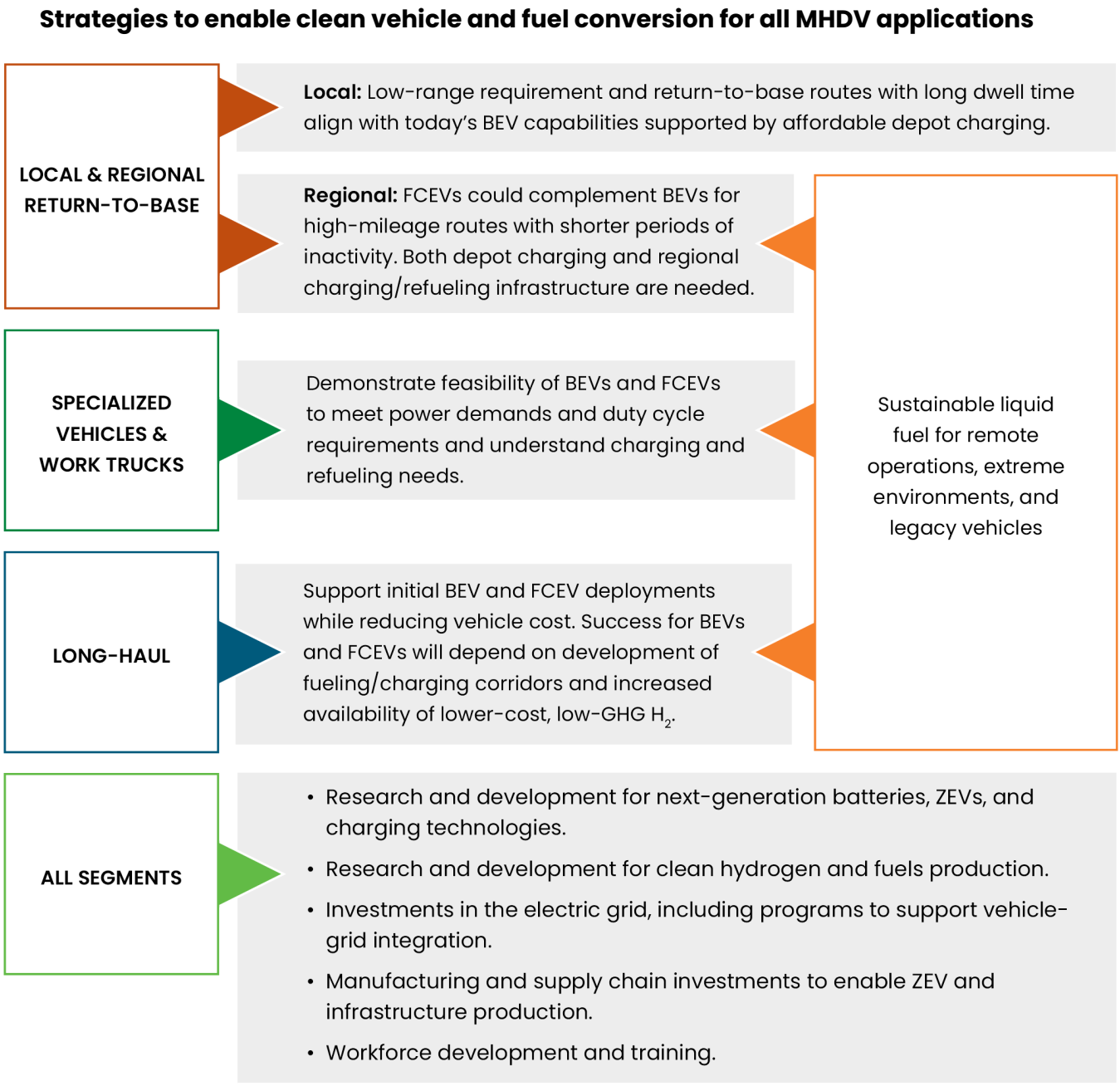


Figure 13. Strategies to enable clean vehicle and fuel conversion for all MHDV applications.

Local and Regional Return-to-Base

Local and regional return-to-base operations are early candidates for decarbonization. While ZEVs are deployed in low numbers today, favorable duty cycles and economics suggest that rapid expansion can occur in the near term—between now and 2030.

Zero-emissions solutions for local and regional return-to-base vehicles are priorities for communities. Many of these vehicles operate near population centers, and particularly near communities with poor air quality. Drayage trucks—those operating out of ports—are a key example. Many ports are major sources of CAPs and are in nonattainment or maintenance areas

as designated by EPA,[127] and a disproportionate number of low-income communities and communities of color reside near ports.[128] Research has shown that zero-emission drayage fleets could substantially reduce incidences of premature mortality and asthma attacks in affected communities due to reduced exposure to $PM_{2.5}$.[129] School buses are another priority. More than 95% of school buses are powered by diesel or gasoline vehicles,[130] and pollution from diesel exhaust particles has been linked to higher incidences of childhood cancer and asthma for school children.[131, 132] These health impacts are often greater for low-income children and those living in environmentally burdened communities, who are disproportionately exposed to older, higher-polluting buses.[133] Research has shown that switching to cleaner school buses improves attendance among school children.[134] Pursuing zero-emission solutions for these vehicles that maximize both climate change and air quality benefits should be prioritized.

Local Return-to-Base

Local return-to-base vehicles, including Class 2B–8 freight vehicles and school buses, drive an average of 9,000 to 14,000 miles per year (Table D1) and include roughly 3.5 million vehicles used in e-commerce, urban and last-mile delivery and parcel delivery applications, and school buses.[135, 136] Today these vehicles account for 11% of VMT (36 billion VMT) and 10% of all GHG emissions (41 MMT CO_2e). Due to their comparatively low annual mileage, low speeds, high efficiency, and return-to-base operations, BEVs have been suggested as a key solution for vehicles in this market segment. These vehicles can utilize slow, overnight charging at centralized locations such as depots ("depot charging") to meet most of their needs, which allows for lower infrastructure costs and the ability to shift charging to less expensive times of day.[137]

BEVs have demonstrated operational viability in this market segment. Many vehicles in this market segment travel less than 100 to 150 miles per day, making them suitable for today's BEV ranges.[138, 139] School buses typically drive two routes per day, with typical route distances below 100 miles and total daily mileage below 200 miles.[140] Demonstrations of battery-electric cargo vans, step vans, and medium-duty (MD) box trucks used in local delivery operations showed that they were able to operate in an equivalent manner to ICEVs for typical daily loads and ranges.[141, 142] Demonstrations and pilot projects of electric school buses (ESBs) have shown that ESBs can meet the needs of school districts across the country in a variety of settings and in both hot- and cold-weather conditions.[143] In demonstrations of both freight vehicles and school buses, high-speed en route charging was not needed in a majority of cases, and ample downtime allowed for opportunities for slow (level 2 [L2]) charging.[144, 145, 146]

BEVs are at or near TCO parity in some vehicle classes, but cost reductions are needed for heavier vehicles. Analysis by the National Renewable Energy Laboratory (NREL) suggests that Class 2B/3 freight vehicles are competitive with diesel today on a total cost of driving basis when vehicle purchase incentives from IRA are considered.[147] Other analysis by the International Council on Clean Transportation (ICCT) suggests that Class 2B/3 vehicles are competitive on a TCO basis with diesel today even without tax credits, though vehicle purchase costs remain higher on average than ICEV counterparts (with manufacturer's suggested retail price ranging from 15% to 45% higher than an equivalent ICEV).[148] Heavier vehicles (Class 4 and above) may need additional cost reductions to reach parity. Data on ESBs shows that these vehicles are still approximately four times as expensive to purchase as ICE equivalents.[149, 150] While operational cost savings can offset some of this and the TCO is positive with incentives,[151] purchase costs must decline to achieve widespread adoption without incentives. Analysis by ICCT suggests that medium- (Class 4–6) and heavy-duty (Class 7–8) BEV freight trucks are between 43% and 86% more costly to purchase up front than equivalent diesel vehicles.[152]

Rapid deployment of BEVs is already occurring, particularly for Class 2B/3 BEVs. Nearly 26,000 Class 2B/3 commercial vehicles were sold in the

United States between 2017 and 2023, with the majority sold in 2022 and 2023.[153] These sales have primarily been of BEV cargo vans used in urban and last-mile delivery operations. Substantial expansions are planned by major e-commerce and parcel delivery companies, with Amazon planning to deploy at least 100,000 electric delivery vehicles in the United States by 2030;[154] FedEx committing to 50% electric parcel delivery vehicle purchases by 2025, 100% by 2030, and full fleet conversion by 2040;[155] DHL planning to purchase 80,000 BEVs by 2030 for last-mile deliveries;[156] and the U.S. Postal Service planning to deploy 45,000 BEVs between 2026 and 2028.[157] About 1,600 MD step vans and box trucks have also been deployed to date (including vehicles used in both local and regional operations).[158] ESB deployments grew by 550% between 2019 and 2023, driven by EPA's Clean School Bus Program, which provides $5 billion in funding from 2022 to 2026 to school districts for vehicle and infrastructure purchases. As of 2023, 3,792 ESBs have been deployed in school districts across the United States and a total of 8,820 have been committed (awarded funding but not yet deployed).[159]

Accelerating depot charging infrastructure deployment is essential to enable further adoption. Long lead times for depot electrification are a major barrier to present-day BEV adoption, impacting not only local return-to-base but many other BEVs relying on a return-to-base depot charging model. Section 3.2.4 of this action plan provides more detail on specific actions needed to address these barriers.

Vehicle-to-grid (V2G) applications should also be evaluated. "V2G" refers to when electricity from vehicle batteries is discharged back into the grid. ESBs in particular show great potential for V2G applications, because school buses have high periods of downtime both during the day and during summer months. V2G can provide benefits to both school districts and utilities—school districts by providing an additional revenue stream from power sales, and utilities by allowing for better management of peak load periods. Recent demonstrations in New York and California have shown that V2G can be a feasible strategy for ESBs.[160, 161]

Regional Return-to-Base

Regional return-to-base vehicles include roughly 3.7 million Class 2B-8 freight vehicles and transit buses, accounting for 33% of VMT (109 billion VMT) and 35% of energy consumption and GHG emissions (1,912 trillion Btu and 144 MMT CO_2e).[162, 163, 164] While sharing many similarities with local return-to-base vehicles, their operations are characterized by higher average VMT—ranging from 20,000 to 37,000 miles per vehicle per year—greater daily driving distances, and greater route heterogeneity, suggesting that a mix of both BEVs and FCEVs may be needed to meet operational needs.

BEVs have demonstrated operational viability in some, but not all regional routes. FCEVs may be suited to other routes. While a majority of regional operating days may be short distance, favoring today's BEVs, a small number can be longer distances.[165] Demonstrations have shown that heavy-duty (HD) BEVs are viable today for routes of 200 miles or less—estimated at roughly 50% of the regional HD market segment by the North American Council for Freight Efficiency (NACFE).[166] Operations data from a sample of passenger transit vehicles (which may include transit buses, shuttles, vans, and other passenger vehicles) in NREL's FleetREDI database showed that 37% of vehicles drive below 100 miles per day, 41% between 100 to 200 miles per day, 16% between 200 and 300 miles per day, and 6% above 300 miles per day.[167] Multishift operations are another potential challenge, as they leave less time for BEVs to recharge using low-speed depot charging methods.[168] To meet all regional use cases, longer BEV ranges, mixed technology strategies such as FCEV adoption, or operational innovations such as mid-day en route or opportunity charging may be needed. Developing regional networks of high-speed charging and/or hydrogen refueling infrastructure will be necessary to decarbonize longer regional operations.

Like local return-to-base, high up-front cost remains a barrier for further adoption, particularly for heavier vehicles and FCEVs. Estimates from early-market demonstrations suggest that battery-electric transit buses are roughly 1.5 to 1.7 times as expensive as conventional diesel buses, while fuel cell electric buses are roughly twice as costly, though costs are projected to decline with higher production volumes.[169, 170, 171] MD and HD BEVs are similarly more expensive, as discussed in the local return-to-base section. FCEV freight trucks may be as high as three to four times as expensive as ICEV counterparts.[172] Furthermore, many conventional heavy-duty vehicles (HDVs) are purchased on the used-vehicle market, creating a greater barrier to financial viability for ZEVs.[173]

Deployment is occurring today, supported by incentive programs. Through funding initiatives such as the Federal Transit Administration (FTA)'s Low- or No-Emission Grant Program, the number of zero-emission buses has rapidly increased. The NTD reports zero-emission buses were roughly 3% of deployed Class 7–8 buses in 2022, while CALSTART reports a total of close to 9% in 2023 (though their numbers include vehicles that were ordered but not delivered).[174, 175] Of these, roughly 95% were battery-electric buses and 5% were fuel cell electric buses. HD BEVs have also been deployed, primarily in drayage applications. As of December 2023, 1,162 vehicles have been deployed, a majority of which are BEVs..[176] While CALSTART reports that only 44 FCEVs have been deployed in MHDV trucking market segments as of December 2023, voucher data from the California Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) shows additional unredeemed vouchers for 356 FCEVs as of June 2024, indicating anticipated near-term growth.[177]

Drayage trucks have additional considerations. First, as mentioned, port emissions are major contributors to air quality, and zero-emission solutions for drayage trucks should be prioritized. Second, ports supply infrastructure for many transportation modes that will be undergoing transformations over the coming decades—including maritime, rail, and off-road cargo handling equipment and yard trucks in addition to MHDVs. Planning for decarbonized port infrastructure capacity, including electricity, hydrogen, and biofuel supply, should jointly consider demands from all modes so that coordinated, least-cost solutions can be identified. In particular, BEV charging patterns and grid needs should be considered jointly across all modes, and optimized charging solutions should be researched to minimize capacity needs and grid impacts.

Specialized Vehicles and Work Trucks

Specialized vehicles and work trucks are commercial MHDVs not used in the movement of passengers or freight. This is the most heterogeneous segment of MHDVs, encompassing a wide range of body types and operational requirements. Given the highly specialized nature of many vehicles, which may be paired with auxiliary equipment such as cranes, lifts, mixers, and other components, and the low production volumes for many vehicle types, this segment has been thought of as particularly challenging to decarbonize, and few ZEVs have been deployed to date.

Commercial Pickups

There are 3.8 million commercial pickups (Class 2B and above, excluding vehicles used for personal purposes) in the United States.[178] These vehicles can be used for a variety of purposes, including towing, hauling cargo, and providing power to work sites, and they can be paired with auxiliary equipment such as snowplows. While most commercial pickups are driven less than 13,000 miles per year on average (Table D1), substantial power is needed for towing and hauling. Vehicles in this class typically have payload capacities of three-quarters of a ton or greater and can tow loads of 12,000 pounds or more.[179] These demands require substantial power and substantially reduce fuel efficiency. Examples from light-duty (LD) BEV pickup trucks suggest that towing loads of 11,000 pounds may reduce range by approximately half.[180] Currently, battery-electric models are under development, with some planned

to be launched as early as 2025.[181] Some Class 2B BEV models are currently available, but primarily used for personal use. However, major automakers have been slower to develop zero-emission heavier-duty commercial models. Ford has announced plans for "multi-energy technology" for its HD Super Duty® series, with production beginning in 2026,[182] while GM has delayed launches of electric HD pickups until 2035.[183] Manufacturers are also exploring other options such as FCEVs to meet the hauling needs of this segment.[184]

Other Specialized Vehicles

There are roughly 2.6 million other MHDVs operating in specialized market segments.[185] These include refuse and dump trucks, utility and other service vehicles, concrete mixers, tow trucks and wreckers, and more. A key characteristic of many specialized vehicles is the use of auxiliary equipment, which includes devices such as cranes, hydraulic lifts, and pumps. While vehicle use data shows that many vehicles in this market segment are driven short distances—a majority of refuse trucks are driven less than 150 miles a day, and most service vans and aerial trucks (also known as bucket trucks) used in utility and telecommunications applications are driven less than 100 miles a day[186, 187]—demands from auxiliary equipment can draw significant power that is not reflected in driving mileage. A study of hybridization potential for aerial trucks showed that stationary work time (time spent operating auxiliary equipment) ranged between three and six hours, while driving time averaged 1.5 hours per day and 26 miles.[188] Some specialized vehicles may also operate in multishift operations with limited downtime. More information is needed to better characterize different operational patterns within this market segment.

Due to the specialized nature of this equipment, the manufacturing process for these vehicles can involve multiple parties, including truck original equipment manufacturers (OEMs) who manufacture the cab and chassis, equipment manufacturers who construct the auxiliary equipment, and body builders and equipment integrators who assemble the final vehicle.[189] The number of parties involved adds complexity to the manufacturing process and can complicate the development of new ZEV prototypes. To date, few ZEVs have been deployed in this segment, with CALSTART reporting 57 BEV refuse trucks on the road as of December 2023.[190] California HVIP voucher data also shows that 10 BEV utility truck vouchers have been redeemed as of June 2024,[191] while Volvo reports one deployment of an electric cement mixer in Germany.[192] FCEV refuse trucks have also been delivered in Australia and Europe,[193, 194] with North American demonstrations planned for 2024 by some manufacturers.[195] One challenge to electrification is integrating demands from the truck and the vehicle body; manufacturers have considered designs incorporating both demands into a single battery or separating truck and body demands into separate power sources.[196] In some cases, ePTO technologies have been deployed to power auxiliary equipment using an electric battery.[197] California HVIP voucher data shows that 239 vouchers have been redeemed for ePTO vehicles for use with utility trucks.[198] Feasibility studies have shown that ePTO and PHEV configurations can reduce CO_2 emissions by 50% or more and NO_X emissions by 80% or more.[199] However, it is important to monitor the extent to which electricity is used in real-world operations to power auxiliary equipment rather than diesel. The HVIP program includes reporting requirements for fleets designed to assess ePTO utilization.[200]

Long-Haul Passenger and Freight

Decarbonizing long-haul HDVs is critical to decarbonizing the MHDV mode. While accounting for 7% of vehicles (1.1 million vehicles), they drive 34% of miles (110 billion VMT) and produce 39% of emissions (160 MMT), the majority of which is produced from HD freight combination trucks.[201, 202] While ZEV solutions are emerging in this market segment, further demonstrations and infrastructure deployment are needed to show viability and spur investments.

Heavy-Duty Long-Haul Freight

Heavy-duty long-haul freight vehicles encompass Class 7–8 tractors (including day cabs and

sleeper cabs) with daily operational radiuses of 200 miles or greater from a home base. Approximately 1.1 million vehicles operate in this segment, producing 157 MMT of GHG emissions, the single largest source out of all MHDVs. Today, nearly all long-haul HDVs are powered by diesel, with less than 1% supplied by CNG or LNG.[203] No ZEVs have been deployed to date, as critical en route fueling infrastructure needed to support long-haul routes does not yet exist.

Technology Options. Both BEVs and FCEVs may play a role in the long-haul segment. However, key technology and cost challenges must be resolved. Today's diesel tractors are driven for roughly 1 million miles over their full lifetimes, have ranges of around 800 to 1,400 miles, and can refuel in roughly 10 to 15 minutes.[204, 205, 206] Developing decarbonization solutions that can match the performance of today's diesel vehicles will require careful consideration of long-haul operational requirements.

BEVs are the most energy-efficient technology with the potential to provide substantial fuel cost savings compared to alternatives. However, today's HD BEVs remain limited by low ranges (typically 100 to 200 miles,[207] though models with ranges of up to 500 miles have been announced and other prototypes are in development[208, 209, 210]); heavy batteries, which can add between 6,500 and 13,500 pounds over a diesel vehicle for BEVs with 250 miles of range;[211] and a lack of fast-charging corridor stations (with 1- to 2-megawatt [MW] speeds required to supply en route stops).[212] FCEVs' longer ranges, more rapid refueling time, and lighter weight address some of these challenges. Like BEVs, they require the build-out of rapid corridor refueling infrastructure to be adopted, as well as a hydrogen production and distribution network. For both BEVs and FCEVs, more research is needed on technology durability and lifespan.[213, 214]

Operating data collected by NREL's FleetREDI database show that long-haul combination trucks have an average operating time of 9.6 hours per day with few starts and stops and an average daily mileage of 457 miles.[215, 216] This is consistent with DOT hours-of-service regulations, which limit the number of driving hours for freight drivers to 11 hours with a 10-hour break in between and a mandatory 30-minute break every 8 cumulative hours.[217] For many vehicles, this places a practical limit on the miles per day that a vehicle can travel. BEVs with 500 miles of range or more may be able to take advantage of mandatory driver rest periods to recharge, limiting the need for rapid en route charging under most circumstances.[218] However, around 18% of long-haul truck drivers operate in teams, which avoids the necessity of stopping and places additional demands on vehicle range and recharging/refueling speed.[219] FCEVs or BEVs coupled with high-speed (in excess of 1 MW) recharging infrastructure may be more suited to such applications. Weight requirements are also varied. Some trucks may carry volume-limited cargo, while others may carry weight-limited cargo. Estimates from surveys of fleet operators and weigh-in-motion data suggest that between 10% to more than 50% of trucks may reach maximum allowable weight limits.[220, 221] Further data collection is needed to better understand weight requirements. Operations that haul volume-limited cargo may be less penalized by the heavier weights of today's BEVs.

Sustainable liquid fuels are also a candidate to decarbonize long-haul routes, particularly in the near term while ZEV availability remains limited. Companies like PepsiCo have used B100 (100% biodiesel) and RD in early tests along rural routes.[222] While sustainable liquid fuels have fewer of the performance challenges faced by ZEVs, substantial uncertainty remains about future availability, CI, and cost.

Other considerations for decarbonization include route grade, climate, and the ability to install infrastructure along rural corridors, which depends on local grid conditions and economic considerations.

Table 2 summarizes present-day challenges and uncertainties for long-haul decarbonization options.

Table 2. Key Uncertainties and Needs for Zero-Emission Long-Haul Freight Operations

Category	Uncertainty	BEV	FCEV	Sustainable Liquid Fuels
TCO	Can vehicle and fuel costs achieve these targets?[i]	• Battery cost below $80/kWh • Electricity cost below $0.18/kWh[223]	• Fuel cell cost below $90/kW • Hydrogen cost below $4–5/kg[224]	Fuel costs competitive with diesel.
Vehicle Operations	Is the payload …			
	Weight limited?	Significant penalty.[225] Battery energy gravimetric density improvements needed.	Minor penalty.[226] Hydrogen storage gravimetric energy density could be improved.	No penalty; same as diesel vehicle.
	Volume limited?	No penalty for higher weight.		
	Are the operations …			
	Single shift?	500 miles likely to be sufficient range; long-duration slower charging at destinations such as travel centers can be used.	500 miles and current dispensing speeds likely to be sufficient.	No penalty; same as diesel vehicle.
	Multishift?	Longer ranges/sub-MW to MW+ fast charging needed.	Longer ranges/faster refueling (target 8–10 kg/minute) needed.	

[i] BEV and FCEV TCO results are sensitive to the assumed price of diesel and incentives assumed. One study found BEV TCO competitiveness with diesel at electricity costs as high as $0.3/kWh and battery costs as high as $123/kWh. Source: Basma, H. Buysse, C., Zhou Y. and Rodriguez, F. 2023. Total Cost of Ownership of Alternative Powertrain Technologies for Class 8 Long-Haul Trucks in the United States. The International Council on Clean Transportation. theicct.org/wp-content/uploads/2023/04/tco-alt-powertrain-long-haul-trucks-us-apr23.pdf

Temperatures	Between 20° and 52°C.	No operational challenges.[227]		
	Outside of 20° and 52°C.	Some operations may require improved performance, particularly for lower temperatures.[228] Extreme cold temperature requires warm-up strategies.	High-temperature operations result in power derates and necessitate enhanced solutions.[229] Extreme cold temperature requires warm-up strategies.	No challenges for 100% RD meeting ASTM D975.[230] Biodiesel meeting ASTM D7467 is limited to 20% or else vehicle retrofitting required for 100% biodiesel meeting ASTM D6751.[231]
Energy Infrastructure	Can technology energy infrastructure needs be met at a national scale?	Requires robust regional development of high-speed charging network; sufficient clean grid capacity.	Requires robust regional high-speed refueling network; sufficient clean hydrogen production and distribution networks.	Requires feedstock and conversion technologies of new feedstocks for other modal demands such as aviation, which also support reducing cost of biofuels for long-haul since biofuel processes tend to co-produce a slate of fuels.
Lifetime	Can the technology demonstrate comparable lifetime and durability to diesel?	Requires further demonstration of million-mile lifetime and durability.[232, 233]		No penalty; same as diesel vehicle.

Economic Competitiveness. The success of both BEVs and FCEVs will depend on competitive TCO compared to ICEVs. This includes vehicle purchase costs (which are substantially driven by component costs of batteries or fuel cells) and fuel costs (including the levelized cost of electricity or hydrogen, inclusive of charging/refueling infrastructure costs borne by the fleet, compared to diesel prices). The 21st Century Truck Partnership found that BEVs can become competitive with ICEVs if battery costs are below $84/kWh, electricity costs are below $0.18/kWh, and comparable diesel costs follow a "high" scenario based on the 2022 AEO.[234] Other analysis by Ledna et al.[235] found that a 500-mile BEV can become competitive on a total cost of driving basis with diesel at a battery cost of $80/kWh or lower, electricity costs of $0.18/kWh to $0.20/kWh, and diesel costs of $3.75/gallon or higher, without vehicle purchase incentives. Finally, analysis by ICCT found that BEVs could become cost competitive at battery costs as high as $123/kWh,

electricity costs between $0.15/kWh and $0.30/kWh, and diesel fuel prices of $4.13/gallon or higher.[236] For fuel cells, Ledna et al.[237] found that FCEVs can become competitive at fuel cell costs below $90/kW, hydrogen prices below $4/kg to $5/kg, and diesel prices above $3.71/gallon. These results are highly sensitive to the diesel prices assumed and the presence of incentives. To achieve FCEV competitiveness, HFTO has set a target of $80/kW for fuel cell component costs by 2030 for a 275-kW fuel cell system and a levelized cost of hydrogen (inclusive of production, delivery, and dispensing) of $4/kg by 2031.[238]

More vehicle component research is needed to address long-haul technology challenges. Developing viable and cost-competitive ZEVs must be a priority for DOE research efforts on batteries, fuel cells, and vehicles. Research and development on lower-cost vehicle components and manufacturer scale-up are needed to lower vehicle purchase costs. Demonstrations and data collection are also needed to guide investments, including demonstrations of the viability of high-speed corridor charging and refueling. Clean hydrogen production costs must also fall for fuel cells to become competitive, and electricity must be delivered at operationally appropriate speeds and cost-competitive rates for BEVs. **The development of a national freight corridor infrastructure network should also be a crucial priority for ZEVs.**

Intercity Passenger Buses

Intercity buses, or "over-the-road buses" are buses designed for transporting passengers over long distances. In the United States, they serve more than 500 million passenger trips per year and are 1% of total MHDV emissions.[239, 240, 241] In the United States today, there are approximately 25,000 buses operated by nearly 1,400 privately owned carriers.[242]

Intercity buses share similar characteristics as long-haul freight trucks, including large vehicle size (typically 35 feet or more in length) and long route distances,[243] which may necessitate rapid en route refueling. Several ZEV demonstrations have already occurred in the United States, including testing of BEVs on routes between Los Angeles and San Diego, Sacramento and San Francisco, and Portland and Seattle.[244] FCEVs and sustainable liquid fuels are also being tested and deployed along long-distance routes in Europe.[245, 246] While further research is needed on typical route and operational characteristics to better understand charging/refueling requirements, decarbonizing intercity buses will likely require similar strategies as long-haul decarbonization, including deployment of high-speed recharging/refueling infrastructure along key routes. BEVs and FCEVs are both candidates for this segment and may play complementary roles, with BEVs electrifying shorter routes with more flexible refueling schedules and FCEVs electrifying longer routes. Sustainable liquid fuels may also play a role for routes where technology characteristics or infrastructure needs make zero-emission buses a less competitive prospect and can help decarbonize these vehicles in the near term as zero-emission solutions emerge. It is important to note that supporting intercity and transit bus expansion can also lead to decarbonization by displacing emissions from LDVs; section 4.3 and the Convenience and Efficiency Action Plans discuss such strategies in greater detail.

4.2.3.3 Near-Term Actions

Coordinated action among federal, state, local, and private actors will be needed to support expanded ZE-MHDV deployments in the near term (before 2030) and transitions toward 100% ZE-MHDV sales in the medium-term and long-term (2030 to 2040 and beyond). Actions should address ZEV needs at different phases of market development, supporting expansion from early adoption into broader market acceptance. Needed actions are as follows:

1) **Support demand for early-market ZE-MHDVs** through existing state and federal incentive programs. Vehicle purchase incentives are an important policy tool in early market phases to encourage early adoption and production scale-up,[247] particularly in market segments such as local and regional return-to-base where ZEV adoption is accelerating. Thanks to legislation including BIL and IRA, historic levels of funding are available for ZE-MHDV purchase across multiple federal agencies. These include:

   - EPA's Clean School Bus Program, the Clean Ports Program, and funding under the Diesel Emissions Reduction Act
   - DOT's Low or No Emission Grant Program for transit buses and funding under the Congestion Mitigation and Air Quality Improvement program
   - Tax credits and incentive programs established by IRA and BIL
   - State and local incentives, such as California's HVIP, the EnergIIZE Commercial Vehicles Project, the New York Truck Voucher Incentive Program, and others, can provide additional funding for vehicle purchases.

   These and other incentives are further described in Chapter 6.3: Funding and Financing for Deployment.

   Loan guarantees are another tool to address the present-day uncertainty surrounding ZEV financing. Today, commercial lenders may be risk averse due to uncertainty surrounding the resale values of ZEVs. State and federal governments can consider loan guarantees for ZEV financing to reduce risks for lenders while more data becomes available.[248] DOE's Loan Programs Office (LPO) has the authority under the Title 17 Clean Energy Financing Program to offer loan guarantees for clean energy technologies, including partial guarantees of commercial debt.

2) **Support ZEV manufacturing scale-up and supply chains.** ZEV and component technology manufacturing scale-up (including batteries and fuel cells) is crucial to enabling cost savings through economies of scale. Working in concert with vehicle purchase incentives to support ZEV demand, manufacturing incentives can further spur increased production of vehicles, components, and charging/refueling infrastructure equipment. Incentives established by IRA invest billions of dollars in domestic supply chains, critical minerals recycling, and clean energy manufacturing that can be used to scale ZEV manufacturing programs. Standardization—for example, of transit bus models—can also enable vehicle cost reductions, and the purchase of standard vehicle models is recommended by DOT for applicants to its Low and No Emission Grant Program.[249] Section 5.2 further discusses programs and targets for ZEV manufacturing scale-up and the scaling of supporting charging/refueling infrastructure and fuel production components.

