Megaregion (MR) Freight Mobility: Impact of Truck Technologies

Robert Harrison, Ronald Matthews, Colton Voorhis, and Sean Mason

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16. Abstract

The report extends the U.S. Department of Energy SuperTruck Program findings and provides estimated Class 8 tractor and trailer impacts for model years 2018, 2021, and 2025 as they relate to fuel consumption, safety, and exhaust emissions. The inadequacy of current U.S Federal and State fuel taxes to meet future metropolitan, regional, and national highway system maintenance, expansion, and reconstruction is noted.

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Table of Contents

List of Figures

List of Tables

List of Acronyms and Abbreviations

BSFC	brake-specific fuel consumption
BTE	brake thermal efficiency
CO2	carbon dioxide
CGVW	combined gross vehicle weight
CBEV	commercial battery electric vehicle
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
DOE	Department of Energy
DOT	Department of Transportation
EPA	Environmental Protection Agency
EGR	exhaust gas recirculation
ELD	electronic logging devices
EU	European Union
GHG	greenhouse gases
HCCI	Homogenous Charge Compression Ignition
HEDGE	High Efficiency Dilute Gasoline Engine
HEGT	High Efficiency Gear Train
HDV	heavy duty vehicles
HVAC	heating ventilation air conditioning
ICC	Interstate Commerce Commission
LSFC	load-specific fuel consumption
LIDAR	Light Detection and Ranging
LTC	low temperature combustion
LTL	less than truckload
MPG	miles per gallon
MPO	metropolitan planning organization
MY	model year
NACFE	North American Council for Freight Efficiency
NHTSA	National Highway Transportation Safety Administration
NOx	nitrogen oxide
OEM	original equipment manufacturer
ORC	Organic Rankine Cycle
PCP	peak cylinder pressures
PCCI	Premixed Charge Compression Ignition
PEV	plug-in electric vehicle
QLHV	lower heating value (kJ/kg)
RCCI	Reactivity Controlled Compression Ignition
ROI	return on investment
RR	rolling resistance
SCR	selective catalytic reduction
VMT	vehicle miles of travel
VVI	variable valve ignition
VGT	variable geometry turbocharger
VGM	Volt Motor Generator Unit
WHR	waste heat recovery

Executive Summary

1. In 2010, the U.S. Department of Energy (DOE) jointly funded a multi-year research project with 15 Class 8 truck industry partners, including 6 original equipment manufacturers (OEMs), to raise 2009 model year (MY) truck freight efficiency by 50%—equivalent to 10 miles per gallon (mpg). Savings in U.S. annual oil consumption and carbon dioxide emissions in the U.S. heavy truck sector would be substantial.
2. OEM teams commercialized 21 technologies by MY 2017, with an additional 26 likely to be commercialized by MY 2020 and 13 more by MY 2025—the period examined in this project. Mechanical engineering researchers at the University of Texas at Austin aggregated these technologies to estimate fuel consumption for MY 2018, MY 2021, and MY 2025. Several DOE prototype trucks exceeded 10 mpg using technologies that are now being phased into MY specifications.
3. Class 8 truck tare weight is also being reduced—using composites, lighter steel and/or aluminum—thereby raising payloads for vehicles operating at their weight limits or directly improving fuel efficiency for those that are not. Various tractor-trailer aerodynamic improvements provide positive contributions to reducing engine power needs on long-distance truckload operations.
4. Urban delivery trucks were not part of the DOE SuperTruck program, but a wide variety of smaller alternative fuel, hybrid, and pure electric trucks are currently under test in U.S. cities. EU and Chinese truck manufacturers are stimulating U.S. OEMs to develop and offer shorter-range hybrid and electric urban delivery trucks.
5. Federal Diesel fuel taxes and Texas Fund 006 Diesel contributions were set in 1992 when Class 8 average consumption was 4.5 mpg. MY 2018 trucks can achieve over 7 mpg, with further technologies planned in the near future. Fuel consumption taxation, while assessed at a small administrative cost, increasingly fails to fully cover both federal and state highway and bridge repair and maintenance costs as less fuel per ton-mile is consumed.
6. Policy solutions include immediately raising Diesel taxes at the “rack” (point of production) while pursuing longer-term solutions that reflect miles traveled, axle loads, and time of travel. Autonomous and connected vehicle research suggests that these data could be collected and used for accurate highway pricing.

Chapter 1. Project Background

U.S. transportation demand is driven by population growth and economic activities, which both changed significantly after World War II. Transportation modes, which were highly regulated at that time, had to accommodate new industries, serve new metropolitan size and densities, and incorporate new transportation technologies to meet safety and environmental legislation. The biggest legislative change came in the 1972–82 decade when deregulation of all major surface modes—trucking[1], air[2], and rail[3]—was authorized and ultimately altered modal market shares.

A critical supporting role was a federal modal one—the creation of the Interstate Highway System, signed in 1956[4], planned and started in the next decade, and largely completed during the 1970–80 period, resulting in a system that transformed trucking, metropolitan planning, and personal mobility. State highway departments ultimately became state departments of transportation (DOTs) funded by a mixture of state and federal funds, together with public-private partnerships, which in the case of highways included toll bridges and roads. This change came in 1991 with the passage of the Intermodal Surface Transportation Efficiency Act (ISTEA), which President George H.W. Bush described as "*an investment in Americas future, for an efficient transportation system is also necessary for a productive and efficient economy*."[5]

The growth of metropolitan areas was recognized by including metropolitan planning organizations (MPOs) in the state highway planning process. MPO revenues came principally from a mixture of local funds, together with state and federal pass-through monies, and public-private partnerships where demand supports a toll system. It was the growth of MPOs and the socio-economic clusters characterizing rapidly growing regions that attracted the attention of regional planners a decade later.

[1] Motor Carrier Act, 1980. See: https://en.wikipedia.org/wiki/Motor_Carrier_Act_of_1980
[2] Airline Deregulation Act, 1978. See: https://en.wikipedia.org/wiki/Airline_Deregulation_Act
[3] Staggers Act, 1980. See: https://www.fra.dot.gov/eLib/Details/L03012
[4] Appendix A.1 provides more information on this subject.
[5] https://www.fhwa.dot.gov/publications/publicroads/01novdec/istea.cfm

U.S. demographic data show that activities within population clusters can be considered by planners as systems where the removal of inefficiencies in one metropolitan area benefit other linked MPOs. Examples include power grids, railroads, water controls, and the subject of this report—highway transportation. The term *megaregion* is used to describe a population and economic cluster in this report. Alternative terms can be used to describe the growing concentration of population and economic activities in U.S. counties within and between state boundaries. This chapter will identify some of the key characteristics of transportation modes in the U.S., which have developed to serve key markets across the U.S., the North American continent, and the world.

Products grown, manufactured, or consumed flow across transportation systems that are multimodal, statewide, multistate, or global—reflecting a choice in logistic chains. Refined fossil fuels, however, dominate freight modal power units—gasoline (autos and SUVs), Diesel (trucks and locomotives), ships (heavy oil and Diesel fuel), and jet fuel (aircraft). Figure 1.1 shows percentages of U.S. fuel volumes consumed in 2017. Automobile use is reflected in gasoline and biofuels, freight is reflected by Diesel fuel, and air passenger and freight demand is captured by jet fuel[6].

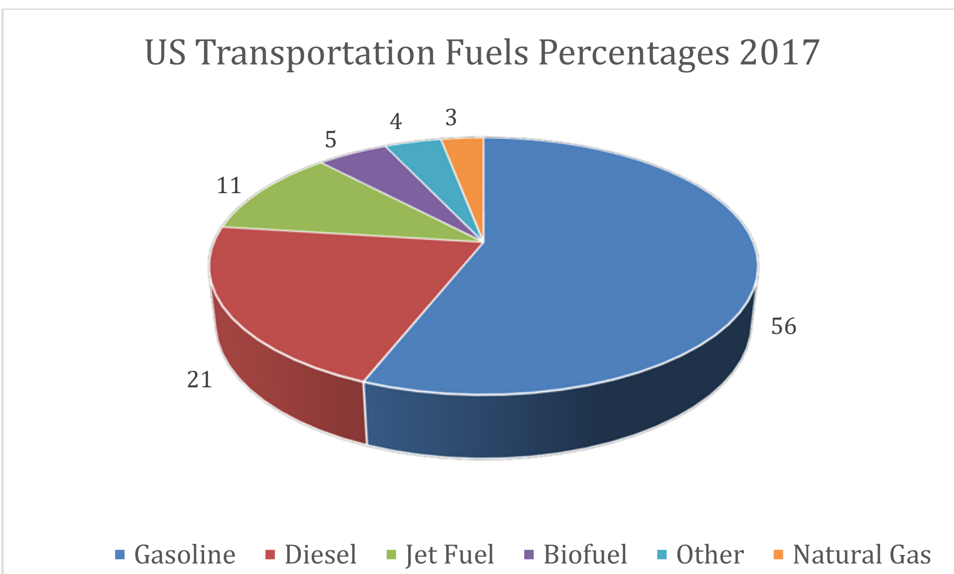

Figure 1.1: U.S. Transportation Fuels Percentages 2017

[6] Jet fuel is either unleaded kerosene (A-1) or naphtha-kerosene (B) after passing specific tests.

Therefore, gasoline, biofuel, and Diesel fuel taxation and registration fees became a cornerstone of U.S. fiscal policy after 1982 since they related, although in an imprecise manner, annual vehicle miles of travel (VMT), infrastructure consumption, and rent[7]. It was also a very efficient tax, more especially when the taxation point was the point of production rather than distribution[8]. U.S. interstate systems were funded by this system even though a number of state and federal cost allocation studies reported that trucks did not pay their full share and were subsidized by other vehicle types. This continues to be a sensitive and unresolved policy issue. State highway planning is challenging and dynamic. Solving key issues, particularly congestion and safety, requires a continuous revenue stream that invests in high maintenance and safety levels combined with dynamic information and control systems to maintain acceptable levels of service across the highway networks. The challenge is that although the fuel system can be considered a fee-based system, it is unfortunately called a tax, which immediately makes it difficult to change in the current U.S. political process. What is possible, but difficult, at the state level[9] has been impossible since 1992 at the federal level. Building and maintaining infrastructure with 2018 costs using taxes fixed at 1992 prices is proving increasingly difficult.

The latest U.S. demographic patterns confirm the migration data between states, rural areas, and industrial hubs within states first noted in 2004[10] and led to the forecast that, by 2050, over two-thirds of the U.S. population would live in 70 counties. The grouping of these metropolitan areas into megaregions does not fit easily into conventional state DOT transportation planning, which generally relies on metropolitan planners to offer projects that may have critical system impacts at the state system level. Ideally, conventional highway planning should consider a two-tier evaluation of highway transportation projects separated into local and inter-metropolitan corridor formats.

[7] Rent is largely ignored in cost allocation studies, although trucks clearly require space for both vehicle length and headways when following other vehicles in the same lane. This is particularly true for large dump trucks, which sometimes carry an illegal warning to stay back 200 ft because “the driver is not responsible for damaged windscreens.”
[8] In Texas, an additional $200 million was raised the year after the point of scale change.
[9] States charge a variety of fuel taxes, In 2018 Texas at 20¢ per gallon retains in the original 1992 level while Pennsylvania charges 58.2¢ per gallon.
[10] Regional Planning Association: http://www.america2050.org/content/megaregions.html

The Texas Department of Transportation (TxDOT) already recognizes the importance of key corridors within the state in its freight planning and has commissioned work[11] that confirms earlier research[12] that freight corridors—for example, those linking NAFTA origins and destinations—are multistate and national in scope and benefit. Class 1 railroad companies have adopted a multistate approach, understanding that a single problem on their key systems impacts overall system efficiency and cost[13]. Highway system elements—corridors, bypasses, urban systems—may be used predominantly by private operators and the general public but freight also plays a role in metropolitan demand as it arrives, traverses, or is created in the metropolitan area. A wide variety of vehicles consequently share these highways[14], which are funded principally through failing cost allocation derived registration fees and fuel taxes.

The technical elements of transportation operations, especially highway users, initially changed at a modest rate compared with the organizational changes that followed deregulation of rail and air transportation. Truck company operations developed distinct logistical systems split first by those dealing with smaller consignments—less than truckload (LTL)—and then larger consignments—truckload (TL). Transportation modes are characterized by costs of entry and reflect modest returns that vary based on capital, fuel[15], and labor costs. These systems adopted the latest technologies to track, monitor, and deliver freight, supported by the internet systems now used by an increasing volume of consumers. Technology has created national and multinational systems linking producers, assembly plants, distribution centers, and urban delivery systems. This has altered, but not yet eclipsed, the modes themselves—ships, airplanes, trains, trucks, and pipelines[16].

This project examines the impact of significantly more efficient (in terms of fuel and payload) and cleaner (in terms of exhaust gases and safety) U.S. Class 8 trucks as they adopt a wide range of new technologies. Funding the U.S. highway system—at both federal and state levels—through

[11] Texas Freight Mobility Plan, TPP, TxDOT 2017. http://ftp.dot.state.tx.us/pub/txdot/move-texas-freight/studies/freight-mobility/2017/plan.pdf

[12] John McCray at the University of Texas at San Antonio coined the term “rivers of trade” to describe U.S. NAFTA trade flows in 1992.

[13] BNSF, for example, operates and funds its system on a multistate corridor basis.

[14] There are also auto-only tolled lanes in metropolitan routes, such as on Austin’s MoPac expressway.

[15] While fuel taxes are fixed, pump prices vary considerably and may be reflected in trucking contracts in the form of “tippers,” which generate additional revenue to the trucker when fuel cost rises above a certain value.

[16] Amazon might be the first retail company to link the chain from customers to final home distribution since Sears in the 1880s.

current registration and fuel taxes does not reflect either the economic or social benefits of truck operations. Technologies are now being tested and implemented that make new trucks (model year [MY] 2018) more efficient, more productive, and cleaner in terms of exhaust emissions. These costs and benefits should be internalized into investment revenues so Federal and State agencies can provide the enhanced interstate and metropolitan systems needed later this century. The project organization is now described.

Chapter 2. Background, Scope, Method, and Organization

Megaregion demand will raise freight mileage over the next thirty years. Modal engines moving freight are dominated by Diesel engines, which impacts truck design. While this may decline with the introduction of new fuels, the Diesel is likely to remain the engine of choice for freight modal movement in the next three decades. It is now accepted that untreated Diesel exhaust is unhealthy and some EU cities like London and Paris are considering banning all Diesel vehicles. However, legislation from U.S. Environmental Protection Agency (EPA) rules in 2002, 2007, and 2010—combined with the removal of most sulfur during Diesel fuel refining—have significantly reduced the levels of pollution on a truck ton-mile basis. However, further reductions are required to meet the higher levels of future truck VMT predicted on megaregion highway systems. Electric power is now being offered as a solution to urban settings, where daily VMT is less than the truck battery storage.

This project addresses intercity trucking and metropolitan delivery systems. Trucking companies are already focusing on a wide variety of methods to raise miles per gallon (mpg) and these will be identified. By MY 2021, original equipment manufacturers (OEMs) are expected to offer some autonomous features—probably focused on safety—while 2025 trucks may reflect higher levels of such features as permitted by state and federal agencies.

Class 8 truck engineering components that are likely to be offered as original equipment to truckers over the MY period 2018–2025 include:

1. Impacts of the 2010 Department of Energy (DOE) SuperTruck and SuperTruck II Fuel Efficiency Programs.
2. This report's findings for Class 8 highway and urban delivery vehicles.
3. Class 8 specifications for MY 2018, MY 2020, and MY 2025.

This work evaluates both the operator and societal costs and benefits from a range of truck design and equipment specifications. A case study of a current Texas truck logistical system is used to identify potential changes in freight patterns in the light of higher VMT levels predicted over the

2018–2025 period. The failure of current revenue models for equitable highway use will be summarized.

The current U.S. freight system is the product of three major historical events—interstate highways, energy crises, and deregulation—and has resulted in the current freight system where trucking carries around 70% of the ton-miles. Diesel emissions have been the subject of increasingly stringent Federal standards[17] since 2002, culminating in the 2010 new truck emission standards (particularly nitrogen oxides [NOx] and particulate emissions) that significantly reduce the U.S. Class 8 fleet societal costs as older engines (and trucks) are scrapped.

This project shows that new trucks after 2018 will reduce external costs in three ways:

a. Technologies and designs are being continuously adopted to raise truck mpg.
b. Truck safety technologies—automatic braking, lane departure signals, and blind spot alerts—offered as new truck options will lower accident rates and fatalities.
c. Urban delivery trucks will test and adopt alternative fuels, particularly electricity.

Trucks play a critical role in freight systems and will be needed to enable larger metropolitan economies to function in future decades. One way to lower trucks emissions is to pay careful attention to specifying the engine to match operations so that it meets performance standards for the required power output. U.S. Class 8 truck engine displacements have fallen from 15 liters in 1990, to 13 liters in 2010 and even 11 liters in recent years, with more emphasis placed on fine-tuning turbocharger performance through sophisticated electronic controls to get flat, high torque curves matched to semi-automatic gearboxes. Power is lost as trucks move in a variety of ways. One EU example reports that the engine of the largest EU truck—a 60-metric-ton truck-trailer combination—running on level, free-flowing highways at 50 mph produces:

- 41% to overcome rolling resistance,
- 38% for aerodynamic drag,
- 9% for auxiliaries,

[17] See : https://www.epa.gov/emission-standards-reference-guide/epa-emission-standards-heavy-duty-highway-engines-and-vehicles

- 7% for the driveline and tire losses, and
- 6% for uphill/downhill hysteresis[18].

These relationships obviously vary with load, grade, and speed, but it clearly shows the key areas of interest when designing a truck to return good fuel consumption figures. Class 8 truck operators in the U.S. are limited to 40 tons (80,000 lb.) gross vehicle weight on Interstate highways (without size and weight permits) and pay careful attention to average speed.

A large Texas company[19] serving retail outlets using a hub-and-spoke route system in the Dallas–San Antonio–Houston Triangle decided not to invest heavily in aerodynamic devices because their average route speed was less than 50 mph, unlike truckers on longer routes where 70 mph (or higher) is permitted. However, they successfully pursued several initiatives—see Box 2.1—that have improved productivity[20], safety, and fuel consumption[21]. The company has a high safety record and one-third of their 800 drivers have exceeded a million miles of accident-free driving—around 10 years of driving at current annual operations. All areas—new vehicle specifications, training, rewards, acknowledgements, and the use of technologies like front radar braking and vehicle position awareness—are carefully integrated to support driver decisions over free-flow and highly congested routes.

Box 2.1: Grocery Deliveries in the Texas Triangle

Fuel consumption was lowered through five operational decisions:

1. Limit speed to 65 mph
2. Lower gearbox weight, removing overdrive
3. Fit smaller fuel tanks
4. Use extra-wide drive and trailer tires—lowering unladen weight
5. Pilot-test liftable axles when unladen

Source: CTR Annual Symposium 2015

[18] Nils-Olof Nylund (2013). "Vehicle energy efficiencies" (PDF). VTT Technical Research Centre of Finland. It should be noted that the EU permits higher vehicle weights and lower speed limits than the U.S.
[19] The company employs 800 drivers and has 600 tractors and over 2000 semi-trailers.
[20] Reductions of both tractor and trailer tare weights have increased payloads.
[21] The 2018 tractors are returning a fleet average of 7.5 mpg in the U.S.

