Heavy-duty Vehicles & Freight Sector Baseline

ALLIANCE 50X50 COMMISSION

ON U.S. TRANSPORTATION SECTOR EFFICIENCY

ALLIANCE TO SAVE ENERGY
using less. doing more.

Report by the Heavy-duty Vehicles
& Freight Technical Committee
September 26, 2018

PREAMBLE

The Alliance to Save Energy launched the 50x50 Commission on U.S. Transportation Sector Efficiency (the "50x50 Commission") to lay out regulatory, policy, and investment pathways to significantly improve energy efficiency in the U.S. transportation sector. Comprising executives and decision makers from a range of key stakeholder groups—including vehicle manufacturers, utilities, federal and subnational governments, technology developers and providers, environmental advocates, and targeted customers— the 50x50 Commission established the goal to reduce energy consumption in the U.S. transportation sector by 50 percent by 2050 on a pump-to-wheel (PTW) basis, relative to a 2016 baseline.

The 50x50 Commission work is complementary to that of the Alliance Commission on National Energy Efficiency Policy, which recommended energy efficiency policies and practices that could lead to a second doubling of energy productivity by 2030. As transportation represents roughly one-third of overall energy consumption in the U.S., the transportation sector offers enormous potential for gains in both energy efficiency and energy productivity.

The outputs of the 50x50 Commission include a foundational white paper that outlines the goals and scope of the Commission's work, a set of five "sector baseline" reports that assess the current state of energy efficiency within the transportation sector, and a suite of policy recommendations outlining the types of government support, at all levels, necessary to achieve the 50x50 goal.

This report, Heavy-duty Vehicles & Freight, is one of the five sector baseline reports that identifies the general market trends for efficient transportation technologies and explores opportunities and challenges related to deploying those technologies. This report and the sector baseline reports covering the other four technology areas—Light-duty Vehicles; Non-road Vehicles; ICT, Shared Mobility & Automation; and Enabling Infrastructure—helped inform the 50x50 Commission's policy recommendations.

Technical Committee

Our sincere thanks and appreciation go to the the 50x50 Commission Heavy-duty Vehicles & Freight Technical Committee:

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While many Alliance to Save Energy staff assisted with the development of this document, special recognition is given to Karen Hughes and Mikelann Scerbo for their significant contributions to this sector baseline.

TABLE OF CONTENTS

INTRODUCTION

Medium- and heavy-duty vehicles (MDV/HDVs) account for a significant fraction of the energy consumed in the U.S. transportation sector and offer potential for substantial efficiency gains. Large trucks account for 23 percent of transportation energy use.[1] In cost-effectively moving large freight (and passengers, for buses) loads, trucks have the highest per-vehicle fuel consumption of highway vehicles, travel the longest distances (tractor-trailers average nearly 62,000 miles per year), and are responsible for 22 percent of petroleum consumption in the U.S.[2,3] In particular, Class 8 heavy-duty trucks, those weighing over 33,000 lbs., consume a disproportionate amount of petroleum: These trucks comprise 41 percent of the MDV/HDV fleet, but consume 78 percent of the total fuel used for MDV/HDV fleets.[4] Since trucks transport 80 percent of goods in the U.S., improving their efficiency has the potential to yield enormous energy and cost savings in the MDV/HDV sector.[5]

Opportunities for improving MDV/HDV fuel economy range from vehicle technology solutions – including hybridization, powertrain selection, fuel diversification, vehicle design, aerodynamics, advanced refrigeration technologies, truck stop electrification (TSE), and lightweighting – to behavioral and infrastructural changes to reduce wasteful fuel use. Small efficiency gains can have significant impacts on fuel use and emissions, especially when the efficiency gains from different opportunities are aggregated. The potential for effective programmatic and regulatory support for such improvements is particularly high in this sector since fewer efficiency and emissions standards have traditionally been placed on HDVs compared to their light-duty vehicle counterparts.

While the technical solutions for greater fuel efficiency are well understood, many of them have not yet been broadly implemented across the MDV/HDV sector; many commercially available, energy-efficient technologies have limited market penetration among HDVs/MDVs. For example, the U.S. Department of Energy's (DOE) SuperTruck initiative developed a heavy-duty truck that achieves 10.7 miles per gallon (mpg), nearly doubling the average heavy-duty truck fuel economy of 5.8 mpg; but heavy-duty trucks in use today continue to average about 4.5 to 6.5 mpg.[6, 7] Similarly, the North American Council for Freight Efficiency's 2017 roadshow "Run on Less" demonstrated seven super-efficient trucks operated by skilled drivers with an average fuel economy of 10.1 mpg; the highest fuel efficiency achieved was 12.8 mpg.[8] These trucks have not yet entered the market at scale, but the efficient driving techniques used by the drivers can be distributed more widely to fleets. Similar opportunities exist in buses and delivery trucks, which due to their large fleet numbers and frequent stops, present significant efficiency and fuel savings opportunities.

This report explores the status of energy efficiency technologies within the MDV/HDV sector as well as the opportunities and challenges for accelerating the deployment of these technologies. While there are many types of HDVs/MDVs, this report focuses on:

- Mass transit buses,
- Heavy-duty tractor-trailers used for regional and long-haul goods delivery, and
- Light- and medium-duty commercial vehicles used for the 'last mile' of delivery of goods between a logistics hub and the final destination.

SUMMARY OF KEY FINDINGS

Disproportionate Energy Use

Because trucks represent only about 6 percent of vehicles on the road, yet consume 23 percent of transportation energy and transport 80 percent of goods in the U.S., the MDV/HDV sector represents an enormous opportunity for energy savings.[9,10,11,12]

Benefits of Standards

Fuel consumption standards are key drivers for future transportation efficiency gains.

Benefits of Alternative Fuels

Alternative fuels offer significant emissions benefits for MDVs/HDVs compared to fossil fuels.

Benefits of Electrification

Electrification offers both significantly lower emissions and improved energy efficiency compared to fossil fuels. The degree of potential market penetration for plug-in electric vehicles (PEVs) varies within the MDV/HDV sector. Buses may be the quickest subsector to adopt PEVs, since total cost of ownership of electric buses is already on par with diesel buses. Due to the high initial cost of electric trucks and the high charging requirements for long-haul applications, long-haul trucking may be the subsector that is furthest away from adopting PEVs.

Existing Opportunities

Immediately deployable opportunities – including improved driver behavior, load consolidation, and effective logistics planning – are increasingly necessary to reduce energy consumption and congestion, especially as e-commerce spurs growth of small package last-mile deliveries.

