21st CENTURY TRUCK PARTNERSHIP[SM]

Freight Operational Efficiency Technical Sector Team

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The 21st Century Truck Partnership would like to acknowledge the valuable inputs from all of our partners in creating this technical roadmap. We greatly appreciate the technical expertise of the subject matter experts at the U.S. Department of Energy's national laboratories in helping create the technical roadmap sections. Thanks also to the many industry and government partners who provided input through participation in group discussions about the roadmap.

NOTE: Achievement of the goals contained in this document is subject to a number of factors, including availability of funding to perform the research work. The Partnership will periodically review this document to ensure that it reflects current goals and funding availability.

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Executive Summary

Proposed Goals and Opportunities for Freight Operational Efficiency Research and Development

The medium- and heavy-duty vehicle (MHDV) industry is undergoing dramatic change. Regulators, society and, in some cases, end users are demanding the industry transition to safer and more efficient freight operations. Traffic congestion continues to rise, Class 8 long haul trip distance is decreasing each year, e-commerce is increasing each year, and logistically on-time performance expectations are rising each year. These drivers are forcing us, as a nation, to reconsider some of the norms that have existed within the MHDV market for many years.

The 21st Century Truck Partnership (21CTP) Freight Operational Efficiency Technical Sector Team (FOETST) aims broadly to **achieve secure, connected, and automated systems by applying deep learning and data analytics to maximize future freight and passenger mobility across the scale, from individual vehicles to interactions of thousands of vehicles**. Many fleets have already undertaken freight efficiency efforts, but far more work is needed to achieve the FOETST targets.

To this end, the FOETST developed this roadmap to identify (1) targets that can form the basis for federally sponsored research and development (R&D) in freight operational efficiency and (2) MHDV-specific R&D strategies that can achieve those targets, thereby facilitating widescale freight operational efficiency improvements. This roadmap has been organized into four primary areas:

- Targets and Objectives
- Technology Status
- Gaps and Barriers
- Strategies to Achieve Targets

In support of the team's mission and current U.S. greenhouse gas (GHG) emission reduction goals, the FOETST has identified the targets below.

- By 2025, establish baseline freight efficiency metrics against which the contributions of 21CTP activities can be measured.
- By 2025, identify pathways to achieve U.S. GHG reduction goals and DOE/21CTP energy use reduction goals, within the scope outlined above (i.e., the highway freight logistics industry). Provide new, actionable insights needed by government and industry decision-makers to achieve existing goals.
- By 2026, identify, document, and report on gaps between technology achievement in the highway freight logistics industry and U.S. GHG reduction goals, as well as DOE and 21CTP well-to-wheel energy use reduction goals.
- By 2026, identify and document the barriers to achieving U.S. GHG reduction goals, as well as DOE and 21CTP well-to-wheel energy use reduction goals, within the highway freight logistics industry.

- Update analyses and models on an ongoing basis to support continued technological and policy advancements toward achievement of the goals. Conduct sensitivity studies to quantify the uncertainties outside of the 21CTP control.

Top-priority R&D needs for improved freight operational efficiency are summarized below.

- ***DATA:*** Data are needed—at both the vehicle and transportation system levels and across the vehicle classes of interest to the 21CTP (Class 3–8)—to facilitate a thorough understanding of transportation system operations. A complete data set would highlight opportunities for efficiency gains and provide consensus among the research community on those data sets to be used in freight efficiency modeling. Establishing a centralized storage area for all modeling assumption data would strengthen our modeling capabilities and support more consistent and predictable results. The storage area should be freely accessible to 21CTP members, national laboratories, and personnel at the DOE and U.S. Department of Transportation (DOT) for their review and contributions.
- ***UNDERSTANDING OF TECHNOLOGY IMPACTS ON EFFICIENCY:*** There is limited understanding of how, and how much, any individual technology option can improve freight efficiency at the vehicle and system levels. These efficiency gains must be validated with real-world testing, and the tradeoffs of these options for fleets and their operations must be better understood.
- ***FEDERAL SUPPORT:*** Development and evaluation of technology options for improving freight efficiency can be costly, but complex, real-world evaluations can lead to nationwide acceptance. DOE and DOT need to stay engaged with these efforts and ensure that projects receiving federal funding disseminate data in the public domain.
- ***INFRASTRUCTURE:*** There is a need for infrastructure development, in parallel with vehicle development, for connected and automated vehicle solutions. These technologies need a reliable and accurate infrastructure that generates stable data streams. In addition, there is a strong need for robust cybersecurity protocols and practices to ensure safe and secure operation of these new technologies.
- ***STANDARDS:*** To promote wide acceptance of technologies and practices to improve freight efficiency, robust and consistent standards are needed. There is an opportunity to collaborate with the light-duty U.S. DRIVE tech teams in this area.
- ***DATA SHARING:*** Much of the fleet-specific and original equipment manufacturer (OEM)-specific data are company proprietary. 21CTP and the national laboratories need to work more closely with fleets and OEMs to gain access to these data and be able to share the (anonymized) data across the industry.
- ***TOOLS AND RESOURCES:*** Computational tools dedicated to complex system-level analysis need further refinement and resources to gain acceptance among a broader audience.
- ***SCALABLE, USABLE TOOLS:*** Once computational tools are developed, these tools and data need to be available at the local and regional levels to facilitate local and regional decision-making and planning.
- ***AUDIENCES:*** Today, the 21CTP research community focuses on federal opportunities. Going forward, new audiences interested in freight operational efficiency research findings, such as local transportation planners and modelers, utilities, and energy/fuel suppliers, should be educated/informed about research findings.

Introduction

The 21st Century Truck Partnership (21CTP) has divided its initiatives into four technical sectors, with teams of partners supporting each one, respectively, as shown in Figure 1. This roadmap provides technical details in the Freight Operational Efficiency team, describing current technology status, outlining recommended goals and targets, identifying major barriers, and suggesting approaches to overcoming these barriers.

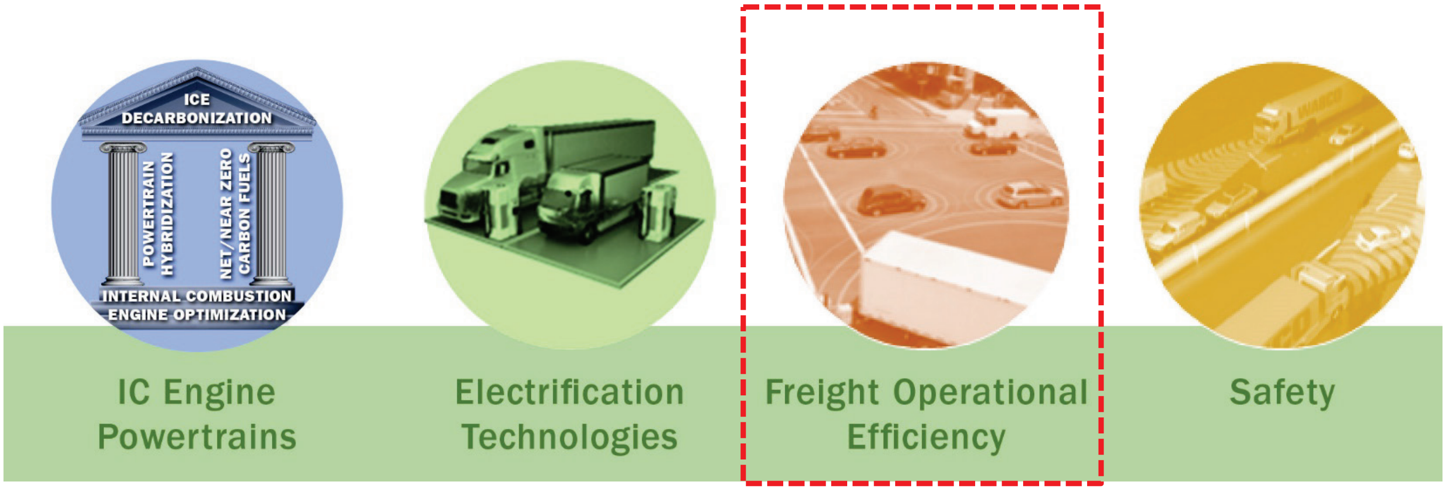

Figure 1. 21CTP Technical Sector Teams

IC=internal combustion

Several factors are converging to reshape the nation's transportation system, for both passenger movement and freight movement, and these will change how people demand mobility services in the future. The U.S. population is growing and aging, people are increasingly concentrated in urban mega-regions, technology choices are expanding, and transportation is increasingly expensive for many people. These broad-ranging changes have definite implications for MHDV transport, particularly for freight; for example, e-commerce is increasing in these urban mega-regions, and demand for goods delivery to aging Americans is growing.

Addressing this growth in MHDV energy use—without associated growth in fuel use and emissions—will require considerable work to increase efficiency at the individual vehicle level. Reducing the fuel consumption of heavy-duty vehicles can be achieved with better engine designs and improvements in other vehicle parameters such as drivetrain configuration and aerodynamics.

However, efficiency improvements to individual vehicles are only part of the solution. Highly efficient vehicles need to be used in an efficient freight system to minimize energy use and emissions while meeting other expectations for freight (time, cost, etc.). Mitigating future increases in energy use will require a systems-level examination of how individual trucks operate in, are affected by, and affect the transportation system. This evaluation can include improved operations at the fleet and vehicle levels to reduce MHDV fuel consumption. Individual fleet managers and vehicle operators can adopt many important approaches in the near term to improve freight efficiency, such as driver training, route management and optimization, and implementation of efficiency aids such as driver telematics or predictive cruise control. Other approaches will require changes to the transportation system, broader supply chain practices and expectations, or wide adoption of regulations associated with truck transport.

The Freight Operational Efficiency Technical Sector Team (FOETST) plays a role in identifying technology impacts on overall freight system performance. Additionally, FOETST contributes to 21CTP understanding of the impact of component technologies, such as the ones developed in the IC Engine Powertrains Sector and Electrification Technologies Sector Teams, on overall vehicle performance. In this way, FOETST helps synthesize targets from across 21CTP into a system-level understanding. The FOETST also works to foster information exchange about targets and technologies with the light-duty partnership, U.S. DRIVE, through participation in joint tech teams exploring analysis and data considerations. This ensures that analysis products include freight considerations wherever appropriate and necessary.

Mission

The FOETST mission is to identify, analyze, and accelerate development of pre-competitive freight vehicle technologies, freight infrastructure technologies (including fueling/charging infrastructure), and freight transportation system technologies that improve the efficiency and environmental sustainability of the freight transportation system while meeting freight delivery expectations. FOETST's mission supports the U.S. greenhouse gas emission goal of reducing net greenhouse gas (GHG) emissions economy-wide by 50%-52% by 2030 relative to a 2005 baseline. FOETST work is also supportive of the U.S. 2050 goal of a net-zero emissions economy (National Climate Task Force n.d.).

Scope

This FOETST Roadmap scope covers applications of individual vehicle efficiency technologies and broader systems efficiency improvements at the vehicle and infrastructure levels. The current scope encompasses the classes of trucks involved in freight hauling that are the highest energy users. Future roadmaps will expand upon this scope to include more freight vocations and passenger-carrying vehicles. The FOETST is engaged in work at both the vehicle efficiency level (how efficient each individual vehicle is in its typical operation) and system efficiency level (how efficient the system of vehicles is in delivering freight). Freight hauling that is conducted by air, sea, or rail (including multimodal transport) is out of scope for this document but could be considered in future updates.