In 2017 the U.S. Government[22] withdrew from the 2015 United Nations Paris Climate Accord[23]. The Accord uses a wide variety of data collected over many decades but coming into sharp policy focus after 2000. U.S. greenhouse gas (GHG) data by economic sector in 2015 are given in Box 2.2, as reported on the EPA website[24]. Autos, trucks, commercial aircraft, railroad locomotives, and marine vessels dominate the sector. Passenger autos and light-duty trucks account for 60% within the sector, while medium- and heavy-duty trucks are the second largest at 23%, both rising strongly since 1990 with increased annual VMT by these trucks.

Box 2.2: Total U.S. GHG Emissions by Economic Sector 2016

- Electricity 28%
- Transportation 28%
- Industry 22%
- Commercial/Residential 12%
- Agriculture 10%

Source: Citation #24

Two general observations can be made about Box 2.2. First, since 2000 a variety of decisions made at personal, city, state, and federal levels have lowered per capita GHG emissions, some significantly. Second, the size of the segments is already changing, for example in electricity generation. The conversion of coal to natural gas-fired electricity generation[25], energy conservation in buildings of all types,[26] and solar generation[27] have significantly reduced fossil fuel generation levels in the U.S. since 2010. In terms of automobiles and heavy trucks, there is clear evidence that 2018 vehicles are significantly more fuel-efficient than recent models. Vehicle ownership cascades through obsolescence and it can safely be assumed that by 2025—the limit of this project—at least 50% of the U.S. auto fleet and 45% of the U.S. Class 8 truck tractor fleet will be MY 2018 or younger.

[22] https://www.nytimes.com/2017/06/01/climate/trump-paris-climate-agreement.html
[23] http://unfccc.int/paris_agreement/items/9485.php
[24] epa.gov "Greenhouse Gas Emissions: Inventory of U.S. Greenhouse Gas Emissions and Sinks." Accessed July 2018
[25] http://www.eesi.org/articles/view/renewables-now-represent-20-of-u.s.-generating-capacity-up-from-15-in-2012
[26] https://www4.eere.energy.gov/femp/requirements/laws_and_requirements/fossil_fuel_reduction
[27] https://energy.gov/eere/solarpoweringamerica/solar-energy-united-states

Chapter 3. Class 8 Trucks: U.S. Operations and Fleet Size

The size of the U.S. heavy-duty truck fleet—Class 8—started to recover from the Great Recession in 2012 and its size in 2013, estimated by R.L. Polk[28], grew to 3.59 million vehicles. Class 8 vehicles are broadly grouped into truckload (TL) and less than truckload (LTL). LTL include mail and parcel carriers like FedEx and UPS. These trucks are the workhorses of the U.S. trucking fleet, moving a wide range of commodities and products directly on U.S. highways or as part of multimodal freight systems. Trucks account for around 70% of the U.S. ton-miles moved by transportation modes and Class 8 vehicles dominate long-distance highway truck freight flows[29]. In 2018, this report estimates that Class 8 fleet size is 3.7 million vehicles, based on Class 8 sales data since 2013 and the retirement of older trucks registered before 2000.

These trucks undertake different operations as they age through their life cycle. These are defined by the expected annual mileage and reliability of service based on a targeted one million miles of service. Inevitably many move from first ownership to the secondhand market at some time in their life. Actual mileage to final scrapping is reached when maintenance costs rise—typically with the failure of a major component—above the market value of the vehicle[30]. Registration fees are not based on vehicle age or mileage, although operational costs rise as mileage increases and fleet managers with older trucks recording higher fuel consumption when compared to newer trucks chose to sell these trucks. Age when a truck goes to the secondhand market ranges from 4 to 7 years for TL premium, single-driver vehicles. Table 3.1 shows the truck categories and annual mileage ranges used in this report.

Table 3.1: Truck Class 8 Categories and Annual Mileage

Truck categories	**Annual mileage ranges used in this report**
TL/LTL Premium 2	Team driven (2 drivers)—over 130,000 miles per year
TL/LTL Premium 1	Single driver—80,000 to 130,000 miles per year
TL/LTL Regional	Single driver—50,000 to 120,000 miles per year
TL Dray	Single driver—25,000 to 50,000 miles per year
TL Specialist	Single to team—15,000 to 100,000 miles per year

[28] Transportation Topics" U.S. Class 8 Fleet Up 2.7%" August 26, 2013
[29] See: https://www.bts.gov/sites/bts.dot.gov/files/docs/FFF_2017_Full_June2018revision.pdf
[30] Chesher, A.D, Harrison, R. "Vehicle Operating Costs in Developing Countries," World Bank, Johns Hopkins Press, 1986

Truck owners put their newest equipment on the longest routes requiring the highest level of service. These inevitably produce the lowest operating costs per mile and highest levels of service reliability, which includes just-in-time and guaranteed services[31]. Team drivers are a relatively small segment that, when combined with high annual mileage single-driver units, move some vehicles to second ownership within a shorter time period—around 3 to 4 years.

These can be attractive units for regional operators with lower annual mileage services. Dayton, Ohio based Jet Express[32] includes these vehicles in its fleet and its President, Kevin Burch, states "some carriers flip new trucks at 250,000 miles[33] and we buy them because they have some warranty coverage and are good deals." Regional TL carries a wide range of commodities within a distinct area such as a megaregion, where many drivers can return to base after making deliveries because they are within their scheduled hours of operation. Multimodal truck operations include working from a marine or river port, airport or railroad hub—termed "dray trucks"—also convey trailers along the U.S-Mexico border, linking premium service carriers in both countries. Dray trucks have been the subject of a number of reports[34] because they traditionally have been the oldest trucks in the U.S. fleet. They are purchased because dray truck annual utilization is typically less than 45,000 miles and repairs can be fixed locally. Box 3.1 provides some information about Texas dray operations.

Box 3.1: Dray Trucks in Texas
Dray trucks operate at rail hubs like Alliance Texas, marine container hubs like Port Houston Bayport, or at the 12 border crossings handling U.S.-Mexico truck trailers. Research shows that the oldest dray trucks operate at border crossings and at Bayport (50% of containers move within Harris County) while rail drays have a lower mileage because they deliver regional loads, some outside Texas boundaries. In the last 2 years, the operation of new dray tractors has been noted, in part to decrease emissions in non-attainment areas.
Source: Citation #35

The TL specialist category is a wide one, encompassing expensive units for the movement of large size and weight loads, which move across defined routes set by the state DOT or Department of Motor Vehicles, which are selected because they can safely move loads using patrol vehicles over

[31] Examples are United Parcel Services (UPS) and FedEx.
[32] Op cit ref 1
[33] These can be leased vehicles at the end of their contract with the first operator.
[34] Harrison, R., et al. "The Impacts of Port, Rail, and Border Drayage Activity in Texas," Center for Transportation Research (CTR), Report 5684-1, Feb 2009.

the route, aided by police assistance at key route locations. Specialized vehicles include trucks moving gasoline and chemicals and trucks linked to oil and gas exploration, although these remain within the 80,000 lb. gross vehicle limit and operate under normal rules.

This report draws heavily from Texas truck research sponsored by both TxDOT and the U.S. DOT although the estimate of increased fuel efficiencies uses national Class 8 data. This is because state truck and trailer registrations do not necessarily reflect the economic activities in each state. The variation in registration numbers for multistate services by trucks and trailers led in 2000 to evidence of "jurisdictional shopping" where companies providing interstate trucking services benefit from easier registration processes and lower taxes and fees[35] in other states. Interstate highway use is monitored through the International Registration Plan (IRP)[36]. This Act, signed in 1973, requires truck owners to register vehicles[37] in their base or home jurisdiction (state). The registrant then provides information on the other states used by the vehicle and a plate is issued by the base jurisdiction which requires the operator to record the miles traveled in each jurisdiction (state), so the IRP Clearinghouse can administer the program equitably.

In 2003 the Texas Transportation Institute reported Texas heavy-truck registrations as 69,472 (the seventh highest) with Oklahoma in the lead with 202,890. Trailers were even more skewed—Texas reported 23,184 (the twelfth highest) while Oklahoma again recorded the top rank with 266,350 units. Although truck travel demand is derived from economic activity, Texas truck and trailer registrations appear unrelated to the size of the gross state product. The IRP data make it difficult to use in this study, so the estimate of fuel technologies is focused on the U.S. fleet rather than the Texas fleet. A recent change in monitoring heavy truck use through electronic logbooks[38], in effect since March 1, 2018 after a three-month trial period, promises the potential to accurately estimate mileage on state and federal highways. Use of such devices will strengthen highway planning and safety enforcement.

[35] Jasek, D., Ojah, M., Hoover, B., "Heavy Truck Registration in Texas," Texas Transportation Institute (TTI) TxDOT Report 4065-1, TxDOT RTI Office, August 2003.
[36] See: https://www.irponline.org/page/Registration
[37] All trucks with two or more axles and a gross weight over 26,000 lb. will operate outside home state limits.
[38] See: https://www.fmcsa.dot.gov/hours-service/elds/electronic-logging-devices

The selected method for this study calls for analysis of the U.S. fleet in terms of age, fuel consumption by age, and weighting engine mpg by annual utilization mileage. An overall, weighted fuel consumption figure is then derived for the 2018 fleet, which is then continued over the research to 2025, using the adoption estimates of key technologies in OEM MY specifications. A further refinement would be to include total vehicle weight to provide a ton-mile per gallon estimate.

3.1 U. S Class 8 Emissions Standards

Heavy-truck Diesel engines have moved from mechanical fuel injection systems in the early 1990s—when Texas and the federal government last changed its fuel taxation—to complex, computer control systems that make an increasingly wide variety of decisions and record them, together with driver responses (like speed and braking), in databases used for regular maintenance and management decisions.

Federal rules regarding the reduction of emissions from heavy-duty Diesel engines, some later stimulated by state rules enacted by California, were introduced in the 1970s to limit air pollution from all vehicles, including heavy vehicles defined as exceeding 33,000 gross vehicle weight rating. A major early milestone was reached when almost all sulfur was removed from Diesel fuel during the refining process, immediately impacting air quality in all major U.S. cities.

The 1998 standards were phased in after 1998 Consent Decrees while several truck Diesel engine manufacturers supplied 2004-compliant engines late in 2002. The 2007 NOx standards were phased in on a sales-percentage basis and reached 100% in 2010. The details are complicated, but the results are clear: heavy truck engines are significantly cleaner after 2010, which means that around half of the current Class 8 engines meet high EPA emissions for NOx and particulate standards. This has profound social benefits, especially in U.S. non-attainment areas where the combination of higher mpg and lower emissions is reducing truck non-attainment contributions. However, better air quality remains an external benefit, since it is not part of truck operating costs except in those states that provide financial incentives to dray truckers fitting new 2010-compliant engines[39]. Table 3.2 provides a summary of the main federal standards[40].

Table 3.2: U.S. Federal Heavy Truck Emission Standards (g/bhp-hr)

Year	CO	HC	NOx	PM
1985	15.5	1.3	10.7	0.62
1991	15.5	1.3	5.0	0.25
1998	15.5	1.3	4.0	0.10
2007	15.5	0.14	0.2	0.01
2015	15.4	0.14	0.02	0.01

Source: Citation #41

3.2 U. S Class 8 Fleet and Age

Annual sales of U.S. Class 8 trucks are shown in Figure 3.1, which captures three trends. First, sales climbed with a growing U.S. economy during 2003–2006, fell during the Great Recession of 2007–10, then recovered after 2011.

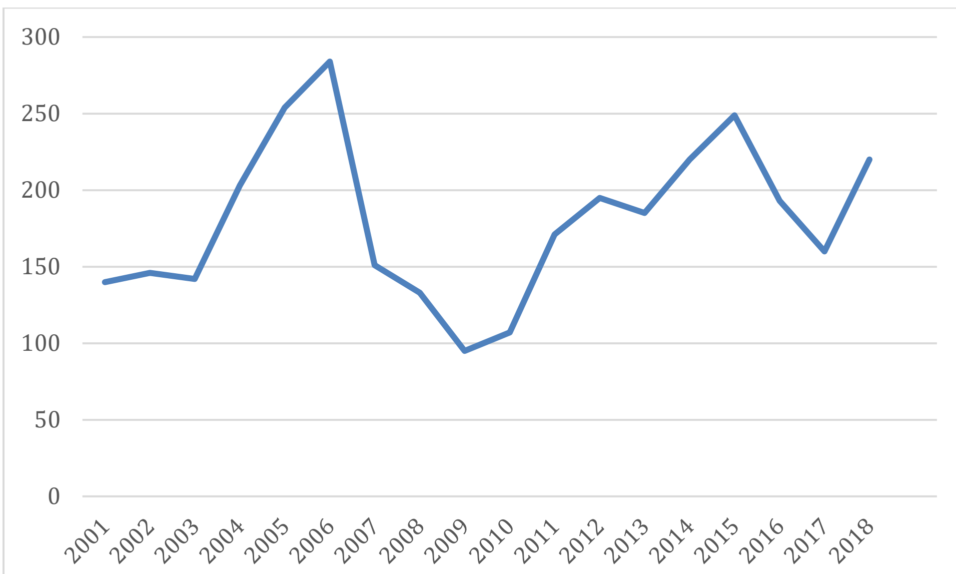

Figure 3.1: U.S. Class 8 Sales 2001–18 (Units 1000)

Technical (truck) and behavioral (driver) innovations after 2011 benefitted from a wide range of truck specifications offered by OEMs with an increasing emphasis on safety. The technical options

[39] Texas has allocated over $20 million since 2011 giving grants to replace old Diesel engines with new EPA-compliant ones. Trucks are included in a variety of qualifying equipment. See: https://www.tceq.texas.gov/airquality/terp

[40] For more detailed information, see: https://www.dieselnet.com/standards/us/hd.php

offered to buyers are noted in the next two chapters and allow transport managers to match their operations—route length, cargo, average speed, congestion levels and service levels—with the OEM options in the basic specifications, which together provide the best truck for the business. Major changes to mechanical specifications during the life of a truck are unusual so as trucks age, maintenance costs, fuel consumption and service levels are adversely impacted, and the vehicle becomes a potential candidate for the secondary market. U.S. Class 8 manufacture is currently around 200,000 units per year. Behavioral innovations include installed safety systems, real-time communication with dispatchers, driver safety incentives and, since December 2017, electronic logging devices that track driver work hours and mandatory rest breaks.

As noted earlier, this report estimates that Class 8 2018 fleet size will be 3.7 million vehicles, based on Class 8 sales data since 2013 and the estimated retirement of older trucks registered before 2001 based on data shown in Figure 3.2. The average age of a Class 8 truck remains around 11 years, although the average age at which a Class 8 truck operator sells a new truck to the secondhand market is 7 years, with an average mileage of 454,000 miles and an average sales price of $39,431[41]. Figure 3.2 shows that almost 90% of the U.S. fleet—and more if weighted by annual mileage—reflects some form of EPA exhaust emission legislation while almost 50% meets the most stringent 2010 EPA rules.

[41] See: https://www.overdriveonline.com/aging-u-s-fleets/border_trade/ and http://www.ttnews.com/articles/sales-used-class-8-trucks-rise-16-november

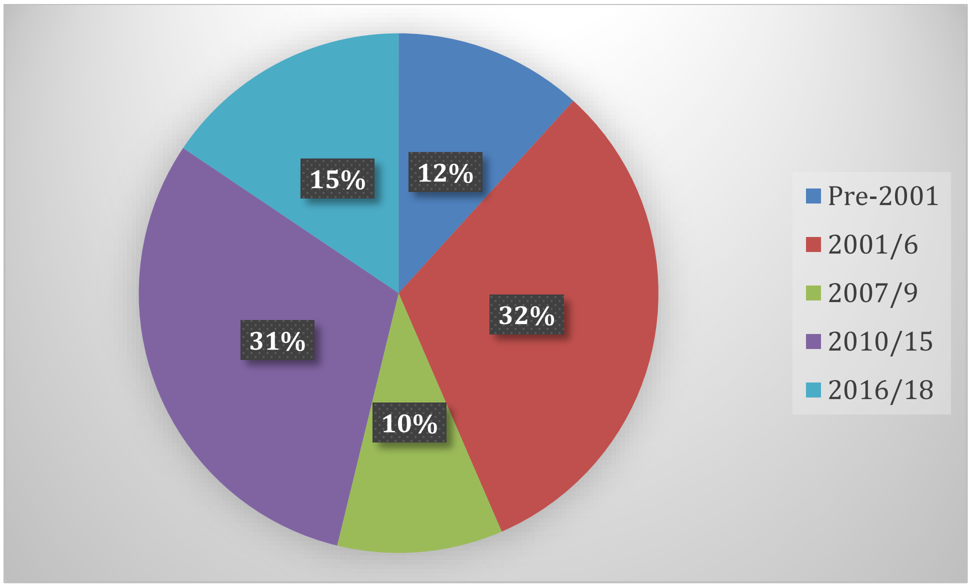

Figure 3.2: 2018 U.S. Class 8 Ages

Fuel costs are consistently recorded by the American Trucking and Research Institute (ATRI) as the second most important cost item for a Class 8 operator, only exceeded by driver salary and benefits[42]. The consumption of petroleum products in motorized vehicles has been a focus of health studies since the 1970s, which in turn has created a range of federal and state[43] emissions standards—as already—and subsidies for both hybrid and electric vehicles, especially automobiles. Hybrid trucks, including some with engines powered by liquid natural gas and compressed natural gas, are being pilot-tested in a variety of states but both natural gas and electric trucks are limited by distribution sites along the main truck networks. It is clear, however, that a small but growing number of trucks will be powered by either natural gas or electricity in the period 2018–2025, especially within metropolitan and megaregional networks. This will be examined in a later section of this report. The current focus of improving Diesel fuel efficiency has now reached a point where only small incremental steps are possible until new trucks designs that reduce engine parasitic power loss are introduced. The current 2018 U.S. Class 8 Diesel truck specifications are the result of over 8 years of federal and private company research and testing that began as the SuperTruck program in 2010. This is the subject of the next chapter.

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[42] Hooper, A., Murray, D. "An Analysis of Operational Costs of Trucking – A 2017 Update" American Trucking and Research Institute (ATRI), 2017. See: http://atri-online.org/wp-content/uploads/2017/10/ATRI-Operational-Costs-of-Trucking-2017-10-2017.pdf

[43] Particularly in California, where emission standards are higher, raising some standards beyond those of the Federal government.