TRENDS & EFFICIENCY OPPORTUNITIES IN VEHICLE TECHNOLOGIES

Non-Powertrain Vehicle and Trailer Technologies

Technologies outside of the engine and powertrain can significantly enhance the efficiency of a vehicle and can often be applied regardless of the vehicle fuel type. Non-powertrain vehicle technologies encompass a wide range of approaches designed to reduce the fuel use of MDVs/HDVs and/or improve their performance through improving vehicle aerodynamics or reducing tire rolling resistance, vehicle weight, idling, or auxiliary loads (see Table 1). The impact on fuel use of any single design approach is generally modest – ranging from 1 to 5 percent fuel reduction – but several approaches can often be combined to achieve greater fuel savings.[13] These technologies generally do not impact safety and do not require any supporting infrastructure external to the vehicle. However, many of these technologies add weight, which can affect the vehicle's load capacity for passengers or goods.

Table 1. Examples of Non-Powertrain Vehicle Technologies Categorized by Method of Fuel Use Reduction

Improves Aerodynamics	Reduces Rolling Resistance	Reduces Idling/ Auxiliary Loads
✓ Cab designs ✓ Side skirts (trailer) ✓ Boat tail (trailer) ✓ Gap filler (trailer) ✓ Roof fairings ✓ Fuel tank fairings	✓ Low rolling resistance tires ✓ Super-single tires ✓ Tire pressure monitoring ✓ Automatic tire inflation system	✓ Battery PTO ✓ Electrified accessories ✓ Diesel APU ✓ Battery APU

The deployment of non-powertrain technologies varies depending on the vehicle application. Most design approaches are technically mature and have penetrated the market for some new vehicles.[a] Many – including auxiliary power units (APUs), trailer side skirts, automatic tire inflation, and tire pressure monitoring systems – are also commercially available for vehicle retrofits. For combination trucks (tractor-trailers), the fuel reduction benefits can be increased significantly if the technologies, such as aerodynamic aids and tire technologies to reduce rolling resistance, are applied to both the tractor and the trailer. The following are examples of the applications of non-powertrain efficiency designs:

- Technology to **reduce tire rolling resistance** is effective on most vehicles.
- Technology to **improve aerodynamics** is most effective on vehicles that mostly travel at highway speeds greater than 50 miles per hour (mph).
- **Weight reduction** strategies, including the use of lightweight materials such as aluminum or composites, generally only apply to new vehicles and trailers. Nevertheless, weight reduction technologies can sometimes be retrofitted onto existing equipment, such as by converting wheels to aluminum rims or wide-based single tires.
- **Idle reduction** technologies and designs to **reduce auxiliary loads** are usually targeted toward specific applications. APUs provide energy for vehicle applications aside from the main engine, such as air-conditioning. Battery or diesel APU reduce the need for overnight idling of tractors equipped with a sleeper cab. Battery power take-offs (PTOs), a type of APUs, are most effective for vehicles that typically idle to supply vocational loads, such as utility bucket trucks or dump trucks.

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[a] Examples include improved aerodynamics through new cab designs, roof fairings and fuel tank fairings.

Internal Combustion Engines

The internal combustion engine (ICE) has long been a key source of motive power for MDVs/HDVs, largely due to its reliability, durability, and versatility. Although ICE engine designs have improved significantly over the past century, considerable opportunity remains for increasing their efficiency. Some research indicates that engine efficiency improvements could increase commercial vehicle fuel economy by over 40 percent.[14] Customer demands for decreased fuel consumption and the potential for more stringent emission standards will drive the need for continued improvement in ICE efficiency.

Noise is also a significant design factor for ICEs but noise reduction technologies often counterbalance efficiency improvement efforts. ICEs, especially those running on higher compression ratio fuels such as diesel, generate significant noise as a byproduct of energy usage. Technology to muffle noise can be effective but often adds weight to vehicles and reduces engine efficiency.

ICEs, which typically use a piston-and-crank configuration, can be divided into three major categories: compression-ignition, spark-ignition, and low-temperature combustion engines. Each type of engine has particular advantages but also faces specific barriers to improved efficiency, creating particular research needs. The benefits and challenges for each engine type are described below:

1. **Compression-ignition engines** are the most common type of engine in nearly all heavy-duty trucks and in many medium-duty trucks, due to their high efficiency and durability. In compression-ignition engines, combustion depends on fuel injection timing. Fuel is injected into highly compressed air in the cylinder and ignites as it contacts the hot compressed air. The four-stroke diesel cycle is the most well-known compression-ignition cycle. Current compression-ignition engines can achieve thermal efficiency of greater than 45 percent despite the efficiency trade-offs inherent in the introduction of emissions control technologies installed to comply with stringent emissions regulations.[15] Typical emissions control technologies, such as selective catalytic reduction and diesel particulate filters, require the engine to maintain high exhaust gas temperatures to function properly, which can negatively impact engine efficiency.[16]

   Although efficiency improvements often come at a high initial cost, they generally result in long-term cost savings related to reduced fuel consumption. Fuel cost savings are especially significant for diesel, given the relatively higher per-gallon cost for diesel – a trend that is expected to continue with increased worldwide diesel demand. While it will be challenging to develop new fuel economy technologies at a reasonable cost for the levels of durability and reliability required, continued advancements in the following compression-ignition engine technologies are projected to push engine thermal efficiency to 55 percent:[17]

   - ✓ Air handling, including turbocharging and exhaust gas recirculation,
   - ✓ Fuel injection to achieve higher pressure and better fuel atomization,
   - ✓ Engine parasitics, such as water pumps, oil pumps, and internal friction,
   - ✓ Engine controls, including model-based controls with better optimization parameters,
   - ✓ Propulsion materials at higher strength to withstand higher engine temperatures and pressures, and
   - ✓ Waste heat recovery, including both electrical/mechanical turbo-compounding and the organic Rankine cycle.

2. **Spark-ignition engines** are predominantly used for light-duty cars and trucks. Nevertheless, since spark-ignition engines tend to cost less than other types of ICEs, they are also used in medium-duty trucks in applications where initial cost is a larger barrier than ongoing operating costs. However, higher operating costs due to lower efficiency may offset the initial cost savings, depending on the truck's duty cycle. Spark-ignition engines also offer an attractive low-emission option for MDV/HDVs, since they can use low-carbon fuels such as natural gas or propane.

In spark-ignition engines, combustion depends on flame propagation from a spark to ignite a premixed air-fuel mixture. The most common cycle is the four-stroke spark-ignition cycle, known as the Otto cycle.