Freight trucks are work tools that must meet a wide range of needs that vary from customer to customer and even day to day. The FOETST seeks to identify solutions that are applicable to and appropriate for a variety of duty cycles and responsive to the business case considerations that drive technology choices. This tech team focuses on solutions that improve freight efficiency based on these important considerations, as these technologies, tools, and techniques are the most likely to reach widespread market acceptance. The FOETST works collaboratively with the other 21CTP tech teams developing technologies to improve individual vehicle efficiency to ensure that these technologies will perform as expected within the broader transportation system.

At its broadest level, the FOETST scope covers all freight moving by trucks within the United States to all end users. Important tasks for the freight system include moving goods from a port or manufacturing plant to the end customer and materials to a manufacturing facility. The FOETST is using the omnichannel logistics framework shown in Figure 2 as an explanatory tool for understanding freight movement and FOETST focus areas. Omnichannel logistics concepts are well-known in modern freight movement, as these form the backbone of e-commerce operations at companies such as Amazon. In general, omnichannel logistics seeks to bring goods from wherever they are imported or produced to the end-use customer quickly and flexibly. The FOETST has chosen this framework as being representative of an increasing amount of freight traffic and thus important to study for future freight needs. As the figure indicates, the framework separates the movement of freight into four major segments to be analyzed individually or as a group:[1]

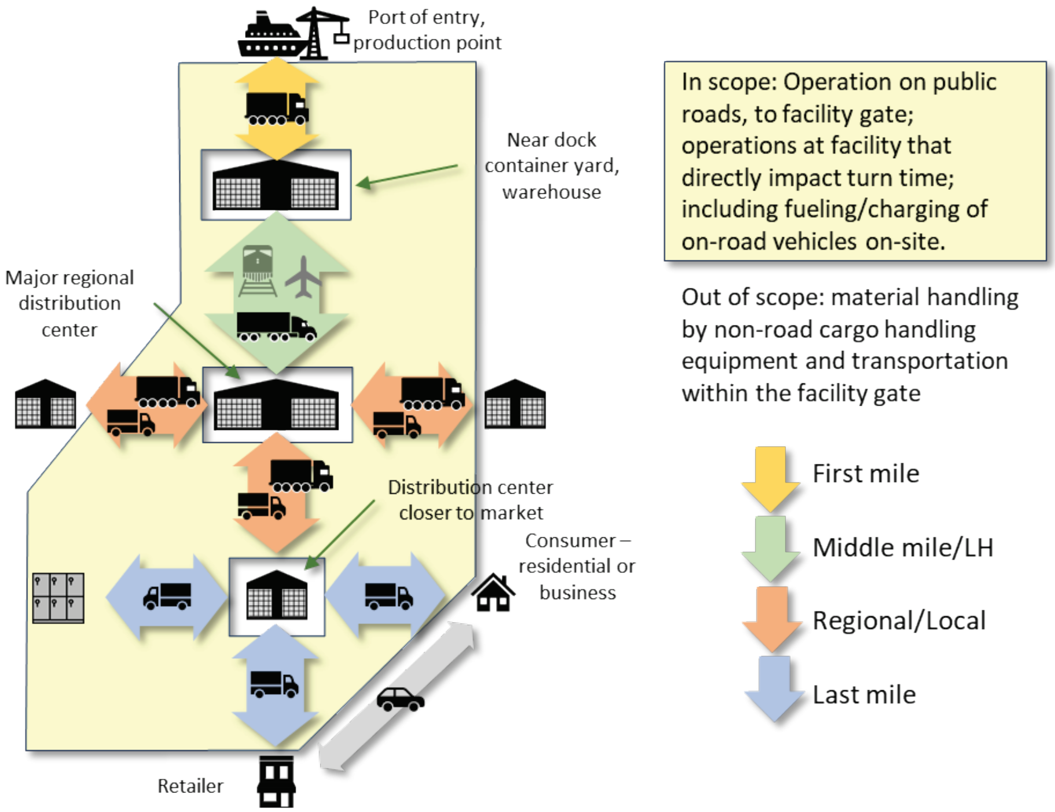

Figure 2. Omnichannel Freight Logistics Framework for Freight Operational Efficiency

- ***First mile***: Trips of roughly 25 miles or less, covering movement of freight mainly at a port or manufacturing facility
- ***Middle mile/long haul***: Trips of 150 miles or more, covering movement of freight from port facilities or manufacturing facilities to regional distribution centers near urban areas or other key markets
- ***Regional/local haul***: Trips of less than 150 miles, covering movement of freight from regional distribution centers to retail stores or other local distribution centers

[1] These segment definitions were determined through a series of meetings of the FOETST Analysis Working Group.

- ***Last mile***: Trips of less than 15 miles, covering movement of freight from retail stores or local distribution centers to final customers (note that this does not include any end-consumer personal travel to a store or shipping center/locker to pick up a package)

This narrows the FOETST scope to a useful and explanatory framework which, while it does not include every freight movement in every situation and every location, is nationally representative and covers the critical segments of freight (first/last mile, regional/local haul, long haul). The framework thus assists the FOETST in understanding the impacts of technologies and efficiency practices on the freight system and generalizing these impacts back to broader freight efficiency research gaps and opportunities. The FOETST is not asserting that this is the only framework for freight movements, but rather that the team chose this framework to facilitate its basic understanding of freight efficiency technology opportunities. Appendix B provides a more detailed description of the omnichannel logistics framework and the FOETST's reasons for choosing it, including the FOETST's analytical methodology for gaining a basic understanding of the efficiency performance of this framework.

Targets, Objectives, and Key Focus Areas

In support of the team's mission and current U.S. GHG emission reduction goals, the FOETST has identified the targets below.

- By 2025, establish baseline freight efficiency metrics against which the contributions of 21CTP activities can be measured.
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The FOETST established three strategies to organize the actions that will meet the tech team's targets:

- ***Analysis and Insight***, covering the need for collecting data and assessing the potential for new technologies to improve freight efficiency

- ► ***Technology Development and Deployment***, covering the need for research, development, and eventual deployment of innovative technologies to improve freight efficiency with associated codes and standards necessary to facilitate success
- ► ***Information Sharing***, covering the need to communicate analysis and technology research findings to a broader audience for further action

More details may be found in the Strategies to Achieve Targets section later in this document.

Exploration of Factors Influencing Freight Efficiency

Future National Freight Trends

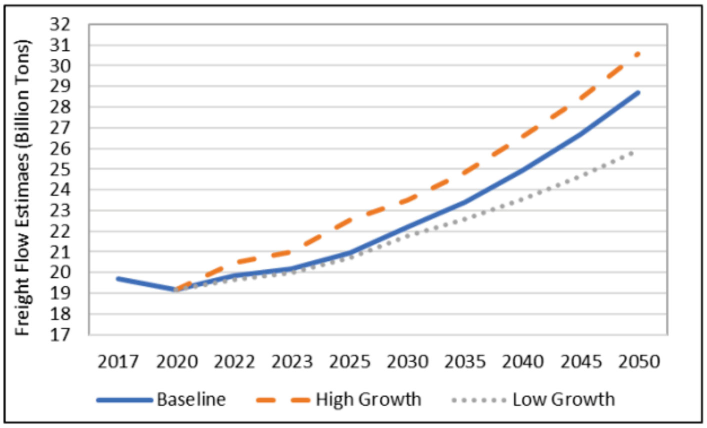

Figure 3. Freight Growth Scenarios to 2050 (U.S. Department of Transportation, Bureau of Transportation Statistics 2021)

Many external demographic and geographic factors are driving rapid change in the transportation landscape, as has already been noted in this roadmap. Projections of future freight activity vary somewhat, but all indicate that freight shipments will rise considerably with future economic growth. In a November 2021 news release, the U.S. Department of Transportation noted that U.S. freight activity will grow by 50% in freight tonnage and double in freight value (U.S. Department of Transportation, Bureau of Transportation Statistics 2021) by 2050. The forecasted increase in freight tonnage is shown in Figure 3. Recent increases in e-commerce have been dramatic, and it seems likely that at least some of this e-commerce activity will remain, with implications for freight logistics. The U.S. Department of Commerce provides a forecasted e-commerce growth rate of 8% through 2025, as shown in Figure 4 (U.S. Department of Commerce, International Trade Administration n.d.).

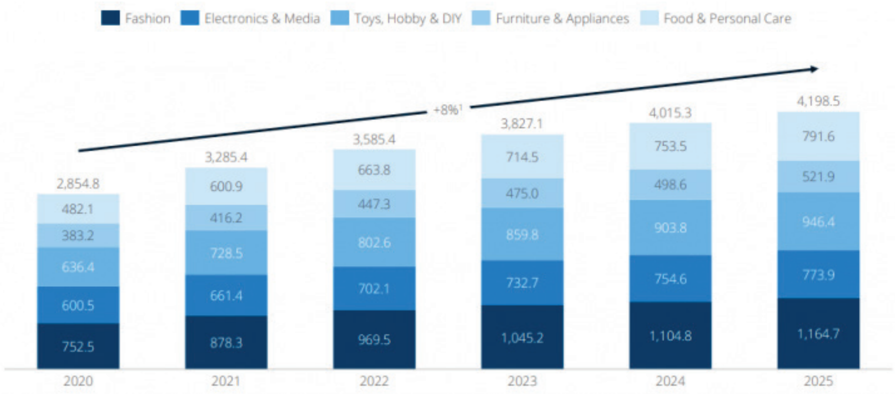

Figure 4. Global e-Commerce Revenue Forecast through 2025 (U.S. Department of Commerce, International Trade Administration n.d.)

Constraints such as driver shortages, customer and shipper expectations for shipment times, and increasing traffic congestion will also have implications for future freight system efficiency. Technology solutions are one potential pathway to addressing freight system changes within the system constraints, but these technology solutions must meet fleet expectations for reliability, durability, total cost of ownership (TCO), fueling time, and return on investment/payback period. Technology solutions must also meet expectations around operations management and service, as new technologies need to be supported for maintenance and repairs at locations throughout the country to ensure the vehicles can complete their missions. It is also important to have a broader systems-level understanding of the impacts of technologies and their interactions, as the freight movement system in the United States is complex, with many interdependencies. This has implications for research across major transportation-related federal agencies to address challenges and take advantage of opportunities.

Transportation Energy Transition in Rural Communities

Rural areas have been and are an important segment of the nation's population and economy. Around one in five Americans live in a rural area (United States Census Bureau 2017). Rural areas are around 97% of the total land area in the United States. Of the roughly 3,000 counties in the United States, about 700 are completely rural and almost 1,200 are mostly rural (United States Census Bureau 2016), as shown in Figure 5 (U.S. Census Bureau n.d.). Although a common narrative is that rural populations in America are shrinking, the number of people in these areas has remained remarkably stable over the past 100 years, as shown in Figure 6 (United States Census Bureau 2016).

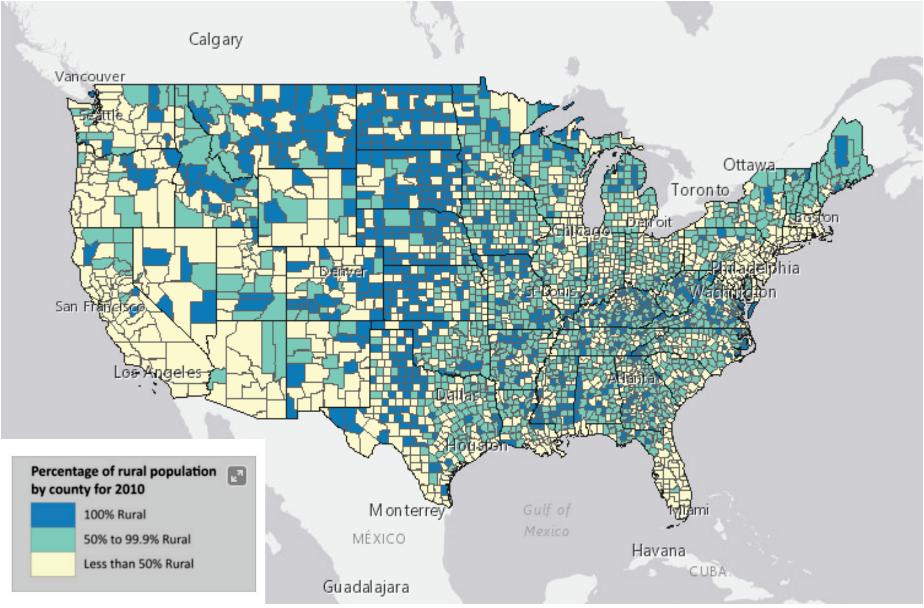

Figure 5. Percentage of Rural Population in the United States, by County (U.S. Census Bureau, n.d.)