Chapter 4. U.S. DOE SuperTruck Program

The 2010 SuperTruck Program was a shared federal and industry initiative to improve Class 8 tractor-semitrailer freight efficiency by 2015 and develop key elements of future truck OEM specifications. The specific goal was to develop and demonstrate a 50% improvement in freight efficiency (ton-miles per gallon) at 65 mph for Class 8 long-haul trucks compared to FY 2009 models by 2015. The $284 million collaborative industry cost-shared research was sponsored by the U.S. DOE Vehicle Technologies Program and supported by the Advanced Combustion Engine R&D, Vehicle and Systems Simulation and Testing, and Materials Technology subprograms. The four competitively selected industry SuperTruck project teams are headed by Cummins, Inc. with Peterbilt; Daimler Trucks North America LLC with Freightliner; Navistar, Inc.; and Volvo Technology of America, Inc. The selected teams represented a significant percentage of U.S. Class 8 OEMs who were expected to adopt proven technologies into Class 8 specifications in future MY designs.

The Daimler-Freightliner SuperTruck, shown in Figure 4.1, reached a freight efficiency improvement of 115% during testing. Improved vehicle aerodynamics are obvious, while engine and transmission elements cannot be seen but play crucial roles in reaching high freight efficiency numbers.

SUPERTRUCK

Figure 4.1: Daimler-Freightliner SuperTruck Program I Prototype

The Daimler Trucks prototype engine demonstrated a 50.2% improvement in brake thermal efficiency (BTE)[44]. This was accomplished via downsizing from 14.8 L to 10.7 L, an improved turbocharger match, optimized liner cooling, use of a lower viscosity oil, piston friction reduction, 15% higher peak cylinder pressure, optimization of the engine calibration, refinements to the shape of the piston bowl and injector matching, decreased exhaust gas recirculation (EGR) with consequent increased engine-out NOx emissions, and model-based controls[45]. Daimler also decreased the parasitic and auxiliary loads via a variable speed water pump, an electric-motor-driven air conditioning compressor, a clutched air compressor with active controls, and a clutched power steering pump with reservoir. Daimler also incorporated an Organic Rankine Cycle with ethanol as the working fluid, using not only waste heat in the exhaust but also waste heat from the

[44] Measure of engine efficiency: fuel consumption rate divided by power output.
[45] National Academies of Sciences, Engineering, and Medicine (2015), *Review of the 21st Century Truck Partnership, Third Report*, Washington, DC: The National Academies Press.

EGR system. Cummins demonstrated a heavy-duty Diesel engine with 51.1% BTE[46] that same year[47], accomplished through improvements in engine design (+2 percentage point increase in BTE), gas flow optimization (+2 percentage point increase in BTE), reduction in frictional and parasitic losses (+1 percentage point increase in BTE), improved aftertreatment (+0.5 percentage point increase in BTE), and an Organic Rankine Cycle waste heat recovery system (+3.6 percentage point increase in BTE).

Table 4.1 provides the commercialized technologies available on MY 2018 Class 8 tractor-trailers where SuperTruck program results had a direct or indirect impact on OEM specifications.

[46] Peak brake thermal efficiency measured over a single point representative of the engine installed in a truck driving at 65 mph on a level road with no wind, not over a transient (i.e., the heavy-duty Federal Test Procedure) or multimode steady-state (i.e., Supplementary Emissions Test) cycles.

[47] Delgado, O., and N. Lutsey (2014), "The U.S. SuperTruck Program: expediting the development of advanced heavy duty vehicle efficiency technologies", white paper presented to the International Council on Clean Transportation; available at https://www.theicct.org/sites/default/files/publications/ICCT_SuperTruck-program_20140610.pdf.

Table 4.1: Selected Commercialized Technologies for MY 2018

Component	Technologies
Engine	• Downspeeding • Intelligent torque management • Integrated engine/transmission controls • Parasitic loss reduction • Synthetic lubrication • Improved EGR and turbocharger
Driveline	• Automated manual transmissions • Optimized transmission ratios for downspeeding • Engine/transmission integration • 6x2 axles • Neutral shifting on downgrades
Aerodynamics	• Tractor front, roof, and tractor trailer fairings • Trailer side skirts, boat tails • Wheel center discs on both tractor and trailer
Weight Reduction	• Aluminum fifth wheel, tractor/trailer wheels • Driveshaft • Composites—truck and trailer replacing metal
Tires	• Single wide-base tires on tractor and trailer • Reduced rolling resistance through new compounds

SuperTruck Program I participants recorded notable successes.

- Cummins/Peterbilt demonstrated a freight efficiency of 86% on a 500-mile two-day highway test route.
- Daimler reached a freight efficiency improvement of 115% testing a 5-day data road trip.

- Volvo demonstrated an 88% improvement over a customer drive-cycle.
- Navistar projected an improvement of 80% or higher.

SuperTruck program teams had already commercialized 21 technologies by 2016, including aerodynamic improvements (tractor and trailer), engine drivetrain integration, and front radar/brake systems. Another 26 technologies have a strong likelihood of OEM adoption by MY 2021 while a further 13 offer the potential by 2025[48].

There is a substantial literature on the SuperTruck program and its products, including a 2012 Argonne National Laboratory economic analysis[49] that found that "under favorable assumptions of technology and fuel costs, market penetration ranged from 18 to 59 percent of MY 2020 specifications, saving an average of 48 million bbl. of oil by 2020." The federal contribution to the program of $142 million was judged to have a 500:1 return on investment.

The key positive test for the program was the announcement in 2016 that the DOE would provide $80 million for a second program, SuperTruck II, with the goal of creating a 100% increase in vehicle freight efficiency and 55% BTE. Cummins (partnering with Peterbilt and Bridgestone among others), PACCAR (partnering with Kenworth, DAF, and UPS among others), Navistar, Volvo Group Trucks (partnering with Wabash National [trailers], Knight Transportation [long-haul fleet], and Wegmans Food Markets [regional-haul fleet] among others) were accepted by DOE for the SuperTruck II program.

The research team for this project developed a list of potential tractor and trailer technologies for Class 8 MYs 2018, 2021, and 2025, building on other researchers and engineers who have estimated the timing of improvements that enhance fuel consumption, efficiency, and air quality. This project's mechanical engineering team searched for the range of fuel-efficient elements for future tractor and trailer specification, starting with those—many based on SuperTruck I results—actually offered on MY 2018 tractors and trailers, together with technologies likely to be offered by OEMs in MYs 2021 and 2025. This is presented in the next chapter.

[48] Department of Energy, SuperTruck Success: Progress on Fuel Efficiency and Market Adoption. June 2016
[49] https://anl.app.box.com/s/3dfq5bvqrjni0veon68by33im7gsgchn

Chapter 5. Mechanical Engineering Specifications for Class 8 MYs 2018, 2021, and 2025

The U.S. DOE set clear targets in both SuperTruck I and II program expectations and some of the technologies from SuperTruck I (originally called simply SuperTruck) are now being refined by OEMs into future MY specifications, including some available on 2018 models. Dean Oppermann, chief engineer of advanced technologies for Navistar Inc.—participating in the SuperTruck II program in November 2016—said:

> "International is using the Navistar SuperTruck as a platform to investigate the global integration potential of technologies for the entire vehicle system. Seldom does an OEM have the opportunity to design a vehicle from the ground up and not be restricted by the legacy systems that are already in production. Navistar is using SuperTruck to better understand what base vehicle architecture changes will be required to meet future GHG[50] requirements—aerodynamics, voltage requirements, and level of hybridization."[51]

As an example, Oppermann pointed to benefits of a 48-volt HVAC system, 48-volt batteries, and 48-volt motor generating unit as examples of a technology that is held back by the legacy 12-volt architecture in existing trucks. Joint sponsored public-private research, together with OEM and multidisciplinary research[52] into all aspects of trucking design and operations, will change consistently over the next 7 years and new models will displace older vehicles and so raise Class 8 average Diesel fuel ton-mile per gallon figures, improve regional air quality, and enhance highway safety.

5.1 Fuel Efficiency Technologies Evaluated

It might be expected that truck owner/operator demands for fuel efficiency improvements would be answered with truck manufacturers providing one or more technologies that offered improved fuel efficiency. However, like most or perhaps all industries, the truck industry is hesitant to invest in the development of many new technologies in the absence of a regulatory requirement. Although light-duty vehicles have been the subject of fuel economy standards since the late 1960s, the heavy-duty segment enjoyed decades during which they only had to meet emissions standards. The

[50] GHG emissions standards
[51] See: http://www.fleetequipmentmag.com/trucks-future-incorporate-supertruck-technologies/
[52] Particularly autonomous, computer, and wireless research

rationale for this discrepancy was that many heavy-duty engine manufacturers do not make the heavy-duty vehicles (HDVs) in which these engines are used. Furthermore, any given heavy-duty engine might be used in a variety of vehicles with different duty schedules, including both on-road and non-road vehicles and equipment. For example, a specific engine might be used in both Class 8 trucks and road graders. Thus, who should be responsible for complying with fuel economy standards—the engine manufacturer or the vehicle manufacturer?

In early recognition of the increasing consumption of transportation fuels by heavy-duty on-road vehicles, a trend that is forecast to continue until 2035[53], the Energy Independence and Security Act of 2007 (EISA) was passed, requiring the U.S. DOT, for the first time in history, to establish fuel economy standards for HDVs. Additionally, in December 2009, the U.S. EPA formally declared that GHG emissions endanger public health and the environment within the meaning of the Clean Air Act, a decision that compelled the EPA to establish the first-ever GHG emissions standards for new motor vehicles, including HDVs.

This is relevant to the present discussion of fuel efficiency because GHG emissions from vehicles are dominated, by a very large margin, by emissions of carbon dioxide (CO2) and CO2 emissions scale—precisely—with fuel efficiency. Following passage of the EISA, the National Highway Traffic Safety Administration (NHTSA), an operating administration of the DOT, asked the National Research Council to recommend the best ways to measure and regulate fuel economy for HDVs, and assess technologies that could improve it. The National Research Council appointed the Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles (NHTSA has three categories of vehicles while the EPA only recognizes light-duty and heavy-duty vehicles, with one exception: the medium-duty passenger vehicle). This committee considered approaches to measuring truck fuel economy, assessed current and future technologies for reducing fuel consumption, addressed how such technologies may be practically implemented in vehicles, discussed the pros and cons of approaches to improving the fuel efficiency of moving goods as opposed to setting vehicle fuel consumption standards, and identified potential costs and other impacts on the operation of HDVs[54].

[53] DOE (2009), "Annual Energy Outlook 2010 (Preliminary)", Washington, DC, December.
[54] Brown, A. D.N. Assanis, R. Bezdek, N.N. Clark, T.M. Corsi, D. Drinkard, D.E. Foster, R.D. Fruechte, R. Graves, G. Hu, J.H. Johnson, D. Kodjak, D.F. Merrion, T.E. Reinhart, A.P. Rousseau, C.K. Salter, J.J. Winebrake, J. Woodroffe, and M.B. Zimmerman (2010), Technologies and Approaches to Reducing the Fuel Consumption of

The report also recommended approaches that federal agencies could use to regulate the fuel efficiency of heavy-duty on-road vehicles, especially via a metric that accounts for the payload (the amount of freight or passengers) carried by these vehicles. Rather than fuel economy, they developed a metric called load-specific fuel consumption (LSFC) that reflects the efficiency with which a vehicle moves goods or passengers. The LSFC metric has units of gallons per ton-mile, which reflects the amount of fuel a vehicle would use to carry a ton of goods one mile. Most importantly from the perspective of this report, for selected categories of HDVs, the heavy-duty engine manufacturers are now required to improve brake-specific fuel consumption (BSFC, the mass rate of fuel consumed per unit power output of the engine, as assessed over the heavy-duty Federal Test Procedure operating cycle) and the vehicle manufacturers are required to make improvements to the remainder of the drivetrain and to the vehicle itself to meet LSFC standards.

On August 9, 2011, President Obama announced HDV fuel efficiency standards that were phased in from 2014 to 2018. The new NHTSA heavy-duty on-road vehicle fuel efficiency standards are phased in simultaneously with the EPA's new GHG emissions standards for HDVs. The CO2 and fuel consumption standards are equivalent standards. These joint standards are applicable to three categories of HDVs.

The first category is "combination tractors"—the semi-trucks that typically pull trailers and move freight on major federal and state highway networks. The rulemaking divides combination tractors into nine subcategories based upon three attributes: weight class, cab type, and roof height. The standards, which pertain to tractors without trailers, were phased in to the 2017 standards. These final standards achieved reductions in CO2 emissions and fuel consumption from affected semi-trucks from 9% to 23% over the 2010 baselines. Thus, these standards have already been achieved. However, in October of 2016, EPA and NHTSA established rules for a comprehensive "Phase 2 Heavy-Duty National Program" that is intended to reduce GHG emissions and fuel consumption from new on-road medium- and heavy-duty vehicles and engines.

Medium- and Heavy-Duty Vehicles, Committee to Assess Fuel Economy Technologies for Medium- and Heavy-Duty Vehicles; National Research Council; Transportation Research Board, The National Academies Press, Washington DC.

The new fuel consumption standards for engines used in Class 8 trucks require a 1.76% improvement by 2021, a 4.17% improvement by 2024, and a 5.05% improvement by 2027, all relative to the 2018 baseline. Additionally, the Phase 2 program, for the first time, set fuel efficiency and GHG emissions standards for trailers used in combination with tractors. Although the agencies did not establish standards for all trailer types, the majority of new trailers were covered. The new standards for the Class 8 tractors are intended to improve fuel consumption by 13% for MY 2021, 20% for MY 2024, and 25% for MY 2027. Improvements to the trailers used with these trucks are intended to improve fuel consumption by an additional 5% for MY 2021, 7% for MY 2024, and 9% for MY 2027.

The second category of heavy-duty on-road vehicles to which the new GHG and fuel consumption standards apply is “heavy-duty pickup trucks and vans” and the final category of heavy-duty on-road vehicles to which the new GHG and fuel consumption standards apply is “vocational vehicles,” such as delivery trucks, buses, garbage trucks, utility vehicles, dump trucks, cement trucks, emergency vehicles, motor homes, and tow trucks. The standards for these two categories are being phased in over different schedules than for combination tractors. Although the latter two categories are not of interest to the present study, they do emphasize that more types of HDVs are being required to become more fuel efficient, in addition to the combination tractors that are of present interest.

The need for combination tractors to meet both BSFC and LSFC standards means that every component within every vehicle subsystem—including the engine—can be viewed as a component to upgrade and gain fractions of percentages which, in the aggregate, will act to produce relatively large increases in fuel efficiency. The intent of the present study was to identify some of the newest and most important technologies and to link them with reasonable costs, adoption rates, and efficiency increases in order to generate a reasonably accurate outlook on what the Class 8 truck fuel efficiencies will be in the near future. Furthermore, it is very important within this frame of reference to realize that fuel efficiency depends on a large variety of factors, such as road material, condition, and grade; traffic; weather conditions; driver discipline and ability; trailer load; and more. Due to this, many of the technology evaluations rely on efficiency data that assumes highway speeds and eliminates as many of the other variables as possible. Generally, the technologies are split into major categories based upon the four different places in which parasitic loss occurs: aerodynamic drag, rolling resistance, engine and drivetrain losses, and auxiliary load losses. Neglecting the engine, these categories account for ~40% of the energy required to move a tractor-trailer system.[55]

In response to the federal requirement that Class 8 truck-trailers must meet engine BSFC standards and that the tractor-trailer vehicle as a whole must meet LSFC, in 2010 the U.S. DOE launched the 21st Century Truck Partnership program. They initially funded several R&D teams in their SuperTruck (later to become SuperTruck I) project. The major goals were to develop and demonstrate a 50% increase in vehicle freight efficiency relative to a baseline 2009 Class 8 tractor-trailer. The improvement in vehicle freight efficiency was to be obtained by a 30% increase via vehicle improvements plus a 20% increase via engine improvements. The latter goal corresponds to achieving 50% BTE from the baseline 42%. Figure 5.1 illustrates the relationship between a heavy-duty Diesel engine's BSFC (the subject of federal regulations) and its BTE (the subject of the SuperTruck engine goal). As this figure demonstrates, as BSFC decreases, BTE improves. For this specific engine at this operating condition, the baseline BTE of 42% corresponds to a BSFC of 200 g/kW-hr and the SuperTruck I goal of 50% BTE corresponds to 168 g/kW-hr. The two are related by BTE = 360/(BSFC*QLHV) where 360 is a unit's conversion factor and QLHV is the constant pressure Lower Heating Value (energy density) of the fuel. The factors that allow increased BTE (decreased BSFC) are discussed in some detail in Appendix A.1. Decreasing the required torque to allow for both cruise and acceleration of the vehicle is among the most important factors.

[55] U.S. Department of Energy (2006), "Roadmap and Technical White Papers," 21st Century Truck Partnership, Dec.; available at
https://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/21ctp_roadmap_2007.pdf

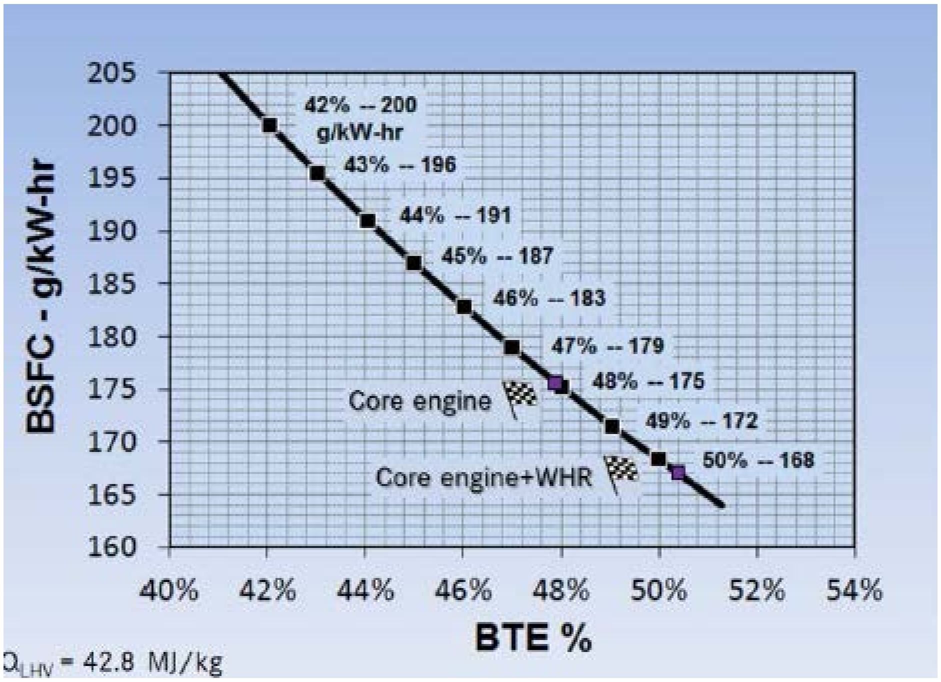

Figure 5.1: Relationship between BSFC and BTE for a Heavy-Duty Turbocharged Diesel[56]

The 21st Century Truck Partnership "Roadmap" established five goals for decreasing the fuel consumption requirements of the tractor-trailer combination,[57] which can be summarized as:

1. Develop and demonstrate advanced technology concepts that reduce the aerodynamic drag of a Class 8 tractor-trailer by 20% (from a drag coefficient of 0.69 to 0.55). Evaluate a stretch goal of 30% reduction in aerodynamic drag from Cd=0.69 to Cd=0.48 for a baseline Cd=0.69 with 9.2 m2 frontal area for a conventional Class 8 tractor with sleeper cabs.
2. Develop and demonstrate low rolling resistance tires that can reduce vehicle rolling resistance and wheel weight for a Class 8 tractor-trailer. Demonstrate a 35% reduction in rolling resistance. Develop and demonstrate technologies that reduce essential auxiliary loads by 50% (from current 20 horsepower to 10 horsepower) for Class 8 tractor-trailers. The baseline for this goal is a Class 8 highway tractor/trailer with sleeper operating 5 days over-the-highway with 80,000 pounds Combined Gross Vehicle Weight (CGVW).
3. Develop and demonstrate lightweight material and manufacturing processes that lead to a 10% reduction in tare weight for a 34,000-pound tractor/trailer. Establish a long-term stretch goal of reducing combined vehicle weight by 20%. The baseline for this goal is a Class 8 highway tractor-trailer with a high roof sleeper and dry van trailer capable of 36,000 kg CGVW.
4. Thermal Management & Friction and Wear: Increase heat-load rejected by thermal management systems by 20% without increasing radiator size. Develop and demonstrate parasitic friction reduction technologies that reduce driveline losses by 50%, thereby improving Class 8 fuel

[56] Rotz, D., and M. Ziegler (2015), "Class 8 Truck Freight Efficiency Improvement Project", Daimler Trucks presentation to the DOE Office of Vehicle Technologies Annual Merit Review, June; available at https://www.energy.gov/sites/prod/files/2015/07/f24/arravt080_vss_rotz_2015_o.pdf

[57] National Academies of Sciences, Engineering, and Medicine (2015), *Review of the 21st Century Truck Partnership, Third Report*, Washington, DC: The National Academies Press.

efficiencies by 3%. The baseline for this goal is a Class 8 highway tractor-trailer with sleeper operating at steady state 65 mph at 36,000 kg[58] CGVW.