Current spark-ignition engines achieve thermal efficiency approaching 40 percent, but research into future engine technologies is seeking to improve on those efficiencies.[18] The U.S. DRIVE Partnership, which is a partnership with the DOE and a variety of automakers, energy companies, and utilities, has set Advanced Combustion and Emissions Control (ACEC) stretch goals to achieve greater than 40 percent efficiency by 2020 and 2025.[19] Similar to compression-ignition technologies, the challenge for future advancements in spark-ignition engines will be to improve efficiency at a level of cost and durability that meets customer expectations. Advancements in the following technologies will likely continue to improve fuel economy in spark-ignition engines:

- Air handling, including turbocharging and variable valve actuation,
- Controls, including cylinder deactivation when less power is required,
- Lean gasoline combustion, and
- Fuel injection.

3. **Low-temperature combustion engines** are an attractive emerging technology with the potential to combine the efficiency of the compression-ignition engine with the benefits of low emissions. Because low-temperature combustion engines typically have lower emissions, especially of nitrogen oxides (NOx), they also have lower costs associated with emissions control systems, for example due to lower requirements for aftertreatment systems.[20] While a low-temperature combustion engine has not yet been launched in the MDV/HDV market, Mazda has announced production plans for a low-temperature combustion engine in 2019 for its model Mazda 3 compact car.[21] In low-temperature combustion engines, combustion is dominated by chemical kinetics processes for ignition, rather than spark-flame propagation or compression heat. Researchers continue to investigate the basic combustion processes to better understand how low-temperature combustion operates.[22,23] Future research will facilitate better controls to expand the operating range of these engines in all vehicle sizes and improve transient performance while reducing noise, vibration, and harshness.[b]

Entities including Argonne National Laboratory continue to carry out research to develop alternative engine designs that can reduce the energy losses from friction and air handling associated with traditional piston-and-crank engines.[24,25] Future ICE engineers may need to consider designs beyond the traditional piston-and-crank four-stroke Otto or Diesel cycle engine. Alternative designs could include other thermodynamic cycles that offer higher efficiency potential.

Regardless of the engine type, emissions-control aftertreatment systems are usually needed for any ICE to meet increasingly stringent global emissions standards. Both federal and state regulatory agencies are considering standards for MDV/HDVs that approach near-zero emissions levels. More stringent emissions standards will likely require more complex aftertreatment systems with associated higher costs. The lower exhaust temperatures of future high-efficiency engines will be challenging for emissions aftertreatment systems, especially for cold-start emissions. While research has demonstrated that compliance with stringent standards is technically feasible, the durability impacts of compliant fuel-efficient technologies are still unknown.[26] For example, while cost and durability for NOx aftertreatment systems have greatly improved relative to earlier designs, the improvements need to be even greater to meet customer expectations.

Alternative Fuel Vehicles

Alternative fuels offer significant emissions benefits for MDVs/HDVs compared to fossil fuels. The alternative fuels discussed below are natural gas, propane, and hydrogen.

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[b] Harshness is how much noise and vibrations affects the vehicle and its occupants.

Natural Gas and Propane

In the U.S. today, the predominant fuel alternative to diesel in heavy-duty and freight on-road vehicles is natural gas. In natural gas vehicles, the fuel is dispensed and stored on-board the vehicle either as compressed natural gas (CNG) or as cryogenically liquefied natural gas (LNG). Natural gas use in buses has risen dramatically over the past decade: natural gas-fueled buses now make up 25 percent of transit bus fleets and account for 50 percent of new bus orders. The introduction of a Cummins Westport spark-ignited natural gas engine in 2013 opened the door for many other types of vehicles to begin transitioning to natural gas.[27, c] In recent years, refuse collection trucks have begun to predominantly use natural gas engines; about 60 percent of new refuse trucks on order today are powered by natural gas.[28,d] Both natural gas engines and propane engines are being introduced for medium-duty applications such as school buses, shuttles, and utility/vocational vehicles.[e] While natural gas engines are available on truck models from most heavy-duty truck manufacturers – including Freightliner, Kenworth, Peterbilt, Volvo, Mack, and International, the long-haul trucking market still represents one of the greatest opportunities for increasing the use of natural gas as a transportation fuel.

Using natural gas as a transportation fuel in the MDV/HDV sector offers several potential benefits. One is the cost savings from using a cheaper (than diesel) and often domestically produced fuel. Using natural gas in long-haul trucking applications, in particular, can reduce costs for shippers, carriers, and consumers.

Significant emissions reductions also can be achieved by switching from diesel engines to natural gas or propane engines. For example, two Cummins Westport natural gas engines are certified by the California Air Resources Board and the U.S. Environmental Protection Agency (EPA) to be “near-zero” emission vehicles, with NOx emissions 90 percent below the existing NOx standard.[f,29,30,31] Various U.S. cities are investing in these commercially available vehicles to address the needs of communities where emissions from HDVs threaten local air quality and health. For example, the Big Blue Bus transit agency serving Santa Monica and Los Angeles recently announced that it will invest $18.3 million to replace old buses with new buses equipped with Cummins Westport near-zero emissions engines fueled by renewable natural gas (RNG).[32] RNG engines also can substantially reduce greenhouse gas (GHG) emissions. Not only does the lower carbon content of RNG result in lower tailpipe emissions, but the creation of RNG from methane captured from dairies, landfills, and other sources also helps remove methane from the environment.

Despite these emissions benefits, natural gas and propane engines present challenges in market adoption:

- The engines for natural gas and propane operate with spark-ignition and throttling control and are roughly 15 percent less efficient than diesel compression ignition engines as described in the ICE discussion.[33, 34] This partly negates the lower pricing of natural gas and propane.
- Particularly for compressed natural gas, the high-pressure storage tanks typically add $40,000 to $50,000 to the cost of a Class 7-8 truck, dominated by the cost of the tank materials.[35, 36]

Engine manufacturers are working to improve the fuel efficiency of natural gas and propane engines, and truck manufacturers are working with operators to make efficiency improvements to the design and operation of vehicles. Strategies to improve the efficiency of vehicles using natural gas or propane engines include:

- Continuing to improve the spark-ignition engines for natural gas and propane through higher compression ratios, lean-burn, higher boosting/power density, and waste heat recovery. New materials technology may be required for the engine internal components and turbocharging systems,
- Optimizing engine controls/transmissions,

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[c] The model of this Cummins Westport engine was specifically 12L ISX-G 400 HP.

[d] An example of a natural gas engine used in refuse trucks is the Cummins Westport model 8.9L ISL-G.

[e] An example is the Cummins Westport model ISB 6.7G.

[f] The certified Cummins engines are models 8.9L L9N and 11.9L ISX12N.