Manufacturing is a very important economic driver in rural areas. Relative to urban areas, manufacturing in rural areas represented a greater share of both private nonfarm jobs (14% vs. 7%) and earnings (21% vs. 11%) in 2015 (U.S. Department of Agriculture 2021). Manufacturing facilities located in rural areas will need to continue to enhance their transportation links with urban centers to ensure goods produced in these regions reach their final markets.

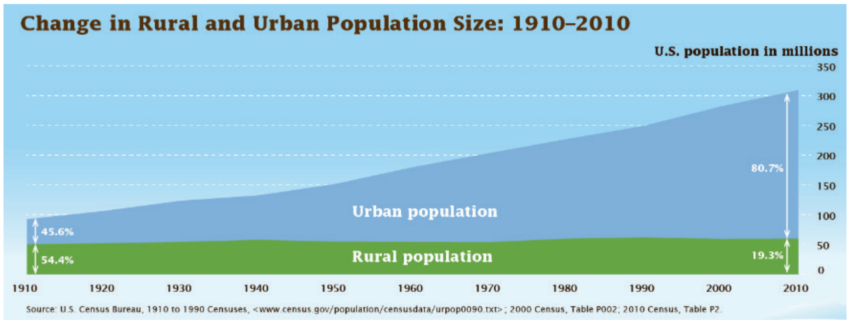

Figure 6. Changes in Rural and Urban Population Sizes in the United States (U.S. Census Bureau 2016)

While rural communities remain an important segment of the nation's economy, expanding critical infrastructure to these communities has historically been hampered by the relatively high cost of that infrastructure expansion and the low population density of these regions. High-density communities represent more favorable business opportunities for the commercial entities capitalizing infrastructure and the associated distribution of services. As a result, government assistance has been critical in stimulating expansion of infrastructure-related services (such as electric, telephone, cellular, and internet services) to rural communities. For example, the Rural Electrification Act of 1936 brought electricity to the nearly 90% of farms that did not have electricity because of the prohibitive cost of servicing these areas (U.S. Department of Agriculture 2017). By 1950, close to 80% of farms had electric service, thanks to federal loans for installing electrical distribution systems in these areas through rural electric cooperatives. A 1947 amendment to the Rural Electrification Act enabled loans for rural telephone service (U.S. Department of Agriculture n.d.a). This support continues today under the authority of the Rural Electrification Act through the Rural Utilities Service that provides funding for electric power and telecommunications (U.S. Department of Agriculture n.d.b).

National sustainability goals cannot be achieved if nearly a fifth of the population is without access to low-carbon transportation energy. Efficient access to high-speed electric vehicle (EV) charging, suitable to support commercial use cases, will be required to ensure significant vehicle electrification extends to the rural business community.

Technology Adoption Rates

In the future, the single largest contributor to reducing GHG and energy usage for the national freight system will be the use of zero-emission vehicles (ZEVs). The adoption rate for these vehicles within the MHDV market has a significant impact on the level of energy consumption and greenhouse gas reductions possible through freight operational efficiency.

In early 2023, the U.S. Department of Energy, the U.S. Department of Transportation, the U.S. Environmental Protection Agency, and the U.S. Department of Housing and Urban Development jointly released *The U.S. National Blueprint for Transportation Decarbonization* (U.S. Department of Energy, U.S. Department of Transportation, U.S. Environmental Protection Agency, and U.S. Department of Housing and Urban Development 2023). This first-of-its-kind strategy for federal leaderships and partnerships is presented as a guide for decarbonizing the U.S. transportation sector. The Blueprint was an outcome of a memorandum of understanding signed by these four federal agencies in September 2022 to collaborate on rapid decarbonization of transportation.

Specific to MHDV markets, the Blueprint calls for 30% zero-emission MHDV sales by 2030 and 100% zero-emission MHDV sales by 2040 as part of a broader strategy to transition all new vehicle sales to zero-emission technologies. Additionally, the Blueprint recommends investment in efficient travel modes for passenger and freight to optimize travel and freight logistics, which aligns well with the overall focus of the FOETST.

Technology adoption rates are only part of the equation for decarbonization of freight transportation. MHDVs have long life expectancies, which results in a significant percentage of legacy diesel vehicles still in operation by 2040. This may limit the overall opportunity for decarbonization of freight movement. The Blueprint acknowledges the need for sustainable fuels to provide low-carbon solutions that are compatible with these existing vehicles to alleviate the turnover challenge.

Within the MHDV market, there is a wide spectrum of opinions/forecasts for the adoption of these new ZEVs with results dependent on assumptions regarding technology progress and energy prices. A recent study at the National Renewable Energy Laboratory for the FOETST (NREL 2022) illustrated the potential well-to-wheels impacts of zero-emission MHDVs on both GHG emissions and energy usage. This study focused on the timeframe from 2020 to 2040 (see Figure 8 and Figure 8) and assumed high ZEV adoption that eliminated sales of combustion engines by 2044. Despite high adoption, GHG emissions and energy usage reduction by the in-use vehicle fleet from 2020 to 2040 is around a modest 15%. This is because the long life expectancy of MHDVs will result in many conventional powertrain (diesel) vehicles being still in operation in 2040.

Other Factors of Uncertainty

In addition to the technology adoption rates, there are several other factors that contribute to the overall uncertainty of meeting the U.S. GHG emission reduction goal and DOE/21CTP energy use reduction goals within the highway freight logistics industry.

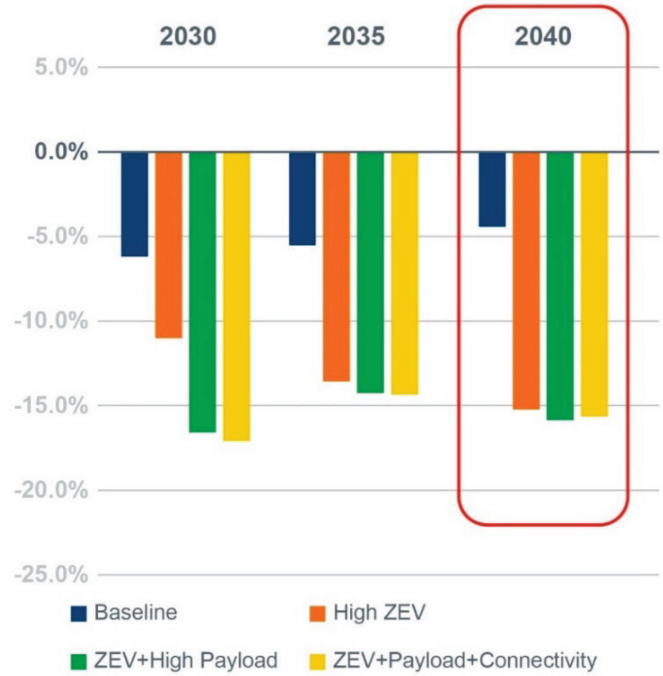

Figure 7. Potential Change in Class 4-8 Truck Fleet Well-to-Wheel GHG Emissions Relative to 2020

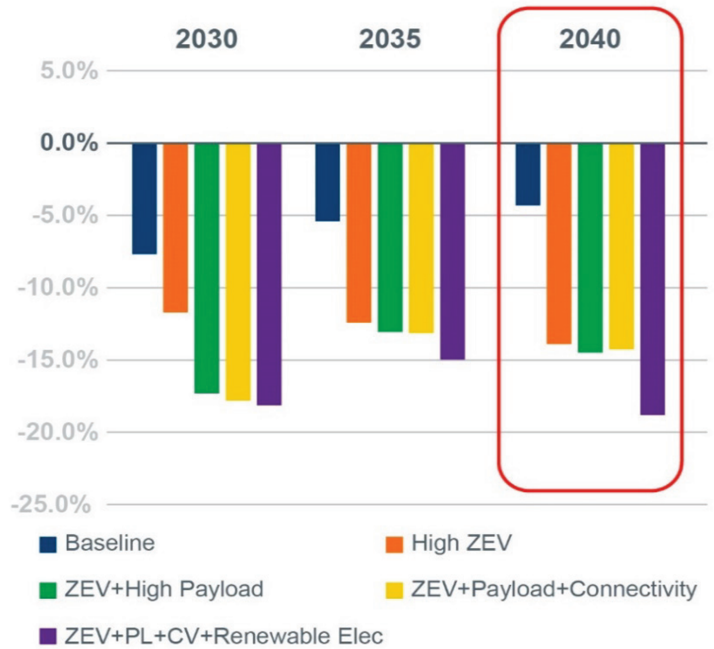

Figure 8. Potential Change in Class 4-8 Truck Fleet Well-to-Tank Energy Consumption Relative to 2020

2005 Baseline

The U.S. GHG emission reduction goal is to reduce net GHG emissions economy-wide by 50%–52% by 2030 relative to a 2005 baseline. It is difficult, however, to establish an accurate 2005 GHG emission and energy use baseline for highway

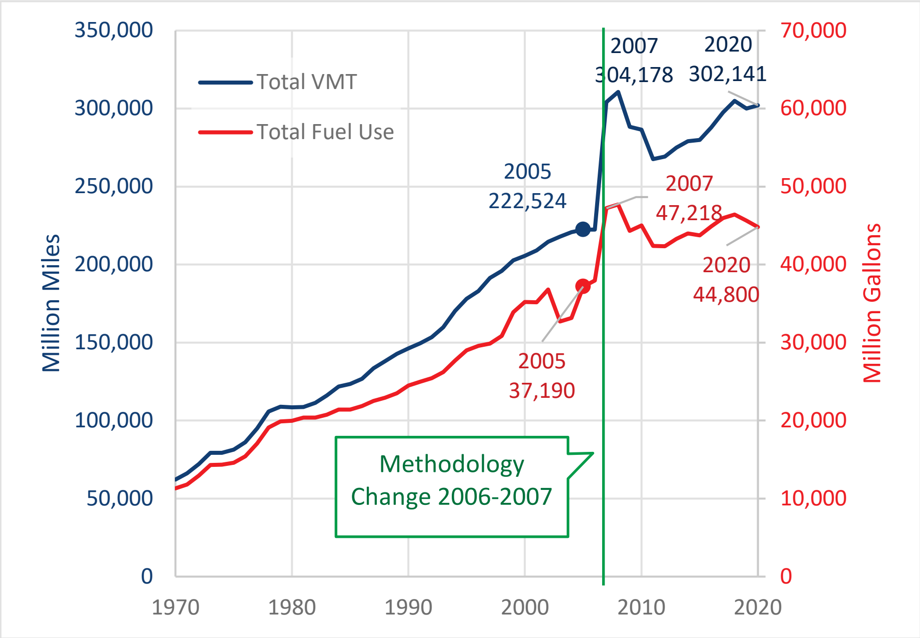

Figure 9. Total VMT and Total Fuel Use from 1970 to 2020, Illustrating the Impacts of a Significant Change in Federal Highway Administration's Energy Use Estimation Methodology between 2006 and 2007 (Oak Ridge National Laboratory 2022)

freight vehicles using historical data. Official emission inventories report U.S. GHG emissions at the sector level and do not give detail on the contribution of various categories of vehicles within the "total transportation" system (passenger car, freight truck, city bus, etc.). There is no known, publicly available data at the vehicle type/class level with which to estimate the emissions contributions of MHDVs, so emissions must be estimated using available data on fuel consumption, vehicle populations, vehicle miles travelled (VMT, as estimated from sample traffic counts), and other variables. Meanwhile, between 2006 and 2007, there was a significant change in a foundational data source regarding the methodology used to estimate energy usage by MHDVs (Figure 9). This change in methodology complicates direct comparison of current energy usage for the MHDV freight market to the baseline year of 2005. Therefore, the 2005 baseline has not been defined in sufficient detail to allow for a good metric against which to measure progress toward the goal in the highway freight logistics industry.

