ANL/ESD-15/9
Rev. 1

The GREET Model Expansion for Well-to-Wheels Analysis of Heavy-Duty Vehicles

Energy Systems Division

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by
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ACRONYMS AND ABBREVIATIONS

AEO	Annual Energy Outlook
AF	alternative fuel
AFV	alternative-fuel vehicle
APTA	American Public Transportation Association
ASTM	American Society for Testing and Materials
BC	black carbon
BTW	brake and tire wear
CAP	criteria air pollutant
CARB	California Air Resources Board
CBD	Central Business District
CID	cubic inch displacement
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon dioxide
DGE	diesel gallon equivalent
DME	dimethyl ether
DOC	diesel oxidation catalyst
DOE	U.S. Department of Energy
DPF	diesel particulate filter
EEV	Enhanced environmentally friendly vehicle
EIA	U.S. Energy Information Administration
EPA	U.S. Environmental Protection Agency
FTP	Federal Test Procedure
GEM	Greenhouse gas Emission Model
GGE	gasoline gallon equivalent
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation
GVW	gross vehicle weight
GVWR	gross vehicle weight rating
HC	total hydrocarbons
HD-UDDS	Heavy-duty Urban Dynamometer Driving Schedule
HDV	heavy-duty vehicle
HEV	hybrid electric vehicle
HHV	hydraulic hybrid vehicle
HPDI	high-pressure direct injection

LEM	Lifecycle Emissions Model
LNG	liquefied natural gas
LPG	liquefied petroleum gas
LSD	low-sulfur diesel
LSFC	load-specific fuel consumption
MOVES	Motor Vehicle Emission Simulator
MPDGE	miles per diesel gallon equivalent
MPG	miles per gallon
MY	model year
NAS	National Academy of Sciences
NG	natural gas
NGV	natural gas vehicle
NHTSA	National Highway Traffic Safety Administration
NMHC	non-methane hydrocarbons
NO_x	nitrogen oxide
NREL	National Renewable Energy Laboratory
NTD	National Transit Database
OC	Oxidation catalyst
OCTA	Orange County Transit Authority
OEM	original equipment manufacturer
PM	particulate matter
$PM_{2.5}$	particles less than 2.5 micrometers in diameter
PM_{10}	particles less than 10 micrometers in diameter
POC	primary organic carbon
psi	pounds per square inch
PTO	power take-off
SCAQMD	South Coast Air Quality Management District
SCR	selective catalytic reduction
SU	single-unit
TWC	three-way catalyst
UDDS	Urban Dynamometer Driving Schedule
ULSD	ultra-low sulfur diesel
VIUS	Vehicle Inventory and Use Survey
VMT	vehicle miles traveled
VOC	volatile organic compounds
WVU	West Virginia University

ABSTRACT

Heavy-duty vehicles (HDVs) account for a significant portion of the U.S. transportation sector's fuel consumption, greenhouse gas (GHG) emissions, and air pollutant emissions. In our most recent efforts, we expanded the Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET^{TM}) model to include life-cycle analysis of HDVs. In particular, the GREET expansion includes the fuel consumption, GHG emissions, and air pollutant emissions of a variety of conventional (i.e., diesel and/or gasoline) HDV types, including Class 8b combination long-haul freight trucks, Class 8b combination short-haul freight trucks, Class 8b dump trucks, Class 8a refuse trucks, Class 8a transit buses, Class 8a intercity buses, Class 6 school buses, Class 6 single-unit delivery trucks, Class 4 single-unit delivery trucks, and Class 2b heavy-duty pickup trucks and vans. These vehicle types were selected to represent the diversity in the U.S. HDV market, and specific weight classes and body types were chosen on the basis of their fuel consumption using the 2002 Vehicle Inventory and Use Survey (VIUS) database.

VIUS was also used to estimate the fuel consumption and payload carried for most of the HDV types. In addition, fuel economy projections from the U.S. Energy Information Administration, transit databases, and the literature were examined. The U.S. Environmental Protection Agency's latest Motor Vehicle Emission Simulator was employed to generate tailpipe air pollutant emissions of diesel and gasoline HDV types.

In addition, the fuel consumption and emissions of a portfolio of alternative fuel (AF) and hybrid options that are being developed and deployed for each of the HDV types were analyzed relative to their conventional counterparts. The AF options include biodiesel, dimethyl ether, renewable diesel, compressed natural gas, liquefied natural gas, liquefied petroleum gases, ethanol, and electricity. The hybrid options include hybrid electric and hydraulic hybrid technologies. Fuel consumption and emissions of AF vehicles from the literature were reviewed and the results were generally presented in the form of changes relative to the conventional baseline vehicles in the GREET model.

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1 INTRODUCTION

Medium- and heavy-duty trucks and buses were responsible for about 24% of the energy consumption and about 23% of the greenhouse gas or GHG (carbon dioxide [CO_2], nitrous oxide [N_2O], and methane [CH_4]) emissions of the U.S. transportation sector in 2013 (U.S. Energy Information Administration, 2015; U.S. Environmental Protection Agency, 2014a). Medium- and heavy-duty truck CO_2 emissions increased by 71% from 1990 to 2013, largely because of a substantial growth in truck miles traveled, which increased by 92% between 1990 and 2013 (U.S. Environmental Protection Agency, 2015). In addition, U.S. truck freight shipments on a ton-mile basis are projected to increase by 52% between 2015 and 2040, likely increasing the environmental impacts of heavy-duty trucks (Freight Analysis Framework Version 3, 2015).

In response to these issues, the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) developed, in 2011, the first GHG emission and fuel efficiency standards for medium- and heavy-duty engines and vehicles, hereinafter referred to as the 2011 Standard (Federal Register, 2011). The 2011 Standard regulates a broad set of highway vehicle types—ranging from pickup trucks to combination truck tractors—representing the second largest mobile source contributor to U.S. oil consumption and GHG emissions, after light-duty passenger cars and trucks.

The 2011 Standard is tailored to three regulatory subcategories of heavy-duty vehicles (HDVs): heavy-duty pickup trucks and vans (Class 2b-3), vocational vehicles (Class 2b-8), and combination tractors (Class 7-8), all of which have a gross vehicle weight rating (GVWR) of 8,501 pounds or greater. Table 1 shows how the EPA classifies vehicles by weight class (U.S. Environmental Protection Agency, 2014b). EPA's GHG emission standards begin with model year (MY) 2014, while NHTSA's fuel consumption standards are voluntary in MY 2014 and 2015 and mandatory in MY 2016–2018. EPA and NHTSA are developing the second phase of heavy-duty engine and vehicle standards for post-MY 2018 (U.S. Environmental Protection Agency, 2014c).

TABLE 1 Vehicle classification by gross vehicle weight rating, adapted from EPA (U.S. Environmental Protection Agency, 2014b)

GVWR (lb)	Up to 6,000	Up to 8,500	Up to 10,000	Up to 14,000	Up to 16,000
Vehicle Classification	LDT 1 & 2	LDT 3 & 4	HDV Class 2b	HDV Class 3	HDV Class 4
GVWR (lb)	Up to 19,500	Up to 26,000	Up to 33,000	Up to 60,000	Larger than 60,000
Vehicle Classification	HDV Class 5	HDV Class 6	HDV Class 7	HDV Class 8a	HDV Class 8b

In the 2011 Standard, EPA and NHTSA followed National Academy of Sciences (NAS) recommendations by adopting GHG emission and fuel consumption metrics that account for the work performed by various types of HDVs (National Research Council, 2010). For heavy-duty pickup trucks and vans, EPA and NHTSA established standards on a per-mile basis (g/mi for EPA and gal/100 mi for NHTSA). For combination tractors and vocational HDVs, the agencies adopted standards expressed in terms of a key measure of freight movement, a single ton of goods moved one mile or, more simply, ton-miles (g/ton-mile for EPA and gal/1,000 ton-miles for NHTSA). The 2011 Standard for these HDV subcategories is summarized in Appendix A.

Given HDVs' significant contributions to energy consumption and emissions by the transportation sector, intensive research and development efforts are under way to reduce their environmental impact. Advancements in engines, body design, transmission, and tailpipe emission control technologies that are being or have recently been achieved are key to meeting existing and new emission and fuel consumption regulations for HDVs. Meanwhile, pursuit of sustainable transportation systems requires evaluation of the environmental impacts of both conventional-fuel and alternative-fuel vehicles (AFVs) and advanced vehicles, with a holistic life-cycle analysis approach.

To achieve this goal, a Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET™) HDV module called GREET3 was developed in the late 1990s to evaluate the life-cycle energy use, GHG emissions, and air pollutant emissions of five HDV types: i.e., trucks ranging from Class 2b to Class 8b and two types of buses. Other life-cycle models, including the Lifecycle Emissions Model (LEM) and the GHGenius model, which is based on LEM but tailored for Canada, are capable of simulating life-cycle emissions of HDVs as an aggregated group of buses or trucks or a combination of both (Delucchi, 2003; (S&T)2 Consultants, 2014). Later, the GREET model was modified to assess the energy and emissions of diesel-powered and five AF-powered Class 8 HDVs in New York in a case study (Meyer et al., 2011) and later in an analysis of CNG HDV emissions (Alvarez et al., 2012).

In this analysis, we revised the early GREET HDV module to incorporate more disaggregated HDV types, which are of importance to fuel consumption and emissions in the U.S. HDV transportation sector. Moreover, we investigated the fuel consumption and criteria air pollutant (CAP) emissions of specific HDV types. The results of the analysis of both conventional HDV types and a portfolio of AFV options are incorporated in the new HDV module of the GREET model developed at Argonne National Laboratory (Argonne National Laboratory, 2014).

2 COVERAGE AND CHARACTERISTICS OF HEAVY-DUTY VEHICLE TYPES

Each of the HDV subcategories in the 2011 Standard consists of a variety of vehicle GVWR classes, body types, and vocations. Fuel economy and emission rates will differ significantly according to these factors, so a more specific breakdown of each HDV type is needed. We identified the HDV types for each subcategory on the basis of U.S. fuel consumption data. Through this process of screening vehicle types representative of conventional trucks and buses, we selected the GVWR class, body type, and vocation of each HDV to be included in GREET.

2.1 CONVENTIONAL HEAVY-DUTY VEHICLES

The U.S. Census Bureau conducted the 2002 Vehicle Inventory and Use Survey (VIUS) to provide national and state-level estimates of HDV populations, characteristics, and usage (U.S. Census Bureau, 2004). The VIUS database contains an inventory of GVWR class, engine fuel type, engine displacement, body type, operating range, vehicle age, average laden weight, fuel consumption, and vehicle miles traveled (VMT), among others parameters, for each truck type. See Appendix B for more details on the VIUS database.

HDVs of different GVWR classes differed significantly from one another in their total fuel consumption and VMT, as shown in Table 2, according to the VIUS and data published by the American Public Transportation Association (APTA, 2013a). Class 8b trucks used the most fuel and had the highest VMT among the HDV GVWR subcategories, followed by Class 8a and Class 6 trucks. Buses accounted for about 3% of the total diesel fuel consumption, and accounted for less than 2% of the total VMT.

We further explored the 2002 VIUS database for the purpose of identifying the specific characteristics of the HDV with the highest U.S. fuel consumption for each of the 2011 Standard subcategories. During the data screening, we excluded those Class 2b vehicles dedicated as passenger vehicles (as well as Class 1 and 2), which are regulated by EPA’s light-duty GHG and fuel economy standards, not by the medium- and heavy-duty fuel consumption and CO_2 standards. Next, we grouped and characterized the remaining vehicles in the three regulatory vehicle categories. We further separated the combination tractor category into long-haul and short-haul tractors, as these vehicles are often differentiated by their range of operation. We also further broke down vocational vehicles into light heavy-duty (Class 2b–5), medium heavy-duty (Class 6–7), refuse (Class 8a), and heavy heavy-duty (Class 8b) single-unit (SU) trucks on the basis of characteristics such as fuel economy, payload, and engine displacement.

TABLE 2 Diesel fuel consumption and VMT of diesel heavy-duty trucks of different GVWR classes and buses in 2002

		Fuel Consumption		VMT	
Vehicle Type	GVWR	Million Diesel Gallons	Share	Million Miles	Share
Trucks[a]	Class 8b	14570	64.8%	82198	58.6%
	Class 8a	3267	14.5%	18999	13.6%
	Class 7	747	3.3%	5032	3.6%
	Class 6	1230	5.5%	9401	6.7%
	Class 5	411	1.8%	3753	2.7%
	Class 4	440	2.0%	4237	3.0%
	Class 3	639	2.8%	6651	4.7%
	Class 2b[b]	617	2.7%	7649	5.5%
Buses[c]		559	2.5%	2236	1.6%
All HDVs		**22571**	**100.0%**	**140331**	**100.0%**

[a] Source: VIUS, 2002 (VIUS was discontinued in 2002).
[b] Non-passenger Class 2b only.
[c] Source: APTA, 2013a; current bus fuel consumption and VMT are similar to 2002 values.

We broke down each vehicle category further, by GVWR class and body type, to more closely examine fuel economy and payload, as shown in Table C1. Table C1 provides fleet-average fuel economy (expressed in miles per gallon, or MPG) and fuel consumption considering effective payload (ton-mile/gallon) to account for the work performed by each HDV type. Information on the engine displacement indicates potential differences in fuel economy and emissions among HDV types of the same subcategory. Finally, the highest-fuel-consuming HDV by GVWR class and body type for each vehicle subcategory was selected for representation in GREET, as shown in Table 3. These highest-fuel-use vehicle classes were GVWR Classes 8b, 6, and 2b; similar observations were noted in a recent NAS study (National Research Council, 2010).

TABLE 3 Fleet characteristics of the highest-fuel-consuming vehicle types by GVWR class and body type in each vehicle subcategory, based on 2002 VIUS data

Engine Fuel	Regulatory Category	Vehicle Subcategory	Vehicle Type	Fuel Consumption (%)	Annual VMT (Wtd. Avg.)[a]	Fuel Consumption (gal/1000 ton-mi) (Wtd. Avg.)	Effective Payload (ton) (Wtd. Avg.)	Engine Displacement (L) (Wtd. Avg.)
Diesel[b]	Combination trucks	Combination long-haul	Trailer: Van, Class 8b	40.6%[c]	105,160	9.0	18.6	13.0
		Combination short-haul	Trailer: Van, Class 8b	7.7%[c]	57,580	11.8	14.7	12.7
	Vocational vehicles	Heavy heavy-duty vocational vehicles	Dump <=50 mi, Class 8b	1.5%[c]	27,640	15.7	12.7	12.2
		Refuse trucks	Trash/Garbage/Recycling, Class 8a	1.4%[c]	25,690	32.0	6.9	10.3
		Medium heavy-duty vocational vehicles	Van, Class 6	2.9%[c]	24,580	35.7	3.6	7.1
		Light heavy-duty vocational vehicles	Van, Class 4	0.8%[c]	24,540	50.6	2.1	6.1
	Heavy-duty pickup trucks and vans	–	Pickup, Mini & Light Van, SUV, Class 2b	1.9%[c]	23,090	7.4[d]	0.7	6.9

TABLE 3 (Cont.)

Engine Fuel	Regulatory Category	Vehicle Subcategory	Vehicle Type	Fuel Consumption (%)	Annual VMT (Wtd. Avg.)[a]	Fuel Consumption (gal/1000 ton-mi) (Wtd. Avg.)	Effective Payload (ton) (Wtd. Avg.)	Engine Displacement (L) (Wtd. Avg.)
Gasoline[e]	Vocational vehicles	Medium heavy-duty vocational vehicles	Van, Class 6	4.5%[f]	9,560	33.0	4.1	6.1
	Heavy-duty pickup trucks and vans	–	Pickup, Mini & Light Van, SUV, Class 2b	30.7%[f]	16,065	7.4[d]	0.9	5.5

[a] Fuel-consumption-weighted average.
[b] Diesel consumption accounted for 88.9% of total fuel consumption of all HDVs in 2002.
[c] These are volumetric shares of the total consumption of diesel gallons by the diesel HDV subcategory.
[d] In units of gal/100 mi.
[e] Gasoline consumption accounted for 10.9% of total fuel consumption of all HDVs in 2002.
[f] These are volumetric shares of the total consumption of gasoline gallons by the gasoline HDV subcategory.

A description of the major HDV types is given below.

2.1.1 Combination Long-Haul Trucks

A combination vehicle is a truck tractor with one or more trailers attached to it. A truck tractor (or tractor) does not have cargo-carrying ability, but rather has a powerful engine that allows it to pull cargo in various trailer types. The most common trailer type used in combination freight trucks is an enclosed dry van semi-trailer that is 53 feet long. Other trailer types include tank, flatbed, refrigerated (or reefer), and dump. These trucks are typically Class 8b vehicles, as their GVWR is greater than 60,000 lb.

Combination freight trucks are often differentiated by their range of operation. A long-haul (or line-haul) combination truck is generally defined as one that travels significant distances between cities using highways and interstates and does not return to the same location (home base) each night. The trucks used for long-haul routes often have a sleeping compartment that can contain other amenities such as a refrigerator, microwave, and television for the comfort of the driver, and are known as sleeper cabins (or cabs) (see Figure 1).

The EPA and NHTSA (U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, 2011) state that long-haul trucks typically travel at least 1000 mi along a trip route, and the EPA/NHTSA base case for sleeper cab tractors is that they are driven 500 mi per day, while the EPA's Motor Vehicle Emission Simulator (MOVES) vehicle emissions modeling program adopts the VIUS definition for combination long-haul trucks as those with a range of operation of over 200 mi (U.S. Environmental Protection Agency, 2013a). Similarly, America's Natural Gas Alliance (2013) states that line-haul trucks can travel more than 500 mi per day, while short-haul trucks drive 200 mi or less per day on average. For our analysis of VIUS data, we followed the VIUS definition and categorized combination trucks with a range greater than 200 mi per day as long-haul.

FIGURE 1 Combination long-haul truck (National Renewable Energy Laboratory, 2014a)

2.1.2 Combination Short-Haul Trucks

In comparison to long-haul trucks, combination short-haul freight trucks drive fewer miles per day and drive at slower speeds. Short-haul (or regional-haul) trucks generally return to the same location each night and thus do not have a sleeping compartment. Tractors without sleeping accommodations are known as day cabins (or cabs) (see Figure 2). However, they are like long-haul trucks in that they are typically Class 8b vehicles with a similar-sized engine. They also pull heavy cargo in various trailer types, with the most common being an enclosed dry van semi-trailer that is 53 feet long. Our analysis of VIUS data showed that the average payload for short-haul trucks was only about 10% lower than for long-haul trucks. However, combination short-haul trucks drove more of their total miles (24%) with no cargo than long-haul trucks (14%), so the effective payload of short-haul trucks is about 21% lower (see Table 3).

The EPA and NHTSA state that regional-haul trucks typically travel less than 500 mi along a trip route (U.S. Environmental Protection Agency and National Highway Traffic Safety Administration, 2011) In contrast, for its vehicle emissions modeling program MOVES, EPA defines combination short-haul trucks as those with a range of operation of up to 200 mi (U.S. Environmental Protection Agency, 2013a). Similarly, America's Natural Gas Alliance (2013) states that on average, short-haul trucks drive 200 mi or less per day. For our analysis of VIUS data, we followed the MOVES definition and categorized combination trucks with a range less than or equal to 200 mi per day as short-haul.

FIGURE 2 Combination short-haul truck (National Renewable Energy Laboratory, 2014b)

2.1.3 Refuse Trucks

A refuse (or garbage) truck is a vehicle designed to collect garbage at multiple locations and haul it to a central location (e.g., landfill). These trucks are typically Class 8a vehicles; while there are combination trucks that haul refuse long distances, our focus is on single-unit trucks used for local waste collection. Depending on the waste being collected, the refuse truck can have various designs to load the garbage into the body of the truck. Figure 3 shows a residential side loader; rear loaders are also a popular configuration for residential pickup, and front loaders are typically used for large industrial and commercial waste containers. Rear- and side-loaders typically make 400–1,200 stops per day, while front-loaders make 100–200 stops.

Refuse trucks have compaction systems to reduce the volume of the waste. These systems typically utilize power take-off (PTO), which allows the vehicle's engine to power the compactor via a connection through the transmission (Muncie Power Products, 2008). Refuse trucks use significant amounts of fuel because of their PTO systems and their drive cycle behavior, which can involve significant stop-and-go driving and long idle times.

FIGURE 3 Refuse truck (National Renewable Energy Laboratory, 2014c)

2.1.4 Vocational Vehicles

A vocational (or work) vehicle is a general term to describe a commercial vehicle (i.e., not a passenger vehicle) designed for a specific function. These vehicles are often sold as a stripped chassis (no body or passenger compartment) or a cutaway (no body but with a passenger compartment), and one or more companies (upfitters) will install a body and other equipment to finish the vehicle to the specifications of the customer. Vocational vehicles include a wide range of truck body types (e.g., dump, utility, plow, armored, tow, concrete mixer, pickup, refuse, and delivery) and bus types (e.g., transit, intercity, and school). In our analysis, we have examined several of these vocational vehicles separately (long-haul combination, short-haul combination, refuse, pickup, transit, intercity, and school).

For other vocational vehicles, as there are so many different types, we used three categories to cover them, based on GVWR: heavy heavy-duty (Class 8, GVWR > 33,000 lb), medium heavy-duty (Class 6–7, 19,500 lb < GVWR ≤ 33,000 lb), and light heavy-duty (Class 2b–5, 8,500 lb < GVWR ≤ 19,500 lb). While the classifications are somewhat arbitrary, they are consistent with the EPA and NHTSA's heavy-duty fuel efficiency regulations (Federal Register, 2011). As described previously, we analyzed VIUS data to determine key vocational types and then selected the one with the highest fleet fuel use to be the representative for each category. For heavy heavy-duty (Class 8) vocational vehicles, Class 8b single-unit dump trucks had the largest fleet fuel use (see Table C1). These trucks are typically used at construction sites and have an open-top box body that can be lifted using a hydraulic system to empty out its contents (see Figure 4). Other heavy heavy-duty vocational body types include concrete mixers, flatbeds, and tanks.

FIGURE 4 Heavy heavy-duty vocational vehicle – Class 8 dump truck (Shutterstock, 2014)

For medium heavy-duty (Class 6–7) vocational vehicles, Class 6 single-unit delivery trucks had the largest fleet fuel use (see Table 3). These trucks are typically used for local or regional pickups and deliveries and have an enclosed van body (see Figure 5). Single-unit trucks with an enclosed van body are often known as "box trucks." Other medium heavy-duty vocational body types include flatbed, tank, beverage, dump, and utility.

FIGURE 5 Medium heavy-duty vocational vehicle – Class 6 delivery truck (Enterprise, 2014)

For light heavy-duty (Class 2b–5) vocational vehicles, Class 4 single-unit delivery trucks had the largest fleet fuel use (see Table 3). These trucks are similar to Class 6 trucks in that they are used for local pickups and deliveries and have an enclosed van body, though they have less cargo-carrying capacity (see Figure 6). Other light heavy-duty vocational body types include flatbed, step van, armored, dump, utility, and tow.

FIGURE 6 Light heavy-duty vocational vehicle – Class 4 delivery truck (Wikimedia, 2014)

2.1.5 Heavy-Duty Pickup Trucks and Vans

Heavy-duty pickup trucks and vans are designed for commercial use and not passenger travel. In our analysis, we focus on Class 2b and Class 3 vehicles (8,500 lb $<$ GVWR $\leq$ 14,000 lb) for this category, to be consistent with EPA and NHTSA's heavy-duty fuel efficiency regulations (Federal Register, 2011). Original equipment manufacturers (OEMs)' Class 2b pickup trucks and cargo vans are often designated with either a "250" or "2500" in their model name, while for Class 3 they are often designated with either a "350" or "3500." We analyzed VIUS data and found that the Class 2b pickup trucks are the vehicle type with the highest fleet fuel use; therefore, we selected them to represent the category.

A pickup truck has an open-top cargo area (or bed) that is used for carrying loads (see Figure 7). A heavy-duty pickup has more cargo capacity and towing capability than a Class 1 or Class 2a truck, as it is typically built with a more powerful engine and stronger chassis. The other body type in this category is a cargo van, which has a van body that often does not have any separation from the passenger seats in the front. However, the van portion can be customized to include a separation along with other features, such as shelving and storage compartments.

FIGURE 7 Heavy-duty pickup truck (Wikipedia, 2014)

2.1.6 Transit Buses

A transit bus is a vehicle designed to transport passengers on local trips, generally within a city. The typical duty cycle is stop-and-go driving on local roads with frequent stops to pick up or drop off passengers along fixed routes. Transit buses come in several different configurations, though we chose a standard transit bus to represent the category. A standard Class 8a transit bus has a rear engine design, a body that is 40 feet long, and a seating capacity of 40, with additional room for other passengers to stand (Laver et al., 2007) (see Figure 8). Other types of transit vehicles include articulated buses and minibuses. An articulated bus has two body sections connected via a pivoting joint, is 60 feet long, and has a seating capacity of 60 passengers.

Minibuses are often used for demand response or paratransit service (along non-fixed routes), are 30 feet or less in length, and have a seating capacity of less than 30 passengers.

FIGURE 8 Transit bus (U.S. Department of Energy, 2013a)

2.1.7 Intercity Buses

An intercity bus (or motorcoach) is a vehicle designed to transport passengers on long-distance trips between cities. The typical duty cycle will involve high-speed travel on interstate highways with infrequent stops to pick up or drop off passengers. Intercity buses are large Class 8a vehicles with some structural features similar to transit buses (BusRates.com, 2014; John Dunham & Associates, 2012). However, unlike transit buses, these vehicles have luggage storage compartments underneath the seating area and may have comfortable reclined seating and bathroom facilities (see Figure 9). An intercity bus is at least 35 feet long and has a seating capacity of at least 30 but often up to 60 passengers.

FIGURE 9 Intercity bus (Shutterstock, 2013)

2.1.8 School Buses

A school bus is a vehicle designed to transport students to and from school or school-related activities. Depending on the school district, the typical drive cycle will vary. For example, the bus may primarily drive slowly on local roads with frequent stops or drive at higher speeds on rural highways with less frequent stops. There are four different school bus configurations, with Type C being the most common (see Figure 10) (School Bus Fleet, 2013). Type C is a large school bus mounted on a stripped chassis with a front engine design, a GVWR greater than 21,500 lb (typically Class 6 or Class 7), and a seating capacity of up to 70 to 80 passengers. Type A (cutaway) and Type B (stripped chassis) are small school buses with seating capacities of up to 20–30 passengers. Type D is a large school bus mounted to a stripped chassis, typically with a rear engine design similar to a transit bus, a GVWR greater than 26,001 lb (Class 7 or Class 8), and a seating capacity of up to 80–90 passengers.

FIGURE 10 School bus (National Renewable Energy Laboratory, 2014d)

2.2 ALTERNATIVE FUEL HEAVY-DUTY VEHICLES

Medium- and heavy-duty vehicles that use a wide range of alternative fuels and advanced heavy-duty vehicle engine and powertrain technologies are being developed to reduce petroleum fuel use, meet emissions requirements, improve vehicle fuel efficiency, reduce environmental impacts such as GHG emissions, and reduce operating costs (U.S. Department of Energy, 2013b). Specifically, alternative fuels that are less costly than conventional fuels, but require additional upfront costs, have found success in high-fuel-use market segments, particularly when on-site fueling is available. Table 4 summarizes the alternative fuel and advanced vehicle options and OEMs for twelve HDV subcategories that we considered in this analysis.