- Reducing the cost of CNG tanks through improved designs and reducing the cost of the tank-reinforcing materials (mostly carbon fiber),
- Integrating fuel tanks into the body of the vehicle to improve aerodynamics,
- Hybridization of spark-ignited natural gas and propane engines,
- Adoption of advancements in the light-duty sector for regenerative braking and anti-idling using battery electric energy storage,
- Development of on-board hydraulic or pneumatic energy storage technologies for heavy-duty and freight applications, and
- Using dual-fuel engines, which simultaneously use natural gas with a reduced amount (e.g., as little as 10 percent) of diesel.[37] Dual-fuel engines benefit from the efficiency of the diesel compression cycle while consuming primarily natural gas.

In pursuit of these and other strategies to further the adoption of natural gas and propane MDV/HDVs, policymakers will need to take existing regulations into account, such as the prohibition of propane vehicles in some tunnels.[38]

Efforts to spur more widespread adoption of natural gas and propane in MDVs/HDVs also face a combination of technical and economic challenges. While the emissions benefits of natural gas and propane in heavy-duty and freight applications are becoming more widely recognized, scaling up adoption of these transportation fuels will likely require additional vehicle efficiency improvements as well as incentives to help overcome the higher initial cost of the vehicles and associated fueling infrastructure.

Hydrogen Fuel Cells

Hydrogen fuel cell electric vehicles (FCEVs) offer significant emissions reduction potential on a PTW basis. Communities with poor air quality can benefit from the use of FCEVs because they only emit water and air, and they do not emit any harmful pollutants. In addition, FCEVs are significantly more efficient – using up to 50 percent less fuel – than conventional ICE vehicles per mile traveled.[39] Nevertheless, creating hydrogen fuel can be expensive and energy intensive, as it requires separating hydrogen from water using electrolysis or separating hydrogen from methane using steam-methane reforming, which emits carbon pollutants. Electrolysis also can emit pollutants if powered by fossil fuels. However, if electrolysis is powered by electricity generated from renewable energy, FCEVs also have emissions reduction benefits on a well-to-wheel (WTW) basis.

While FCEVs have yet to be widely adopted in the MDV/HDV market, the range and fueling features of FCEVs may be well-suited for trucking. FCEVs often can travel further and refuel faster than PEVs. For example, Nikola recently launched an FCEV truck with a range of 1,200 miles.[40] In addition, Navistar's fuel cell tractor, with a driving range of 200 miles, can be refueled in less than nine minutes.[41] Yet there were only four medium- and heavy-duty FCEV models commercially available in 2016, and Energy Information Administration's (EIA) AEO data found that fewer than 1,000 hydrogen fuel cell MDV/HDVs were on the road as of February 2018.[42,43] In comparison, more than 6.7 million diesel MDV/HDVs were on the road as of February 2018.[44]

Challenges to the adoption of FCEVs include vehicle and infrastructure costs, availability of fueling stations, and the vehicle's heavy weight. While the operational cost of refueling a vehicle with hydrogen is comparable to refueling with a conventional fossil fuel, the costs of the vehicle and the installation of fueling infrastructure are higher for FCEVs than for ICE vehicles.[45] For example, while installing a CNG fueling station that can fill at least 30 buses per day can cost up to $1.8 million, installing a hydrogen fuel cell station that can fill about 25 buses per day would cost about $5 million.[46,47] In addition, up-front costs for FCEVs are compounded by the fact that there is not yet a critical mass of fueling stations; there are currently only 41 public hydrogen fuel cell stations in the U.S., 36 of which are public retail stations located in California.[48] Also, because hydrogen fuel is less energy-dense than gasoline on a volumetric basis, hydrogen must be densified and stored at very high pressures (10,000 psi in contrast to 3,600 psi for natural gas) to yield an acceptable amount of energy in a reasonable storage space.[49,50] As a result, hydrogen fuel tanks are larger and weigh up to about 1,300 lbs more than a diesel tank for a typical bus.[51] Nevertheless, some companies are moving toward FCEVs for freight operations. For example, Anheuser-Busch ordered 800 Nikola FCEV semi-trucks as of May 2018.[52] Furthermore, California has 21 FCEV buses in operation, with a goal to add 32 more buses to its fleet in the next few years.[53]

Diesel Hybrids, Plug-in Hybrids and Full Electric Technologies

Diesel hybrid vehicles, which include both an ICE and an electric motor, are becoming increasingly viable and offer opportunities for improved efficiency and emissions savings. Several DOE SuperTruck projects involve diesel hybrids. For example, Volvo developed its first diesel hybrid long-haul truck as part of a research activity in Sweden that operated in parallel with the SuperTruck initiative. The Volvo diesel hybrid truck achieves 5 to 10 percent in fuel savings while allowing the ICE to be turned off for up to 30 percent of transportation time, resulting in 30 percent emissions savings compared to a conventional diesel truck.[54] A 2017 report by the International Council on Clean Transportation (ICCT) found that while diesel hybrid HDV freight trucks have comparable costs to diesel-only HDV freight trucks, the diesel hybrid trucks typically reduce fuel consumption by 5 percent. In addition, ICCT predicts that as technology advances, diesel hybrids will consume over one-third less energy by 2030.[55] As the prices for batteries and electric motors continue to fall and fuel costs savings improve, diesel hybrid trucks may become increasingly appealing.[56]

Using battery electric vehicles (BEVs) or plug-in hybrid electric vehicles (PHEVs) for passenger transport, public transit, last-mile delivery, long-haul vehicles, and regional and vocational vehicles also has significant potential to reduce energy consumption. Given the potential added operational cost savings of these types of vehicles – including savings from low maintenance costs due to fewer moving parts – widespread adoption of medium-duty and heavy-duty plug-in and fully electric vehicle technologies could significantly reduce the total cost of MDV/HDV ownership.

Examples of recent deployments include the Motiv Power Systems BEV garbage trucks, which will be piloted in Los Angeles. These trucks could save 6,000 gallons of fuel annually and can operate for a whole day on a single charge.[57] The City of Palo Alto is also deploying BEV garbage trucks from BYD. The BYD garbage trucks have 76 miles of range on a single charge and are anticipated to save about $16,000 annually due to less maintenance and lower energy costs.[58]

Additional benefits of electrification include improved air quality and reduced noise pollution. Since ICEs require combustion and an exhaust system (unlike electric powertrains), ICE vehicles are inherently louder than PEVs (including both BEVs and PHEVs). In addition, hybrid vehicles – especially those with significant electric drive range – can switch to electric usage when in noise-sensitive areas and to conventional fuel usage in less noise-sensitive areas.