3) **Simultaneously, support expansion of ZEVs into new applications,** including the specialized vehicles and work trucks market segment and the long-haul market segment. The following actions are needed to expand ZEV adoption to these segments:

a. **Continue research on ZEV technologies.** This includes research on component technologies—batteries and fuel cells—with the aim of reducing costs, improving efficiency, improving specific energy (for batteries), and other performance goals, as well as improving manufacturing efficiency and production processes. Research is also needed on vehicle efficiency (including component lightweighting and aerodynamic efficiency), vehicle durability and reliability to meet the needs of long-haul operations, and charging/refueling station infrastructure. This research will also enable reduced cost and improved performance for ZEVs in more established market segments. DOE funds an array of programs aimed at improving ZEV technologies and infrastructure, as discussed in section 4.2.1. Section 5.5 further expands on ZEV research, analysis, and data needs and ongoing funding programs to support these efforts. Part of this effort should include **target setting**—that is, the identification of component cost and performance needs for ZEVs to become economically and operationally viable in all MHDV market segments.

b. **Support ZEV development and demonstration** for specialized and long-distance operations. Few full ZEV models are available for specialized operations today. The federal government should encourage partnerships between OEMs, auxiliary equipment manufacturers, and vehicle integrators to develop and demonstrate full ZEV models, including evaluating full-range, auxiliary load, towing, and trailing needs to serve median and full-market use cases**. Demonstrations of BEVs and FCEVs along real-world long-haul freight corridors** are also needed, including demonstrations of high-speed charging and refueling infrastructure. The data collected from such demonstrations will be invaluable in determining relative strengths and weaknesses of each technology and in dictating future research and investment needs. Such demonstrations will also benefit intercity buses, which will have similar range and refueling requirements. The SuperTruck 3 Initiative, a partnership between DOE and vehicle manufacturers, includes funding for development and demonstration of BEVs and FCEVs in MD and long-haul freight market segments.

c. **Expand data collection and analysis.** Expanded data collection efforts are needed to inform analysis on ZEV duty cycles, vehicle power requirements, and infrastructure needs across a wide range of applications, which can in turn direct investments into ZEV prototypes and be used in research on ZEV loads and infrastructure needs. This is particularly important for specialized vehicle applications where data is sparse. NREL's FleetREDI database contains information about driving patterns for a range of specialized, passenger, and freight MHDVs. However, this repository or other such tools could be expanded to include additional analysis:

    i. **Expanded data collection for ZEV duty cycles and operations, particularly for long-haul** and **specialized vehicles and work trucks.** This should include energy demand from auxiliary loads. **Additional data on long-haul operations,** such as telematics data and surveys of driver operations, is needed to better characterize the portion of operations that are suitable for ZEVs with today's technology and drive further research and development aims. Additional data is also needed on the towing needs of HD pickups.

    ii. **Evaluate real-world PHEV energy consumption and emissions for specialized vehicles.** Studies of specialized vehicles conducted before 2020 have shown that PHEV demonstrations can produce substantial emissions reductions compared to diesel vehicles by electrifying auxiliary loads. However, questions remain on the extent to which such vehicles will be operated in electric mode in real-world fleets. The federal government, in partnership with private actors, should support research (surveys and data collection efforts) on real-world PHEV operations to evaluate the extent to which these

vehicles achieve emissions reductions. Support for such vehicles should be tied to data reporting requirements to achieve these aims.

4) **Support charging/refueling infrastructure deployment and a cost-competitive clean fuel supply.** This is a critical component of supporting competitive ZEV TCO and operational viability for all market segments and is discussed in section 4.2.4.

5) **Existing federal regulatory actions** by EPA and the National Highway Traffic Safety Administration (NHTSA) will lower emissions across all MHDVs and improve fuel economy for lighter vehicles. These are discussed in the section below.

These actions, working in conjunction with one another and enabled by strong collaborative partnerships across governments, industry, academia, and nonprofits, along with additional actions such as education and workforce development, can ensure that the MHDV Plan's core goals are met—including expanding ZEV sales into the broader market (30% sales by 2030 and 100% by 2040), achieving full ZEV cost parity with ICEVs in the long-haul heavy-duty truck market segment by 2030, and achieving phased build-out of a national corridor charging/refueling network.

The SuperTruck 3 Initiative

The SuperTruck 3 Initiative is a DOE-funded public-private partnership with HD vehicle manufacturers aimed at advancing MHDV decarbonization. While prior iterations of the SuperTruck Initiative focused on improving HD truck freight efficiency, specifically 18-wheeler fuel efficiency (SuperTruck 1 and SuperTruck 2), the current program focuses specifically on decarbonizing MHDVs. A total of $127 million has been awarded to five projects led by PACCAR Inc., Volvo Group North America LLC, Daimler Trucks North America LLC, Ford Motor Company, and General Motors LLC. SuperTruck 3 participants are developing full battery-electric and fuel cell power trains for MHD trucks to demonstrate 75% reduction in GHG and air pollution emissions as well as reduce the TCO when compared to a 2020/2021 model-year truck. The program also includes demonstrations of MW charging stations.[250, 251]

Regulatory Actions

Federal Emissions Standards

Federal emissions standards set by EPA will spur near-term ZE-MHDV adoption and emissions reductions across all market segments. EPA's mission is to protect human health and the environment. The Clean Air Act requires EPA to set and enforce emissions standards for new motor vehicles, including MHDVs. In March 2024, EPA released final rulemaking governing NO_x, $PM_{2.5}$, and GHG emissions from passenger cars and light- and medium-duty (Class 2B to 3) trucks[252] and GHG emissions from heavy-duty (Class 4–8) trucks and buses.[253] These standards govern new vehicles sold during MYs 2027 to 2032. EPA standards are performance based and technology neutral—that is, they specify emissions standards rather than mandating the choice of a particular technology. Compliance with new EPA standards can be achieved using ZEVs, HEVs, PHEVs, alternative-fuel ICEVs, and emissions control technologies on conventional ICEVs.

New EPA standards were developed through a multiyear process of technology assessment, regulatory cost and benefit analyses, and engagement with a multitude of stakeholders, including community groups and environmental justice organizations; engine and vehicle manufacturers and suppliers; labor groups; and state, local, and Tribal governments. For MD vehicles (including commercial Class 2B/3 trucks included in this action plan), these standards are anticipated to reduce GHG emissions by 44% by MY 2032 compared to MY 2026. For HD vehicles, these regulations are anticipated to reduce GHG emissions by 25% to 60% by MY 2032 compared to MY 2026 across covered vehicle classes and applications.

Federal Fuel Economy Standards

In June 2024, NHTSA, a DOT agency, announced final fuel economy standards for heavy-duty pickup trucks and vans (HDPUVs).[254] HDPUVs include Class 2B and 3 work trucks and vans, which may fall under the local and regional return-to-base and specialized vehicles and work trucks market segments within this MHDV Plan. These standards will cover MYs 2030 to 2035 and will mandate that fleet average fuel efficiency increases by 10% per year between MY 2030 and 2032 and 8% per year between MY 2033 and 2035. Like EPA standards, these standards are performance based and technology neutral. NHTSA estimates that these standards will result in a cumulative 5.6 billion gallons of avoided gasoline consumption between now and 2050 and cumulative emissions reductions of 55 MMT of CO_2 during the same period.

4.2.4 ENERGY INFRASTRUCTURE AND CORRIDORS

Charging/refueling infrastructure is a critical need for the success of MHDV ZEVs. Regardless of the technology adopted, a transition to ZEVs will require major infrastructure investments, covering production/generation, transport/distribution, and dispensing of electricity and hydrogen at dedicated stations suitable for various MHDVs. These investments require careful planning, technology harmonization, sequencing, and coordination across multiple stakeholders, including fleets, vehicle and infrastructure manufacturers, retail fuel providers and depot operators, landowners, electric utilities, hydrogen producers and distributors (for FCEVs), local planning offices, and state and federal regulatory agencies. Federal leadership on infrastructure-related developments and deployment can help ease barriers, promote collaboration among these stakeholders, and ensure support at all stages of network development, including developing standards, protocols, and best practices; funding early deployments; convening stakeholders; providing technical assistance; providing long-term vision; and more.

Different ZEVs will have different charging/refueling infrastructure needs. Most ZE-MHDVs are unable to use existing LDV charging/refueling infrastructure due to size, on-site clearance and turning radii, refueling capacity (for FCEVs), and trailer requirements.[255, 256] Charging and refueling infrastructure must meet the mobility needs of a given MHDV use case, including adequate charging/refueling speed and cost given specific fleet duty cycles. Some MHDV operations with high downtime may benefit from low-speed, long-duration charging—for example, overnight at depots. Others may require high-speed charging or hydrogen refueling to minimize disruptions to operations. Fleet considerations will also impact charging/refueling options—for example, smaller fleets may be more reliant on semiprivate or public stations.

Planning for charging and refueling infrastructure is essential. Thousands of sites will be needed, requiring major investments and complex coordination between multiple stakeholders—including fleets, retail fuel providers, depot operators, logistics centers, utilities, site owners, and local and state regulatory agencies. Moreover, supplying ZEVs with electricity and hydrogen will require long-term planning for energy production and transport. U.S. utility-scale electricity generation in 2023 totaled 4,178 terawatt-hours (TWh).[257] Studies by NREL and ICCT have estimated that MHDV BEVs may add between 8 and 70 TWh of electricity demand to the grid by 2030 (less than 1% to 2% of 2023 demand).[258, 259, 260] Early-market demand for ZE-MHDVs and charging/refueling infrastructure will be concentrated in states and counties that are likeliest to succeed first,[261] such as regions with high freight activity and market-enabling regulations, as well as provide reasonable expectations of predictable utilization for charging and refueling infrastructure. By 2050, demand from BEVs could range between under 200 TWh to over 500 TWh, or 4% to 11% of 2023 electric generation.[262, 263] If the majority of long-haul vehicles are FCEVs, projections suggest that future hydrogen demands could be as high as 9 MMT by 2050.[264] If this hydrogen is produced from electrolysis using grid electricity, this could add roughly 400 TWh of electric demand, or roughly 10% of 2023 generation (assuming electrolyzer efficiencies based on HFTO technical targets[265]). Substantial uncertainty is inherent in these estimates, which will depend on the number of BEVs and FCEVs adopted, their usage (annual miles traveled), their fuel efficiency, and (for FCEVs) the way hydrogen is produced.

While the expected number of BEVs and FCEVs in different applications is unknown and will depend on future technology progress, manufacturer investments, fleet needs, fuel costs and availability, and other factors, the need to provide hydrogen refueling and BEV charging solutions is growing rapidly. This infrastructure should meet the following criteria:

- Be appropriate for MHDV duty-cycles and vehicle needs
- Be cost-effective (supporting TCO competitiveness for fleets)
- Be deployed in a timely manner as ZEVs are adopted and sequenced in such a way that minimizes stranded and underutilized assets.

Planning for deployments must start now to address the substantial investments needed, regardless of the balance of BEVs and FCEVs. Planning needs include charging/refueling network and corridor planning and prioritization, transmission, distribution, and capacity upgrades, as well as coordination and regulatory alignment at local, state, and federal levels. Infrastructure plans must also be sensitive to changing market conditions, especially emerging adoption patterns between BEVs and FCEVs and evolving vehicle charging/refueling needs as well as other trends impacting future electricity and energy systems. Planning must be undertaken by different sets of stakeholders from myriad private-sector industries and at all levels of government. Private actors can begin to plan for their near-term needs, such as constructing local depots and regional stations to support current adoption. More coordinated action between government and private actors is likely to be needed to support national corridor network development. The following sections lay out strategies to deploy BEV charging and hydrogen refueling networks, with a section focusing specifically on corridor charging and refueling networks for long-haul ZEVs. Near-term actions are laid out in the final section.

4.2.4.1 BEV Charging Infrastructure

Current Status and Charging Infrastructure Needs

Estimating current MHDV charging station deployment is challenging due to limited data availability. The Alternative Fuels Data Center (AFDC) reports that as of June 2024, there were 87,731 available and planned L2 and direct current fast-charging (DCFC) stations in the United States. Of these, 521 support access to MD (Class 3–5) vehicles and 155 to HD (Class 6–8) vehicles[266] (figure 14). However, this estimate may not consider all private "behind-the-fence" (BTF) charging installations; for example, in the state of California alone there were 215 completed and 13 projected private charging infrastructure stations for school buses as of June 2024.[267] Despite this uncertainty, it is clear that substantial scale-up of MHDV charging infrastructure will be needed—at private, semiprivate, and public locations in regional hubs and along corridors.

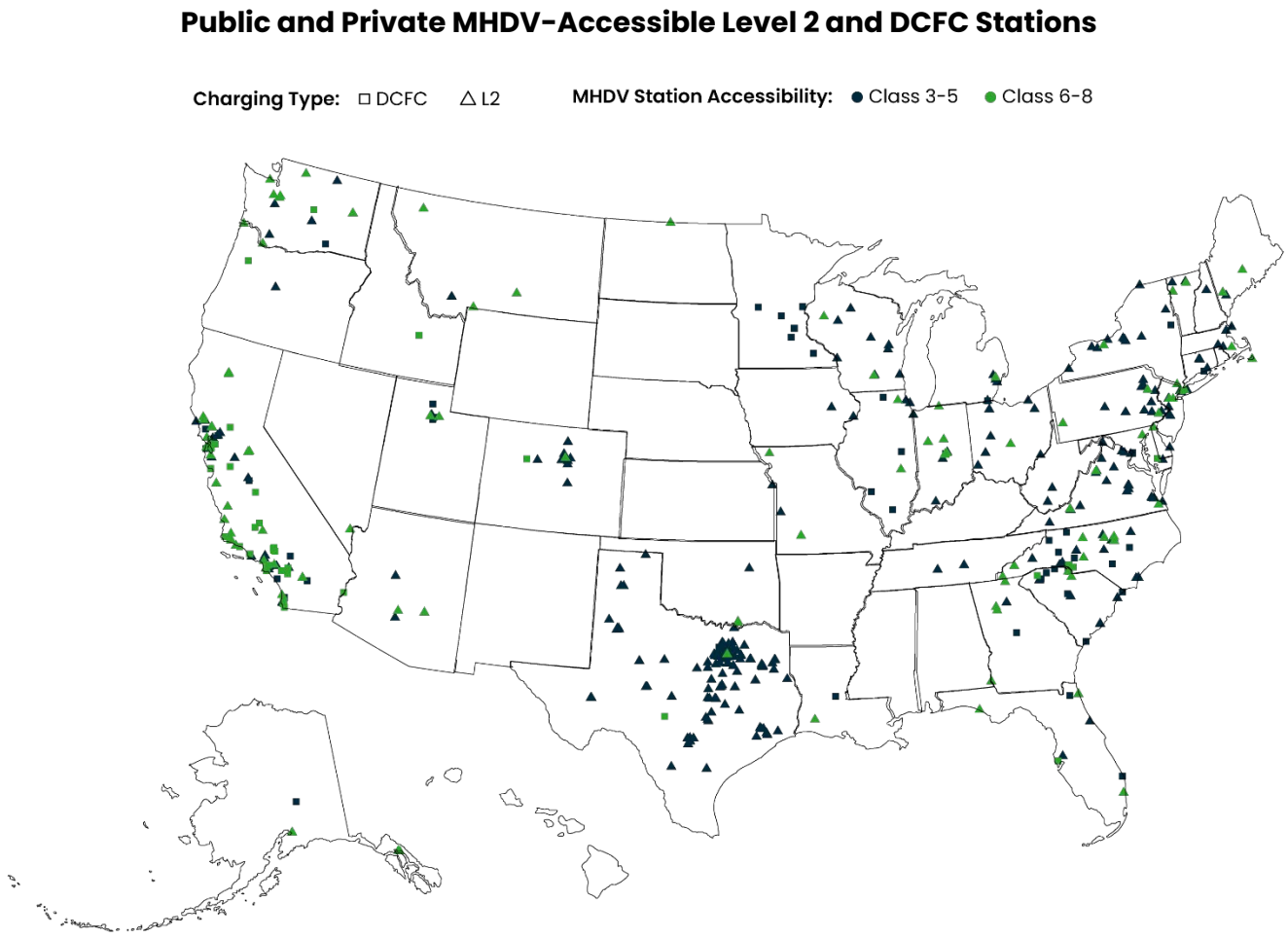


Figure 14. Public and private MHDV-accessible L2 and DCFC stations. Additional private stations may be deployed but not reported in AFDC data. Source: AFDC.[268]

Charging infrastructure needs will vary by MHDV market segment. If present-day patterns hold, a majority (94%) of ZEVs are likely to operate in Local and Regional Return-to-Base and Specialized Vehicles and Work Trucks market segments, accounting for approximately 61% of MHDV energy consumption.[269] Evidence from the 2021 VIUS shows that more than 80% of MHDV trucks in all market segments have access to a home base, suggesting that a depot-based charging model may be feasible for many of these vehicles as they convert to BEVs (Share of MHDVs with Access to Home Base by Class and Market Segment Figure 15). **Depot charging** is convenient (requiring no unplanned downtime) and cost-effective (charging at lower power levels reduces both cost of charging equipment and cost of electricity[270]), and it avoids placing unnecessary stress on batteries. Depot charging can also enable shifting and managing charging to reduce peak loads and adjust to high-cost periods. Some vehicles, particularly Class 2B/3, may rely on L2 charging at residential locations, like LDVs. These forms of charging are being deployed today, requiring large near-term investments and planning.

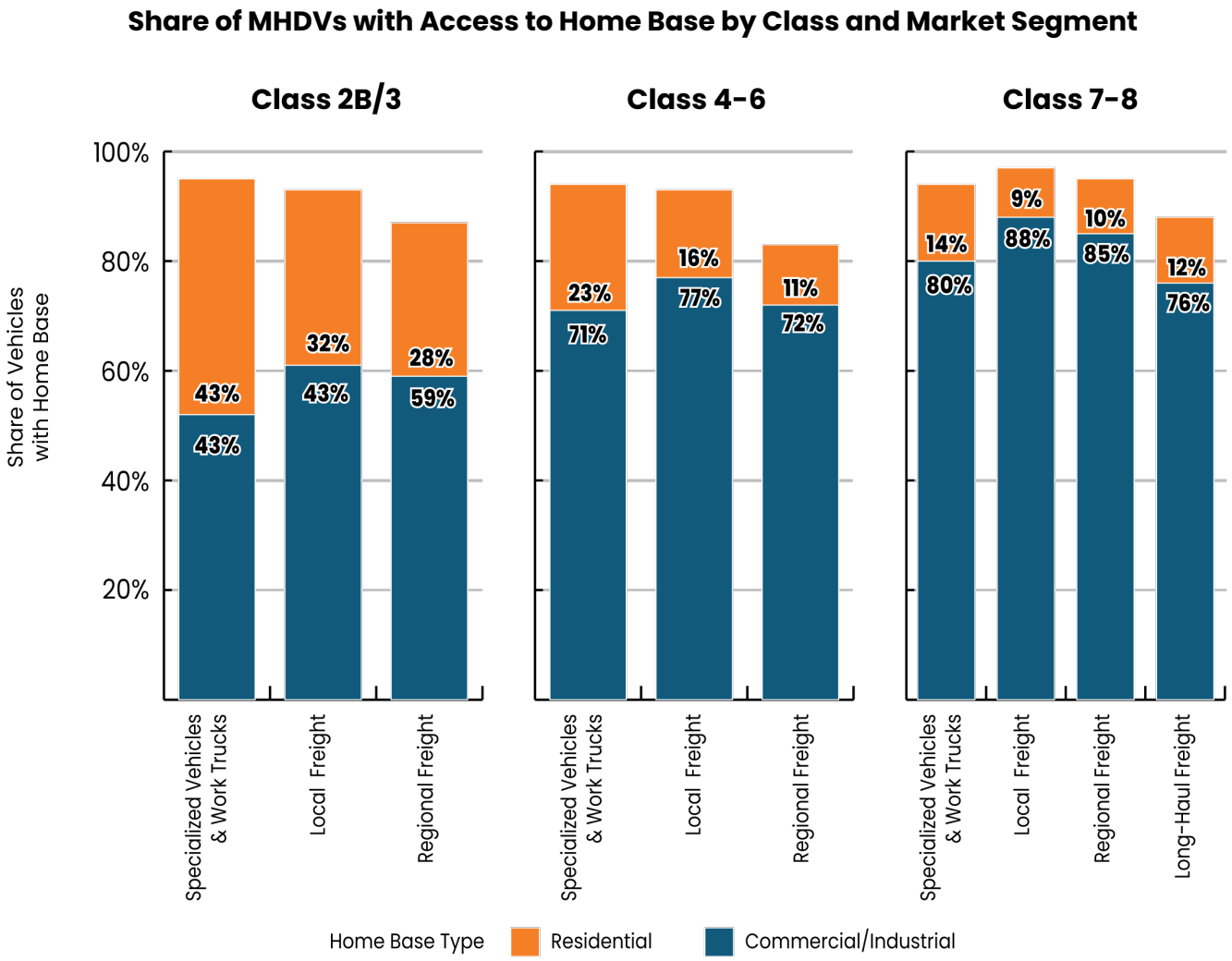


Figure 15. Share of MHDVs with access to home base by class and market segment. "Residential home base" refers to vehicle home base location in private residences. "Commercial/industrial home base" refers to vehicle home base located in commercial/industrial sites. Source: VIUS.[271]

For BEVs traveling longer distances (longer regional passenger and freight, or vocations with high power demands), opportunity charging during midshift breaks or en route charging may be needed to extend range. Atlas Public Policy estimates that between 10% and 25% of local and regional BEV fleets may use en route or opportunity charging at speeds of 150 kW to 350 kW.[272] Regional, publicly accessible charging stations can meet these needs and address gaps for small fleets and vehicles traveling longer routes, as well as provide a starting point for the development of a broader national network. Strategically located stations—near ports, warehouses, distribution centers, and other freight activity hubs—with adequate station size and parking requirements to support larger vehicles and trailers will be needed to supply en route charging at speeds of 150 kW and above outside of depots and provideaccess to long-duration charging for small fleets. Finally, for long-haul BEVs, a national network of corridor charging stations will be needed.

The decision to use each of these different charging options will be determined by both cost and ability to meet the transportation needs of an MHDV user/fleet/operator. Table 3 summarizes charging options for different MHDV applications.

Table 3. BEV Infrastructure Requirements by Market Segment and Technology. Adapted from Sujan et al. (forthcoming).[278]

Market Segment	Charging Options	Operational Considerations

Local and Regional Return-to-Base	• Off-Shift Charging:
	  ○ BTF depot charging (larger fleets)
	  ○ Semiprivate or public access charging (smaller fleets)
	• On-Shift Charging:
	  ○ Opportunity charging at loading/unloading zones
	  ○ High-speed en route charging
		• Right-sizing battery and charging infrastructure
		• Downtime and route predictability
		• Grid capacity/siting
		• Co-located generation and storage
		• Charging flexibility

Specialized Vehicles and Work Trucks	• Off-Shift Charging:
	  ○ BTF depot charging (larger fleets)
	  ○ Semiprivate or public access charging (smaller fleets)
	• On-Shift Charging:
	  ○ Opportunity charging at work sites
	  ○ High-speed en route charging
		• Right-sizing battery and charging infrastructure, considering towing and auxiliary loads
		• ePTO plug-in opportunities at work sites
		• Other considerations same as Local and Regional Return-to-Base

Long-Haul Passenger and Freight	• Off-Shift Charging:
	  ○ Truck stops/travel centers
	• On-Shift Charging:
	  ○ High-speed en route charging
		• National network needed
		• Rural infrastructure considerations (grid capacity, transmission/distribution)

National-level analysis of medium- and heavy-duty battery electric vehicle (MHD-BEV) charging needs has been conducted by several groups. ICCT[273] projects that 522,000 overnight (50–150 kW) chargers, 28,500 fast (350 kW) and 9,540 ultrafast (2 MW) chargers will be needed by 2030 to support 1.1 million MHD-BEVs. Atlas Public Policy[274] projects that 470,000 to 564,000 10–150 kW depot charging ports, 254,000 L2 home charging ports (to support some Class 2B/3 trucks), and 7,000 to 32,000 150–350 kW opportunity charging ports will be needed in 2030 for a vehicle fleet of roughly 1 to 1.5 million MHD-BEVs. Around 10,000 to 19,000 2-MW fast-charging ports are also estimated to be needed to meet 2030 demands (including long-haul needs). Regional variation in adoption is expected in the early market, with adoption clustered in states with ZEV-friendly policies, such as California.[275] For example, at the state level, the California Energy Commission estimates a need for 109,497 depot chargers ranging from 20 to 150 kW and 5,527 en route chargers ranging from 350 kW to 1 MW by 2030 to support the deployment of 155,000 MHD-BEVs.[276] Preliminary analysis by NREL projects a need for 2.3 million additional charging ports by 2032 across five states (California, Oklahoma, Illinois, Pennsylvania, and New York) to support the adoption of 3.9 million PEVs of all vehicle classes (including LDVs).[277] Further analysis is needed at local, regional, state, and national levels to refine estimates of charger needs and assess potential grid impacts of MHD-BEV adoption.

Costs of charging stations will vary depending on charging types, station capacity, and required grid upgrades. Atlas Public Policy estimates nationwide hardware and project costs at between $100 billion and $160 billion (excluding electrical upgrades covered by utilities).[279] Fleets can minimize costs by choosing appropriate forms of charging and right-sizing BEV batteries and charging infrastructure to meet operational needs. Strategies such as VGI (including managed charging) and co-location of renewable power and storage technologies may also help minimize costs for both fleets and station operators. These are discussed in the next section.

Charging Types and Technologies

Charging stations provide a location at which PEVs, including BEVs and PHEVs, can connect to a power source to recharge their batteries. Two primary technologies are used to recharge MHD-BEVs:[517]

- L2 charging equipment, which uses alternating current (AC) at 208 or 277 volts, generally supporting power of 2.9 to 19.2 kW, with higher-power L2 equipment on the horizon.
- DCFC equipment, which enables rapid charging at speeds above 19.2 kW. Typical DCFC speeds today range from 50 to 500 kW, depending on equipment capabilities, with stations under development to enable speeds of 1 MW or more.

MHDV charging needs are defined by both the speed at which charging occurs and the operational context of charging. They can be broadly classified into three categories (Figure 13):

Depot charging: L2 and DCFC ranging from 10 to 150 kW that occurs during off-shift periods at a centralized location (such as a depot).[518, 519] Depots are typically private-access, BTF charging. Smaller fleets may charge at semiprivate or public locations.

- **Opportunity charging**: charging that takes place midshift during times when the vehicle is not operating, such as while loading or unloading a vehicle. This typically uses DCFC at speeds between 50 and 350 kW.
- **En route charging:** high-speed charging during normal operations, ranging from speeds of 150 kW to 1 MW or more.

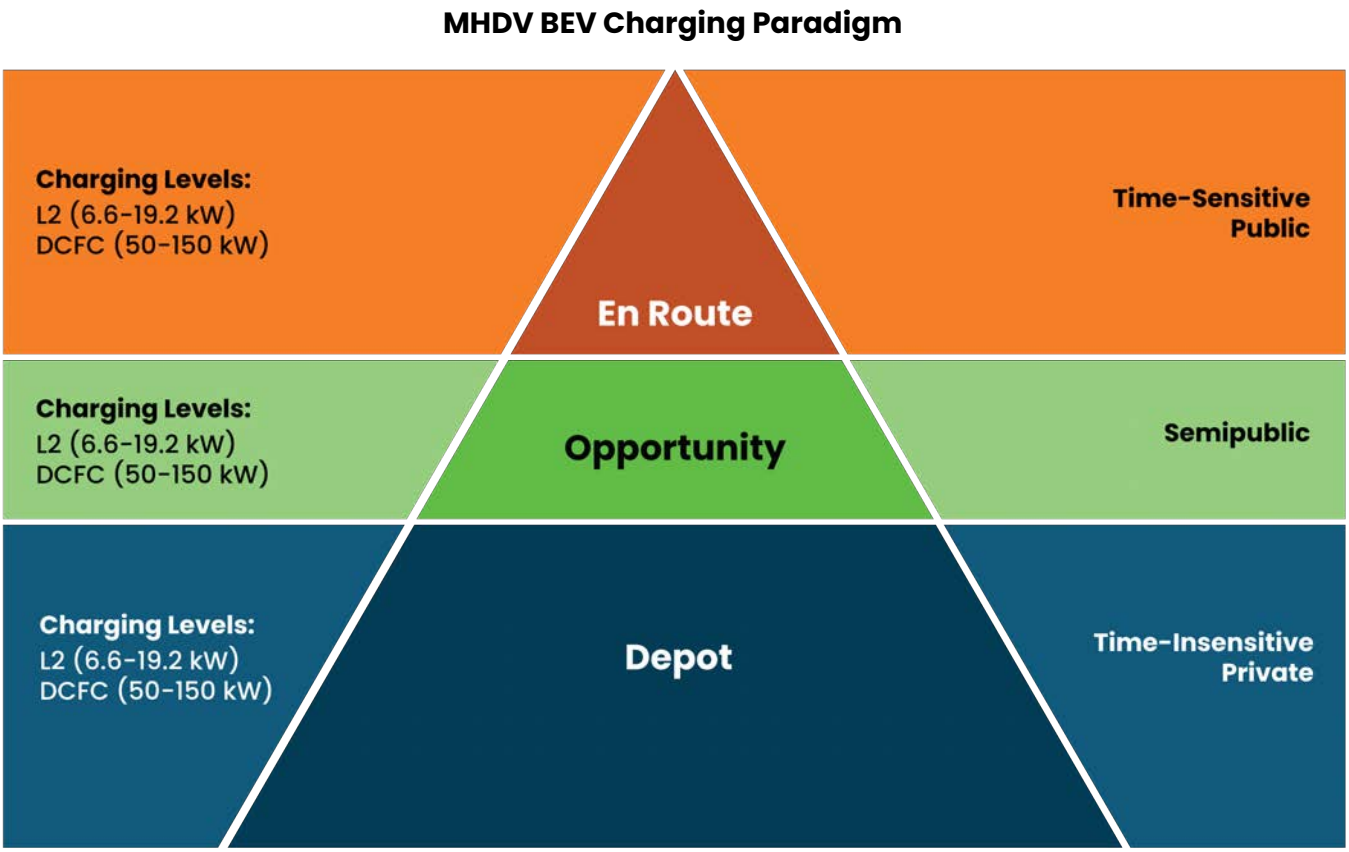


Figure 16. MHD-BEV charging paradigm. Source: Muratori and Borlaug,[280] inspired from National Research Council.[281]

Emerging technologies may also offer charging solutions beyond charging stations. In general, these technologies are in early phases, with more research and development needed to become competitive. Electrified road technologies, including **dynamic wireless power transfer (DWPT)** and **overhead catenary charging,** present opportunities for MHDVs to charge while being driven or during brief stops. DWPT uses a magnetic field to charge BEVs while traveling, without the need for wires or cables.[282] Federal- and state-funded research is underway to develop and test DWPT technologies.[283, 284] Overhead catenary charging supplies power to a vehicle via an overhead wire constructed over a roadway. Multiple pilot projects of this technology have taken place in the United States and Europe, though more research is needed to assess cost and feasibility.[285] **Battery swapping** is an additional potential solution which allows MHD-BEVs to rapidly replace a depleted battery with a charged one, relieving the driver of the need to stop and recharge the battery. Multiple demonstrations have been conducted in China, and U.S.-based companies are developing battery-swapping technologies.[286, 287, 288] Finally, **mobile fuel cells** may offer a solution in remote and infrastructure-limited locations to supply portable power using hydrogen fuel cell technologies, which can generate electricity to charge BEVs. This technology has been trialed in the United States through funding by the U.S. Department of Defense.[289]

BEV Charging Infrastructure Strategies

Charging infrastructure deployment presents both challenges—including long deployment times, station accessibility, and information barriers—and opportunities, such as managed charging, which can reduce charging costs and provide benefits to the grid. Coordinated actions between

private actors and across all levels of government will be needed to address barriers and ensure continued expansion of the BEV charging network. The following are strategic priorities for BEV charging infrastructure:

Reducing long deployment timelines will be a key need to support continued BEV adoption. Early-market estimates of BEV infrastructure deployments range between 6 months for stations to 4 years or more depending on grid upgrade requirements.[290, 291, 292] Reasons for delays include challenges with local permitting processes, delays in receiving equipment, staffing shortages, site design changes, and more. Some fleets have reported that utilities and local agencies lack appropriate processes for handling their requests; in other cases, fleets themselves have faced challenges in navigating the process and determining their own charging needs.[293] The need for grid upgrades is a frequently cited reason for delays, which may be accompanied by complex processes and the need for back-ordered equipment such as distribution transformers.[294] Higher-capacity stations are more likely to require upgrades or additions to electrical infrastructure, such as feeder breakers, transformers, and substations.[295] These upgrades may substantially delay charging station deployment and impose high costs for fleets. Strategies to reduce deployment timelines include **streamlining and standardizing permitting processes, modernizing regulatory frameworks** to enable utilities to plan for charging station deployments, and **improving forecasting data and tools** used in grid planning.