2.2.1 Biodiesel

Biodiesel is a mix of fatty acid methyl esters and can be produced from seed oils, fats, and grease through the transesterification process. In the U.S., most biodiesel is produced from soybean oil. This renewable fuel is typically blended (2% to 20% by volume) with petroleum diesel and can be used in a compression-ignition engine without significant engine modifications (Keller et al., 2007). According to the National Biodiesel Board, all OEMs' diesel vehicles in the U.S. allow at least B5 under warranty and almost 90% of the medium- and heavy-duty truck manufacturers allow B20 or higher blends in at least some of their vehicles (National Biodiesel Board, 2014). Blends containing up to 5% biodiesel by volume must meet the conventional diesel fuel standard, the American Society for Testing and Materials (ASTM) D975, while blends containing 6–20% biodiesel by volume must meet the ASTM D7467 standard. If B100 is to be used in a vehicle, it must meet the ASTM D6751 standard (ASTM International, 2014). In the past decade, the sales volume for biodiesel in the United States has increased dramatically, from about 14 million gallons in 2003 to 1.4 billion gallons in 2013 (U.S. Energy Information Administration, 2014b).

2.2.2 Natural Gas

Natural gas (NG) is stored aboard an HDV as either a compressed gas or a liquid. Compressed natural gas (CNG) is pressurized in a storage tank (also called a cylinder) at up to 3,600 pounds per square inch (psi). These tanks can come in various designs, ranging from full metal (typically steel) construction (Type 1), hoop-wrapped composite with a metal liner (Type 2), full composite wrap with a metal liner (Type 3), and full composite wrap with a plastic liner (Type 4). As weight is often an important consideration for HDVs, they typically use the lightest types of tanks (e.g., Type 3 and Type 4). Even at 3,600 psi, CNG has a lower energy density than either gasoline or diesel, so vehicle range can be reduced unless the vehicle carries a significant number of cylinders. In trucks and buses, cylinders can be mounted in several places, including the frame rails, back of the cabin, roof, and under the vehicle. Liquefied natural gas (LNG) is produced by purifying NG to remove impurities such as hydrogen sulfide and CO_2 and then cooling the NG to –260ºF. LNG is stored in double-walled, vacuum-insulated tanks and is used in HDVs, as it is more energy-dense, and hence requires smaller storage volumes to provide sufficient range, than CNG.

Currently, Cummins Westport is the primary manufacturer of NG engines for HDVs. Its offerings include the 8.9-liter ISL G engine, which was released in 2007, for refuse, transit, shuttle, school, vocational, and freight applications up to 66,000 lb GVWR. In 2013, it released the larger 11.9-liter ISX12 G engine for more demanding freight applications (up to 80,000 lbs GVWR). These engines utilize spark-ignition and turbocharging, and can use either CNG or LNG as fuels. To meet EPA and California Air Resources Board (CARB) 2010 heavy-duty engine emission standards, these engines use stoichiometric combustion with cooled exhaust gas recirculation and a three-way catalyst (TWC). These engines do not need to use particulate filters or selective catalytic reduction (SCR) for particulate matter (PM) or nitrogen oxide (NO_x) emission control.

Cummins Westport plans to start production in 2015 of its 6.7-liter ISB G engine to provide a less powerful but more fuel-efficient option for medium-duty vehicles. Cummins planned to develop a 15-liter ISX15 G for freight applications, but in 2014, it announced that the project was on hold (Bates, 2014).

In 2010, Westport Innovations released the HD 15-liter high-pressure direct injection (HPDI^{TM}) diesel pilot ignition engine. The HPDI engine uses a small amount of diesel (about 5% on an energy basis), which ignites at a lower temperature compared to NG, to enable compression-ignition of NG, and may exhibit significantly improved engine efficiency while consuming NG as its primary fuel (Gao et al., 2013). In this system, LNG is directly injected into the cylinder at a high pressure (4,500 psi) along with the diesel pilot fuel, as shown in Figure 11. This lean-burn engine maintains "diesel-like" torque and thermodynamic efficiency but requires a diesel particulate filter (DPF) and SCR to meet 2007/2010 emission standards. In 2013, the engine was discontinued because of market considerations, though Westport announced the development of its next-generation HPDI 2.0 engine with improved reliability and reduced costs. Volvo had planned to use the HPDI 2.0 technology for a 13-liter engine to be released in 2015, but recently announced it was putting the project on hold (Piellisch, 2014).

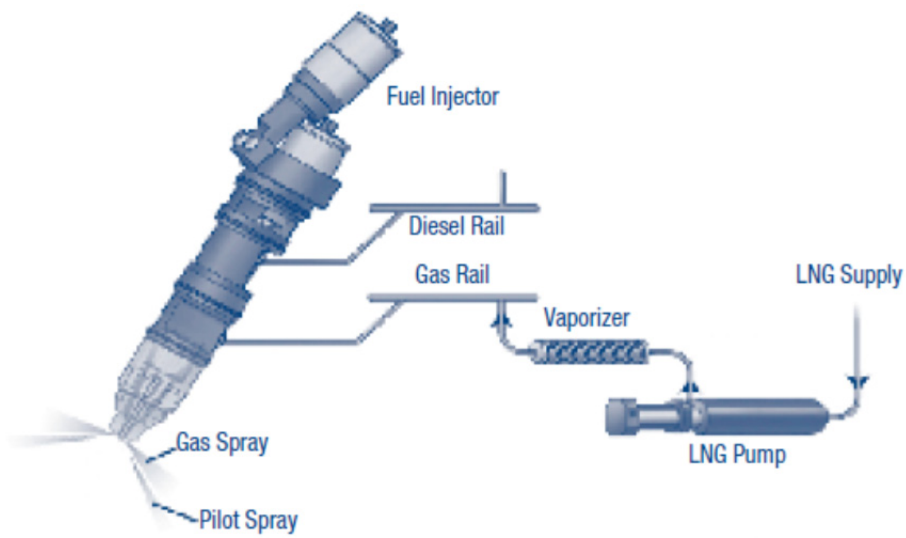

FIGURE 11 HDPI fuel system on LNG trucks (Chandler and Proc, 2004)

In addition to these larger-displacement engines based on diesel blocks, companies such as Westport, Landi Renzo, and BAF convert OEM gasoline engines, such as Ford's 6.8-liter V10, to NG for use in HDVs. These engines are typically used for medium-duty applications, such as shuttle buses and heavy-duty pickups and vans.

The U.S. Energy Information Administration estimates that in 2011, there were 8,216 medium-duty pickup trucks, 9,192 medium-duty vans, 15,164 heavy-duty trucks and 22,931 heavy-duty buses in the U.S. that ran on NG (U.S. Energy Information Administration, 2014c). The American Public Transportation Association (APTA, 2013b) showed that 18.6% of U.S. transit buses used CNG, LNG, and blends in 2011. The industry projects that as many as 60% of new refuse trucks sold will be CNG-fueled by 2016 (Boyce, 2013), while the U.S. Government estimates that 60% of the entire transit bus fleet could be NG-fueled by 2035 (U.S. Energy Information Administration, 2014a). Natural gas trucks might also account for a significant portion of the future combination freight market, with projections ranging from 20 to 40% of new sales in 2035, depending on fuel prices (National Petroleum Council, 2012). With combination freight vehicles accounting for a significant portion of HDV fuel use, that development would constitute a major change in the U.S. transportation system.

2.2.3 Liquefied Petroleum Gas

Currently, OEMs do not produce heavy-duty engines fueled with liquefied petroleum gas (LPG, commonly referred to as propane). Rather, companies such as Roush and Icom convert OEM gasoline engines, such as Ford’s 6.8-liter V10, for use in HDVs. Larger-displacement on-road LPG engines are not currently being developed (LP Gas, 2014). LPG trucks and buses have achieved success where supplies are readily available, duty cycles can be satisfied with light or medium heavy-duty vehicles, and vehicles return to a base location each day. School buses, shuttle buses, and heavy-duty pickups and vans have been early niche markets. The U.S. Energy Information Administration estimates that in 2011, there were 8,122 medium-duty pickup trucks, 8,159 medium-duty vans, 40,034 heavy-duty trucks and 6,515 heavy-duty buses running on LPG in the U.S. (U.S. Energy Information Administration, 2014c).

2.2.4 Hybrid Vehicles

Hybrid vehicles use an engine and motor along with a rechargeable energy storage system to deliver power to the vehicle. Hybrid electric vehicles use an electric motor along with a battery pack, while hydraulic hybrids use a hydraulic pump/motor combination along with a hydraulic accumulator. Hybrids are typically used in HDVs with drive cycles that involve significant amounts of stop-and-go driving and idling. Hybrids can take advantage of stop-and-go driving through the use of regenerative braking, which captures energy for use in the vehicle that would otherwise be lost during braking. Key vocational types for which hybrids have been used include transit buses, school buses, refuse trucks, and local delivery vehicles.

2.2.5 Battery Electric Vehicles

A battery electric vehicle, or all-electric vehicle, uses a battery pack to power an electric motor that drives the vehicle. Many types of batteries can be used in these vehicles, including lead acid, nickel metal hydride, and lithium ion, each of which can be recharged by plugging into an electrical source. However, owing to weight considerations, most HDVs being developed use lithium ion chemistries. Several companies have been developing this technology. Smith Electric has produced all-electric vehicles for many years, including the Newton delivery vehicle since 2006. Motiv has recently deployed an all-electric refuse truck in Chicago (Motiv Power Systems, 2014). In 2014, Chinese electric bus manufacturer BYD Motors demonstrated two all-electric buses using lithium iron phosphate batteries in the U.S.: one 40-foot bus with a range of 155 miles and one 60-foot bus with a range of 170 miles (Clover, 2014; Edwards, 2014). In addition, Proterra has produced a heavy-duty all-electric transit bus using lithium titanate batteries, which have fast-charge capabilities and significantly improved fuel economy as compared to diesel buses (Proterra, 2014). So far, production volumes of battery electric heavy-duty vehicles have been very low and confined to short-range urban applications.

2.2.6 Ethanol

Ethanol is an alcohol fuel that can be produced from various feedstocks such as corn, sugar cane, perennial grasses, and woody biomass. In the U.S., most ethanol is produced from corn, though there has been significant research and development done to produce it from cellulosic sources. This renewable fuel is commonly blended into conventional gasoline at up to 10% by volume, with blends up to 15% by volume being legal for 2001 and newer cars. Higher-level blends containing up to 85% ethanol by volume can be used in spark-ignited flexible-fuel vehicles. Ethanol to be used for blending must meet the requirements of ASTM standard D4806. Fuels with ethanol content from 51-85% by volume must meet the requirements of ASTM standard D5798. As it is used in spark-ignited engines, ethanol currently is only used in medium-duty vehicles. Specifically, General Motors has certified its 6.0-L engine to run on high blends of ethanol.

2.2.7 Dimethyl Ether

Dimethyl ether (DME) is a synthetic, sulfur-free, oxygenated fuel that can be produced from a variety of fossil feedstocks (including NG and coal), renewable biomass feedstocks, and waste. It has been identified as a substitute for diesel fuel in compression-ignition engines, as it has a high cetane number and favorable physical properties (e.g., no carbon-to-carbon bonds) for vaporization and atomization that promote cleaner combustion. Volvo has recently announced plans to commercialize the first DME-powered heavy-duty commercial vehicles in North America (Volvo, 2013).

2.2.8 Other Alternative-Fuel Vehicles

We exclude a few AFVs that are being developed and becoming available in the market owing to lack of available data on vehicle efficiency and emissions. These include electric Type-A school buses powered by a 120-kW induction motor with lithium-ion batteries, which are manufactured by companies like Trans Tech; hydrogen fuel-cell electric transit buses and tractor trailers; electric tractor trailers; electric heavy-duty vans and vocational trucks (U.S. Department of Energy, 2013b); and plug-in electric trucks. These vehicle types may be added to GREET in the future when their performance data become available.

TABLE 4 Consideration status and original equipment manufacturers of heavy-duty vehicles with various alternative fuel and vehicle technology options

Baseline vehicles	Biodiesel		Ethanol		CNG		LPG		LNG, Spark-Ignition	
	Considered?	OEM	Considered?	OEM	Considered?	OEM	Considered?	OEM	Considered?	OEM
Diesel combination long-haul	Yes	Multiple			Yes	Kenworth			Yes	Kenworth, Volvo, and others
Diesel combination short-haul	Yes	Multiple			Yes	Kenworth			Yes	Kenworth
Diesel heavy heavy-duty vocational vehicles	Yes	Multiple			Yes	Peterbilt			Yes	Peterbilt
Refuse trucks	Yes	Multiple			Yes	Heil Environ-mental			Yes	Mack Trucks
Diesel medium heavy-duty vocational vehicles	Yes	Multiple			Yes	Ford				
Gasoline medium heavy-duty vocational vehicles			Yes	Ford	Yes	Ford	Yes	Ford		
Light heavy-duty vocational vehicles	Yes	Multiple	Yes	General Motors	Yes	Ford	Yes	Ford		
Diesel heavy-duty pickup trucks and vans	Yes	Multiple			Yes	General Motors			\	
Gasoline heavy-duty pickup trucks and vans			Yes	General Motors	Yes	Ford	Yes	Ford		
Transit buses	Yes	Multiple			Yes	Nova and North American Bus Industries			Yes	North American Bus Industries
Intercity buses	Yes	Multiple			Yes					
School buses	Yes	Multiple			Yes	Blue Bird	Yes	Blue Bird		

TABLE 4 (Cont.)

Baseline vehicles	LNG, Diesel Pilot Ignition		Hydraulic Hybridization		Electric Hybridization		Battery Electricity	
	Considered?	OEM	Considered?	OEM	Considered?	OEM	Considered?	OEM
Combination long-haul	Yes	Peterbilt						
Combination short-haul	Yes	Peterbilt						
Heavy heavy-duty vocational vehicles					Yes	Kenworth		
Refuse trucks			Yes	Peterbilt			Yes	Motiv Power Systems
Medium heavy-duty vocational vehicles					Yes	Kenworth		
Light heavy-duty vocational vehicles					Yes	Eaton		
Diesel heavy-duty pickup trucks and vans					Yes	Toyota and Ford		
Transit buses Intercity buses					Yes	Nova Bus	Yes	Proterra
School buses					Yes	Thomas Built Buses		

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3 FUEL CONSUMPTION AND EMISSIONS OF CONVENTIONAL DIESEL AND GASOLINE VEHICLES

3.1 CONVENTIONAL DIESEL AND GASOLINE TRUCKS AND VOCATIONAL VEHICLES

3.1.1 Fuel Consumption

Using the proper functional units for fuel consumption is important when examining the efficiency of all vehicles. Additionally, for HDVs one needs to correctly account for the work performed by these vehicles. Fuel consumption per distance traveled has been shown to be the fundamental metric to properly judge fuel efficiency improvements from both engineering and regulatory viewpoints (National Research Council, 2010). Conversely, fuel economy (e.g., MPG) is not the appropriate measure for heavy-duty trucks because this metric does not take into account that these vehicles are designed to carry loads.[1] However, when fuel consumption is normalized to the vehicle's payload (e.g., gallons per ton-mile), the load-specific fuel consumption (LSFC) reflects this factor. Fuel economy, which is reported as an indicator of vehicle fuel efficiency in many HDV studies, can be readily translated to fuel consumption, as they are reciprocal, and to LSFC if the payload is known.

Following NAS recommendations for calculating LSFC (National Research Council, 2010), we analyzed the VIUS database, EPA's Greenhouse gas Emissions Model (GEM), and other data sources to estimate the real-world vehicle fuel consumption of various HDV types in relation to the work performed. The work performed is measured by calculating the average effective payload, which takes into account both the typical payload and miles driven without a load. Since fuel economy is a commonly reported parameter, it is estimated from the fuel consumption and used as an input parameter in GREET along with average effective payload.

MY-specific fuel economy data are used in GREET and in this analysis to evaluate the environmental impacts of advances in vehicle technologies. The real-world MY 2002-specific fuel economy and carried payloads from VIUS for nine HDV subcategories are shown in Table 5. In addition, we adopted the real-world fuel economy and payloads of pre-MY 2000 vehicles from the 2002 VIUS data for use in GREET. The VIUS fuel economy for combination long-haul trucks with sleeper cabs is adopted for combination long-haul trucks, while the VIUS fuel economy for combination short-haul trucks with day cabs is adopted for combination short-haul trucks.

The variation in fuel economy values among the vehicle types is due to differences in vehicle specifications and duty cycles. The vehicle specifications that vary can include GVWR, engine size, and payload. Concurrently, the duty cycle can range from high-speed highway operation

[1] Using fuel economy can be misleading, as the relationship between the percent improvement in fuel economy and the percent reduction in fuel consumption is nonlinear. For example, 10%, 50% and 100% increase in fuel economy correspond to 9.1%, 33.3% and 50%, respectively, decrease in fuel consumption.

with few stops, which is the case for long-haul combination trucks, to low-speed urban operation with many stops, which is the case for refuse trucks. Other factors that affect the fuel economy of specific HDVs include the idling time, tire rolling resistance, vehicle aerodynamic drag, and grade effects.

The carried payloads of MY 2002 HDV subcategories from VIUS were very close to the average carried payloads of EPA's SmartWay HDVs by GVWR class (U.S. Environmental Protection Agency, 2012). For example, Class 8b, Class 6, Class 4, and Class 2b SmartWay trucks had average carried payloads of about 20.5, 4.6, 2.4, and 1.1 tons, respectively, in 2011,

TABLE 5 Fuel economy, carried payloads, and load-specific fuel consumption of MY 2002 conventional diesel and gasoline HDVs by subcategory

Engine Fuel	Regulatory Category	Vehicle Subcategory	Vehicle Type	Fuel Economy (MPG)	Carried Payload (tons)	LSFC (gal/1000 ton-mi or gal/100 mi)
Diesel	Combination trucks	Combination long-haul	Trailer: Van, Class 8b	6.3[a]	20.4	7.8[b]
		Combination short-haul	Trailer: Van, Class 8b	6.3[a]	20.5	7.7[b]
	Vocational vehicles	Heavy heavy-duty vocational vehicles	Dump, Class 8b	6.3[a]	22.6	7.0[b]
		Refuse trucks	Trash/Garbage/ Recycling, Class 8a	4.9[a]	9.8	20.9[b]
		Medium heavy-duty vocational vehicles	Van, Class 6	8.2[a]	4.8	25.5[b]
		Light heavy-duty vocational vehicles	Van, Class 4	9.9[a]	2.4	41.6[b]
	Heavy-duty pickup trucks and vans	Heavy-duty pickup trucks and vans	Pickup, Mini & Light Van, SUV, Class 2b	20.3[a,c]	1.1	4.9[d]
Gasoline	Vocational vehicles	Medium heavy-duty vocational vehicles	Van, Class 6	7.5[e]	4.0	33.0[d]
	Heavy-duty pickup trucks and vans	Heavy-duty pickup trucks and vans	Pickup, Mini & Light Van, SUV, Class 2b	15.3[e]	1.2	6.6[d]

[a] In miles per diesel gallon.
[b] In gallons per 1000 ton-miles.
[c] Estimated on the basis of the fuel economy of gasoline heavy-duty pickup trucks and vans, by assuming a relative fuel efficiency of 120% for diesel heavy-duty pickup trucks and vans on a gasoline-gallon-equivalent basis.
[d] In gallons per 100 miles.
[e] In miles per gasoline gallon.

which were almost identical to those of the MY 2002 counterparts in VIUS. This suggests that the carried payloads of individual HDV subcategories have not changed much since 2002. Therefore, we assume the same payloads of individual HDV subcategories for the various years examined in GREET.

The major drawback of the 2002 VIUS data is that they are outdated and not necessarily representative of the vehicle efficiency of today's HDVs. To evaluate this factor, we looked at fuel economy data for new MY trucks in historical releases of the Annual Energy Outlook (AEO) by the U.S. Energy Information Administration (EIA). Since 2002, EIA has made fuel economy projections for medium- (Classes 3–6 combined) and heavy-duty (Classes 7 and 8 combined) trucks based on 2002 VIUS fuel economy, as well as on assumptions of the market penetration of advanced truck technology components and their respective fuel economy gains. Starting in 2014, EIA segregated the light-medium (Class 3) category from the medium-duty trucks. Meanwhile, the payloads from the 2002 VIUS were held constant when EIA made the fuel economy projections (U.S. Energy Information Administration, 2014a).

We adopted the AEO fuel economy projections for new MY vehicles available in the latest AEO releases for MY 2002 to MY 2013. The time-series projections revealed that EIA predicted a small penalty in fuel economy for MY 2002–2010 new medium- and heavy-duty trucks, and a small improvement in fuel economy for MY post-2010 new medium- and heavy-duty trucks, as shown in Table 6. This projection is similar to the historical trend that saw lower fuel economy for diesel HDVs once they began using DPFs in 2007; then in 2010, OEMs were able to improve fuel efficiency through engine optimization enabled by SCR aftertreatment (Greszler, 2010). However, it is unclear why AEO projects a reduction in fuel economy for MY 2007-2008 gasoline vehicles, as they do not use DPFs.

Projections of improved fuel economy for MY post-2011 new medium- and heavy-duty trucks reflect EIA's consideration of the effects of implementing the 2011 Standard. Without real-world measurement or statistical data that could shed more light on fuel economy of new MY vehicles within various HDV subcategories, we relied on the EIA's projections for post-2002 new MY vehicles. We used these projections to estimate the MY-specific fuel economy of various HDV subcategories for MY 2002–2013 vehicles, as shown in Table 7. We assumed that the fuel economy of the HDV subcategories we analyzed changed at the same rate as the corresponding EIA vehicle types (by GVWR class) relative to MY 2002.

The estimated fuel economies for MY 2012 Class 8b combination long-haul and short-haul trucks were within the fuel economy range of the vast majority of the SmartWay Class 8b fleet in 2012, and were reasonably close to the upper bound of the range (U.S. Environmental Protection Agency, 2013d). The small variation in fuel economy from MY 2002 to MY 2013 vehicles agrees with the NAS finding that HDV fuel economy has not changed significantly over the past few decades (National Research Council, 2010); this finding is reflected by the minimal change in HDV fleet average fuel economy over the past decade reported by the Federal Highway Administration, as shown in Figure 12 (U.S. Department of Transportation, 2014a, 2014b).

TABLE 6 EIA projections of fuel economy, in miles per gasoline gallon equivalent, for medium- and heavy-duty vehicles, and fuel economy relative ratios for MY 2003–2013 vehicles relative to their MY 2002 counterparts

		2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Diesel heavy-duty vehicles	MPG	5.76	5.69	5.65	5.63	5.61	5.52	5.59	5.59	5.59	6.04	6.06	6.08
	Relative ratio (%)		98.8	98.0	97.7	97.3	95.9	97.1	97.0	97.1	104.9	105.2	105.5
Diesel medium-duty vehicles	MPG	8.68	8.59	8.52	8.51	8.50	7.99	7.97	7.96	7.95	8.34	8.43	8.53
	Relative ratio (%)		99.0	98.2	98.1	97.9	92.1	91.8	91.7	91.7	96.1	97.1	98.3
Gasoline medium-duty vehicles	MPG	8.99	8.97	8.95	8.94	8.94	7.56	7.59	10.24	10.13	10.08	10.15	10.23
	Relative ratio (%)		99.7	99.6	99.4	99.4	84.1	84.4	113.9	112.7	112.1	112.8	113.8

TABLE 7 Estimation of model-year-specific fuel economy of various HDV subcategories from 2003 to 2013

Engine Fuel	Regulatory Category	Vehicle Subcategory	Vehicle Type	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
Diesel	Combination trucks	Combination long-haul	Trailer: Van, Class 8b	6.3	6.2	6.2	6.1	6.1	6.0	6.1	6.1	6.1	6.6	6.6	6.6
		Combination short-haul	Trailer: Van, Class 8b	6.3	6.3	6.2	6.2	6.2	6.1	6.2	6.2	6.2	6.7	6.7	6.7
	Vocational vehicles	Heavy heavy-duty vocational vehicles	Dump, Class 8b	6.3	6.3	6.2	6.2	6.2	6.1	6.1	6.1	6.1	6.6	6.7	6.7
		Refuse trucks	Trash/Garbage/ Recycling, Class 8a	4.9	4.8	4.8	4.8	4.8	4.7	4.8	4.8	4.8	5.1	5.2	5.2
		Medium heavy-duty vocational vehicles	Van, Class 6	8.2	8.1	8.0	8.0	8.0	7.5	7.5	7.5	7.5	7.9	7.9	8.0
		Light heavy-duty vocational vehicles	Van, Class 4	9.9	9.8	9.8	9.8	9.7	9.2	9.1	9.1	9.1	9.6	9.7	9.8
	Heavy-duty pickup trucks and vans	Heavy-duty pickup trucks and vans	Pickup, Mini & Light Van, SUV, Class 2b	20.3	20.1	19.9	19.9	19.9	18.7	18.6	18.6	18.6	19.5	19.7	20.0
Gasoline	Vocational vehicles	Medium heavy-duty vocational vehicles	Van, Class 6	7.5	7.5	7.5	7.5	7.5	6.3	6.3	8.6	8.5	8.4	8.5	8.6
	Heavy-duty pickup trucks and vans	Heavy-duty pickup trucks and vans	Pickup, Mini & Light Van, SUV, Class 2b	15.3	15.2	15.2	15.2	15.2	12.8	12.9	17.4	17.2	17.1	17.2	17.4

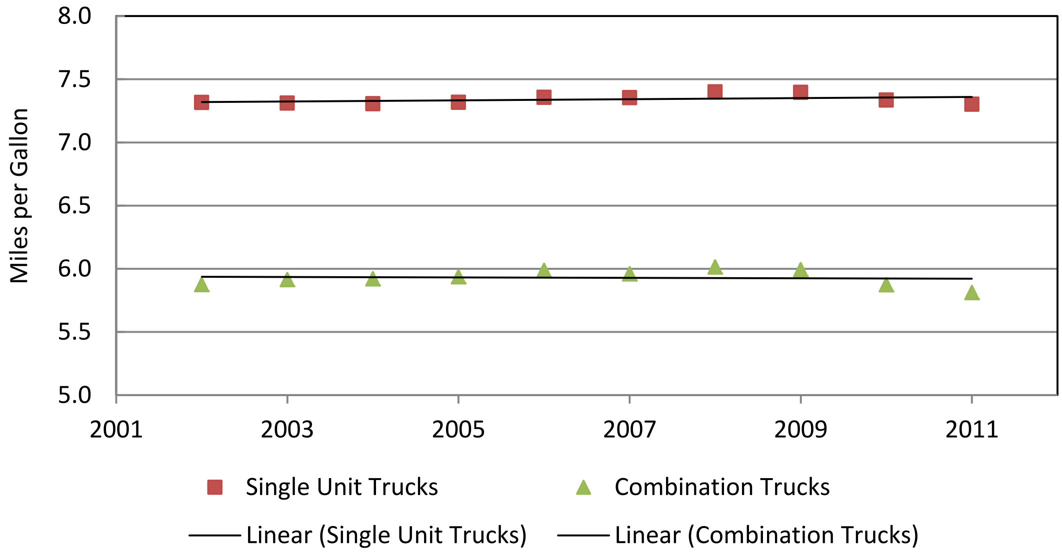

FIGURE 12 Recent trends in fuel economy of combination trucks and single-unit trucks

Refuse trucks have various body configurations (e.g. front-loaders, side-loaders, roll-offs) and duty cycles, depending on customers and trash type serviced (Sandhu et al., 2014). Our analysis of the 2002 VIUS database shows that MY 2002 Class 8a refuse trucks travel on average more than 25,000 mi per year and have a fuel economy of 4.9 mi per diesel gallon equivalent (MPDGE). However, a recent case study analyzing the real-world vehicle operation data of three refuse hauler fleets found that they traveled about 14,500 mi and consumed about 6,800 diesel gallon equivalents (DGEs) per year, and had a fuel economy of about 2.1 MPDGE, ranging from 1.9 to 2.3 MPDGE (Laughlin and Burnham, 2014a). According to Sandhu et al. (2014), the typical diesel side-loader fuel economy is 2.0–4.0 MPDGE, while it is 2.0–3.0 MPDGE for front-loaders and 3.9–5.5 MPDGE for roll-offs.