Passenger Transport and Public Transit

Buses represent a major transportation sector with significant opportunities for efficiency benefits through electrification. There are roughly 820 urban transit systems in the U.S. and nearly 1,400 additional smaller transit systems in rural areas.[59] Most of these systems offer predominantly bus-based services. Across the nation, buses account for roughly half of all transit trips, or more than five billion passenger trips per year.[60] About 60 percent of transit buses run on diesel or other fossil fuels, while 12 percent of transit buses are hybrid electric and just 0.2 percent are powered by electricity alone.[61]

Electrification is well-suited to achieve energy savings in urban bus fleets due to the fixed nature and multiple stops that characterize urban bus routes: fixed routes make the location of charging stations straightforward, and the constant starting and stopping along the bus routes enables the capture of otherwise-wasted energy through regenerative braking and battery electric energy storage. Some bus routes even offer opportunities to recharge during longer stops – for example, when picking up passengers at transit junctures and hubs – to extend the daily range of electric buses.

Though buses currently on order indicate a rising trend toward battery electric buses, significant opportunities remain for bus transit systems to further increase their share of electric vehicle fleets. While the initial purchase cost remains significantly higher for electric buses (up to $750,000) than diesel counterparts (about $450,000), the lifetime operating cost savings of roughly $400,000 make electric buses a cost-competitive alternative to diesel buses.[62] The transit industry also has the potential to become one of the quickest adopters of PEVs: the average bus has a lifetime of 12 years, making it possible for transit systems to transition their whole fleet over the course of a decade.[63] Furthermore, all major bus manufacturers in North America offer PEV buses in their suite of available models. Range anxiety is also being addressed by recent technological advances – for example, U.S.-based bus manufacturer Proterra drove an electric bus 1,100 miles on a single charge.[64]

Last-Mile Delivery

Electrification offers significant energy saving opportunities for the growing number of large retailers, such as Amazon, Target, and Walmart, that rely heavily on providing last-mile deliveries that are quick and cost expeditious. Last-mile delivery is the final route in the supply chain to a variety of end recipients including retail, wholesale and a customer's home; the demand for this service and the need for last-mile logistics management have grown exponentially due to the rapid expansion of e-commerce. Last-mile delivery involves fleets consisting of box trucks and service vans. These last-mile delivery vehicles often have high annual operating costs due to their high vehicle mileage and low mpg. As a result, package delivery fleets such as UPS and FedEx are looking to electrification to reduce operating costs.

Last-mile delivery vehicles also can be retrofitted to gain the energy savings and noise reduction benefits of plug-in hybrids. Furthermore, quieter last-mile delivery vehicles are beneficial in zones that include hospitals, schools, or residential neighborhoods. A last-mile delivery vehicle retrofit involves removing the ICE drive shaft and installing an electric drive motor, batteries, and a controller to achieve a fully operational hybrid with no change to the original operation and a significant increase in mpg. Workhorse Group estimates that energy costs to power PEVs for last-mile delivery vehicles are about 35 percent of energy costs to power diesel last-mile delivery vehicles.[65] Workhorse Group is partnering with UPS to deploy electric delivery trucks.[66] IDTechEx predicts that the last-mile global PEV market will grow to $792 billion by 2028.[67]

Long-Haul and Regional Distribution

Although there is potential for sizable energy savings through electrification in long-haul and regional distribution applications, adoption of plug-in hybrid technology for heavy-duty trucks has been relatively slow. Currently, about 80 percent of goods are transported by long-haul or regional distribution vehicles.[68] Yet the extra components, added complexity, and increased first costs of plug-in hybrids have slowed acceptance of these types of vehicles in long-haul trucking. To incentivize a transition to PEVs in this sector, it will be important to define and articulate the potential total cost of ownership reductions stemming from lower energy use and lower lifetime operational and maintenance costs. These factors, along with rapidly advancing technologies, should help put PEV long-haul trucks financially on par with diesel and alternative fuel powertrains in the near future.

Another challenge to market penetration of PEVs in long-haul and regional distribution applications are the in-route charging requirements. (The Enabling Infrastructure Sector Baseline discusses charging infrastructure in more detail.) Existing and planned highways, rest areas, and truck stops will require more sophisticated logistics planning to accommodate charging stations. Ideally, long-haul routes can be optimized to concentrate charging infrastructure strategically at common hubs.

TRENDS & EFFICIENCY OPPORTUNITIES IN TECHNOLOGIES EXTERNAL TO VEHICLES

TRENDS & EFFICIENCY OPPORTUNITIES IN TECHNOLOGIES EXTERNAL TO VEHICLES

There are opportunities to reduce energy consumption and emissions of MDVs/HDVs in stationary applications using technologies external to the vehicle, including stand-alone APUs, and trucking electrification solutions.

Stand-Alone APUs

Improved efficiency in stand-alone APUs, which help power non-engine functions such as refrigeration for trailers, can reduce energy use and emissions when MDVs/HDVs are stationary. Stand-alone APUs include battery PTOs and hybrid diesel-electric transport refrigeration units (eTRUs). Both battery PTOs and eTRUs are immediately deployable across the industry and present an opportunity for energy savings and reduced emissions, since they can rely at least partly on a battery – rather than entirely on the vehicle's diesel-powered engine – for power.

PTOs are typically associated with applications such as utility truck booms, tow trucks, dump trucks, and emergency equipment. Battery PTOs can use their battery to help power a piece of stationary equipment rather than rely entirely on the vehicle engine power like in a typical PTO.

eTRUs are designed to maintain temperatures for perishable products transported by a vehicle. An eTRU can be plugged in and powered by electricity while the truck is stationary. eTRUs present an attractive solution for municipalities looking to reduce emissions from refrigerated trailers at loading docks and other stationary locations close to urbanized populations.

Truck Stop Electrification

Reducing unnecessary truck idling can save fuel, improve profitability, extend engine life, and reduce emissions. Long-haul trucks typically idle between five and eight hours per day. According to the EPA, an average idling truck consumes 0.8 gallons of diesel fuel per hour, amounting to between 900 and 1,400 gallons of fuel wasted annually due to idling.[69,70]

Truck stop electrification (TSE) represents an enormous opportunity to reduce fuel waste while trucks are stationary. TSE infrastructure electrically powers functions such as climate control and auxiliary power without requiring idling of the vehicle engine. To take advantage of TSE, the powered equipment on a truck or trailer needs to be capable of switching to the use of an alternative electrical energy source. A functional TSE system thus involves both on-board equipment (such as power inverters and plugs) and off-board equipment (such as electrified parking spaces or systems that directly provide heating or cooling). TSE systems operate independently of the vehicle engine and allow the vehicle engine to be turned off as the off-board systems supply heating, cooling, and electrical power. TSE systems provide electrical power to operate the following:

- Independent heating, cooling, and electrical power systems,
- Truck-integrated heating and cooling systems, or
- Plug-in refrigeration systems that would otherwise be powered by an engine.