Addressing information asymmetries and coordination challenges are a key contributor to deployment timelines. The charging deployment process today is a complex multistep process and involves collaboration between fleets, utilities, site owners, electric vehicle supply equipment (EVSE) providers, and regulatory agencies.[296, 297] Fleets must assess their charging needs when making requests to their electric utility, including the number and speed of the chargers they order, their requested capacity, estimated utilization patterns, and their anticipated flexibility to participate in programs such as off-peak charging and managed charging. Site owners are also major players in this decision; as fleets often rent spaces for depots, the site owner may take long-term responsibility for the charging installation.[298] Utilities must assess average and peak loads for the depot, load variability, impacts on grid resiliency, and needed upgrades to grid infrastructure. Finally, depending on the project, state and federal regulatory agencies may be involved through incentive or grant programs or in station approval processes. **Tools and guidance** are needed to facilitate information sharing and best practices across all parties.

Ensuring adequate station utilization is another consideration, particularly for regional stations. Depot and opportunity charging investments will be undertaken by private actors such as fleets, port terminals, and distribution centers, typically occurring at the time when new BEVs are purchased. Other business models such as independently operated stations and charging-as-a-service providers—which provide access to chargers for fleets with minimal up-front investment—may also play a role in supplying regional charging. High levels of utilization are needed to defray up-front costs and ensure competitive rates for customers.[299, 300] Careful sequencing of stations is needed to match station deployment with MHD-BEV demands.

Ensuring station accessibility for small fleets—particularly for depot charging—is another key need. Depot charging enables low-power charging, which provides benefits to fleets such as reduced charging costs, reduced battery degradation, and the ability to participate in managed charging programs that may provide additional revenue streams. However, many small fleets face barriers such as high up-front costs of obtaining equipment and installing stations, a lack of resources and expertise when interacting with utilities, difficulties navigating various federal and state funding opportunities, or lack of a

permanent depot or ability to install charging infrastructure entirely.[301] Given the critical role that small fleets play in the U.S. trucking industry (44% of all on-road vehicles operate in fleets of 10 vehicles or less), special efforts are needed to ensure access to overnight depot charging for these fleets.

Managed charging and VGI can help address many of the core challenges surrounding charging station site energization, including reducing infrastructure installation costs (by reducing the amount of needed capacity), reducing energy costs (by shifting demand to off-peak times), and providing flexibility to utilities. These systems are of particular interest for MHD-BEVs with flexible charging schedules and long periods of downtime, such as school buses and local freight operations. See "Managed BEV Charging Can Provide Many Benefits for Fleets and Utilities" for a full description of benefits.

Innovative charging solutions, such as microgrids and co-located storage, are emerging as mechanisms to provide BEV charging during periods between vehicle delivery and permanent charging station installation and as long-term BEV charging solutions. The private sector has recognized the need for investments in microgrids and on-site storage to meet immediate BEV charging demands. Recent examples include Prologis Mobility and Performance Team – A Maersk Company's recently completed microgrid project in Torrance, California that provides 9 MW of capacity and 18 MWh of storage to meet the needs of an HD truck fleet, powered by a combination of hydrogen and natural gas.[302] Another recent example is WattEV's deployment of a solar-powered BEV truck stop in Bakersfield, California—the first example of a solar-powered truck stop in the United States.[303] Transit agencies are also receiving funding to deploy renewable microgrids to power zero-emission transit buses, including projects in California and Maryland.[304] Such solutions may provide opportunities to charge vehicles at lower costs, reduce electricity emissions, and enhance resiliency during grid outages; however, long-term viability will depend on station sizing and economics.[305] Further research and pilot deployments can evaluate the environmental and economic benefits of innovative charging solutions.

Managed BEV Charging Can Provide Many Benefits for Fleets and Utilities

What Is Managed Charging?

Managed BEV charging systems use control mechanisms to optimize BEV charging in response to grid conditions while meeting vehicle charging needs. This ultimately puts downward pressure on electricity rates and reduces charging costs while also supporting the electricity system to improve reliability and reduce cost of electricity for all consumers.[520] Unlike traditional charging models, where BEVs begin charging as soon as they are plugged in, managed charging systems intelligently control the charging process—including starting, stopping, and modulating charging rates responding to signals from utilities. Bidirectional charging (in which vehicles can also be discharged to power other loads such as buildings or inject electricity back into the grid, also called vehicle-to-everything [V2X]) is related to but distinct from managed charging and can further support the grid and create additional revenue streams for BEV users.[521]

Implementing managed charging techniques has many benefits for fleets and the grid, including reducing needed infrastructure investments and grid upgrades (and associated timelines), reducing stress on electricity systems—especially valuable during extreme or emergency events—increasing asset utilization and efficiency, and more.[522, 523] Studies have shown that BEV managed charging can offer substantial value along these various value streams.[524, 525, 526]

- **Cost Savings:** Managed charging can lower BEV charging electricity costs, furthering the BEV cost competitiveness. At the same time, managed charging reduces the need for electricity assets and the cost of managing them, reducing electricity costs for all.
- **Enhanced Infrastructure Utilization:** Efficient use of existing infrastructure defers or eliminates the need for investments in new grid capacity, reducing costs and energization timelines.
- **Grid Stability:** By intelligently managing the demand for electricity, these systems help maintain grid stability. They reduce peak demand periods, which can prevent blackouts and reduce the strain on the grid infrastructure.
- **Environmental Impact:** Managed charging can align charging times with periods of high renewable energy availability, optimizing the use of renewables and reducing emissions.
- **Dynamic Load Balancing:** These systems can distribute the charging load across multiple BEVs to avoid overloading the electric grid. This ensures that the available grid capacity is used efficiently, preventing the need for costly infrastructure upgrades.
- **Integration with Distributed Energy Resource (DER) and Long-Duration Energy Storage:** Managed charging can prioritize the use of renewable energy or other DERs combined with long-duration storage systems for BEV charging. By coordinating with energy storage systems and real-time data on renewable energy production, it ensures that BEVs are charged when green energy is abundant, reducing reliance on conventional fuels.

Approaches to implement managed charging can be utility controlled, such as demanding response programs; using third-party aggregation of grid edge assets; or employing approaches on the customer side of the meter, such as automated load management for fleet charging. In all cases, any desirable grid service needs to be paired with incentives to compensate customers for providing flexibility in their charging needs.[527] Guiding principles that ensure the success of managed charging programs include the following:[528]

- **Customer centered** – Managed charging prioritizes user needs, such as required departure times and charging levels
- **Appropriately incentivized** – Offers value for providing charging flexibility
- **Universal value** – Good for BEV drivers, the grid, and other electricity consumers
- **Seamless and interoperable** – Based on accepted and streamlined standards and protocols.

Integrating managed charging systems with existing grid infrastructure requires advanced technology and seamless communication protocols. Ongoing research and development are focused on creating interoperable systems that can work across various platforms. Effective implementation of managed charging also requires supportive policies and regulations, including market mechanisms that incentivize smart charging practices and support the development of necessary infrastructure. Finally, educating consumers and other stakeholders about the benefits of managed charging is crucial for widespread adoption.

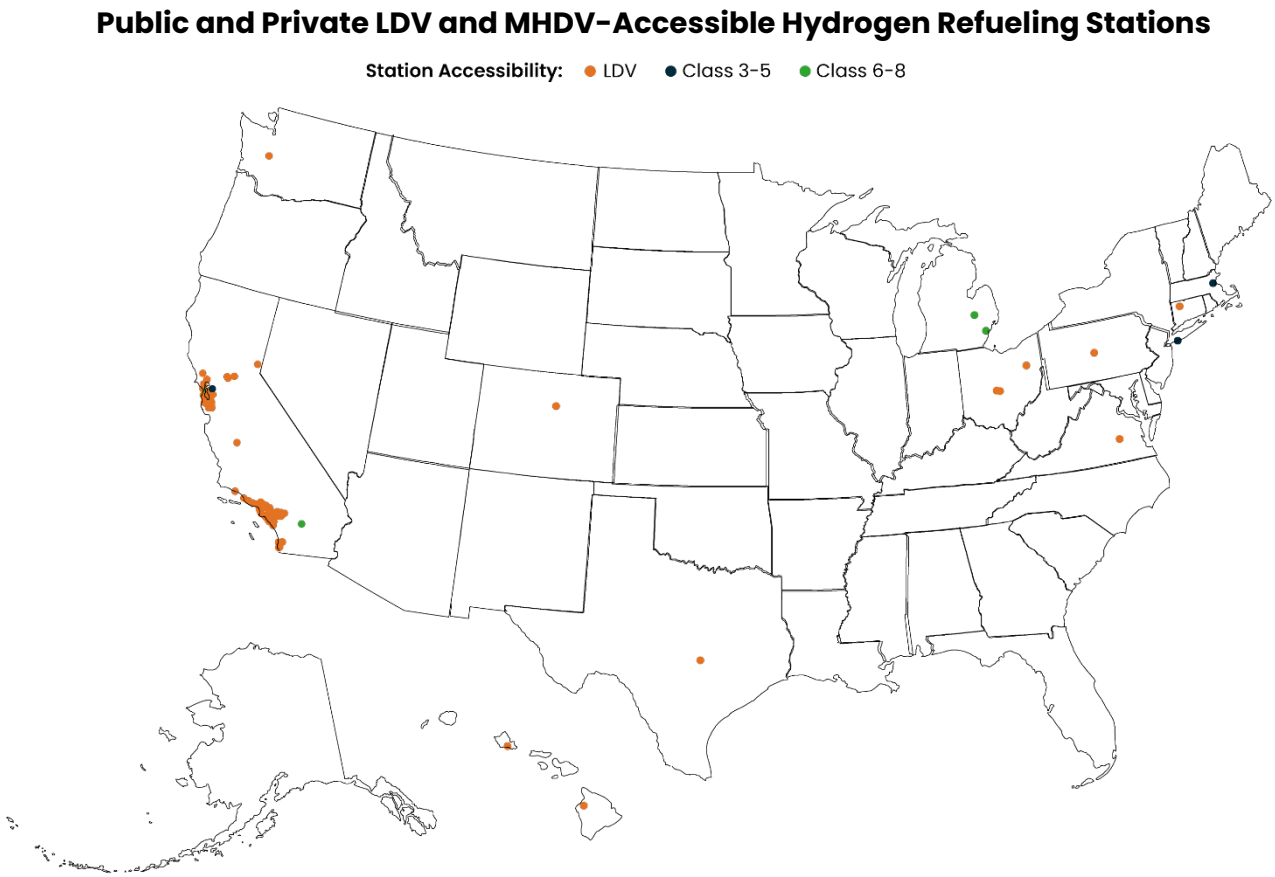


Figure 17. Public and private LDV and MHDV-accessible hydrogen refueling stations. Additional private stations may be deployed but not reported in AFDC data. Source: AFDC.[306]

4.2.4.2 Hydrogen Refueling Infrastructure

Current Status and Infrastructure Needs

As with BEVs, estimating current hydrogen refueling station deployments is challenging. AFDC reports a total of 101 hydrogen refueling stations in the United States as of June 2024.[307] Of these, eight are accessible to MD vehicles (Class 3–5) and five are accessible to HDVs (Class 6–8) (Figure 17). However, this data likely excludes private BTF fueling stations, such as a recently opened hydrogen truck stop at the Port of Oakland.[308] The California Energy Commission reports an additional 28 planned public MHDV hydrogen stations under development in California as of 2024.[309] Improved data collection in partnership with fleets and station operators will be needed to track station deployment more accurately.

Like BEVs, FCEVs will also have varied refueling infrastructure needs. Depot-based refueling models may be suitable for large fleets, with many trucks serving local and regional operations. On the other hand, a more traditional "gas station" model of a regional network of publicly accessible stations may also serve local and regional needs. Vocations such as transit buses, longer and multishift regional freight, and specialized applications with high sustained power demands, long-range requirements, and low downtime may use FCEVs for some or all operations. A national network of high-speed charging or refueling stations along corridors (en route) will be needed for long-haul operations, whether BEV or FCEV.

Table 4. FCEV Refueling Infrastructure Requirements by Market Segment and Technology

Market Segment	Refueling Options	Operational Considerations
Local and Regional Return-to-Base	• Private depots (larger fleets) • Semiprivate / public-access refueling ("gas station model")	• On-site hydrogen production • Co-located renewables and storage
Specialized Vehicles and Work Trucks	Same as Local and Regional Return-to-Base	
Long-Haul	• High-speed refueling network can serve off- and on-shift needs	• National network needed • Rural infrastructure considerations (hydrogen production/distribution)

Projections of future hydrogen station needs are limited. The ICCT projects that between 7,500 and 22,000 stations could be needed by 2050 to meet demands from long-haul trucks, depending on the FCEV adoption rate assumed (85,000 or 250,000 vehicles). This would require a nationwide daily hydrogen production capacity of between 3,000 and 8,000 metric tons.[310] The California Energy Commission projects that anywhere from 1 to 601 stations could be needed in California by 2030 and between 11 and 2,000 by 2035, reflecting substantial uncertainty about future MHDV FCEV demand in the state.[311] Further research and analysis are needed to estimate station requirements across all MHDV market segments, considering trade-offs with BEVs.

Today's station costs are estimated at roughly $5 million per station for transit bus stations serving up to 25 buses per day.[312] Research and development are ongoing into future station designs that could reduce the costs of both station deployment and hydrogen production.

What a Hydrogen Refueling Station Looks Like: Energy and Storage Needs

A hydrogen fueling station is a complex system with integrated components designed to safely produce, store, compress, cool, and dispense hydrogen fuel. Each component plays a crucial role in ensuring the efficient and safe operation of the station, ultimately supporting the adoption and use of hydrogen as a clean fuel alternative. The main components are described here.

Hydrogen Production or Delivery

On-site hydrogen production systems may use electrolyzers, which use electrical energy to split water into hydrogen and oxygen. Electrolyzers can be based on proton exchange membrane, alkaline, or solid oxide technology. Electrolysis is a method of hydrogen production with zero end point emissions, although emissions may be generated upstream through the electricity production process.[313] More research is needed on

the cost-effectiveness of co-locating hydrogen production via electrolysis with on-site renewables and storage. Alternatively, hydrogen can be produced via thermal conversion processes such as steam methane reformers, which produce hydrogen through a reaction between methane and steam.[314] Carbon capture and storage is needed to reduce the CO_2 emissions generated from this process.

If hydrogen is not produced on-site, it can be delivered today through compressed gas trucks, which transport hydrogen gas at high pressures (typically 200–500 bar), or through cryogenic liquid hydrogen trucks, which deliver hydrogen in liquid form, stored at cryogenic temperatures (-253°C). In the future, pipelines may also deliver hydrogen in gaseous form. Reducing hydrogen delivery costs is a key priority for lowering the total levelized cost of dispensed hydrogen.[315]

Overview of Hydrogen Refueling Station Components

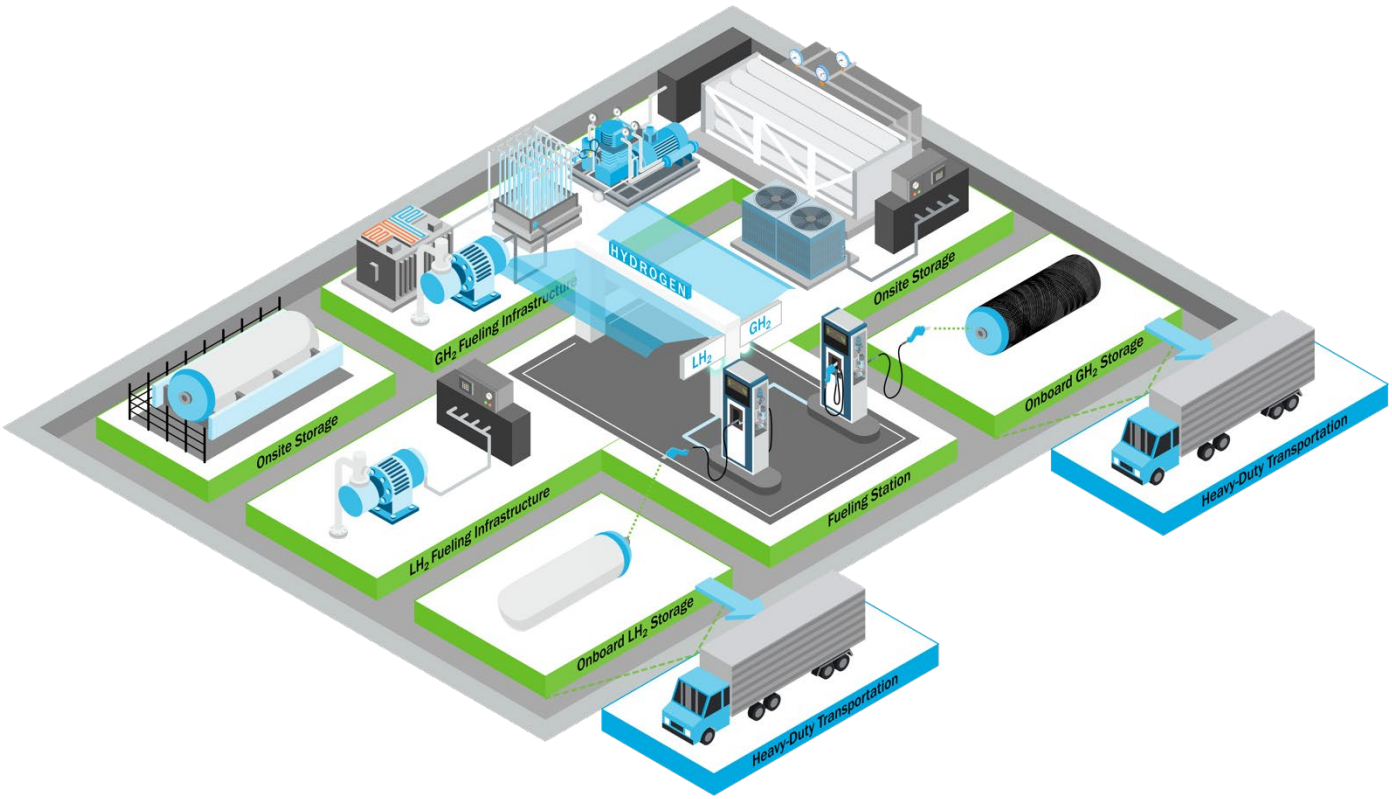


Figure 18. Overview of hydrogen refueling station components. Source: HFTO

Storage Tanks

After hydrogen is produced, it must be stored on-site at the station. Hydrogen storage is a multifaceted challenge involving various methods, each with its own advantages and limitations. Compressed gas hydrogen storage and liquid hydrogen storage are well-established and widely used, while solid-state and chemical storage offer promising alternatives with unique benefits. Large-scale geological storage provides a solution for bulk hydrogen storage. In compressed gas hydrogen storage, hydrogen is stored in high-pressure cylinders made from materials like steel or carbon fiber composites. Liquid hydrogen storage involves storing hydrogen in its liquid form, which requires maintaining the hydrogen at cryogenic temperatures. This method is used to increase the density of hydrogen for applications where high storage efficiency is crucial.[316, 317] The choice of storage method depends on the specific application, required storage capacity, safety considerations, and economic factors. Robust safety systems are essential across all storage technologies to ensure the safe and efficient use of hydrogen as an energy carrier. HFTO has set near-term research efforts and targets to improve current storage technologies, reduce costs and leakage, and improve safety.[318]

Hydrogen Compressors, Pumps, and Fuel Dispensers

Hydrogen compressors and cryopumps compress hydrogen to the necessary pressures for dispensing to vehicles. These include various technologies, such as diaphragm compressors, reciprocating piston compressors, and cryopumps.[319, 320] Precooling units are also used to cool compressed hydrogen gas before dispensing to compensate for the heat of compression during fueling.[321] Fuel dispensers deliver hydrogen to vehicles. They include equipment to ensure secure, leak-free connections between vehicles and tanks, metering systems to measure the amount of hydrogen dispensed, hoses, breakaways, and nozzles.[322] Hydrogen-powered MHDVs can refuel rapidly—at speeds of up to 10–15 minutes. Research on high-speed hydrogen dispensing is ongoing to enable lower cost and faster refuel times similar to diesel, with an ultimate target of 10 kg per minute.[323]

Safety Systems

Hydrogen safety systems are an integrated set of technologies and protocols designed to detect, prevent, and respond to potential hazards associated with hydrogen use. These will be essential for vehicle infrastructure associated with hydrogen refueling, service, maintenance, and inspection. Key components include advanced leak detection sensors, automatic shutoff valves, effective ventilation systems, flare stacks, pressure relief devices, fire suppression systems, emergency shutdown mechanisms, explosion-proof equipment, grounding and bonding measures, comprehensive safety protocols, and robust monitoring and control systems.[324, 325] These components work together to ensure the safe operation of hydrogen fueling stations and related facilities.

DOE funds research and development efforts aimed at improving all aspects of hydrogen fueling stations. With continued research and demonstrations, deployment of safe, reliable, and high-speed hydrogen dispensing stations can be achieved to meet regional and long-haul MHDV needs.

Hydrogen Refueling Infrastructure Strategies

While BEVs have been the targets of early energy infrastructure deployment efforts, FCEVs will also require a buildout of hydrogen refueling stations both at regional levels and along corridors. Near-term strategies include scaling and **reducing the cost** of clean hydrogen production and distribution, continuing research, demonstrating **station technologies**—including compression, storage, and dispensing—and investing in **strategic station deployments**.

Hydrogen production and distribution. Clean and cost-effective hydrogen production and delivery mechanisms are essential for FCEV success. While for electricity, production and distribution

infrastructure is already well characterized, hydrogen faces the added challenge of the need to develop distribution systems from the ground up. Clean hydrogen can be produced on-site or at central plants through several pathways, including electrolysis powered by renewables, steam methane reforming with carbon capture and storage, and others. Delivery mechanisms may include compressed or liquid hydrogen truck transportation, gaseous delivery through pipelines, transportation through hydrogen carriers such as NH_3 and methanol, or on-site delivery mechanisms. DOE has set ambitious near- and long-term milestones for the levelized cost of clean hydrogen production, including a target of $2/kg for production of clean hydrogen by electrolysis by 2026 and $1/kg by 2031 and a levelized cost target of $7/kg in the 2024–2028 timeframe and $4/kg in the 2029–2036 timeframe, inclusive of production, delivery, and dispensing.[326] These targets are consistent with conditions for overall FCEV cost competitiveness in regional and long-haul applications.[327, 328]

Station Research and Development Needs. While LDV hydrogen stations have been demonstrated, challenges remain for cost-effective station design. Research is needed into advanced **off-board storage technologies** to reduce costs and minimize losses, **high-speed hydrogen dispensing** at high pressures, and reduced cost and improved reliability of compression and dispensing technology. This research can enable lower-cost, more reliable hydrogen stations in the future.

HFTO's Multi-Year Program Plan describes this research agenda and technology-specific targets in further detail.[329] Critical development efforts and support will continue to be required in efficient and safe hydrogen storage spanning a wide range of disciplines, from materials science to systems engineering, and requires a coordinated effort to address technical, economic, and safety challenges. These include:

1) **Materials development**, including high-strength materials that can withstand high pressures, low temperatures, and hydrogen embrittlement without degrading over time; lightweight composites to reduce the weight of storage tanks, which is particularly important for transportation applications, liquid carriers, and hydrides; and adsorbents that can store hydrogen at lower pressures and moderate temperatures with higher densities.
2) **Storage technologies**, including improving the safety, durability, and cost-effectiveness of high-pressure hydrogen storage systems, advancing cryogenic storage technologies such as liquid hydrogen and subcooled liquid hydrogen to minimize boil-off losses and improve insulation techniques, developing and optimizing cryo-compressed hydrogen storage systems that combine the benefits of both cryogenic and high-pressure storage, and exploring innovative solid-state hydrogen storage concepts that can achieve high densities at ambient temperatures and pressures.

3) **Compatibility and standardization**, establishing standards and protocols for hydrogen storage and dispensing (high-flow hydrogen fueling) systems to ensure compatibility and interoperability across different applications and industries.
4) **Safety and risk management**, including improving hydrogen leak detection technologies, safety protocols, and materials testing.
5) **Efficiency and cost reduction**, including reducing the energy requirements for hydrogen compression, liquefaction, and storage and innovating manufacturing processes to lower the production costs of storage tanks and related infrastructure.
6) **Environmental impact**, including conducting life cycle analyses to assess the environmental impact of different hydrogen storage technologies and researching sustainable materials and processes for hydrogen storage systems to minimize environmental impact and enhance recyclability.

Aligning station refueling capacities with MHDV needs. Analysis by the U.S. Council for Automotive Research has identified gaps in the development of hydrogen refueling stations to meet MD needs. Many of today's LD stations do not support dispensing for vehicles with greater than 10 kg of onboard storage capacity, while MDs may have storage capacities of 10 to 35 kg. Conversely, HD stations may support refueling for higher storage capacities but are inaccessible to MDs.[330] Additional research, standards development, and station deployments and upgrades are needed to address this gap.

Station utilization and siting. Regional FCEV station deployment will require similar considerations as BEVs surrounding timing and utilization. For centrally supplied stations, utilization rates (defined as the ratio of dispensed hydrogen to station capacity) of 80% or greater and dispensing volumes of 8 metric tons per day or more will be needed to reach costs of below $7/kg by 2030. On-site production may result in more favorable economics and lower required utilization rates—assuming that production costs of $1.5/kg or less can be achieved.[331] These economies of scale mean that **regional stations must be co-located with high levels of hydrogen production and vehicle deployment to be competitive—beginning with Clean Hydrogen Hubs.**

The Regional Clean Hydrogen Hubs Program

The Regional Clean Hydrogen Hubs Program was established by BIL, which sets aside $8 billion for the establishment of hydrogen hubs across the United States. These hubs, which are currently being established by the Office of Clean Energy Demonstrations (OCED) in DOE, are aimed at establishing regional hydrogen production centers, connective infrastructure, and end-use demands. Figure 19 shows a map of hubs selected for award negotiations through this program. As of July 2024, three of the seven selected hubs have been awarded:

- The Appalachian Hydrogen Hub, which will receive up to $925 million in federal investment and has a goal of producing over 1,500 metric tons of clean hydrogen per day.
- The California Hydrogen Hub, which will receive up to $1.2 billion in federal investment and aims to power 5,000 or more fuel cell electric trucks and 1,000 or more fuel cell electric buses, cargo-handling equipment at three large ports, one large marine vessel, and turbines and stationary fuel cells. In addition, this hub plans to deploy 60 HD fueling stations.
- The Pacific Northwest Hydrogen Hub, which will receive up to $1 billion in federal investment and plans to produce at least 335 metric tons of clean hydrogen per day.

Along with other criteria outlined in the National Zero-Emission Freight Corridor Strategy (discussed in the next section), hydrogen hubs should be prioritized when making near-term station deployment decisions.

Map of Planned Regional Hydrogen Hubs

Figure 19. Map of planned regional hydrogen hubs. Source: OCED.[332]

4.2.4.3 Corridor Charging and Refueling

Current Status and Infrastructure Needs

Establishing a **national network of high-speed corridor charging/refueling stations** is essential to enable the adoption of long-haul ZEVs. Today, there is substantial uncertainty about long-haul ZEV technologies, which are still in the early stages of development. Both BEVs and FCEVs may play a role in the Long-Haul market segment, but further demonstrations are needed to understand the trade-offs between technologies and their feasibility under real-world conditions.