Factors Outside of 21CTP Control

Projecting future GHG emissions and energy usage entails many assumptions that are outside 21CTP control:

- Cost of electricity
- Cost of diesel fuel
- ZEV adoption rate (noted above), which is dependent on energy prices as well as:
  - ZEV infrastructure availability (electric and/or hydrogen)
  - New technology reliability
- National economy (see Figure 9, which shows a dip in Class 3–8 VMT and fuel usage in 2009 from the recession and in 2020 from the COVID-19 pandemic)
  - Significant impacts on both GHG and energy usage
  - Future growth in economic activity will create higher demand for freight movement and could hinder reductions in total energy use and emissions
  - Past and potential future retractions in economic activity should not be deemed as progress toward higher freight efficiency

Technology Status and Opportunities

Many technologies that improve freight efficiency already exist but are at widely varying stages of development. This section outlines the high-level status of many of these technologies to provide further context about future potential research needs. The next section discusses the numerous barriers and gaps facing these technologies; this section sets the stage for that discussion.

Analysis and Data

Analysis and data are important to freight operational efficiency because they provide the research community with a way to explore technology effects on a complex system. Analysis helps explain how technology improves the efficiency of individual trucks as well as how these efficient trucks work together in a freight system. Data on truck populations, truck sales, truck operations, freight movements, and a wide variety of other factors are critical in ensuring the analysis produces plausible answers and becomes a useful tool for understanding the future potential of technology. The Fleet DNA project may provide some useful data to meet this need (National Renewable Energy Laboratory n.d.). Data on factors outside the freight trucks and facilities themselves are also important, as road conditions, weather, traffic, electric grid conditions, and fueling infrastructure play important roles in optimizing freight movements for efficiency.

Analysis Tools

Available analysis tools have varying levels of capability in providing insight about a portion of the U.S. freight system and its freight movements. The U.S. Department of Energy and its national laboratories have developed and refined transportation system models as part of the Energy Efficient Mobility Systems program. These agent-based models can emulate the decisions of millions of individual agents to explore the traffic patterns, energy use, and emissions in a region. Commercial modeling software companies are also entering this space with system simulation tools that build on the companies' existing vehicle simulation platforms. In the future, there may be opportunities to use some of these vehicle simulation platforms for fleet management, as well as vehicle development. Analysis tools are a critical enabler for integrating and processing data into useful solutions for improving freight efficiency.

Data Sources

Data sources are available to the freight efficiency analyst to characterize some aspects of freight movement in the United States, with data sets updated at varying levels of detail on varying timescales. Several companies offer commercial data sets on the MHDV population and MHDV sales. The U.S. Department of Transportation maintains the Commodity Flow Survey to provide a high-level multimodal assessment of national freight flows (commodities shipped, origin/destination, value/weight, and transport mode). The Department also offers the Freight Analysis Framework to integrate data from multiple sources and create a more comprehensive picture of freight movement among states and metropolitan areas. The American Trucking Associations offers yearly updates of key freight indicators through its annual American Trucking Trends and forecasts of freight trends through the annual Freight Transportation Forecast. The Vehicle Inventory and Use Survey has been a critical data source for many freight transportation analysts because of its breadth of information about truck characteristics, truck operation, and truck populations. The U.S. Department of Transportation, in collaboration with the U.S. Census Bureau, the U.S. Department of Energy, and other contributing stakeholders, is in the process of updating this information (last revised in 2002) in the 2021 revision, expected to be published in Fall 2023.

Metrics

One of the targets of this team is to establish baseline freight efficiency metrics against which the contributions of 21CTP activities can be measured by 2026. Metrics are a challenging area for freight operational efficiency but are necessary for gauging success (that which can be measured can be improved). At a fundamental level, freight operational efficiency is linked directly to the amount of freight carried by the freight system each day, with the time, energy, emissions, costs, and other factors associated with this freight movement. However, it can be difficult to express the performance of this system in moving freight with metrics that capture the breadth of what stakeholders are interested in measuring. Metrics can be expressed in terms of total energy, emissions, cost, or other factors for the system, or normalized per ton-mile, per cubic-foot-mile, per unit of trip time, or per unit of TCO, as just a few examples. Metrics are available to cover energy use in gallons of fuel or kilowatt-hours of energy, well-to-wheels CO_2-equivalent GHGs or carbon impact, trip time in minutes/hours/days, and so forth. Volume-based metrics may be better than weight-based metrics for freight shipments that are volume-limited, as are most freight shipments in the United States currently. External pressures nationally (and globally) for reducing GHG emissions will likely drive the need for some sort of GHG metric as part of any comprehensive freight efficiency analysis. Time-based metrics are important for shippers, carriers, and customers as a measure of the freight system's efficiency in delivering goods in the timeframes expected, but the most time-efficient freight system may not be the most energy-efficient one. In short, there is no shortage of freight operational efficiency metrics, but picking the right one(s) to use to measure the technology and system improvements sought by this tech team is challenging.

The FOETST identified potential metrics that could be used to begin to characterize what areas of freight efficiency are important and to quantify how much these areas are improved by research, development, and deployment of technologies. The universe of relevant potential metrics is quite large:

- ***Speed-/time-based metrics***: Travel time, facility turn time, dwell time (searches for parking or fuel, waiting to load/unload, etc.), average speed in network, congestion measures (total delay time, percent of miles congested, hours of congestion per unit time, etc.)
- ***Logistics-based metrics***: Volume of cargo moved, weight of cargo moved, deliveries per mile, travel distance per delivery, ratio of empty miles to total miles
- ***Economics-based metrics***: Total travel cost for all freight shipments in the framework per unit time, total cost per shipment/per mile/per ton/per cubic foot, shipment cost per dollar of freight moved
- ***Energy-based metrics***: Total energy use for all freight shipments in the framework per unit time, energy use per shipment/per mile/per ton/per cubic foot
- ***Environment-based metrics***: Greenhouse gas metrics (total or per-unit weight/volume shipped, focus on well-to-wheels measures), criteria emissions (NOx, particulate matter, others, total or per-unit weight/volume shipped), noise, safety (incidents per mile/per shipment), impacts on underserved communities
- ***Driver-based metrics***: Driver productivity (amount of freight moved per unit of time), driver retention and promotion, cost per company/per year to recruit and retain drivers

After extensive discussions on the merits of each of these metrics the FOETST concluded that no single metric adequately captured the “freight efficiency” concept. The FOETST thus decided to focus on characterizing freight system efficiency in terms of system-wide GHG emissions and energy use in support of the U.S. greenhouse gas reduction goals while concurrently continuing analysis toward establishing baseline freight efficiency metrics. FOETST analyses will be constrained to ensure that shipping times, freight cost, and vehicle safety characteristics are maintained at current or improved levels.

Appendix C contains a more comprehensive discussion of the FOETST’s exploration of possible freight efficiency metrics as a reference.

Technology Development and Deployment

Connectivity and Automation

Connectivity and automation technologies offer a potential pathway to improve freight efficiency and reduce freight movement cost. In the context of this roadmap, connectivity covers any of the variety of communication protocols, systems, and platforms necessary to exchange information between and among vehicles and with the built infrastructure and the aligned industries and service systems. Automation covers all levels of vehicle automatic control, from cooperative adaptive cruise control through high driving automation, including informally what is often called "self-driving."

Connected automated vehicle (CAV) technology is often cited as having the potential to significantly affect transportation performance in several areas. Most existing studies and analyses are heavily, if not exclusively, oriented to passenger (light-duty) vehicles but can offer some general guidance in the broader transportation research space. Anticipated impacts of CAV technology adoption are listed below.

- Reduction in traffic accidents due to fewer human errors, which cause 94% of traffic crashes (National Highway Traffic Safety Administration 2017)
- Reduction in travel cost, primarily due to recovering productive time while riding and eliminating the need to search for parking
- Increase in frequency of delivered goods due to per-mile cost reduction, specifically in "last-mile" operations
- Potential increase in vehicle efficiency due to eco-routing, driving automation, vehicle configuration changes, and vehicle energy optimization and planning; potential for increased highway speeds (safer than before) and vehicle programming that optimizes for travel time rather than efficiency, which could potentially offset the efficiency gains
- Uncertain impacts on traffic congestion due to unknown effects on vehicle miles traveled resulting from increased mobility accessibility and reduced travel cost

Connectivity and automation encompass multiple technologies. Several of particular importance are listed below.

- Eco-driving and features such as predictive cruise control that offer opportunities for fuel economy improvement in long haul applications
- Charge management for electrified vehicles (plug-in hybrids or full battery electric trucks) (connectivity to charging stations required for optimal freight operation planning)
- Fleet management optimization using connectivity-enabled data and automation technology
- Cooperative driving automation for fuel economy (example scenarios: highway merging or lane changing)

Connectivity and automation systems at lower levels of sophistication are presently in widespread use in MHDVs, and experiments and demonstrations of trucks equipped with high driving automation have been conducted. Systems offering higher levels of automation are still nascent and face several challenges from technology, policy, and customer acceptance standpoints.

Artificial Intelligence and Machine Learning

Artificial intelligence and machine learning tools can be an important part of connectivity and automation, particularly in the development of algorithms that handle the unpredictable elements of everyday driving on public roads. These tools also have applications in collecting and analyzing large data streams from multiple connected vehicles to understand potential maintenance problems, driver behavior trends, and fleet optimization opportunities, as well as road conditions, traffic, weather, and other external influences on freight efficiency.

System Optimization

In the context of this roadmap, system optimization refers to any technology or operational practices intended to improve the freight efficiency of the entire freight system. System optimization could include fleet route optimization algorithms, predictive maintenance practices, managed truck-only lanes for conventional or automated freight trucks, supply chain management practices, and so forth. System optimization can be closely aligned with the connectivity and automation technologies described above, as these technologies can contribute to the efficient operation of the system and the necessary data flows for optimization. The forecasted changes in freight needs (such as the potential shift from long-haul cross-country freight movement to more regional operation through hub-and-spoke warehouses) often imply changes to the structure of our freight system, so system optimization is important to making the most of technologies and operations for freight efficiency. For example, electrification technologies are currently difficult to incorporate into the freight system at scale, but the hub-and-spoke distribution model employs reduced route lengths that are better suited to battery electric vehicle range capabilities, thereby allowing fleets to take advantage of these technologies.

Opportunities exist to co-optimize future freight vehicles and advanced powertrains and the freight infrastructure. If routes and freight corridors are more defined, future freight vehicles could be more specifically optimized to a known freight route and conditions along that route. In addition, vehicles can be matched with routes based on the vehicles' particular characteristics, which can be done with existing vehicles as well as advanced future vehicles. The advantages of vehicle–route pairing should be balanced against fleet requirements to have multiple vehicles available for multiple routes, providing enough flexibility to meet freight movement missions regardless of circumstances.