Advanced Truck Stop Electrification (ATSE) is a specific TSE technology that can achieve further emissions savings. ATSE systems address energy needs for the tractor only and not as an alternative power source for trailer refrigeration. ATSEs do not require tractors to be equipped with power inverters or to have the ability to plug in. Specially constructed parking bays with ATSE include external equipment that provides the cab with electrical power for heating and cooling, as well as for other amenities such as telecommunications and Internet connectivity, operated through an external console that fits into a truck's window frame. The console can contain temperature controls, air exchangers, a credit card reader, and plug-in outlets. While ATSE remains a viable alternative for fleets, it requires additional coordination for integration with parking areas. ATSE installations at truck stops ideally should not negatively impact the number of truck parking spaces.

BEST PRACTICES EQUIPMENT, LOGISTICS, & DRIVER BEHAVIOR

BEST PRACTICES: EQUIPMENT, LOGISTICS, & DRIVER BEHAVIOR

The energy used by heavy-duty and freight vehicles for goods delivery is not only a function of the vehicle and power train design; energy consumption is also heavily influenced by how fleet managers manage logistics, how they promote positive driver behavior, and which technologies they choose to deploy.

Fleet managers can enhance efficiency by deploying technologies and coordinating logistics appropriate for the services provided, types of goods transported, and types of routes used. Fleet managers can also take advantage of the many fuel-efficient technologies currently in the marketplace, including aerodynamic devices (such as side skirts or roof fairings), low rolling resistance tires, and idle reduction equipment. In addition, fleet managers can improve overall fleet efficiency by optimizing trailer loads, planning routing efficiently, and minimizing delivery windows. Tools for achieving these goals include routing software packages, employee performance standards, and company incentive programs.

This section highlights key logistical, driver behavior, and technology integration solutions that fleet managers can implement to reduce total vehicle energy consumption for goods transport.

Navigating Congestion with Effective Logistics Planning

Energy consumption can be reduced by efficiently managing delivery routes and maximizing the use of loading space in the vehicles. Delivery practices in urban versus non-urban areas have different characteristics that may require different solutions. In urban areas, for example, deliveries need to navigate congested streets and accommodate the high demand for a wide variety of goods, as well as the high density of people, vehicles and businesses served. Delivery to widely disparate locations requires the logistical capacity to meet varying needs while minimizing VMTs per delivery.

Traffic congestion increases vehicle energy use for urban deliveries since operating in stop-and-go modes requires significant energy use. Advanced vehicle designs can ameliorate energy losses – for example, by recovering thermal heat energy during braking through hybrid regeneration – but reducing or avoiding congestion remains critical for major energy savings. Congestion is a function of the total vehicle volumes that use specific routes, as well as the time of day, such as rush hour. Other events, like accidents or construction, restrict vehicle flow and significantly affect the frequency and degree of congestion. Congestion is generally increasing in many urban areas as more vehicles are used for passengers and deliveries.

Congestion can be reduced if vehicles avoid operating during rush hour commuting times or other times of heavy demand. Congestion is typically lightest at night or very early in the day. Studies of "off-hours" delivery have shown significant energy, pollution, and driver productivity benefits.[71] A 2017 McKinsey study quantified impacts of actual logistics trials using off-hour versus normal-hour delivery schemes.[72] The study found that the energy consumed by commercial vehicles dropped 65 percent during off-hours, mainly due to significantly lower congestion and more efficient routes. As the average vehicle speed vastly improved, the efficiency of the labor used for delivery improved 35 percent. This allowed the vehicle to potentially perform more deliveries during off-hours, thereby further reducing congestion. The overall commercial impact was an estimated reduction in total delivery costs (including costs for energy, labor, and vehicle capital) of 40 percent.

However, there are barriers to transporting goods during off-hours. It is difficult to attract drivers and other workers to off-hours jobs at loading and unloading terminals due to social preferences. In addition, it is challenging for vehicles and loading/unloading terminals to adhere to the noise requirements or preferences that are often stricter during off-hours. Companies and drivers also have security concerns with transporting valuable loads at night.

While autonomous vehicles (AVs) could help mitigate lack of labor availability for off-hour deliveries, much simpler technologies also are available to enhance delivery efficiencies at both loading and unloading terminals. For example, pre-loading vehicles during the daytime and staging loaded vehicles can offer efficiency benefits with minimum impact to operations. In addition, technologies are being tested to support the secure delivery of goods without delivery attendants for smaller deliveries. For example, camera systems, radio-frequency identification, global positioning systems (GPS), and other technologies can allow drivers to access secure zones, can verify goods delivery, and can monitor goods after the driver has left. For larger deliveries, such as to urban grocery stores, restocking during off hours may be a more appropriate approach to minimize the impact of deliveries on the store's overall functions.

Small Package Delivery

As noted above, the growth of small package delivery to homes, apartments, and small businesses is increasing. The volume of small package deliveries will continue to grow with the expansion of online retailers, especially those that make package delivery affordable and convenient, such as Amazon and Google Express. The efficiency of small package delivery is influenced by the frequency of delivery as well as the presence of a receiver for goods that require proof of delivery. Security of packages delivered and left on the doorstep is also a significant and growing concern.

An attractive solution to reduce security concerns, eliminate the need for the presence of a receiver, and reduce VMTs (thereby increasing delivery efficiency) is the use of parcel delivery lockers. Parcel delivery lockers are secured boxes that can be located in centralized and convenient locations and that use technology to drive delivery efficiency and offer package security to the recipient. Unlock codes are sent to a recipient through an Internet application (app) or email and provide information about how to retrieve the package from the locker. Studies have estimated up to 70 percent reduction in miles traveled per parcel in last-mile delivery using parcel delivery lockers.[73] These systems have been in use for over a decade and are offered by companies such as PackCity by NeoPost. Yamato Logistics, a last-mile delivery service in Japan, recently partnered with Neopost to deploy parcel delivery lockers.[74]

A key way to promote increased use of parcel delivery lockers is to reserve space in public areas. Parcel delivery lockers need to be placed in convenient and easily accessible areas to promote routine use, while still maintaining security by ensuring restricted access to the lockers. Parcel delivery lockers are especially effective if positioned in places with high customer touch points, such as mass transit terminals, apartment building lobbies, and neighborhood common areas. Savings in delivery costs generated from the effective use of parcel delivery lockers could potentially be used to fund infrastructure development for the lockers.