Not all infrastructure needs to be deployed at once. Focusing early deployments in key freight hubs and corridors where ZEVs are likely to have the greatest market penetration avoids issues of stranded assets and underutilization of stations.[333, 334, 335] Several studies have assessed near-term charging network needs for long-haul BEVs. ICCT finds that to provide corridor charging every 50 miles along NHFN, 844 charging stations of up to 6-MW capacity each would be needed in 2030, which could accommodate 85% of long-haul needs.[336] A study by Atlas Public Policy estimates that 4,151 to 5,785 charging ports would be needed for minimum and full build-out of the NHFN, at speeds of 2 MW.[337, j] Analysis remains limited for FCEVs; in the previously referenced study, ICCT estimates that between 7,500 and 22,000 hydrogen refueling stations could be needed by 2050 to meet long-haul needs, but they do not estimate a minimum viable network.

Given substantial market uncertainty and the need for strategic investments, the federal government has released the National Zero-Emission Freight Corridor Strategy ("Corridor Strategy")[338] to guide phased investments in corridor charging.

[j] Charging stations may have multiple ports. ICCT (Ragon et al, 2023) also estimates that 9,500 ultrafast [2-MW] chargers will be needed in 2030.

The National Zero-Emission Freight Corridor Strategy

While depot and opportunity-charging decisions are being made by fleets in alignment with their electrification timelines, early-market deployments of publicly accessible local, regional, and corridor en route charging and refueling stations will be determined by a combination of government incentive structures and private investments. For such deployments, **alignment on timing of infrastructure supply with ZEV adoption is essential**.

The Corridor Strategy provides a framework for prioritizing corridor infrastructure deployments. The strategy is laid out in four phases (Figure 20).

- **Phase 1** of the strategy (covering 2024 through 2027) prioritizes establishing corridor infrastructure in key freight hubs covering 12,000 miles (23%) of the NHFN. This infrastructure can also satisfy regional charging/refueling needs.
- **Phase 2** (covering 2027 to 2030) prioritizes connections between freight hubs, covering 19,000 miles and 36% of the NHFN. Criteria for designating Phase 1 and 2 hubs and corridors include freight volumes, port and intermodal facility locations, ZEV deployments, environmental burdens, and the presence of state incentives.
- **Phase 3** (2030 to 2035) expands the charging network, covering 37,000 miles, or 72% of the NHFN.
- **Finally, Phase 4** (2035 to 2040) completes the national network, covering 49,000 miles, or 94% of the NHFN, aligned with 100% nationwide ZEV sales targets by 2040.

The MHDV Plan recommends that **the Corridor Strategy criteria be adopted by federal agencies when making funding decisions for corridor infrastructure.** To overcome early-market barriers such as high capital costs and low utilization, this plan further recommends **deploying ZEV corridor infrastructure in priority hubs and corridors**, as well as **near-term demonstrations of corridor charging/refueling effectiveness** to build market confidence in long-haul ZEVs.

Additional Corridor Strategy Areas

In addition to supporting **sequenced deployment of charging/refueling networks**, demonstrating **high-speed charging infrastructure along corridors** and considering the need for **standards for charging/refueling speed** are necessary to promote industry investment. Fuel-specific factors such as grid impacts for high-speed charging and the development of hydrogen production and distribution networks must also be considered for BEVs and FCEVs, respectively.

Corridor demonstrations. While BEVs and FCEVs have been demonstrated and deployed in local and regional applications, demonstrations are still needed for long-haul vehicles and infrastructure, which will enable the collection of critical data on technology development needs and operational suitability. Demonstrations of vehicle technologies and infrastructure are ongoing through the SuperTruck 3 Initiative, including for both FCEVs and BEVs.

En route charging/refueling speed. Because en route charging/refueling takes place when the vehicle would otherwise be operating, speed is important to minimize disruptions to delivery schedules. For BEVs, studies suggest that charging speeds ranging between 1 and 2 MW will be necessary to remain within 5% to 10% of operating margins for HD fleets.[339] The Megawatt Charging System (MCS), which defines an industry standard to enable charging at up to 3,000 amps and 1,250 volts (up to 3.75 MW), is under development,[340] with successful demonstrations of prototype technologies in 2020 and final standards expected in 2024.[341] For hydrogen-powered vehicles (including FCEVs and hydrogen ICE), standards for fast hydrogen fueling are also under development.

HFTO has set hydrogen fill rate targets of 8 kg per minute by 2030 and an ultimate target of 10 kg per minute;[342] the latter has been demonstrated in experimental conditions by NREL for gaseous hydrogen refueling.[343] Rapid liquid hydrogen refueling has been demonstrated by industry.[344] Further research and standards development are needed to finalize fast hydrogen fueling standards.

Overview of the National Zero-Emission Freight Corridor Strategy Phased Infrastructure Deployment Timeline.

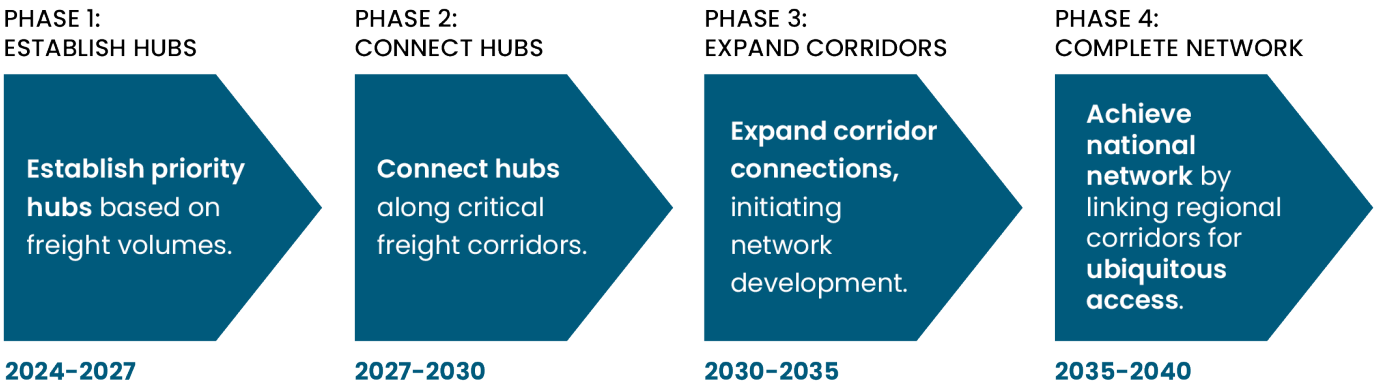


Figure 20. Overview of the National Zero-Emission Freight Corridor Strategy phased infrastructure deployment timeline. Source: The U.S. National Zero-Emission Freight Corridor Strategy.[345]

4.2.4.4 Near-Term Actions

Actions to deploy charging/refueling infrastructure will require collaboration among private actors and across all levels of government. These include the following:

Support Cost-Competitive Charging/Refueling Prices

BEV-Focused Actions

Action 1: Support research, demonstration, and deployment on managed charging and VGI. More research and demonstrations are needed to identify how managed charging can benefit different types of MHDV fleets and vocations, to advance standards and best practices for implementation, and to enable widespread deployment at scale. Collaboration between private, local, state, and federal actors can accomplish the following:

- **Develop standards and communication protocols for managed charging and VGI.** Similar to the application of smart charge management network architecture for LD vehicle charging required in the National Electric Vehicle Infrastructure Standards and Requirements, communication protocols used as the basis for the Combined Charging System are planned for within the MCS.[346] Vehicle and charger manufacturer implementation of the smart charging in the MCS use case will be essential for safely and securely managing demand at MHDV charging locations. Private actors and the federal government can continue research collaborations to develop these standards.
- **Demonstrate the benefits of managed charging and VGI.** Early demonstrations of VGI in ESBs have shown that VGI can provide substantial revenue streams for school districts and provide resiliency benefits to utilities.[347] However, more research is needed in collaboration between fleets, utilities, and state and federal governments to identify benefits in other MHDV applications and to assess the values provided by BEV managed charging along the entire electricity system. The SuperTruck Charge program will provide $72 million in funding to demonstrate VGI and managed charging solutions at depots near key ports and logistics centers and at truck stops along travel corridors. The Joint Office of Energy and Transportation (Joint Office) will also support investments in managed charging implementation and standards development through the Communities Taking Charge Accelerator.
- **Share learnings and support decision-making to enable widespread adoption.** Technical assistance, best practices, and learnings from real-world demonstrations can be shared among private and government actors.

Action 2: Support manufacturing scale-up for chargers and electrical equipment (private actors and federal government). Manufacturing scale-up for equipment such as chargers and transformers can ensure that these components are affordable and available on a timely basis. The Qualifying Advanced Energy Project Credit (Provision 48C) of the IRA provides tax credits for U.S. manufacturing projects supporting these and other components of a clean energy economy. To date, 35 projects across 20 states—including several in grid component manufacturing—have received support. Since 2021, companies in the United States have announced production capability of at least 60,000 fast chargers per year.

FCEV-Focused Actions

Action 1: Support low-cost clean hydrogen production and scale-up. Several currently funded federal programs support clean hydrogen production and scale-up in line with stated hydrogen cost milestones. In addition to the previously discussed Regional Clean Hydrogen Hubs Program, other incentive mechanisms include tax credits enacted by the IRA for hydrogen and fuel cell technologies. Examples include the Clean Hydrogen Production Tax Credit (45V) (defined as hydrogen produced with a well-to-gate CI of <4 kg carbon dioxide equivalent/kg

hydrogen)[348] and the 30C Alternative Fuel Vehicle Refueling Property Credit. Additional programs funded by HFTO aim to advance manufacturing technologies of electrolyzers, reduce cost of electrolysis at scale, and reduce the cost of fueling components. These activities are further discussed in the *U.S. National Clean Hydrogen Strategy and Roadmap* and *Pathways to Commercial Liftoff: Clean Hydrogen* reports.

Action 2: Support hydrogen station research and development priorities. HFTO lays out a detailed research agenda for hydrogen refueling stations in its Multi-Year Program Plan. Continued support and collaboration between DOE and private actors such as industry and research institutions can enable advancements in hydrogen station design and cost reductions.

Reduce Barriers and Streamline Processes for Charging Infrastructure Deployment

BEV-Focused Actions

Action 1: Align and streamline regulatory frameworks for station permitting and promote standardization. Actions by state, local, and federal governments can streamline and improve BEV charging infrastructure permitting processes, a key contributor to today's long lead times.

- At the state level, legislative efforts can be adopted in the model of California's Assembly Bills (AB) 1236 and 970 and Colorado's HB24-1173, which aim to streamline local charging infrastructure permitting and zoning processes.
- Local efforts can include adopting streamlined permitting processes and planning codes consistent with state legislation.
- Federal leadership, guidance, and technical support are also needed. Federal actions include:
    - **Providing streamlined permitting models and templates for local municipalities.** Federally developed templates and guidebooks can assist municipalities in updating their planning codes and permitting processes to incorporate BEV infrastructure and promote standardization across jurisdictions. State actions can serve as models—for example, California, New York, and New Jersey have all developed guidance for local municipalities on developing permitting best practices for EVSE.[349]
    - **Technical support and assistance** through existing federal programs can provide direct assistance to local communities as they develop best practices. Examples of recently launched programs include DOE's Charging Smart program, a pilot project that provides assistance to local governments on how to streamline BEV charging deployment, and the i2X Innovative Queue Management Solutions (iQMS) program, which provides funding to utilities to develop solutions for managing BEV charging and renewable interconnection and energization requests.

Action 2: Modernize utility regulatory frameworks and improve planning tools. These actions can enable utilities to make proactive grid-planning investments, which are crucial to accelerating MHDV site energization timelines and avoiding long backlogs for grid infrastructure upgrades.

- Efforts by utilities, civic organizations, and state and local governments can help to develop new approaches to electric grid planning that include transportation end-use demands.
- Federal efforts include providing improved tools and analysis to assist utilities in planning for the number of BEVs in their jurisdiction; load forecasting, including managed charging and other VGI approaches across different fleet sizes and vocations; and the resulting upgrades to generation, transmission, and distribution infrastructure.

Action 3: Facilitate collaboration and information sharing across utilities and fleets. Fleets, utilities, and regulatory agencies have access to data and knowledge that may be useful to other parties. The federal government and national laboratories can promote collaboration across these parties by hosting summits and workshops to bring together utilities and fleets and other stakeholders and share insights and lessons learned from early experiences. Data-sharing platforms to allow fleets to anonymously upload operational and charging information would also be useful for utilities in developing forecasting tools. This MHDV Plan establishes a near-term milestone of hosting a charging-infrastructure stakeholder workshop by 2026 to facilitate collaboration across stakeholders.

Action 4: Develop educational resources, tools, and best practices for fleets. Many fleets, particularly smaller operations, may face challenges with preparing requests for utilities and navigating local permitting processes. Tools are needed to help prepare fleets to make their charging requests, including assessing their needed capacity, the number of chargers per vehicle, and potential charging strategies. Additional assessment tools could consider the impacts of co-located storage and renewable generation resources on their requests and assist fleets in optimizing the economics of their depots. DOE, the Joint Office, and national laboratories are well-situated to provide such tools. The EVI-X suite developed by DOE, the state of California, and NREL is one example of resources developed for LD BEVs that could be extended for MHDVs. The HEVI-LOAD tool developed by Lawrence Berkeley National Laboratory and the California Energy Commission is another example of an MHDV-specific assessment tool. These tools can also be used by utilities to assist in grid-planning efforts.

Integrating electricity and transportation system plans and investments is critical to build a national network of decarbonized fueling infrastructure.

Integrating planning and investment spanning the transportation and electricity systems is essential to accelerating the cost-effective build-out of robust fueling infrastructures across the United States. The increasing demand for electricity, directly for EVs and indirectly to produce low-carbon fuels, requires a commensurate response that accelerates the accommodation of these new end uses into electricity policy, utility regulation, and the deployment of needed energy infrastructure.

A refreshed approach to electric grid planning that extends the utility regulatory compact to also include the transportation end uses critical for meeting climate change goals will help ensure the timely provision of reliable, safe, affordable, and resilient electric services. Stakeholders will need to account for new transportation loads, advanced grid management technologies, and new business models in demand forecasts and operating practices. These demand forecasts could extend the time and geography included in their capital infrastructure plans beyond those located in their service territory to reflect and support the achievement of regional or national transportation goals. Importantly, collaboration will facilitate public and private financing to ensure that new decarbonized fuels and electricity are affordable for drivers, fleets, and utility customers alike.

The federal government's longstanding research and development efforts with private industry to advance grid technology have commercialized to enable mass customer adoption of DERs operating in smarter and increasingly flexible utility systems. Deployment programs in the Infrastructure Investment and Jobs Act (IIJA) and incentives enabled by the IRA are accelerating this modernization. *Across the country, while these deployments help lay the foundations for transportation decarbonization, decision-making among the private sector, civic organizations, and the public sector at local, state, and federal levels that guide electric system regulation, planning, and operation must be harmonized to construct fuel networks benefitting all Americans.*

In IIJA, Congress recognized the importance of federal leadership in these cross-sectoral planning needs in establishing the Joint Office[k] and acknowledged the importance of coordinated multistate freight corridor compacts[l] to develop and finance infrastructure while considering the needs of a broad range of stakeholders. IIJA also established a new planning standard for transportation electrification[m] under the Public Utilities Regulatory Policies Act, enabling initial utility actions to expand rates, charging infrastructure, and investment and to recover associated costs to support EVs. Although these provisions provide initial resources, their distinct frameworks and scopes underscore the need for integrated transportation and energy planning and investment across the United States to respond to customers' growing calls to timely construct their contributions toward a broader, nationwide decarbonized fueling infrastructure network that is economical and resilient.

In implementing the action plans, utilities and transportation planners—working with their regulatory authorities and public- and private-sector entities, and in coordination with DOE and DOT—should incorporate local, regional, and national multimodal mobility goals into energy infrastructure plans by:

- ***Extending planning horizons.*** Utilities and states can continue to implement EV charging programs, specifically considering more recent technology assessments and the associated energy demanded by long-term decarbonization goals, thereby identifying cost-effective electricity system investments that support timely service to and energization of customers.

[k] 23 U.S. Code § 151 established the Joint Office to facilitate collaboration between the DOE and the DOT to study, plan, coordinate, and implement zero-emission transportation and related infrastructure. Among other responsibilities, the Joint Office is charged with technical assistance related to the deployment, operation, and maintenance of EVSE and hydrogen fueling infrastructure; vehicle-to-grid integration; data sharing to inform the network build out of EVSE and hydrogen fueling infrastructure; studying national and regional needs to support the distribution of grants; and electric infrastructure and utility accommodation planning in transportation rights-of-way; studying, planning, and funding for high-voltage distributed current infrastructure in the rights-of way of the Interstate System and for constructing high-voltage and or medium-voltage transmission pilots in the rights-of-way of the Interstate System; among other activities.

[l] Multi-state freight corridor planning, authorized under 49 U.S.C. § 70204 recognizes the right of states, cities, regional planning organizations, Tribes, and local public authorities (including port authorities) that are regionally linked with an interest in a specific nationally or regionally significant multi-state freight corridor to enter into multi-state compacts to promote the improved mobility of goods. These compacts allow for projects along corridors that benefit multiple states to assemble rights-of-way and perform capital improvements and employ a variety of financing tools to build projects, including with support of DOT.

[m] 16 U.S.C. § 2621 amended PURPA to establish a requirement wherein each state's utility ratemaking authority, electric utilities, and nonregulated electric utilities shall consider measures to promote greater transportation electrification. The standard describes measures that states and utilities could pursue, including the establishment of rates that promote affordable and equitable options for light-, medium-, and heavy-duty EV charging; improving the customer experience including by reducing charge times; accelerating third-party investments; and appropriately recovering the marginal costs of delivering electricity to EVs and charging. The provision allows states with existing EV rate standards to be exempt from the standard, and it permits states that decline to implement the standard to publish a statement of reasons.

- ***Expanding end-use forecasts.*** This allows utilities to plan for and serve anticipated electricity demand from non-road transportation end uses, including maritime, rail, and aviation, as well as associated efficiency measures.
- ***Contributing to the national network.*** State departments of transportation and utilities can coordinate to better understand and serve the electricity demand associated with inter-utility, interstate, interregional transportation to deploy electricity delivery infrastructure that meets the needs of regional and national interest mobility corridors timely and cost-effectively.
- ***Improving efficiency of capital investments.*** Utility and transportation planners can seek information from stakeholders to understand needs, priorities, and issues to maximally leverage private-sector financing and other means to reduce the marginal costs of delivering electricity to transportation end uses.

Support Deployment of Local, Regional, and National Charging/Refueling Networks

BEV and FCEV-Focused Actions

Action 1: Provide continued incentives for charging/refueling infrastructure deployment. Incentives at both state and federal levels can help defray up-front costs of infrastructure investments.

- State-level incentives, such as those provided by the California Clean Transportation Program, can support charging/fueling infrastructure deployment. Incentives may also be offered by utilities and local governments (see the AFDC for a list of state and local incentives).
- At the federal level, existing ZEV adoption grant programs such as EPA's Clean School Bus Program and the Low or No Emission Grant Program provide funding for school and transit bus purchases and charging infrastructure installations. The National Electric Vehicle Infrastructure (NEVI) Program provides $5 billion to deploy EV charging infrastructure (though the focus thus far has been on LDVs). Finally, the Charging and Fueling Infrastructure Discretionary Grant Program provides $2.5 billion to deploy EV charging infrastructure and hydrogen, propane, and natural gas fueling infrastructure in communities along designated Alternative Fuel Corridors and in other publicly accessible locations. In January 2024, DOT announced funding for seven projects totaling $249 million that have an HD vehicle focus under the CFI program. For example, the New Mexico Department of Transportation will receive $63.8 million to build two BEV charging centers for MHD commercial BEVs traveling along Interstate 10, which will serve as the nation's first network of high-powered charging centers connecting HD trucks from San Pedro ports in Southern California to El Paso, Texas. These and similar programs should continue to support charging infrastructure installations and consider the potentially greater costs associated with grid upgrades for large projects. The following are gaps in current federal incentive programs:
    - **Support for small fleets:** Federal incentive programs that target small fleets explicitly through financing and grant programs could help support access to depot charging, shared depots, and charging as a service.[350]

- **Support for private infrastructure:** Currently authorized programs support only infrastructure at public locations and for public fleets. Private infrastructure funding could enable continued support for depot charging/refueling infrastructure, and MHDV fleet expansion.

Action 2: Support infrastructure demonstrations and standards development for high-speed MHDV charging/refueling stations.

- Research partnerships between federal and private actors are ongoing through programs such as SuperTruck 3 to finalize the MCS and demonstrate MW+ charging systems. Similarly, ongoing research funded by DOE in partnership with private institutions is continuing for standards development for high-speed hydrogen refueling under real-world conditions. In addition, DOT has developed standards for direct current fast-charging stations receiving federal funding through the NEVI Program. DOT is seeking public input on whether standards are needed for MHDV charging stations receiving federal funding.

Action 3: Support sequenced deployment of MHDV charging/refueling stations. State governments and federal agencies can adopt criteria developed through the Corridor Strategy to prioritize phased deployment of corridor infrastructure investments.

Action 4: Explore opportunities for innovative charging solutions. Clean and innovative charging solutions such as renewable microgrids and co-located storage have emerged as mechanisms to provide temporary and permanent BEV charging and may also be a solution for on-site hydrogen production at hydrogen refueling stations. State and existing federal programs can explore opportunities to further support these technologies, which can serve dual purposes by providing solutions to infrastructure deployment delays and enhancing station resilience. Through the SuperTruck program, DOE has released a notice of intent, SuperTruck Charge, to fund projects relating to large-scale charging installations that use innovative approaches to alleviate potential grid capacity challenges, such as load sharing, peak shaving, delayed charging, bidirectional power flow, use of on-site DERs (e.g., battery energy storage, solar gen eration), and coordination with other on-site loads.

4.2.5 LEGACY VEHICLES AND SUSTAINABLE LIQUID FUELS

While with ZEV adoption the conventional MHDV fleet will decline in size, long vehicle lifetimes suggest that many ICEVs will remain in operation even in 2050, representing vehicles sold between now and 2040 (if U.S. goals of 100% ZEV sales are met by 2040). For a scenario with 38% ZEV sales in 2030 and 97% in 2040, Ledna et al.[351] project that up to 25% of 2050 MHDV stock could be ICEVs, demanding substantial volumes of sustainable liquid fuels to fully decarbonize. However, uncertainty remains surrounding MHDV lifetimes and flows of used vehicles between vocations in all studies aiming to model future fleet turnover and energy demands. **Improved data collection on MHDV survival rates and VMT schedules is needed to understand future legacy fleet energy demands.**

Fully decarbonizing the legacy fleet will require **sustainable liquid fuels**, which include biofuels, including RD and biodiesel. Repowers—conversions from conventional vehicles to ZEVs—may also be an option for some legacy vehicles and have been demonstrated for ESBs.[352] In addition to legacy vehicles, across all market segments there may be regional and operational constraints that make ZEVs difficult to deploy. With today's technology constraints, both BEVs and FCEVs lose performance in colder weather.[353] Furthermore, in some remote and low-population areas of the country, needed investments in grid infrastructure and hydrogen production capacity to deploy ZEVs may be economically prohibitive. Sustainable liquid fuels may also be solutions for duty cycles with high energy demands and minimal time to refuel (such as long-haul team driving operations). Trade-offs between these fuels and other technologies such as FCEVs will depend on economic and infrastructure considerations.

Starting in 2025 through 2027, the U.S. Treasury Department will offer the Section 45Z Clean Fuel Production Credit, supported under the IRA. The 45Z credit consolidates and replaces several credits scheduled to expire at the end of 2024 and has a maximum value of $1 per gallon of nonaviation fuel.

Another federal policy incentive is EPA's Renewable Fuel Standard, created under the Energy Policy Act of 2005 and further expanded by the Energy Independence and Security Act of 2007. The Clean Air Act provides EPA with authority to set renewable-fuel volume targets for calendar years after 2022 via rulemaking, which must be set with consideration of other factors, including the impact of renewable fuels on the cost to consumers of transportation and the impact of the use of renewable fuel on job creation, price and supply of agricultural commodities, rural economic development, and food prices. From 2016 to 2021, DOE supported the Co-Optimization of Fuels & Engines (Co-Optima) initiative. Co-Optima focused on improving MHDV truck performance by identifying sustainable new biobased blend stocks, engine technologies, and combustion approaches capable of reducing environmental impacts. Co-Optima demonstrated the ability of biobased blend stocks to cut life cycle GHG emissions by greater than 60%, developed a ducted fuel injection strategy that could reduce engine-out soot production by greater than 99%, demonstrated multimode combustion approaches that could cut NO_x emissions by greater than 90%, and demonstrated that using lower-sooting biobased blend stocks could reduce NO_x and soot production in diesel engines.

MHDVs fueled by sustainable liquid fuels are not ZEVs. Criteria pollutant emissions at the tailpipe include NO_x, $PM_{2.5}$, VOCs, and CO. State-funded testing measured that NO_x from state-of-the-art diesel engine technology with state-of-the-art emissions control, fueled with RD, is not statistically different from the same engine and emissions control setup fueled with petroleum diesel, and NO_x increases with the same setup fueled by biodiesel.[354] That study also concluded there were no statistical differences in PM emissions in the state-of-the-art diesel engines using biofuel or petroleum diesel, indicating that the exhaust aftertreatment systems effectively control PM. Biodiesel can be blended up to 20% without vehicle modification and reduces CO and PM tailpipe emissions, but it results in increases in NO_x emissions.[355] Further tailpipe emissions testing of

biofuels is needed, particularly to maintain datasets corresponding to the real-world biofuel blends coming to market under the conditions of new-technology diesel engines. Appendix B provides additional information about biofuels.

4.3 Convenience and Efficiency

The Blueprint provides a framework to transition to a net-zero GHG transportation system through three interrelated strategies that tackle the main drivers of passenger and freight transportation GHG emissions: (1) convenience (distance traveled between destinations), (2) efficiency (energy intensity of each mile traveled), and (3) clean (CI of the fuels). While other sections of this MHDV Plan focus on the clean strategy, this section focuses on the convenience and efficiency strategies as they relate to MHDVs.

Improved convenience and efficiency can offer substantial direct economic benefits and indirect co-benefits, ranging from fuel cost savings and lowered costs of freight movement, reduced GHG and air pollutant emissions, improvements in traffic, and easing of the transition toward sustainable fuels—for example, by reducing the level of investments needed in clean electricity capacity. The federal government is currently undertaking or has identified a range of investments in convenience and efficiency.

4.3.1 STRATEGIES TO IMPROVE MHDV CONVENIENCE

4.3.1.1 Freight Strategy Areas

Improving freight system convenience can be a powerful tool to alleviate decarbonization challenges, including by reducing route distances, which may increase the number of feasible routes for shorter-range ZEVs, and by alleviating pressure on fuel production and infrastructure systems. While market forces already provide strong incentives for fleets to optimize routing and reduce mileage where it is financially beneficial to do so, other convenience-improving measures such as large-scale investments in the built environment require coordination at state, local, and federal levels. Core freight convenience strategies include **advanced freight movement planning solutions**, including curbside demand management and off-peak deliveries. Other strategies such as land-use planning are further discussed in the Convenience Plan.

Curbside demand management. Managing the curb is an increasingly important task that can contribute to VMT reductions from freight in both urban and downtown rural core contexts. Curbside demand management can help reduce the amount of time freight vehicles search for adequate parking to make deliveries.[356] Curb management options include dedicated freight/commercial zones, parking spot reservation systems, and off-peak deliveries. Delivery lockers may also reduce curb congestion and respond to an increase in demand for deliveries. However, the decarbonization potential of delivery lockers is highly context dependent. VMT of the households to reach the lockers must be considered to properly evaluate the emissions reduction potential of this strategy.[357]

Off-peak deliveries. Truck deliveries during peak periods can worsen traffic congestion, which can lead to idling and add to vehicle-induced air quality issues. Off-peak delivery programs encourage delivery companies and receiving businesses to shift to evening or overnight deliveries. Off-peak deliveries can be made through traditional assisted delivery (i.e., people in the business available to receive delivery) or via delivery lockers or staging areas. Curb management can encourage off-peak deliveries by allowing for free or lower-cost parking during specific off-peak periods. Road usage charges and other pricing strategies, which typically charge drivers higher tolls or per-mile fees during peak periods, can also encourage shippers to shift to off-peak hours. Benefits of off-peak deliveries include increased productivity of freight operations, decreased truck traffic, and reduced freight-related environmental impacts such as reduced emissions from idling.[358]

4.3.1.2 Passenger Strategy Areas

Passenger buses are currently a small share of total MHDV travel demand, accounting for 5% of MHDV VMT.[359] Efforts to improve convenience across personal travel modes will primarily focus on LD vehicle travel demand management, and sector-wide convenience and efficiency investments may result in net increases in bus VMT as part of an overall strategy to increase transit ridership. Strategies such as **transit-oriented development, zoning reform**, and siting and development of location-efficient housing can reduce the miles needed to move passengers to their destinations and increase bus ridership.

Transit-oriented development involves supporting mixed-use development to reduce trip distances and improve the convenience of public transportation. This form of development has been shown to have high GHG emissions reduction potential—up to 31%—through mode shifting and trip reductions.[360] The federal government—including DOT and HUD—funds a number of programs aimed at financing transit-oriented development and providing guidance for local communities.

Zoning reform can help reshape the built environment to locate residential locations closer to jobs, businesses, and community locations. Many zoning codes often require strict separation of uses (e.g., residential and commercial districts), which results in car-dependent communities and longer distances between homes and destinations. Improved zoning and land-use codes—which are primarily undertaken by states and local governments—can be used in conjunction with transit-oriented development to improve overall transportation system convenience and increase transit bus ridership.[361]

4.3.1.3 Near-Term Actions

Actions to improve convenience will involve collaboration among the private sector and at all levels of government. The Convenience Action Plan presents a detailed action agenda across the full transportation sector. Highlighted actions specific to MHDVs include the following:

Private sector. Private-sector-led actions include piloting alternative delivery programs such as delivery lockers, access point locations, and off-peak deliveries, and supporting public-private partnerships for transit and rail.

Local and regional governments. Local and state governments can fund new development near transit through DOT financing programs such as the Transport Infrastructure Financing and Innovation Act and modify state and local land-use regulations to support diversified housing options near transit. Local and regional governments can also implement strategies such as managed lanes.