Roll-off refuse trucks are typically used for commercial waste and are most often operated by a private company rather than a municipal government. A recent study showed that roll-off refuse trucks had a fuel economy of 4.0 MPDGE for MY 2007 trucks and 5.6 MPDGE for MY 2012 trucks (Sandhu et al., 2015). The higher fuel economy for roll-off refuse trucks compared to that of side- and front-loader refuse trucks is attributable to their absence of compaction and higher percentage of time driving on freeways, often to a transfer station or landfill (Sandhu et al., 2015).

In GREET, we adopted the fuel economy and carried payload of the refuse trucks surveyed in VIUS. The 2002 VIUS dataset is based on a sample of private and commercial trucks registered in the United States as of July 1, 2002 (U.S. Census Bureau, 2004). The survey excludes trucks owned by local, state, and federal governments. Therefore, the refuse trucks surveyed in VIUS is likely more representative of roll-off refuse trucks, given the real-world fuel efficiency performance of front-loader, side-loader, and roll-off refuse trucks (Sandhu et al., 2014; Sandhu et al., 2015), and might not be representative of refuse truck fleets as a whole.

Analysis of other specific configurations of refuse trucks with GREET would require particular characterization of their fuel efficiency performance and the associated payload carried.

EPA created the GEM to determine compliance with the 2011 Standard using factors such as vehicle aerodynamic drag and tire rolling resistance (U.S. Environmental Protection Agency, 2013b). This simulation tool was developed following a suggestion from the National Research Council (2010). The 2011 Standard has set up baseline LSFCs for MY 2010 Class 7 and Class 8 day cab and sleeper cab combination trucks with three different roof configurations: low roof, mid roof, and high roof (Federal Register, 2011). The average LSFC for these three roof types of MY 2010 Class 8 sleeper cabs, which we assumed to be an appropriate surrogate for long-haul combination trucks, is 7.8 gal/1000 ton-miles, while the average LSFC for the three roof types of MY 2010 Class 8 day cabs, which we assumed to be an appropriate surrogate for short-haul combination trucks, is 7.7 gal/1000 ton-miles.

The 2011 Standard also defined the baseline fuel consumption of MY 2010 diesel light, medium, and heavy heavy-duty vocational vehicles and MY 2011 gasoline vehicles. The baseline fuel consumption was not mandated for MY 2011 or MY 2010 HDVs; rather, it was determined to provide a reference point for MY 2014 and later vehicle standards. Table 8 compares the LSFC, carried payloads, and fuel economy of MY 2002 combination long-haul and short-haul trucks, and light, medium, and heavy heavy-duty vocational vehicles derived from the 2002 VIUS to those of their MY 2011 or MY 2010 counterparts in the 2011 Standard.

TABLE 8 Comparison of fuel consumption performance of MY 2010 light, medium, and heavy heavy-duty vocational vehicles and combination long-haul and short-haul trucks derived from the 2002 VIUS to performance in the 2011 Standard

		LSFC, gal/1000 ton-miles		Payload, tons		Fuel economy, MPG	
		2002 VIUS	2011 Standard	2002 VIUS	2011 Standard	2002 VIUS	2011 Standard
Diesel	Class 8b combination long-haul vans	7.8[a]	8.6[a]	20.4	19.0	6.3[a]	6.1[a]
	Class 8b combination short-haul vans	7.7[a]	9.4[a]	20.5	19.0	6.3[a]	5.6[a]
	Class 8b dump trucks	7.0[a]	23.2[a]	22.6	7.5	5.0[a]	5.7[a]
	Class 8a refuse trucks	20.9[a]	23.2[a]	9.8	7.5	3.0[a]	5.7[a]
	Class 6 vocational trucks	25.5[a]	24.3[a]	4.8	5.6	7.7[a]	7.3[a]
	Class 4 vocational trucks	41.6[a]	40.0[a]	2.4	2.9	9.5[a]	8.8[a]
Gasoline	Class 6 vocational trucks	33.0[b]	24.3[a]	4	5.6	7.5[b]	7.3[b]

[a] In diesel gallons.
[b] In gasoline gallons.

Small differences were found between the baseline LSFC in the 2011 Standard and the values we derived from the 2002 VIUS data, as shown in Table 8, except for Class 8b dump trucks and gasoline Class 6 vocational trucks. It is clear that the difference between the payloads for heavy heavy-duty vocational vehicles assumed by the 2011 Standard and surveyed in VIUS was the primary cause for the different LSFC estimates of this HDV subcategory. For gasoline medium heavy-duty vocational vehicles, the VIUS-based LSFC was translated to about 21.5 gallons of diesel per 1000 ton-miles when the payload difference was normalized, compared to 24.3 gallons of diesel per 1000 ton-miles in the 2011 Standard. Therefore, new MY 2002 vehicles in most of the HDV subcategories were close to the baseline LSFC determined by the 2011 Standard. Table 9 summarizes the fuel economy, carried payloads, and the LSFC of MY 1990 to MY 2013 HDVs by subcategory in GREET.

We configured GREET to make the payload of an individual HDV subcategory an input parameter, to allow for adjustment when improved fuel consumption and payload data become available. However, testing shows that vehicle payloads affect fuel economy. Real-world measurements of six Volvo Class 8 long-haul freight trucks engaging in normal freight operations showed that vehicle fuel efficiency decreases as vehicle weight increases, and the relationship between fuel efficiency and vehicle weight is not linear, especially for vehicle weights above 65,000 pounds (Franzese, 2011). Therefore, one must be careful when adjusting the payloads for heavy-duty vocational and freight trucks to make sure the fuel economy and payload data are reasonable with respect to each other.

3.1.2 Emissions

The EPA and CARB certify the air pollutant emissions of heavy-duty on-road engines and typically do not perform chassis tests of complete HDVs[2] (DieselNet, 2014). Specifically, emission standards require a sample engine from an engine make and model family to undergo testing on an engine dynamometer (USGPO, 2014, sec. 401). Therefore, air pollutant emission standards are based on grams per brake horsepower-hour (g/bhp-hr), rather than grams per mile (g/mi). The air pollutants that are currently regulated include NO_x, PM, non-methane hydrocarbons (NMHCs), and carbon monoxide (CO).

It has been found that diesel HDVs contribute substantially to NO_x and PM emissions, and to the resultant air quality effects of ground-level ozone formation driven by NO_x and the adverse health impacts of PM (Nelson et al., 2008; Peretz et al., 2008; Pope, 2004). In 2008, 227 counties, with a total population of 123 million people, were in ozone nonattainment (i.e., did not meet the air quality regulations) with respect to the latest standard (U.S. Environmental Protection Agency, 2014d). Two counties in California with a total population of 20 million were designated as “extreme” ozone nonattainment areas (U.S. Environmental Protection Agency, 2014d). In 2006, 74 counties, with a total population of 43 million people, were in $PM_{2.5}$ nonattainment areas (U.S. Environmental Protection Agency, 2014e).

2 HDVs under 14,000 lb GVWR have the option to be chassis certified.

TABLE 9 Fuel economy, carried payloads, and LSFC of MY 1990 to MY 2013 vehicles in GREET

Engine Fuel	Vehicle Subcategory	MY 1990	MY 1995	MY 2000	MY 2002	MY 2005	MY 2010	MY 2013
MPG								
Diesel	Class 8b combination long-haul vans	5.2	5.7	5.8	6.3	6.1	6.1	6.6
	Class 8b combination short-haul vans	6.0	6.2	6.0	6.3	6.2	6.2	6.7
	Class 8b dump trucks	5.3	5.4	5.2	6.3	6.2	6.1	6.7
	Class 8a refuse trucks	4.2	4.3	4.6	4.9	4.8	4.8	5.2
	Class 6 vocational trucks	8.7	8.6	8.1	8.2	8.0	7.5	8.0
	Class 4 vocational trucks	7.5	9.6	9.8	9.9	9.8	9.1	9.8
	Class 2b heavy-duty pickup trucks and vans	15.4	17.8	17.8	20.3	19.9	18.6	19.9
Gasoline	Class 6 vocational trucks	7.0	9.8	7.6	7.5	7.5	8.5	8.6
	Class 2b heavy-duty pickup trucks and vans	11.6	13.4	13.4	15.3	15.2	17.2	17.4
Payload, tons								
Diesel	Class 8b combination long-haul vans	20.8	23.5	21.0	20.4	20.4	20.4	20.4
	Class 8b combination short-haul vans	21.7	21.6	16.2	20.5	20.5	20.5	20.5
	Class 8b dump trucks	22.3	20.3	21.9	22.6	22.6	22.6	22.6
	Class 8a refuse trucks	8.7	10.2	9.8	9.8	9.8	9.8	9.8
	Class 6 vocational trucks	4.5	4.6	4.7	4.8	4.8	4.8	4.8
	Class 4 vocational trucks	2.0	2.2	2.4	2.4	2.4	2.4	2.4
	Class 2b heavy-duty pickup trucks and vans	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Gasoline	Class 6 vocational trucks	6.1	4.4	3.9	4.0	4.0	4.0	4.0
	Class 2b heavy-duty pickup trucks and vans	1.2	1.2	1.2	1.2	1.2	1.2	1.2
LSFC, gallons per 1000 ton-miles or gallons per 100 miles								
Diesel	Class 8b combination long-haul vans	9.3	7.5	8.2	7.8	8.0	8.0	7.4
	Class 8b combination short-haul vans	7.7	7.5	10.4	7.7	7.9	7.9	7.3
	Class 8b dump trucks	8.4	9.1	8.9	7.0	7.2	7.2	6.6
	Class 8a refuse trucks	27.2	23.0	22.0	20.9	21.4	21.5	19.8

TABLE 9 (Cont.)

Engine Fuel	Vehicle Subcategory	MY 1990	MY 1995	MY 2000	MY 2002	MY 2005	MY 2010	MY 2013
Diesel (cont.)	Class 6 vocational trucks	25.6	25.2	26.0	25.5	26.0	27.9	26.0
	Class 4 vocational trucks	66.5	47.7	42.8	41.6	42.4	45.4	42.3
	Class 2b heavy-duty pickup trucks and vans	9.9	6.9	7.3	8.5	5.0	5.4	5.0
Gasoline	Class 6 vocational trucks	23.7	23.0	33.4	33.0	33.2	29.3	29.0
	Class 2b heavy-duty pickup trucks and vans	8.6	7.4	7.4	6.6	6.6	5.8	5.8

These findings have led to increasingly stringent standards for NO_x and PM emissions, with the EPA tightening the HDV engine standards for both emissions by ~98% from 1988 to 2010 (see Figure 13). Currently, the EPA and CARB standards for NO_x and PM are 0.2 g/bhp-hr and 0.01 g/bhp-hr, respectively (U.S. Environmental Protection Agency, 2013c). Beginning in 2006, the allowable level of sulfur in on-highway diesel fuel was lowered from 500 ppm to 15 ppm (compliant fuel was designated as ultra-low-sulfur diesel, or ULSD) to allow the introduction of advanced aftertreatment systems such as DPFs and NO_x SCR.

Because of severe air quality concerns in California, CARB adopted optional low NO_x standards in 2014, with three levels to which engines can be certified: 0.10, 0.05, or 0.02 g/bhp-hr (California Air Resources Board, 2014a). Engine manufacturers that meet these optional standards receive credits and become eligible for the Carl Moyer Program, which provides funding for vehicles that provide emission benefits beyond required regulations (California Air Resources Board, 2014b).

HDVs have received less regulatory scrutiny with respect to other regulated pollutants, such as NMHCs and CO (see Figure 14), since HDV emissions of NMHCs and CO are very low relative to those of gasoline vehicles.

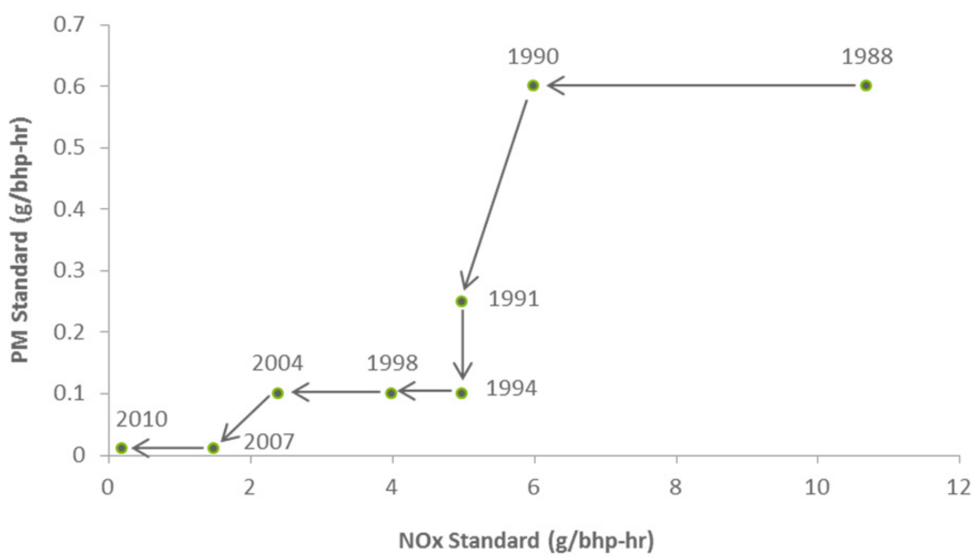

FIGURE 13 EPA PM and NO_x emission standards for heavy-duty engines, 1988–2010

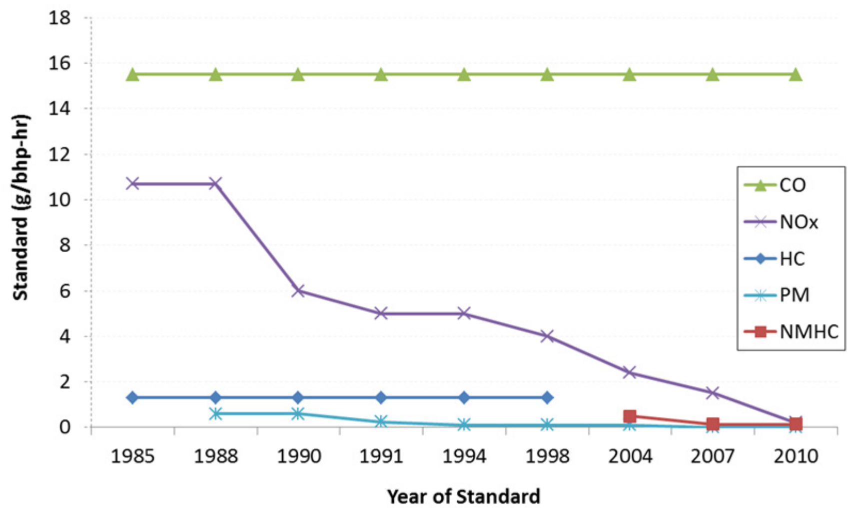

FIGURE 14 EPA HDV emission standards, 1988–2010

We used the EPA's MOVES model (version 2014) to estimate the model-year-specific tailpipe CAP emission factors of the selected diesel and gasoline HDV subcategories (see Table 3). Table 10 shows the mapping of vehicle categories in GREET and MOVES.

TABLE 10 Mapping of vehicle categories in GREET and MOVES2014

GREET Vehicle Category	Vehicle GVWR Rating	MOVES2014 Vehicle Category
Combination long-haul trucks	HDV Class 8b, > 60,000 lb	Class 8 combination long-haul trucks
Combination short-haul trucks	HDV Class 8b, > 60,000 lb	Class 8 combination short-haul trucks
Heavy heavy-duty vocational vehicles	HDV Class 8b, > 60,000 lb	Class 8 heavy heavy-duty single-unit short- or long-haul trucks
Refuse trucks	HDV Class 8a, 33,000–60,000 lb	Class 8 refuse trucks
Medium heavy-duty vocational vehicles	HDV Class 6, 19,500–26,000 lb	Class 6 and 7 medium heavy-duty single-unit short- or long-haul trucks
Light heavy-duty vocational vehicles	HDV Class 4, 14,000–16,000 lb	Class 4 and 5 light heavy-duty single-unit short- or long-haul trucks
Heavy-duty pickup trucks and vans	HDV Class 2b, 8,500–10,000 lb	Class 2b passenger trucks or light commercial trucks
LDT 2	LDT 3 & 4, 6,000–8,500 lb	Light-duty trucks
LDT 1	LDT 1 & 2, up to 6,000 lb	Light-duty trucks
Transit buses	HDV Class 8a, 33,000–60,000 lb	Class 8 transit buses
Intercity buses	HDV Class 8a, 33,000–60,000 lb	Class 8 intercity buses
School buses	HDV Class 6 or 7, 19,500–33,000 lb	Class 6 and Class 7 school buses

MOVES2014 is the latest version of EPA's vehicle tailpipe emission factor model. MOVES2014 incorporates the impacts of EPA rulemaking, including the 2011 Standard that phases in during MYs 2014–2018 and the Tier 3 regulations for diesel-fueled Class 2b and Class 3 heavy-duty pickup trucks and vans, both of which were promulgated since the last MOVES release (MOVES2010b). The model also incorporates new real-world in-use emissions for HDVs, using data from portable emission monitoring systems (U.S. Environmental Protection Agency, 2014f). In addition, MOVES2014 enables emission output by vehicle regulatory class, which provides more detailed breakdown of vehicle types than was available in MOVES2010b.

We have conducted emission simulations with MOVES2014 to characterize the tailpipe, evaporative, and brake and tire wear emissions of various diesel, gasoline, and E85 HDV subcategories. The simulations captured the temporal variations in CAP emission factors of HDVs in response to many variables, including advances in engine technologies; changes in fuel specification regulations; deterioration due to vehicle mileage accumulation; implementation of tighter on-road emission controls, such as inspection and maintenance programs; and adoption of advanced emission control technologies, such as second-generation onboard diagnostics, SCR, DPFs, and diesel oxidation catalysts (DOCs). Significant changes in HDV emissions factors were found, particularly for post-MY 2006 vehicles, compared to those estimated from MOVES2010b (Cai et al., 2013).

Emission factors from MOVES simulations reflect the impacts of real-world driving cycles. Using MOVES emission outputs for every five calendar years from 1990 to 2050, we calculated MY-specific VMT-weighted emission factors over a vehicle's lifetime. We adopted the regulatory class-specific emission factors from MOVES2014 for the GVWR-specific vehicle subcategories emphasized in this analysis. The Class 2b heavy-duty pickup truck and van subcategory falls under the definition of the MOVES "light commercial trucks" vehicle type. MOVES2014 provides emission factors for Class 2b light commercial trucks separately from Class 1 and Class 2a light commercial trucks. Thus, we adopted the emission factors of Class 2b diesel and gasoline light commercial trucks with four tires and two axles, respectively, for Class 2b diesel and gasoline heavy-duty pickup trucks and vans, as shown in Tables 11 and 12. Emission factors of black carbon (BC) and primary organic carbon (POC), two short-term climate forcers, are estimated to aid in the evaluation of potential climate change effects of HDVs when they are considered.

Single-unit vocational vehicles vary widely in their GVWRs, engine sizes, and vehicle configurations to fulfill multiple vocations. Class 4 (light heavy-duty) and Class 6 (medium heavy-duty) vocational vehicles are widely used as cargo delivery trucks. We adopted the MOVES aggregated emission factors for Class 4 and Class 5 diesel SU short-haul vocational trucks for our GREET Class 4 diesel light heavy-duty vocational truck category, as shown in Table 13. We deemed that these aggregated emission factors were representative of those of the Class 4 SU trucks because the emission factors of Class 4 and Class 5 SU trucks were close enough, given their similar engine sizes (see Table C1 in Appendix C).

TABLE 11 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 2b heavy-duty pickup trucks and vans

MY	CO	NO_x	N_2O	PM_{10}[a]	$PM_{2.5}$[b]	PM_{10}, BTW[c]
1990	1.568	5.500	0.002	0.447	0.411	0.088
1995	4.729	6.568	0.003	0.811	0.746	0.088
2000	2.881	5.273	0.003	0.300	0.276	0.088
2005	2.185	3.596	0.003	0.235	0.216	0.088
2010	0.368	0.942	0.003	0.012	0.011	0.088
2015	0.369	0.945	0.003	0.012	0.011	0.088
2020	0.371	0.552	0.003	0.012	0.011	0.088
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC[d], exhaust	VOC, evaporative
1990	0.036	0.076	0.289	0.003	0.785	0.016
1995	0.036	0.159	0.519	0.003	1.335	0.019
2000	0.036	0.049	0.206	0.003	0.835	0.011
2005	0.036	0.038	0.162	0.003	0.639	0.012
2010	0.036	0.001	0.001	0.083	0.078	0.012
2015	0.036	0.002	0.001	0.086	0.080	0.012
2020	0.036	0.002	0.001	0.087	0.081	0.011

[a] Particles less than 10 micrometers in diameter.
[b] Particles less than 2.5 micrometers in diameter.
[c] Brake and tire wear.
[d] Volatile organic compounds.

TABLE 12 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for gasoline Class 2b heavy-duty pickup trucks and vans

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	20.137	2.689	0.056	0.039	0.034	0.045
1995	30.211	3.732	0.077	0.038	0.034	0.045
2000	17.430	3.328	0.095	0.018	0.016	0.045
2005	19.083	2.703	0.043	0.011	0.010	0.045
2010	7.597	0.509	0.043	0.012	0.010	0.045
2015	7.487	0.461	0.012	0.011	0.010	0.045
2020	3.842	0.307	0.012	0.012	0.010	0.045
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.018	0.018	0.007	0.108	1.781	0.771
1995	0.018	0.018	0.007	0.093	1.871	0.756
2000	0.018	0.009	0.003	0.053	1.007	0.328
2005	0.018	0.005	0.002	0.086	0.506	0.111
2010	0.018	0.005	0.002	0.017	0.190	0.105
2015	0.018	0.006	0.002	0.017	0.174	0.108
2020	0.018	0.006	0.002	0.013	0.145	0.093

TABLE 13 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 4 light heavy-duty vocational vehicles

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	1.659	9.786	0.002	0.678	0.624	0.142
1995	4.086	14.231	0.003	1.224	1.126	0.142
2000	2.943	7.273	0.003	0.472	0.434	0.142
2005	2.486	6.303	0.003	0.438	0.403	0.142
2010	0.376	1.031	0.003	0.015	0.014	0.142
2015	0.363	0.950	0.003	0.014	0.013	0.142
2020	0.365	0.955	0.003	0.014	0.013	0.142
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.059	0.261	0.226	0.004	1.375	0.032
1995	0.059	0.495	0.418	0.004	1.783	0.032
2000	0.059	0.191	0.162	0.003	1.291	0.022
2005	0.059	0.179	0.151	0.002	0.778	0.023
2010	0.059	0.002	0.001	0.074	0.072	0.024
2015	0.059	0.002	0.001	0.076	0.071	0.023
2020	0.059	0.002	0.001	0.077	0.072	0.022

We adopted the MOVES aggregated emission factors for Class 6 and Class 7 diesel and gasoline SU short-haul vocational trucks, respectively, as shown in Tables 14 and 15, for Class 6 diesel and gasoline medium heavy-duty vocational trucks. We deemed that these aggregated emission factors were representative of those of the Class 6 SU trucks because the aggregated fleet was dominated by Class 6 SU trucks.

TABLE 14 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 6 medium heavy-duty vocational vehicles

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	2.382	9.642	0.002	0.696	0.641	0.142
1995	4.586	14.064	0.003	1.180	1.085	0.142
2000	3.463	7.143	0.003	0.468	0.430	0.142
2005	2.983	6.181	0.003	0.435	0.400	0.142
2010	0.902	0.902	0.003	0.015	0.014	0.142
2015	0.896	0.822	0.003	0.014	0.012	0.142
2020	0.916	0.823	0.003	0.014	0.013	0.142
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.059	0.268	0.231	0.004	1.402	0.032
1995	0.059	0.477	0.403	0.004	1.674	0.032
2000	0.059	0.190	0.160	0.003	1.262	0.022
2005	0.059	0.177	0.150	0.002	0.761	0.023
2010	0.059	0.002	0.001	0.072	0.069	0.024
2015	0.059	0.002	0.001	0.074	0.068	0.023
2020	0.059	0.002	0.001	0.075	0.069	0.022

TABLE 15 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for gasoline Class 6 medium heavy-duty vocational vehicles

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	55.639	4.280	0.055	0.061	0.054	0.061
1995	78.177	6.310	0.069	0.060	0.053	0.062
2000	27.258	4.127	0.079	0.038	0.034	0.063
2005	26.340	3.370	0.034	0.018	0.016	0.062
2010	16.426	0.816	0.034	0.018	0.016	0.063
2015	15.995	0.666	0.009	0.017	0.015	0.063
2020	16.046	0.486	0.009	0.017	0.015	0.063
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.016	0.029	0.010	0.262	2.465	1.483
1995	0.016	0.029	0.009	0.248	2.079	1.285
2000	0.016	0.019	0.006	0.030	1.061	0.644
2005	0.016	0.009	0.003	0.021	0.568	0.364
2010	0.016	0.008	0.003	0.014	0.153	0.358
2015	0.016	0.009	0.003	0.017	0.134	0.359
2020	0.016	0.009	0.003	0.017	0.128	0.328

We adopted the MOVES emission factors for Class 8 diesel SU short-haul trucks, as shown in Table 16, for Class 8b diesel SU dump trucks with less than 50 mi of hauling distance per day.

TABLE 16 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 8b single-unit short-haul dump trucks

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	2.869	9.642	0.002	0.505	0.464	0.068
1995	5.528	14.064	0.003	0.847	0.780	0.072
2000	4.352	10.232	0.003	0.600	0.552	0.073
2005	2.727	5.796	0.003	0.552	0.508	0.070
2010	0.895	0.898	0.003	0.022	0.021	0.070
2015	0.887	0.811	0.003	0.020	0.019	0.070
2020	0.907	0.812	0.003	0.020	0.019	0.070
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.018	0.177	0.193	0.002	0.826	0.032
1995	0.019	0.285	0.372	0.002	0.984	0.032
2000	0.019	0.223	0.235	0.002	0.778	0.022
2005	0.018	0.206	0.217	0.002	0.685	0.023
2010	0.018	0.003	0.002	0.071	0.068	0.024
2015	0.018	0.003	0.002	0.072	0.067	0.024
2020	0.018	0.003	0.002	0.073	0.068	0.023

We adopted the MOVES emission factors for Class 8 refuse trucks, as shown in Table 17, for Class 8a refuse trucks. We deemed this appropriate since the MOVES refuse trucks primarily consist of Class 8a refuse trucks (U.S. Environmental Protection Agency, 2013a).