Centralized Logistics

Additional strategies to improve delivery efficiency and reduce VMTs include reducing the number of partially loaded trips and reducing the number of stops. Centralizing logistics management through the use of urban consolidation centers can be an effective solution. These centers work to consolidate loads from many individual deliveries to integrate last mile deliveries. For example, consolidation centers can implement load pooling, using information technology to better aggregate diverse loads and maximize the use of cargo space. Consolidation centers can vastly reduce the number of vehicles in operation in urban environments (see Figure 1), reduce congestion, and reduce vehicle energy consumed in last-mile deliveries.[75] Consolidation centers can save an estimated 45 percent in energy used for last-mile delivery per parcel.[76]

Consolidation centers often require municipal support for the development of infrastructure – including commercial vehicle lanes – and to secure an optimal location. Convenient access and strong support by municipal governments are keys to success. Regulations restricting the number and types of vehicles entering city centers, especially at certain times of day, can also incentivize delivery companies to pursue the development of consolidation centers. During off-hours, use of high-occupancy vehicle (HOV) lanes by commercial delivery vehicles can also improve efficiency with minimum impact on commuter time.

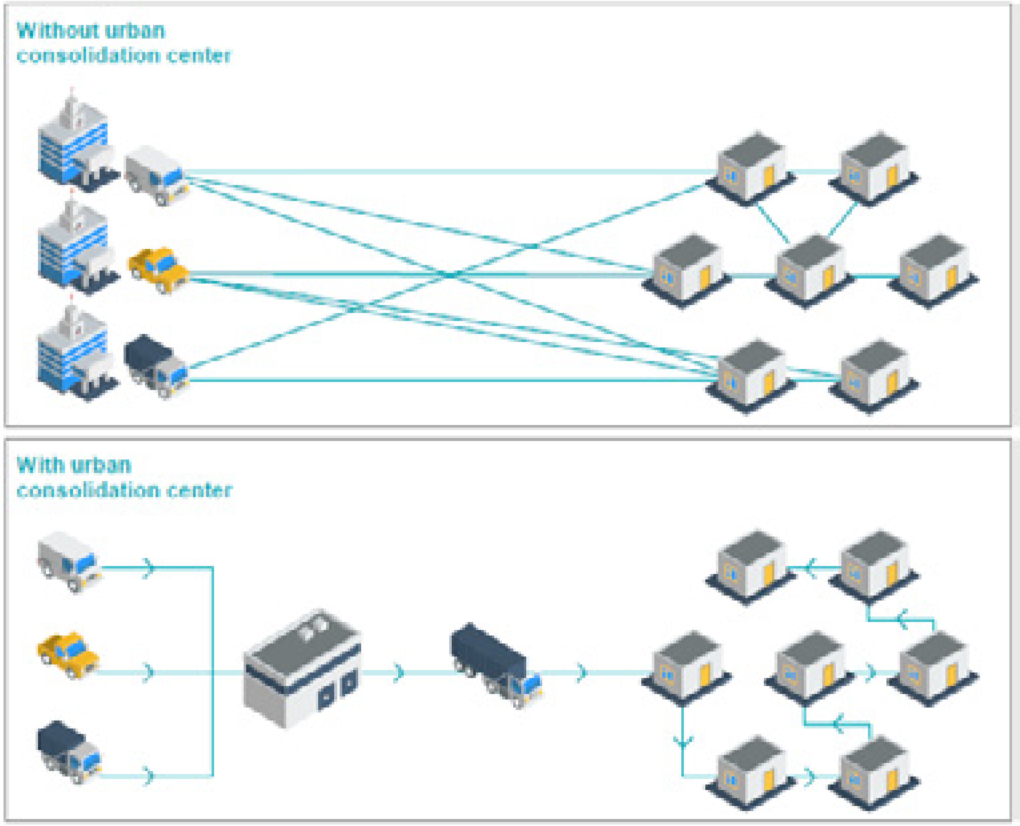

Figure 1. With and Without Urban Consolidation Centers

Exhibit from "An integrated perspective on the future of mobility, part 2: Transforming urban delivery", Sept 2017, McKinsey & Company, www.mckinsey.com. Copyright© 2018 McKinsey & Company. All rights reserved. Reprinted by permission.

Centralized logistics also are key for supporting the effective implementation of transmodal services. Transmodal shipments enable mode shifting – for example, shifting freight shipments from trucks to a less fuel-intensive transportation mode such as rail. Centralized logistics can save energy by effectively enabling mode shifting to maximize rail use while optimizing load consolidation in the last-mile deliveries for on-road vehicles.

Driver Behavior & Automation

Driving style has a significant effect on fuel use for commercial and transit vehicles, with differences of up to 20 percent between the best and worst vehicle in a given fleet.[77] Practices that can reduce fuel use include optimizing shifting to reduce high engine revolutions per minute (RPM), reducing driving speed, reducing aggressive accelerations, improving braking, and anticipating traffic conditions to minimize stops and near-stops, especially during congestion.

Even modest changes to driver behavior, applied consistently, could reduce fleet fuel use by up to 10 percent.[78] An Elsevier study estimated that annual savings of 33 million metric tons of carbon dioxide and cost savings of $7.5 to $15 billion are possible if only a third of U.S. drivers adopt eco-driving techniques.[79] While driver training and monitoring can help improve the skills of individual drivers, such approaches are often labor intensive and require constant vigilance to maintain the benefits across a vehicle fleet.

Another approach to improve driver behavior is to implement various driver-assist technologies to enable the vehicle to continually enforce fuel-efficient driving behaviors. The simplest driver-assist technologies monitor various vehicle conditions, such as speed and engine RPM. When the driver deviates from best practices for vehicle operation, the driver-assist technology communicates with the driver by providing visual or audio feedback or signaling specific suggested actions, such as shifting gears. More sophisticated driver-assist systems, such as adaptive cruise control, use various sensors to detect conditions surrounding the vehicle, and automatically adjust vehicle speed without driver intervention. Daimler's Cascadia Freightliner trucks have already incorporated adaptive cruise control.[80]

Many driver-assist technologies are more directly targeted toward reducing accidents than reducing fuel use, although the fuel reduction benefits of improved safety are significant. The Federal Motor Carrier Safety Administration estimated that over 80 percent of crashes involving combination trucks result primarily from driver errors or fatigue.[81] Technologies targeted at reducing accidents include lane departure warning systems, lane-keeping assist systems, and automated or emergency braking systems. These automation technologies have the potential to significantly reduce truck crashes, which will indirectly reduce transportation fuel use by reducing one of the major causes of congestion delays. A 2014 Texas A&M Transportation Institute study estimated that commercial trucks experience 17 percent of the total cost of congestion delays, despite accounting for only 7 percent of VMTs.[82,g] In addition, the American Transportation Research Institute estimates that the trucking industry experienced 996 million hours of delays on the national highway system due to congestion in 2015.[83] These delays added an average of $0.23/mile to the cost of operating a commercial truck, amounting to more than $22,000 additional cost annually for a long-haul truck that travels 100,000 miles per year and resulting in almost 1 billion gallons of additional fuel use.[84,h]