Federal government. The federal government can play a role by conducting research, providing financing, and developing tools and technical assistance. More detail on these actions is as follows:

- **Fund research quantifying the benefits of convenience investments** at national scales. While studies have evaluated Convenient actions in local contexts, a full quantification of their benefits at scale and comparisons between strategies remains a crucial gap in the literature. Several ongoing projects aim to address this gap. The Energy Efficient Mobility Systems-funded project National Impacts of Community-Level Strategies to Decarbonize and Improve Convenience of Mobility[362] is exploring the impacts of different strategies to improve mobility convenience across communities in the United States. This project will estimate county-level and national-scale impacts on energy, emissions, and travel to inform investments and decision-making to support transportation decarbonization. DOT also supports research related to freight and goods movement through two university partnerships: the Freight Mobility Research Institute at Florida Atlantic University and the Center for Freight Transportation for Efficient & Resilient Supply Chain at the University of Tennessee, Knoxville.

- **Finance Convenient passenger and freight projects** through existing programs, such as DOT's Transport Infrastructure Financing and Innovation Act to improve transit bus infrastructure and support transit-oriented development.
- **Develop tools and provide technical assistance** for local communities, including planning tools, guidebooks, and analysis support for developing siting and zoning reforms; implementing transit-oriented development practices; and implementing curbside management. Examples of existing guidance include the Primer for Improved Urban Freight Mobility and Delivery developed by the Federal Highway Administration (FHWA), which provides best practices for urban freight planning, and the Thriving Communities Program, which provides technical assistance to local communities to facilitate the planning and development of transportation and community revitalization activities.

More actions and programs are described in further detail in the Convenience Action Plan.

4.3.2 STRATEGIES TO IMPROVE MHDV EFFICIENCY

As with improving convenience, improving transportation system efficiency may substantially reduce the investment required to reach net-zero GHG emissions. Efficiency improvements can occur at three levels:

- **System-level efficiency** encompasses efforts to improve efficiency across transportation modes. Core strategies include **expanding affordable access to efficient modes** for passenger and freight movement.
- **Operational efficiency** involves improving vehicle and fleet operations through strategies such as idling and congestion reduction, optimized route planning, and intelligent transportation systems (ITS).
- Finally, **vehicle-level efficiency** involves energy efficiency improvements at the level of the vehicle, through the development of advanced vehicle components and materials and support for aftermarket efficiency solutions such as gap reducers, truck skirts, and low-rolling resistance tires.

4.3.2.1 System-Level Efficiency

Expanding Affordable Access to Efficient Modes

Expanding affordable access to efficient modes can improve system-wide efficiency for both passenger and freight movement. For passenger movement, this includes investments in modes such as transit buses and rail, which offer highly energy-efficient alternatives for moving people. For freight modes, this includes investments in rail, maritime, and intermodal or multimodal freight.

Freight. Expanding access to efficient freight modes involves supporting rail, maritime, and multimodal freight to ensure that freight shippers have access to affordable and energy-efficient options for moving goods. Multimodal freight involves goods movement on multiple modes of transport, such as rail and trucks. "Intermodal transport" refers to the transport of goods in a single unit, such as a shipping container, for the duration of its journey.[363]

Rail and maritime modes are the most energy-efficient means of moving freight. Inland marine shipping can move 1 ton of freight 675 miles on 1 gallon of diesel fuel, and rail can move it 472 miles by the same amount of fuel. In contrast, trucks can move 1 ton of freight 151 miles with 1 gallon of diesel.[364] However, past growth in freight transportation has been primarily concentrated in MHDVs, which grew by 8% between 2000 and 2022 on a ton-mile basis and 20% on a GHG emissions basis, while rail and maritime transportation demands increased more slowly or declined.[365, 366]

Intermodal hubs or terminals are strategically located facilities where two or more transport modes converge to transfer goods and passengers more efficiently. With optimization and other improvements, these hubs can reduce GHG and criteria pollutant emissions, as well as regional VMT.[367, 368, 369] Investments in intermodal

freight facilities can enable shippers to combine modes in the same shipment, such as using rail or maritime for the largest distance of a freight shipment and transferring to truck to reach the destination. Supporting lower-emission freight modes and intermodal facilities will give shippers more modal choices to optimize the energy efficiency of their shipments.

Due to inherent modal and infrastructure limitations, different modes cannot always substitute for one another on a one-to-one basis. Efforts to expand access to alternative modes must consider factors such as speed, flexibility, and customer service, which freight customers may prioritize when making choices between modes.[370] CAPs must also be considered when estimating the benefits and costs of expanded mode choice. Using lower- and zero-emission forms of transport should be prioritized wherever possible to maximize the benefits of expanded access to efficient freight modes. Despite this complexity, substantial benefits could be realized from expanded access to efficient freight modes, including improved energy efficiency, reduced emissions, increased freight system resiliency, and lowered costs.[371, 372]

Other strategies to increase freight efficiency through expanded mode choice include actions to improve the efficiency of first- and last-mile trips through the promotion of shared mobility and micromobility for passengers, as well as cargo bikes and unmanned automated vehicles for deliveries. Emerging modes such as electric cargo bikes may also play an important role in decarbonizing last-mile deliveries.

Passenger. Providing passengers with expanded transportation options—including rail and bus modes—may also produce substantial GHG reduction benefits.[373] The Efficiency and Rail Action Plans discuss efforts to support expanded access to these modes. While current trends of low ridership have resulted in transit buses currently having greater energy consumption per passenger mile than LDVs or rail,[374] increasing ridership and transitioning to ZEVs can reverse this trend and produce efficiency gains.

Freight consolidation is another strategy that can be used to improve the efficiency of goods movement. For example, shippers can merge partial and low-density shipments into full-truckload intermodal containers headed to and from ports, thereby optimizing container weight and volume to reduce the number of containers needed. Companies can also use less packaging to fit more products into each container, thus reducing the overall number of containers and truck or rail delivery miles in and around ports.

Near-Term Actions

The following are near-term actions for the federal government to expand access to efficient modes. Additional actions may occur at state and local levels and among private actors.

Research and analysis are needed to establish long-term targets and investment priorities**.** Improved modeling of mode choice is needed to identify priority infrastructure investments and assess life cycle impacts. In addition, as MHDV vehicle and operational efficiency improve, efficiency improvements in other modes must also continue to realize the benefits of this strategy. One example of ongoing research is DOE's Advanced Research Project Agency, which announced funding under the exploratory topic INcreasing Transportation Efficiency and Resiliency through MODeling Assets and Logistics (INTERMODAL) to fund projects that develop technology to model the low-carbon intermodal freight transportation system of the future.

Investment needs will include infrastructure investments to reduce bottlenecks within the rail network to improve freight rail efficiency and attractiveness as a shipping mode. Inland waterways have many of the same real and perceived disadvantages as rail when compared to trucks.[375] Inland ports have traditionally been limited by a lack of investment, and many are not prepared to handle large shipments.[376] Investments in inland ports could boost shipments on inland waterways

both as a substitute for some truck and rail routes and as a component of multimodal shipments. Investments in intermodal hubs will also be needed.

Current federal funding programs include the DOT Office of Multimodal Freight Infrastructure and Policy, which funds investments in multimodal freight mobility; DOT's Mega and INFRA grant programs; the Federal Railroad Administration's Consolidated Rail Infrastructure and Safety Improvements program, which funds investments in improved rail infrastructure, safety, and reliability; and the Port Infrastructure Development Program and the Marine Highway Program, which fund investments in port infrastructure and marine corridors. DOT will designate a National Multimodal Freight Network in 2024 that supports the use of lower-carbon modes. The Efficiency Action Plan, the Maritime Action Plan, and the Rail Action Plan also provide more details about these programs.

Federal actions to increase **transit bus ridership** include increased funding for public transportation systems, increased investments in "transit deserts" and disadvantaged communities, expanded frequency and hours of service, and expanded free- and reduced-fare programs. Funding through FTA formula funding and discretionary grant programs can help local transit agencies implement these actions.

4.3.2.2 Operational and Vehicle-Level Efficiency

Operational best practices and vehicle-level efficiency improvements offer near-term opportunities to improve the energy efficiency of MHDVs on the road today. Strategic priorities include the following:

1) **Improve congestion management and reduce vehicle idling**, through strategies such as **freight digitization** with a particular emphasis on areas with high freight activity, such as **ports** and **intermodal hubs**.
2) **Encourage the uptake of current best practices**, such as aftermarket anti-idling technologies and tractor and trailer aerodynamic devices, through funding programs and regulation.
3) **Support research** in emerging technologies and operational practices, including vehicle lightweighting and aerodynamic improvements and truck platooning.

Improving MHDV vehicle and operational efficiency often has direct economic benefits for fleets, resulting in substantial existing market pressures to implement efficiency-improving measures wherever it is financially beneficial and operationally feasible to do so. Efforts to improve MHDV efficiency at the federal level should address areas where market barriers or misaligned incentives exist, such as actions with high up-front investments or high uncertainty, information asymmetries, or coordination challenges across different stakeholders.

Operational Strategies to Reduce Congestion and Vehicle Idling

Idling is a substantial contributor to fuel consumption and local air pollution, with studies suggesting idling times between 2 and 8 hours for some truck classes and up to 8% of fuel burned for sleeper trucks.[377, 378, 379] Efforts to reduce vehicle idling can both produce fuel savings for fleets and improve local air quality for impacted communities.

Freight digitization is one strategy with substantial potential benefits. Digital solutions include advanced scheduling and routing systems, location tracking using geographic information systems (GIS), and vehicle-to-vehicle and vehicle-to-infrastructure technologies (V2V/V2I, or V2X). The International Transport Forum analyzed the overall impacts of a "digital transformation" scenario on freight-related CO_2 emissions and found that implementing a range of digital solutions to the freight sector will result in over 20% lower CO_2 emissions in 2050 compared to the no-action baseline.[380]

Most freight and goods movement innovations are developed by industry-leading companies, which have strong incentives to reduce unnecessary travel, delays, and other factors that contribute to higher operating costs. However, the federal government can play a role in easing coordination

problems across private organizations and incentivizing innovation at key areas such as ports. A key example is **truck appointment systems**, which allow trucks to schedule their visits in advance. Early demonstrations have shown that truck appointment systems have substantial potential to reduce congestion, idling, and emissions for drayage trucks at ports[381] and have been implemented at the Port of New York and New Jersey, the Ports of Los Angeles and Long Beach, and the Port of New Orleans.[382, 383] A key need for the expansion of these programs is the **development of streamlined and interoperable systems** across port terminals to enable ease of scheduling for drivers.

Other digital solutions, such as the development of truck parking reservation systems, may also improve both efficiency and convenience by reducing the number of miles driven in search of parking and reducing time spent idling while waiting for spots to open. Substantial public benefits may result from such solutions; the state of Colorado estimates a value of more than $7 returned for every dollar of investment, with benefits including improved safety as well as emissions reductions.[384]

Best Practices for Fleet-Level Efficiency Improvements

Incentivizing the adoption of today's efficiency-improving measures can produce fuel cost savings for fleets and substantial air quality, climate, and public health benefits.[385] Behind driver wages, fuel is the second-largest source of operational costs for many MHDV fleets,[386] providing strong incentives for commercial fleets to implement strategies to improve MHDV efficiency where economically beneficial. A number of fuel-efficiency-improving devices are available on the market today, including tractor and trailer aerodynamic devices such as gap reducers, underbody devices, skirts, boat tails, improved tires with reduced rolling resistance, and anti-idling technologies such as auxiliary power units.

Efficiency is improving across the MHDV fleet in part thanks to fleet-level actions; deadhead miles (miles in which a truck drives without a load) reduced to a new low of 24% of miles in 2021 (15% when tankers were excluded).[387] However, adoption of efficiency-improving technologies may not always occur due to economic considerations (such as the cost of diesel, which can impact payback periods for efficiency-improving devices), or other factors such as driver preferences or a lack of education. Since 2010, combination truck fleet-wide average fuel economy has improved by only 3%, from 5.9 to 6.1 miles per gallon of diesel.[388] Substantial potential exists for improvement—NACFE estimates that with the best currently available technologies and practices, tractor-trailer fuel efficiency could reach 8.3 to 10.1 miles per gallon.[389]

Innovative Technology Solutions

Innovative technology solutions include vehicle improvements such as component lightweighting and aerodynamic innovations, as well as emerging solutions such as truck platooning, which improves vehicle efficiency using connected and autonomous vehicle technologies. These vehicle-level efficiency solutions have benefits for all power trains, including ZEVs. For ZEVs, these technologies not only offer fuel cost savings but may act as functional range extension for short-range vehicles, making them particularly important for early adopters of BEVs.

The 2016 SuperTruck 2 program, a DOE- and industry-funded partnership, demonstrated 11 to 13 miles per gallon increases in MHDV fuel economy (more than double the fuel economy of diesel vehicles).[390] Innovative ideas included optimizing tractor and trailer aerodynamic design, deploying gap-reduction technologies, reducing rolling resistance through improved tires, improving brake thermal efficiency, vehicle and trailer lightweighting, and 48-V hybridization of vehicle accessories. Many of these innovations have entered the market today, but further research in some areas, such as cost and benefits of vehicle lightweighting—including for zero-emission power trains—can enable continued commercialization and uptake of these technology innovations.[391]

Connected and autonomous vehicle technologies, and in particular truck platooning, are emerging as a solution with substantial fuel-efficiency-savings potential. Truck platooning, which involves between two and four trucks traveling at close distances enabled by using connected adaptive cruise control technology and vehicle-to-vehicle communication, has the potential to reduce fuel use by up to 10% by improving aerodynamic efficiency. Recent projects funded by DOT have resulted in the development of a pilot system to enable partially autonomous truck platooning, with field operational tests ongoing.[392, 393]

Near-Term Actions

Private actors and government partnerships can continue to improve MHDV fleet and vehicle-level efficiency. Areas for action include the following:

Private actors. Private actors, including fleets, ITS providers, and automakers, can continue to adopt and improve upon best practices for fleet-level efficiency, including the adoption of advanced scheduling, routing and GIS, and efficiency-improving technologies to minimize fleet energy consumption and reduce idling.

Federal government. The federal government can support existing research programs and industry partnerships to improve efficiency and promote coordination and interoperability among ITS. Existing regulatory actions will also incentivize the uptake of efficient practices. These actions include the following:

- **Support of improved port efficiency.** Federal guidance can facilitate the expansion of truck appointment systems at U.S. ports and terminals, including the development of interoperable systems across multiple terminals. The EPA Ports Initiative includes a suite of operational strategies port operators can employ to accomplish substantive emissions reductions as well as time and cost savings through establishment and implementation of port operational strategies.
- **Regulation.** EPA and NHTSA's recently released emissions and fuel economy standards for MHDVs provide a regulatory framework to encourage the adoption of efficiency-improving technologies beginning in MY 2027 (for EPA standards) and MY 2030 (for NHTSA standards, covering Class 2B and 3 pickup trucks and vans).
- **Provision of incentives for existing efficiency-improving technologies.** Existing federal programs such as the Reduction of Truck Emissions at Port Facilities Grant Program provide incentives and education for fleets on the benefits of adopting efficiency-improving technologies and practices.
- **Continued research into emerging efficiency solutions.** Federal and industry partnerships should continue to investigate the commercialization of advanced efficiency-improving solutions such as vehicle lightweighting and aerodynamic design, which will be especially important for reducing the weight of ZEVs and increasing feasible payloads. Additional research is also needed into truck platooning to further assess potential barriers, such as public acceptance and interactions with LD vehicles, and to explore economic and regulatory frameworks that may make such solutions feasible.

5. CROSS-CUTTING STRATEGIES TO SUPPORT TRANSPORTATION DECARBONIZATION

5.1 Building Good Jobs and a Stronger MHDV Economy

MHDVs play a role in a broad range of passenger, freight, and other commercial applications. As of 2024, there were over 2 million passenger and freight motor carriers,[394] transporting approximately 65% of the country's freight by weight.[395] In the passenger sector, buses served nearly half of the 7.1 billion trips made on public transportation in 2021.[396] The workforce employed in these sectors includes approximately 2 million heavy-truck drivers[397] and 1 million light-truck drivers,[398] approximately 185,000 transit and intercity bus drivers,[399] and over 371,000 school bus drivers employed across the country.[400] The automotive industry (including both LDVs and MHDVs) employs more than 1 million workers in motor vehicle and parts manufacturing and more than 2 million in vehicle and parts dealerships. The supporting workforce also includes around 1 million people who are employed in the automotive repair and maintenance industry (also serving both LDVs and MHDVs).[401]

Transitioning to a decarbonized MHDV sector will substantially affect these industries, involving increased production and jobs in ZEVs, component technologies, fuels, and infrastructure.[402] Continued federal leadership is needed to ensure the clean MHDV transition benefits all workers and communities, including those that have been historically left behind, through actions such as policies and incentives to support high-quality job creation and retention, as well as ongoing investments in domestic industries and supply chains and programs to facilitate worker training (including reskilling and upskilling).

Maintaining and improving the quality of jobs in the industry is also key to ensuring a smooth and sustained transition. Through its EOs on Worker Organizing and Empowerment, Tackling the Climate Crisis, and others, the administration has underscored its focus on retention and creation of good-paying, high-quality jobs. Good Jobs Principles developed by the U.S. Departments of Commerce and Labor outline eight principles for good jobs to guide efforts across industry and government levels. The eight principles include stable living wages; family-sustaining benefits; equitable opportunities for career advancement and skill building; organizational cultures that value employees and promote empowerment and representation, and where workers can form and join unions; workplaces that are committed to diversity, equity, inclusion, and accessibility and provide job security and safe working conditions; and active recruitment and hiring that is free from discrimination.

A key example of MHDV-focused innovation and industry expansion is the Regional Clean Hydrogen Hubs Program created by the BIL. This program will stimulate investments in the production and distribution of hydrogen; in supporting industries such as infrastructure, maintenance, and repair; and in end uses such as industry and transportation, creating thousands of skilled jobs in the process. Other opportunities for high-quality job creation, innovation, and industry expansion through MHDV decarbonization include ZEVs, component and infrastructure manufacturing and assembly, research and development, infrastructure deployment (including charging and refueling installation and operation and grid upgrades and modernization), maintenance and repair (of ZEVs, infrastructure, and fuel production

systems), and sustainable liquid fuel feedstock development and production. These will create and retain jobs in many skilled professions, including engineering, construction trades, installation, maintenance and repair, motor vehicle operations, manufacturing and assembly, and more.[403] The federal government is committed to ensuring a sustainable economic transition, through sustained focus on proactive worker and community outreach and engagement, high labor standards, equitable investment, enhanced domestic manufacturing and infrastructure, and support for workers and businesses at all stages of the transition.

5.2 Supply Chain and Manufacturing

Investments in scalable vehicle and component manufacturing processes and supply chains are a core part of the pathway toward lowering ZEV costs and capturing economic and jobs benefits. Many ZE-MHDVs are manufactured at low volumes today, resulting in higher costs due to a lack of economies of scale. Upstream components used in the production of fuels and infrastructure—such as hydrogen electrolyzers and sustainable liquid-fuel technologies—will also need to scale manufacturing to enable competitive costs. Investments in domestic BEV manufacturing and supply chains will be crucial to maintain U.S. economic security and global competitiveness and can substantially invigorate the U.S. manufacturing and clean energy industries, while building partnerships with key allies can fill in remaining supply gaps that cannot be filled domestically. Compliance with the Build America Buy America Act and other Buy America requirements for publicly procured fleets, such as municipal and school buses, and for charging infrastructure also provides a key demand signal and additional domestic jobs benefits.

Access to critical supplies such as batteries, power controls, and cabling will directly determine the potential to scale up zero-emission technology. Dedicated efforts to increase the efficiency of battery production and to recycle critical materials will lower capital costs and reduce environmental and social consequences of mining. Current global battery manufacturing capacity is expected to reach 6,500 GWh by 2030,[404] with 1,200 GWh annually in the United States (compared to current global demand of about 300 GWh).[405] DOE maintains a dashboard tracking announced U.S. investments in batteries, ZEVs and component parts, hydrogen production, and more.[406] As of July 2024, announcements include:

- Battery cell factories sufficient to supply 10 million new BEVs per year.
- Production sufficient for 60,000 fast chargers per year.
- Manufacturing capacity of 12 GW of electrolyzers per year and 4 GW of fuel cells.

In addition to these announcements, a facility in Mississippi was announced in January 2024 by Cummins, Daimler Trucks, and PACCAR to produce 21 GWh of battery cells for commercial EVs, with planned production beginning in 2027.[407]

In addition to this progress, additional objectives have been established. Objectives for scaled ZEV, component, and infrastructure manufacturing set by DOE and others include the following:

- Ensuring access to reliable sources of critical minerals for battery production, including sustainably increasing U.S. mineral production capacity.
- Increasing U.S. domestic minerals processing and battery production capacity.
- Increasing U.S. recycling capability for critical battery materials.[408]
- Scaling clean hydrogen production from 1 MMT per year as of 2023 to 10 MMT per year by 2030, aligned with a pathway to 50 MMT by 2050.[409]
- In support of this, scaling electrolyzer production and investing in innovations to reduce stack and balance of plant costs. Manufacturing and stack innovations and

economies of scale could reduce electrolyzer capital costs by more than two-thirds.[410]

- Scaling HD fuel cell stack manufacturing to 20,000 stacks per year for a single manufacturing system.[411] Hydrogen investments are expected to enable production of 14 GW of fuel cells per year annually in the United States, enough to produce 50,000 MHDV FCEVs per year, or 15% of the market.[412] Fuel cell manufacturing at scale could reduce fuel cell system production costs by more than one-third by 2030.[413]

Investments in grid upgrades and modernization will also be critical to sustain increased electricity demand from ZEVs and hydrogen production processes.

NEAR-TERM ACTIONS

The federal government has made substantial investments in ZEV manufacturing and supply chains. Near-term actions will involve the continued implementation of these investments. The IRA and BIL allocate billions of dollars in incentives for achieving manufacturing and supply chain targets. These include the following incentives, financing, research, and development programs:

- $3.5 billion in funding through the BIL to build a domestic supply chain for critical minerals and components, expand domestic battery minerals and materials processing capacity, and expand U.S. advanced battery manufacturing capacity.
- The Qualifying Advanced Energy Project Credit (48C), which allocates $4 billion in tax credits for investments in clean energy manufacturing and recycling, critical materials, and industrial decarbonization, with an additional $6 billion announced. $2.5 billion in funding will be centered on designated energy communities, which include communities with retired coal mines.
- The Advanced Manufacturing Production Tax Credit (45X), which includes tax credits of up to $10/kWh for manufacturers of battery modules using battery cells, such as lithium-ion batteries.
- Biodiesel excise tax credits and income tax credits of up to $1.00/gallon, applying to biodiesel, agri-biodiesel, and RD.
- The Clean Hydrogen Production Tax Credit (45V), allocating tax credits of up to $3/kg for production of clean hydrogen (defined as hydrogen with a CI of up to 4 kg CO_2-equivalent emissions per kg of production).
- The Regional Clean Hydrogen Hubs Program, allocating $8 billion for hydrogen production, manufacturing, and distribution.
- The Advanced Technology Vehicles Manufacturing Loan Program, which has conditionally committed or loaned more than $20 billion since 2020 for facilities, with several billion dollars engaged in manufacturing eligible vehicles (including MHDVs) and components, including critical materials for batteries, manufacturing charging infrastructure, and modernizing facilities.
- The Domestic Automotive Manufacturing Conversion Grants program, which allocates $2 billion in grants for domestic manufacturing of HEVs, PHEVs, BEVs, and FCEVs, with a focus on conversion of facilities and retention of jobs currently in the ICE supply chain.

Other programs include DOE's Hydrogen Shot program, which allocates funding to reduce the cost of clean hydrogen to $1/kg by 2031, including funding for industry demonstrations.

5.3 Workforce Development and Transition

Workforce development programs are an essential component of expanding ZEV adoption in industries such as manufacturing, infrastructure installation and maintenance, and vehicle operations and maintenance. Appropriately skilled and trained workers are key to ensuring safety, efficiency, and effective ramp-up of new

production. High-quality training pathways that train for careers in industry, not just individual tasks, are critical to attracting, retaining, and ensuring a workforce that can evolve as the industry does.

Automotive workers will need to be trained in new production methods for BEVs, FCEVs, and battery production, while BEV operators will need to be trained in skills such as driving with regenerative braking, charging, and interpreting vehicle state of charge and range. BEV mechanics will require training on working with high-voltage electrical systems, safety, and maintenance of BEV-specific vehicle components.[414] Additional training will be required for maintaining FCEVs, as well as on working with hydrogen production, delivery, and storage systems.

Training for this transition is already underway through existing industry, union, and educational organization training partnerships, and numerous organizations and consortia are actively providing or developing training programs and resources for ZEVs, batteries, and EVSE. Expanding pathways into and through these programs can fill specific gaps, while retention, training, and upskilling of existing production workers, mechanics and operators will be key to rapid and flexible adoption and will also maintain critical skill sets and job quality. Examples include:

- California Energy Commission: Offers programs focusing on BEV technology and infrastructure.
- Colorado Department of Transportation: Provides funding opportunities for ZEV workforce development in the state.
- Michigan Department of Labor and Economic Opportunity: Develops workforce training programs for emerging clean energy technologies.
- National Alternative Fuels Training Consortium: The only nationwide organization in the United States offering training on alternative fuel vehicles and advanced technology vehicles.
- Center for Hydrogen Safety: Focuses on training and safety protocols related to hydrogen fuel cell vehicles.
- Transit Workforce Center (TWC): Provides training and resources for public transportation workers, including those working with electric and hydrogen-fueled buses.
- Society of Automotive Engineers (SAE): Provides training on standards, regulations, safety practices, battery technologies, vehicle architectures, high-voltage safety, and fuel cells.
- The Electric Vehicle Infrastructure Training Program (EVITP): A curriculum and certification program developed through partnerships among industry, labor, and educational institutions to train electricians in installing and maintaining BEV charging stations. Such certifications are now required for electricians installing or maintaining EPA-funded charging stations.

Programs as part of federal agencies and funding programs include the following:

- The DOE-convened Battery Workforce Initiative is a partnership between government and stakeholders in the advanced battery industry to develop training and materials for workers in key occupations to advance workforce development.
- EPA's Clean School Bus Program encourages schools and school districts to develop workforce readiness plans to support the ZEV transition, with several resources offered on EPA's website.
- Hydrogen Education for a Decarbonized Economy is a collaboration among government, industry, and universities that aims to provide training in hydrogen production, delivery, storage, end uses, and safety.

- FTA funds the TWC to support public transit workforce development. TWC uses its extensive experience and knowledge of bus electrification operations and maintenance to reskill and upskill current and future transit workers.

NEAR-TERM ACTIONS

While many programs are under development, gaps remain. Today's training opportunities are often limited, particularly for vehicle maintenance. The World Resources Institute found that BEV maintenance training is typically offered by OEMs but lacks standardization or follow-up courses.[415]

Future federal efforts should focus on the following areas:

- **Expand national curricula and certifications**—such as EVITP—to ensure that workers have the necessary skills and knowledge to operate and maintain ZEVs and their infrastructure. Certifications can also provide a clear career pathway for individuals entering the field. Programs should be standardized to ensure uniformity in the quality of training.
- **Increase support for technical schools and community colleges** to develop and expand ZEV-related programs. These programs can help acquire equipment, develop curricula, and train instructors.
- **Promote partnerships among industry, unions, and educational institutions** to facilitate the development of relevant training programs. These partnerships can also provide students with hands-on experience and access to the latest technology.
- **Conduct public awareness campaigns.** Increasing public awareness about career opportunities in the ZEV sector can attract more individuals to the field. Campaigns should highlight the benefits of working with clean technologies and the potential for job growth.

By addressing these gaps through coordinated efforts and targeted investments, the government can ensure the creation of a skilled workforce capable of supporting the widespread adoption and maintenance of ZEVs and their infrastructure. This will not only facilitate the transition to a cleaner transportation system but also create high-quality jobs and promote economic growth.

5.4 Community Impacts

Reducing emissions from all transportation sectors, and especially the MHDV sector, results in reduced negative impacts on communities.

In addition to GHG emissions, the transportation sector and MHDVs are responsible for other emissions that affect communities. Though representing only a small portion of vehicles on the road, MHDVs contribute disproportionately to air pollution, and the MHDV sector is the single largest emitter of on-road NO_x.[416]

MHDVs' outsized emissions of air pollution can be linked to the use of diesel fuel. Though diesel engines are increasingly cleaner, diesel exhaust and associated CAP and precursor emissions can still contribute to asthma, respiratory illnesses, cancer, and heart and lung disease, resulting in high numbers of hospital visits, absences from work and school, and premature death.[417, 418, 419, 420, 421, 422] Children, older adults, people with preexisting cardiopulmonary disease, people of low socioeconomic status, and racial and ethnic minorities are among those at higher risk for health impacts.[423, 424]

Noise and air pollution affect millions of people, especially those who live near transportation hubs such as highways, ports, warehouses, or rail yards or near petroleum extraction, refinery, storage, or transport infrastructure.[425, 426] Transportation emissions can also increase downwind ambient concentrations of non-GHG pollutants such as those mentioned above. Nationally, impacts from air pollution affect people of color disproportionately; for example, Black Americans are 40% more likely to have asthma and almost three times more likely to die from asthma-related causes than non-Hispanic white Americans.[427] These health disparities result in part from the

historical federal, state, and local laws that supported racial segregation, including transportation, home finance, and tax laws.[428, 429, 430, 431] People of color and low-income people are more likely to live near truck routes and ports.[432]

Transit buses and school buses can also create air pollution and exacerbate poor air quality in overburdened communities. Exposure to diesel exhaust from school buses has been linked with school absences, and research has shown that attendance improves when schools replace their school buses with cleaner vehicles.[433] Transit riders can be exposed to pollution while waiting at bus stops. Zero-emission public transit and school buses can provide transit riders and children with a way to travel to and from work or school with reduced exposure to dangerous emissions, reduce the exposures to traffic-related air pollution among people near major roads, and, in part, "remove or overcome the effects of the prior discriminatory practice or usage."[434]

NEAR-TERM ACTIONS

Improving communities through MHDV emissions reduction can occur at all levels of government and through private actions. Private, local, and state government actions can include actions to spur ZEV adoption, as discussed in Chapter 3. Private actions can also include partnerships with government agencies to improve emissions inventories in transport hubs, such as ports—an example being EPA's partnership with Port Everglades. Other private actions may include efficiency-improving actions in transportation hubs such as ports, such as efforts to reduce MHDV idling. State governments can adopt regulations such as California's Advanced Clean Trucks rule and tailor state-level ZEV incentive programs to prioritize ZEV and infrastructure deployment in environmentally burdened and disadvantaged communities.[435]

Federal actions. The federal government's actions to reduce emissions from the transportation system can result in significant benefits to public health and welfare.[436, 437, 438] Proposed and ongoing actions can be summarized as follows:

Invest in multimodal zero-emission freight operations. Federal investments—especially in maritime, rail, off-road, and MHDV modes—have the potential to transform air quality in areas near high levels of freight activity through the replacement of aging gasoline and diesel vehicles with clean technologies. Substantial federal investments in vehicles, infrastructure, and workforce development are ongoing through federal programs, including the NEVI and CFI deployment grants (though NEVI thus far has been targeted toward LDVs), and many other DOE-, DOT-, EPA-, and HUD-funded initiatives relating to MHDVs. Several programs are highlighted below:

- EPA's Clean Ports Program provides $3 billion in funding for zero-emission mobile equipment to reduce emissions at ports, including for zero-emission drayage trucks and infrastructure.
- EPA's Clean Heavy-Duty Vehicles Program provides $1 billion to replace Class 6 and 7 vehicles with zero-emission models.
- EPA's Clean School Bus Program provides $5 billion to replace old school buses with clean alternatives.