In 2016, shortly before the end of SuperTruck I, DOE established SuperTruck II. The goals of SuperTruck II are to research, develop, and demonstrate technologies to improve Class 8 tractor-trailer freight efficiency by more than 100%, relative to a manufacturer's best-in-class 2009 truck (compared to the 50% improvement target for SuperTruck I), and a BTE of at least 55% (compared to the 50% BTE target for SuperTruck I) with an emphasis on technology cost-effectiveness and performance. The engineering team on the present project evaluated a wide variety of fuel-efficient elements and grouped them into potential specifications available in three Class 8 MYs: 2018, 2021, and 2025. Details of the elements evaluated and selected for the report are given in Appendix A.1.

By 2013, well before the end of SuperTruck I, Cummins' team surpassed the target of a 50% improvement in vehicle freight efficiency by achieving a 61% improvement over 27 realistic drive cycles. This was achieved via aerodynamic improvements for both the tractor and trailer (24.9% improvement in freight efficiency), weight reduction (~ 3%), decreased engine speeds (~3.5%), low–rolling resistance tires (also ~ 3.5%), the use of driver tools and route management systems (2.5%), and by increasing the engine's BTE from 42% to 51.1%.

Also, by 2013 Daimler had also surpassed the target of a 50% improvement in vehicle freight efficiency by achieving a 56.5% improvement in freight efficiency. They achieved this by increasing the engine's BTE from 42% to 48.1% (which provides a 14.5% improvement in freight efficiency), tractor and trailer aerodynamics (16%), powertrain and drivetrain technologies (16.5% from hybridization and optimization of the transmission, axles, wheel ends, wheels, and low rolling resistance tires), lightweighting (5%), energy management including idle reduction (3.5%), and reduction in parasitic losses (1%). Daimler used an automated manual transmission to enable downspeeding of the engine.

The next chapter considers the impacts of both Class 8 and hybrid urban trucks on the current freight logistics chains and the consumption of fossil fuels.

58 79,200 lbs.

Chapter 6. Megaregion Logistics

The last two decades have seen the growth of large metropolitan areas create a variety of freight model demand patterns, especially in the multimodal export and import freight sectors. All modes are impacted and both metropolitan and megaregional modal centers channel maritime, air, rail, truck, and pipeline through major modal hubs to serve local communities. Trucks of all sizes facilitate in this process either directly or a part of a multimodal trip. Table 6.1 gives ton-mile estimates for trucking in 2015 and 2045[59].

Truckload (TL) trips directly serve locations within the metropolitan areas, either bringing loads to a site and leaving empty or carrying other loads from the same or a different location. Less than truckload (LTL) trips arrive at centers where cargo is sorted and then delivered to individual buildings, companies, or households on smaller trucks. Manufacturing sites in metropolitan areas receive a variety of inputs and outputs—both TL and LTL— which demand strict service levels to meet production targets. Growing metropolitan areas create demand for accommodation and housing, retail, educational, and medical services, together with transportation services, including highway space.

Table 6.1: Truck and Multimodal, 2015 and 2045, Ton-Miles (Million)

Year	2015	2045
Total	17,978	25,346
Trucks	10,776	14,829
Share	60%	58.5%
Multimodal and Mail	1346	2962
Share	7.5%	11.2%

The traditional regional Class 8 logistic models fall into two categories:

- Goods—some as interim components—are taken by TL operators to final assembly plants, manufacturing sites, or large distribution centers, and
- LTL hub-and-spoke systems where the final and initial stages in the chain are undertaken by smaller Class 4/5 trucks such as those used by FedEx, Amazon, and UPS.

[59] Source: USDOT, Bureau of Statistics, See: https://www.bts.gov/content/weight-shipments-transportation-mode-0

Since 2005, U.S. shopping has altered at an accelerating pace with online systems growing market share in many retail commodity markets. Shopping malls and retail strip centers have lost key retail shops that “anchored” demand and are now struggling to maintain economic viability in some metropolitan areas. Auto traffic patterns to shopping centers or big box centers are also changing, with grocery shops offering pick-up services for busy families, which reduces parking and in-store impulse buying.

Statista has recently produced U.S. retail data for 2011, 2016, and estimates for 2021 showing the changes in market share for a variety of categories: food and alcohol; drugs, health, and beauty care; furniture and home furnishings; apparel and footwear; toys and sporting goods; books, magazines, music, and videos; electronics and appliances; and finally, computer and office products. Figure 6.1 shows the Statista data for the categories for 2011, 2016, and 2021.These changes impact urban auto origin and destination patterns and forecasts, and the patterns of metropolitan freight traffic. These shifts have also created proposals to use multi-service taxis—like Uber—to make household deliveries and also stimulated solutions that would use drones to make the final delivery from urban delivery trucks.

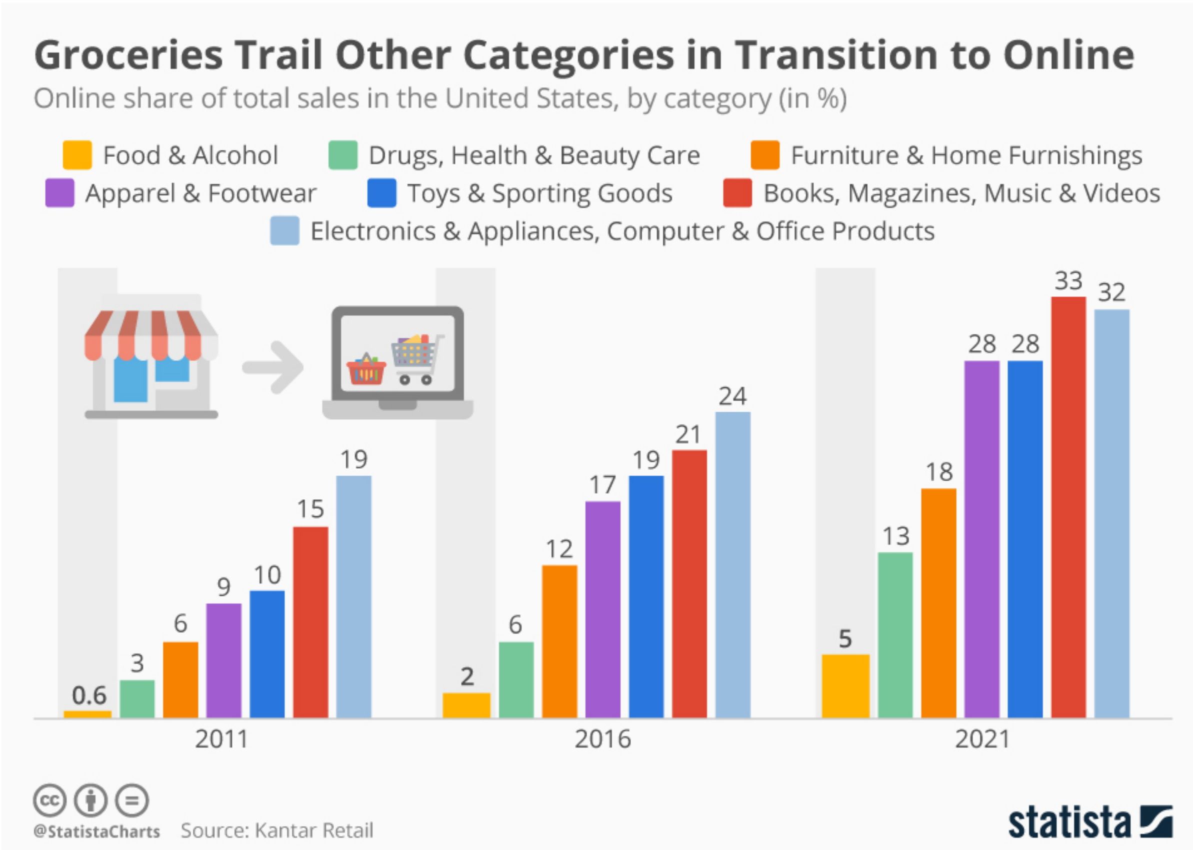

Figure 6.1: Retail Sales Transitions from Store to Online—2011, 2016, and 2021[60]

Class 8 and urban truck design is arguably going through the most significant phase in its history. This project examines the impacts on Diesel engine vehicles of a wide variety of mechanical engineering, aerodynamic, and weight innovations to increase fuel efficiency. Various alternative fuels have been tested, most notably natural gas (compressed and liquid forms), hybrid systems, and pure electric engines requiring storage batteries and plug-in systems to store and replenish electricity.

Electricity is not new and was used as a power source when automobiles were in their infancy. Gasoline quickly became the main motive power for U.S. trucks after 2008 and lasted until the 1960s, although in Europe electricity was used to replace horses in certain urban service sectors on short stop-and-start routes, especially the regular household delivery of bread and milk. Designs were very simple, based on a series of lead acid batteries mounted under a monocoque platform

[60] https://infographic.statista.com/normal/chartoftheday_14852_share_of_online_sales_by_product_category_n.jpg

(termed a “float”[61]) that were charged overnight. In the two decades after 1950, the UK apparently had one of the largest registered electric delivery fleets in the world. Figure 6.2 shows an electric milk float. They had a working range of around 40 miles, a speed of 10 to 15 mph, and served urban areas with household concentrations. However, urban auto demand patterns and the growth of supermarkets significantly impacted their viability and use. The U.S. had only specialized applications, with the wide ownership of autos before the Second World War, and the growth of suburbs and supermarkets soon afterwards.

Figure 6.2: Electric Milk Float 1960 UK

In Europe, China, and the U.S., plug-in electric vehicles (PEVs) are reappearing in test fleets in key cities. PEV research and pilot testing is currently high in the EU and China for a variety of reasons but principally to reduce urban diesel air pollution and related social costs like noise. FedEx is testing a PEV light truck system based on the Nissan NV200[62] electric van in London and there appears to be a segment of the urban truck fleet where PEVs will establish a viable market share.

[61] See: https://en.wikipedia.org/wiki/Milk_float
[62] See: https://www.youtube.com/watch?v=2MkPGaT9lvM

All electric vehicles are limited by battery technologies and control systems that require further pilot testing and maintenance related to use, range, and cost. The Volvo FE/L electric urban trucks are currently under test for urban distribution and refuse collection[63]. Box 6.1 provides some of the key specifications of the FL truck.

Box 6.1: Volvo 2018 FL Urban Truck

a. Gross vehicle mass 28 tons;
b. Driveline: 2 electric motors with 349 BHP continuous power;
c. Volvo 2-speed transmission;
d. Energy source: Lithium-ion batteries, 200–300 kW;
e. Range: 186 miles;
f. Charging: 2 systems—150 kW DC; 22 kW AC; and
g. Charging time: 1.5 hrs. DC; 10 hrs. AC

Source: Citation #62

At the time of this report (2018), all leading Class 8 manufacturers, together with many truck engine companies, are engaged in evaluating the performance, cost, and operator benefits of both hybrid and fully electric vehicles. The term "hybrid" in this report defines the primary use of Diesel to drive the transmission and the use of electricity to account for all other auxiliary losses that legacy Diesel engines use to power a variety of components. Timing of fully tested trucks for U.S. use will arrive later in the period of study, probably around 2021.

Navistar International[64] Vice President of powertrains and advanced technology Darren Gosbee was recently asked[65] when electric vehicles might enter the U.S. MY market. His comments on various topics can be summarized into three categories.

> <u>Timing</u>: Navistar will provide as variety of electric truck designs for the market, based on customer operations. The company is collaborating with Volkswagen and expects to launch a medium-duty truck in the U.S. market early 2020.
>
> <u>OEM Strategy</u>: Tesla and others offer a propulsion system, not a vehicle solution. Currently, it is not (financially) feasible for Navistar to develop a specific segment with so many challenges related to servicing and recharging sites. Commercial trucks require special networks linking suppliers, manufacturer assembly and sites to support Class 8 truck services and these need large capital investment programs.
>
> <u>Truck Segment</u>: Medium duty—Classes 6/7—are the best business cases for introducing electric trucks into the U.S. market. These vehicles have more predictable loads and routes. They typically make shorter trips and return to the same distribution center at the end of the day where an operator can optimize the charging infrastructure system and its investment. They have fewer moving parts which is likely to reduce total costs of

[63] See: https://insideevs.com/volvo-debuts-vl-electric-truck-with-up-to-300-kwh-battery/
[64] A holding company—Navistar International—now owned by Volkswagen
[65] HDT Truckinginfo, Fuel Smarts, Q&A: Navistar's Gosbee on When to Expect Electric Trucks 7/18/18

> operation. In addition, they have zero carbon impact in cities and from tail pipe emissions of NOx and other gases and this makes a significant contribution to meeting metropolitan emission standards.

The remarks on disruptors and market share were confirmed in late July 2018 when Uber confirmed that it was ‘shuttering” its autonomous truck research division and concentrating on its automobiles. The company said in a statement that it intends to continue to explore autonomous vehicle technology using passenger cars as the foundational research unit but will maintain relationships with trucking OEMs as this technology matures[66]. The Uber Freight division will not be affected by this decision.

LTL companies are also examining the potential for alternative fuels—notably compressed natural gas (CNG) tractors for selected corridor routes. In June 2018, UPS announced plans to build an additional five CNG fueling stations and add more than 700 new CNG vehicles, including 400 semi-tractors and 330 terminal trucks at a cost of $130 million. The company will have invested in over $1 billion since 2008 on alternative fuels and technologies.

UPS’s use of renewable natural gas (RNG) yields up to a 90% reduction in lifecycle GHG emissions when compared to conventional Diesel fuel. The company is the largest consumer of RNG in the transportation sector and the initiative will help UPS reach its 2020 goal of one in four new vehicles purchased being an alternative fuel or advanced technology vehicle. The company has also set a goal of replacing 40% of all ground fuel with sources other than conventional gasoline and Diesel fuel to support UPS’s commitment to reduce its GHG emissions from global ground operations to 12% by 2025. These are social benefits not usually internalized into transportation pricing.

An earlier CTR study[67] examined a range of 2011 hybrid urban delivery trucks—package, beverage, and refuse—and at that time found that only the refuse truck merited consideration based on a combination of lower maintenance costs (especially brakes) and air quality benefits (see Box

[66] See: https://www.truckinginfo.com/310008/uber-shutters-autonomous-truck-business-division?utm_source=email&utm_medium=enewsletter&utm_campaign=20180731-NL-HDT-HeadlineNews-BOBCD180731015&omdt=NL-HDT-HeadlineNews&omid=1009784356

[67] G. Anderson and R. Harrison; “Hybrid Distribution Trucks: Costs and Benefits,” U.S. DOT UTC Region 6, SWUTC/11/476660-00080-1, June 2011.

6.2). Even with government incentives and social benefits estimated at $32,000, package and beverage delivery trucks were difficult to justify on financial grounds.

It should be recognized, however, that substantial progress has been made since 2011 on both sides of the economic cost-benefit calculations. First, hybrid systems have been refined and economies of scale have reduced their costs. This includes smaller electric PEV trucks that are competitive with Diesel trucks in the urban package sector. Second, on the benefit side, in the fast-growing cities that constitute megaregions and large metropolitan areas where future growth is predicted, air quality issues are now accepted as civic responsibilities that must be addressed by policy changes. Although the focus of PEV adoption has been the automobile, it is increasingly likely that urban delivery systems will be the fastest growing segment of PEV adoption, especially since megacities and megaregions are globally predicted to introduce further emission controls—and prices—as population and auto use grows based on employment and services.

Box 6.2. Hybrid Refuse Truck Operational Cost System Elements

- Hybrid hydraulic (fluid not electricity);
- Cost $20,000; 25% urban cycle fuel reduction;
- Brake wear halved in urban use;
- Urban payback of 7 years, with fuel cost at $3.50 a gallon;
- Rural setting not economically viable.

Source: Citation #71

Freight flows from production centers to final consumers using multimodal platforms and systems developed over the past three decades. Much has been reported on the critical role played by trucking and the difficulty of truck driver retention—especially in Class 8 operations. This has been evident over the last three years as the U.S. economy continued to grow and both urban and long-haul driver salaries and compensation packages have competed for a limited driver pool,[68] which is estimated by the American Trucking Association staff to reach 50,000 drivers in 2018[69]. Salaries still lag behind the levels reached before deregulation[70] but are set to recover over the next two years. The first is the "pull" from retail distribution and just-in-time services, underpinned by the "push" of electronic logging devices that record driver hours of service and can be accessed by state and federal police and safety officers. These record drivers who exceed hours of service and

[68] See: https://www.ttnews.com/articles/shortage-drivers-slows-booming-truck-demand
[69] See: http://www.trucking.org/article/New%20Report%20Says-National-Shortage-of-Truck-Drivers-to-Reach-50,000-This-Year
[70] See: https://www.businessinsider.com/trucking-shortage-eld-mandate-cdl-truck-driver-salary-2018-6

is producing changes in logistics chain and distribution strategies. The range of mechanical and electrical systems reported in this research allow drivers to concentrate on safety and the electronic logging systems ensure that drivers are not overworked.