TABLE 17 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 8a refuse trucks

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	3.360	22.289	0.002	0.715	0.657	0.093
1995	6.376	27.035	0.002	1.183	1.088	0.094
2000	5.273	18.622	0.002	0.748	0.688	0.093
2005	2.554	9.167	0.002	0.679	0.624	0.102
2010	0.630	1.434	0.002	0.032	0.030	0.102
2015	0.617	1.282	0.002	0.029	0.026	0.102
2020	0.628	1.284	0.002	0.029	0.026	0.102
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.024	0.134	0.448	0.003	0.734	0.054
1995	0.024	0.198	0.806	0.003	0.993	0.055
2000	0.024	0.152	0.471	0.002	0.826	0.054
2005	0.026	0.138	0.429	0.002	0.610	0.054
2010	0.026	0.004	0.003	0.054	0.051	0.056
2015	0.026	0.004	0.002	0.053	0.050	0.055
2020	0.026	0.004	0.002	0.053	0.050	0.054

As shown in Table C1, the diesel Class 8b combination long-haul trucks with a van trailer have the highest fuel use, a slightly higher average annual VMT, and a very similar engine size compared to other trailer types. Therefore, we assume that the CAP, CH_4, and N_2O emission factors from MOVES simulations of Class 8 combination long-haul trucks, as shown in Table 18, are representative of those for Class 8b combination long-haul trucks with a van trailer. Similarly, we assume that the CAP emission factors from MOVES simulations of Class 8 combination short-haul trucks are representative of those for Class 8b combination short-haul trucks with a van trailer, as shown in Table 19.

TABLE 18 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 8b combination long-haul trucks with a van trailer (extended idling emissions not included)

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	3.558	26.452	0.002	0.787	0.725	0.071
1995	7.629	31.960	0.002	1.354	1.246	0.076
2000	6.315	22.964	0.002	0.872	0.802	0.078
2005	3.643	13.011	0.002	0.801	0.737	0.077
2010	1.451	3.717	0.002	0.046	0.042	0.077
2015	1.426	3.492	0.002	0.041	0.038	0.077
2020	1.424	3.485	0.002	0.041	0.038	0.077
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.018	0.156	0.454	0.012	2.333	0.061
1995	0.020	0.255	0.877	0.005	1.907	0.062
2000	0.020	0.202	0.511	0.005	1.700	0.062
2005	0.020	0.185	0.472	0.005	1.508	0.063
2010	0.020	0.008	0.005	0.349	0.360	0.063
2015	0.020	0.008	0.005	0.346	0.356	0.059
2020	0.020	0.008	0.005	0.345	0.355	0.058

TABLE 19 MY-specific lifetime weighted average CAP, POC, BC, CH_4, and N_2O emission factors (g/mi) for diesel Class 8b combination short-haul trucks with a van trailer

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	2.920	19.329	0.002	0.621	0.571	0.068
1995	6.457	27.543	0.002	1.199	1.104	0.072
2000	4.982	18.927	0.002	0.744	0.685	0.073
2005	2.511	9.388	0.002	0.692	0.637	0.070
2010	0.558	1.472	0.002	0.033	0.030	0.070
2015	0.526	1.287	0.002	0.029	0.027	0.070
2020	0.521	1.281	0.002	0.029	0.026	0.070
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.018	0.120	0.383	0.003	0.790	0.055
1995	0.019	0.208	0.806	0.003	1.012	0.056
2000	0.019	0.155	0.464	0.002	0.783	0.056
2005	0.018	0.145	0.432	0.002	0.626	0.054
2010	0.018	0.004	0.003	0.055	0.052	0.056
2015	0.018	0.004	0.002	0.055	0.051	0.054
2020	0.018	0.004	0.002	0.054	0.050	0.053

Note that the MOVES-based idling emissions are excluded in the emission factors of combination long-haul trucks presented in Table 18. Class 8b combination long-haul trucks typically engage in extended idling during long-distance freight service, using fuel and producing air emissions. We allocated the extended-idling emissions on a per-mile basis for Class 8b combination long-haul trucks on the basis of MOVES simulations, as shown in Table 20. Extended idling represented a significant portion of the total CO, NO_x, VOC, and CH_4 emissions, accounting for about 60%, 55%, 85%, and 50%, respectively, of these emissions for MY 2010 and later vehicles.

Compared to the MOVES emissions per hour of idling for Class 8b combination long-haul trucks, results from the measurement of 75 heavy-duty engines and vehicles, ranging from MY 1969 to 2005, with electronic fuel injection systems showed similar idling CO and PM emissions, but much lower hydrocarbon emissions for pre-MY 2010 vehicles (Khan et al., 2006). Idling NO_x emissions for electronic fuel injection systems reported by Khan et al. (2006) were about twice as high as those in MOVES.

According to MOVES2014, extended idling emissions per mile have been reduced for MY 2010 and later vehicles because the hours of idling per mile have been reduced from 0.0137 to 0.00961 hours per mile, as shown in Table 21. The emissions per idling hour have been reduced for PM_{10}, $PM_{2.5}$, VOC, and NO_x, as shown in Table 22. In GREET, we introduced the idling hours per mile and the emission factors per idling hour as individual parameters to define the idling emission factors per mile.

One must be cautious when adjusting these parameters, as they affect not only the modeling of idling emissions, but also the energy consumption of the Class 8b combination long-haul trucks. For example, five Class 8 trucks showed idling fuel consumption varying from 0.5 to 1.8 gallons per hour (Storey et al., 2003). Limited studies were available to provide data on idling fuel consumption of HDVs (Brodrick et al., 2002; Frey and Kuo, 2009; Khan et al., 2006; Khan et al., 2009; Huai et al., 2006; Pekula et al., 2003). Therefore, one must make sure that revisions in GREET of the two parameters for the Class 8b combination long-haul trucks properly address emissions and fuel use.

Inconsistencies in idling emission intensity between the literature (Brodrick et al., 2002; Frey and Kuo, 2009; Khan et al., 2006; Khan et al., 2009; Huai et al., 2006; Pekula et al., 2003; Storey et al., 2003) and the MOVES model suggest that characterization of idling fuel use and emissions of HDVs warrants further investigation, particularly for MY 2010 and later vehicles. Federal and state regulations have been put into place to reduce extended-idling emissions (California Air Resources Board, 2013; Cummins, 2007). An evaluation of the effectiveness of such regulations in reducing extended-idling emissions is warranted.

TABLE 20 Extended-idling emissions on g/mi basis and their contribution to the total vehicle emissions for Class 8b combination long-haul trucks

	Extended idling emissions, g/mi							
MY	CO	NO_x	PM_{10}	$PM_{2.5}$	POC	BC	CH_4	VOC
1990	0.1925	0.2700	0.0111	0.0102	0.0053	0.0025	0.0060	0.6404
1995	0.1998	0.4088	0.0125	0.0115	0.0059	0.0030	0.0040	0.4791
2000	0.2072	0.5477	0.0139	0.0127	0.0065	0.0035	0.0020	0.3177
2005	0.2072	0.5477	0.0139	0.0128	0.0065	0.0035	0.0020	0.3156
2010	0.1446	0.3386	0.0003	0.0002	0.0001	0.00005	0.2976	0.1381
2015	0.1446	0.3386	0.0003	0.0002	0.0001	0.00004	0.2976	0.1381
2020	0.1446	0.3386	0.0002	0.0002	0.0001	0.00003	0.2976	0.1381
	Contribution of extended idling emissions to total emissions							
MY	CO	NO_x	PM_{10}	$PM_{2.5}$	POC	BC	CH_4	VOC
1990	18%	5%	6%	6%	15%	2%	73%	46%
1995	19%	9%	8%	8%	18%	2%	64%	35%
2000	19%	15%	10%	10%	26%	4%	52%	28%
2005	33%	26%	12%	12%	32%	4%	51%	31%
2010	59%	55%	8%	8%	8%	6%	85%	49%
2015	60%	59%	9%	9%	10%	5%	86%	50%
2020	60%	59%	9%	9%	11%	4%	86%	50%

TABLE 21 MOVES extended idling hours per mile for Class 8b combination long-haul trucks

MY	Extended idling, h/mi
1990	0.0137
1995	0.0137
2000	0.0137
2005	0.0137
2010	0.0096
2015	0.0096
2020	0.0096

TABLE 22 MOVES extended idling emissions in grams per idling hour for Class 8b combination long-haul trucks by model year, in comparison to literature

	CO	NO_x	PM_{10}	$PM_{2.5}$	POC	BC	CH_4	VOC
MY 1990[a]	14.0	19.7	0.8	0.7	0.4	0.2	0.4	46.7
MY 1995[a]	15.1	39.9	1.1	1.0	0.5	0.3	0.1	21.6
MY 2000[a]	15.1	39.9	1.0	0.9	0.5	0.3	0.1	23.2
MY 2005[a]	15.1	39.9	1.0	0.9	0.5	0.3	0.1	23.0
MY 2010[a]	15.1	35.3	0.03	0.03	0.01	0.005	31.0	14.4
MY 2015[a]	15.1	35.3	0.03	0.02	0.01	0.004	31.0	14.4
MY 2020[a]	15.1	35.3	0.03	0.02	0.01	0.003	31.0	14.4
Khan et al. (2006)[b]	20	86	1					6[c]
Khan et al. (2006)[d]	35	48	4					23[c]
Brodrick et al. (2002)	14.6 – 189.7	103 – 254						1.4 – 86.4[c]
Frey and Kuo (2009)	9 – 60	89.4 – 101	1.3 – 1.7					3.5 – 3.9[c]
Huai et al. (2006)		60						
Pekula et al. (2003)		97 – 181						

[a] From MOVES2014;
[b] For electronic fuel injection vehicles;
[c] For hydrocarbon emissions;
[d] For mechanical fuel injection vehicles.

3.2 CONVENTIONAL DIESEL BUSES

3.2.1 Fuel consumption

According to the American School Bus Council, the average school bus had a fuel economy of 7.0 mi per diesel gallon and carried 54 students in 2010 (American School Bus Council, 2012). These ridership data do not provide a breakdown of miles traveled without passengers, so potentially this value could be lower. The Clean Cities Program sponsored by the U.S. Department of Energy (DOE) estimated that school buses had an average fuel economy of 7.1 MPDGE, with a range from 5.8 to 7.9 MPDGE during 1996–2000 (Laughlin, 2004). Thus, school bus fuel economy has remained steady since the 1990s. In GREET, we adopted a fuel economy of 7.0 MPDGE for MY 1990–2010 Class 6 diesel school buses and an average of 54 students per bus.

We analyzed the National Transit Database (NTD) and American Public Transportation Association (APTA) datasets, which provide annual data on vehicle characteristics, energy consumption, VMT, and ridership of U.S. transit buses. The NTD publishes historic data on diesel fuel consumption by conventional and hybrid diesel vehicles running on real-world driving cycles, but doesn't separate them. Using APTA data, we assumed that 10% of the total transit bus VMT were driven by diesel hybrid transit buses (APTA, 2013a). With a fuel economy of 140% of their diesel counterparts, we estimated that the fuel economy of diesel transit buses in 2002, 2005, 2010 and 2012 was 3.54, 3.55, 3.86, and 3.75 MPDGE, respectively (Federal Transit Administration, 2014). We analyzed the NTD and estimated that there were on average 10.7 passengers serviced per transit bus in 2010.

To examine intercity buses, we looked at the Motorcoach Census, a benchmarking study commissioned by the American Bus Association Foundation, which estimated that there were 4,088 carriers operating 39,324 intercity buses in 2010 (John Dunham & Associates, 2012). The census data showed that the average intercity bus traveled 55,000 mi/year, carried 34.4 passengers/trip, and had a fuel economy of 6.0 MPDGE. In GREET, we adopted these average passenger and fuel economy data for MY 1990–2010 intercity buses.

3.2.2 Emissions

We adopted the MOVES-based emission factors for the aggregated Class 6 and Class 7 school buses, Class 8 transit buses, and Class 8 intercity buses, as shown in Tables 23–25, to represent the emission profiles of the dominant Type C Class 6 school buses, Class 8a transit buses, and Class 8a intercity buses, respectively (U.S. Environmental Protection Agency, 2013a). The NO_x emission factors for MY 2010 and later transit buses agree with the chassis dynamometer testing results for a 2010 Cummins ISL transit bus equipped with SCR driving under the Orange County Transit Authority (OCTA) cycle, and were lower than those measured during the more stop-and-go MAN cycle with probably lower SCR efficiency (Lammert et al., 2012).

TABLE 23 Lifetime mileage-weighted average air pollutant emission factors (g/mi) of diesel type C Class 6 school buses for MYs 1990–2020

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	2.962	12.030	0.002	0.755	0.695	0.079
1995	4.308	14.580	0.003	1.115	1.026	0.079
2000	3.804	7.368	0.003	0.474	0.436	0.079
2005	3.293	5.898	0.003	0.440	0.405	0.079
2010	1.115	0.963	0.003	0.017	0.015	0.079
2015	1.044	0.841	0.003	0.014	0.013	0.079
2020	1.046	0.837	0.003	0.014	0.013	0.079
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.020	0.274	0.294	0.005	1.411	0.032
1995	0.020	0.405	0.451	0.005	1.566	0.033
2000	0.020	0.182	0.179	0.004	1.352	0.033
2005	0.020	0.169	0.166	0.003	0.783	0.033
2010	0.020	0.002	0.001	0.072	0.068	0.034
2015	0.020	0.002	0.001	0.069	0.064	0.032
2020	0.020	0.002	0.001	0.069	0.064	0.031

TABLE 24 Lifetime mileage-weighted average air pollutant emission factors (g/mi) of diesel Class 8a transit buses for MYs 1990–2020

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	4.572	20.077	0.002	0.609	0.561	0.048
1995	6.924	24.626	0.002	1.060	0.975	0.048
2000	5.748	16.186	0.002	0.708	0.651	0.048
2005	2.697	9.034	0.002	0.658	0.605	0.048
2010	0.563	1.336	0.002	0.027	0.025	0.048
2015	0.519	1.175	0.002	0.023	0.021	0.048
2020	0.516	1.167	0.002	0.023	0.021	0.048
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.012	0.130	0.366	0.004	1.117	0.045
1995	0.012	0.216	0.668	0.003	1.179	0.045
2000	0.012	0.173	0.407	0.003	0.983	0.046
2005	0.012	0.161	0.378	0.002	0.709	0.046
2010	0.012	0.004	0.002	0.053	0.052	0.047
2015	0.012	0.003	0.002	0.052	0.048	0.045
2020	0.012	0.003	0.002	0.052	0.048	0.044

TABLE 25 Lifetime mileage-weighted average air pollutant emission factors (g/mi) of diesel Class 8a intercity buses for MYs 1990–2020

MY	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	3.455	19.222	0.001	0.705	0.649	0.108
1995	6.330	27.271	0.002	1.220	1.123	0.108
2000	5.084	18.747	0.002	0.780	0.718	0.108
2005	2.502	9.439	0.002	0.721	0.663	0.108
2010	0.449	1.437	0.002	0.033	0.030	0.108
2015	0.426	1.388	0.002	0.032	0.029	0.108
2020	0.426	1.384	0.002	0.032	0.029	0.108
MY	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.028	0.143	0.436	0.003	0.893	0.055
1995	0.028	0.222	0.807	0.003	1.008	0.055
2000	0.028	0.169	0.478	0.002	0.809	0.056
2005	0.028	0.156	0.443	0.002	0.655	0.056
2010	0.028	0.004	0.003	0.051	0.047	0.057
2015	0.028	0.005	0.003	0.050	0.047	0.057
2020	0.028	0.005	0.003	0.050	0.047	0.055

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4 FUEL CONSUMPTION AND EMISSIONS OF ALTERNATIVE-FUEL VEHICLES

We examined the current literature on fuel consumption of the AFVs selected in this analysis, as shown in Table 4. Since fuel efficiencies of both conventional vehicles and AFVs vary with a broad spectrum of factors, it is important to judge the fuel efficiency of AFVs relative to that of their conventional counterparts, measured with similar, if not identical, testing procedures and duty cycles. Specifically, we estimated the fuel economy of AFVs relative to their conventional counterparts for use in GREET.

AFV engines comply with the 2007/2010 heavy-duty engine emission standards (U.S. Environmental Protection Agency, 2013c) through the integration of sophisticated engine controls and aftertreatment devices, and not by solely relying on the inherent qualities of the fuel. To understand the vehicle emissions of AFVs, particularly their performance relative to conventional counterparts, studies were completed to measure tailpipe emissions of AFVs on engine and chassis dynamometers or on real-world driving cycles. It was found that SCR and DPFs reduce tailpipe NO_x and PM emissions to extremely low levels in pre-MY 2007 HDVs[3] (Clark et al., 2010). It was found that advances in vehicle technologies and emission control technologies have been the main measures taken to meet tighter emission standards (Nylund and Koponen, 2012). Therefore, it is important to consider the impacts of various emission standards on the relative emissions of AFVs compared to conventional vehicles.

Although the MOVES model includes emission simulations for conventional vehicles, it does not have them for AFVs (except for ethanol-blended gasoline vehicles and CNG transit buses). We investigated CAP emission factors of AFVs relative to conventional vehicles primarily using the research literature. We categorized the literature into pre-MY 2007 and post-MY 2007 vehicle studies to evaluate the emissions of AFVs relative to those of their conventional counterparts. Through this method, we determined the percentage differences in emissions between AFVs and conventional vehicles that comply with the same emission standards applied in particular phases.

4.1 BIODIESEL

4.1.1 Fuel Economy

Biodiesel has been promoted as a renewable, low-carbon, and clean fuel alternative to conventional diesel, and numerous studies have investigated biodiesel effects on fuel economy and air pollutant emissions from vehicle operations.

[3] A HDV may have an engine MY that differs from the MY of the vehicle. As HDV emission standards are based on the engine MY, that is our focus. However, in the literature, sometimes only the vehicle MY is provided; in those cases we assume the engine is the same MY.

McCormick et al. (2006) tested the fuel economy and emissions of eight HDVs, including three transit buses (MY 2000), two school buses (MY 2004 and MY 2006), two Class 8 trucks (MY 1999 and MY 2006), and one motor home (MY 2004), on a chassis dynamometer using conventional (petroleum) diesel and biodiesel (B20, 20% biodiesel blended with 80% conventional diesel by volume). Fuel economy, in MPG, decreased by an average of 1.4% when using B20 as compared to conventional diesel. The energy content of the biodiesel was not provided, but the expected volumetric fuel economy reduction is expected to be approximately 1.4%, according to the energy content of conventional diesel and biodiesel in GREET. Thus, these test results suggest that the energy-equivalent fuel economy for conventional diesel and biodiesel (B20) HDVs was equivalent.

Proc et al. (2006) tested nine transit buses (MY 2000), five of which operated exclusively on B20 and four on conventional diesel, on a chassis dynamometer, and found a 2.1% to 2.4% reduction in fuel economy using B20, with an energy content difference of 2.4% between the B20 and conventional diesel. Therefore, there were no significant differences in fuel economy between conventional-diesel- and B20-fueled transit buses. This finding agrees with the finding by Clark et al. (2010) that the use of B20 caused no significant difference in fuel economy for MY 2002–2008 buses. In addition, B20 has no significant fuel economy effects on MY 2007 heavy heavy-duty diesel trucks, and this finding may be attributed to the fact that conventional diesel and biodiesel exhibit similar chemical and thermodynamic properties (Olatunji et al., 2010).

It was found that the use of higher biodiesel blending (B35) made no significant difference in engine performance or fuel economy for heavy heavy-duty diesel trucks (Wang et al., 2000). In GREET, we assumed that conventional diesel and biodiesel HDVs have the same energy-equivalent fuel economy.

4.1.2 Emissions

The EPA's 2007/10 heavy-duty engine standards required PM emissions to be lowered from 0.1 g/bhp-hr to 0.01 g/bhp-hr (effective in 2007) and NO_x emissions to be lowered from 2.0 g/bhp-hr to 0.2 g/bhp-hr (phased in from 2007 to 2010) (U.S. Environmental Protection Agency, 2013c). This reduction by a factor of 10 was achieved with the introduction of diesel fuel with less than 15 ppm sulfur (ULSD), beginning in June of 2006, and the use of DPFs for PM and SCR for NO_x (Williams et al., 2006). The current literature mostly examines biodiesel emission impacts on pre-MY 2007 vehicles.

In 2002, EPA conducted a review of the effects of biodiesel blends on vehicle exhaust emissions, based on then-available emission test data primarily for heavy-duty highway engines and vehicles. EPA developed a correlation algorithm to predict the impacts of biodiesel blending ratios on the relative changes in NO_x, total hydrocarbons (HC), CO, and PM emissions. The findings showed that HC, CO, and PM emissions were reduced by up to 67%, 58%, and 57%, respectively, with engines running on 100% biodiesel, while the use of 100% biodiesel increased NO_x emissions by up to 10% (U.S. Environmental Protection Agency, 2002a). However, EPA later acknowledged that the magnitude of biodiesel NO_x impact remained uncertain

(U.S. Environmental Protection Agency, 2007). In addition, EPA's 2002 review suggested a discrepancy between engine and vehicle tests with respect to the effects of B20 on air pollutant emissions.

The National Renewable Energy Laboratory (NREL) revisited the data in the EPA (2002a) study and showed that the EPA analysis was based on unrepresentative engine datasets. After reviewing published data, including more recent studies, NREL suggested that there was no difference in biodiesel emission effects between engine and vehicle testing (McCormick et al., 2006). The NREL study (McCormick et al., 2006) reported emission test results for one MY 2005 and one MY 2000 Class 8 truck, fueled with diesel with less than 500 ppm sulfur and with B20, respectively, running on an urban low-speed, stop-and-go driving cycle and a freeway driving cycle, respectively. The PM emissions were reduced by 27% and 35%, respectively, on the urban and freeway driving cycles, which were statistically significant values ($p<0.05$). This study also concluded that NO_x was highly variable, with the percentage change due to the use of B20 ranging from −7% to +7%, and that on average, B20 had no net impact on NO_x emissions.

EPA examined the effects of B20 on criteria emissions for regulatory impact analysis and found that B20-fueled pre-MY 2007 vehicles had NO_x emissions that were 2.2% higher than diesel vehicles (U.S. Environmental Protection Agency, 2010). However, a study by the Desert Research Institute reviewed 94 published reports on biodiesel impacts on emissions with various engine types, operating conditions, and control technologies for the period of 2000–2008. The study showed that use of biodiesel, even at a 20% blend level, decreased CO, HC, and PM emissions, generally by 10–20%, regardless of engine type (light-duty or heavy-duty), engine technology, or testing conditions, and B20 did not differ from conventional diesel in NO_x emissions (Robbins et al., 2009). Yanowitz and McCormick (2009) assessed the emission impacts of mostly pre-MY 2007 engines, and found that B20 reduced CO, HC and PM emissions in the range of 10–20%. In addition, the emission effects of B20 with heavy-duty diesel truck engines did not show any correlation with MY or type of fuel injection technology.

For conventional school buses that adopted a DOC but no DPF, the NREL test results showed that B20 had a statistically significant effect, decreasing PM and CO emissions by 24.0% and 22.6%, respectively, but meantime increased NO_x emissions by 6.2% on a composite school bus driving cycle developed by Rowan University (McCormick et al., 2006). On the other hand, the test results showed that there was no statistically significant difference between the PM emissions from B20 and conventional diesel buses equipped with DPFs (both were very low), in agreement with similar findings for passenger cars with DPFs in a European study (Verbeek et al., 2008).

Chassis emissions tests on the urban driving cycle showed that B20 reduced all measured pollutants, including NO_x, when compared to conventional diesel (McCormick et al., 2006; Proc et al., 2006). Six buses spanning engine MYs from 1998 to 2011 were tested on a heavy-duty chassis dynamometer with California certification diesel, certification B20 blend, low aromatic diesel, low aromatic B20, and B100 fuels over the Manhattan, Orange County, and Urban Dynamometer Driving Schedule (UDDS) test cycles (Lammert et al., 2012). The study found that the biodiesel effect on NO_x emissions was not statistically significant for most buses and duty cycles for the biodiesel blends.

West Virginia University (WVU) researchers compared the NO_x and PM emissions of eight 40-foot-long transit buses running on ULSD vs. a blend of 20% biodiesel and 80% ULSD on the Heavy Duty UDDS (HD-UDDS) and the California OCTA driving schedules (Clark et al., 2010). Four of the buses tested were MY 2007–2008 buses equipped with DPFs (but not SCR), so the test results allowed an investigation of the effect of B20 in the presence of DPFs. The results showed substantial PM reductions for B20-fueled buses not equipped with DPF, compared to their ULSD-fueled counterparts. Much smaller reductions in PM emissions were observed for B20-fueled buses equipped with DPF, compared to their ULSD-fueled counterparts. In addition, NO_x emissions of B20-fueled buses with and without a DPF varied widely, and no clear trend of the emission ratio relative to their ULSD-fueled counterparts could be discerned. Overall, there was a small increase in NO_x emissions, with no statistical significance because of the limited number of tests.

Table 26 summarizes the ratio of NO_x, CO, HC, and PM emissions for B20-fueled vs. conventional-diesel-fueled heavy-duty vehicles from a review of literature focusing on pre-MY 2007 heavy-duty vehicles. The variation in NO_x emissions in the literature could be attributable to differences in the tested driving cycles, engine designs, or diesel and biodiesel properties, and thus no clear conclusion is possible about the NO_x emission effects of B20-fueled HDVs. Therefore, we assumed in GREET that NO_x emissions were the same for conventional diesel fuel and B20 blends for pre-MY 2007 HDVs.

Using the emission ratios in the literature that are statistically significant, we averaged the relative CO, HC, and PM emission reductions on different driving cycles for pre-MY 2007 trucks not equipped with DPF or SCR. We assumed that variations in HDV type under different driving cycles have little impact on the relative emission ratios despite their significant impacts on absolute levels of emissions, as found previously (Yanowitz and McCormick, 2009). In addition, we combined the data from vehicles fueled with low-sulfur diesel (LSD) and ULSD because no statistically significant impacts of fuel sulfur content were found on CO, HC, or PM emissions. As a result, we assumed that B20-fueled pre-MY 2007 HDVs exhibited 80%, 80%, and 75%, respectively, of the CO, HC, and PM emissions of their diesel counterparts.

For post-MY 2007 HDVs equipped with DPF and SCR, PM and NO_x emission levels are very low (National Renewable Energy Laboratory, 2011; Nylund and Koponen, 2012). To assess the PM emission effects of biodiesel on these vehicles, we reviewed a NREL study that examined emission effects of biodiesel blends with ULSD in a heavy-duty engine with and without a DPF installed (Williams et al., 2006). The study showed that B20 can achieve a statistically significant ($p<0.05$) reduction of PM emissions, by 27% and 24%, respectively, with and without a DPF installed, compared to emissions from the certification engine running on ULSD.