Other federal programs are intended to aid disadvantaged and overburdened communities with funding for climate and air pollution solutions, and this funding is flexible depending on community needs. These programs include the Greenhouse Gas Reduction Fund and Environmental and Climate Justice Program. DOT administers the Reduction of Truck Emissions at Port Facilities program and the Port Infrastructure Development Program, which provides funding for various emissions reduction measures at ports, including purchasing ZE-MHDVs and installing charging and fueling infrastructure.

Identify priority communities. As investments in cleaner transportation solutions increase, it will be important to ensure that disadvantaged communities reap the benefit of those investments, including jobs and business opportunities. The Climate and Environmental

Justice Screening Tool and Equitable Transportation Community Explorer assist federal agencies and stakeholders in identifying disadvantaged communities.

Additional actions to **identify priority freight hubs** can support ongoing federal programs. Research, data collection, and outreach can help ensure prioritization of the most affected communities. This can include the following actions:

- Improved data collection on freight activity, emissions, air quality, and community health outcomes in critical areas, such as warehouses, ports, and intermodal hubs.
- Tool development and analysis to assess impacts of ZEV investments in priority areas.
- Proactive stakeholder outreach, engagement, and participation—including communities, nonprofits and other stakeholders—integrated throughout this process.

Federal regulations. Federal regulations are being enacted to reduce transportation emissions. EPA's 2022 final rule on heavy-duty engine and vehicle standards sets stronger emissions standards to further reduce air pollution from HD vehicles and engines. That rule alone is projected by 2045 to reduce up to 2,900 premature deaths and 18,000 cases of asthma in children annually.[439] EPA's 2024 rulemaking governing NO_x, $PM_{2.5}$, and GHG emissions from passenger cars and light- and medium-duty (Class 2B/3) trucks will also reduce air pollution and improve public health.[440]

Public engagement. Seeking public input and feedback has been embedded into federal decarbonization programs and rulemakings and is a key component of achieving a decarbonized transportation system that supports all communities. DOT has released a meaningful public involvement guide for transportation practitioners and DOT funding recipients to engage with the public and communities in transportation decision-making. These principles have been incorporated throughout DOT programs. For example, as part of the development of and annual updates to NEVI state BEV infrastructure deployment plans, states are instructed to involve federally recognized Tribal governments and stakeholder groups in their plan's development, including the general public; government entities; labor organizations; private sector/industry representatives; utilities; representatives of the transportation and freight logistics industries; state public transportation agencies; and urban, rural, and underserved or disadvantaged communities.[441] EPA similarly maintains a Public Participation Guide, which provides tools for government agencies to guide public participation in environmental decision-making. Continued public engagement aligned with these principles must be integrated throughout MHDV decarbonization strategies.

Research and analysis. Further research is needed on the impacts of infrastructure investments, fuel production and storage, and MHDV operations on air quality, safety, racial segregation, and environmental outcomes for impacted communities. Further development of modeling tools is needed to assess the environmental impacts and distributional implications of MHDV ZEVs and sustainable-fuel vehicle and infrastructure investments on outcomes such as air quality, access to goods and services, economic benefits, and energy burdens. The Joint Office funds a number of ongoing projects and modeling tools aimed at answering such questions. Future research efforts should ensure that MHDV decarbonization efforts are incorporated into such tools and that these tools assess impacts from all decarbonization strategies, including ZEVs, sustainable liquid fuels, and efficiency measures. Improved monitoring of MHDV activity—particularly in critical locations such as at ports, warehouses, and intermodal hubs—will also be needed to quantify the impacts of ZE-MHDV deployments in these locations for neighboring and downwind communities.

Tribal engagement. Tribes must be consulted and Tribal sovereignty must be respected in all federal MHDV decarbonization efforts. The 2023 EO on

Tribal self-determination and the 2022 Memorandum on Uniform Standards for Tribal Consultation lay the foundation for processes and guidelines by which principles of Tribal sovereignty and Tribal self-determination are upheld by federal agencies engaging in any transportation decarbonization activities. The EV Initiative for Tribal Nations, which provides technical assistance to Tribes to deploy BEV infrastructure and access funding for zero-emission school buses and transit buses through the EPA Clean School Bus Program and the DOT Low- or No-Emission Grant Program. Tribal inclusion in national BEV and hydrogen fueling infrastructure projects will require proactive planning, consultation, and support to address historical inequities and underinvestment in infrastructure.

5.5 Safety and Standards

Safety, codes, and standards development are a key enabler of successful ZEV adoption. The safety and standards for BEVs and FCEVs encompass a wide range of considerations, from battery and electrical safety to crashworthiness and charging or fueling infrastructure. Developed by international and national organizations, these standards ensure that both BEVs and FCEVs are safe for consumers and can operate reliably within existing transportation systems. Continuous research and development in this field are essential to address emerging challenges and improve the overall safety and performance of these vehicles. Key priorities of safety, codes, and standards development are as follows[442]:

- Advancing **research** on safety for ZEV components and charging/refueling infrastructure technologies, including identifying risk management practices to reduce risks and mitigate consequences of potential incidents
- Promoting harmonization of codes and standards across industry and private actors and at local, state, national, and international levels
- Providing safety resources and support.

KEY ACTORS

Industry, U.S. government, and international organizations play important roles in establishing BEV and hydrogen vehicle safety standards. Industry includes the following:

- The International Electrotechnical Commission, which develops global standards for EV components, batteries, and charging systems.
- SAE, which provides comprehensive standards covering battery-electric and hydrogen components, vehicles, and infrastructure safety, performance, and testing procedures.
- The International Organization for Standardization, which publishes international standards for a wide array of industries, including conventional and electric vehicle safety standards, ensuring uniformity and quality across global markets.
- Underwriters Laboratories, an independent organization responsible for developing safety standards and certifying BEV charging equipment, ensuring reliability and safety in charging infrastructure.
- The National Fire Protection Association (NFPA), which develops codes and standards for the safe handling and use of hydrogen technologies, prioritizing safety in hydrogen applications.

Within the federal government, DOT agencies include NHTSA, which issues and enforces the Federal Motor Vehicle Safety Standards governing the safety of on-road vehicles; the Federal Motor Carrier Safety Administration, which regulates the safety of commercial motor carriers; and FHWA, which provides stewardship over the construction, maintenance, and preservation of the nation's highways, bridges, and tunnels. FHWA also conducts research and provides technical assistance to state and local agencies to improve safety and mobility and to encourage innovation. DOT's Pipeline and Hazardous Materials Safety

Administration ensures the safe shipment of hazardous materials and pipelines, including the safety of hydrogen distribution. Other federal agencies, such as DOE, also fund research and development relevant to ZEV and recharging/fueling infrastructure components and safety.

Internationally, the European Union develops regulations and directives to establish safety and performance standards for vehicles within member states. The United Nations Economic Commission for Europe (UNECE) develops Global Technical Regulations and UNECE regulations for vehicle safety, fostering international collaboration and standardization. Additionally, the Canadian Standards Association provides standards for hydrogen vehicle storage systems and fueling infrastructure, ensuring safety and reliability in hydrogen transportation within Canada. Together, these organizations collectively contribute to the establishment of robust safety standards, fostering the growth and adoption of ZEVs worldwide.

RESEARCH AND DEVELOPMENT OBJECTIVES

While significant work has already been accomplished across these organizations in developing standards for BEV and FCEV safety, recharging, and refueling infrastructure safety, as well as hydrogen handling and storage, key gaps and research priorities remain that must be addressed. For BEVs, these include the following:

- **Continued research on battery safety and longevity:** A major focus of battery safety research efforts is on preventing thermal runaway through advanced materials and designs that improve heat dissipation.[443] The development of next-generation thermal management systems, such as those using phase change materials or liquid cooling, is needed to improve heat dissipation during operation and charging. Improving battery management systems with predictive analytics and machine learning models can further help in anticipating and mitigating potential safety issues before they escalate.[444] Investigating long-term battery degradation and enhancing battery life is another critical area. Conducting in-depth studies on the mechanisms of electrode and electrolyte degradation over time will help identify and mitigate factors that reduce battery life.[445] Next-generation battery technologies such as solid-state batteries are a potentially safer option that is less prone to thermal runaway than present-day lithium-ion technologies. Moreover, establishing robust standards and technologies for the recycling and safe disposal of BEV batteries is essential to address environmental concerns.[446]
- **High-voltage system and electromagnetic compatibility (EMC) safety:** Enhancing isolation standards for high-voltage systems and ensuring EMC standards are essential for preventing electric shock and interference between electrical systems and hydrogen safety systems. Additional research is needed for new insulation materials that provide better protection against electric shock and short circuits at high voltages. Advanced fault detection systems and automated response mechanisms are also crucial for quickly isolating and mitigating electrical faults. Research aims include implementing real-time monitoring systems with high-resolution sensors and designing automated shutdown mechanisms.[447, 448] Developing standardized repair procedures and comprehensive, safety-oriented training programs for technicians are also necessary.
- **Charging infrastructure:** Enhancing standards for ultrafast charging to reduce charging times without compromising battery safety and longevity is a significant area of focus. While the MCS is actively developing standards for high-power charging of BEVs, particularly for HD trucks, significant work remains. This includes finalizing technical specifications, ensuring interoperability between different manufacturers' equipment, and addressing infrastructure challenges such as grid capacity and charging station

deployment. Additionally, industry-wide adoption and regulatory approval are necessary to make these standards widely operational.[449, 450] Furthermore, developing safety and performance standards for wireless charging technologies is essential to ensure efficiency and user safety. Another area of importance is ensuring the interoperability of charging infrastructure across different regions and manufacturers—particularly to facilitate cross-border BEV operations.[451]

For hydrogen, research priorities include the following:

- **Fueling infrastructure and standardization:** Improving high-flow dispensing technology and developing advanced nozzle designs are necessary to enhance refueling speed and safety.[452, 453] This includes advancing cryogenic pump development and creating nozzle designs that minimize hydrogen release and ensure robust sealing to prevent leaks.[454] Developing universal interoperability standards and harmonizing international standards for hydrogen fueling infrastructure are crucial for facilitating cross-border hydrogen vehicle operations.
- **Advanced hydrogen storage solutions:** Development of innovative materials for hydrogen storage tanks is essential for advancing hydrogen storage technology. Doing so will necessitate new certification codes and standards for assessing structural integrity of these systems. Research efforts should focus on improving hydrogen absorption/desorption kinetics, storage capacity, and material stability over multiple cycles.[455] The development of advanced composite materials is necessary to enhance the safety and efficiency of hydrogen storage systems under extreme conditions.[456] Enhancing testing protocols for high-pressure hydrogen vessels, including more rigorous fatigue testing and impact resistance assessments, is necessary to ensure the long-term durability of storage vessels both on and off the vehicle.
- **Leak detection and mitigation:** To address hydrogen leaks effectively (in transport, storage, and end use), the development of highly sensitive and reliable hydrogen sensors and associated standards for design, validation, monitoring, and inspections is critical.[457, 458, 459, 460] Integrated safety systems combining leak detection, ventilation, and automatic shutdown mechanisms are essential to prevent hazardous situations. This involves designing automated ventilation and purge systems capable of rapidly diluting hydrogen to prevent accumulation in confined spaces, as well as implementing redundant leak detection networks to ensure reliable detection.

Cross-cutting issues affecting both batteries and ZEVs include the following:

- **Crashworthiness and structural integrity:** This includes testing and inspection standards focused on improving crashworthiness and structural integrity, including integrating lightweight, high-strength materials, improving vehicle designs to provide better protection for batteries and hydrogen storage systems in collisions, and developing advanced crash simulation models to predict mechanical, thermal, and chemical interactions of vehicle systems in collision scenarios.[461, 462]
- **Fire safety and management:** Development of advanced systems for early warning of battery or hydrogen fires is critical. Integrating advanced gas sensors to detect the early stages of hydrogen leaks[463, 464] and sensors to monitor battery packs for abnormal temperature increases can provide early warnings.[465] Developing effective fire-suppression systems specifically designed for EVs and their battery packs is also necessary. Additionally, creating comprehensive training programs and guidelines for first responders

dealing with battery and fuel cell EV-related incidents is essential, as well as developing standardized procedures for safely disabling high-voltage systems and handling ZEV-specific hazards during emergencies.[466]

- **Highway infrastructure impacts assessments:** These include further ZE-MHDV safety assessments for roads, bridges, and tunnels as well as assessments of road wear and maintenance needs. Of particular importance is further research on safe operations in tunnels, for which hydrogen-powered vehicles may present specific hazards.[467]
- **Cybersecurity:** Developing and standardizing secure communication protocols and establishing strong authentication mechanisms for V2G and V2X interactions are important to protect data integrity and confidentiality. Real-time monitoring and anomaly detection systems are necessary to identify and respond to potential cybersecurity threats effectively.[468, 469] DOT is developing the Security Credential Management System to address V2X security and interoperability. DOE's Office of Cybersecurity, Energy Security, and Emergency Response also funds research in BEV and EVSE cybersecurity.

HARMONIZATION OF CODES AND STANDARDS

Codes and standards harmonization is necessary to enable manufacturing at scale and to accelerate deployment of ZEVs and charging/refueling infrastructure by minimizing complexity across jurisdictions.[470] **Model code development**—in collaboration with government and private actors—can help inform standardization of safety codes at state and local jurisdictions. Working toward global harmonization of battery-electric and hydrogen vehicle standards is necessary to facilitate international trade (including cross-border ZE-MHDV travel) and ensure consistent safety and performance.[471] Developing **unified testing protocols** can ensure consistent evaluation of ZEV safety and performance across different regions. Adaptive regulatory frameworks that can quickly respond to technological advancements and emerging safety concerns in the BEV and FCEV industries are also needed.

SAFETY RESOURCES AND SUPPORT

Resources for first responders are necessary to ensure up-to-date training and experience with incident response for emerging ZEV technologies. The U.S. government and private actors both provide guidance and training for first responders dealing with hydrogen-related emergencies—such as the National Hydrogen and Fuel Cell Emergency Response Training developed by Pacific Northwest National Laboratory and the California Hydrogen Fuel Cell Partnership—as well as training for dealing with electrical infrastructure and BEV-related emergencies. AFDC maintains a database of resources for first responders dealing with electrical incidents, including guidebooks and training programs.

NEAR-TERM ACTIONS

The following are near-term actions that can be undertaken by private actors and federal, state, and local governments:

- **Private actors**, such as industry and standards organizations, can continue to develop codes and standards in collaboration with government researchers and work toward harmonization across industry, as well as provide safety resources for first responders.

Federal government can:

- Continue **research and development** on fundamental safety issues for ZEVs, in collaboration with industry on standards development, through departments such as DOE and DOT. Ongoing stakeholder outreach will also inform new standards development for ZEVs and recharging/refueling infrastructure.
- Provide **guidance on standardization** for state and local jurisdictions. Examples of such guidance provided by DOE include permitting tools developed by HFTO to inform the

development of codes and standards for hydrogen and fuel cells.

- **Continue to provide safety resources and support** for first responders that are adaptive to changing technologies and best practices, in collaboration with private actors.
- **State and local governments** can evaluate and consider codes and standards developed by the U.S. government and industry and decide how and whether to incorporate them into state and local ordinances. For example, many states have adopted some or all aspects of the National Electrical Code maintained by NFPA.[472] NFPA 2 (Hydrogen Technologies Code) is also commonly used, in some cases with modifications across state and local jurisdictions.[473, 474]

5.6 International Coordination

International collaboration on ZE-MHDV adoption can help accelerate the transition to ZEVs both in the United States and worldwide. Key topics for international coordination include the following:

Coordination on international trade. MHDV freight trucks play a major role in international overland trade between the United States, Canada, and Mexico, accounting for 55% of freight moved between Canada and the United States and 71% of freight between the United States and Mexico in 2022.[475] Policies to enact ZEV adoption in one country will affect cross-border trade with its neighbors, requiring international coordination. Canada is a signatory to the Global MOU committing to 30% ZEV truck sales by 2030 and 100% by 2040. Through the Zero-Emission Trucking Program, the Canadian government provides funding and education to support the deployment of ZE-MHDVs. While Mexico is not a Global MOU signatory, the government has committed to 50% zero-emission LD vehicle sales by 2030 and has one of the largest public charging station networks in Latin America.[476]

Establishing cross-border corridor infrastructure is essential to enabling zero-emission cross-border trade.[477] Collaboration should occur on station siting, design, and standards for charging/refueling infrastructure along key cross-border corridors, as well as on regulatory issues such as GVWR standards for ZEVs. Financing mechanisms, such as through the North American Development Bank, may assist in addressing barriers to infrastructure deployment along the U.S.-Mexico border. Information exchanges between countries can help address barriers to transitioning to ZEVs. The United States-Mexico-Canada Agreement, a free trade agreement adopted in 2020, includes provisions for cooperation "to address matters of mutual interest with respect to air quality," including data sharing, transparency, and cooperation on pollution-control technologies and practices.[478]

International knowledge sharing can help countries develop best practices to address issues such as infrastructure deployment, grid management, hydrogen, and sustainable liquid-fuel production ecosystems, as well as develop supportive ZEV policy environments. The U.S. government actively participates in several international initiatives, including the Electric Vehicles Initiative, a global policy forum dedicated to accelerating BEV adoption worldwide, and the Zero Emission Vehicles Transition Council, a multinational political forum aimed at accelerating the global transition to ZEVs. These collaborations should be further strengthened for MHDVs.

6. NEXT STEPS – GETTING TO 2030

6.1 Core Strategic Plans and Milestones

Table 5 lays out near- and long-term national milestones, based on U.S. commitments in the Global MOU and administration targets. Achieving these targets will require a whole-of-government approach using multiple levers, including regulations, incentives, research and development, education and workforce development, and strategic partnerships and outreach.

Table 5. MHDV Decarbonization Milestones, Now Through 2050

By	Milestone	MHDV Subsector	Source
2030	30% of new MHDV sales nationwide are zero-emission	All	Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (the Global MOU)
2035	All federal fleet MHDV procurements must be zero-emission	MHDVs used in federal fleets	EO 14057
2040	100% of new MHDV sales nationwide are zero-emission	All	Global MOU
2050	Full decarbonization of all on-road MHDVs	All	Global MOU

To support these milestones, the MHDV Plan establishes two additional core objectives:

- Achieve **cost parity by 2030 between new zero-emission long-haul heavy-duty trucks and existing ICE long-haul trucks**
- Through collaborative planning and public-private investments, realize **36%** completion of the NHFN **by 2030** and close to **100%** by **2040**.

Interim milestones are needed to track progress toward supporting strategies to meet near- and long-term decarbonization targets. These milestones are organized into four phases. In the **near term (Phase 1; before 2030),** the MHDV Plan establishes the following milestones:

By	Milestone
2025	• Establish vocation-specific ZEV component targets for batteries and fuel cells • Develop monitoring and data-collection plan
2026	• Develop operating expense targets for electricity • Develop metrics for assessing charging/refueling infrastructure adequacy along corridors and in local/regional contexts • Complete initial data collection on vehicle duty cycles, including nationally representative data on daily mileage, dwell times, and auxiliary power demands across all MHDV applications • Host an MHDV charging infrastructure stakeholder workshop to promote collaboration across stakeholders • Finalize initial design for clean hydrogen production hubs and distribution networks through DOE's Regional Clean Hydrogen Hubs Program
2027	• Demonstrate long-haul ZEV operations and infrastructure on a real-world freight corridor in partnership with industry and nonprofits • Demonstrate prototypes for specialized vehicles and commercial pickups • Complete Phase 1 of the Corridor Strategy—deploying charging at regional freight hubs • Implement a public dashboard of indicators tracking progress toward goals
2028	• Meet the clean hydrogen levelized cost target of $7/kg (inclusive of production, distribution, and dispensing)

Medium-term milestones (2030–2040) will build on prior actions to further technology and fuel progress, expand infrastructure networks, and achieve ZE-MHDV sales targets consistent with the Global MOU and administration commitments. In addition to the milestones listed above and core objectives for TCO parity and corridor infrastructure deployment, these include the following milestones:

By	Milestone
2030	• Connect key zero-emission freight hubs (Phase 2 of the Corridor Strategy) • Support industry in deploying long-haul ZEVs along corridor routes • Support industry in deploying ZEVs in specialized applications and work trucks
2031	• Meet clean hydrogen levelized cost target of $4/kg (inclusive of production, distribution, and dispensing)
2035	• Expand corridor connections between critical freight hubs (Phase 3 of the Corridor Strategy) • Scale sustainable liquid-fuel production to meet interim multimodal demands

Long-term milestones (2040 and beyond) will mark progress toward full ZEV adoption, 100% ZE-MHDV sales (aligned with the Global MOU), full infrastructure deployment and corridor build-out, and deployment of sustainable liquid fuels for legacy vehicles. These milestones will continue to evolve as the market for MHDVs is reassessed in future years.

By	Milestone
2040	• Achieve long-term DOE technology targets for batteries and fuel cells • Complete the national zero-emission freight corridor infrastructure network (Phase 4 of the Corridor Strategy)
2050	• Fully decarbonize the legacy fleet using sustainable liquid fuels and reach net-zero GHG emissions

6.2 Federal Actions Now Through 2030

In line with the milestones listed above, significant federal actions will be needed in the near term (between now and 2030) to lay the groundwork for long-term transitions. Figure 23 outlines the sequencing of actions across core strategy areas: clean vehicles, fuels, and infrastructure (including ZEV technology deployment, ZEV energy infrastructure deployment, and sustainable fuel production and distribution [encompassing hydrogen production and distribution scale-up and sustainable liquid fuels]); improvement of system-wide efficiency and convenience; and additional supporting actions. Three phases of action are envisioned, encompassing near-term (before 2030), medium-term (2030–2040), and long-term (2040 and beyond) actions. Additional longer-term actions after 2030 will be developed after assessment of the evolution of the MHDV decarbonization landscape and consultation with stakeholders.

PHASE 1 ACTIONS (BEFORE 2030):

Near-term actions (before 2030) fall into several categories. First, under the Clean Fuels, Emerging Technologies, and Infrastructure strategy area, efforts will focus on scaling ZE-MHDV and fuel production and deployment in the most advanced market segments; conducting demonstrations, data collection, and prototype development for market segments such as Long-Haul and Specialized Vehicles and Work Trucks; and deploying charging/refueling infrastructure. These include the following actions:

Vehicles

- **Support ZEV TCO reductions** through administration of the significant IRA and BIL **incentive programs** for vehicle purchase, fuel production, and manufacturing, with the aim of unlocking **economies of scale**. This includes scaling production of sustainable fuels—clean hydrogen and sustainable liquid fuels through established programs.
- **Conduct research and development** on advanced vehicle components and manufacturing processes to meet operational requirements for additional market segments and further reduce costs. As part of this process, conduct **target setting** for vehicle component cost and performance across all MHDV market segments.
- **Demonstrate and deploy ZEVs in additional market segments**—including Long-Haul and Specialized Vehicles and Work Trucks. This includes expanded data collection efforts on vehicle duty cycles and technology and infrastructure needs.

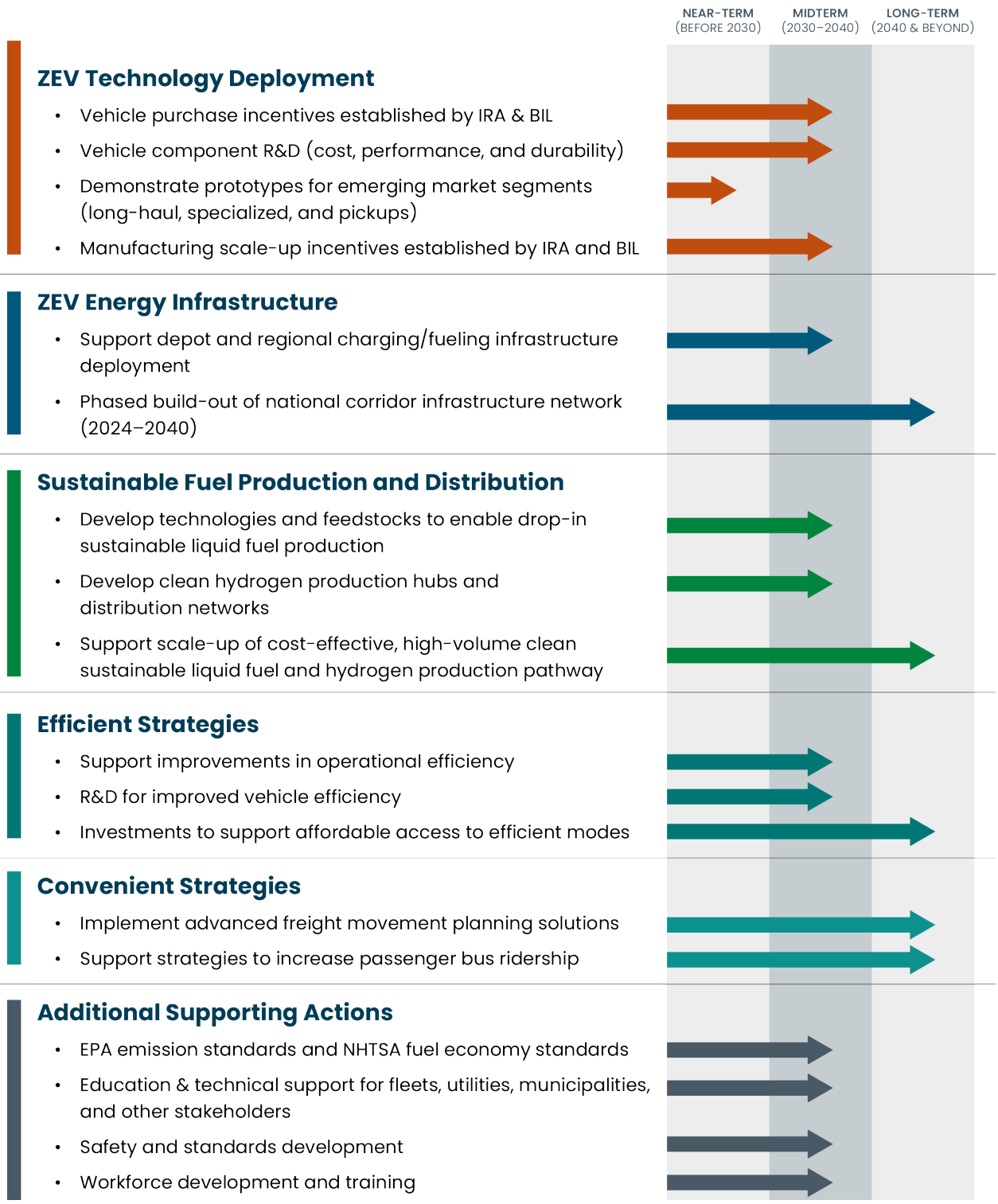


Figure 21. Core strategy areas and supporting actions to promote MHDV decarbonization

Energy Infrastructure

- **Streamline charging infrastructure deployment** by supporting modernization and streamlining of utility and permitting regulatory frameworks; promoting standardization; and supporting tool development, stakeholder outreach, and education efforts.
- **Demonstrate business cases for managed charging and VGI** in support of electricity cost reductions and improved VGI for BEVs.
- **Support low-cost clean hydrogen production and scale-up** through existing programs.

Convenient and Efficient

Efficient actions involve laying the groundwork for system-wide efforts to expand access to efficient modes and to improve operational and vehicle-level efficiency. These include the following actions:

- **Support tool development and analysis** to assess multimodal investment priorities and further refine near- and long-term targets, including modeling frameworks for freight and passenger mode choice and multimodal operations.
- **Encourage efficiency-improving measures** to reduce idling at ports and intermodal locations and ITS measures such as truck parking reservation systems, prioritizing air quality improvements in disadvantaged communities.
- **Conduct research on next-generation vehicle-level and operational efficiency improvements**—including advanced aerodynamics and materials lightweighting and truck platooning.

Near-term Convenient actions will require additional analysis and target setting to clarify MHDV strategic priorities. These include the following:

- **Support research quantifying the benefits of convenience investments** to identify system-wide emissions reduction potential from strategies such as improved siting, curbside demand management, and travel demand management for passenger and freight operations.
- **Finance Convenient passenger and freight projects** through existing federal programs.
- **Develop tools and provide technical assistance** to communities implementing Convenient strategies.
- **Identify medium-term and long-term targets for Convenient strategies**, in line with the findings of the research agenda.

Finally, additional supporting actions will involve the following:

- **Support ZEV workforce development and fleet education**—including manufacturing and maintenance training programs and education for fleets, drivers, utilities, and other stakeholders.
- **Invest in domestic manufacturing and supply chains** through existing federal programs.
- **Support safety and standards development** for ZEVs, fuels, and infrastructure.
- **Advance community benefits** through **multimodal investments in zero-emission operations** (with particular emphasis on low-income communities and key freight hubs) and research on expanded **life cycle assessment and modeling capabilities** to capture the impacts of ZE-MHDVs more thoroughly and sustainable liquid-fuel deployment for GHG emissions and air quality, with special attention to the distribution of benefits and costs for disadvantaged communities.

Cross-cutting actions will also include the development of **data collection and monitoring programs** to track progress along key MHDV decarbonization indicators.

Phase 2 medium-term and Phase 3 long-term actions (2030 to 2040 and 2040 and beyond) will build on near-term programmatic efforts with the aim of expanding ZEV adoption from early-market to full-scale production, reducing production costs and improving performance of vehicle components and fuels, expanding ZEV adoption to new market segments, establishing regional and corridor infrastructure networks, and supporting the long-term deployment of sustainable liquid fuels for legacy vehicles. They will also include actions to pursue Convenient and Efficient programmatic efforts. Specific medium- and long-term actions will remain flexible to changing MHDV market conditions and technology developments and will be revisited in future editions of this MHDV Plan.