Logistics operations constantly adjusts demand—and therefore market share—between modes based on origins and destinations, modal schedules and capacity, service levels, including reliability and just-in-time, together with costs per mile, to produce the most cost-effective transportation systems for specific commodities. Currently fuel and driver costs dominate trucking, and researchers on autonomous vehicles justifiably use the current truck driver shortage as one factor supporting the adoption of fully autonomous systems.

The use of electricity as the prime motive power for trucks is in the early stages of impacting ownership and a decade of auto hybrid ownership in the U.S. has not met the prior forecasted market share, even with substantial subsidies from the Federal government. A recent University of California at Davis article[71] noted that

> "while the global plug-in electric vehicle (PEV) market has been growing for several years, its continued expansion faces threats, caught up in potential trade wars and a roll back of favorable policies. In 2017, the global PEV market [including battery and plug-in hybrid electric vehicles (EVs)] grew by 65%, hitting 1.2 million PEV sales. The report estimates the total number of PEVs in the world at over 3.5 million."

Virtually all the PEV units are automobiles but their development is stimulating a variety of prototype small electric trucks that will be tested in increasing numbers on urban networks during the period to 2025. In the U.S., modest testing of electric trucks in urban systems is underway and reports apparently show competitive total cost comparisons with Diesel trucks[72].

European truck makers have been evaluating electric trucks for both long distance and urban use since 2010. This has stimulated research into electric trucks in the U.S., most especially through U.S. companies controlled by European manufacturers like Daimler (Freightliner) and VW. Their adoption in the U.S. is currently limited to pilot testing models in urban areas with daily routes under 150 miles—although this may increase with new battery designs in the research period.

[71] Accessed August 2018: https://its.ucdavis.edu/blog-post/global-electric-vehicle-sales-are-accelerating-but-could-tariffs-and-uncertain-policies-make-it-hit-the-brakes/

[72] https://www.greencarreports.com/news/1115722_ups-says-50-workhorse-plug-in-hybrid-trucks-cost-no-more-than-regular-vehicles

Batteries raise the truck unladen weight, so operator cargoes that cube-out (like parcels) rather than weigh-out (like beverages) are the more obvious sectors where electric trucks have operational advantages.

The relevance of electric and alternative fuel in truck operations will be tested during the next phase of the federal heavy-duty fuel economy standards, which currently planned to phase in between MY 2021 and MY 2027 for engines and tractors and between MY 2018 and MY 2027 for trailers[73,74]. However, these standards are almost certain to be complicated and manufacturers will be scored on the entire range of trucks to reach a compliant fuel efficiency rating. An OEM selling electric trucks will get credits that will allow more Diesel engine models to remain in the truck portfolio. In addition to the "pull" of federal regulations, there is a growing "push" from states and cities[75] where air quality is an issue.

Daimler is testing a variety of refuse trucks in Europe similar to the Volvo FE details in Box 6.1. BYD is building Chinese refuse trucks and has expanded its plant in Lancaster, California.[76] Concentrations of heavy trucks—for example, at U.S. container ports—is another area where electric vehicles could play a role in reducing Diesel emissions levels from older pre-2010 dray tractors.

The North American Council for Freight Efficiency (NACFE) published a report in 2018 that found a range of positive and negative support for commercial battery electric vehicles based on weight, technology, cost, and refueling[77]. The arguments are provided in Table 6.2.

[73] "Phase 2 Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles", Congressional Research Services, July 18, 2018; available at: https://fas.org/sgp/crs/misc/IF10927.pdf
[74] This may well change after the Presidential election in late 2020.
[75] New York City's "NYC Clean Fleet" aims to cut greenhouse gases by half in 2025 and over 75% by 2035. See: http://www.nyc.gov/html/dcas/downloads/pdf/fleet/NYC_clean_fleet_plan.pdf
[76] See: https://cleantechnica.com/2018/05/16/byd-lands-deal-for-500-electric-refuse-trucks-with-two-companies-in-shenzhen/
[77] See: https://nacfe.org/future-technology/electric-trucks/

Table 6.2: 2018 NACFE Report of Arguments against Adoption of Commercial Battery Electric Vehicles

Factor	For Electric Trucks	Against Electric Trucks
Weight	• Weight not an issue for many operations	• Truck tare weight too high
Technology	• Proven and available • Maintenance less costly • Battery life beyond 10 years	• Not ready for arduous schedules • Costs not yet measured in field • Not proven at 2018
Cost	• Trucks competitively priced • Less expensive to operate • Premium resale price	• Competitive ROI too high • operating costs higher • Unknown at this date
Charging	• Market will provide sites • Recharging times will fall • Grid and market will increase growth of adoption rates	• Infrastructure not ready • Too slow—impacts schedules • Electric grid cannot support growth of electric trucks

The main economic arguments center on operational costs since the social costs—certainly in terms of air quality and GHG emissions—favor electric power. Mercedes-Benz[78], a pioneer of truck Diesel engine utilization, believes that commercial electric vehicles will rise significantly over the study research period ending in 2025, driven by total cost of ownership as e-vehicles offer lower energy and maintenance costs. This assertion will be tested extensively during the 2018–2025 period and will coincide with Diesel engine technologies that will raise fuel efficiencies in terms of ton-mile costs. On these grounds it would appear that air quality and GHG impacts will substantially fall from current U.S. transportation sector levels.

The logistic systems now established in metropolitan, regional areas and megaregions will be refined over the 2018–2025 study period with the real-time, dynamic data collection and

[78] In 2017 Electric Mobility Group at Daimler Trucks North America was formed. See: https://daimler-trucksnorthamerica.com/influence/blog/new-electric-vehicle-initiatives-at-dtna/

improvements in route conditions, dynamic corridor signaling, and targeted highway investment. Hub-and-spoke systems will be enhanced with new rail inland ports and airport freight centers with increasing numbers of cleaner Diesel trucks on corridors and electric or low emissions trucks on urban delivery networks. It is highly likely that a new category of truck distribution hubs and rail inland ports will emerge to serve growing cities—like Austin, Texas—in current megaregions. Metropolitan planning would be strengthened if the designation of transload centers could be explicitly linked into corridor and urban network investments, working closely with the relevant State DOT and MPOs. This is a fundamental recommendation of this report. MPOs should base decisions on TxDOT corridor planning and select potential sites for transloading truck freight. An example of this would be the development of an inland port in Austin, east of the city's primary passenger airport. The area has freeway access to IH 35 and the State Highway 130 toll road and can serve new housing in both Travis and Williamson counties, which continue to grow their populations[79]. The MPO must actively identify, promote, and incentivize areas suitable for freight hubs, based on reductions in truck flows, operating costs, and social benefits.

The next, and final, chapter reports findings and offers policy recommendations for state and federal transportation planners.

[79] See: http://austin.culturemap.com/news/city-life/04-04-18-us-census-bureau-austin-growth-slowing-down-texas-increase/

Chapter 7. Study Findings and Highway Transportation Policy Impacts

Megaregion research remains in a formative state with little agreement on the best way to approach the issue from a planning perspective. Megaregions are (to some) "just one of an increasingly large number of competing spatial imaginaries which purport to reflect globalization's new urban form"[80]. The federal government, however, appears to recognize the value of exploring their planning consequences, especially for transportation planning. In late 2016, the FHWA revised transport planning regulations to strengthen regional planning through unified planning products for each urbanized area, even if there are multiple MPOs in that urbanized area[81]. Provisions included joint unified products where multiple MPOs lie within areas expected to be urbanized within a forecasted 20-year period.

This report does not attempt to explore urban imaginaries and their future. It focuses on a key element of the success of any urban imaginary—efficient, safe, and cleaner freight transportation. We argue that transportation systems have already recognized how to serve various urban forms, including large metropolitan urban areas and the multistate, regional urban forms mentioned in the 2016 notice. It focuses on the freight trucking system that in 2017 accounted for 60% of the U.S. volume—in ton-miles—in both single and multimodal freight systems.

Further, this report emphasizes the engineering success in raising both Diesel engine efficiencies—particularly trucks—and societal benefits. The latter derive from attaining both higher levels of regional air quality standards and truck safety—all based on new technologies. Its contribution emphasizes what is absent from the megaregion debate at this point—namely that growing population centers require higher and more diverse freight volumes and trucking plays a major role in maintaining these commodity flows. Moreover, trucking technologies likely to be introduced over the next eight years will improve safety, air quality, and efficiency. The movement of people is addressed in some published work (for example, the use of high-speed rail to connect cities within U.S. megaregions) but economic success and freight demand remains largely ignored.

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[80] Harrison, J. and M. Hoyler, "Megaregions: Globalization's New Urban Form?' 2017

[81] See: https://www.federalregister.gov/documents/2016/06/27/2016-14854/metropolitan-planning-organization-coordination-and-planning-area-reform

The U.S. relies on efficient trucking use of federal, state, and county highways to move commodities and semi-finished and finished goods by truck, multimodal systems, and distribution gateways. Large metropolitan and megaregional urban forms critically depend on trucks. In Texas, for example, the 2017 TxDOT Freight Plan reports:

> "growing population and employment in Texas' urban areas means increased demand for the delivery of goods. The growth of freight movement within Texas urban areas intensifies congestion, since the movement of goods, like the movement of passengers, contributes to (raising) traffic (demand). Congestion in urban areas greatly impacts the efficient movement of goods and affects the reliability, timing and distribution of freight.[82]"

The first order of state DOT freight highway planning analysis is corridors within state boundaries, whether they are federal interstate and state highways. Metropolitan highway planning, though recognizing corridors, concentrates on the urban networks that move both people and freight. Texas has 25 MPOs broadly located east of IH 35[83] that form sub-groups to develop strategies and advise TxDOT. It is uncertain, but likely, that each MPO currently comes to the table with needs that lie within their boundaries. It therefore rests on TxDOT's Planning and Programming Department to resolve the connective needs that link them together in terms of state freight efficiency. The private sector organizations—whether single modes like railroads or consolidators like logistic companies—consider the overall efficiency of their multistate systems, based on network origin and destination data. BNSF Railway, for example, will improve a specific state bottleneck[84] to improve multistate system efficiency, rather than service to a single point. BNSF has also explicitly recognized the term *megaregion* in its network planning[85].

A key result of the project is confirmation that new trucks are benefiting from Diesel engine technologies, automatic braking, transmission/engine matching, aerodynamic tractor and trailer elements, low rolling resistance tires, and tag axles, which acting together significantly lower fuel costs on a ton-mile basis. Class 8 fuel consumption targets estimated by this study are at least 7.5 mpg for 2018, 8.5 mpg by 2021, and 9 mpg by 2025. These efficiency levels linked to cleaner exhaust systems will make a positive impact on both urban air quality and national GHG levels.

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[82] See: ftp://ftp.dot.state.tx.us/pub/txdot/move-texas-freight/studies/freight-mobility/2017/plan.pdf Slide. 1-6
[83] See: https://www.texasmpos.org/texas-mpos/
[84] BNSF and UP combined forces to win a Tiger grant to address rail congest at Tower 55 in the DFW area.
[85] Dennis Kearns, BNSF, interview 2012.

In addition, the introduction of alternative fossil fuels like natural gas and of pure electric trucks, first on the urban networks then corridors, will further drive down state truck revenues from Diesel fuel taxes.

These results will strengthen two key goals of TxDOT—safety and economic growth—yet create a critical negative impact on traditional highway funding. Well-established warnings about TxDOT revenues will only become sharper as new truck Diesel consumption falls, adversely impacting both construction and maintenance of the state highway system. Several states have responded by raising the state portion of Diesel fuel—California charges over three times that of Texas at 0.6916 cents/gallon. Truck associations[86] favor raising the fuel tax incrementally, while other states like California are looking at a range of options, including truck annual mileage, which recognizes both improvements in Diesel truck fuel economy and the introduction of alternative fuels, including electricity.

Texas trucks, especially in the Class 8 category, are paying less annually per mile for highway use. In 1998[87], a Class 8 LTL truck running at 80,000 miles per year in Texas consumed 17,778 gallons and paid $3,556 in state taxes while a 2018 truck reporting the same mileage consumes 10,667 gallons and pays $2,133. And consumption is predicted to fall over the study period; in 2025 trucks may well reach 9 mpg or better. The long-term solution may be resolved with the adoption of autonomous vehicle technologies where truck type, highway use, weight, and route timing will form an integrated platform for equitable and efficient pricing. Raising state fuel taxes might be the only practical option over the next five years and even that may encounter resistance at the legislative levels of state government.

[86] See: https://www.truckinginfo.com/279067/ata-urges-action-from-congress-on-infrastructure-plan
[87] 1998 truck: 4.5 mpg; 2018 truck: 7.5 mpg.

Appendix A.1: Details on Selected Class 8 Fuel Efficiency Technologies

The mechanical engineering team examined, evaluated, and grouped a range of tractor-trailer elements comprising fuel efficiency impacts and potential incorporation into MY specifications that operators could use to determine the best set of options for the type of trucking they offered to customers. The major elements are shown in Figure A.1.1 and discussed in the remainder of this appendix.

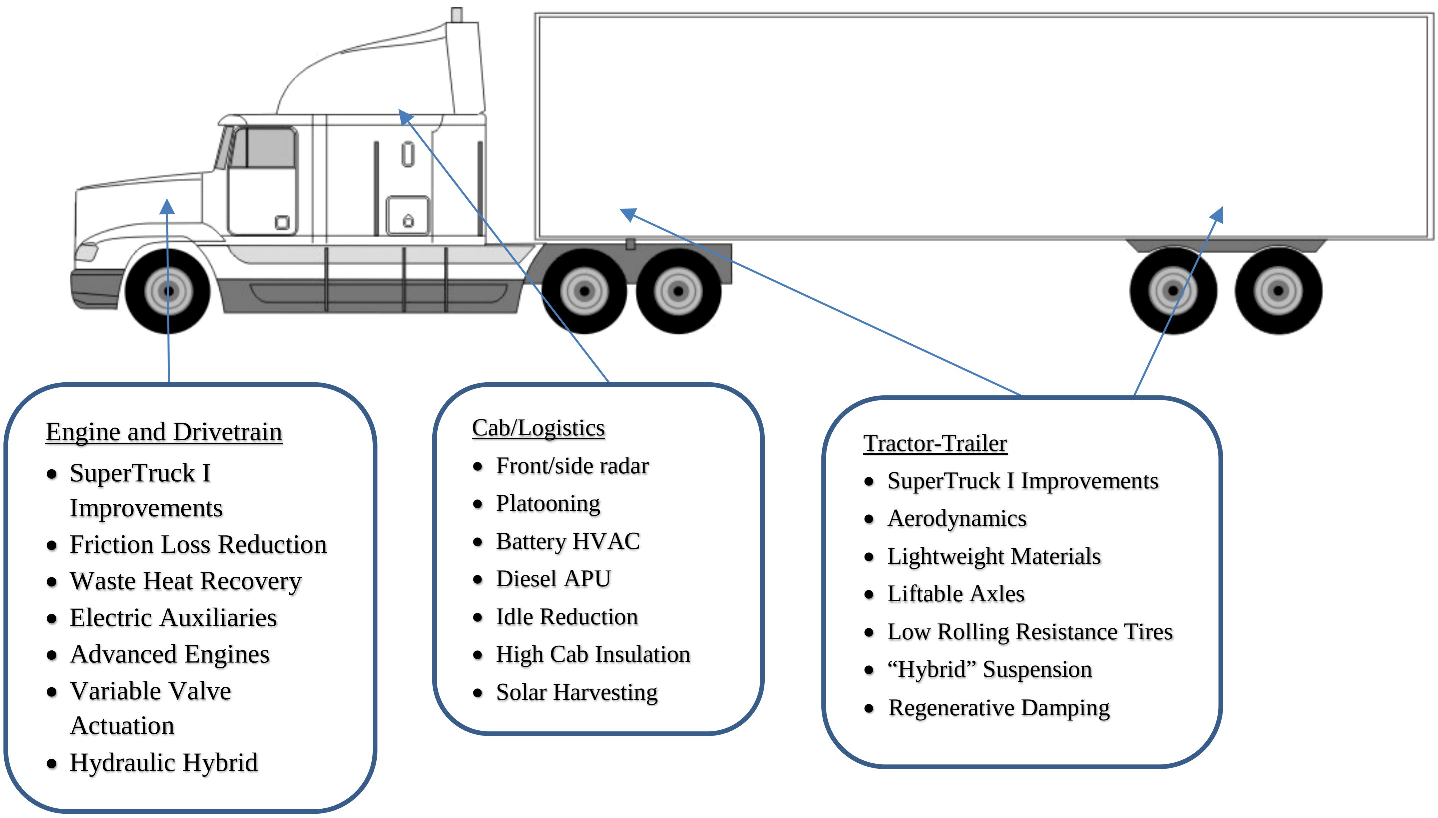

Figure A.1.1: Illustration of the technologies evaluated in this study

These and other technologies evaluated are now briefly discussed with citations provided for further details.

A.1.1 Engine and Drivetrain

A.1.1.1 SuperTruck Impacts88

The SuperTruck I program produced several improvements that began to appear in MY 2016/17 Class 8 specifications. These included "downspeeding" the engine, which reduced frictional losses between the combustion chamber and the engine's output shaft by operating the engine at a lower speed since the engine's frictional losses depend upon the square of engine speed. This is accomplished for a Class 8 truck operating at highway speeds by the correct selection of the transmission and differential gear ratios. Other engine and drivetrain improvements that were commercialized from SuperTruck I included improved engine controls (intelligent torque management and integrated engine/transmission controls) and improvements for the driveline. The driveline efficiency improvements included optimized transmission gear ratios and automated manual transmissions to enable downspeed engines. Manual transmissions are more efficient than automatic transmissions but require higher driver skills. A dual clutch transmission is as efficient as a manual but shifts automatically. This offers higher driveline efficiency, smoother gear shifts, and better fuel economy. It also allows a greater degree of gear selection than an automatic, allowing the driver to make decisions as to which gear to use in load/speed and highway situations. The driveline efficiency improvements also include predictive transmission shifting, transmission/engine integration, neutral shifting on downgrades, and reduced parasitic losses in the transmission and differential via improved gear oils/transmission fluids and improved transmission design.