Driver feedback and training can also play a role in system optimization. Drivers can be given feedback on ways to operate trucks more efficiently, more efficient routes that avoid traffic, and interactions with higher levels of connectivity and automation to get the most out of those systems.

System optimization also includes a topic that continues to be of interest to many stakeholders in the freight industry: high-productivity vehicles. Longer combination vehicles offer the opportunity to improve operational efficiency through increases in weight and volume moved with a single tractor/power unit. Longer combination vehicles could take the form of longer individual trailers (potentially with additional axles) or combinations of multiple trailers. However, implementing such vehicles will involve considering turning radius, bridge loadings, clearances, and other inhibiting factors. Appendix D offers more detail on this topic.

Alternative Fuels

Alternative fuels, such as biofuels, electricity, natural gas, propane, electro-fuels, and hydrogen, are a primary focus of other 21CTP tech teams from a technology development standpoint (that is, what powertrain technologies are needed to implement these fuels successfully in vehicles). Alternative fuels are also an FOETST topic because of their potential impacts on operations (fueling locations, fueling time, fueling frequency, driving range, changes in operator best practices for efficiency, and so forth). Adoption of these fuels—particularly renewable electricity, renewable hydrogen, or net-zero carbon liquid fuels options—presents an opportunity to reduce the GHG emissions profile of the freight system to low or near-zero levels. Rising national emphasis on solutions to reduce GHGs will likely increase the interest in these fuel options.

Some of these fuels have achieved a relatively advanced level of development and deployment in freight trucking (e.g., natural gas), while others are still in the development stages for use in the freight system (e.g., hydrogen and electricity). Many of the support systems necessary for alternative fuel success (training, education, outreach, etc.) have already been established and can be pressed into service for encouraging alternative fuel use as part of an efficient freight system.

The relationship between alternative fuels and freight operations is complex. In some ways, alternative fuels can improve freight efficiency through more efficient vehicles (e.g., electric vehicles). In other ways, alternative fuels and operations are in opposition, particularly for technologies that have range restrictions. Opportunities exist to change operations based on the characteristics of the alternative fuel technology (provided the benefits of the technology in this modified operation are compelling) or to change the fuel technology to meet the operations requirements (push improvements in the alternative fuel technology to fit the operation). In all cases, getting the job done (moving the freight to where it needs to be at the time it needs to be there) will be a primary focus.

Alternative fuels have different performance characteristics that make them more suited for subsets of freight truck operation, versus gasoline and diesel, which are more applicable to a wide range of duty cycles. Battery electric trucks may be best for first-/last-mile delivery, hydrogen fuel cell trucks may be suited for regional hauls, and hydrogen fuel cell or net-zero carbon-liquid-fueled IC engine trucks may serve long-haul runs best. Transition technologies such as hybrids and range-extended EVs could be steppingstones to a more sustainable freight system. Any large-scale transition involving technology adoption requires careful planning and should be implemented over time, as abrupt and widespread changes in fuel technologies can have broad and significant impacts on the freight industry.

Infrastructure is a key consideration for alternative fuels, as the refueling/recharging network for these fuels is not as well-developed as conventional gasoline and diesel infrastructure. Centrally fueled fleets rely on their own infrastructure at their facilities, which may offer early opportunities for deployment of alternative fuels. These fleets often have return-to-base operations, which makes them better suited to electrification. For example, many fleets using fuels such as natural gas use central depot fueling for their vehicles. Options such as vehicle-to-grid energy transfers could offer new revenue options for EVs that would make the return on investment more favorable. Electrification infrastructure for rural areas (with important economic roles in agriculture and manufacturing) will be critical for connecting these regions to urban markets and ensure these rural areas have adequate access to decarbonization technologies.

With the transportation energy transition in rural areas an important factor influencing freight efficiency, as noted above, rural communities present particular challenges for use of alternative fuels. It will be important that the FOETST identify the needs and solution sets to ensure clean energy is conveniently available to rural businesses.

Emissions reductions (both criteria and GHG) are important potential benefits of alternative fuels. Systems-level assessments of alternative fuels through well-to-wheels analysis tools and vehicle powertrain assessments through vehicle cycle analysis tools will be important for the FOETST in understanding these potential impacts. This is an area where the FOETST can leverage the past and ongoing analytical work from the light-duty U.S. DRIVE partnership to ensure consistent and complementary results.

Tax policy is another consideration for alternative fuels. Fuel has historically been the taxed input to trucking that supports the transportation infrastructure these vehicles use, and changes to fuel used in trucking will affect this tax revenue and the infrastructure that depends on it. The ways in which tax policy evolves in the future will influence how technologies are adopted and the associated success in increasing freight efficiency through these technologies. While not a factor that partnerships such as 21CTP can affect directly through research recommendations, tax policy is a factor on which the FOETST will stay informed.

Testing and Validation of Technologies

Testing and validation of new technologies to demonstrate the potential benefits for energy use, cost, or GHG emissions reduction is very important to fleet customers. New freight trucks are major capital investments, and fleets are generally cautious about purchasing new technologies that are often perceived to be unproven. Testing and validation can provide an independent assessment of the benefits and challenges for technologies, particularly when this service is performed by trusted third parties who are respected by the fleet community. Best practices and methodologies for rigorous testing and validation are already well-established and generally accepted by the fleet and research communities.

Vehicle-Level Efficiency Technologies

Individual vehicle efficiency plays an important role in ensuring the efficiency of the entire freight system. Maximizing system efficiency begins with vehicles that are highly efficient. 21CTP tech teams are pursuing aspects of vehicle energy efficiency, including IC engine powertrains and electrified powertrains. The FOETST scope includes vehicle-systems-level efficiency, encompassing the non-powertrain efficiency opportunities within a single vehicle that are not otherwise covered in 21CTP, such as aerodynamics, idling reduction, vehicle lightweighting, and tire rolling resistance. The unifying theme is in how these technologies work together as part of the vehicle system to improve efficiency.

Aerodynamics on modern trucks, particularly Class 8 long haul trucks, are very highly refined. Opportunities likely remain for further improvements to these trucks in the areas of active aerodynamics, replacement of external mirrors with cameras, optimizing tractor–trailer pairings (as was done in the SuperTruck projects), and extension of aerodynamic aids to other classes and vocations of trucks.

Idling reduction is a consideration within the FOETST because of the considerable opportunity for energy savings, as well as the need to address idling from a systems perspective. All idling of IC engines uses fuel and produces emissions while achieving zero freight movement. Some idling is mission-driven, but much idling is wasteful and could be avoided. Both technology solutions and operational changes are needed to address idling adequately. Several idling reduction technologies are available commercially today. For instance, some drivers leave the engine running during rest periods to keep heating and air conditioning systems operational, but systems can now address such cab comfort needs through battery or diesel auxiliary power units. These sources provide electrical power for cab hotel loads (e.g., heating and air conditioning), as well as other electrical demands for trucks. Systems are mostly developed by suppliers and mounted in trucks by third-party installers or by original equipment manufacturers (OEMs) themselves. Despite the availability of some commercial solutions, idling reduction technology can be improved further and is an area of continued research. All four SuperTruck I teams employed idling reduction technology as part of their systems approach to achievement of freight efficiency goals. Work continued in SuperTruck II, mainly focused on providing idling reduction through the use of electrified HVAC systems and power for hotel loads integrated into a broader electrification strategy. The U.S. Environmental Protection Agency is also addressing this issue through efficiency standards for MHDVs, which incentivize development and adoption of technologies to reduce idling.

Lightweighting of trucks can increase payload (for weight-limited applications) and offset the additional weight of new powertrains and energy storage systems. Composite materials offer the opportunity to serve both lightweighting and flexible geometry purposes. As new connectivity and automation technologies become more widespread, there may be opportunities to incorporate radio frequency or electromagnetic field shielding functionality into structural components.

Tires are another area of opportunity to improve energy efficiency of individual vehicles. Tire manufacturers are continually working to improve tire rolling resistance characteristics through new designs and materials. Advanced sensors to monitor and report on tire conditions in real time are also being developed. Optimizing regenerative braking in electric drive vehicles will also impact tire design (as well as transmission and axle design). Surface friction estimation will be an important future capability to ensure the safety and efficiency of future automation technologies. Lastly, although tire pressure monitoring is a commercial technology without its own pressing research and development (R&D) needs, it is an essential source of information for reducing fuel use, decreasing maintenance, and improving safety and is therefore still of interest to the FOETST, particularly from a deployment standpoint.

Safety of Freight Operational Efficiency Technologies

Safety is an important consideration for freight movement. New technologies introduce the opportunity to improve safety in some cases, while in others, it can have negative effects on safety. These impacts encompass both product safety (inherent to the technology itself) and functional safety (how the technology is used in real-world applications). 21CTP's structure includes a tech team specifically focused on safety implications and research opportunities. The FOETST will consider the impacts of new technologies on the system wide freight efficiency as part of its broader technology exploration and will collaborate closely with the Safety Tech Team on the specific safety implications of technology choices. Technology impacts to freight efficiency may not always be straightforward. For example, a speed limiting device would intuitively have a negative impact upon freight efficiency since it would take longer to deliver each load of freight. However, if the slower driving resulted in fewer traffic accidents, and thus fewer backups on the highway system, the speed limiting technology could also be having a positive impact upon freight efficiency and environmental sustainability.

Information Sharing

Information sharing can take several forms in the context of the FOETST. The industry, national laboratories, and the academic research community can learn about FOETST and 21CTP technical accomplishments and findings and build on them for their own freight efficiency work. Senior leaders and decision makers in industry and government need to understand FOETST findings to make future research and product planning decisions. The general freight community of fleet owners/managers, vehicle operators, and technicians can benefit from understanding what future freight technologies are being researched, when they are likely to reach market viability, and what benefits the community can see from these technologies. Other tech teams within 21CTP can learn from and leverage the FOETST systems-level viewpoint to explore the impacts of their technologies on the broader freight system. Information sharing will provide essential information for freight community stakeholders to take actions that contribute toward the overall FOETST goal of increasing freight efficiency.

The 21CTP research community already maintains information dissemination frameworks to distribute FOETST findings to appropriate audiences. These frameworks provide the channels to which many stakeholders turn for reliable and objective third-party information about technologies. Good examples of such data channels include the U.S. Department of Energy's Alternative Fuels Data Center and the many resources of the North American Council for Freight Efficiency. Case studies, technology summaries, research presentations, and technical reports are all necessary elements of information dissemination and are well-established standard reference materials.

Information sharing is ongoing between FOETST and its counterparts in the light-duty partnership, U.S. DRIVE. FOETST members are regular participants on joint tech teams between 21CTP and U.S. DRIVE and foster information exchange and sector perspectives between light-duty and heavy-duty stakeholder groups.

Gaps and Barriers

As discussed in the previous section, many technology options are available to improve freight operational efficiency. These technology options offer significant promise for improvement but also may be facing technology, operational, or policy gaps and barriers. This section will explore some of these challenges in more detail.

Analysis and Data

At the highest level, the major barriers associated with analysis and data are:

- ***INSUFFICIENT DATA:*** Lack of data at the vehicle and transportation system levels at sufficient fidelity across vehicle classes to facilitate thorough understanding of transportation system operations and opportunities for efficiency, as well as consensus within the research community on data sets to be used in freight efficiency modeling.
- ***LIMITED TOOL AND RESOURCE AVAILABILITY:*** Limited availability of intermediate-level computational tools, technical expertise, and computing resources to conduct system-level analyses quickly and accurately for a

broader audience. Current tools, available primarily in the national lab environment, require long run times for complex multivariable simulations.