TABLE 26 Literature review of the ratio of NO_x, CO, HC, and PM emissions for B20-fueled vs. conventional-diesel-fueled heavy-duty vehicles

Data Source	HDV Type	Model Year of Engines	LSD[a] or ULSD?	Blending Ratio	Driving Cycle	DPF Equipped?	SCR Equipped?	DOC Equipped?	NO_x[b]	CO[b]	HC[b]	PM[b]
U.S. Environmental Protection Agency, 2002a		Mostly 1997 and earlier	LSD	B20	Mostly FTP[c] composite or hot start	No	No	No	1.02[d]	0.89 [d]	0.79 [d]	0.90 [d]
Robbins et al., 2009		Pre-2007	Mostly LSD	B20	Multiple cycles	No	No	No	0.99	0.81	0.79	0.76
Yanowitz and McCormick, 2009		Mostly 1997 and earlier	LSD	B20	FTP				1.02	0.84	0.84	0.87
McCormick et al., 2006	Class 8 trucks	2005	LSD	B20	CILCC[e]	No	No	No	1.00	0.85	0.83	0.73
	Class 8 trucks	2005	LSD	B20	Freeway	No	No	No	1.02	0.86	0.88	0.65
	Class 8 trucks	2000	ULSD	B20	CSHVC	No	No	No	1.02	0.89	0.85	0.81
	Class 8 trucks	2000	ULSD	B20	Freeway	No	No	No	1.04	0.93	0.84	0.74
	Motor home	2003	ULSD	B20	CSHVC	No	No	No	1.03	0.78	0.86	0.72
	Motor home	2003	ULSD	B20	HD-UDDS	No	No	No	1.03	0.81	0.97	0.70
	Transit buses	2000	LSD	B20	CSHVC[f]	No	No	No	0.96	0.80	0.72	0.67
	Transit buses	2000	LSD	B20	CSHVC	No	No	No	0.94	0.73	0.72	0.73
	Transit buses	2000	LSD	B20	CSHVC	No	No	No	0.96	0.81	0.72	0.80
	Transit buses	2000	LSD	B20	CSHVC	No	No	No	0.97	0.88	0.80	0.83
	School buses	2006	ULSD	B20	CSHVC	Yes	No	No	0.99	0.84	0.65	1.28
	School buses	2006	ULSD	B20	RUCSBC[g]	Yes	No	No	1.02	0.58	0.93	1.16
	School buses	2004	ULSD	B20	CSHVC	No	No	Yes	0.99	1.10	0.99	1.03
	School buses	2004	ULSD	B20	RUCSBC	No	No	Yes	1.06	0.77	0.80	0.76
Proc et al., 2006	Transit buses	2000	LSD	B20	CSHVC	No	No	No	0.94	0.73	0.72	0.83
	Transit buses	2000	LSD	B20	CSHVC	No	No	No	0.96	0.80	0.72	0.80
Data source	HDV type	Model year of engines	LSD[a] or ULSD?	Blending ratio	Driving cycle	DPF equipped?	SCR equipped?	DOC equipped?	NO_x[b]	CO[b]	HC[b]	PM[b]

TABLE 26 (Cont.)

Data Source	HDV Type	Model Year of Engines	LSD[a] or ULSD?	Blending Ratio	Driving Cycle	DPF Equipped?	SCR Equipped?	DOC Equipped?	NO_x[b]	CO[b]	HC[b]	PM[b]
Clark et al., 2010	Transit buses	2007	ULSD	B20	OCTA	Yes	No	No	1.02			0.69
	Transit buses	2007	ULSD	B20	HD-UDDS	Yes	No	No	1.03			0.73
	Transit buses	2005	ULSD	B20	OCTA	No	No	No	1.01			0.72
	Transit buses	2005	ULSD	B20	HD-UDDS	No	No	No	1.02			0.67
	Transit buses	2002	ULSD	B20	OCTA	No	No	No	1.05			0.84
	Transit buses	2002	ULSD	B20	HD-UDDS	No	No	No				
Anderson, 2012	Mostly Class 8 trucks and transit and school buses	Mostly pre-2007	LSD and ULSD	B20	Multiple cycles				0.97		0.79	0.86

[a] Low sulfur diesel, with a sulfur content of less than 500 ppm;
[b] Results are statistically significant ($p<0.05$), except for those highlighted in red;
[c] EPA Federal Test Procedure, which is composed of the HD-UDDS followed by the first 505 seconds of the HD-UDDS. It is often called the EPA75;
[d] Data had poor HDV engine representativeness and thus are not adopted in this analysis;
[e] Combined International Local and Commuter Cycle, which was developed by NREL for testing Class 4 to 6 hybrid electric delivery vehicles;
[f] City-Suburban Heavy-Vehicle Cycle, with an average driving speed of 18.4 mi per hour, in comparison to the 29.6 mi per hour on the HD-UDDS driving cycle;
[g] Rowan University Composite School Bus Cycle, which is an aggressive cycle that has high average speed and acceleration rates.

However, Nylund and Koponen (2012) found that PM emission rates for BD20- and petroleum diesel-fueled MY 2010 buses were so low that the emission variation could potentially be attributed to variations in the functioning of the exhaust aftertreatment system rather than to the fuel. As a result, no conclusive relationship between the PM reduction and biodiesel fuel content could be derived for these buses. In addition, Lammert et al. (2012) found that most tests on post-MY 2007 buses equipped with DPF showed negligible PM emissions and that no clear trends of PM emissions from ULSD- or B20-fueled buses could be drawn. In GREET, we assumed that B20 has no impact on PM emissions for MY 2007 and later heavy-duty trucks, as the literature suggests no consensus on this issue.

For MY 2010 and MY 2011 buses equipped with SCR, Lammert et al. (2012) found that the biodiesel effect on NO_x emissions was not statistically significant, as the SCR aftertreatment system was so effective that emissions were reduced to near the detection limit for both ULSD- and B20-fueled buses. Nylund and Koponen (2012) found that NO_x emissions of BD20-fueled MY 2010 buses varied and no clear trend of increase or decrease was observed compared to those of the petroleum diesel counterparts. Moreover, recent work at NREL showed that biodiesel's impact on NO_x is inconclusive for post-MY 2007 vehicles (Williams and McCormick, 2011). Therefore, we assumed that B20 has no effect on NO_x emissions of post-MY 2007 HDVs compared to 100% conventional diesel in GREET.

However, blends of more than 20% biodiesel with conventional diesel tend to lead to larger PM emission reductions and to larger NO_x emission increases than B20 (Walkowicz et al., 2009; Hajbabaei et al., 2012). Further, the emission effects of biodiesel showed a nonlinear response to the biodiesel blending level. The limited number of studies on this issue prevented a quantification of the relationship between emission reductions and the biodiesel blending level for post-2007/2010 vehicles.

Furthermore, recent work at NREL showed that biodiesel's impact on HC and CO can no longer be seen in DPF-equipped engines (Williams and McCormick, 2011). Therefore, we assumed that post-MY 2007 biodiesel vehicles have the same VOC and CO emissions as conventional diesel vehicles do. In the present analysis, we focused on the fuel consumption and emission effects of low biodiesel blend levels up to B20, and the adopted relative emission changes may not be representative of the emission changes of higher biodiesel blend levels. Further investigation of this issue is warranted.

4.2 COMPRESSED NATURAL GAS

4.2.1 Fuel Economy

In the past few decades, NG engines have undergone significant changes in their performance, emissions, and fuel economy (Boyce, 2013). Numerous published studies have shown that NG vehicles, especially those developed prior to the issuance of EPA and CARB 2007/2010 standards, generally have lower fuel efficiency than their diesel counterparts. Some of the reasons for the lower efficiency of spark-ignited NG engines are their lower compression ratio, slower combustion speeds, and need for throttling at partial loads as compared to compression-ignition diesel engines (Gao et al., 2013; Zhang et al., 1998).

In 1995, tests of early generations of lean-burn spark-ignited NG engines (the 8.5-L Detroit Diesel Series 50 and 10.0-L Cummins L-10) employed in refuse haulers showed a 10%–14% fuel economy penalty as compared to their diesel counterparts (Clark et al., 1998b). The results of these tests and others described below are on an energy-equivalent basis.

In-use tests of medium-duty CNG transit buses powered by 1997 Cummins 5.9-L CNG engines showed an average of 17% lower fuel economy than those using 5.9-L diesel engines (Frailey et al., 2000). Other NG and diesel heavy-duty transit bus comparisons have documented in-use fuel economy penalties for the NG-powered buses ranging from 20% to 28% (Chandler et al., 1996, 1998; Clark et al., 1997). Spark-ignited engines operating at low speeds and low loads will have poor thermal efficiency because of throttling losses when compared with compression-ignition diesel engines.

Tests of a Cummins 8.3-L CNG lean-burn engine used in a freight truck showed a 25% fuel economy penalty compared to a similar 1997 Cummins 8.3-L diesel-engine-powered tractor (Kamel et al., 2002). Ullman et al. (2003) performed a detailed characterization of school buses powered by CNG and diesel that met the 1998 EPA exhaust emission standards. Those results showed that the CNG school buses had 35% lower fuel economy compared to their diesel counterparts.

Currently available CNG engines, such as the Cummins Westport's 8.9-L ISL G and 11.9-L ISX12 G, have exhibited higher fuel economy than older models, largely owing to the introduction of closed-loop control and optimization of the air-fuel control system (Yoon et al., 2013). Gao et al. (2013) compared the fuel consumption of NG and diesel heavy-duty Class 8 trucks using Argonne's Autonomie model to simulate the vehicles on various drive cycles. The results of those simulations showed that the NG heavy-duty trucks had 6%–13% lower fuel economy relative to the diesel HDVs.

In contrast to transit buses, NG spark-ignited engines in freight trucks driving on a long-haul drive cycle will operate at high speeds and high loads and therefore will have lower throttling losses and improved fuel efficiency. Gao et al. (2013) also investigated the effect of a vehicle's total mass on fuel economy, and found that the fuel economy penalty for NG-powered trucks decreased from 6%–13% to 5%–11% compared to the diesel truck fuel economy (on a DGE basis) with increased vehicle total mass (e.g., when additional load is carried).

At WVU, several types of NG and diesel HDVs, including transit buses and refuse trucks, were tested on various duty cycles (Carder et al., 2014). This testing showed that a single NG refuse truck had 32% better fuel economy than the diesels tested. However, the engines were not all from the same OEM, nor did they have the same displacement, and only one NG truck was tested, so it is difficult to draw conclusions from these results when nearly all other testing shows a reduction in NG fuel economy relative to diesel.

On the basis of these findings, we made the following assumptions in GREET about the relative fuel economy of CNG HDVs compared to their diesel counterparts: CNG combination long-haul and short-haul trucks have a 20% fuel economy penalty for MY 1990–2005 and a 10% penalty for MY 2010–2020. CNG transit buses have a 25% fuel economy penalty for MY 1990–2005 and a 15% penalty for MY 2010–2020. CNG refuse trucks have a 25% fuel economy penalty for MY 1990–2005 and a 15% penalty for MY 2010–2020. CNG school buses have a 25% fuel economy penalty for MY 1990–2005, and the penalty decreased to the equivalent level of performance for transit buses, which is 15%, for MY 2010–2020. Finally, CNG intercity buses have the same fuel economy penalty as that for combination trucks, owing to their exposure to significant amounts of highway driving.

In GREET, it is assumed that CNG medium and light heavy-duty vocational vehicles based on a diesel engine have a 15% fuel economy penalty for MY 2010–2020, while the fuel economy penalty is 10% for CNG-fueled heavy heavy-duty vocational vehicles to reflect the impacts of duty cycle and weight on fuel economy. Spark-ignited CNG heavy-duty pickups based on a compression-ignition diesel engine have a 15% fuel economy penalty for MY 2010–2020 as well. In addition, it is assumed that spark-ignited CNG heavy-duty pickup trucks and vans and CNG medium heavy-duty vocational vehicles based on a gasoline spark-ignition engine have a 5% fuel economy penalty on a gasoline-gallon-equivalent (GGE) basis compared to their gasoline counterparts.

Table 27 summarizes the assumptions regarding fuel economy differences for CNG HDVs, by subcategory, relative to their diesel and gasoline counterparts.

TABLE 27 GREET fuel economy ratios for spark-ignited NG HDVs compared to their diesel and gasoline counterparts

HDV Subcategory	MY 1990–2005	MY 2010–2020
Combination long-haul or short-haul trucks	0.80	0.90
Heavy heavy-duty vocational vehicles	0.80	0.90
Refuse trucks	0.75	0.85
Medium and light heavy-duty vocational vehicles	0.75	0.85
Heavy-duty pickup trucks and vans	0.75	0.85
Medium heavy-duty vocational vehicles[a]	0.95	0.95
Heavy-duty pickup trucks and vans[a]	0.95	0.95
Transit buses	0.75	0.85
Intercity buses	0.80	0.90
School buses	0.75	0.85

[a] Compared to their gasoline counterparts on a gasoline-gallon-equivalent basis. All other vehicles are compared on a diesel-gallon-equivalent-basis

4.2.2 Emissions

As mentioned previously, CNG engines have changed significantly over the past few decades. An initial driver for CNG engine development was their ability to reduce air pollutant emissions. Numerous published studies show that NG vehicles, especially those developed prior to the issuance of the EPA and CARB 2007/2010 standards, have significantly lower PM emissions (Clark et al., 1995, 1998b; Frailey et al., 2000; Ullman et al., 2003; Wang et al., 1993) and lower NO_x emissions (Clark et al., 1998a, 1999), but increased CH_4 emissions compared to their diesel counterparts (Clark et al., 2007). However, with the implementation of stricter emission standards (see Figure 13 and Figure 14), the emissions of diesel HDVs have decreased significantly and thus the absolute emission benefits of NG vehicles have decreased (Cai et al., 2013).

Engine and exhaust control technologies used in CNG HDVs have advanced from lean-burn, to lean-burn with an oxidation catalyst, to stoichiometric combustion with a TWC (Yoon et al., 2013) to meet these tighter emission standards. Chassis dynamometer emission testing showed that in CNG trucks with 1994 C-Gas Plus engines with oxidation catalysts, NO_x emissions were significantly reduced, by 24–45% depending on duty cycles, and PM emissions were reduced by more than 90%, relative to their conventional diesel counterparts (Lyford-Pike, 2003). The Detroit Diesel Series 50G NG-powered buses using open-loop fueling controls produced, on average, 34% less NO_x and 96% less PM on the Central Business District (CBD) cycle compared to Detroit Diesel Series 50 diesel-powered buses.

Cummins L10 NG-powered buses using closed-loop fueling controls emitted 18% less NO_x and 96% less PM compared with their Cummins M11 diesel-powered counterparts (Clark et al., 1997, 1998a). Clark et al. (1999) reported that school buses in California powered by Cummins 8.3-L NG engines and employing closed-loop fueling management emitted 12% less NO_x and 61% less PM than similar buses powered by Cummins 8.3-L diesel engines. Medium-duty CNG buses powered by 5.9-L Cummins engines produced even lower NO_x emissions compared to equivalent diesel buses, with 58% lower NO_x and 98% lower PM (Frailey et al., 2000). Similarly, Ayala et al. (2002) reported an average PM emission reduction of 85% across all cycles for CNG buses.

One reason why CNG lean-burn engines had lower NO_x emissions than their diesel engine counterparts was that the CNG engines had lower heat release rates and in-cylinder temperatures, which resulted in a low formation rate of NO_x. The formation of HCs by CNG vehicles is linked to incomplete fuel combustion. So for lean-burn engines without any aftertreatment device, the NO_x and HC emissions are inversely related: if one is high, the other will be relatively low (Wang et al., 1993).

For CNG engines, the HC mass primarily consists of CH_4, with a limited portion being NMHCs. NMHC emissions from lean-burn CNG trucks with oxidation catalysts were found to be comparable to those from their diesel counterparts (Lyford-Pike, 2003). Tests of transit buses powered by 1997 Cummins 10-L lean-burn engines showed that about 95% of their HC emissions were CH_4 (Clark et al., 1997), which is typical for lean-burn NG vehicles (McKain et al., 2000). In addition, data from a seven-year study of emissions from CNG powered refuse haulers in New York City showed that CH_4 accounted for about 90% of the HC emissions (Clark et al., 1998b).

For lean-burn engines with oxidation catalysts, a duty-cycle-averaged tailpipe CH_4 emission factor of 7.7 g/mi was measured for heavy-duty trucks (Lyford-Pike, 2003). The tailpipe CH_4 emission factors for U.S. CNG transit buses with lean-burn engines tested by Yoon et al. (2013) were 9.0 g/mi (standard error of 0.4 g/mi) for the CBD drive cycle, 6.4 g/mi (standard error of 0.2 g/mi) for the HD-UDDS drive cycle, and 3.0 g/mi (standard error of 0.3 g/mi) for a steady-state 45-mi-per-hour cruise test. In addition, figures shown by Hajbabaei et al. (2013) show that lean-burn CNG transit buses with oxidation catalysts had tailpipe CH_4 emissions ranging from 15 to 20 g/mi.

CNG buses without oxidation catalysts actually had several times higher CO emissions compared to their diesel counterparts (Clark et al., 1999). Ayala et al. (2003) compared emissions from CNG transit buses using lean-burn engines with and without oxidation catalysts and showed that use of an oxidation catalyst significantly reduced NMHC and CO emissions. This finding agrees with the WVU findings that lean-burn CNG transit buses with oxidation catalysts had about 84% less CO emissions compared to their diesel counterparts (Clark et al., 1999). Chassis dynamometer emission testing of MY 1997 diesel and MY 1994 CNG tractor trailers with oxidation catalysts showed that the CNG trucks had 90% less CO emissions compared to their diesel counterparts (Lyford-Pike, 2003).

In order to meet 2007/2010 EPA and CARB emission standards, Cummins-Westport developed a CNG engine with stoichiometric combustion, cooled exhaust gas recirculation, and a TWC. The benefit of the stoichiometric/TWC engine design is that it does not require DPFs or SCR to meet the standards. Compared to CNG lean-burn engines with an oxidation catalyst, CNG stoichiometric engines with a TWC have significantly lower levels of NMHC emissions, owing predominately to the higher conversion efficiency of a TWC compared to an oxidation catalyst, and had about 95% less CH_4 emissions, owing primarily to the larger size and higher precious-metal loadings for the TWC (Hajbabaei et al., 2013). Significantly lower NMHC and CH_4 emissions from stoichiometric engines with TWCs compared to lean-burn engines with oxidation catalysts were also measured on both the HD-UDDS and steady-state driving cycles (Yoon et al., 2013). Moreover, about 80% lower CH_4 emissions from stoichiometric engines with TWCs compared to lean-burn engines with oxidation catalysts were measured for European CNG buses (Nylund and Koponen, 2012).

Testing of MY 2007–2009 CNG buses with a stoichiometric engine and TWC showed higher levels of CO, but significantly reduced NO_x emissions compared to MY 2000–2004 CNG buses with a lean-burn engine and oxidation catalyst (Hajbabaei et al., 2013; Yoon et al., 2013, 2014). PM emissions were slightly higher for the MY 2009 stoichiometric CNG buses than the 2003–2004 lean-burn CNG buses (Hajbabaei et al., 2013), while PM was significantly reduced for MY 2007 stoichiometric CNG buses relative to the 2000–2001 lean-burn CNG buses (Yoon et al., 2013, 2014). Recent emission testing done by WVU for California's South Coast Air Quality Management District (SCAQMD) showed that NG vehicles (NGVs) using stoichiometric engines had PM emissions ranging from 60% lower to 40% higher than diesels equipped with DPFs, depending on the duty cycle. NG engines, independent of the combustion system, deliver low PM emissions that are equivalent to those of DPF-equipped diesel engines (Nylund and Koponen, 2012).

The emission testing done by WVU also showed that NGVs using stoichiometric engines (MY 2008–2011) had significantly lower NO_x emissions than their EPA/CARB 2010-compliant diesel counterparts using SCR (MY 2010–2011) (see Table 28) (Carder et al., 2014). Specifically, the NGVs outperformed diesel vehicles in duty cycles with low speeds and low engine loads (e.g., drayage port operation and local deliveries), as engine temperatures for the diesels did not support sustained SCR performance in those operations. The only exception was for CNG refuse trucks, where on the SCAQMD drive cycle, the NO_x emissions were about 200% higher than for diesel engines. However, when the CNG refuse trucks were compared on the HD-UDDS cycle, the emissions were 70% lower than for diesel engines. As mentioned previously, the engines compared in this study did not all have the same OEM and displacement, making it hard to draw conclusions from the results. In addition, further testing of newer MY diesel engines would clarify whether the OEMs have improved the systems with time, taking into consideration that SCR was first required for MY 2010.

In 2015, Cummins Westport will begin field tests of transit buses with an 8.9-L stoichiometric engine that will meet CARB's optional NO_x standard of 0.02 g/bhp-hr, which is 90% lower than the current standard, with minimal impact engine efficiency California Air Resources Board, 2014a). Lower NO_x from diesel engines is possible by improving current technologies. OEMs see a path to 0.1 g/bhp-hr with a small reduction in fuel efficiency; though further NO_x reductions would likely cause larger efficiency penalites (Eckerle, 2015). Even with new advanced diesel technologies reaching 0.02 g/bhp-hr NO_x levels will be challenging (Eckerle, 2015). It will be important to understand both how NG and diesel engine emissions and fuel efficiency will be impacted with future regulations and technologies.

TABLE 28 NO_x emissions (g/mi) from recent diesel and NG freight HDV tests (adapted from Carder et al., 2014)

Engine	Duty Cycle	NO	NO_2	NO_x	NO_x Emissions Relative to Diesel
Diesel with DPF and SCR	HD-UDDS	1.62	0.36	1.98	
	Near-dock	7.92	1.12	9.04	
	Local	5.09	0.8	5.89	
	Regional	1.31	0.16	1.47	
HPDI with DPF and SCR	HD-UDDS	0.4	0.35	0.75	38%
	Near-dock	0.69	0.19	0.88	10%
	Local	0.32	0.33	0.65	11%
	Regional	0.21	0.26	0.47	32%
Stoichiometric NG	HD-UDDS	0.43	0.01	0.44	22%
	Near-dock	0.44	0	0.44	5%
	Local	0.32	0.01	0.33	6%
	Regional	0.17	0	0.17	12%

Gautam et al. (2011) measured extended idling emissions (over one-hour periods) of two U.S. CNG transit buses with stoichiometric engines and TWCs; no diesel buses were tested to compare the results. The NO_x, PM, and CO emissions were 0.054 grams per hour (g/h), 13.2 g/h, and 0.018 g/h, respectively. NMHC emissions were not presented, as the researchers stated that an oxidation catalyst reduced their concentration to very low levels and in some cases lower than ambient levels.

Similarly to other NGV studies, the WVU tests showed that for freight NGVs with stoichiometric engines, about 97% of HCs were CH_4 (Carder et al., 2014). The NMHC emissions of those NGVs were similar to those of the diesel trucks tested (Carder et al., 2014). The CH_4 tailpipe emission factors for U.S. CNG transit buses with stoichiometric engines and TWCs analyzed by Yoon et al. (2013) were 3.5 g/mi (standard error of 0.4 g/mi) for the HD-UDDS drive cycle and 1.3 g/mi (standard error of 0.2 g/mi) for a steady-state 45 mi per hour cruise test, while extended-idling CH_4 emissions were 21.8 g/h or 197.9 g/million Btu (Gautam, 2011).

In addition, figures shown by Hajbabaei et al. (2013) show that similar U.S. CNG transit buses with stoichiometric engines had CH_4 tailpipe emissions ranging from 0.3 to 0.9 g/mi. Measurements of CH_4 emissions of international CNG transit buses with stoichiometric engines and TWCs ranged from 0.4 to 2.4 g/mi, while a Euro V lean-burn engine had emissions of 3.1 g/mi (Nylund and Koponen, 2012; Hesterberg et al. 2009). However, an examination of high-mileage (230,000 miles) U.S. CNG transit buses with stoichiometric engines by Wang et al. (2015) found higher tailpipe emissions, 4.1–6.1 g/mi for in-use routes and 7.2–8.6 g/mi for dynamometer tests.

WVU's test results for NG freight trucks with stoichiometric engines showed CH_4 tailpipe emissions of 1.7 g/mi (Carder et al., 2014). However, tests of NG refuse trucks with stoichiometric engines showed significantly higher CH_4 emissions, 6.4 g/mi (Carder et al. 2014). It is not clear why the high-mileage transit bus and the WVU refuse truck results show higher tailpipe emissions, but duty-cycle aging of the engine and aftertreatment systems may play a significant role (Thiruvengadam, 2015a; Greszler, 2015).

The studies presented in Table 29 only examine tailpipe CH_4 emissions, but ongoing testing has shown that crankcase emissions are also important (Clark, 2015; Greszler, 2015). Crankcase emissions can occur as gases escape or "blow-by" the piston rings owing to high cylinder pressure. Researchers at West Virginia University, in collaboration with the Environmental Defense Fund and other industry groups, are measuring CH_4 emissions of NGVs and infrastructure (Clark, 2015). Limited publicly available data on total vehicle (or crankcase) CH_4 emissions are available.

TABLE 29 Tailpipe CH_4 emissions from recent NG vehicle tests

Vehicle Type	Engine	Engine Technology	Emission Control	Driving Cycle	Tailpipe CH_4, g/mi[a]	Tailpipe CH_4, g/million Btu[b]	Source
CNG and LNG freight trucks	2008–2011 Cummins Westport ISL-G 320 8.9-L SI	Stoichio-metric	TWC	HD-UDDS	1.7	44.6	Carder et al., 2014
LNG HPDI freight truck	2008–2011 Westport GX 450 14.9-L HPDI CI	Lean-burn	DPF and SCR	HD-UDDS	2.6	71.3	Carder et al., 2014
LNG refuse truck	2008 Cummins Westport ISL-G 320 8.9-L SI	Stoichio-metric	TWC	HD-UDDS	6.4	159.7	Carder et al., 2014
CNG bus	2007 Cummins Westport ISL-G 280 8.9-L SI	Stoichio-metric	TWC	HD-UDDS	3.5	115.4	Yoon et al., 2013
				SS[c]	1.3	106.7	
	2008 Cummins Westport ISL-G 8.9-L SI	Stoichio-metric	TWC	OCTA	7.2	173.3	Wang et al., 2015
				HD-UDDS	8.6	281.9	
				In-use – local route[d]	6.1	185.9	
				In-use – highway route[e]	4.1	203.4	
	2009 Cummins Westport ISL-G 8.9-L SI	Stoichio-metric	TWC	CBD	0.6	21.0	Hajbabaei et al., 2013
	6.0-L SI, Hino WO6E	Stoichio-metric	TWC	MDC[f]	2.4	61.8	Sundar et al., 2004
	2009 11.9-L SI, EEV[g] Standard	Stoichio-metric	TWC	Braun-schweig	0.4	12.0	Nylund and Koponen, 2012
				Ademe	0.6	13.1	
				HD-UDDS	0.8	29.2	
	9.0-L SI, Euro V Standard	Lean-burn	Oxidation Catalyst	Braun-schweig	3.1	99.9	Nylund and Koponen, 2012

[a] Estimates in this table are tailpipe only emissions; crankcase emissions are not included.
[b] Estimates based on fuel throughput; calculated using reported CO_2 g/mi from the reference and GREET1_2014 data on NG emission, 59,000 g CO_2/million Btu
[c] Steady-state at 45 mi per hour cruise.
[d] In-use local route in Sacramento; average speed 13.3 mph
[e] In-use highway route in Sacramento; average speed 32.4 mph
[f] Mumbai drive cycle (see Appendix D)
[g] Enhanced environmentally friendly vehicle (EEV); European standard between Euro V and Euro VI

EPA certification engine testing, which uses the Federal Test Procedure (FTP) heavy-duty transient cycle, includes both crankcase and tailpipe emissions and provides results in g/bhp-hr. The MY 2014 Cummins Westport 8.9-L engine had 1.95 g/bhp-hr, while the 11.9-L engine had 1.04 g/bhp-hr (EPA, 2014g). Cummins Westport reports that 55% of the 8.9-L engine's and 90% of the 11.9-L engine's CH_4 emissions, 1.07 g/bhp-hr and 0.94 g/bhp-hr, respectively, are from the crankcase (Frazier, 2015). Cummins Westport noted that the 11.9-L engine had lower tailpipe emissions on a bhp-hr basis because of engine control and aftertreatment catalyst changes.