Although not frequently listed as a result of the SuperTruck I program, many Class 8 truck engines have also been reduced to smaller displacement engines—for example, using a 13-liter rather than a 15-liter unit[89]. The primary benefits of engine downsizing include decreased CO2 and NOx emissions in addition to increased fuel efficiency. The practice is quite common in light-duty cars[90] and trucks, which can move down from a port fuel-injected, naturally aspirated, spark-ignited V8

[88] DOE (2016), "Adoption of new fuel efficient technologies from SuperTruck", Report to Congress, June; available at
https://www.energy.gov/sites/prod/files/2016/06/f32/Adoption%20of%20New%20Fuel%20Efficient%20Technologies%20from%20SuperTruck%20-%206-22-16%20%28002%29.pdf
[89] Some SuperTruck prototype engines were 1-liter, inline 6-cylinder units.
[90] 2018 Honda Accord engines, for example.

to a direct-injection, turbocharged, spark-ignited inline 4-cylinder engine. Although downsizing is also attractive for the heavy-duty Diesel engines used in Class 8 trucks, it is more challenging because almost all Class 8 truck engines are already turbocharged and, more importantly, the torque produced by the engine scales with displacement. That is, the engine can be downsized only if the torque required from the engine is smaller. However, the aerodynamic improvements and other technologies developed as part of SuperTruck I were intended to require less torque from the engine. In addition to all these elements, engineers also lowered the weight of components where feasible and these decisions, though at times relatively small, result in an aggregated weight benefit that translates to higher payload and lower tare weights when empty, lowering fuel consumption.

Downsizing the heavy-duty turbocharged Diesel truck engine requires some, or all, of the following:

1) improving the smaller engine design to raise efficiency,

2) decreasing the "auxiliary loads" on the engine, sometimes referred to as "auxiliary losses,"

3) reducing the tractor and/or tractor-trailer unladen ("tare") weight through reducing the mass of the engine[91] and transmission (especially the rotating components), the wheels, the tractor chassis, the trailer frame, and the decreased size of the fuel tank. This raises the payload to achieve higher ton-miles per gallon productivity within the class limits and probably focusses on reducing the rotating mass in the powertrain, wheels, and tires together with a smaller displacement engine,

4) decreasing the torque required from the engine to maintain the tractor-trailer cruising speed—typically 65 mph—at high torque engine ranges.

Several additional engine and drivetrain improvements that might be expected to enter Class 8 specifications in the period ending in MY 2025 are discussed in the remainder of this appendix.

A.1.1.2 Reducing Friction Loss

The frictional losses of an engine, transmission, and differential all involve one metal surface moving relative to another in the presence of a lubricant. The losses in all three components can

[91] https://www.ttnews.com/articles/cummins-takes-over-lead-heavier-class-8-engines

be decreased via improved lubricant formulations, where it must be noted that all three components use different lubricants. Additionally, the transmission and differential both involve gear pairs—multiple gear pairs in the case of the transmission. Torque transmission via a gear pair involves frictional, windage (the combination of hydrodynamic and aerodynamic drag), bearing, and sometimes seal losses. The inefficiency of this torque transmission (generally an inefficient torque multiplication) can be decreased via an improved gear set design. Frictional losses in the engine are dominated by the piston rings and the camshaft. Improved design of the rings and all of the engine bearings, including the camshaft bearings, can decrease these losses. Replacement of sliding friction with rolling friction, such as for the lifters, can also be used to decrease engine internal friction. The engine also has parasitic and auxiliary losses. The parasitic losses are those that result from the energy used to operate the components that are essential to engine operation: the oil, fuel, and coolant pumps and the alternator. The auxiliary losses are those energy demands from the engine for non-engine purposes, such as the power steering pump and the HVAC system.

A.1.1.3. Waste Heat Recovery

Many Diesel engines used in Class 8 trucks are already turbocharged, recovering much of the waste heat in the engine's exhaust. However, the exit stream from the turbine section of the turbocharger is still hot enough under many engine operating conditions to create additional opportunities for waste heat recovery. Waste heat recovery systems that can be applied to the turbine exit stream include Organic Rankine Cycles, thermoelectric generators, and turbo-compounding.

Turbo-compounding refers to placing an additional turbine downstream from the turbocharger's turbine. The additional turbine recovers additional waste heat, but instead of powering a compressor as in a turbocharger, the additional turbine is connected to the crankshaft through a gear train. In July of 2017, Volvo Trucks announced release of the new 13-liter Volvo D13TC turbo-compound engine intended for customers with long-haul, mostly steady-speed operations. They claim a 6.5% improvement in fuel efficiency[92].

[92] Volvo Trucks (2017), https://www.volvotrucks.us/news-and-stories/press-releases/2017/july/volvo-d13-turbo-compound-engine-powers-new-volvo-vnl-series/

Thermoelectric generators use a solid-state device exposed to exhaust heat that converts heat flux (the heat transfer rate—driven by a temperature difference—per unit area) directly into electrical energy through a phenomenon called the Seebeck effect,[93] which can be used to power key electrical components of the engine and/or vehicle. In May 2013, John Fairbanks of the DOE Vehicle Technologies Office targeted a 5% or better improvement in fuel economy for light-duty vehicles[94] using such an approach. However, the target for HDVs would necessarily be smaller because the Diesel engine is more efficient than the gasoline engine that is used in the vast majority of light-duty vehicles, such that the turbocharged Diesel's exhaust temperature (post turbine) is lower than for a gasoline engine. Organic Rankine Cycles are similar to steam power plants but use a working fluid that will boil at a lower temperature—an organic working fluid such as R152a (difluoroethane) and R601 (normal pentane). Organic Rankine Cycles have the most potential for energy generation and have moderate costs in packaging and maintenance compared to the other two, so they are the most common[95].

A.1.1.4. Electrification of Auxiliaries

Many engine parasitic and auxiliary loads must function properly at idle but are over-speeded away from idle. Two common examples of auxiliary loads are the power steering pump and the air conditioning compressor. The engine's parasitic loads are those components that are essential to operation of the engine: water pump, oil pump, fuel pump, and alternator. It is impractical to drive the alternator and oil pump with an electric motor, and little is gained by driving the fuel pump with an electric motor. However, the engine's cooling requirement is a much stronger function of "torque demand" (the accelerator pedal position) than of engine speed so the water pump is a candidate for electrification. The fuel economy of trucks can be increased by driving suitable components with an electric motor, allowing control of their speed to be independent of engine speed (rpm), and thereby reducing belt-driven parasitic and/or auxiliary losses. Currently, electrification is economically feasible for the water pump, the air compressor for the air brake

[93] See: https://www.britannica.com/science/Seebeck-effect
[94] Fairbanks, J.W. (2013), "Automotive Thermoelectric Generators and HVAC", presentation at the 2013 Annual Merit Review and Peer Evaluation Meeting, DOE Vehicle Technologies Office, May; available at https://www.energy.gov/sites/prod/files/2014/03/f13/ace00e_fairbanks_2013_o.pdf
[95] Kanchibhotla, S., and S. Bari (2018), "Optimum design point to recover maximum possible exhaust heat over the operating range of a small diesel truck using bottoming Rankine cycle", SAE Paper 2018-01-1377; available at https://doi.org/10.4271/2018-01-1377

system, the compressor for the air conditioning system, and the radiator fan (e.g., Redfield et al.[96] and Vehr et al.[97]).

A.1.1.5. Advanced Heavy-Duty Engines

In SuperTruck I, the primary objective of development of advanced heavy-duty engines was a brake thermal efficiency (BTE, the ratio of brake power to the product of the mass consumption rate of the fuel and the energy density—constant pressure Lower Heating Value—of the fuel) of 50% with a stretch goal of 55%. As briefly discussed later in this subsection, the SuperTruck I goal of 50% BTE was accomplished via optimizing the fuel delivery and combustion processes, including the combustion chamber shape, higher peak cylinder pressure, minimizing frictional and parasitic losses, downsizing and downspeeding the engine, gas flow optimization, improved aftertreatment, and waste heat recovery.

Low temperature combustion (LTC) may be a key to accomplishing the stretch goal (which became a goal for SuperTruck II) because it minimizes emissions of NOx and particulate matter. For the heavy-duty market, there are three strategies for attaining LTC: "Advanced Diesel Combustion," Reactivity Controlled Compression Ignition (RCCI), and the High Efficiency Dilute Gasoline Engine (HEDGE). In their discussion of Diesel LTC, Musculus and co-investigators[98] wrote "Numerous LTC strategies with various names and acronyms have been proposed in investigations in the literature. In recent years, the defining characteristics of the various strategies have become less distinct as they have evolved and/or broadened so that they overlap with each other." Thus, the term "Diesel LTC" is used in this report to categorize all LTC strategies that use Diesel fuel, other than RCCI and HEDGE. Chadwell and coworkers[99], from modeling and analysis, found that, as of late 2010, the efficiency of the conventional Diesel engine was equal to

[96] Redfield, J., B. Surampudi, B., Gustavo, A. Montemayor, and H. McKee (2006), "Accessory electrification in Class 8 tractors", SAE Paper 2006-01-0215; available at https://doi.org/10.4271/2006-01-0215
[97] Vehr, S., K. Pistone, and M. Gariety (2018), "Implementation of electrified air conditioning on a Class 8 long haul vehicle", SAE Paper 2018-01-0061; available at https://doi.org/10.4271/2018-01-0061
[98] Musculus, M.P.B., P.C. Miles, and L.M. Pickett (2013), "Conceptual models for partially premixed low-temperature Diesel combustion", *Progress in Energy and Combustion Science*, **39**:246-283.
[99] Chadwell, C., T. Alger, C. Roberts, and S. Arnold (2011), "Boosting simulation of high efficiency alternative combustion mode engines", SAE Paper 2011-01-0358; also, in: *Journal of Engines*, 4(1):375-393.

or better than any of the high-efficiency combustion concepts. In 2013, Stanton[100] summarized Diesel LTC research as among the ongoing efforts to decrease GHG emissions (improve fuel consumption) from heavy-duty Diesels used in commercial vehicles. He noted that "there is a wide range of fuel efficiency associated with the different modes of LTC." He found that premixed charge compression ignition with an "early" start of combustion had been shown to produce a higher BTE, ~48%, than the other Diesel LTC strategies. It must be noted that this is lower than the 50% BTE goal of SuperTruck I, but additional advances in the various LTC strategies should be expected.

In the U.S. DOE's SuperTruck I program, Cummins demonstrated a heavy-duty Diesel engine with 51.1% BTE[101] that same year[102], accomplished through improvements in engine design (+2 percentage point increase in BTE), gas flow optimization (+2 percentage point increase in BTE), reduction in frictional and parasitic losses (+1 percentage point increase in BTE), improved aftertreatment (+0.5 percentage point increase in BTE), and an Organic Rankine Cycle waste heat recovery system (+3.6 percentage point increase in BTE).

Additionally, Daimler Trucks reported 50.2% BTE for the same operating condition[103]. This was accomplished via downsizing from 14.8 L to 10.7 L, an improved turbocharger match, optimized liner cooling, use of a lower viscosity oil, piston friction reduction, 15% higher peak cylinder pressure, optimization of the engine calibration, and refinements to the shape of the piston bowl and injector matching, decreased EGR with consequent increased engine-out NOx emissions, and model-based controls[104]. Daimler also decreased the parasitic and auxiliary loads via a variable speed water pump, an electric motor driven air conditioning compressor, a clutched air compressor

[100] Stanton, D.W. (2013), "Systematic development of highly efficient and clean engines to meet future commercial vehicle greenhouse gas regulations", SAE Paper 2013-01-2421, the 2013 L. Ray Buckendale Award lecture; also, in: *Journal of Engines*, 6(3):1395-1480.

[101] Peak brake thermal efficiency measured over a single point representative of the engine installed in a truck driving at 65 mph in level road with no wind, not over a transient (i.e., the heavy-duty Federal Test Procedure) or multimode steady-state (i.e., Supplementary Emissions Test) cycles.

[102] Delgado, O., and N. Lutsey (2014), "The U.S. SuperTruck Program: expediting the development of advanced heavy duty vehicle efficiency technologies", white paper presented to the International Council on Clean Transportation; available at https://www.theicct.org/sites/default/files/publications/ICCT_SuperTruck-program_20140610.pdf.

[103] Rotz, D., and M. Ziegler (2015), "Class 8 Truck Freight Efficiency Improvement Project", Daimler Trucks presentation to the DOE Office of Vehicle Technologies Annual Merit Review, June; available at https://www.energy.gov/sites/prod/files/2015/07/f24/arravt080_vss_rotz_2015_o.pdf

[104] National Academies of Sciences, Engineering, and Medicine (2015), *Review of the 21st Century Truck Partnership, Third Report*, Washington, DC: The National Academies Press.

with active controls, and a clutched power steering pump with reservoir. Daimler also incorporated an Organic Rankine Cycle with ethanol as the working fluid, using not only waste heat in the exhaust but also waste heat from the EGR system. Figure A.1.2 illustrates how these modifications, together with aerodynamic, rolling resistance, and other improvements to the tractor-trailer system (the various improvements to the tractor-trailer system are discussed later in this appendix), affected the torque required from the engine during operation over a 10-mile stretch of reasonably flat highway.

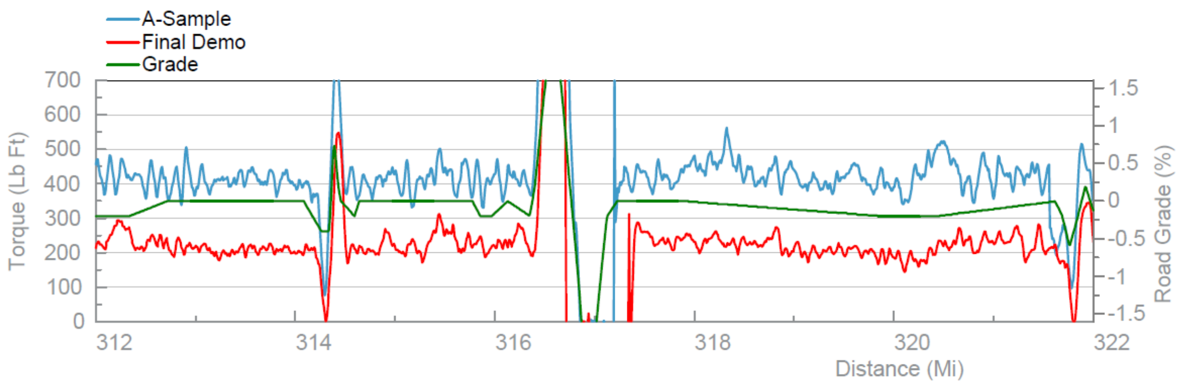

Figure A.1.2: A large decrease in required torque was realized between an intermediate (blue) and the final versions (red) of Daimler's SuperTruck I engine[105].

Figure A.1.3 illustrates how this affected the fuel consumed as a function of percent load during operation of the Daimler Trucks SuperTruck I experimental Class 8 tractor-trailer on IH 35 between Dallas and San Antonio, Texas.

[105] Rotz, D., and M. Ziegler (2015), "Class 8 Truck Freight Efficiency Improvement Project", Daimler Trucks presentation to the DOE Office of Vehicle Technologies Annual Merit Review, June; available at https://www.energy.gov/sites/prod/files/2015/07/f24/arravt080_vss_rotz_2015_o.pdf

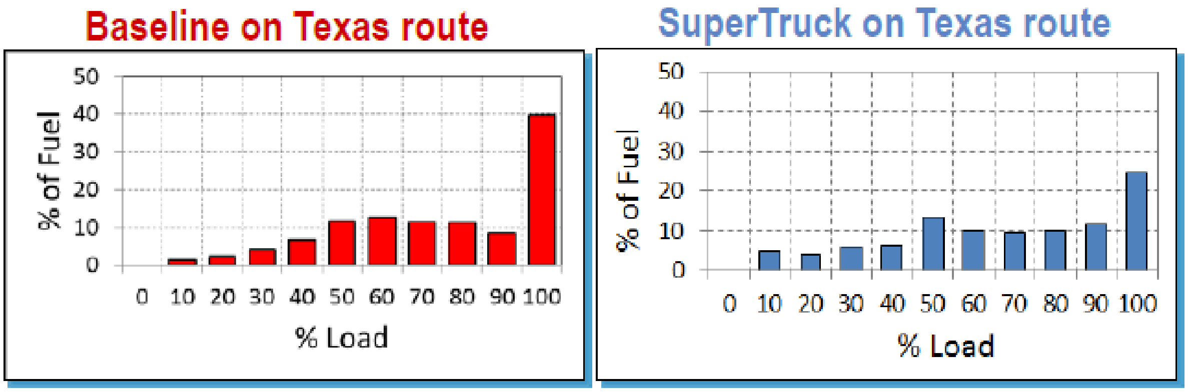

Figure A.1.3: Decreased torque requirement and drivetrain improvements (blue) produced less fuel consumption at full load for Daimler's SuperTruck I[106]

Figure A.1.4 compares the BSFC maps of Daimler's baseline Detroit Diesel DD15 14.8 L Diesel to that of their optimized, downsized 10.7 L, downspeed SuperTruck I engine. The thick red line is the full load torque curve of the DD15 engine while the thick blue line is that for the downsized, downspeed 10.7 L SuperTruck I engine. The SuperTruck I engine has more torque below ~950 rpm but less torque at higher speeds. The thin grey lines in Figure A.1.4 are constant power curves. The SuperTruck I engine develops less rated power than the DD15. In other words, the SuperTruck engine has also been "derated" relative to the DD15, but rated power is of less practical interest than full load torque. Of most interest in Figure A.1.4 are the thick purple curves, which illustrate the percentage improvement in BSFC for the SuperTruck I engine relative to the DD15 baseline, as a function of engine speed and required torque. The improvements in BSFC are impressive and are a result of the numerous engine improvements Daimler incorporated, as listed above.

[106] Rotz, D., and M. Ziegler (2015), "Class 8 Truck Freight Efficiency Improvement Project", Daimler Trucks presentation to the DOE Office of Vehicle Technologies Annual Merit Review, June; available at https://www.energy.gov/sites/prod/files/2015/07/f24/arravt080_vss_rotz_2015_o.pdf

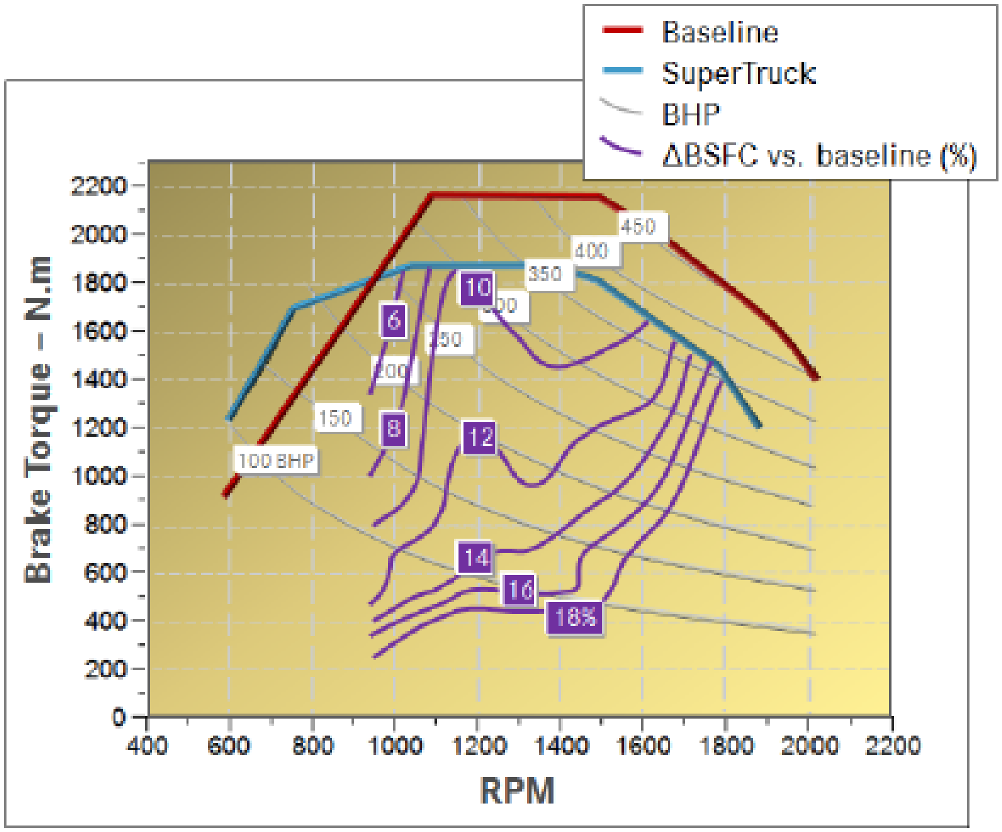

Figure A.1.4: Detroit Diesel DD15 14.8L versus Daimler SuperTruck 10.7 L engines

Volvo Group Trucks joined the SuperTruck program a year later than Cummins and Daimler. However, they demonstrated 50.0% BTE with application of a variety of engine and combustion improvements, including waste heat recovery via turbo-compounding[107]. Their major combustion improvement was incorporation of a new piston bowl design that yielded an increase in fuel economy of ~2% along with a 90% decrease in particulate matter emissions[108]. As an additional means of using waste heat, Volvo also used an Organic Rankine Cycle downstream from the turbo-compound technology.