Truck platooning can potentially further reduce fuel use by improving the aerodynamics of an entire group of vehicles. Truck platooning involves groups of combination trucks traveling together with reduced spacing between each truck. Truck platooning is implemented through a combination of adaptive cruise control, automated emergency braking, and vehicle-to-vehicle communication.[i] Several industry- and government-led demonstrations of truck platooning have been carried out, but safety concerns still remain.[85]

While fully autonomous vehicles could reduce fuel consumption by driving more efficiently and operating during off-peak hours, full automation is not yet technically mature or commercially available for trucks. Various driver-assist technologies currently available form the major building blocks for fully automated vehicles. Both truck manufacturers and technology companies (including Tesla, Uber, Google, Delphi, and Freightliner) are developing prototypes for fully-automated freight trucks.[86] The widespread use of fully automated MDVs/HDVs could reduce overall fuel use in this sector, however, a potential unintended consequence of this trend could lead to the opposite result: if the use of AVs lowered costs enough to spur an increase in VMTs, then congestion and therefore fuel consumption could increase.

Education

Training and educational programs for drivers, dispatchers, and company employees provide significant potential for fuel efficiency improvements in fleets. While it is often difficult to quantify the overall fuel savings from a better-educated driver workforce nationwide, opportunities exist to significantly reduce fuel consumption. Training courses both at driver schools and at individual companies, along with behavioral monitoring, incentive programs, and refresher courses, have the potential to reap financial savings for fleets. Training modules on topics including the impacts of braking, acceleration, idling, speed, coasting, and shifting can positively influence driver behaviors and yield substantial dividends for companies.

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[g] Delay costs include both labor and fuel costs.

[h] Conservatively assuming 1 gallon/hour idle fuel use.

[i] Platooning requires technology enhancements beyond current adaptive cruise control systems, including advanced GPS, cameras, and wireless communication between trucks.

POLICY CONSIDERATIONS

POLICY CONSIDERATIONS

Policies and regulations can help drive investments in improved fuel economy. In August 2016, the EPA and the U.S. Department of Transportation (DOT) released their Regulatory Impact Analysis for Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles – Phase 2.[87] The Analysis found that the technologies that saved the most fuel involved improved aerodynamics, tire rolling resistance, and idle reduction. The MDV/HDV industry is expected to heavily invest in fuel efficient tires and aerodynamic devices for both vehicles and trailers to achieve the 2027 Phase 2 milestones. Upon full implementation, 2027 tractors will be up to 25 percent more fuel efficient, and trailers additionally will be up to 9 percent more fuel efficient than equipment manufactured in 2017.[88]

While fleets are already heavily investing in many fuel-efficient technologies – many with short payback periods – the market penetration rates of fuel-efficient technologies are widely varied. Many different factors affect fleet acceptance of new technology, including technical maturity, cost, fuel prices, payback periods, maintenance, and the availability of financial incentives. Federal incentives would likely accelerate the use of many fuel-efficient technologies and strategies. Issues that should be considered when developing MDV/HDV regulations include:

- The relaxation of federal excise taxes and equipment weight exemptions can expedite market uptake of fuel saving technologies. The elimination of any federal excise tax payments can be offset by other funding sources to avoid any negative impacts on the nation's Highway Trust Fund.
- National harmonization is a key principle to addressing any future fuel efficiency standard-setting measures. Given that vehicles are mobile by nature and routes are not confined by geographical borders, it is critical that the MDV/HDV industry is not impeded by a patchwork of regulations that vary among states. For example, EPA's and DOT's Phase 2 Rule coordinated with states to ensure the harmonization of fuel efficiency standards across the nation.
- Government educational grants can be critical enablers to support training modules that help advance fuel efficiency practices at driver vocational schools.

For natural gas and propane MDVs/HDVs, there is a significant need for policy support, product development investments, and incentives to allow these alternative fuels to reach their full potential in contributing to overall energy reductions in the freight sector. Supportive policy programs could help:

- Assist equipment manufacturers to overcome the risk of investments in developing more efficient products,
- Reduce the overall cost of development and ownership of alternative fueling stations,
- Train operators, service and maintenance personnel, code officials, and first responders to operate alternative fuel vehicles, and
- Invest in research and development to improve natural gas and propane engine efficiency so that the domestic security and environmental benefits of these alternatives to diesel can be simultaneously realized while reducing energy use.

For hybrid or all-electric technologies in the MDV/HDV sector, incentives to convert existing fleets to hybrid or all-electric vehicles based on equivalent mpg can help support the adoption of hybrid and electric technologies. In addition, regulatory relaxations of vehicle weight and size restrictions can enable hybrid or electric applications that carry a weight or size penalty. Nevertheless, it is critical to consider the safety impacts of any weight exemptions – including the potential to increase the intensity of accidents – with heavier vehicles as well as the potential to exacerbate road degradation.

Incentives can also be applied to eTRUs and TSE. Since eTRUs are more expensive than traditional diesel-powered TRUs and require charging infrastructure, government financial incentives would expedite their introduction and help drive deeper market penetration. eTRUs would be further incentivized if the purchase of eTRUs afforded credit under current GHG and fuel efficiency regulations for trucks and trailers. State efforts to reduce truck idling and improve air quality have increasingly focused on the use of TSE as well. Advancing government incentives for the installation of TSE could support the expansion of such networks.

Logistics practices, especially off-hours delivery, can be influenced by both incentives and restrictions. Incentives may include reduced taxes or license fees for vehicles that are restricted to certain hours of usage in certain zones. Special vehicle lanes, such as HOV lanes used for passenger vehicles, can be made available to commercial vehicle traffic during off hours. Direct restrictions on commercial traffic flow also can be adopted, but without efforts to make off-hours delivery more workable, such restrictions could have negative commercial impacts.

While there is potential for major cost savings through adoption of autonomous freight trucks, especially in the long-haul sector, aggressive adoption will require significant regulatory support at both the state and federal levels. However, it may be premature to adopt long-term regulations, since the technology is still experimental. In the near-term, federal and state governments can support pilot programs and limited deployments to allow the technology to mature. Lessons learned from early deployments will be critical to guiding the long-term regulatory structure that can enable the benefits of AVs.

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