While there is not a clear translation of the FTP transient cycle tests into per-mile results, the EPA (U.S. Environmental Protection Agency, 2002b) conversion factor used in the MOBILE6 emission model (predecessor to MOVES) was 4.68 bhp-hr/mi for diesel transit buses and 3.03 bhp-hr/mi for diesel Class 8b trucks. While these data are for previous engine/vehicle technologies (MY 1997), Wang et al. (2015) calculate a similar average value for the CNG transit buses tested, 4.4 bhp-hr/mi (ranging from 2.9 to 5.7 bhp-hr/mi, depending on duty-cycle). Using the MOBILE6 conversions, the 8.9-L engine would translate to 9.1 g/mi for a transit bus and the 11.9-L engine would translate to 3.1 g/mi for a Class 8b truck. These translations are higher than the test results seen in Table 29 (only the 8.9-L engine has been independently tested).

Testing of the high-mileage buses with the 8.9-L engine cited by Wang et al. (2015) for the in-use highway route showed CH_4 emissions of 4.1 g/mi from the tailpipe and 5.5 g/mi from the crankcase (Thiruvengadam, 2015b). Thiruvengadam (2015b) suggested that the large crankcase emissions were potentially a function of engine age and that the numbers would be expected to be lower with better sealing by the piston rings. However, the percentage of CH_4 emissions from the crankcase (57%) is very similar to what Frazier (2015) reported.

U.S. heavy-duty NG engine manufacturers currently use open crankcase ventilation, which allows the CH_4 emissions to escape to the atmosphere. However, crankcase emissions can be eliminated by using closed crankcase ventilation, which redirects emissions into the combustion chamber (Cummins, 2012). In Europe, closed crankcase ventilation is the industry standard (Andersson, 2015), while OEMs offer these systems in the U.S. for diesel engines and thus they could be installed in future U.S. heavy-duty NG engines (Cummins, 2015; Navistar, 2011). The Cummins European 8.9-L engine equipped with closed crankcase ventilation was certified to Euro 6 standards at 0.09 g/kWh (or 0.12 g/bhp-hr), about 94% lower than the U.S. 8.9-L engine.

The use of a relative ratio when comparing NG versus diesel CH_4 emissions is not illustrative, as the ratio is very sensitive to the very low diesel emissions, which are subject to uncertainty. Thus, a small change in the low diesel CH_4 emission can change the ratio significantly even though the absolute difference between the NG and diesel CH_4 emissions does not change much. For this reason, we expressed the NG CH_4 emissions as absolute values in Table 30. However, for NGVs based on spark-ignited gasoline engines, we follow the previous GREET analyses and recent tests showing that those NGV CH_4 emissions are about 10 times those of their gasoline counterparts (Wang, 1999; Argonne National Laboratory, 2014; Duoba and Keller, 2012).

TABLE 30 CH_4 and CO emissions for spark-ignited NG HDVs

		Fuel Use	Tailpipe CH_4		Crankcase CH_4		Total CH_4		CO
Vehicle Type[a]	MY	Btu/mi	g/ million Btu	g/mi	g/ million Btu	g/mi	g/ million Btu	g/mi	g/mi
Combination long-haul trucks	2000	27,907	290	8.1	59.5	1.7	349	9.7	[b]
	2010	23,586	49	1.1	59.5	1.4	108	2.6	23.0
Combination short-haul trucks	2000	26,977	285	7.7	54.5	1.5	340	9.2	[b]
	2010	23,206	45	1.0	54.5	1.3	99	2.3	8.0
Heavy heavy-duty vocational vehicles	2000	31,127	285	8.9	54.5	1.7	340	10.6	[b]
	2010	23,586	45	1.1	54.5	1.3	99	2.3	8.0
Refuse trucks	2000	37,533	246	9.2	138.9	5.2	385	14.4	[b]
	2010	31,737	114	3.6	138.9	4.4	252	8.0	23.0
Medium heavy-duty vocational vehicles	2000	21,315	246	5.2	138.9	3.0	385	8.2	[b]
	2010	20,312	114	2.3	138.9	2.8	252	5.1	8.0
Light heavy-duty vocational vehicles	2000	17,617	246	4.3	138.9	2.4	385	6.8	[b]
	2010	16,741	114	1.9	138.9	2.3	252	4.2	8.0
Heavy-duty pickup trucks and vans	2000	9,699	246	2.4	138.9	1.3	385	3.7	[b]
	2010	8,190	114	0.9	138.9	1.1	252	2.1	8.0
Medium heavy-duty vocational vehicles[c]	2000	14,762	25	0.4	0[d]	0[d]	25	0.4	[b]
	2010	13,199	18	0.2	0[d]	0[d]	18	0.2	[b]
Heavy-duty pickup trucks and vans[c]	2000	8,813	70	0.6	0[d]	0[d]	70	0.6	[b]
	2010	6,866	30	0.2	0[d]	0[d]	30	0.2	[b]
Transit buses	2000	48,771	246	12.0	138.9	6.8	385	18.8	[b]
	2010	39,466	114	4.5	138.9	5.5	252	10.0	23.0
Intercity buses	2000	26,977	285	7.7	54.5	1.5	340	9.2	[b]
	2010	23,979	45	1.1	54.5	1.3	99	2.4	8.0
School buses	2000	24,664	246	6.1	138.9	3.4	385	9.5	[b]
	2010	21,763	114	2.5	138.9	3.0	252	5.5	23.0

[a] All vehicles are relative to diesel counterparts (using a diesel compression ignition engine converted to NG spark ignition), except as noted.
[b] See Table 31 for relative ratios.
[c] These vehicles are relative to gasoline counterparts (using a gasoline spark ignition engine converted to NG spark ignition).
[d] NGVs based on spark-ignited gasoline engines do not have a type of closed crankcase ventilation.

As CH_4 emissions data are not available for many of the vocations we are examining for GREET, we decided to use fuel throughput to estimate emissions. This approach assumes that tailpipe and crankcase methane slip for an engine will be dependent on the vehicle's duty cycle, and thus, we use fuel consumption as a proxy to differentiate the vehicles (MY 2000 and MY 2010).

We used the average of the stoichometric bus and refuse throughput tailpipe emissions (g/million Btu) in Table 29 to represent vocations with significant urban driving and the stoichiometric freight truck to represent vocations with significant highway driving. For lean-burn CNG vehicles (pre-MY 2007), the average of transit bus testing (Yoon et al. 2013; Hajbabaei et al. 2013) is used to represent vocations with significant urban driving; and data for HDVs from Lyford-Pike (2003) were used to estimate vocations with significant highway driving.

For NGVs with a stoichiometric engine, crankcase CH_4 emissions are assumed to be about 22% higher than tailpipe emissions on a throughput basis, using data provided by Thiruvengadam (2015b) and Frazier (2015). For lean-burn engines, it is assumed that the crankcase emissions will be the same on a throughput basis as for stoichiometric engines. NGVs based on spark-ignited gasoline engines are not adjusted in this manner, as they have a type of closed crankcase ventilation.

Extended-idling CH_4 emissions for long-haul NG vehicles were estimated using results from Gautam et al. (2011), tailpipe freight truck results from Table 29, and MOVES2014 long-haul activity data (89 million idling hours and 9.3 billion miles driven for 2015). Owing to range limitations of current NGVs, it is not clear whether these trucks will be used in long-haul applications requiring significant overnight idling.

Unfortunately, there are currently no test data for vehicles using the Cummins Westport 11.9-L engine, which was developed for freight applications. Further analysis is needed to better represent various engines and duty cycles that have not been tested. In addition, if OEMs begin to use closed crankcase ventilation or other controls to reduce CH_4, testing will be needed to verify potential reductions.

According to the EPA's engine certification testing data, Cummins NG engines have significantly higher CO emissions, 8–14 g/bhp-hr (these engines meet the 15.5 g/bhp-hr standard), compared to diesel engine counterparts having 0.1 g/bhp-hr (U.S. Environmental Protection Agency, 2014g). A review study on emissions from CNG and diesel transit buses showed that CNG transit buses with a TWC had much higher CO emissions, 4.9 g/mi, compared to their diesel counterparts with DPF, having 0.6 g/mi (Hesterberg et al., 2009). Further tests of CNG transit buses found CO emissions to be 27.4 g/mi (standard error of 3.4 g/mi) for the HD-UDDS drive cycle and 5.0 g/mi (standard error of 0.7 g/mi) for a steady-state 45 mi per hour cruise test (Yoon et al. 2013).

Carder et al. (2014) also showed that NG freight trucks had significantly higher CO emissions, 7.1–9.4 g/mi, than diesels, with 0.2–0.8 g/mi, depending on the duty cycle. Furthermore, Carder et al. (2014) found very high CO emissions for CNG transit buses, 14.4–19.9 g/mi, and CNG refuse trucks, 22.7–36.6 g/mi, depending on the duty cycle. CARB testing showed that a heavy-duty CNG vehicle with a TWC had very high CO emissions, 30 g/mi, compared to a diesel with SCR and a DPF, with 0.2 g/mi (Herner et al., 2012).

The use of relative ratio when comparing NG versus diesel CO emissions is not illustrative, as the variation in low diesel emissions can make the value significantly different even though the absolute difference does not change much. The results show that post-MY 2007 SI NGV CO emissions are significantly higher than those of diesels, and for duty cycles with more transients, such as transit bus and refuse truck cycles, emissions seem to be even larger. Hajbabaei et al. (2013) state that SI CNG vehicles operate richer and thus less oxygen is available to oxidize CO to CO_2, with its stoichiometric combustion as compared to diesel lean-burn combustion.

We assume that the CO emissions are 8.0 g/mi for all post-2010 SI NGV combination short-haul trucks, all vocational vehicles, and heavy-duty pickups and vans, while the emissions are 23.0 g/mi for refuse trucks, transit buses, and school buses. Extended idling emissions for long-haul NG vehicles have not been examined, but we assume that like diesel trucks, the idle CO emissions for the NG vehicle will account for a significant amount of emissions. We expect this result because NGVs at idle will likely have more incomplete combustion; our placeholder assumption is that the combination long-haul will have the same CO emissions as the refuse trucks and buses, 23.0 g/mi.

The WVU study also examined N_2O emissions of various types of NG HDVs and found that those with stoichiometric engines had emissions ranging from 0.01 g/mi to 0.04 g/mi, depending on the duty cycle (Carder et al., 2014). The study presented N_2O emissions for diesel freight and refuse trucks, and in general, the emissions of the stoichiometric NGVs were significantly lower than those of the diesels.

On the basis of these findings on emissions, it is assumed in GREET that CNG buses powered by stoichiometric engines with TWCs are the representative CNG engine and emission control technology for MY 2010–2020, while earlier CNG vehicles were represented by oxidation catalyst (OC)-powered lean-burn engines with OCs that met the EPA Tier 1 emission standard. Therefore, the emission profiles for CNG-fueled HDVs in this analysis only represent specific vehicle technologies instead of the whole vehicle fleet, consisting of multiple engine and emission control technologies. Table 31 shows the emissions of various CNG HDV types relative to their diesel or gasoline counterparts. In particular, we estimated the CH_4 emission ratios of the HDV types relative to those for the baseline counterparts (see Sections 3.1.2 and 3.2.2), according to the different emission factors of lean-burn and stoichiometric engine technologies.

Owing to data limitations, it is assumed that CNG heavy, medium, and light heavy-duty vocational vehicles have the same emission ratios as CNG combination short-haul trucks, that CNG intercity buses have the same emission ratios as CNG combination long-haul trucks, and that CNG school buses and CNG refuse trucks have the same emission ratios as CNG transit buses. In addition, it is assumed in GREET that CNG heavy-duty pickup trucks and vans and CNG medium heavy-duty vocational vehicles have the same ratio of emissions relative to their gasoline counterparts as CNG Class 2a light-duty vehicles relative to their gasoline counterparts in GREET. Furthermore, no studies focus on evaporative VOC emissions of NG HDVs. Therefore, we assumed that NG HDVs have the same evaporative VOC emissions as their diesel counterparts.

TABLE 31 Summary of ratios of air pollutant emissions for spark-ignited NG HDVs relative to their diesel or gasoline counterparts

Vehicle Type	MY	VOC, Exhaust	CO	NO_x	PM_{10}, Exhaust	$PM_{2.5}$, Exhaust	N_2O
Combination long-haul trucks	1990–2005	100%[a]	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]
Combination short-haul trucks	1990–2005	100%[a]	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]
Heavy, medium, and light heavy-duty vocational vehicles	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%	[e]	50%[f]	100%	100%	25%[g]
Refuse trucks	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]
Heavy-duty pickup trucks and vans	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%	[e]	50%[f]	100%	100%	25%[g]
Medium heavy-duty vocational vehicles[h]	1990–2005	60%	80%	100%	100%	100%	60%
	2010–2020	100%	100%	100%	100%	100%	100%
Heavy-duty pickup trucks and vans[h]	1990–2005	60%	80%	100%	100%	100%	60%
	2010–2020	100%	100%	100%	100%	100%	100%
Transit buses	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]
Intercity buses	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]
School buses	1990–2005	100%	15%[b]	65%[c]	10%	10%	100%
	2010–2020	100%[d]	[e]	50%[f]	100%	100%	25%[g]

a Lyford-Pike (2003).
b Representing the lean-burn engine technology with oxidation catalyst, according to Clark et al. (1999) and Lyford-Pike (2003).
c Representing properly tuned lean-burn engines.
d Both MY 2010 diesel and stoichiometric CNG vehicles had shown reductions of VOC emissions (Hajbabaei et al. [2013]). It is assumed that these vehicles have no differences in their VOC emissions.
e See Table 30.
f U.S. Environmental Protection Agency (2014g); Carder et al. (2014).
g Carder et al. (2014).
h Relative to gasoline counterparts; all other vehicles are relative to diesel counterparts.

4.3 LIQUEFIED NATURAL GAS

With its volumetric energy content roughly 2.5 times that of CNG at 3,600 psi, LNG can deliver more range with smaller fuel tanks compared to CNG, and thus has been used as an alternative fuel for long-haul trucking operations (Howell and Harger, 2013). Outside of fuel tank weight, there is little difference between spark-ignited NGVs using CNG vs. LNG, as the engines will operate exactly the same way. LNG vehicles will typically weigh less than CNG vehicles with the same range, owing to the lower weight of the storage tanks and fuel, though the difference is small.

Studies conducted as part of the DOE's Advanced Vehicle Testing Activity (Chandler et al., 2000a, 2000b, 2001) showed that the fuel economy for spark-ignited lean-burn LNG trucks was 13%–38% lower than for comparable diesel trucks. A 27% fuel economy penalty was measured for LNG trucks; however, those trucks hauled 34% more refuse by weight than their diesel counterparts (Chandler et al., 2001). A 38% fuel economy penalty was reported for LNG trucks that were used for shorter, stop-and-go trips at generally lower speeds than their diesel counterparts; this penalty affected the comparative energy efficiency of the fleets (Chandler et al., 2000a).

These tests of LNG spark-ignited NG vehicles that predated the 2007/2010 EPA and CARB emission standards typically showed a fuel economy penalty of 15%–30% when compared to their diesel counterparts. Not surprisingly, this range is similar to the results for CNG HDVs tested during this time frame. As the weight difference is typically small, we assumed in GREET that spark-ignition LNG trucks and other HDV types have the same DGE-based fuel economy as the corresponding CNG HDVs, as summarized in Table 27.

Moreover, it is assumed that LNG HDVs have the same relative air pollutant emissions as CNG HDVs compared to their diesel counterparts, owing to the equivalence of their engine technologies and aftertreatment systems. For example, studies showed that LNG trucks averaged about 80% less NO_x emissions and about 96% less PM mass emissions than diesel trucks (Chandler et al., 2000a), in agreement with the findings for CNG trucks.

Westport has developed an alternative to the stoichiometric NG engine, specifically, the LNG HPDI™ engine with diesel pilot injection ignition. This technology involves injecting a small amount of diesel, typically 5% on an energy basis, into the engine cylinder to provide compression ignition for the NG, which allows the engine to have similar performance and fuel efficiency to a diesel compression-ignition engine while consuming NG as its primary fuel (Gao et al., 2013). In this system, LNG is pumped up to high pressure, vaporized, and delivered to the engine at approximately 4,500 psi and is ignited after the diesel pilot ignition in a compression-ignition cycle, as shown by Chandler and Proc (2004). This technology was implemented in Class 8 trucks upon its release in 2010, although market conditions caused Westport to stop production in the U.S. in 2013. Westport has announced plans to release its next generation of the technology, which would reduce costs and improve performance (Green Car Congress, 2014).

The fuel economy and emissions of trucks converted to HPDI technology were evaluated as part of DOE's Advanced Vehicle Testing Activity to explore the LNG engine's potential for diesel-like fuel economy and power (Chandler and Proc, 2004). The HPDI LNG trucks had an 11% lower energy-equivalent fuel economy than the new diesel trucks. The HPDI LNG engines had 35% lower NO_x and 38% lower PM emissions than the comparable diesel engines (Chandler and Proc, 2004).

In separate testing by Graham et al. (2008), two Class 8 trucks with standard diesel-fueled engines (2004 Cummins ISX450 engines) were converted to run with HPDI fuel systems, and the LNG HPDI trucks had only a 3% fuel economy penalty. In addition, that study measured the CH_4 tailpipe emissions to be 4.2 g/mi for these LNG HPDI trucks, which were prototypes of the version released for public sale in 2010 (Graham et al., 2008). Recent emission testing done by WVU for California's SCAQMD showed that 2008 LNG HPDI freight trucks had about 9% lower fuel economy than EPA/CARB 2010-compliant diesels in a regional hauling application (Carder et al., 2014). On shorter duty cycles, the 2008 LNG HPDI trucks' fuel economy penalty ranged from 12% to 19%, which is larger than expected (Carder et al., 2014). WVU performed emission testing of a 2011 LNG HPDI truck, which was the generation that was publicly released, but fuel economy results were not presented (Carder et al., 2014).

Similarly to results for stoichiometric-engine NGVs, WVU testing (Carder et al., 2014) showed that the 2011 LNG HPDI freight truck had significantly lower NO_x emissions than its EPA/CARB 2010-compliant diesel counterpart using SCR (see Table 28). Test results for that truck showed similar NMHC emissions, significantly lower CO emissions, and slightly lower PM emissions for the regional-haul duty cycle. WVU found that CH_4 tailpipe emissions from LNG HPDI freight trucks were 2.6 g/mi, about 50% higher than from stoichiometric-engine NG HDVs (Carder et al., 2014). No data were available for crankcase CH_4 emissions of HPDI vehicles, but CH_4 slip from fuel tank venting is potentially much more significant on HPDI trucks, owing to the lack of evaporative cooling systems (Greszler, 2015). Overall, the N_2O emissions of LNG HPDI trucks were about 40% higher than those of the diesel trucks; however, MY 2011 emissions were significantly higher than those of the MY 2008 trucks, potentially because of catalyzation of the DPF and oxidation of ammonia over the SCR substrate.

In accordance with these studies, we made assumptions in GREET about the fuel economy and emissions of LNG long-haul and short-haul combination trucks with diesel pilot injection, as shown in Table 32. In addition, we assume these vehicles use 95% LNG and 5% diesel on an energy basis. For the reasons mentioned earlier, when comparing NG versus diesel vehicle CH_4 emissions, we adopted the NG CH_4 emissions expressed in their absolute values using a throughput approach, estimated crankcase emissions to be 22% higher than tailpipe emissions, and estimated extended idling emissions using MOVES2014 activity data. Results are shown in Table 33.

TABLE 32 Relative fuel economy and emission ratios of LNG HPDI trucks compared to their diesel counterparts, in GREET

Vehicle Type	Model Years	Fuel Economy[a]	CO[b]	NO_x[b]	PM[b]	N_2O[b]	Other Pollutants
Combination long-haul trucks	1990–2005	0.90	1.00	0.65	0.62	1.00	1.00
	2010–2020	0.95	0.50	0.50	0.90	1.40	1.00
Combination short-haul trucks	1990–2005	0.90	1.00	0.65	0.62	1.00	1.00
	2010–2020	0.95	0.50	0.50	0.90	1.40	1.00

[a] DGE MPG.
[b] on a per-mile basis.

TABLE 33 CH_4 emissions for LNG HPDI trucks

Vehicle Type	MY	Fuel Use	Tailpipe CH_4		Crankcase CH_4		Total CH_4	
		Btu/mi	g/ million Btu	g/mi	g/ million Btu	g/mi	g/ million Btu	g/mi
Combination long-haul trucks	2000	24,806	75	1.9	91.6	2.3	166	4.1
	2010	23,586	49	1.1	59.5	1.4	108	2.6
Combination short-haul trucks	2000	23,979	71	1.7	87.2	2.1	159	3.8
	2010	23,206	45	1.0	54.5	1.3	99	2.3

4.4 LIQUEFIED PETROLEUM GAS

LPG has been used for several decades as a transportation fuel and is well suited for spark-ignited engines. The LPG vehicles available today use converted gasoline engines and will typically have similar engine efficiencies (Nylund et al., 2004). Recently, the University of California-Riverside tested a MY 2009 LPG school bus equipped with TWC for SCAQMD and compared it with a MY 2007 diesel school bus with a DPF (and no SCR). The LPG school bus utilized an 8.1-L engine based on a General Motors gasoline engine, which was available between 2008 and 2011 (Laughlin and Burnham, 2014b). Results showed that the LPG school bus had 12% lower fuel economy, 7.1 MPG for diesel vs. 4.1 MPG or 6.2 MPDGE for LPG, on the CBD drive cycle. The LPG bus exhibited much lower NO_x emissions and lower PM emissions, but higher CO, HC, and CH_4 emissions than its diesel counterpart, as shown in Table 34 (Miller et al., 2013).

TABLE 34 Air pollutant emissions of LPG school buses compared to their diesel counterparts, as measured by Miller et al. (2013)

	NO_x[a]	PM	HC	CO	CH_4
LPG	0.1	2.0	0.13	9.8	0.2
Diesel	7.1	6.0	0.03	0.2	0.02

[a] CBD cycle.

In addition, Miller et al. (2013) tested a MY 2005 port truck that had been converted using a MY 2009 LPG 8.1-L engine and compared it to various post-2007 and post-2010 diesels. The researchers found the LPG truck difficult to test; it nearly overheated, as the engine was not properly sized for the chassis and duty cycle (loads were set at 69,500 lb for goods movement testing). The LPG truck had significantly higher emissions than the diesel trucks (Miller et al., 2013). It is difficult to draw any conclusions from the LPG port vehicle tests, as the engine was not designed for that application.

Owing to the limited test data available, we assumed that LPG HDVs have the same fuel economy on a GGE basis as their gasoline counterparts. In addition, analysis of heavy-duty LPG engine certification data shows similar emissions in comparison to their gasoline counterparts (U.S. Environmental Protection Agency, 2014g). Therefore, we adopted the emissions of gasoline school buses, which we estimated with the EPA's MOVES model, as shown in Table 35. Further testing expanding on the work of Miller et al. (2013) is needed to see whether LPG engines operating on the correct duty cycles can provide in-use emission benefits.

TABLE 35 MOVES air pollutant emissions of gasoline school buses as surrogates for those of LPG-fueled school buses

Model Year	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	16.1793	1.0314	0.0108	0.0187	0.0168	0.0125
1995	11.0365	0.8483	0.0122	0.0139	0.0124	0.0125
2000	5.8936	0.6651	0.0137	0.0091	0.0080	0.0125
2005	5.6594	0.4077	0.0060	0.0016	0.0014	0.0125
2010	3.8553	0.0972	0.0059	0.0016	0.0014	0.0125
2015	3.6553	0.0888	0.0016	0.0015	0.0013	0.0125
2020	3.6481	0.0793	0.0016	0.0015	0.0013	0.0125
Model Year	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.0016	0.0096	0.0030	0.2410	2.3787	1.2001
1995	0.0016	0.0062	0.0022	0.1388	1.9764	0.9592
2000	0.0016	0.0028	0.0014	0.0367	1.5741	0.7184
2005	0.0016	0.0004	0.0008	0.0268	0.8274	0.7351
2010	0.0016	0.0004	0.0007	0.0231	0.2284	0.7347
2015	0.0016	0.0004	0.0007	0.0234	0.2037	0.7243
2020	0.0016	0.0004	0.0007	0.0234	0.2013	0.6654

Owing to the lack of emission measurement data for Class 2b heavy-duty pickup trucks and Class 4 and Class 6 vocational trucks, we adopted those of gasoline Class 2b heavy-duty pickup trucks and vans (see Table 12 in Section 3.1.2), and those of gasoline Class 6 medium heavy-duty vocational trucks (see Table 15 in Section 3.1.2) as surrogates for the LPG counterparts. Furthermore, we adopted the MOVES emission factors for Class 4 gasoline light heavy-duty vocational trucks, as shown in Table 36, for Class 4 LPG light heavy-duty vocational trucks.

TABLE 36 MOVES air pollutant emissions of Class 4 gasoline light heavy-duty vocational vehicles as surrogates for those of LPG-fueled light heavy-duty vocational vehicles

Model Year	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	14.5959	1.1660	0.0129	0.0137	0.0125	0.0108
1995	10.1701	0.9402	0.0144	0.0103	0.0093	0.0108
2000	5.7443	0.7143	0.0159	0.0070	0.0062	0.0108
2005	5.5704	0.5528	0.0070	0.0012	0.0010	0.0108
2010	3.9568	0.1306	0.0071	0.0012	0.0010	0.0108
2015	4.0429	0.1092	0.0020	0.0012	0.0010	0.0108
2020	4.1985	0.0849	0.0021	0.0012	0.0010	0.0108
Model Year	$PM_{2.5}$, BTW	POC	BC	CH_4	VOC, exhaust	VOC, evaporative
1990	0.0014	0.0069	0.0023	0.2639	2.1535	1.5128
1995	0.0014	0.0050	0.0017	0.1505	1.7958	1.1145
2000	0.0014	0.0031	0.0011	0.0371	1.4381	0.7161
2005	0.0014	0.0003	0.0006	0.0288	0.7603	0.4979
2010	0.0014	0.0003	0.0006	0.0241	0.2124	0.4733
2015	0.0014	0.0003	0.0006	0.0302	0.2048	0.5429
2020	0.0014	0.0003	0.0006	0.0296	0.1973	0.4550

4.5 HYBRID ELECTRIC VEHICLES

Vehicles can achieve fuel efficiency improvements from hybridization, owing to two major factors. First, hybrid technology makes it possible to resize a vehicle's engine closer to its average power demand, which will allow it to run at more consistent loads, providing improved fuel efficiency. Second, hybrid technology allows for the recovery of braking energy, otherwise lost as heat, which can be used to drive the vehicle.