Navistar's SuperTruck I vehicle achieved 13 mpg and demonstrated 50.3% BTE[109] using a variety of efficiency elements shown in Box A.1. These are also shown in Figure A.1.5.

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[107] Gravel, R. (2016), "Freight mobility and SuperTruck"; available at https://www.iea.org/media/workshops/2016/egrdtransportsystemsofthefuture/4SuperTruckBriefingOct2016IEAMtgRmG.pdf

[108] Gibble, J., and P. Amar (2016), "SuperTruck powertrain technologies for efficiency improvement", presentation to the 2016 DOE Annual Merit Review meeting, June.

[109] Zukouski, R. (2016), "Development and Demonstration of a Fuel-Efficient, Class 8 Tractor & Trailer Engine System"; Final Scientific/Technical Report for SuperTruck Project**,** Department of Energy National Energy

Box A.1. Navistar SuperTruck I Prototype

Technology Updates:

- Redesigned H.E Variable Geometry Turbocharger
- Low Pressure Drop EGR System
- Redesigned High Flow Efficiency Cylinder Head

- Redesigned combustion chamber design including:
    - piston bowl optimization;
    - increased peak cylinder pressure, and
    - improved thermal management

- Heat loss reduction: Electrical Thermostat and hood shutter system, Thermal Barrier Coatings (piston, head, liner)
- Parasitic loss reduction: Water and Oil Pumps
- Friction reduction: downspeed, Low Viscosity Lube Oil,
- High Efficiency Aftertreatment System with decreased pressure drop
- High Efficiency Gear train
- Waste Heat Recovery with Organic Rankine Cycle

Performance Metrics:

- Downspeed Lug Curve with 400 HP rating
- Low Base Engine Heat Rejection: ~18%
- Engine BTE: ≥ 50.3% (w/WHR)

Technology Laboratory, Dec., revision June 2018; available at https://www.osti.gov/servlets/purl/1460104dia.navistar.com/index.php?s=43&item=812

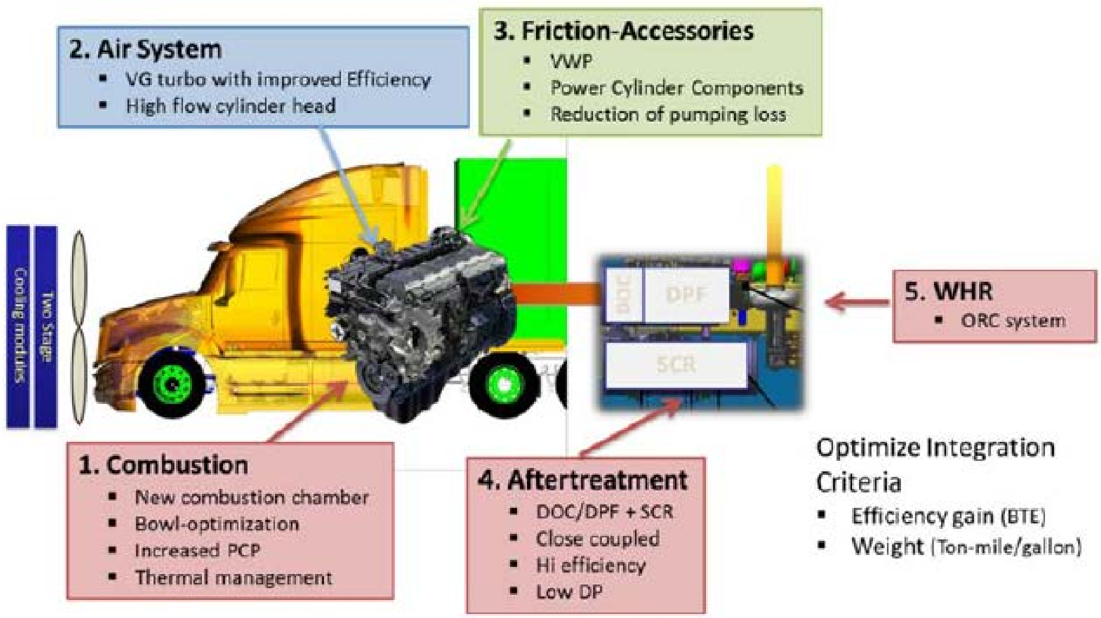

Figure A.1.5: Navistar SuperTruck I Prototype Truck: Five Focus Areas

Navistar's predictive cruise control technology is one example of a significant technical innovation the company achieved through the SuperTruck program. Predictive cruise control looks ahead of the vehicle and recognizes the terrain and continuously calculates the most efficient speed and gear for optimal fuel economy in real time. Unlike conventional predictive cruise technology, the company's predictive cruise control uses preinstalled GPS maps and the latest commercial route data to adjust cruising speed without the need to pre-drive the route. The next step is to update information collected by other Navistar vehicles and update GPS systems of all Navistar units to capture not only terrain but accidents, congestion, and states' highway maintenance and repair activities.

Other improvements included the following:

- Advanced integration of Navistar® N13 Engine utilizing proprietary intelligent controls and high efficiency combustion.
- Reduction in aerodynamic drag through replacement of cab- and hood-mounted mirrors with a series of cameras and interior-mounted monitors, which also yield equal or better indirect vision for the driver.

- A new LED headlamp system that reduces lamp size for a more aerodynamic shape and cuts electrical power requirements by greater than 80%, while improving luminous output and light color for improved night-time direct driver vision and reduced driver fatigue.
- An all-new shape with a sloped windshield and wedged cab for improved aerodynamics. Innovative use of lighter-weight carbon-fiber panels in the upper body, roof headers, back panel, and dash panel.
- A hybrid front suspension and lightweight rear suspension that leverages lightweight alloys with composite materials, reducing weight and enabling an electronic ride height management system, which provides dynamic ride height and pitch control for improved aerodynamics.
- Aerodynamic improvements that reduce the trailer's drag coefficient by more than 30%.

A.1.2 Additional Truck Engine Research Areas

A.1.2.1. Combustion Chamber Systems

Combustion chamber systems appear to have a number of future benefits, though not in the immediate future. Cummins, Daimler, and Volvo all used a conventional diffusion combustion process rather than the premixed controlled compression ignition, RCCI[110], homogenous charge compression ignition, or HEDGE[111] concepts. Thus, application of these concepts to heavy-duty truck engines appears to be well beyond the 2025 limit of this project.

A.1.2.2. Variable Valve Actuation

Two of the major elements of the 21st Century Truck Partnership (see Citation #55) were the following: "Develop and apply reliable, low-cost methods for fully variable valve timing to enhance low temperature combustion, aftertreatment, air handling, and compression braking. Develop optimum control strategies."

[110] See: http://www.w-erc.com/services/rcci/
[111] See: https://phys.org/news/2010-06-hedge-technology-low-speed-pre-ignition-highly.html

A.1.2.3. Hydraulic Hybrid

Hydraulic hybrids use a hydraulic motor in addition to the regular combustion engine to drive the vehicle. The hydraulic motor is powered by regenerative braking, which re-pressurizes fluid that is then used by the motor to help power the vehicle. This utilizes the kinetic energy expended during braking of the vehicle into a reusable form: high pressure hydraulic fluid. In addition to improving energy efficiency by 60 to 100%, hydraulic hybrids also reduce emissions by up to 40%[112]. The manufacturing cost is low and there is a decreased need for both brake and engine maintenance[113].

A.1.3 Cab and Operational Improvements

A.1.3.1. Vehicle Positioning—LIDAR (Pulsed Laser Light) and RADAR

All Class 8 tractor manufacturers are currently testing various systems that locate the vehicle relative to the traffic around it, most especially "blind spots" and the relative speed of the vehicle to the vehicle ahead in the same lane. These systems can provide first audible warnings and then apply the brakes if the closing speed is considered high. These systems are being continually refined with feedback from users. A fleet operator working in the Texas Triangle (Fort Worth/Dallas – San Antonio – Houston) who has specified these systems since MY 2016 attests that the systems contribute to the high safety rates of the company,[114] although the system is sensitive to city entry ramps on the network, especially where autos join at high convergence speeds during rush hour travel. Positioning technologies is an area of high benefits for both operating and social costs and can be linked into GPS mapping THAT can update other vehicles in the fleet with real-time traffic condition data.

A.1.3.2. Platooning

Platooning is a major element of autonomous research being tested in selected U.S. states and in many countries, including the E.U. and China. It is not considered in this project because of the

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[112] EPA (2012). "Hydraulic Hybrids", 9 Aug.; available at https://archive.epa.gov/otaq/technology/web/html/research-hhvs.html

[113] Further details, together with details of the application applied to refuse trucks is given in Citation #67

[114] The company has over 550 tractors and 800 drivers, with over 300 attaining accident-free 1 million miles of driving.

current literature and the early stages of adoption that place it after 2025. A connected platoon has several advantages to the freight operator who sends several trucks at the same time to destinations along a known route. However, most trucks are not loaded and dispatched in this way, creating wait times at the dispatching area and potential problems with the electronic logging devices now mandated for Class 8 use. Platooning requires the systems described in A.1.3.1 above, with the addition of braking system links that follow the braking decisions of the lead truck.

A.1.3.3. Battery HVAC

Fuel is wasted when trucks run the air conditioner or heater for long periods at idle. By using electricity to run the heating and air conditioning, these auxiliary losses are reduced and fuel consumption during idle can also be reduced as the air conditioning can be run for around two hours without using the engine.

A.1.4. Tractor-Trailer Aerodynamics

Truck motion first overcomes rolling resistance as speed increases until, around 45 mph, air resistance becomes a larger non-linear force, most especially when cruising speed exceeds 65 mph. In general, reducing the aerodynamic drag of a vehicle, especially Class 8 vehicles, is one of the most cost-effective ways to increase fuel efficiency. The upgrades that decrease aerodynamic drag are related to the shape of the tractor-trailer system and how easy it moves through the air. If air is allowed a smooth transition from the leading edge to the end of the system, it produces less flow resistance. Many of these upgrades require very little in terms of materials, can be installed on existing systems, and are relatively simple—requiring less engineering time in relation to, for example, new driveline components. Some examples of these include boat tails, wheel covers, side skirts, and trailer gap reduction, all of which require only thin shaped panels of metal or composite, which are cheap, light, and easy to produce and install. It is also important to note that percentage individual improvements noted in the literature on drag reduction do not necessarily fully aggregate to reflect system benefits.

A.1.4.1 Commercialized Aerodynamic Technologies

The technology types available in 2016, near the end of the SuperTruck I program, included tractor aerodynamics (bumper designs, roof fairings, chassis fairings, tractor/trailer gap fairings) and trailer aerodynamics (side skirts, boat tails, gap fairings). Additionally, those aerodynamic technologies that were expected to be available by 2018 were all in the trailer aerodynamics spectrum (full trailer skirts including trailer wheels, engineered trailer surfaces for reduced drag). By 2020, it was anticipated that even more features would become commercially available, including active aerodynamic features (moving radiator grill shutters, etc.), more extensive redesigns of tractor aerodynamic surfaces (cabs, hoods, etc.), tractor and trailer underbody aerodynamics, and tractor/trailer gap reduction. The longer-term aerodynamic features included cameras to replace outside mirrors, articulating/active tractor/trailer gap closures, and reconfiguration of tractor and trailer to reduce aerodynamic drag (e.g., engine and transmission placement, etc.). Several of these aerodynamic improvements are illustrated in Figure A.1.6 and are discussed in the following subsections.

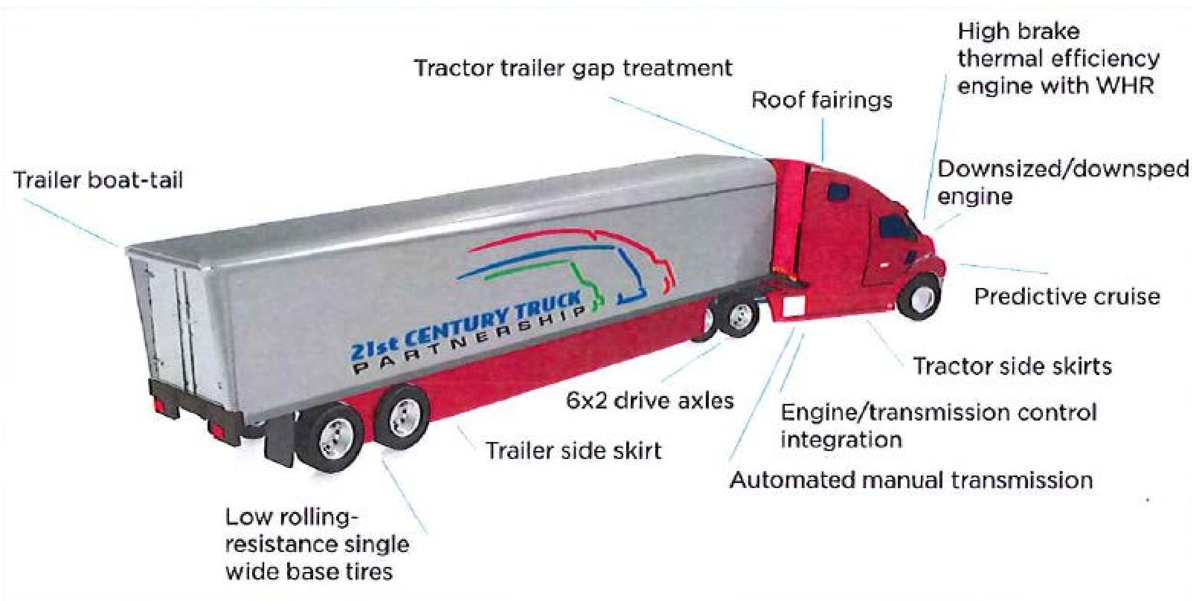

Figure A.1.6: Approximate locations of several fuel efficiency technologies, including aerodynamic improvements, evaluated in SuperTruck I[115]

Figure A.1.7 presents Daimler Trucks' final SuperTruck I design.

[115] DOE (2016), "Adoption of new fuel efficient technologies from SuperTruck", Report to Congress, June; available at https://www.energy.gov/sites/prod/files/2016/06/f32/Adoption%20of%20New%20Fuel%20Efficient%20Technologies%20from%20SuperTruck%20-%206-22-16%20%28002%29.pdf

Figure A.1.7: Daimler Trucks' final SuperTruck I design showed an overall freight efficiency improvement of 115% (image from citation[116])

A.1.4.2. Mirror Removal

Class 8 trucks are equipped with large, rectangular side mirrors to offer maximum visibility and limit the amount of space to the sides of the vehicle that are considered "blind spots." The large surface area, shown in Figure A.1.8, adversely affects the coefficient of drag of the system as well as the frontal area, and if made more aerodynamic can cause roughly a 1% drag reduction on the entire tractor-trailer system. Ideally, with the rapid decrease in video and screen costs, the entire side mirrors can be removed and replaced with in-cab side view displays. A full delete of the mirrors has been tested to show roughly a 2% drag reduction[117] for the entire system. This is not without issue, as the current road laws do not allow for a vehicle to operate without side-view mirrors, even though side-view displays would likely completely eliminate "blind spots." This technology has recently been displayed on the new Class 8 Tesla truck. This 1–2% drag reduction is equivalent to roughly a 0.5–1% increase in fuel efficiency.

[116] Jensen, S. (2016), "SuperTruck Returns", *OEM Off Highway*, August; available at https://www.oemoffhighway.com/engines/article/12231403/doe-announces-supertruck-ii-freight-efficiency-program
[117] See: https://www.trucks.com/2018/04/16/stoneridge-removes-truck-side-mirrors/

Figure A.1.8: The Cummins-Peterbilt final SuperTruck I design showed an overall freight efficiency improvement of 86% (citation[118])

A.1.4.3 Side Skirts

Side skirts are thin metal or composite sheets fitted along the sides or bolted beneath the trailers. These skirts are usually half as long or as long as the distance between the front trailer axles to the rear trailer axles. They work to lower the coefficient of drag by giving the air moving around the system a smooth surface to glide over, rather than creating turbulence after the front trailer axles because of the large open space. Half skirts and full skirts reduce drag on the system by roughly 4% and 6% respectively[119], or 2% and 3% increases in fuel efficiency.

A.1.4.4. Turbulence

Turbulence can be generated by the gap between the truck and trailer. This turbulence, created as the air flows over the cab of the truck, can be virtually eliminated by using trailer gap reducers. These can be metal, composite, or very flexible materials such as rubber and are fixed to the trailer. They extend from the trailer to as close to the rear of the cabin as possible or are simply attached

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[118] Jensen, S. (2016), "SuperTruck Returns", *OEM Off Highway*, August; available at https://www.oemoffhighway.com/engines/article/12231403/doe-announces-supertruck-ii-freight-efficiency-program
[119] See: https://www.truckinginfo.com/113851/sae-fuel-economy-tests-reveal-aero-device-performance

to the rear of the cabin. When attached, a partial gap reducer and a full gap reducer reduce drag by 1% or 2% respectively, or 0.5% to 1% increases in fuel efficiency.

A.1.4.5. Boat Tails

Boat tails are add-on metal or composite sheets attached to the rear of the trailer that allow the flow of air at the rear of the trailer a slower transition to the surrounding air. These extensions work to reduce the parasitic turbulence due to the low-pressure area that is created by a vehicle when it is at speed. This upgrade decreases aerodynamic drag by roughly 4%, or a 2% increase in fuel efficiency.