6.3 Funding and Financing For Deployment

Funding and financing for ZE-MHDV purchases, charging/refueling infrastructure, manufacturing scale-up, and sustainable liquid-fuel production are essential to enable early-market adoption and scaling. Today's BEVs and FCEVs have higher up-front costs than their diesel counterparts—particularly those in heavier vehicle classes and with longer ranges. While vehicle and infrastructure costs are expected to come down with increases in manufacturing volume, streamlined supply chains, learning, market entry, and further technology progress, financing and funding are necessary in the near term to sustain early markets and enable supply-side investments to occur. The following are federal funding and financing programs for ZE-MHDVs, sustainable liquid fuels, energy infrastructure, and other projects to improve system efficiency and convenience.

U.S. DEPARTMENT OF TRANSPORTATION

DOT administers many programs providing funding for ports, transit buses, and investments in zero-emission or clean infrastructure. For transit buses, these include the Low or No Emission Grant Program, which will provide $1.5 billion in 2024 to state and local governments to purchase zero- and low-emission transit buses, deploy supporting infrastructure, and train workforces. Other DOT-funded programs are not specifically focused on ZEVs but may support ZEV purchases, infrastructure investments, and investments in transit buses. These include the FTA's Urbanized Area Formula Grants, which provide funding to public transportation agencies in urbanized areas for a range of investments, including investments in bus-related activities such as vehicle replacements. The Neighborhood Access and Equity Grant Program further allocates $3.155 billion for community investments in equity, safety, and affordable transportation access, including buses. The Capital Investment Grants Program provides discretionary funding through FTA for transit capital investments, including bus rapid-transit programs. Finally, the Rebuilding American Infrastructure with Sustainability and Equity discretionary grant program will allocate $1.845 billion to state and local projects for freight and passenger transportation infrastructure.

Beyond buses, the Congestion Mitigation and Air Quality Improvement Program provides funding to state and local governments for projects to improve air quality, including projects that fund the purchase of zero-emission replacements for diesel MHDVs and the installation of charging/refueling infrastructure. The National Highway Freight Program includes funding through 2026 for a range of projects, including those that "reduce the environmental impacts of freight movement on the NHFN." Infrastructure-specific programs include the NEVI formula program, which provides $1 billion in funding to states annually through 2026 to invest in public EV charging infrastructure (though a majority of funding to date has focused on LDV infrastructure). The CFI Discretionary Grant Program offers a further $2.5 billion over 5 years to state and local governments for projects that deploy BEV charging or other alternative fueling infrastructure,

including for MHDVs. The Carbon Reduction Program provides $6.4 billion in funding over 5 years for a range of projects, including investments in truck stop electrification, public transportation, congestion management, and electrification at ports. DOT's Reduction of Truck Emissions at Port Facilities program provides $400 million over 5 years for projects to reduce truck-idling emissions and improve operational efficiency, including purchase of zero-emission trucks and installation of charging infrastructure. Finally, the Port Infrastructure Development Program, administered by the Maritime Administration, provides discretionary grant funding of up to $2.25 billion over 5 years (through 2026) for projects, including improving the efficiency of goods movement in, out, and within ports. A compilation of DOT funding programs related to reducing GHG emissions can be found here.

U.S. ENVIRONMENTAL PROTECTION AGENCY

EPA administers multiple programs to fund zero- and low-emission vehicle adoption and reduce emissions from diesel-powered vehicles. These include the Clean School Bus Program, which provides $5 billion between 2022 and 2026 to replace school buses with zero-emission and clean options, accompanied by funds for infrastructure deployment and workforce training. The Clean Ports Program includes an additional $3 billion to fund zero-emission port equipment purchases, including drayage trucks. The Clean Heavy-Duty Vehicles Grant Program includes $1 billion for the replacement of Class 6 and 7 non-ZEVs with ZEVs. Finally, the Diesel Emissions Reduction Act reauthorization allocates up to $100 million per year through 2024 for projects to reduce diesel emissions from various sources.

U.S. DEPARTMENT OF ENERGY

DOE administers several programs for funding and financing of alternative-fueled vehicles and infrastructure. These include LPO, which provides loans to establish, expand, or re-equip facilities for the manufacturing of qualified vehicles and components through the Advanced Technology Vehicles Manufacturing Loan Program. Manufacturers of battery cells and electrified power train components, lightweighting materials, BEV and FCEV charging, and fueling station components, among others, are eligible for these loans.[479] LPO also provides financing through the Energy Infrastructure Reinvestment program, which supports projects such as replacing aging and retired energy infrastructure with clean infrastructure, and its Clean Energy Financing program may finance the deployment of vehicles as energy assets. Title 17 of the Clean Energy Financing Program enables LPO to offer loan guarantees for clean energy technologies, including partial guarantees of commercial debt. On fuel production, OCED oversees the Regional Clean Hydrogen Hubs Program, which provides up to $7 billion for projects involving the production, delivery, storage, and end uses of clean hydrogen in 6 to 10 regional hubs.

U.S. DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

There are several HUD programs that may support siting or development of location-efficient housing adjacent to or in proximity to public transit, including passenger bus services. Programs that support the siting and development of affordable housing in proximity to bus rapid-transit corridors, multimodal transit centers, or passenger bus routes include Federal Housing Administration-insured multifamily mortgage insurance programs; the Home Investment Partnerships Program and Housing Trust Fund grants that are awarded by formula to cities, counties, states, or local consortia; and competitive grant programs such as Choice Neighborhoods and Section 202 Supportive Housing for the Elderly.

STATE AND LOCAL FUNDING

Financing and grants are also available at state and local levels. California HVIP offers point-of-sale vouchers of between $7,500 and $120,000 for purchases of low- and zero-emission Class 2B–8 commercial vehicles, including trucks and buses. Voucher amounts may be adjusted based on fleet size, technology type (reduced for hybrid and remanufactured vehicles), operating location, and

vehicle vocation. Additional programs include financing and funding for small fleets through the Innovative Small e-Fleet Program, which provides vouchers for truck-as-a-service, leasing, and peer-to-peer truck-sharing programs for small fleets (20 vehicles or less), and the Zero-Emission Truck Loan Pilot Project, which replaces previous efforts to provide financing opportunities for heavy-duty ZEVs and infrastructure for small businesses. Other state point-of-sale voucher programs compiled by CALSTART[480] include the New York Truck Voucher Incentive Program, the New Jersey Zero-Emission Incentive Program, Massachusetts Offers Rebates for Electric Vehicles – Trucks, and the Drive Clean Chicago program. Many vouchers include incentives of up to several hundred thousand dollars for heavier vehicles; programs vary on the funding amounts, vehicle eligibility, and other criteria. Some states also have non-voucher grant and incentive programs. AFDC maintains a database of existing state laws and incentives for zero- and low-emission vehicles, including trucks.

ADDITIONAL FUNDING AND FINANCING NEEDS

Support for Small Fleets. Small fleets—those with 10 vehicles or less—are 90% of all registered passenger and freight carriers and 44% of all vehicles in the United States.[481, 482] Many small fleets report facing barriers to accessing ZEVs, including limited information about their benefits and availability, a lack of financial resources to overcome high ZEV purchase costs, and a lack of access to infrastructure. Resources and other support could be directed to small fleets and owners-operators to assist them in navigating funding application processes. Programs should approach small fleets during federal information-gathering and solicitation efforts to ensure that their voices are represented and their specific concerns and barriers to accessing financing and grants are addressed. Innovative financing solutions offer another approach, such as programs modeled after the California Air Resources Board's Innovative Small e-Fleet Program.

Infrastructure-Only Grants. While many funding and financing programs provide support for ZEV deployment including charging/refueling infrastructure and vehicle purchases, fewer opportunities exist for infrastructure-only projects. The CFI Discretionary Grant Program is one such program, providing $2.5 billion over 5 years to deploy LD and MHDV charging and refueling infrastructure. These dedicated infrastructure-only funding programs can incentivize ZEV adoption by providing confidence to fleets that needed infrastructure will be available. Supporting charging-as-a-service projects can also lower market entry barriers for small fleets who use these services in lieu of fleet-owned depots. Future infrastructure grants could also consider future funding opportunities aimed at private stations.

6.4 Policy and Regulatory Opportunities and Gaps

Safety and Standards Development. Continued research into and development of MHDV safety and standards are needed, as described in section 5.5. DOT is conducting ongoing stakeholder outreach to better understand ZE-MHDV infrastructure needs, including safety, station size, and parking and vehicle size requirements. DOE also participates in safety and standards research in partnership with private actors.

Infrastructure Permitting Guidance and Utility Regulatory Modernization. Federal guidance is needed to help state and local governments plan and permit new MHDV ZEV charging and refueling stations. Needed guidance includes streamlined permitting processes and timelines that can be adopted by state and local governments, models for updating planning codes to accommodate zero-emission infrastructure, and technical assistance. In addition, guidance is needed to assist in modernizing utility regulatory frameworks to enable needed investments in the electrical grid to accommodate MHDVs. The federal government can assist by providing guidance and

support to state regulatory agencies and utilities, and by developing forecasting tools to help utilities in better planning for future MHDV electricity demand.

6.5 Research, Analysis, and Data Needs

A wide-ranging research agenda will be needed to support this MHDV Plan's near- and long-term targets; encompassing vehicle, infrastructure, and fuel technology development and production; Convenient and Efficient operational innovations; and cross-sectoral planning and forecasting. Research products will include improved technologies and manufacturing processes, tool development, and analysis products to better inform stakeholders and future strategic plans.

Table 6. Key Research Topics and Relationships to Strategy Priorities

Research Area	Key Topics	Relationship to Strategy
Vehicle, Infrastructure, and Fuel Technologies and Production Pathways	Technology development—vehicle and infrastructure components and fuel production processes, including manufacturing innovations and scale-up	• Clean: reduce ZE/net-zero TCO, improve vehicle availability, and reduce emissions intensity of fuels • Efficient: improve vehicle-level efficiency
	Recycling and end of life	• Clean: reduce emissions intensity of fuels
	Technoeconomic analysis and life cycle assessment	• Clean: reduce ZE/net-zero TCO
	Vehicle demonstration and deployment	• Clean: reduce ZE/net-zero TCO and improve vehicle availability
Convenience, Efficiency, and Operations	Multimodal operations and freight mode choice	• Efficient: improve transportation system efficiency
	Vehicle duty cycles	• Clean: improve ZEV operational suitability and support infrastructure deployment
	Managed charging and VGI	• Clean: reduce ZEV TCO, reduce emissions intensity of fuels, and deploy ZEV charging/refueling infrastructure
	Fleet logistics and operations	• Convenient: improve siting and routing • Efficient: improve fleet operational efficiency
	Energy infrastructure siting and network development	• Clean: deploy ZEV charging/refueling infrastructure
Cross-Sectoral Planning and Forecasting	Forecasting and managing grid loads—BEVs and hydrogen production	• Clean: reduce ZEV TCO, reduce emissions intensity of fuels, and deploy ZEV charging/refueling infrastructure
	Multimodal and multisectoral fuel and feedstock supply and demand	• Clean: reduce ZE/net-zero TCO, reduce emissions intensity of fuels

VEHICLE, INFRASTRUCTURE, AND FUEL TECHNOLOGIES AND PRODUCTION PATHWAYS

Continued research on improved vehicle and infrastructure components, fuel production technologies and feedstocks, and scalable production pathways is core to achieving Clean strategic priorities of reducing ZEV and net-zero fuel TCO, improving vehicle availability and operational suitability, and reducing the emissions intensity of fuels. Vehicle component-level research also meets Efficient aims of improving energy efficiency within the MHDV mode. DOE is a leading actor in pursuing this agenda, with several programs already developed through various offices. This research involves sustained partnerships among the federal government, national laboratories, academia, and industry.

Current research efforts are pursuing agendas on advanced vehicle components, improved infrastructure technologies, and improved manufacturing processes, which are of primary importance to improve the cost, performance, efficiency, and durability of candidate technologies. These include programs funded by VTO, HFTO, and the Advanced Materials and Manufacturing Technology Office. Key BEV-focused efforts include improving current and next-generation battery technologies, developing advanced battery manufacturing processes, and developing the MCS. Key FCEV research priorities include improving present-day fuel cells' cost, efficiency, and durability; exploring advanced fuel cell technologies; and accelerating domestic manufacturing of fuel cells. In addition to these programs, the 21st Century Truck Partnership is another DOE-funded partnership that conducts research and analysis across multiple vehicle technologies, including drafting roadmaps and establishing technology targets.

Research is also ongoing on improving **component recycling and reuse**, which is necessary to reduce the costs of critical materials and reduce environmental impacts throughout the vehicle life cycle. Such research is being conducted for batteries as part of the United States Advanced Battery Consortium's research efforts and the Recovery and Recycling Consortium, which develops methods for recycling and reusing clean hydrogen materials and components.

Ongoing research and tool development for technoeconomic and life cycle assessment is funded through DOE programs and at national laboratories. This research is needed to enable identification of least-cost, lowest-emissions solutions for sustainable liquid fuels, hydrogen production pathways, and other processes. Examples of tools include ANL's GREET model, which assesses environmental and emissions impacts of vehicle operations and fuel production pathways, and various bioenergy models developed by multiple national laboratories, which evaluate biofuel production processes, cost, and emissions across multiple pathways.

In addition to these programs, the following are key research needs for vehicle, infrastructure, and fuel technologies:

- Establish strategic partnerships to develop and demonstrate ZEV prototypes for commercial pickups and specialized vehicles.
- Establish strategic partnerships to **demonstrate long-haul MHDV and infrastructure operations** in real-world corridors. The SuperTruck 3 Initiative includes several projects aimed at demonstrating longer-range ZEVs and high-speed charging infrastructure.
- Expand target setting to establish ZEV component cost and performance goals for a broader range of MHDV applications. This work is ongoing under the 21st Century Truck Partnership.
- Continue research on **improved vehicle efficiency**, including **aerodynamics and lightweighting**, building on previous work completed in the SuperTruck 2 program.
- Develop improved MHDV **modeling tools** with the aim of conducting spatially resolved, comprehensive life cycle analysis of the air quality impacts of MHDV operations, fuel

production, and vehicle production and end of life. This is of particular importance to improve assessment of the distribution of benefits of ZE-MHDVs across disadvantaged communities—and any costs that may fall on communities due to upstream processes.

CONVENIENCE, EFFICIENCY, AND VEHICLE OPERATIONS

A second core research agenda centers around convenience, efficiency, and vehicle operations. This includes supporting research on **freight mode choice**; Convenient **siting and land use**; **fleet operational improvements**, including **optimizing managed charging potential**; and **infrastructure siting and network development**.

Key priorities include the following:

- **Improve data collection on vehicle operations**, including duty cycles, dwell times, and vehicle survival and scrappage. Highly resolved and nationally representative data can serve multiple research aims, including identifying energy demands for specialized vehicles and work trucks, identifying hard-to-decarbonize routes and operations, developing fleet-facing tools to optimize managed charging and depot charging capacity, and forecasting future liquid fuel demands from legacy fleets. A key priority of data collection should be ensuring standardization of reporting across sources and vehicles, which will be necessary to streamline analysis and ensure accuracy.
- **Develop fleet-facing tools** aimed at enabling fleets to estimate payback times for ZEV adoption, plan for charging infrastructure needs and capacity requests (for BEVs), and identify opportunities for managed charging (for BEVs) and co-location of renewables and storage (including for depot charging or on-site hydrogen production).
- **Develop improved models to assess mode choice and multimodal operations** in passenger and freight modes. These models will be needed to inform target setting and investments in efficient multimodal actions.
- **Improve infrastructure planning tools** aimed at forecasting the number of needed charging/refueling infrastructure stations, optimizing site locations, and forecasting charging demands and grid impacts. Examples of existing DOE-funded tools include the HEVI-LOAD and EVI-X suite of modeling tools aimed at forecasting BEV charging demands, station locations, deployment costs, and grid impacts. These tools should be expanded to consider infrastructure needs for wider ranges of MHDV vocations and operational patterns. Additional tools aimed at hydrogen infrastructure planning should also be expanded.
- **Improve land-use planning tools** by incorporating greater consideration of full freight networks and better accounting for freight externalities.

CROSS-SECTORAL PLANNING AND FORECASTING

Finally, research at the intersection of energy production sectors and transportation modes can improve understanding and planning for the impacts of ZEV transitions. Core research needs include research on **grid impacts**—including load-forecasting tool development for utilities to assess future demands from BEVs; electrified hydrogen production pathways; and other end uses, such as buildings. Research is also needed on **sustainable liquid fuel demands and production pathways** within the transportation sector and across other end uses, particularly industry. Examples of currently funded projects include DOE's EVGrid Assist initiative aimed at developing tools to forecast MHD-BEV adoption and charging loads to help utilities better plan for future electrification. DOE-funded models such as the Transportation Energy and Mobility Pathway Options (TEMPO) model and the Bioenergy Scenario Model developed by NREL may be used in estimating whole-of-transportation liquid fuel demands and implications for upstream biofuel production pathways.

6.6 Indicators of Progress

A robust monitoring and data collection agenda is needed to track progress on core MHDV Plan milestones and adapt to changing market conditions. Table 7 lists key indicators to track this progress. These indicators will monitor progress on deployment of clean fuels and infrastructure, ZEV deployment and operation, and progress toward a sustainable and economic transition. The MHDV Plan sets a milestone of developing a monitoring and data collection plan by 2025 and implementing a public dashboard of MHDV indicators by 2027.

Expanded scope and frequency of data collection will be needed to enable the development of many indicators. Agency, industry, and national laboratory partnerships should be leveraged to expand existing monitoring programs and implement new ones. A key priority is the increased frequency of the Bureau of Transportation Statistics' (BTS's) VIUS, which provides crucial nationally comprehensive data on MHDV operations and efficiency. Expanding the VIUS survey frequency to every 3 years from the current every 5 years would assist in monitoring the indicators included in this plan. In addition, expanding the survey to include automobiles, buses, and government vehicles would provide a more complete picture of the entire vehicle fleet and offer crucial nationally comprehensive data on MHDV operations and efficiency.

Table 7. Indicators of Progress on MHDV Decarbonization

Strategy Area	Indicator	Cadence	Data Sources
Clean Fuels and Infrastructure	Number and location of private and publicly accessible zero-emission charging/refueling stations; port counts and charging speed (EVSE); capacity of hydrogen stations; connectivity of stations along freight corridor routes	Ongoing	Alternative Fuels Data Center
	Clean hydrogen production volume; carbon and pollutant intensity and price; location, capacity, and type of hydrogen production plants	Annual	DOE and industry partners
	Carbon and pollutant emissions intensity of the electric grid	Annual	EPA Emissions & Generation Resource Integrated Database; Energy Information Administration (EIA)
	Sustainable liquid-fuel production volume, carbon and pollutant intensity and price	Annual	EPA Renewable Fuel Standard database
ZEV Deployment	Number of zero-emission MHDV sold by vehicle class, body type, and application (examples: freight, bus, vocational); number of available MHDV models	Annual	Transit buses: National Transit Database All other MHDVs: State and industry partnerships needed to collect data on all MHDV registrations. Additional partnerships will be needed to collect data on third-party body up-fits.
	Zero-emission MHDV component cost and performance data, including MHDV-specific battery pack price and energy density; hydrogen fuel cell and onboard storage tank prices	Annual	DOE and industry partners
	Domestic battery and fuel cell production volume	Annual	DOE and industry partners
	Activity, energy consumption, and efficiency of the legacy and zero-emission MHDV fleet (annual and daily mileage, vehicle loads, and fuel consumed per ton-mile transported)	Semiannual (3 to 5 years)	BTS VIUS, with additional questions on vehicle load and daily mileage patterns and expanded scope to include automobiles, buses, and government vehicles

	Consumption of sustainable liquid fuels by MHDVs	Annual	DOE-EIA partnership
Efficient Transportation Systems	Energy and emissions intensity per passenger-mile and ton-mile of freight moved	Semiannual (3 to 5 years)	DOT, compiled through existing cross-office data collection programs
Sustainable and Economic Transition	Number of zero-emission and conventional vehicles operating near ports, warehouses, and intermodal hubs and near disadvantaged communities; miles traveled by these vehicles	Annual	Partnerships with ports and intermodal facilities on ZEV drayage adoption and utilization initiatives
	Jobs created in development, production, and maintenance of clean vehicles, fuels, and infrastructure, including those located in disadvantaged communities	Annual	Bureau of Labor Statistics
	Air quality changes in disadvantaged communities attributable to the deployment of zero-emission MHDVs and supporting infrastructure and fuel production, including addressing secondary pollutant formation and impacts for near-highway and downwind communities	Biannual	Partnership with air quality modeling teams at EPA and national laboratories, in consultation with DOT

7. CONCLUSION

A Holistic, Comprehensive Approach

Transportation is the largest source of GHG emissions and the second-largest household expense. Decarbonizing the transportation sector is integral to achieving a net-zero-emission economy that benefits all communities. Moving toward zero transportation GHG emissions is critical not only for tackling climate change, but also for the accompanying transformation of the passenger and freight mobility systems toward sustainable solutions and technologies that will save lives and improve quality of life of all Americans. It will increase U.S. competitiveness, decrease household costs, increase economic growth, reduce pollution, and increase accessibility and community opportunities.

The historic MOU signed by DOE, DOT, EPA, and HUD in September 2022 initiated collaboration across the federal government to rapidly decarbonize transportation. The agreement recognizes the unique expertise, resources, and responsibilities of each agency, setting the foundation for solutions that are more innovative and far-reaching than any of the agencies could achieve independently.

The U.S. National Blueprint for Transportation Decarbonization (Blueprint), the first step in this collaboration, created a national vision for a decarbonized transportation system. The Blueprint embraced five core principles—initiate bold action; embrace creative solutions across the entire transportation system; ensure safety, equity, and access; increase collaboration; and establish U.S. leadership—to serve as the foundation for all strategies.

The Blueprint provided a holistic, system-level approach to decarbonizing the transportation sector, proposing actions that address all aspects of transportation GHG emissions, from land use patterns and development to design of individual vehicles. The Blueprint focused on three key strategies—Convenience, Efficiency, and Clean—which will support and complement each other in achieving the goals of the Blueprint (see Figure 23).

Figure 22. The Blueprint's five principles

1

Increase Convenience

by supporting community design and land-use planning at the local or regional level that ensure that job centers, shopping, schools, entertainment, and essential services are strategically located near where people live to reduce commute burdens, improve walkability and bikeability, and improve quality of life…

…Because every hour we don't spend sitting in traffic is an hour we can spend focused on the things and the people we love, all while reducing GHG emissions.

2

Improve Efficiency

by expanding affordable, accessible, efficient, and reliable options like public transportation and rail, and improving the efficiency of all vehicles…

…Because everyone deserves efficient transportation options that will allow them to move around affordably and safely, and because consuming less energy as we move saves money, strengthens our national security, and reduces GHG emissions.

3

Transition to Clean Options

by deploying zero-emission vehicles and fuels for cars, commercial trucks, transit, boats, airplanes, and more…

…Because no one should be exposed to air pollution in their community or on their ride to school or work and eliminating GHG emissions from transportation is imperative to tackle the climate crisis.

Figure 23. Blueprint decarbonization strategies

As part of the Clean strategy, the Blueprint committed to developing specific mode-based action plans for the light-duty vehicle, medium- and heavy-duty vehicle, rail, maritime, off-road, and aviation sectors to chart pathways to accomplish this complex task over the next three decades. The modal action plans propose near-term, medium-term, and long-term actions to achieve net-zero emissions in each of the different modal sectors by 2050. This phased approach leverages the historic federal BIL and IRA funding; encourages deployment of scalable, market-driven technologies; provides industry and stakeholders with certainty about transforming the transportation sector; recommends planning and proposes policy opportunities at multiple levels of government; and promotes expanded RDD&D to support innovative approaches to decarbonize the transportation sector, including new technologies and fuels. The phased actions across all modes are summarized below.

Actions over the near-term (initiated before 2030) involve leveraging IRA and BIL incentives to support the deployment of ZEVs in early MHD markets and expand their market share in passenger (LD) vehicles. Billions of dollars in transportation tax credits, infrastructure, and supply chain investments are currently being made throughout the United States through BIL and IRA funds. The Blueprint outlined the critical need to **develop energy refueling infrastructure**, particularly critical freight hubs. After the release of the Blueprint, the U.S. National Zero-Emission Freight Corridor Strategy was developed and released. This plan outlined the phased approach of critical EV charging and hydrogen fueling networks. Work must continue with **utilities, utility regulators, and other grid stakeholders** to ensure a balance of needs for electrification. There is a critical need to **scale up ZEV component manufacturing and fuel production** incentivized by IRA tax credits, including domestic tax credits for the manufacturing of batteries, hydrogen production tax credits, and biofuels for legacy vehicles. The United States will also need to expand production of biofuels and hydrogen to further support the harder-to-decarbonize sectors of rail, maritime, and off-road. **Engaging in further research, data collection, demonstrations, and outreach** for future ZEV deployments will be essential for expansion into additional market segments. **International leadership** will continue to play a critical role in building out international infrastructure and standards for aviation, rail, and maritime, and for facilitating the deployment of cross-border corridor infrastructure for ZE-MHDVs. These actions will set the foundation for future actions to fully decarbonize the transportation system by 2050.

Medium-term actions (2030 to 2040) will need to focus on finalizing and ensuring BIL and IRA investments are fully leveraged. **Transitioning demonstrations to market technologies** will be essential during this timeframe. The United States will need to **expand ZEV adoption** from early-market to full-scale production and new market segments. This will include **further establishing regional and international corridors and intermodal infrastructure networks** for passenger, freight, maritime, off-road, and rail fueling networks and **scaling and supporting investments** in zero and low-emission vessels and vehicles. **Implementing EPA's emissions standards and NHTSA's Corporate Average Fuel Economy Standards** through MY 2032 will continue the deployment and adoption of ZEVs in the light-, medium-, and heavy-duty sectors. Medium-term actions may also involve future rulemaking and legislative efforts in these sectors.

Long-term actions (2040 and beyond) will be responsive to market developments and will likely include expanding ZEV and low-emission vessel and vehicle adoption to all market segments, as well as achieving full build-out of corridor energy infrastructure for all modes, both domestically and internationally. Realizing cost reductions in ZEVs to reach parity with ICEVs, as well as supporting sustainable liquid-fuel adoption for legacy vehicles, will be essential. Production and bunkering of zero- and low-emission fuels will need to expand and scale for use in the aviation, maritime, and off-road sectors. Long-term actions may also involve future rulemaking and legislative efforts in these sectors.

A Report on Actions for Medium- and Heavy-Duty Vehicle Energy and Emissions Innovation

The report for MHDVs summarizes strategies and actions to nearly eliminate GHG emissions in the U.S. commercial on-road MHDV sector and reduce or eliminate emissions of criteria pollutants, prioritizing communities facing the largest air pollution impacts. In the near term, the plan proposes strengthened and continued development of ZE-MHDV power trains (i.e., battery-electric and hydrogen fuel cell vehicles), coupled with incentives to reduce costs, scale manufacturing, and accelerate ZEV and infrastructure deployment in established market segments and demonstrate viability in emerging market segments. We must also continue to make

investments in zero-emission energy infrastructure at depots and regional hubs, as well as leverage opportunities to use available low-carbon liquid drop-in fuels. Near-term goals are established of achieving cost parity between long-haul freight ZEVs and ICEVs by 2030 and realizing **36%** completion of the NHFN **by 2030** and close to **100%** by **2040**. Long-term solutions must focus on a full transition to ZEVs across all MHDV applications, a full build-out of the ZEV national corridor network, and support for sustainable liquid fuels for legacy vehicles and hard-to-decarbonize operations, especially in remote areas. We also need to implement actions and strategies to improve system-wide convenience and efficiency of freight and passenger movement across modes. In addition, there are several cross-cutting actions across all action plans in support of the Blueprint: develop a framework to collect the data necessary to track progress with the decarbonization objectives, support development of the workforce needed to manufacture and maintain new vehicle technologies and infrastructure, and decarbonize the national electricity grid.

Call to Action

Transforming the MHD sector, other transportation modes, and the entire national transportation system over the next three decades will be a complex endeavor, but by taking a comprehensive and coordinated approach, it is a challenge that we can, and must, solve. The strategies presented in these action plans identify unique opportunities and will be most effective if decision-makers, acting quickly and in concert, continually increase the ambitions of their actions, collaboration, and investments. There is no one technology, policy, or approach that will solve our transportation challenges unilaterally; we need to develop, deploy, and integrate a wide array of technologies and solutions to ensure we achieve our 2030 and 2050 goals.