The benefits of hybridization depend on the driving cycle, with low-speed stop-and-go driving cycles providing the largest fuel-saving benefits on a per-mile basis (Zou et al., 2004; Santini and Burnham, 2013). In the HDV sector, hybrid electric vehicle (HEV) propulsion systems are mostly used in transit buses, as they typically have regular stop-and-go driving patterns, but hybrid systems are also becoming available for delivery vehicles and smaller-sized trucks (see Table 4). Refuse hauling represents another potential hybrid application because of its driving cycle.

Numerous studies have been conducted to evaluate the fuel economy and emissions of hybrid electric buses, refuse trucks, and vocational vehicles. NREL collected operational data, including fuel consumption and emissions, from 10 MY 1998 and MY 1999 hybrid buses running between 1999 and 2001, and compared them to 14 conventional diesel transit buses. Results showed significantly increased fuel economy and reduced NO_x and PM emissions for the HEVs: for MY 1998 hybrid buses with regenerative braking and the air conditioning and heating off, fuel economy was improved by 23–64%, depending on the test cycle. The buses might show less improvement with air conditioning or heating on.

MY 1999 hybrid electric buses equipped with a DPF had 38% lower CO, 49% lower NO_x, 450% higher HC, and 60% lower PM emissions than diesel buses with a catalyzed DPF operating on the CBD cycle (Chandler et al., 2002). The increase in HCs for the hybrid buses was not typical, but the reason was not explained in the study. As mentioned previously, HEVs gain increased powertrain fuel efficiency by recapturing energy while braking and by allowing the engine of the vehicle to be sized closer to the average power demand rather than peak demand (as long as sustained high power is not required, e.g., for hill climbing).

Engine downsizing can be beneficial for reducing engine-out NO_x emissions, since NO_x production is roughly proportional to the engine's indicated power and increases strongly with the engine brake output (Clark et al., 2010). However, there may not be a tailpipe-out NO_x benefit for post-2010 U.S. diesel hybrids, as higher loads raise exhaust temperature to the point where the SCR is very efficient. Hybrids may, in fact, have increased NO_x emissions unless care is taken in calibration of the system, as shown in recent EU studies (Nylund and Koponen, 2012). PM and CO emissions are reduced through hybrid operation by smoothing transient operation (Clark et al., 2010).

Fuel consumption and air pollutant emissions from five diesel hybrid electric buses and diesel buses were measured on the chassis dynamometer by WVU (Clark et al., 2000). The results showed about 13% fuel economy gain and significant air pollutant emission reductions for MY 1998 hybrid buses on the CBD cycle, compared to their diesel counterparts.

New York City Transit reported that a MY 2004 Orion VII hybrid bus running on ULSD showed fuel economy improvements of 32% to 48% over comparable conventional diesel buses, and reduced air pollutant emissions, in comparison to a diesel bus with a DPF and a CNG bus (Callaghan and Lynch, 2005). These findings indicated that the Orion VII diesel-hybrid achieved PM levels comparable to those of diesel buses equipped with DPFs, and to those of CNG buses. However, it was unclear whether the DPFs were the same type as used in MY 2007 and later heavy-duty engines.

NO_x emissions from 170 in-use New York City transit buses comprising conventional diesel buses, diesel hybrid electric buses, and CNG buses were sampled and measured (Shorter et al., 2005). Results showed that NO_x emissions from hybrid buses were comparable to those from CNG buses, and were approximately 50% of those from conventional transit buses.

Later, NREL evaluated and compared 30 MY 2004 diesel and 10 MY 2004 diesel hybrid electric buses that were identical except for the General Motors Allison EP50 parallel hybrid system (Chandler and Walkowicz, 2006). The conventional and hybrid buses were equipped with DPFs, and had similar service and duty cycles during the 12-month evaluation. The results showed that the hybrid buses had, on average, 27% higher fuel economy (ranging from 24% to 30% improvement) as compared to the diesel buses. The hybrid buses achieved reductions in NO_x and CO to a varying extent, depending on duty cycles. However, no conclusion about the hybridization effect on HC emissions could be drawn because higher HC emissions were measured under the Manhattan duty cycle, despite lower emissions under the CBD duty cycle and a custom driving cycle made up of various King County runs. PM emissions were typically reduced by the hybrids, even though both the hybrids and diesels had DPFs which significantly reduced emissions to 0.05–0.4 g/mi. These PM reductions were duty-cycle-dependent and varied widely, ranging from -73% to 97%.

A 19–35% fuel consumption saving relative to a conventional diesel bus was measured for a MY 2007 6.7-L engine-powered hybrid transit bus on various driving cycles in Europe (Nylund and Koponen, 2012), which translated to a fuel economy gain of 23–54%. Both the conventional and hybrid diesel buses were equipped with DPFs and were certified to the EPA 2007 emission standard. For PM emissions, no clear trend for the effect of hybridization could be seen, as emissions were very similar. However, hybridization seemed to increase NO_x emissions on MY 2007 vehicles, which did not have SCR. As argued by the authors, this was likely the result of changes to the exhaust temperature profile that may arise when a diesel engine is coupled with a hybrid drive system; operation may differ from that of a standard diesel engine during engine certification testing.

On-board fuel consumption and vehicle emissions were measured for a European "enhanced environmentally friendly vehicle" (EEV) diesel bus with an Eaton hybrid electric powertrain and a Euro 4 conventional diesel bus used in China. No DPFs or SCR were adopted for PM or NO_x emission control. In this study (Hu et al., 2009), the hybrid bus achieved a 41–44% higher fuel economy and 13% lower NO_x, 28% lower PM, and 35% lower HC emissions than the diesel bus.

Information on the performance of one MY 2005 and one MY 2009 hybrid electric school bus and two diesel counterparts, all running on B20, were collected during 2008 and 2010 to evaluate the in-use fuel economy of these buses while operating in Iowa (Hallmark et al., 2011). Results from 18 seasonal observations showed that one hybrid bus had an overall fuel economy 29.6% higher than that of the conventional bus, and results from 13 seasonal observations showed that the other hybrid bus had an overall fuel economy 39.2% higher than that of the other conventional diesel bus.

Table 37 summarizes the ratios of fuel economy and emissions of hybrid electric buses vs. their diesel counterparts from vehicle chassis testing and road measurements reported in the literature. The difference in fuel economy improvement for hybrid buses is related to varied duty cycles and the fact that earlier versions of the HEV systems tested were not always optimized (as many were demonstration projects).

On the basis of these findings, we made the assumptions shown in Table 38 regarding the relative fuel economy and air pollutant emissions of hybrid electric transit buses compared to their diesel counterparts. We assumed that hybrid buses do not have NO_x, PM, or HC emission reduction benefits. We made this assumption on the basis of results from Nylund and Koponen (2012), which suggested that there was a wide variation in the relative emission ratios of NO_x, HC, and PM, and no conclusions could be reached on NO_x, HC, and PM emission differences between HEVs and diesel vehicles equipped with SCR and DPFs, running under different duty

TABLE 37 Ratios of fuel economy and emissions of hybrid electric buses vs. their diesel counterparts from vehicle chassis testing and road measurements in the literature

Data source	HDV Type	Model Year	Driving Cycle	DPF Equipped?	SCR Equipped?	Fuel Economy	NO_x	CO	HC	PM
Chandler et al., 2002	Transit bus	1998	CBD	No	No	1.23	0.64	0.03	0.57	0.5
Clark et al., 2000	Transit bus	1998	NYBC	No	No	1.64	0.56	0.44	1.88	0.23
	Transit bus	1998	Manhattan	No	No	1.48	0.56	0.02	0.72	0.01
	Transit bus	1999	CBD	Yes	No	1.59	0.51	0.62	4.5	0.4
	Transit bus	1998	CBD	Yes	No	1.13	0.7	0.04	0.6	0.51
Callaghan and Lynch, 2005	Transit bus			Yes		1.32-1.48	0.34	0.25	1	1
	Transit bus	2004	Manhattan	Yes	No	1.75	0.61	0.85	1.25	0.07
	Transit bus	2004	OCTA	Yes	No	1.51	0.71	0.68	1.00	0.49
	Transit bus	2004	CBD	Yes	No	1.48	0.73	0.52	0.25	0.03
	Transit bus	2004	KCM[a]	Yes	No	1.30	0.82	0.41	0.44	1.73
Nylund and Koponen, 2012	EU EEV Transit bus		ADEME	Yes	Yes	1.48	1.39	0.44	[b]	[b]
	EU EEV Transit bus		Manhattan	Yes	Yes	1.52				
	EU EEV Transit bus		OCTA	Yes	Yes	1.41				
	EU EEV Transit bus		UDDS	Yes	Yes	1.20	[b]	0.50	[b]	1.60
	EU EEV Transit bus		Braunschweig	Yes	Yes	1.30	0.75	0.36	0.75	[b]
	EU EEV Transit bus		NYBUS	Yes	Yes	1.40	1.92	0.20	[b]	[b]
	U.S. Transit bus	2007	Manhattan	Yes	No	1.45	1.59	0.70		2.67
Hallmark et al., 2011	School bus	2009	Road trip in a school district	No	No	1.30				
	School bus	2005	Road trip in a school district	No	No	1.39				

[a] A custom driving cycle made up of various King County runs.
[b] Inconclusive trend in relative emissions between hybrids and their diesel counterparts.

TABLE 38 Ratios of fuel economy and air pollutant emissions for hybrid electric buses vs. their diesel counterparts

Model Year	Fuel Economy	CO	HC	NO_x	PM
1990–2005	135%	50%	100%	60%	20%
2010–2020	140%	50%	100%	100%	100%

cycles. The fuel economy of MY 2010–2020 hybrid transit buses was assumed to be 140% relative to their diesel counterparts, which is slightly higher than the results shown for MY 1990–2005, as we expect improvements from better optimization of commercial products. Furthermore, no studies focus on evaporative VOC emissions of diesel hybrid electric HDVs. We assumed that diesel hybrid electric HDVs have the same evaporative VOC emissions as their diesel counterparts.

Heavy-duty vocational vehicles employed for pickup and delivery applications represent an ideal duty cycle for hybrid electric powertrains because the low speed and frequent stop-and-start operation provides good opportunities for enhancing engine operation efficiency and recovering braking energy by adding an electric drive system to the vehicle (Nellums et al., 2003). The technical development of hybrid electric powertrains and their application to heavy, medium, and light heavy-duty vocational vehicles have been evaluated primarily by simulations.

A Class 5 hybrid electric light heavy-duty vehicle for delivery services was simulated on a new composite drive cycle, which was designed to represent the typical driving pattern of Class 4–6 heavy-duty hybrid vehicles. The results showed that this hybrid HDV achieved a fuel economy gain of about 35% relative to its diesel counterpart (Zou et al., 2004). A MY 1999 Class 4 hybrid electric truck for pickup and delivery applications developed by Eaton was tested on a chassis dynamometer for performance and emission evaluation. Results showed that the hybrid truck had a 45% increase in fuel economy and a decrease of PM and NO_x emissions by 93% and 54%, respectively, compared to its diesel counterpart (Nellums et al., 2003). In another study, an MY 2007 and an MY 2010 Class 7 hybrid pickup and delivery truck had 35–52% and 17–32%, respectively, higher fuel economy compared to their diesel counterpart (Proust and Surcel, 2012).

An Autonomie-based simulation found that a diesel hybrid electric Class 8 truck had 40% and 10% higher fuel economy than its conventional diesel counterpart on the UDDS and freeway driving cycles, respectively (Gao et al., 2013). These findings can be translated to about a 28% fuel economy gain for a Class 8 heavy-duty vocational truck that travels on a 60%/40% split of city and highway driving cycles. Zhao et al. (2013) reported that Class 8 hybrid trucks can achieve improvements of 50% in fuel economy over their conventional diesel counterparts on the simulated urban driving cycle and 28% on the simulated freeway driving cycle.

Daw et al. (2013) compared the simulated fuel economy and emissions for both conventional and hybrid electric Class 8 heavy-duty diesel trucks operating on multiple urban and highway driving cycles. Results showed that the cumulative fuel savings for the hybrid were up to 36.4% on the city driving cycle, which represented a fuel economy gain of up to 57%.

Compared to the conventional diesel truck, the simulated tailpipe CO, HC, and NO_x emissions for the light-load hybrid were reduced by 50%, 72%, and 9%, respectively, on the urban driving cycle. At higher loads, the hybrid advantage in CO and HC emissions was smaller but still significant (13% and 40% reduction, respectively).

Results of these simulations and chassis dynamometer testing suggested fuel economy benefits and emission impacts that were similar to what chassis and road measurements had suggested for buses. Therefore, we assumed that hybridization would have the same effects on fuel economy and emissions for heavy-duty vocational vehicles as it does for buses, as shown in Table 38.

4.6 HYDRAULIC HYBRID VEHICLES

Unlike HEVs, which use electrochemical (battery) or electrostatic (ultracapacitor) energy storage, hydraulic hybrid vehicles (HHVs) capture kinetic energy during braking events, store it in hydro-pneumatic accumulators, and return energy to the driveline during vehicle acceleration (Boretti and Stecki, 2012). Hybrid hydraulic powertrains fit certain HDV applications because of their high power density (Surampudi et al., 2009). The EPA found that hydraulic hybrid systems were cost-effective for heavy-duty hybrid vehicles and concluded that they could be a solution until large-capacity batteries become more affordable (Alson et al., 2004). Other studies showed that hydraulic regenerative systems could recover more energy and achieve higher efficiency than electric regenerative systems (Ning et al., 2012; Woon et al., 2011).

The EPA and its partners have successfully installed hydraulic hybrid technology in a variety of vehicles, including delivery trucks and work trucks. Their testing has shown real-world fuel economy improvements of 30% to over 100% over their conventional counterparts (U.S. Environmental Protection Agency, 2014h). Kim and Rousseau (2013) evaluated the performance of Class 6 HHVs and compared it to conventional diesel and diesel HEVs. The results demonstrated that HHVs achieve about 25–190% higher fuel economy than their diesel counterparts on aggressive drive cycles like the UDDS, CBD, Manhattan, and New York cycles. The 190% fuel economy gain seems unlikely to be achieved in practice. Also, HHVs achieve higher fuel savings than HEVs when driven on these aggressive drive cycles because of higher system efficiency during regenerative braking events, as well as a higher charging power.

HHV technology has been demonstrated in the past few years as a viable technology for brake energy recovery for transit buses and refuse trucks, which are engaged in heavy urban stop-and-go or highly transient duty cycles, regenerating a large portion of the energy that is dissipated during braking. For extremely short driving cycles, as are common with refuse vehicles, the use of hydraulic regenerative systems reduces fuel consumption by up to 30% for Class 8 refuse trucks, equivalent to a fuel economy gain of 43% (Baseley et al., 2007). The City of Denver has employed the Peterbilt Model 320 hydraulic hybrid refuse truck, which utilizes Eaton's hydraulic launch assist system. The truck has achieved 25% better fuel economy than its non-hybrid counterparts, supporting the assessment of DOE's Clean Cities Program (Lauron, 2009; Shea, 2011).

Parker reported that replacing Class 8 refuse trucks, with conventional drivetrains, with its RunWise hydraulic hybrid drivetrains resulted in a fleet average 43% (35%–50%) reduction in diesel consumption, depending on route density and operating conditions (Parker, 2013). The company reports that high fuel saving is achieved by decoupling the engine from the wheels at speeds under 45 mph, which allows the engine to operate at its peak efficiency, and by recovering brake energy to reduce the total vehicle fuel consumption. Emission testing of the Parker hydraulic hybrid refuse truck showed significant reductions in CO and NO_x emissions relative to its conventional counterpart, as shown in Table 39 (Parker, 2013). However, information was not presented regarding the MY or specific vehicle technologies used for these fuel economy and emissions comparisons.

TABLE 39 Comparison of fuel economy (DGE MPG) and air pollutant emissions (g/mi) from conventional and hydraulic hybrid diesel refuse trucks on low-speed and high-speed cycles

		Fuel Economy	CO	NO_x	HC
Low-speed cycle	Diesel	0.88	14.01	3.8	0
	Diesel HHV	1.31	7.25	2.29	0.13
High-speed cycle	Diesel	3.78	1.16	2.13	0.06
	Diesel HHV	4.32	1.6	2.29	0.01
Combined cycle[a]	Diesel	1.46	11.44	3.47	0.012
	Diesel HHV	1.91	6.12	2.29	0.11
Ratio of HHV to conventional diesel		1.31	0.53	0.66	8.83[b]

[a] With 80%/20% split between the low- and high-speed cycles.

[b] This ratio is deemed not meaningful, owing to a possible testing error relating to the HC emissions from the diesel refuse vehicle on the low-speed cycle.

Another study found that heavy-duty diesel-powered refuse trucks equipped with hydraulic regenerative braking systems provided fuel economy improvements of 4.0% relative to their conventional diesel counterparts on the WVU Refuse Truck Cycle and 7.2% on the New York City Garbage Truck Cycle, compared to a fuel economy improvement upper limit of 25.1% on an ideal driving cycle consisting of a high proportion of low-speed, stop-and-go driving with little idling, PTO or transient operation (New West Technologies, LLC, 2011).

In GREET, we assumed that hydraulic hybrid refuse trucks have a 25% higher fuel economy (20% lower fuel consumption) than their diesel counterparts. While the study by Parker (2013) showed CO and NO_x emission reductions of 47% and 34%, respectively, we used emission assumptions for diesel HEVs for this vehicle type, since there was a limited amount of vehicle testing of HHVs. With a 20% fuel saving, we assumed that the tailpipe CO emissions are reduced by 50% for hydraulic hybrid refuse trucks compared to their diesel counterparts.

4.7 BATTERY ELECTRIC VEHICLES

The first all-electric refuse truck in the U.S., manufactured by Motiv Power Systems, began operations in Chicago in 2014. The all-electric refuse truck is equipped with 200 kilowatt-hours of energy that supplies enough electricity to move the truck and power the hydraulics, with a payload capacity of nine tons and 1000 pounds per cubic yard of compaction (Motiv Power Systems, 2014). The refuse truck has a drive range of 60 miles, allowing a 10- to 20-mi drive while consuming a large amount of the electrical energy by compaction and by driving the truck under full load (Motiv Power Systems, 2014; Castelaz, 2014). With this information, we estimated a fuel economy of about 11.3 MPDGE, which was about 375% of that of the diesel refuse truck. When a charger efficiency of 88% and battery-in and battery-out efficiency of 95% are accounted for, the fuel economy gain is reduced to 314%.

Proterra's EcoRide BE35 transit bus is the world's first heavy-duty, fast-charge, battery-electric bus. Proterra's regenerative braking system enables the EcoRide BE35 to recapture 90% of the vehicle's kinetic energy available during braking, which in turn increases the total distance the bus can drive by 31–35%. During a road test, the bus drove more than 700 mi in 24 hours at an average speed of 29 mi per hour with the air conditioning system running. According to Proterra's report on the fuel economy of in-service customer fleet operations, the electric bus exhibits a typical fuel economy of more than 17 MPDGE, or a 300–500% improvement over conventional combustion engines (Proterra, 2014). We assumed that electric transit buses represented by Proterra EcoRide BE35 have a fuel economy of 400% of that of their diesel counterparts, based on energy drawn from the battery.

4.8 ETHANOL

Ethanol flexible fuel (E85) heavy-duty pickup trucks and vans and Class 4 (light heavy-duty) and Class 6 (medium heavy-duty) delivery trucks are available (see Table 4. Owing to lack of measurement data on the fuel economy and emission profiles of these ethanol-fueled HDV types, we assumed in GREET that ethanol-fueled heavy-duty pickup trucks and vans and Class 6 delivery trucks have fuel economy equivalent to that of their gasoline counterparts on a GGE basis, while the ethanol-fueled Class 4 trucks display a 15% fuel economy penalty relative to their diesel counterparts on a GGE basis.

We assumed in GREET that the ratios of air pollutant emissions for ethanol-fueled heavy-duty pickup trucks and vans and Class 6 medium heavy-duty vocational vehicles relative to their gasoline counterparts are the same as those between Class 2a ethanol and gasoline light-duty vehicles assumed in GREET, as shown in Table 40. Furthermore, we estimated the ratios of air pollutant emissions for ethanol-fueled Class 4 delivery trucks relative to their diesel counterparts on the basis of emissions of gasoline and diesel Class 4 vocational vehicles, as shown in Table 41. Lower NO_x and PM emissions from ethanol vehicles compared to their diesel counterparts were also found in measurements by others (Nylund and Koponen, 2012).

TABLE 40 Ratio of air pollutant emissions for ethanol-fueled heavy-duty pickup trucks and vans and medium heavy-duty vocational vehicles vs. their gasoline counterparts

Model Year	VOC (Exhaust)	VOC (Evaporative)	CO	NO_x	PM_{10}	$PM_{2.5}$	CH_4	N_2O
1990	0.85	0.85	0.75	1.00	0.80	0.80	0.70	1.00
1995	0.85	0.85	0.80	1.00	0.95	0.95	0.75	1.00
2000	1.00	0.85	0.90	1.00	1.00	1.00	0.80	1.00
2005	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00
2010	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00
2015	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00
2020	1.00	0.85	1.00	1.00	1.00	1.00	1.00	1.00

TABLE 41 Ratio of air pollutant emissions for ethanol-fueled Class 4 light heavy-duty vocational vehicles vs. their diesel counterparts

Model Year	CO	NO_x	N_2O	PM_{10}	$PM_{2.5}$	PM_{10}, BTW
1990	32.18	0.47	25.85	0.08	0.08	1.00
1995	20.75	0.51	29.00	0.09	0.09	1.00
2000	10.90	0.59	32.20	0.10	0.10	1.00
2005	12.80	0.53	14.37	0.02	0.02	1.00
2010	59.43	0.72	14.43	1.07	1.04	1.00
2015	62.47	0.64	4.00	1.18	1.14	1.00
2020	64.11	0.49	4.09	1.20	1.16	1.00
Model Year	**$PM_{2.5}$, BTW**	**POC**	**BC**	**CH_4**	**VOC, exhaust**	**VOC, evaporative**
1990	1.00	0.11	0.04	86.66	2.09	53.30
1995	1.00	0.07	0.03	45.26	1.20	42.07
2000	1.00	0.12	0.04	15.16	1.06	37.06
2005	1.00	0.02	0.02	12.05	0.89	21.46
2010	1.00	0.79	2.66	0.26	2.38	20.16
2015	1.00	0.88	3.07	0.30	2.20	24.03
2020	1.00	0.89	3.13	0.30	2.14	21.03

4.9 DIMETHYL ETHER

Dimethyl ether (CH_3-O-CH_3) is a synthetic, sulfur-free, and oxygenated fuel. It has been identified as a possible replacement for diesel fuel because of its normally higher cetane number than diesel and its favorable physical properties for vaporization and atomization, which promote cleaner combustion (Fonseca de Carvalho e Silva, 2006). Like LPG, DME does not require high-pressure pumps or cryogenic storage.

DME produces extremely low PM emissions because of its low auto-ignition temperature, its almost instantaneous vaporization when injected into the cylinder, its high oxygen content (35% by mass), and the absence of carbon-to-carbon bonds in its molecular structure (Jung et al., 2011). Thus, a dedicated DME vehicle might not require a particulate filter (Teng and McCandless, 2006; Zhang et al., 2008). Significant reductions in PM emissions were observed when a converted shuttle bus without an oxidation catalyst was operated on DME–diesel blends, although there were increases in unburned HC, NO_x and CO (Eirich et al., 2003). Most recently, testing of a European vehicle running on DME showed that the PM emissions ranged from about 0.03 to 0.07 g/mi on various driving cycles (Nylund and Koponen, 2012), which were somewhat higher but still within the same range compared to the very low levels of PM emissions from U.S. diesel buses.

A number of characteristics of DME—e.g., its higher evaporation latent heat, smaller actual dynamic fuel injection advanced angle, lower burning temperature, and higher achievable exhaust gas recirculation rate relative to diesel—would help DME vehicles meet the EPA's NO_x emission standard, with potentially lower NO_x than diesel (Teng and McCandless, 2006; Zhang et al., 2008). On the other hand, Jung et al. (2011) found that DME exhibits higher NO_x emissions than diesel, partly because its injection duration is longer. CO and HC emissions from incomplete DME combustion can be treated relatively easily with the same type of oxidation catalyst used for diesel, e.g., very low CO and HC emissions were measured from a DME engine equipped with an oxidation catalyst converter (Hansen et al., 2000).

Although the emission levels indicated by engine testing in the aforementioned studies were low and comparable to diesel, to the best of our knowledge, field measurement results on real-world DME vehicle emissions have yet to be published. This data gap makes it difficult to compare DME vehicles with modern diesel counterparts that comply with the EPA's heavy-duty engine emission standards. Therefore, in this analysis, it is assumed that DME HDVs are equivalent in air pollutant emissions to their diesel counterparts from MY 2010 and beyond. It is also assumed that DME HDVs are equivalent in fuel economy to diesel vehicles on a DGE basis (Volvo, 2013). Volvo is the first manufacturer to announce plans to commercialize DME-powered heavy-duty commercial vehicles in North America (Volvo, 2013).

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5 PROJECTION OF FUEL ECONOMY BY HDV SUBCATEGORY

The 2010 NAS study identified many technologies for reducing the LSFC of conventional HDV, including those for improved engine and transmission efficiency, hybridization, aerodynamic vehicle body design, and vehicle mass reduction (National Research Council, 2010). One of the study's findings was that development of fuel-saving engine technologies and their effective integration into the powertrain are critical for reducing fuel use by HDVs. As a result, the fuel economy of new HDVs depends on the market penetration of specific fuel-saving technologies determined by consumer preference or regulatory requirements.