- ***LIMITED UNDERSTANDING OF IMPACTS ON EFFICIENCY:*** Limited understanding of the potential efficiency gains—at both vehicle and system levels—of individual technology options; limited validation of efficiency gains with real-world testing, especially across all medium- and heavy-duty commercial vehicle (MHDV) vocations; and limited assessments of the tradeoffs and benefits of efficiency technology options for fleets and their operations.

Several gaps and challenges are associated with ***vehicle-level data*** in the freight operational efficiency space. Understanding of truck configurations and their performance would be valuable in modeling efficient freight systems. Obtaining this understanding can be challenging, as OEMs consider these models and data sets highly confidential because of their importance in product design. Payload characteristics of individual vehicles are also needed— including both total payload at the endpoints of the trip and payload capacity utilization (volume and weight) throughout the freight trip—but are difficult to obtain (aside from highly aggregated average payload and distance data sets). Measurement techniques for obtaining these payload weights quickly, comprehensively, and accurately are also lacking. Duty cycles for individual trucks within the freight system are needed; these must reflect not only current truck operation but also the likely duty cycle for trucks in future freight systems (for example, the duty cycle for an electric urban box truck may not be the same as the current diesel box truck). More information is needed to estimate the components of TCO for future freight vehicles, particularly maintenance and operating costs and likely resale value trends. The latter is likely to be particularly challenging, as the resale models for future trucks may not resemble those in use today (for example, future resales may include battery electric trucks whose batteries were leased to the end customer separately). Past experience in deploying other technologies in the freight sector, such as natural gas trucks, may be of assistance in understanding general resale trends for these new technologies.

From a ***systems-level data perspective***, gaps exist in understanding the operational characteristics of freight movement, including freight types and distances traveled, specific shipment-level information, current and future trends in e-commerce and its impacts on last-mile travel and truck choices, and the effect of e-commerce choices on energy use in freight. In addition, gaps exist in understanding the skill levels of drivers (particularly as driver shortages bring new drivers into the mix).

In general, ***data collection and use*** present challenges. Because of the role of data in company operations (freight carriers, OEMs, suppliers), these data sources are usually confidential and difficult or impossible to access and use in analysis. Also, data ownership is a major obstacle in using operational data from sources such as telematics data. An OEM may operate the telematics system and be open to providing data summaries or insights for analysis, but the fleet, not the OEM, owns the data set. This leads to complex multi-party data agreements and lengthy negotiations to access data sets, delaying or potentially eliminating access to necessary data sources. In this context, data encompasses not only vehicle-level data but also broader operational data and environmental data that contribute to the understanding of the broader freight system, and these data sets are also challenging to obtain. Cybersecurity is another aspect of data collection and use that needs to be addressed, as data sets of most use in freight efficiency often contain some level of proprietary information that could compromise business competitiveness if released. This risk may limit participants' willingness to contribute to data sets that could improve freight efficiency.

The major gap related to ***metrics*** is the identification of the appropriate metric or metrics suitable for measuring and influencing the freight operational efficiency outcome desired (improvements in energy, emissions, time, cost, or all of these). A particular gap is in identifying and deciding upon the appropriate normalization basis for metrics: weight-based, volume-based, TCO-based, or something else. Also important is the inclusion of all freight movement activities in a productivity metric, not just the activities with the truck in motion. For example, fueling or recharging the truck is part of the freight movement activity and contributes to the overall time efficiency of the freight movement. Applicability of metrics is also a challenge, as some metrics may be more useful for expressing stretch research targets, while others are of more use in optimizing ongoing fleet operation. In a related note, metrics may vary in usefulness between different fleet types. For example, captive fleets that serve a single parent company may have different measures for success than a for-hire less-than-truckload fleet.

From the standpoint of ***tools***, gaps exist in the areas of complex, large-scale, system-level modeling and simulation tools to measure system efficiency and understand efficiency improvement opportunities with appropriate system boundaries. Tools to explore efficiency opportunities for a variety of different scenarios are needed. Gaps also exist in what models are being developed (at what level of complexity and detail in the results) and how they are being used. Tradeoffs between simplicity of use and accuracy need to be better understood. Finally, there is a need for additional detailed lifecycle assessments of MHDVs across a wide range of technologies to understand each technology's effect on lifecycle costs, emissions, and energy use. Assessment findings would (1) add to the understanding in the literature of the different drive cycles and vocations and (2) support other modeling tools, allowing for modeling technologies within these drive cycles and vocations accurately.

Technology Development and Deployment

At the highest level, the major barriers associated with technology development and deployment are:

- ***COST:*** Development and evaluation of technology options for improving freight efficiency can be costly, particularly those involving multiple vehicles and infrastructure elements in a test system.
- ***INFRASTRUCTURE:*** Infrastructure and vehicles for connected and automated vehicle solutions must be developed in parallel. There is a need for reliable and accurate infrastructure that generates stable data streams, particularly to facilitate connectivity and automation. Robust cybersecurity protocols and practices are also needed to ensure safe and secure operation of new technologies.
- ***STANDARDS:*** Robust and consistent standards for technologies and practices to improve freight efficiency will help ensure wide acceptance. In this topic area, the FOETST is benefiting from collaboration with light-duty U.S. DRIVE tech teams.

Connectivity and automation technology faces barriers associated with the technology. This technical area lacks a thorough understanding of the requirements for bandwidth for these systems, necessary cybersecurity protections, and computing power levels, including both what is currently needed to operate these vehicles and what may be needed in the future. As the technology develops, open issues to address—on both the vehicle and infrastructure sides—include defining the operating design domain, required sensing capability, and safety system requirements. Additionally, there are concerns about connectivity and automation resulting in significant increases in energy use for freight. (Ideally, these technologies can encourage energy use reduction through vehicle control algorithms.) Driver interaction with connected and automated vehicles is another concern, as it is unclear how drivers of different skill levels and demographics will work with these systems, both in automated operation and in the handoff between full automation and manual driver control. Questions remain about how connectivity and automation will affect vehicle selection and the overall design of freight systems, particularly hub-and-spoke freight delivery. Infrastructure is another major connectivity and automation barrier, covering roadside communication units (and the algorithms and software to operate/control these), managed lanes specifically for connected and automated freight trucks, vehicle monitoring, and staging yards at the transition points between long-haul automated freight corridors and the first-/last-mile travel that will likely still be human-operated. Challenges with platooning technology involve the logistics of establishing platoons among trucks that may initially be widely separated, apportionment of fuel savings benefits across trucks in a platoon (particularly if the trucks are operated by different fleets), and the tradeoff between the complexity/benefits of platooning versus full automation. Data security, privacy, and confidentiality issues remain to be addressed in detail for connected and automated vehicles. The regulatory framework for supporting the energy and emissions reduction aspects of connected and automated vehicles is lacking, as current regulations involve fixed duty cycles that may not represent the operational characteristics of these vehicles under real-world driving conditions. While 21CTP does not have a direct regulatory role, the FOETST will remain informed of these considerations, as they may influence future research needs.

Artificial intelligence and machine learning approaches are needed to manage freight operations efficiently at a very large scale (potentially much larger than today's systems can handle). Future systems will require extensive data streams on vehicle and powertrain characteristics, transportation network conditions, infrastructure locations and operating status, fleet logistics, and other critical inputs.

System optimization is a broad category with several notable barriers and gaps. This category covers the uncertain impact of new modes and technologies such as drones and micromobility (small low-speed vehicles such as electric bicycles, electric scooters, or small delivery vehicles) on the traditional medium-duty and heavy-duty freight transportation modes. There is also uncertainty around how customer demands and preferences (such as those for e-commerce) may affect the freight system and how the freight system should be optimized for efficiency around these changing demands. New freight system configurations are still likely to require Class 7–8 trucks for at least a portion of the freight transportation route, but their configuration might change in ways that are not well-defined (e.g., the role of electrification in these vehicles in a future freight system). High-productivity vehicles offer the opportunity to increase freight efficiency, but policy gaps and public perception barriers would need to be overcome before such vehicles would be implemented.

Alternative fuels are a consideration for several 21CTP tech teams and are the focus of the Electrification Tech Team. Within the context of freight operational efficiency, the main barriers and gaps center on the availability of fueling or charging infrastructure and the changes to existing facilities and operations implied by the specific characteristics of alternative fuels. In some cases, new fuel technologies will change over time to meet the use cases that fleets require (e.g., development of longer-range EVs or higher fuel capacities for natural gas trucks), but in other cases, the use cases will change to meet the characteristics of the fuels (e.g., shorter haul distances and longer warehouse layovers for EVs). Cost and payload weight impacts continue to be barriers for alternative fuels. The combination of cost and availability of alternative fuels across the country is likely to dictate the level of technology uptake. Unlike today, when one fuel (petroleum) can meet all freight transportation needs, the future freight landscape may involve different fuels for different applications (potentially low-carbon liquid fuels for long-haul trucks, hydrogen fuel cells for regional-haul, and battery electric vehicles for local and first-/last-mile applications). Because the characteristics of different fuels make them more suitable for some applications than others, fleets will be able to optimize their operations at the fleet level and maintain a suite of different powertrains for different routes. Although the variety provides efficiency opportunities, the traditional operation of many fleets may make adjustments challenging; many fleets will likely take the position that a new alternative fuel is unacceptable (and thus not worth pursuing at all) if it cannot meet all duty cycles and applications. EV charging for commercial freight vehicles faces several particular barriers. The technology entails high power requirements (potentially 350 kW or more) on utility-side infrastructure and facility demand charges. Facilities also present challenges: MHDVs require specialized access requirements and power levels that preclude, or at least impede, significant infrastructure-sharing with the light-duty EV population. Additionally, EVs present TCO challenges, as they usually have higher initial capital costs but lower operating costs. Depending on the fleet's financial situation, even a good overall TCO may not drive adoption if the fleet cannot address the components of TCO appropriately (e.g., if there is no available capital to obtain a vehicle that would be lower in operating cost). New purchase models for advanced technologies, such as battery leasing for EVs, will need to be more widespread to address cost issues more effectively. Achieving widespread deployment of the necessary EV charging infrastructure in rural areas to serve these populations will likely be costly and challenging to implement.

For ***vehicle-level efficiency technologies***, many of the gaps and challenges associated with improving a freight truck's overall fuel efficiency using a systems perspective are technology-based. Availability of technologies is somewhat limited in the areas of aerodynamics, tire rolling resistance, idling reduction, and lightweighting, particularly technologies that are reliable and meet customer expectations for payback period. In addition, some technologies that may offer benefits to the first owner of a freight truck may be a disbenefit to subsequent owners. For example, aerodynamic treatments that are valuable for the first owner of a Class 8 truck may not be as useful for a subsequent owner who will use that truck in a regional-haul setting. Some vehicle-level efficiency technologies may present operational challenges as well. For example, achieving very low aerodynamic drag from a Class 8 tractor–trailer combination may require permanent matching of those units, an approach not often used with freight trailers. Also, some aerodynamic aids may work well on smooth highways but less well on uneven terrain, as the clearance between these devices and the road is quite small. Specific to idle reduction, a number of technologies are available commercially, but initial cost and long-term reliability have limited their uptake.

Additionally, ***deployment*** of new technologies is a continual challenge. These technologies often enter the marketplace with limited real-world data and case studies to demonstrate value to fleet customers, resulting in limited initial uptake and slow reductions in costs through economies of scale. There is a need to secure these real-world experiences from sources credible to fleet customers and distribute the information through information channels fleet customers trust.