In addition to leadership at the federal level, reaching these ambitious climate goals will require collaboration with all levels of government, industry, communities, and nonprofit organizations. The action plans are intended to send a strong signal to our partners and other stakeholders to use the documents as guideposts and frameworks to support and complement their own planning and investments and to coordinate actions in each sector. We will continue to set bold targets for improving our transportation systems and transitioning to zero-emission vehicles, vessels, and fuels on a timeline consistent with achieving economy-wide 2030 and 2050 emissions reduction goals. As we decarbonize our transportation system, we can create a more affordable and fair transportation system that will provide multiple benefits to all Americans for generations to come. It will be important to continually evaluate and update our actions as technology and policy continue to evolve, and to continue to strengthen the collaborations among DOE, DOT, EPA, HUD, and all our partners. Together, we must act decisively now to provide better mobility options, address inequities, and offer affordable and clean mobility solutions to ensure the health of the planet for future generations. **It is up to all of us to make that vision a reality and move forward with creative and innovative solutions toward a better future for all.**

ACRONYM LIST

AB	assembly bill
AEO	*Annual Energy Outlook*
AFDC	Alternative Fuels Data Center
ANL	Argonne National Laboratory
BETO	Bioenergy Technologies Office
BEV	battery-electric vehicle
BIL	Bipartisan Infrastructure Law
BT23	2023 Billion-Ton Report
BTF	behind-the-fence
BTS	Bureau of Transportation Statistics
Btu	British thermal unit
CAP	criteria air pollutant
CI	carbon intensity
CNG	compressed natural gas
CO	carbon monoxide
CO-Optima	Co-Optimization of Fuels & Engines
DCFC	direct current fast-charging
DER	distributed energy resource
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
DWPT	dynamic wireless power transfer
EIA	Energy Information Administration
EMC	electromagnetic compatibility
EO	executive order
EPA	Environmental Protection Agency
ePTO	electric power takeoff
ESB	electric school bus
EV	electric vehicle
EVITP	Electric Vehicle Infrastructure Training Program
EVSE	electric vehicle supply equipment
FCEV	fuel cell electric vehicle
FHWA	Federal Highway Administration
FOG	fat, oil, and grease
FTA	Federal Transit Administration
GHG	greenhouse gas
GHGI	Inventory of U.S. Greenhouse Gas Emissions and Sinks
GIS	geographic information system
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GVWR	gross vehicle weight rating
H2ICE	hydrogen internal combustion engine
HD	heavy-duty
HDPUV	heavy-duty pickup trucks and vans
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICCT	International Council on Clean Transportation
ICE	internal combustion engine
ICEV	internal combustion engine vehicle
IIJA	Infrastructure Investment and Jobs Act
IRA	Inflation Reduction Act
ITS	intelligent transportation system
L2	Level 2
LD	light-duty
LDV	light-duty vehicle
LNG	liquified natural gas

LPO	Loan Programs Office
MCS	Megawatt Charging System
MD	medium-duty
MHD	medium- and heavy-duty
MHD-BEV	medium- and heavy-duty battery-electric vehicle
MHDV	medium- and heavy-duty vehicles
MMT CO_2e	million metric tons of carbon dioxide equivalent
MOU	memorandum of understanding
MW	megawatt
MY	model year
NACFE	North American Council for Freight Efficiency
NEI	National Emissions Inventory
NEVI	National Electric Vehicle Infrastructure
NFPA	National Fire Protection Association
NH_3	ammonia
NHFN	National Highway Freight Network
NHTSA	National Highway Traffic Safety Administration
NOx	nitrogen oxide
NREL	National Renewable Energy Laboratory
NTD	National Transit Database
OCED	Office of Clean Energy Demonstrations
OEM	original equipment manufacturer
PEM	polymer electrolyte membrane
PHEV	plug-in hybrid electric vehicle
PM	particulate matter
RD	renewable diesel
RD&D	research, development, and demonstration
RDD&D	research, development, demonstration, and deployment
SAE	Society of Automotive Engineers
SAF	sustainable aviation fuel
SO_2	sulfur dioxide
TCO	total cost of ownership
TEMPO	Transportation Energy and Mobility Pathway Options
TWC	Transit Workforce Center
TWh	terawatt-hour
UNECE	United Nations Economic Commission for Europe
U.S.	United States
USG	U.S. government
V2G	vehicle-to-grid
V2X	vehicle-to-everything
VGI	vehicle-grid integration
VIUS	Vehicle Inventory and Use Survey
VMT	vehicle-miles traveled
VOC	volatile organic compound
VTO	Vehicle Technologies Office
WRI	World Resources Institute
ZEV	zero-emission vehicle

APPENDIX A: VEHICLE TYPES AND VOCATIONS

Table A1. MHDV Vehicle Class by Gross Vehicle Weight Rating; Source: Environmental Protection Agency[483]

Vehicle Class	Gross Vehicle Weight Rating (Pounds)
Class 2B	8,501 to 10,000
Class 3	10,001 to 14,000
Class 4	14,001 to 16,000
Class 5	16,001 to 19,500
Class 6	19,501 to 26,000
Class 7	26,001 to 33,000
Class 8	33,001 and above

Table A2. MHDV Body Type Definitions. Source: Argonne National Laboratory[484]

Body Type	Definition
Single-Unit Truck	Class 7/8 vehicle used to transport goods, construction materials, and other equipment. These vehicles feature a single cargo area on a chassis with a cabin area for the driver.
Combination Truck (also known as "tractor-trailer")	Class 7/8 vehicle with one or more trailers towed by a tractor. These vehicles are used in intercity and interstate transportation of goods.
Cargo Van	Class 2B/3 vehicle used for short-distance transportation of goods in suburban and urban areas. The size, shape, and design of the van can be customized to fit certain needs.
Pickup	Class 2B/3 vehicle used for personal and commercial hauling. Class 2B vehicles are primarily used for light hauling, carrying passengers, and towing recreational products. Class 3 vehicles are primarily used to transport landscaping and construction materials.
Step Van	Class 2B vehicle used for parcel delivery. The vehicle is designed for ease of maneuverability in urban settings and allows for the driver to access cargo efficiently.
Box Truck	Class 3–6 vehicle used for transportation of large cargo, often including furniture. These vehicles feature a large, enclosed cargo area on a chassis.
Utility Truck (also known as "Bucket Truck")	Class 5 vehicle with a hydraulic arm used to elevate service workers for aerial work. The arm is built into the chassis of a pickup truck.
Refuse Truck	Class 7 vehicle designed to collect, compact, and dispose of waste.

Dump Truck	Class 8 vehicle that carries dirt, debris, and other loose materials. These vehicles are often used at construction sites.
Intercity Bus	Class 8 passenger vehicle designed to shuttle large numbers of passengers between cities or regions.
Transit Bus	Class 7/8 passenger vehicle designed to maneuver through urban and suburban areas. These vehicles provide regular transportation services.
School Bus	Class 6/7 passenger vehicle used to shuttle students to and from academic institutions. Smaller vehicles are built on a Class 3 chassis.

APPENDIX B: BIOFUELS' ROLE IN DECARBONIZING THE TRANSPORTATION SECTOR

Context

Historically, the U.S. transportation sector has overwhelmingly relied on liquid petroleum-based fuels, which supplied over 90% of its energy needs in 2022.[485] The U.S. Transportation Decarbonization Blueprint laid out a bold plan to move the transportation sector to net-zero emissions, using a range of low-GHG fuels, including electrification, hydrogen, and liquid fuels from biomass and other waste carbon resources, such as CO2 and food waste (referred to here collectively as "biofuels"). Biofuels already contribute to on-road light-, medium-, and heavy-duty transportation on the order of billions of gallons, driven by decades of U.S. policy objectives such as energy security, clean air, lead-free octane enhancement of gasoline, climate change mitigation, and rural economic development. The Blueprint identifies aviation as the transportation sector with the greatest long-term opportunity for biofuels, as aviation is limited in low-GHG options. Due to biofuel compatibility with existing fleets and fueling infrastructure, biofuels will play an important role in reducing carbon emissions across all modes during the transition to zero-emission solutions. In particular, biofuels will be important in decarbonizing the legacy fleet in the rail, marine, and off-road sectors due to long equipment lifetime and slow fleet turnover in these modes. The Blueprint also recognizes that biofuels will play a supporting role where electrification and hydrogen may not be as practical. Successfully managing these competing demands for biofuels will be a key challenge going forward. Converting bioenergy from one sector to another does not automatically reduce transportation GHG emissions unless the first sector is reduced or carefully replaced with another energy source. More biofuels beyond current production are needed. To avoid direct land-use actions such as converting to more agricultural land for producing corn and soybeans currently used for biofuels, a critical near-term action within approximately 10 years for biofuels is to pivot to accessing unused and underused biomass already available, which is estimated at around 350 million dry tons per year, including over 130 million dry tons of agricultural residues, over 170 million dry tons of a variety of wastes, and over 30 million dry tons of forestland resources.[486]

The United States Aviation Climate Action Plan establishes a goal of net-zero emissions from U.S. aviation by 2050. The SAF Grand Challenge establishes a goal of, by 2030, 3 billion gallons of sustainable aviation fuel (SAF) that achieves at least a 50% reduction in emissions on a life cycle basis and 35 billion gallons by 2050.[487] The SAF Grand Challenge Roadmap,[488] which was developed by USG agencies with extensive input from researchers, nongovernmental organizations, and industry, outlines a whole of-government approach with coordinated policies and activities that should be undertaken by federal agencies to achieve both the 2030 and 2050 goals. In the SAF Grand Challenge Roadmap, the vast majority of the policies and activities focus on the needs for innovation in feedstock and conversion technologies that are largely agnostic to fuel type. As discussed in the action plans, decarbonizing maritime freight may require large volumes of methanol, decarbonizing noncommercial maritime vessels may require significant volumes of green gasoline, and decarbonizing the off-road, rail, and long-haul heavy-duty modes may require large volumes of biomass-based diesel.

The Blueprint recognizes that biofuels will play a leading role for aviation decarbonization while playing a supporting role for decarbonizing other transportation sectors.

In addition to the Blueprint, the U.S. goals and strategies for biofuels are also driven by the National Biotechnology and Biomanufacturing Initiative and coordinated through the National Bioeconomy Board. This appendix seeks to complement modal plans by summarizing USG goals and strategies for biofuels that are not specific to individual modes of transportation and thus not fully integrated within specific modal plans.

Biofuels Background

The United States is the world's largest biofuels producer, producing 15 billion gallons of ethanol and over 3 billion gallons of biomass-based diesel in 2022.[489] These fuels are typically blended into gasoline and diesel, respectively, for use in on-road transportation. Most U.S. ethanol is produced from fermentation of cornstarch. U.S. biomass-based diesel is currently produced via either hydroprocessing, co-processing, or transesterification and uses lipid feedstocks that include oilseeds (e.g., soy, canola) and waste fats, oils, and greases (FOGs), such as used cooking oil. While the United States has these domestic supplies of biofuels, the supply is far from sufficient to satisfy the energy needs of the entire U.S. transportation sector.

Maximizing the impact of biofuels in support of the Blueprint will require expanding biofuels production, primarily through new feedstocks and production pathways. Government support will continue to play an important role in developing technologies, building supply chains, and scaling up biofuels production to meet the need for low-carbon liquid fuels. Policy and regulation at the federal and state levels have played and will continue to play a critical role for biofuels production in the United States to drive down CI and expand production.

Domestic Resource Potential for Biofuel Production

Currently, most biofuels in the United States are produced from corn and soybean planted on agricultural land. It is important for the U.S. agricultural system to prioritize its most productive land to produce food, feed, and fiber. Therefore, there are limits to the amount of agricultural land that can be used for biofuel production to meet the energy demands of our transportation sector. While productivity improvements can increase the amount of biofuel feedstock produced from the same acreage, these gains are modest in comparison to the needs for biofuels expansion. USDA projects 2% annual yield improvements for corn and 0.5% yield improvements for soy over the next 10 years.[490] The deployment of intermediate oilseeds that are planted and harvested in between these cash crop rotations could also sustainably expand lipid feedstock supply that can be converted using commercially ready technologies to increase production of SAF and biomass-based diesel with little impact on land use.[491] However, in order to support decarbonization, domestic biofuels production must expand primarily through the use of new feedstocks resources that are not grown on prime agricultural land.

The *2023 Billion-Ton Report* (BT23) estimates the United States has the capacity to sustainably and economically produce 1.3 to 1.5 billion tons of biomass and organic wastes per year in the future, over triple the amount the current U.S. bioeconomy utilizes today.[492] These resources include:

- Agricultural residues (e.g., corn stover, wheat straw) from the production of food, grain, and fiber
- Wastes, including animal manure; wastewater sludge; inedible FOGs; sorted municipal solid waste including unrecyclable paper/cardboard waste, yard waste, and food waste; and landfill gas

- Forest thinnings from small-diameter trees that need removal to increase forest health and reduce wildfire potential, and logging and mill processing residues
- Purpose-grown energy crops (e.g., perennial grasses, fast-growing trees) that can be grown on less productive land with improved environmental performance and lower carbon-intensity than traditional agricultural production.

Because biomass production potential is contingent upon market pull, the BT23 presents production capacity by market scenario. One scenario presented in the BT23 is the "near-term scenario", which illustrates resources that exist today[n] (and in 2030). This includes 350 million tons per year of unused biomass (including ~250 million tons per year of cellulosic biomass) in addition to the ~340 million tons of biomass currently used for energy and coproducts (Figure B1). The mature-market scenarios, adding ~440–800 million tons more biomass, include energy crops, which will not be fully deployed by the 2030 SAF target. However, the 2030 SAF target of 3 billion gallons per year would require 50–60 million tons of biomass per year[o], which is merely ~15% of the Near term scenario untapped production capacity. (See BT23 Figure ES-1 and Table ES-2).

[n] Near-term presents resources that are annually available (within specified environmental constraints, at specified prices, and available for collection).

[o] At an assumed average conversion rate of 55 gallons of biofuels per ton.

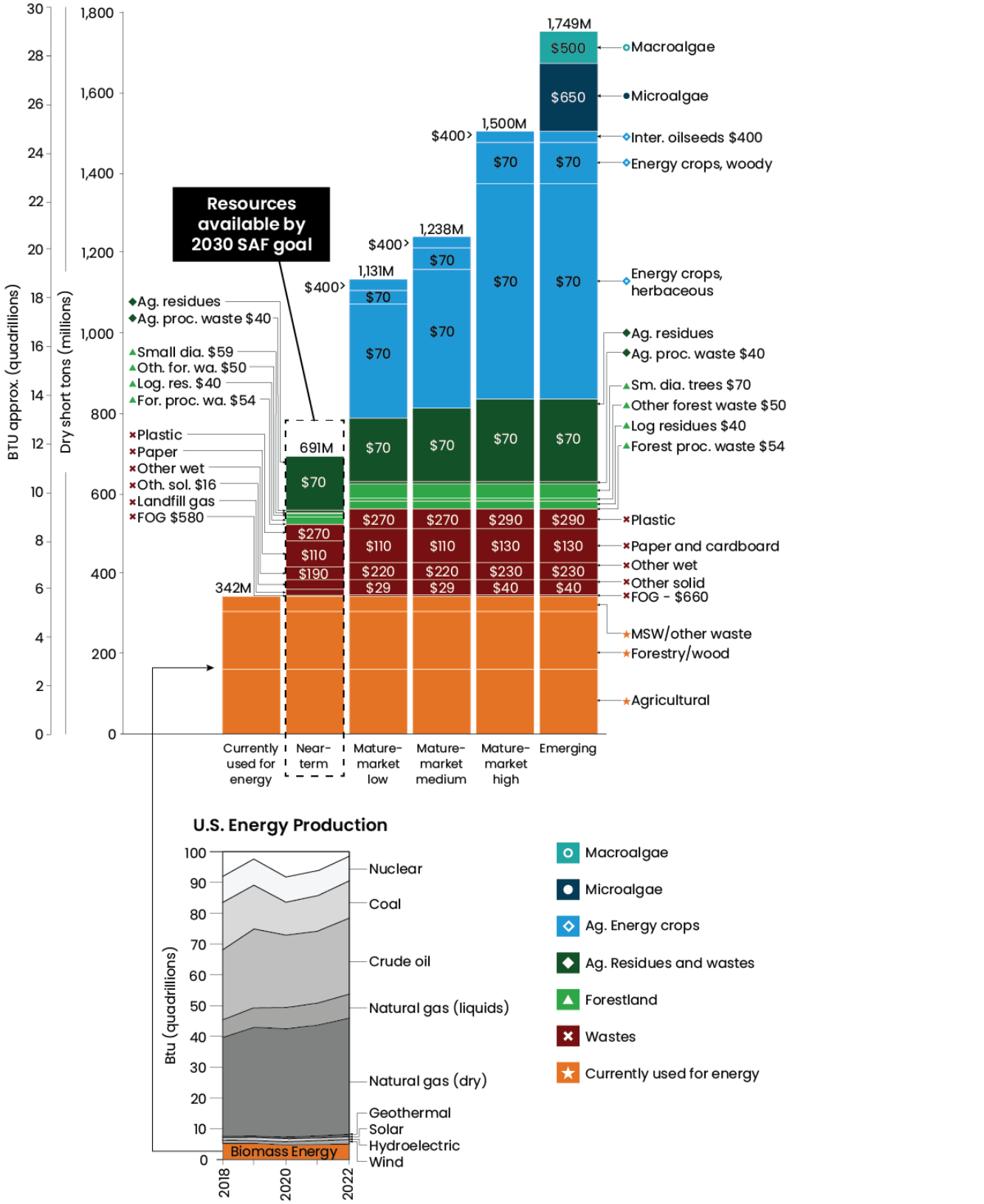


Figure B1. Estimated biomass production capacity of the US. The near-term scenario is highlighted, which identifies production capacity in 2030, including 235 million tons per year of unused cellulosic biomass resources. (Source: USDOE 2023 Figure ES-1[493].)

USG Goals and Strategies for Biofuels

The U.S. Transportation Decarbonization Blueprint prescribed five guiding principles to guide future policymaking and research, development, demonstration, and deployment in the public and private sectors, which are exemplified by the USG's coordinated approach and leadership on biofuels:

- Implement bold actions to achieve measurable results.
- Embrace creative solutions across the entire transportation system.
- Ensure safety, equity, and access.
- Increase collaboration.
- Establish U.S. leadership.

The USG has a long history of biofuels coordination since the Biomass Research and Development Act of 2000. Since then, the Biomass R&D Board has coordinated biofuels-related activities to advance a range of policy objectives, including climate change, energy security, domestic manufacturing and competitiveness. In recent years, these efforts have been driven by the National Biotechnology and Biomanufacturing Initiative and the SAF Grand Challenge with the mutual objectives of increasing domestic production of biofuels and improving the CI of biofuels production.

Federal government agencies developed a series of Bold Goals for U.S. Biotechnology and Biomanufacturing R&D in March 2023,[494] which include several goals that align with the U.S. Transportation Decarbonization Blueprint. These goals focus on expanding the availability and sustainability of feedstocks for the production of biofuels and increasing the production of SAF and biofuels for other hard-to-decarbonize modes of transportation.

Bold Goals for U.S. Biotechnology and Biomanufacturing R&D:

GOAL 1.1 Expand Feedstock Availability – In 20 years, collect and process 1.2 billion metric tons of conversion-ready, purpose-grown plants and waste-derived feedstocks and utilize >60 million metric tons of exhaust gas CO2 suitable for conversion to fuels and products, while minimizing emissions, water use, habitat conversion, and other sustainability challenges.

GOAL 1.2 Produce SAF – In 7 years, produce 3 billion gallons of SAF with at least 50% (stretch 70%) reduction in GHG life cycle emissions relative to conventional aviation fuels, with production rising to 35 billion gallons in 2050.

GOAL 1.3 Develop Other Strategic Fuels – In 20 years, develop technologies to replace 50% (>15 billion gallons) of maritime fuel, off-road vehicle fuel, and rail fuel with low net GHG emission fuels.

GOAL 3.1 Develop Measurement Tools for Robust Feedstock Production Systems – In 5 years, develop new tools for measurement of carbon and nutrient fluxes in agricultural and bioeconomy feedstock systems that contribute to a national framework.

GOAL 3.2 Engineer Better Feedstock Plants – In 5 years, engineer plants and manipulate plant microbiomes to produce drought-tolerant feedstocks capable of growing on underutilized land with >20% improvement in nitrogen and phosphorus use efficiency.

STRATEGIES TO ACHIEVE NEAR-TERM BIOFUEL GOALS

BT23 estimates there are 350 million dry short tons per year of biomass above current uses that are near-term opportunities that could be accessible for biofuels in the next 5–10 years. Some of these resources, such as wastes, are already collected but then landfilled. Others, such as agricultural residues and timberland resources, exist in fields and forests but must be collected for use. Most of this near-term biomass is lignocellulosic. Technologies to produce liquid fuels from lignocellulosic biomass have not been fully derisked. Given the significant lead time required for biofuels production infrastructure to be built, the path to meeting near-term goals focuses on actions to scale the harvesting/collection and scaling of these resources and the production facilities that can turn them into biofuels as quickly as practicable. These actions include:

- Demonstrate new biofuel pathways that can produce biofuels from additional feedstocks beyond lipids and starch.
- Build and support stakeholder coalitions through outreach, extension, and education to set the stage for biofuel feedstock and biofuel supply chains to develop and sustain themselves and replicate with continuous improvement.
- Increase deployment of alternative lipid feedstocks including intermediate oilseeds that can be readily converted to SAF and biomass-based diesel through commercially available conversion technologies.[3]
- Improve the CI of biofuels production using commercially available feedstocks and infrastructure.
- Develop improved environmental models and data for biofuels to support optimization of existing policies and implementation of new policies that could be enacted.
- Inform biofuels policy development with analysis of gaps and impacts of policies under consideration.
- Stakeholder outreach and engagement on sustainability to exchange data and information about best practices to reduce lifecycle GHG emissions from agricultural and forest-derived feedstocks and optimize other environmental and social impacts.
- Enable use of drop-in unblended biofuels and biofuel blends up to 100% to simplify blending requirements, reduce cost of logistics, and facilitate supply.

STRATEGIES TO ACHIEVE LONG-TERM BIOFUEL GOALS

The path to meeting long-term biofuel and decarbonization goals requires a continuing focus on innovation, including research, development, and demonstration (RD&D) of new feedstock and conversion technologies, increasing production capacity with continued progress in cost reductions and CI. This effort occurs simultaneously with the near-term strategies above such that these innovations can be demonstrated and scaled by 2050. Technologies in this portfolio are expected to result in a dramatic build-out and expansion of alcohol, waste-based, lignocellulosic, and waste and captured carbon gas pathways.

- Conduct RD&D on scaling and sustainability of biomass, waste, and residue feedstocks to enable innovations in technologies and strategies that increase the availability of purpose-grown energy crops, wastes, and agricultural and forestry residues at reduced CI and cost. This includes addressing the social, environmental, and economic sustainability aspects of feedstock supply chains.
- Conduct RD&D on feedstock logistics and handling reliability to increase efficiencies and decrease cost and CI of supply logistics from the producer's field to the conversion facility door.
- De-risk scale-up through R&D and integrated piloting of critical pathways by 2030 to accelerate fuel conversion technology scale-up and improve financeability of critical conversion pathways that utilize the full potential of an expanded feedstock supply.
- Model and demonstrate sustainable regional supply chains for critical pathways by 2035 to

promote commercialization of biofuel supply chains through process validation and risk reduction via access to critical data and tools that empower rapid, informed decision making when evaluating biofuel supply chain options.

- Build and support regional stakeholder coalitions through outreach, extension, and education to continue to expand a biofuels industry that improves environmental and economic performance while supporting job creation and social equity in multiple regions of the country.
- Continue to invest in industry deployment to help overcome barriers to project financing through creative financing, government loans and loan guarantees, and outreach.
- Continue to inform biofuel policy development to enable aligned policy incentives that will support long-term biofuel deployment.

Conclusion

Biofuels will play an important role in reducing carbon emissions across all modes of transportation, whether as a long-term decarbonization strategy or as a transition to zero-emission solutions. USG agencies have identified goals and strategies to improve CI and sustainability of biofuels and to expand biofuels production—particularly through developing supply chains and technology necessary to produce biofuels from purpose-grown energy crops, wastes, and agricultural and forest residues. While USG has placed a priority on producing biofuels for aviation due to the lack of alternative low-GHG options, it will be important to periodically assess fleet turnover and zero-emission vehicle adoption rates across various modes of transportation to inform the optimal allocation of biofuels across these modes to maximize the GHG benefits of biofuel use.

APPENDIX C: MORE DETAIL ON SELECTED DECARBONIZATION ACTIONS

Table C1. Announced Vehicle Manufacturer Decarbonization Commitments (Based on information compiled by CALSTART[495] and updated with more recent data. All commitments current as of June 11, 2024.)

Organization	Commitment	Target Year
Cummins Inc.	25% reduction in Scope 3 absolute lifetime emissions from newly sold products	2030
Daimler Truck North America	Offer only new vehicles that are carbon dioxide equivalent (CO_2e)-neutral in driving operation ("from tank to wheel")	2039
Ford Motor Company	Reduce Scope 3 greenhouse gas (GHG) emissions from use of sold products 50% per vehicle-kilometer (relative to a 2019 baseline)	2035
General Motors	Reduce Scope 3 GHG emissions from use of sold products 51% per vehicle-kilometer (relative to a 2018 baseline)	2035
Hyundai	30% electrification of all vehicles sold by 2030 and 100% by 2045	2030/2045
Isuzu	Net-zero GHG emissions across entire life cycle of Isuzu Group products	2050
Navistar	50% zero-emission new vehicle sales by 2030 and 100% by 2040	2030/2040
PACCAR	Reduce Scope 3 emissions by 25% from a base year of 2018 (on a gram CO_2e/vehicle-kilometer basis)	2030
Volvo Group	Reduce truck and bus Scope 3 emissions by 40% on a per-vehicle-kilometer basis	2030
Clean Truck Partnership*	Meet California's vehicle standards that will require the sale and adoption of zero-emission technology in the state, regardless of any attempts by other entities to challenge California's authority	N/A

*Includes Cummins Inc., Daimler Truck North America, Ford Motor Company, General Motors Company, Hino Motors Limited Inc., Isuzu Technical Center of America Inc., Navistar Inc., PACCAR Inc., Stellantis N.V., Truck and Engine Manufacturers Association, and Volvo Group North America.

APPENDIX D: MARKET SEGMENTATION AND EMISSIONS ACCOUNTING

MHDV Market Segmentation

Except for buses, medium- and heavy-duty vehicle (MHDV) market segments were defined based on an assessment of the 2021 Vehicle Inventory and Use Survey (VIUS)[496] based on a combination of vehicle class, body type, and operating characteristics. Table D1 shows resulting vehicle population and vehicle-miles traveled (VMT). Personal Class 2B and 3 vehicles were excluded from this report. Initial 2022 bus population and VMT estimates were gathered from separate sources.

Table D1. Commercial MHDV Population and Operating Statistics by Class and Market Segment (Non-bus population data were scaled to 2022 using growth rates from the *Annual Energy Outlook*.[497])

Vehicle Class	Market Segment	2022 Vehicle Population (Million)	Average Annual VMT (Miles/Vehicle)	Sources
Class 2B/3	Local Freight	1.5	11,477	VIUS[498]
	Regional Freight	1.4	20,253	
	Commercial Pickups	3.8	12,781	
	Specialized Vehicles	1.1	12,787	
Class 4–6	Local Freight	0.7	9,256	
	Regional Freight	0.9	24,947	
	Specialized Vehicles	0.7	12,880	
Class 7/8	Local Freight	0.8	12,023	
	Regional Freight	1.3	37,097	
	Long-Haul Freight	1.1	85,401	
	Specialized Vehicles	0.8	15,092	
Transit Bus		0.1	42,940	Stock: 2022 National Transit Database (NTD),[499] including the following vehicle types: articulated bus, bus, cutaway, double-decker bus, trolleybus, and over-the-road bus; VMT: Alternative Fuels Data Center (AFDC)[500]
School Bus		0.5	14,084	Stock: School Bus Fleet Fact Book[501]; VMT: AFDC[502]

Intercity Bus	0.03	44,519	American Bus Association[503]

Activity, Energy Consumption, and GHG Emissions

MHDV activity, energy consumption, and greenhouse gas (GHG) emissions are aligned with the 2024 Inventory of U.S. Greenhouse Gas Emissions and Sinks (the GHGI).[504] The GHGI provides aggregated energy consumption data by fuel type for MHDVs and buses. VMT data by fuel type are also provided based on data from the Federal Highway Administration. Activity, energy consumption, and GHG emissions were disaggregated by MHDV market segment using VIUS for non-bus commercial MHDVs and a range of sources for buses. Bus sources are listed below:

1. For transit and school buses, activity and fuel economy data from the AFDC were used to estimate energy consumption shares.[505, 506] Fuel type shares were based on data from the World Resources Institute (WRI) for school buses[507, 508] and the NTD for transit buses.[509]
2. For intercity buses, activity and fuel economy data from the American Bus Association were used to estimate energy consumption.[510, 511]

Table D2 shows the resulting estimates of 2022 VMT, energy consumption, and GHG emissions by market segment.

Table D2. Estimated VMT, Energy Consumption, and GHG Emissions by MHDV Market Segment

Vehicle Class	Market Segment	2022 VMT (Billion Miles)	2022 Energy Consumption (Trillion British Thermal Units)	2022 GHG Emissions (MMT CO_2e)
Class 2B/3	Local and Regional Freight	26.9	240.9	17.9
	Commercial Pickup	38.1	330.8	24.5
Class 4–6	Local and Regional Freight	29.8	379.0	28.3
Class 7/8	Local and Regional Freight	75.5	1527.0	116.3
	Long-Haul Freight	107.9	2,055.7	156.6
Class 2B–8	Specialized Vehicles	34.6	527.7	39.4
Transit Buses		6.2	193.6	14.3
School Buses		6.9	119.1	9.0
Intercity Buses		2.2	38.4	2.9

Zero-Emission Vehicle Deployment Estimates

Zero-emission vehicle deployments and current model availability were taken from several sources. These are listed in Table D3 below.

Table D3. Zero-Emission Vehicle Deployment Estimates by Market Segment

Vehicle Class	Market Segment	Technology	2023 Vehicle Sales	Cumulative (2022–2023) Vehicle Deployments	Sources
Class 2B/3	Local and Regional Freight	Battery-electric vehicle (BEV)	16,828	25,931	CALSTART[512] *
Class 4–6	Local and Regional Freight	BEV	455	1,604	
Class 7/8	Local and Regional Freight	BEV	218	1,118	
		Fuel cell electric vehicle (FCEV)	30	44	
Class 2B–8	Specialized Vehicles	BEV	20	67	
Class 7/8	School Buses	BEV	1,266	3,792	WRI[513]*
Class 7/8	Transit Buses	BEV	53	2,031	NTD[514]**
		FCEV	0	89	

* Data current as of December 2023

** Data current as of 2022

Table D4. Model Availability and Vehicle Characteristics of Existing ZEVs

Vehicle Class/Body Type	Available Models	Median Range (Miles)
Class 2B/3 Van	23 BEV	170
Class 4–6 Step Van and Truck	48 BEV; 5 FCEV	150 (Step Van BEV); 170 (Medium-Duty BEV); 112 (Step Van FCEV); 217 (MD FCEV)
Class 7/8 Truck	19 BEV; 6 FCEV	150 (BEV); 500 (FCEV)
School Bus	21 BEV; 3 FCEV	125 (BEV); 236 (FCEV)
Transit and Shuttle Bus	36 BEV; 2 FCEV	195 (Transit BEV); 150 (Shuttle Bus BEV); 315 (Transit FCEV)
Commercial Pickup*	10 BEV (as of 2022)	300 (as of 2022)
Other Specialized Vehicles	4 BEV; 1 FCEV (1 bucket BEV, 4 refuse)	125 (BEV); 125 (FCEV)
Intercity Bus	11 BEV; 1 FCEV	184 (BEV); 250 (FCEV)

*Commercial pickup models include some Class 2B vehicles that may be used primarily for personal use.

(Model availability data may exclude some announced vehicles, such as the Tesla Semi, which have been deployed in demonstrations but are not yet available on the market. It may also exclude vehicle models with exclusive contracts with fleets. Source: CALSTART[515] and ICCT.[516])

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DOE/EE-2958 | December 2024