A.1.4.6 Wheels and Tires

Other sources of aerodynamic drag occur around the cavities of the wheels. This is fixed through using metal or composite panels to cover either (a) the wheel cavity or (b) the entire side of the tractor and trailer axles, which creates a smooth flow along the entire vehicle. However, for operational needs, access must be made available for safety and tire replacement or checking. This upgrade can decrease drag by roughly 1%, or a 0.5% increase in fuel efficiency.

A.1.4.7 Lighter Metals, Axles, or Composites

Traditional steel frames offer strength and value but can be heavy. Using aluminum instead of steel, the chassis weight can be reduced by up to around 60%, with a weight saving of around 700 pounds in the frame rails alone. This does come at a cost, but rising prices of fuel make it a more cost-efficient option. Certain parts of the frame can even be made from carbon fiber should manufacturing costs come down, namely aerodynamic modifications.

A.1.4.8 Liftable Axles

State laws mandate that truck weight must be spread over multiple axles to preserve infrastructure. However, when trucks are unloaded, the extra axles only add rolling resistance and decrease fuel economy. In addition, in U.S. regions where there is little freezing, tractors can be specified in 6x4 format where a tag axle follows the leading single driving axle. When running empty, operators can raise one tractor and/or one trailer axle—termed “liftable”—and, as long as trucks meet braking performance and weight axle limits, this lowers rolling resistance and raises engine efficiency.

A.1.4.9 Tire Technologies

Class 8 trucks can lower the rolling resistance of tires in two ways. First, they can purchase tires with lower resistance, now made by all leading tire companies. Second, they can replace dual tires with one extra-wide or “super single” tire, which has a tread area less than the two it replaces. Additional benefits are gained when the extra-wide tires are fitted on aluminum wheels, which reduces tare weight. Alcoa claims that extra-wide tires on aluminum hubs can save 1,272 lbs. on a Class 8 tractor-trailer[120].

A.1.4.10 Air Suspensions

Air suspensions can decrease a truck’s aerodynamic profile, but they are prone to failure, and are more expensive than traditional suspensions. By integrating components of an air suspension into a traditional composite leaf spring system, Navistar has been able to achieve dynamic ride height and pitch, while reducing the weight of the suspension, and adding stability[121]. Current weight savings range from 65 to 90 pounds depending on wiring complexity and base suspension[7].

A.1.4.11 Regenerative Dampening

Regenerative dampening harnesses the waste energy from truck suspensions and provides energy to supplement the alternator. This decreases the alternator’s load on the engine, yielding a fuel savings of 0.44% in a recent study[122]. Cost has not yet been evaluated for a full regenerative damping system on Class 8 trucks, but it is one of a number of research projects to provide vehicle electrical energy and reduce engine parasitic power loss.

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[120] See: http://www.tirereview.com/super-wide-tires-aluminum-wheels-weight-savings/

[121] Gehm, Ryan, “Navistar's SuperTruck II explores composites, Wi-Fi to Cut Weight”, article in SAE Truck & Off-Highway Engineering, pg. 29, SAE International October 2017; available at http://www.nxtbook.com/nxtbooks/sae/17TOFHP10/index.php#/30.

[122] Mossberg, J., Anderson, Z., Tucker, C., and Schneider, J., "Recovering Energy from Shock Absorber Motion on Heavy Duty Commercial Vehicles," SAE Technical Paper 2012-01-0814, 2012, https://doi-org.ezproxy.lib.utexas.edu/10.4271/2012-01-0814.

Appendix A.2: U.S. Trucking and the Adoption of Diesel Engines

Dr. Rudolf Christian Karl Diesel patented a design for a high compression engine in 1893 and spent another 4 years refining the design at Maschinenfabrik Augsburg Nurnberg (MAN) AG in Augsburg, Germany[123]. MAN Diesel engines appeared on German submarines during the First World War[124] and until 1930, most applications were in the marine sector. Prior to the Second World War (WW2), use of trucks with Diesel engines was confined to Europe—especially Germany and the UK—and then gained slow but steady market share in tractors, buses, and trucks after 1945 (see Box A2.1).

Box A2.1: Diesel Engine Development 1880 to 1950

1880 – 1900 various stationary engines tested

1914 – MAN marine Diesel engines fitted to German submarines

1920s – Marine applications tested

1930s – Large MAN truck engine (160 BHP; 120 KW); medium truck Gardener 4-cylinder LW (80 BHP; 60 KW) engines fitted to Foden, Atkinson, ERF models and 1936 Mercedes Benz 260 D (45 BHP; 35 kW) truck/auto models

1940s – WW2 applications, principally German; Cummins patented common rail fuel delivery systems; German and UK trucks

The attraction of the Diesel engine lies in its thermal efficiency and longevity. European transportation, especially trains, buses, and trucks, moved to Diesel power throughout the 1950s. Truck operators in Europe faced high fuel taxes imposed to pay wartime debts and extensive urban and industrial reconstruction after WW2. European gasoline was more expensive as a truck fuel and Diesel engines were reaching a million miles of life before major rebuilds. Emission particulates were recognized as different from gasoline exhaust gases but were accepted as externalities and did not prevent most city buses across the world being powered by Diesel engines[125]. The first U.S federal emission limits were introduced in 1974 and gradually tightened in a number of steps. The current mandatory emission standards for heavy-duty Diesel were undertaken after 2000, culminating in the 2007–10 period.

[123] A patent to Herbert Akroyd Stuart, given two years earlier, lacked the high compression and thermal efficiency of Diesel's patent.
[124] Maschinenfabrik Augsburg Nurnberg (MAN) AG built Diesel engines for the German WW1 submarines in 1914 and was a leader in offering Diesel engines to European truck manufacturers.
[125] In Europe, large cities provided public transport services using high quality bus engines and maintenance services which reduced particulate emissions.

A.2.1. Evolution of Diesel Usage in the U.S.

In the U.S., low fuel prices and taxes together with the regulated structure of the trucking industry did not encourage the purchase of higher-cost Diesel engines. Gasoline truck engines could be easily serviced over most truck networks. Three overlapping 1956 to 1990 events occurred that made Diesel the engine of choice in the U.S. medium and large truck classes.

A.2.1.1. The Passage of the 1956 Federal-Aid Highway Act[126]

Weaknesses in the U.S. national highway system were well known in the decade leading up to WW2, but most states focused on improving their systems of rural highways to all-weather conditions, using either paved or gravel designs.[127] Key corridors were improved in certain states, funded by state or toll investments[128] but first the recovery from the 1930s recession, followed by the wartime economy, delayed any attempts to address national highways needs.

This delay made the 1956 Act one of the two most important pieces of transportation legislation in the twentieth century. It proposed to link all cities with populations of 50,000 with national boundaries using a 41,000-mile controlled access highway system, funded with an authorization of $25 billion and built over a 12-year period. It was to be a federal system, subject to federal laws—speed, design, life cycle performance (20-year pavement design and 50-year bridge design lives)—with the federal government paying 90% of the cost and each state paying the remaining 10%. It was overly ambitious in terms of scope but not scale and was only completed in 1992[129]. It was funded through the creation of the Highway Trust Fund and used federal fuel taxes as its main source of revenue, supported by state fuel taxes. It required State Highway Departments to restructure their operations so that they could efficiently implement the new federal system while maintaining their state highway system. This involved raising state fuel taxes on gasoline and Diesel fuel, instituting registration fees for all vehicles, and taking responsibility for public safety on the new system.

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[126] Also known as the National Interstate and Defense Highways Act (Public Law 84-627).
[127] This was known as "pulling the famer out of the mud."
[128] This funding technique is also termed "public-private partnerships."
[129] This section was 1-70 at Glenwood Canyon, Colorado. The 12-mile section included 40 tunnels and bridges was claimed to be the most expensive piece on the final interstate system.

In Texas, for example, pavement designs were developed in the late 1950s and a decision was made to provide frontage roads at each side of the controlled access lanes, increasing the right-of-way needed for each interstate mile. Most states, however, chose to limit highway right-of-way acquisitions to the federal main lanes. Interstate lane construction began in the early 1960s, while interstate bridge construction peaked during the 1968–1974 period so that the Texas interstate system was completed in the early 1980s. Texas had 3417 centerline miles of Interstate highways and 7453 miles of frontage roads as of 2014[130] and trucks carry 70% of the freight ton-miles on Texas state and interstate corridors.

The interstate bypassed city centers, which dramatically lowered travel times, making trucks more competitive with railroads. Traffic moving through San Antonio prior to the interstate system passed in front of the Alamo; using IH 35 cut travel time by almost an hour. The interstate system drove up the demand for trucking and Class 8 truck gross weight rose from 58,000 lbs. in 1958 to 80,000 lbs. by 1982. Critically, the interstate system extended the daily truckload mileage from around 200 miles per day[131] to over 400 miles per day, which contributed to the decline of the railroads after WW2. This was a major final step towards making trucking the major U.S. transportation mode in terms of reach, economic impact, and therefore political strength.

A.2.1.2. 1970s Energy Crises

The construction of the Interstate Highway system did not at first encourage U.S. truck operators to move away from gasoline, unlike truckers in some other countries. U.S. fuel was inexpensive, plentiful, and available through stations built near interstate sections as they were completed. However, in October 1973, an Arab attack on Israeli-held positions, known as the Yom Kippur War, failed in its attempt to move back Israel's borders. Shortly thereafter, members of the Organization of Arab Petroleum Exporting Countries (OPEC) decided to impose an embargo on those countries that had supported Israel. They increased the posted price per barrel by 70%, which in the U.S. created widespread fuel shortages (and some panic) as fuel prices rose significantly and

[130] See http://texashighwayman.com/texhwys.shtml
[131] Railroads were largely limited to labor rules fixed during the steam era at around 130 miles per shift.

demand exceeded refinery capacities[132]. The embargo ended in March 1974, when the price had risen from US$3 per barrel to nearly $12 globally with U.S. prices significantly higher.

The embargo caused an oil crisis that had both short- and long-term effects on global politics and the global economy. It was then followed by a second event in 1979 that was later called the "second oil shock." The impact of higher energy prices spread beyond trucking and impacted the U.S. economy. The world financial system was set on a path of recessions and inflation persisted until the early 1980s, with oil prices remaining elevated until 1986. This had a profound impact on trucking operations in two ways. First, it stimulated use of Diesel—even in U.S. automobiles—and created a pathway for widespread Diesel adoption in U.S. trucking. Second, fuel costs were now second only to driver costs and it made truckers concentrate on adopting measures and technologies to lower fuel consumption—an objective still critical in 2018[133].

Over the long term, the 1973 oil embargo changed U.S. policy towards increased exploration, alternative energy research, and energy conservation, culminating in the diverse current program embracing electric and hybrid autos, tax subsidies on reducing energy loss, solar power, and strict Diesel truck emissions legislation. The third element critical to enhancing the role of U.S. freight transportation came in the form of extensive modal Federal deregulation legislation largely passed in the 1975–1980 period.

A.2.1.3. Transportation Deregulation[134]

Regulation of public and private operations is an accepted responsibility of almost all democratic governments to ensure a safe, competitive, and sustainable transportation system. In the U.S., Federal regulations passed in the 1880s were undertaken to address monopolies although it was an imperfect system in the sense that not all essential data could be either collected or analyzed to set efficient and equitable prices. The most notable U.S. Federal agency engaged in regulation was the Interstate Commerce Commission (ICC), which was operated from 1887 to 1996, though in a

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[132] Panic buying, where drivers tried to keep their tanks full, overwhelmed U.S. refinery capacity.
[133] ATRI estimated that driver salaries and benefits constituted 45% of operating costs, followed by fuel at 21%. See: http://atri-online.org/wp-content/uploads/2017/10/ATRI-Operational-Costs-of-Trucking-2017-10-2017.pdf
[134] Industrial regulation plays an important role in economic history and theory which is not the focus of this report. Further information can be found at www.uu.nl/rebo/ecoomie/researchpapers

much-altered form after 1976. The agency's original purpose in 1887 was to regulate railroads, which were the major domestic transportation mode and able to fix prices to take advantage of monopoly positions faced by many farmers or drive out competition by lowering prices (as they did with many canals). The ICC was required to ensure fair rates, eliminate rate discrimination, and regulate other aspects of railroad operations. Congress expanded ICC authority in 1906 to interstate trucking and telecommunications. In 1934, Congress gave authority for telecommunications to a new Federal Communications Commission and in 1935 passed the Motor Carrier Act, which extended ICC authority to regulate interstate bus lines and trucking under "common carrier" rules. Finally, it was abolished in 1995 and its remaining rail functions were transferred to the Surface Transportation Board.

Post-WW2 economic theories of benefits from reducing transportation regulation gained favor and influenced the presidencies of Nixon, Ford, Carter, and Reagan. Table A.2.1 shows a series of comprehensive deregulation legislation was passed into law during a two-decade period that profoundly impacted modal operations, particularly trucking and rail.

Table A.2.1: Major U.S. Legislation to Deregulate Transportation Modes

Date - Act
1976 – Railroad Revitalization and Regulatory Reform Act (4R Act) PL 94-210
1978 – Airline Deregulation Act PL 95-50
1980 – Motor Carrier Act PL 96-296
1980 – Staggers Rail Act PL 96-448
1982 – Bus Regulatory Reform Act PL 97-261
1984 – Ocean Shipping Act
1986 – Surface Freight Forwarder Deregulation Act
1994 – Federal Aviation Administration Authorization Act 49 US Code 14501
1996 – Telecommunications Act PL 104-104

The first comprehensive proposal to deregulate transportation in the United States was forwarded to Congress in 1971. This proposal was initiated and developed by an interagency group that included the Council of Economic Advisors, the Department of Transportation, the Department of Labor, and other agencies. It addressed rail and truck transportation and built a coalition of users, Federal agencies, and academics that was used in all subsequent deregulation legislative planning. President Ford, with the allied interests, secured passage of the first significant change in regulatory policy in a pro-competitive direction, in the Railroad Revitalization and Regulatory Reform Act of 1976. This Act, also known as the "4R" Act, addressed some of the more critical operating characteristics of the U.S. railroad sector, including support of some failing companies. President Carter presided over the most important legislation of the decade, including the Airline Deregulation Act (signed October 24, 1978), the Staggers Rail Act (signed October 14, 1980), and the Motor Carrier Act of 1980 (signed July 1, 1980). President Reagan signed legislation addressing competition in various forms: interstate buses (1982) and freight forwarders (1986). States sometimes pushed back against new federal laws and the Federal Aviation Administration Authorization Act of 1996 reasserted federal authority preventing "two or more States from enforcing any law, rule, regulation, standard with respect of motor vehicles, freight forwarder, motor carrier on intrastate travel."

The dominant common theme of these Acts was to lessen barriers of entry in transport markets and promote more independent, competitive pricing among transport service providers, substituting the freed-up competitive market forces for detailed regulatory control of entry, exit, and price making in transport markets. Therefore, U.S. deregulation promoted competition over a wide range of modes, although those governing maritime transportation were less successful since they lacked the authority over the domestic modes.

Deregulation stimulated multimodal systems, particularly as containerization[135] systems grew in the 1960s to dominate non-bulk global freight movements[136]. The study of freight logistics became refined during the same time period and now comprises information systems that collect, analyze,

[135] Malcolm McLean, a U.S. trucker, pioneered containerization in the 1960s when he formed Sea-Land and perfected a series of patents that were made available royalty-free to the International Organization for Standardization (ISO). https://en.wikipedia.org/wiki/Malcom_McLean. Accessed Feb 19, 2018

[136] U.S. domestic containers—larger than export containers—in 2016 formed approximately half of U.S. rail intermodal (containerized) business. U.S. rail domestic rail hubs now serve all major metropolitan areas with final delivery made using drayage trucks.

and improve freight movements and support a more competitive multimodal transportation system. This approach is also known as *supply chain management*. Final delivery of freight is dominated by trucking and their operations will play a critical role in future metropolitan and megaregional planning operations. Autonomous truck research—either with or without drivers—has attracted attention since 2012 and is now producing reports on several key areas of vehicle operations and safety[137], but an area of immediate impact is the potential for trucks of all types to be cleaner, safer, and more efficient in the next decade, supporting the current systems of supply chain management and lowering the social costs, especially those related to safety and air quality. Autonomous systems produce substantial volumes of dynamic data that will enable state DOTs to price highway use based on time of day, utilization levels, and axle loads to produce efficient and equitable funding mechanisms irrespective of fuel choice.

[137] Kockelman, K. et al. Bringing Smart Transport to Texans: Ensuring the Benefits of a Connected and Autonomous Transport System in Texas (Phase 2)—TxDOT Project 0-6838—Final Report, Center for Transportation Research, July 2018. http://library.ctr.utexas.edu/ctr-publications/0-6838-3.pdf

Appendix A.3: Supplemental Images of Trucks Described in This Report

Urban vehicle manufacturers are concentrating on designing cleaner vehicles, particularly in the larger cities. The UK Royal Mail is now testing electric using prototype trucks from Banbury-based Arrival in London. They will operate out of the Mount Pleasant depot and move packages between mail distribution centers in the city and the local area. It's also stated the trucks meet vision standards, which says drivers or large vehicles should be able to see pedestrians and cyclists without using mirrors or cameras.

Separately, the Royal Mail bought 100 zero emission electric delivery vans built by Peugeot earlier this year. The vans, which will used on delivery rounds, will enter service in December. Charging stations will be installed at delivery offices to support the roll-out.

The Arrival vehicles, shown in Figure A.3.1, have been designed with the ability to run on their battery for 100 miles and the firm says they will produce zero emissions for this time. A dual power mode within the vehicles can be used after the first 100 miles to top-up the battery.

Figure A.3.1: A U.K Royal Mail Electric Arrival Truck 2018[138]

[138] https://www.wired.co.uk/article/royal-mail-electric-truck-test-arrival

Volvo has electric trucks in production as well; Figure A.3.2 presents the Volvo FE. Selected Volvo FE features include the following:

- Fully electrically powered truck for distribution, refuse collection, and other applications in urban conditions; GVW of 30 tons
- Driveline: Two electric motors with 370 kW max power (260 kW cont. power) with a Volvo 2-speed transmission. Max torque electric motors 626 lb.-ft. Max torque rear axle 28 kNm.
- Energy storage: Lithium-ion batteries, 200–300 kWh
- Range: Up to 124 miles
- Charging: Two different charging systems are available. CCS2: Maximum charge power 150 kW DC. Low Power Charging: Maximum charge power 22 kW AC
- Charging time: From empty to fully charged batteries (300 kWh): CCS2 150 kW approximately 1.5 hours; low power charging approximately 10 hours.

Figure A.3.2: Volvo FE Urban Electric Truck

In 2018 Mercedes-Benz and Daimler Trucks unveiled a prototype called the Urban eTruck, a heavy-duty all-electric truck meant to be used in and around big cities (Figure A.3.3). The truck will have a weight capacity of 29 US tons and a range of 200 kilometers (124 miles). The two brands, which are both overseen by Daimler AG, plan to begin production in the early 2020s.

Figure A.3.3: Mercedes Benz Urban eTruck