The roles of many players and their specific needs and motivations must be considered in new technology deployment. These stakeholders include end users (fleet managers, fleet owners, drivers, and maintenance and repair technicians) and suppliers (OEMs, equipment and component suppliers, and energy/fuel companies). All the essential parties must have their voices heard and their concerns addressed so the overall technology deployment will progress more smoothly.

Information Sharing

At the highest level, the major barriers associated with information sharing are:

- ***DATA SHARING:*** 21CTP researchers have limited ability to share tools and detailed analysis results containing proprietary company or fleet-specific data.
- ***SCALABLE USABLE TOOLS:*** There is limited availability of scalable analytical tools that translate complex analysis findings into usable insights for local or regional decision-making.
- ***AUDIENCES:*** The 21CTP research community has limited contact with potential new audiences interested in freight operational efficiency research findings, such as local transportation planners and modelers, utilities, and energy/fuel suppliers.

Although information dissemination channels for FOETST research findings do exist and are well-developed, there are challenges to address. This roadmap has described the breadth and complexity of the freight operational efficiency space. Translating the research results and their associated assumptions and limitations into actionable insights can be challenging. Audiences for this research need insights that are clear and concise but not so simplified that they lack relevance for taking action or making purchase decisions.

The potential use of proprietary data sources to create these insights also presents some barriers, as the results need to be processed and summarized at a high enough level to protect these sensitive data inputs but must be detailed enough to be practical.

These research results must be delivered to all the audiences necessary to successfully address freight efficiency, using optimal information channels and meeting messaging expectations for these audiences. Although 21CTP participants have connections to a wide range of stakeholders, it is not clear that the Partnership and its tech teams have access to all these audiences and information delivery systems.

Finally, the FOETST and its research partners must ensure that the information presented is viewed as being provided by an independent third party with an objective view of the benefits and challenges of the technologies (rather than as “just another vendor sales pitch”).

Strategies to Achieve Targets

The FOETST has developed action-oriented strategies (see Figure 10) in three specific areas to meet the team's targets for freight efficiency:

- ***Analysis and Insight***, covering the need to collect data, develop analysis tools and techniques, and assess the potential for new technologies to improve freight efficiency
- ***Technology Development and Deployment***, covering the need for research, development, and eventual deployment of innovative technologies to improve freight efficiency with associated codes and standards necessary to facilitate success
- ***Information Sharing***, covering the need to communicate analysis and technology research findings to a broader audience for further action

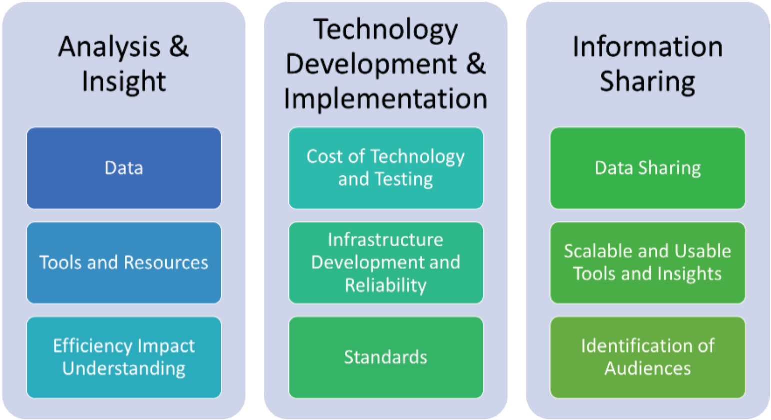

Figure 10. Freight Operational Efficiency Action Strategies

Figure 10 also reiterates the major high-level barriers associated with each of the broad strategies that were originally introduced in the Gaps and Barriers section above.

While 21CTP and the FOETST are focused on the market for freight and truck technologies in the United States, the global nature of both freight movement and truck and technology manufacturing means that the FOETST will need to consider the effect of worldwide trends. These would include trends in global economics and freight movement as well as market and regulatory trends that will drive technology development.

Within the framework of the goals set forth for the FOETST, a number of potential actions could be taken to address one or more of these goals. The list below provides some suggested actions but is by no means exhaustive.

In the strategy area of Analysis and Insight, the following actions are proposed for consideration.

- Identify critical and specific research questions that must be addressed to facilitate increased freight efficiency in the United States. These questions should center on understanding the characteristics of the current and future freight system and refining technology needs for future research recommendations.
- Refine existing freight models and explore development of new models, as appropriate, to answer these freight efficiency research questions directly.
- Identify and secure necessary data sets to support modeling and analytical activities, including targeted data collection from specific truck vocations and duty cycles, if necessary.
- Collaborate to develop and/or update relevant and significant data sets. Potential partners include federal organizations such as the U.S. Department of Transportation and the U.S. Department of Commerce as well as

industry partners such as OEMs, large fleets, and/or industry associations. Consider requiring federally funded MHDV research, development, and demonstration projects to collect vehicle data and disseminate it in the public domain.

In the strategy area of Technology Development and Deployment, the following actions are proposed for consideration.

- Collaborate to identify appropriate research focus areas with maximum benefit, based on analytical work in the Analysis and Insight strategy area. Potential partners include federal research organizations such as the U.S. Department of Energy's Energy Efficient Mobility Systems team, federal national laboratories, and industry partners.
- Conduct targeted research, development, and pilot demonstrations of technologies across the freight system, and disseminate the data in the public domain.
- Review and, as appropriate, provide input to new and ongoing research, development, and demonstration projects with relevance to freight efficiency funded by federal research organizations such as the U.S. Department of Energy as well as projects funded by the private sector and projects conducted internationally. Ensure that data from federally funded projects is disseminated in the public domain.

In the strategy area of Information Sharing, the following actions are proposed for consideration.

- Conduct robust information exchange within the FOETST to explore research results, discuss progress toward tech team targets, and identify future research gaps, supplementing internal expertise with external contributors/guest speakers as appropriate. In addition, robust communication to the Executive Management Team (EMT) and the Senior Executive Steering Committee (SESC) within 21CTP, leading up to various departments within the U.S. Departments of Energy and Transportation, provides decision makers with the information they need to influence future R&D.
- Collaborate with federal research organizations, such as the U.S. Department of Energy's Energy Efficient Mobility Systems and Technology Integration programs, to summarize and disseminate research and analytical results to spur further technology adoption among fleets and other interested parties.
- Present research results at public conferences and meetings to facilitate information exchange.

Appendix A. Terminology and Acronyms

Acronym	Definition
21CTP	21st Century Truck Partnership
BTU	British Thermal Unit
CAV	Connected Automated Vehicle
CO2	Carbon Dioxide
db	Decibel
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EV	Electric Vehicle
FOEM	Freight Operational Efficiency Model
FOETST	Freight Operational Efficiency Technical Sector Team
GHG	Greenhouse Gas
GVW	Gross Vehicle Weight
HVAC	Heating, Ventilation, and Air Conditioning
IC	Internal Combustion
kW	Kilowatt(s)
kWh	Kilowatt-Hour(s)
LCV	Longer Combination Vehicle
MHDV	Medium- and Heavy-Duty Vehicle
mpg	Miles per Gallon
NOx	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
PM	Particulate Matter
R&D	Research and Development
TCO	Total Cost of Ownership
USMCA	United States–Mexico–Canada Agreement
ZEV	Zero Emission Vehicle

Appendix B: Omnichannel Logistics

It is challenging to represent a system as large and complex as the U.S. freight system in such a way that meaningful insights can be gleaned, relationships between system components can be understood, and improvements can be identified. Establishing a framework for and defining the boundaries of FOETST's analysis of freight efficiency required considerable discussion and research. Figure B1 below represents the traditional retail logistics model used in the past. Unfortunately, this model is too simple to accommodate today's (and tomorrow's) logistical landscape, which is rapidly changing as e-commerce accelerates and population demographics shift.

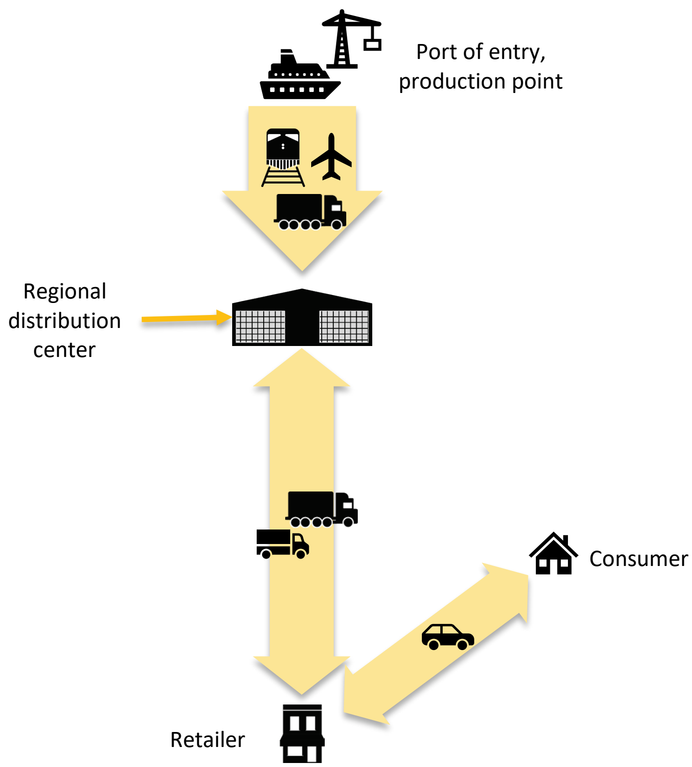

Figure B1. Traditional retail model:
single channel via brick and mortar

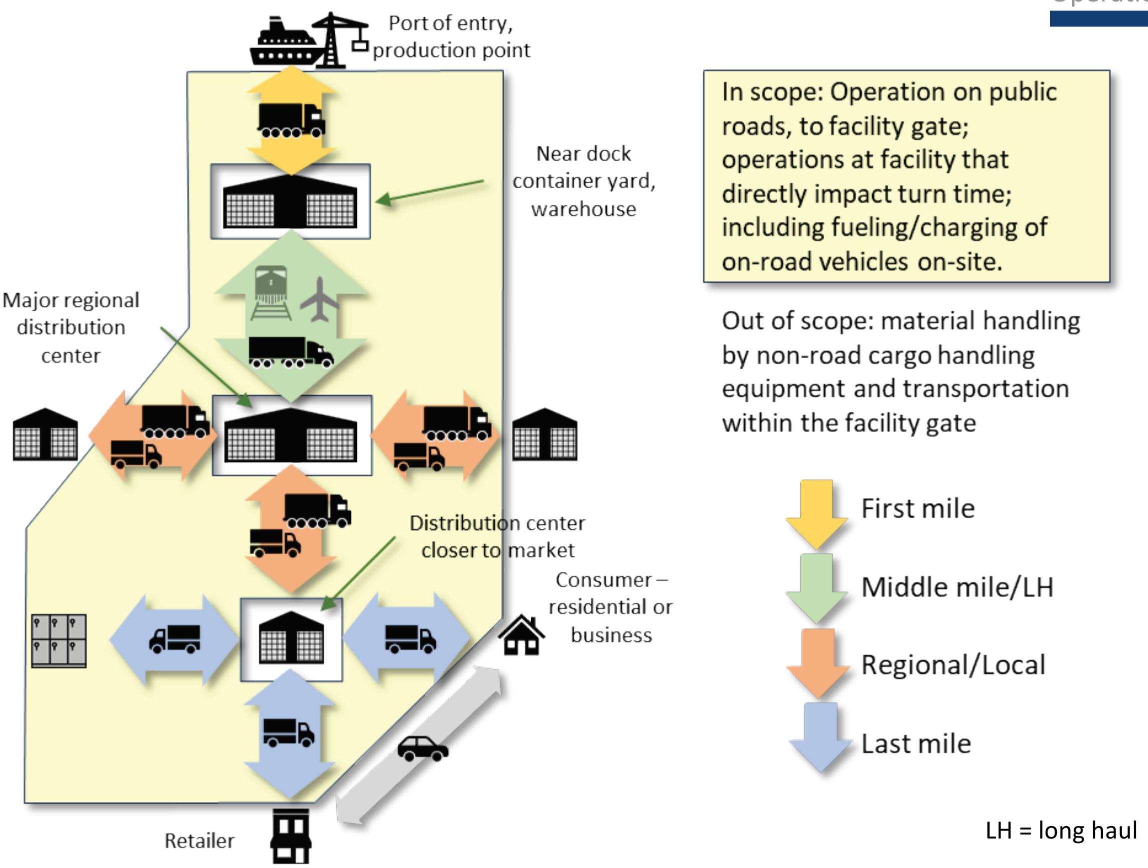

Figure B2. Omni-channel retail model with hub-and-spoke distribution

Figure B2 illustrates the omnichannel logistics model, which accounts for many of the moving parts in a modern-day logistical system. This framework was selected for the current analysis because it better represents the complexity of today's U.S. freight system and the interactions between various system components. While it doesn't cover the entire freight system, it does include a generalized freight pathway (not specific to an industry, a particular vehicle OEM, or geographic location) from the initial goods production or importation through the logistics chain to the final end user. The omnichannel logistics model encompasses a great variety of vehicles/duty cycles (drayage, first mile/last mile, long-haul freight, regional-haul freight) and powertrains (IC engine, natural gas engine, battery EV, fuel cell EV).

For our work in the 21CTP FOETST, we have placed many of the model pieces "in scope":

- Logistics and operations at the incoming port or loading dock for domestically manufactured goods
- Freight transit to a regional distribution center via road
- Logistics and operations at regional distribution centers associated with getting the packages out of and back into trucks (i.e., on the grounds of the distribution center but outside the walls of the facility itself)
- Movement of goods from regional distribution centers to smaller local centers, retail outlets, parcel lockers, or end users
- Movement of returned goods from consumers back to distribution centers.

Having said that, we have also placed a few model pieces "out of scope":

- Energy use/emissions outside the United States

- Energy use/emissions of raw material extraction and/or goods manufacture (domestic or overseas) and shipment to the port via air or water
- Energy use/emissions at a distribution center or warehouse for activities *within* that center (e.g., logistics picking of items within the warehouse; moving packages inside the warehouse or parts and products inside a manufacturing facility via forklift, conveyor, or robot; other energy-using activities within the facility)
- Energy use at a retail site for activities *within* that site (movement of goods from trucks to shelves, etc.)
- Energy use/emissions of the end user of the freight (including travel by the consumer to pick up packages at a parcel locker or retail store)
- Energy use/emissions associated with mode shifts (e.g., shifting freight transport from rail to truck, or vice versa)

Technologies that fit inside the boundaries of our analysis include the following:

- Improvements in overall individual vehicle efficiency, including matching powertrains to duty cycles
- Logistics improvements (routing systems, route optimization, rightsizing vehicles, high-productivity vehicles)
- Connectivity and automation (full automation, truck platooning)
- Cybersecurity for connectivity; collaboration with safety tech team, whose primary roles include cybersecurity

Decisions regarding the analysis boundaries were made based largely on the ability of 21CTP member organizations to influence the efficiency of the framework components.

Using this framework, the FOETST will (1) identify areas where technology development is needed to meet efficiency goals, (2) develop new concepts for making freight movement more efficient, (3) determine how individual vehicles fit into the framework, (4) identify the duty cycles that are used within the established framework, (5) identify powertrains and vehicles that meet these duty cycles, and (6) understand how the pieces of the framework are connected.

The National Renewable Energy Laboratory has developed the Freight Operational Efficiency Model (FOEM) based on the working elements contained within the omnichannel model. The FOEM has the capability to adjust many of the input parameters, such as technology adoption rate, connectivity level, segment- vs. system-level analysis, and total vs. levelized miles. The output is then calculated and displayed as cost per mile or total cost for the baseline year of 2020—out to the year 2050—based on the input parameters considered. The attribute assumptions for this model have come from the Electrification Tech Team's Power System Architecture Working Group.

The current state of this model has been highly influenced by the FOETST Analysis Working Group team members, who choose which elements have been included or excluded from the model. For example, the current model considers only diesel and battery EVs as possible powertrains. As technology and logistical expectations move forward, and when resources are made available, we will want to update this model to reflect current thinking. Examples include:

- Adoption of multiple new technologies – hybrid EVs, plug-in hybrid EVs, fuel cell EVs
- Multiple adoption rates – by technology and vehicle class
- Updated energy cost – electricity and hydrogen
- Mode shifting – e.g., from rail to trucks or vice versa

Appendix C: Exploration of Metrics

The FOETST Analysis Working Group spent considerable time discussing and debating possible metrics that could be used to measure freight operational efficiency. A summary of the feedback from Analysis Working Group members on possible metrics is presented below. Efficiency can mean different things to different people with different goals. For example, prioritizing minimized emissions and prioritizing minimized time would lead the analysis to very different conclusions. The output from the National Renewable Energy Laboratory's FOEM contains a few of these metrics. Going forward, additional metrics can be added as time and resources permit.

Metrics: How we measure operational efficiency within the segment and define targets

Network (or system)	Average speed or travel time
	Congestion (delay per mile, percentage of miles congested, hours of congestion)
	Reliability (ratio of travel time during congestion to free-flow travel time)
	Resilience (number of alternative routes available on specified time schedule)
Time	Total travel (delivery) time
	Facility turn time
	Driving time
	Time searching for parking
	Time searching for fueling
	Time for services (loading/unloading)
	Time for fueling
	Time for resting
Logistics	Unit volume (number of trucks, number of tours)
	Unit weight (ton or cu ft/vehicle(capacity), ton or cu ft/day, ton or cu ft/tour)
	Deliveries/mile or tour
	Travel distance/delivery
	Empty travel miles/loaded mile
	Empty travel miles/tour
Economics	Total travel cost ($)
	Total unit cost (per mile, ton, cu ft)
Energy	Total energy usage (kWh)
	Unit energy consumption (per mile, ton, ton-mi, cu ft, $, etc.) – segment level
Environment	GHG emissions (CO_2/mile, total tons)
	Criteria emissions (NOx/mile or ton-mi, PM/mile or ton-mi, total tons)
	Noise (db-mile, db-person-hr), miles > threshold?
	Safety incidents (crashes, fatalities per mile)

Appendix D: Longer Combination Vehicles

Length and weight for improved efficiency of MHDVs have long been considered. Length and weight policy is not uniform across the United States or within the United States–Mexico–Canada Agreement (USMCA) region (National Academy of Sciences 2020). U.S. federal and state governments have their own policies that apply to roads under their respective authority. For example, state roads are governed by individual state policies, while interstate and national network facilities are governed by federal law. Even within itself, federal law is not uniform in terms of vehicle weight. While the stated allowable gross vehicle weight (GVW) on the interstate system is restricted to 80,000 pounds, grandfather rights were given to states whose acceptable GVWs were higher than federal law at the time the Interstate Highway Program was established (1956). More than a dozen states have GVW limits on state roads that exceed the limits on the interstate and other national truck network routes, and many more states have commodity- or industry-specific exemptions that allow even higher truck weights on specific routes. Canada now allows GVWs up to 102,500 pounds. This patchwork of truck size and weight limits presents challenges for interstate trucking operations, as well as for public regulation of the trucking industry. The complexity increases the cost of operations for truckers and contributes to suboptimal transport efficiency. The Surface Transportation Assistance Act of 1982 effectively froze size and weight limits on the national network, limiting vehicle weight to 80,000 pounds and limiting so-called longer combination vehicles (LCVs) to twin 28-foot trailers. Other countries have increased length and weight limits in what may be seen as a move to balance infrastructure consumption with vehicle productivity and safety, thereby making substantial improvements in transportation efficiency. LCVs can improve efficiency by increasing the cargo hauled by each combination vehicle through multiple trailers per tractor. Examples of different LCVs are twin 33-foot trailers, triple trailers, and twin 53-foot trailers. There is considerable evidence that the reduction in vehicle miles traveled that would result from more closely aligning U.S. regulations with those of USMCA partners would more than make up for any additional danger to passenger car drivers and vulnerable road users that might result from longer and heavier vehicles. Lastly, safety technologies such as stability control, forward collision warning and mitigation systems, and lane departure warning systems may improve the safety performance of LCVs and increase the acceptability of such vehicles.

Bibliography

National Academy of Sciences. 2020. *Reducing Fuel Consumption and Greenhouse Gas Emissions of Medium- and Heavy-Duty Vehicles, Phase Two: Final Report.* Committee on Assessment of Technologies and Approaches for Reducing the Fuel Consumption of Medium- and Heavy-Duty Vehicles, Phase Two, Washington, DC: The National Academies Press.National Highway Traffic Safety Administration. 2017. "USDOT Releases 2016 Fatal Traffic Crash Data." NHTSA 01-17. October 6. https://www.nhtsa.gov/press-releases/usdot-releases-2016-fatal-traffic-crash-data.

National Renewable Energy Laboratory. 2022. "Freight Operational Efficiency Metrics: Analysis Results." Virtual presentation to the Freight Operational Efficiency Technical Sector Team. March 30.

Oak Ridge National Laboratory. 2022. *Transportation Energy Data Book: Edition 40*. ORNL/TM-2022/2376. February. https://tedb.ornl.gov/wp-content/uploads/2022/03/TEDB_Ed_40.pdf.

U.S. Census Bureau. n.d. "Did You Know These Rural Facts?" *Rural America*. Accessed January 3, 2022. https://mtgis-portal.geo.census.gov/arcgis/apps/MapSeries/index.html?appid=49cd4bc9c8eb444ab51218c1d5001ef6.

U.S. Census Bureau. 2016. "Measuring America – Our Changing Landscape." PDF data tables. December 8. https://www.census.gov/content/dam/Census/library/visualizations/2016/comm/acs-rural-urban-text.pdf.

U.S. Census Bureau. 2017. "One in Five Americans Live in Rural Areas." *United States Census Bureau – What Is Rural America?* August 9. https://www.census.gov/library/stories/2017/08/rural-america.html.

U.S. Department of Agriculture. n.d.a. *Informational Publication 100-1 Reference Guide to the Rural Electrification Act of 1936.* Accessed January 3, 2022. https://www.rd.usda.gov/files/UEP_IP_100-1.pdf.

U.S. Department of Agriculture. n.d.b. *Rural Utilities Service.* Accessed January 3, 2022. https://www.rd.usda.gov/about-rd/agencies/rural-utilities-service.

U.S. Department of Agriculture. 2017. "Celebrating the 80th Anniversary of the Rural Electrification Administration." February 21. https://www.usda.gov/media/blog/2016/05/20/celebrating-80th-anniversary-rural-electrification-administration.

U.S. Department of Agriculture. 2021. "Manufacturing is Relatively More Important to the Rural Economy than the Urban Economy." August 4. https://www.usda.gov/media/blog/2017/09/12/manufacturing-relatively-more-important-rural-economy-urban-economy.

U.S. Department of Commerce, International Trade Administration. n.d. "eCommerce Sales and Size Forecast." Accessed December 23, 2021. https://www.trade.gov/ecommerce-sales-size-forecast.

U.S. Department of Transportation, Bureau of Transportation Statistics. 2021. "Freight Activity in the U.S Expected to Grow Fifty Percent by 2050." November 22. https://www.bts.gov/newsroom/freight-activity-us-expected-grow-fifty-percent-2050.