EIA's AEO considered future fuel-saving technologies from the 2011 Standard, such as advanced transmissions, lightweight materials, synthetic gear lubrication, advanced drag reduction, advanced tires, electronic engine controls, turbo-compounding, and hybrid powertrains in its projection of HDV fuel economy (U.S. Energy Information Administration, 2014c). We projected the fuel economy by HDV subcategory up to 2020, as shown in Table 42. We calculated these values from the estimated baseline fuel economy for each subcategory (see Table 5) and the projections for light medium (Class 3), medium (Class 4-6), and heavy (Class 7 and 8) trucks in the AEO (U.S. Energy Information Administration, 2014d), as shown in Equations 5-1 and 5-2. (Since AEO's projection starts with MY 2011, we used the fuel economy of MY 2011 vehicles as a surrogate for that of MY 2010 vehicles.) It is noted that EPA and NHTSA are in the progress of developing the next round of medium- and heavy-duty fuel efficiency standards, which may increase the fuel economy of baseline vehicles (U.S. Environmental Protection Agency, 2014c).

$$\boldsymbol{FE_{2015}} = \boldsymbol{FE_{2010}} \times \frac{\boldsymbol{AEO_{2015}}}{\boldsymbol{AEO_{2010}}} \qquad \text{Equation (5-1)}$$

$$\boldsymbol{FE_{2020}} = \boldsymbol{FE_{2010}} \times \frac{\boldsymbol{AEO_{2020}}}{\boldsymbol{AEO_{2010}}} \qquad \text{Equation (5-2)}$$

TABLE 42 Projection of fuel economy (MPG) of HDVs by subcategory in 2015 and 2020, in comparison with historic fuel economy performance based on the 2002 VIUS

	Historic Performance	Projections	
	MY 2002	MY 2015	MY 2020
Diesel combination long-haul trucks[a]	6.3	7.3[c]	7.7[c]
Diesel combination short-haul trucks[a]	6.3	7.4[c]	7.8[c]
Diesel heavy heavy-duty vocational vehicles[a]	6.3	7.4[c]	7.8[c]
Diesel refuse trucks[a]	4.9	5.7[c]	6.0[c]
Diesel medium heavy-duty vocational vehicles[a]	8.2	8.3[d]	8.8[d]
Diesel light heavy-duty vocational vehicles[a]	9.9	10.1[d]	10.7[d]
Diesel heavy-duty pickup trucks and vans[a]	20.3	20.8[d]	22.4[d]
Gasoline medium heavy-duty vocational vehicles[b]	7.5	8.8[e]	9.5[e]
Gasoline heavy-duty pickup trucks and vans[b]	15.3	17.8[e]	19.2[e]
Diesel transit buses[a]	3.5	4.1[c]	4.4[c]
Diesel intercity buses[a]	6.0	6.6[c]	7.0[c]
Diesel school buses[a]	7.0	7.7[c]	8.2[c]

[a] In miles per diesel gallon.
[b] In miles per gasoline gallon.
[c] Estimate based on AEO’s fuel economy projection of diesel heavy trucks.
[d] Estimate based on AEO’s fuel economy projection of diesel medium trucks.
[e] Estimate based on AEO’s fuel economy projection of gasoline medium trucks.

With the projected fuel economy of the HDV subcategories (see Table 42) and their payloads that we assumed would remain as for MY 2013 vehicles see Table 9), we calculated the fuel consumption of the HDV subcategories, as shown in Table 43. In that table, we also compare our projections with the fuel consumption mandates in the 2011 Standard. Combination long-haul and short-haul trucks, heavy heavy-duty vocational vehicles, and refuse trucks are projected to achieve a fuel consumption reduction of 17% and 21% for MY 2015 and MY 2020 vehicles, respectively, relative to the levels of MY 2010 vehicles. Other HDV subcategories are expected to reduce their fuel consumption by 10–11% and 15–17% for MY 2015 and MY 2020 vehicles, respectively.

Fuel-saving technologies, without the adoption of hybridization technologies, have the potential to achieve a reduction in fuel consumption by about 18–24% for heavy and medium heavy-duty vocational vehicles (National Research Council, 2010). Therefore, advanced engine and vehicle technologies have the potential to achieve the projected fuel economy for a variety of the HDV subcategories.

TABLE 43 Projection of fuel consumption of various HDV subcategories in comparison with fuel consumption mandates in the 2011 Standard

	Projection				Mandates in the 2011 Standard			
	Gallons per 1000 ton-mi		Gallons per 100 mi		Gallons per 1000 ton-mi		Gallons per 100 mi	
	MY 2015	MY 2020	MY 2015	MY 2020	MY 2014–2016	MY 2017	MY 2015	MY 2018 and later
Diesel combination long-haul trucks[a]	6.7	6.3			7.4	7.2		
Diesel combination short-haul trucks[b]	6.6	6.3			8.7	8.4		
Diesel heavy heavy-duty vocational vehicles	6.0	5.7				21.8		
Diesel refuse trucks	18.0	17.0				21.8		
Diesel medium heavy-duty vocational vehicles	25.1	23.7				22.1		
Diesel light heavy-duty vocational vehicles	40.9	38.6				36.7		
Diesel heavy-duty pickup trucks and vans[c]			4.8	4.5			6.3	5.6
Gasoline medium heavy-duty vocational vehicles	32.4	30.6				22.1		
Gasoline heavy-duty pickup trucks and vans[e]			6.4	5.9			7.1	6.5

Table 43 shows that the projected fuel consumption levels for MY 2015 and MY 2020 HDVs meet or exceed the fuel consumption standards set for most MY 2014–2016 and MY 2017 vehicles, respectively. The exceptions are MY 2020 diesel and gasoline medium heavy-duty vocational vehicles and MY 2020 diesel light heavy-duty vocational vehicles. These exceptions may result from an underestimation of the carried payload based on our analysis of VIUS, as compared to the payloads specified in the regulatory impact analysis of the 2011 Standard, as shown in Table 44. Therefore, we adjusted the carried payloads from VIUS to those in the 2011 Standard for MY 2020 vehicles in these HDV subcategories. This adjustment results in compliance with the fuel consumption standard for these vehicle subcategories, as shown in Table 44.

TABLE 44 A comparison of carried payloads for diesel and gasoline medium heavy-duty vocational vehicles, as well as diesel light heavy-duty vocational vehicles, based on VIUS and the 2011 Standard

	Payload in VIUS, tons	Payload in 2011 Standard, tons	New Fuel Consumption, Gallons per 1000 ton-mi
Diesel medium heavy-duty vocational vehicles	4.8	5.6	20.2
Gasoline medium heavy-duty vocational vehicles	4.0	5.6	18.9
Diesel light heavy-duty vocational vehicles	2.4	2.85	32.7

In GREET, we adopted the projections, shown in Tables 43 and 44, for MY 2015 and MY 2020 combination long-haul and short-haul trucks; diesel heavy, medium, and light heavy-duty vocational vehicles; diesel refuse trucks; diesel and gasoline heavy-duty pickup trucks; and gasoline medium heavy-duty vocational vehicles.

6 DISCUSSION AND OUTSTANDING ISSUES

The HDV sector is extremely diverse and complex in several respects, including types of manufacturing companies involved, the range of sizes of trucks and engines they produce, the types of work the trucks are designed to perform, and the regulatory history of different subcategories of vehicles and engines (Federal Register, 2011). To evaluate the life-cycle energy use, GHG emissions, and CAP emissions of key subcategories of the HDV sector, we examined the vehicle fuel economy and emissions in relation to the actual work done by a variety of HDV subcategories. These subcategories encompass vehicles from ‘‘18-wheeler’’ combination tractors to school, transit, and intercity buses, to vocational vehicles such as refuse trucks, dump trucks, and utility service trucks, as well as the largest pickup trucks and vans. We incorporated these vehicle types in the GREET HDV module to examine the fuel consumption and emissions impacts of alternative fuel and advanced vehicle technologies for this diverse market. Even though we collected data and analyzed key issues during this project as extensively as we could, there are many outstanding issues and information gaps that could significantly affect energy and emission results of HDVs. We discuss some of the issues and gaps below.

6.1 FUEL CONSUMPTION

We used the 2002 VIUS database to estimate the fuel economy and payloads carried for various HDV subcategories fueled by diesel or gasoline. Results showed that the fuel consumption for a given amount of work performed varied widely among the baseline diesel and gasoline HDV types. Little variation in the fleet-average fuel economy of HDV types was found over the past decade. A small overall improvement in the fuel economy for new MY 2010 and later vehicles over MY 2002 vehicles was estimated on the basis of AEO fuel economy projections. Improvements in HDV fuel economy over time were reduced by particulate emission control requirements, while in 2010 the NO_x aftertreatment equipment helped improve fuel economy, as it allowed for engine optimization.

Advanced engine and transmission, vehicle mass reduction, and vehicle aerodynamic and tire rolling resistance technologies have been developing to provide promising technical paths for conventional HDVs to meet the tighter fuel consumption standards. However, there has been limited publicly available data from real-world vehicle fuel efficiency testing to address the advances in engine and emission aftertreatment technologies over the years. This lack of data has been a major challenge for the evaluation of the effects of vehicle technological innovation on vehicle fuel efficiency achievements. With the introduction of the EPA/NHTSA Phase 2 fuel consumption standard for HDVs underway, continued evaluation of the impacts of advanced vehicle technologies on vehicle fuel consumption is warranted.

Similarly, there is a lack of data on recent payload trends of various HDV types. While the payloads carried by EPA’s SmartWay fleet of various types of HDVs in 2011 showed little change compared to those in the 2002 VIUS database, some industry stakeholders stated that payloads have increased since 2002 owing to more efficient logistics systems. Modern HDVs record fuel consumed and miles driven and many can download payload data with the proper payload sensing equipment. Therefore, research programs to collect and analyze these data would help to better understand both the fuel economy and the work done under real-world driving conditions for the wide range of HDV types. In addition, improved HDV simulations could help better understand how technologies can reduce fuel consumption for various drive cycles.

Both fuel economy and payloads were incorporated into GREET as separate parameters to define the LSFC per ton-mile. This metric is used in GREET to calculate the life-cycle energy use and GHG and CAP emissions of the various HDV subcategories. However, we did not quantify the relationship between changed payloads and fuel economy for various HDV subcategories in this analysis. One needs to make sure that assumptions about payload and fuel consumption are considered together when evaluating the impacts of HDV applications. While some studies have addressed the effect of a change in payloads for certain vehicles types in support of the EPA/NHTSA standards, further research in this area is warranted.

6.2 AIR POLLUTANT EMISSIONS

The EPA emission standard for heavy-duty highway diesel engines and vehicles beginning in MY 2007 has been met by HDV engine and vehicle manufacturers primarily by deployment of advanced engine technologies and tailpipe emission control technologies. In accordance with the standard, PM emissions have been reduced by more than 90% and NO_x emissions by more than 80% for most diesel HDVs.

EPA's latest vehicle tailpipe emission model, MOVES2014, was used to generate GVWR- and MY-specific VMT-weighted average lifetime emission factors of CAPs, CH_4, N_2O, BC, and POC of various diesel and gasoline HDV subcategories in real-world operations. The emission factors reflect the impacts of recent emission regulations on vehicle and engine performance. Low levels of NO_x emissions were found for post-MY 2010 diesel HDVs in MOVES simulations, indicating that SCR is assumed to work effectively to reduce the emissions. On the other hand, poor SCR efficiency and resultant high NO_x emissions were found for low-speed, low-load duty cycles in which the exhaust was not hot enough (Lammert et al., 2012; Misra et al., 2013; Carder et al. 2014). Testing of new MY diesel HDVs would clarify whether this issue has been addressed.

Extended idling has been a target for reducing the fuel consumption and emissions of combination long-haul trucks, with a focus on reducing the time spent idling through driver behavior changes and new equipment. In GREET, we have introduced the idling hours per mile and the idling emissions per hour as separate parameters to calculate idling emissions per mile. This provides the capability in GREET to model the impact of reduced idling on fuel consumption and emissions of Class 8b combination long-haul trucks. However, the impact of idling events on per trip fuel consumption and emissions and other trip characteristics needs to be further quantified. Moreover, inconsistencies in the magnitudes of the idling emissions for Class 8b combination long-haul trucks were found between the MOVES data and vehicle chassis testing results elsewhere (Khan et al., 2006). Therefore, more testing of the emissions and fuel consumption associated with idling is warranted, particularly for MY 2007 and later vehicles, to reconcile the discrepancies between different studies and to improve the confidence of evaluating the idling impacts on fuel consumption and emissions of HDVs. In addition, more data on the idling emissions and activities of other HDV types is needed.

We have observed consistently, from both the earlier and the latest versions of MOVES, that the CH_4 emissions for diesel HDV subcategories increase by more than one order of magnitude for MY 2010 and later vehicles compared to those for pre-MY 2010 vehicles. The reason for this abrupt change in CH_4 emissions in MOVES is unknown. This highlights another outstanding issue associated with the emission modeling with MOVES and the need for further emission data validation and improvement within the model.

6.3 ALTERNATIVE FUEL AND ADVANCED VEHICLES

A portfolio of AFV options are being developed and deployed to reduce the diesel and gasoline consumption, GHG emissions, and tailpipe air pollutant emissions of the HDV sector. While biodiesel (especially lower-level blends up to B20) has shown little effect on vehicle fuel economy on a DGE basis, it can reduce HC, CO, and PM emissions to a varying extent among the HDV subcategories, with little or no contribution to NO_x emission changes. For example, with the introduction of SCR for NO_x emission control in MY 2010 and later vehicles, the biodiesel effect on NO_x emissions was not statistically significant in these vehicles. However, there is an OEM concern that biodiesel could accelerate the deterioration of SCR performance. Further research is needed to investigate long-term effects of biodiesel on SCR systems.

Spark-ignited NG HDVs display a fuel economy penalty relative to their diesel counterparts because of the engine's properties, though stoichiometric NG engines have reduced the penalty as compared to previous lean-burn NG engines. In addition, the penalty has been reduced as diesel engines had to meet stringent air pollutant emission standards. LNG HPDI vehicles have shown an improvement in fuel economy compared to spark-ignition NG vehicles, as they can achieve a diesel-like performance using diesel for pilot ignition. Real-world testing of new NG HDVs has been limited; therefore, further analysis of these vehicles on various duty cycles is needed to understand their life-cycle energy use and emissions.

Lean-burn NG HDVs had shown some reductions in NO_x and PM emissions relative to their pre-MY 2007 diesel counterparts. Modern stoichiometric NG HDVs with TWCs have lower NO_x but higher CO emissions than their diesel counterparts. Methane slip from both past and current NG vehicles results in much higher CH_4 emissions than for their diesel counterparts. Currently, U.S. NG HDVs have an open crankcase that may produce about the same amount of CH_4 emissions as measured in tailpipe slip. The current literature has focused on tailpipe CH_4 slip only; however, a forthcoming WVU study aims to measure both crankcase and tailpipe CH_4 emissions from NG HDVs. The results would be helpful in filling the current data gap for this important issue. In addition, this topic relates to an important consideration when examining existing vehicle performance. If an area is of concern, technologies often can be developed to reduce the impacts. In this specific case, technologies used in European NGVs have been shown to significantly reduce CH_4 emissions and could likely be introduced by OEMs in the U.S. in response to the need to address this issue.

Biomass-derived drop-in renewable diesel is another AF option being developed and promoted to displace conventional diesel fuel. Nylund and Koponen (2012) suggested that renewable diesel in EU engines may have some positive emissions impacts. Owing to lack of data for the U.S. heavy-duty engines, we assumed that renewable diesel vehicles would achieve the same air pollutant emissions as conventional diesel vehicles. Fischer-Tropsch synthetic fuels sourced from natural gas, coal, and biomass are also being developed and promoted as AF options. Further studies to investigate the fuel economy and emission impacts of U.S. HDVs running on renewable drop-in and synthetic fuels are needed to validate the potential emission benefits and fuel consumption implications.

Both hybrid-electric and hydraulic hybrid technologies have the potential to reduce fuel consumption, especially in demanding duty cycles that consist of frequent stop-and-go and low-speed driving. The emission reduction potential of hybrid HDVs is highly duty-cycle-dependent, and demonstrations of these HDVs have shown little emission benefit compared to MY 2007 and later diesel vehicles. Hydraulic hybrid powertrains have been applied commercially to refuse trucks, owing to their high power density, and have demonstrated fuel and emission benefits over their diesel counterparts. Battery electric powertrains have been commercially deployed for refuse trucks and transit buses. These vehicles have demonstrated significant fuel economy benefits over their diesel counterparts. However, limited data are available on these still-developing technologies, especially as compared to the newest diesel vehicles. Further analysis is needed to understand both the fuel economy and emissions performance of these vehicles.

Data on the fuel economy of MY 2007 and later AFVs (including those mentioned above as well as LPG and ethanol vehicles) that operate on comparable, if not exactly the same, duty cycles as their conventional diesel or gasoline counterparts remain very limited. Research focusing on testing of HDV fuel economy of AFVs in comparison to their conventional counterparts is warranted to fill the information gap. Particularly, the vehicle testing procedures for conventional vehicles and AFVs should minimize the potential differences between the vehicles (e.g., drive cycle and vehicle engine optimization) to elucidate the true differences in fuel economy for various HDV applications.

In addition, as many AF and advanced HDVs are being demonstrated and just becoming available to consumers, it will be important to understand how these technologies will improve with time. As AFVs enter new vocational applications, work will need to be done to estimate their performance. Technologies not addressed in this report, such as fuel cell vehicles and plug-in hybrid electric vehicles, will need to be examined as well.

With the low levels of tailpipe CAP emissions brought about by advanced engine and tailpipe emission control technologies for baseline diesel and gasoline HDVs, the emission reduction potentials of AFVs relative to MY 2007 and later HDVs are likely smaller than they were prior to the EPA 2007/2010 standards. However, emission data from real-world vehicle driving tests and chassis dynamometer tests, comparing modern AFVs with their post-MY 2010 conventional counterparts, is needed to better understand the potential emission benefits or penalties of AFVs.

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APPENDIX A: CO_2 EMISSIONS AND FUEL CONSUMPTION STANDARD FOR HEAVY-DUTY VEHICLES

According to the 2011 Standard, EPA and NHTSA defined the CO_2 emissions and fuel consumption standards for heavy-duty pickups and vans by the following formulae:

CO_2 Target (g/mi) = $[a \times \text{WF}] + b$ — Equation A1

Fuel Consumption Target (gallons/100 mi) = $[c \times \text{WF}] + d$ — Equation A2

Where
WF is work factor, as depicted in Equation A3; and
Coefficients *a*, *b*, *c*, and *d* are taken from TABLE A1, which is Table II–12 of the 2011 Standard.

Work Factor = [0.75 × (Payload Capacity + xwd)] + [0.25 × Towing Capacity] — Equation A3

Where
Payload Capacity = GVWR minus curb weight, which is the total weight of a vehicle with standard equipment, all necessary operating consumables, and a full tank of fuel, while not loaded with either passengers or cargo, in lb;
xwd = 500 lb if the vehicle is equipped with four-wheel drive, otherwise 0 lb; and
Towing Capacity = the gross combined weight rating, which describes the maximum load that the vehicle can haul, including the weight of a loaded trailer and the vehicle itself, minus GVWR, in lb.

TABLE A1 Coefficients for HD Pickup and Van Target Standards (from the 2011 Standard)

MY	a	b	c	d
Diesel Vehicles				
2014	0.0478	368	0.00047	3.61
2015	0.0474	366	0.000466	3.6
2016	0.046	354	0.000452	3.48
2017	0.0445	343	0.000437	3.37
2018 and later	0.0416	320	0.000409	3.14
Gasoline Vehicles				
2014	0.0482	371	0.000542	4.17
2015	0.0479	369	0.000539	4.15
2016	0.0469	362	0.000528	4.07
2017	0.046	354	0.000518	3.98
2018 and later	0.044	339	0.000495	3.81

Figure A1 shows the EPA CO_2 target standards and NHTSA fuel consumption target standards for diesel heavy-duty pickups and vans as a function of the work factor.

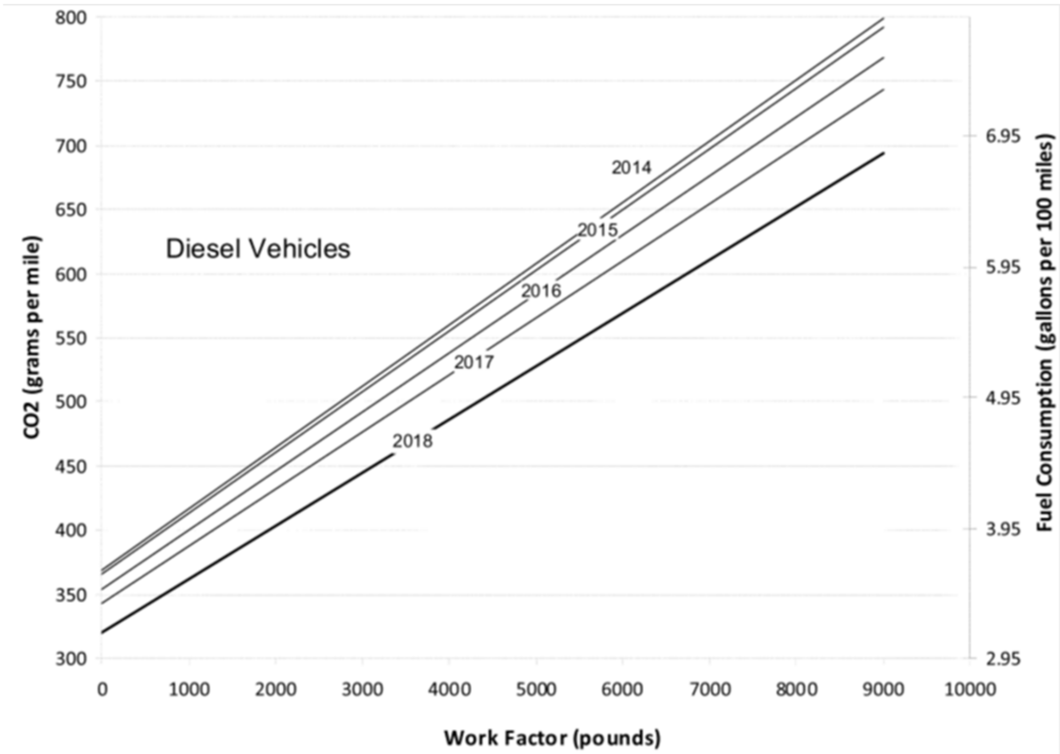

FIGURE A1 EPA CO_2 target standards and NHTSA fuel consumption target standards for diesel heavy-duty pickups and vans (Federal Register, 2011)

The EPA’s and NHTSA’s target standards for combination trucks are presented in Table A2, which is Table II–1 of the 2011 Standard.

TABLE A2 Heavy-Duty Combination Tractor Emissions and Fuel Consumption Standards

	Day Cab		Sleeper Cab
	Class 7	Class 8	Class 8
2014–2016 MY CO_2 grams per ton-mile			
Low roof	107	81	68
Mid roof	119	88	76
High roof	124	92	75
2017 MY CO_2 grams per ton-mile			
Low roof	104	80	66
Mid roof	115	86	73
High roof	120	89	72
2014–2016 MY gallons per 1000 ton-miles			
Low roof	10.5	8.0	6.7
Mid roof	11.7	8.7	7.4
High roof	12.2	9.0	7.3
2017 MY gallons per 1000 ton-miles			
Low roof	10.2	7.8	6.5
Mid roof	11.3	8.4	7.2
High roof	11.8	8.7	7.1

The EPA's and NHTSA's target standards for vocational trucks are presented in Table A3, which is Table I–4 of the 2011 Standard.

TABLE A3 Final 2017 EPA Emissions Standards (g CO_2/ton-mile) and NHTSA Fuel Consumption Standards (gal/1,000 ton-miles) for MY 2017 Class 2b-8 Vocational Vehicles

	Light Heavy-duty Class 2b–5	Medium Heavy-duty Class 6-7	Heavy Heavy-duty Class 8
grams per ton-mile			
CO_2 emissions	373	225	222
gal per 1,000 ton-miles			
Fuel consumption	36.7	22.1	21.8

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APPENDIX B: ANALYSIS OF 2002 VEHICLE INVENTORY AND USE SURVEY

The U.S. Census Bureau conducted the 2002 Vehicle Inventory and Use Survey (VIUS) as a part of the Economic Census. The survey provides national- and state-level estimates of truck population, truck characteristics, and usage. Prior to 1997, the survey was called Truck Inventory and Use Survey and was conducted every five years, during calendar years ending in 2 and 7. Because of budget constraints, the survey was dropped from the Economic Census after 2002. Thus, the 2002 VIUS is the last survey that provides information relating to truck characteristics and usage. Argonne National Laboratory has used the 1977 through 2002 surveys to conduct various analyses related to trucks.

The 2002 VIUS is based on a sample of private and commercial trucks registered (or licensed) in the United States as of July 1, 2002 (U.S. Census Bureau, 2004). The survey excludes trucks owned by local, state, and federal governments; ambulances; buses; motor homes; and farm tractors.

The final data file of the 2002 VIUS contained 98,682 observations, of which 3,250 represented "Not in Use" trucks with zero VMT. The resulting number of useful observations was 95,432. When expanded by using sample weights, these 95,432 observations represented 83,491,000 trucks traveling 1,114,728,001,000 mi annually.

Of the 95,432 useful observations, 18,053 did not have any fuel economy (MPG) information. In order to assign some reasonable fuel economy estimate to these observations, the 77,379 records that had fuel economy information were analyzed and average estimates were created by two variables: (1) average weight-based gross vehicle weight (GVW) and (2) truck body type. These averages of known fuel economy were assigned to the 18,053 observations that did not have any fuel economy information by matching GVW and body type. Annual fuel gallons were estimated for each observation by using expanded annual miles and fuel economy.

The VIUS 2002 data file contained two GVW fields: (1) average weight-based GVW and (2) VIN-based GVW. The average weight-based GVW field has 15 gross weight classes: (1) <=6,000 lb, (2) 6,001–8,500 lb, (3) 8,501–10,000 lb, (4) 10,001–14,000 lb, (5) 14,001–16,000 lb, (6) 16,001–19,500 lb, (7) 19,501–26,000 lb, (8) 26,001–33,000 lb, (9) 33,001–40,000 lb, (10) 40,001–50,000 lb, (11) 50,001–60,000 lb, (12) 60,001–80,000 lb, (13) 80,001–100,000 lb, (14) 100,001–130,000 lb, and (15) over 130,000 lb. We combined gross weight classes 9 through 11 to form GVW class 8a and combined gross weight classes 12 through 15 to form GVW class 8b.

The 2002 VIUS contains 29 body types for single-unit trucks and 18 trailer types for combination trucks. The single-unit truck body types are (1) pickup, (2) minivan, (3) light van other than minivan, (4) sport utility, (5) armored, (6) beverage, (7) concrete mixer, (8) concrete pumper, (9) crane, (10) curtain-side, (11) dump, (12) flatbed, stake, or platform, (13) low boy, (14) pole, logging, pulpwood, or pipe, (15) service-utility, (16) service-other, (17) street sweeper, (18) tank-dry bulk, (19) tank-liquids or gases, (20) tow/wrecker, (21) trash, garbage, or recycling, (22) vacuum, (23) van-basic enclosed, (24) van-insulated non-refrigerated, (25) van-insulated refrigerated, (26) van-open top, (27) van-step, walk-in, or multistep, (28) van-other, and (29) other-not elsewhere classified. A blank body type signified the truck to be a combination tractor trailer. The combination tractor trailer types were (1) automobile carrier, (2) beverage, (3) curtain-side, (4) dump, (5) flatbed or platform, (6) livestock, (7) low boy, (8) mobile home totter, (9) open top, (10) pole, logging, pulpwood, or pipe, (11) tank-dry bulk, (12) tank-liquids or gases, (13) trailer with mounted equipment, (14) van-basic enclosed, (15) van-drop frame, (16) van-insulated non-refrigerated, (17) van-insulated refrigerated, and (18) trailer not elsewhere classified. A truck tractor was further classified as one without a cab sleeper or one with a cab sleeper. Also, each truck tractor was assigned the trailer type most often attached to it. In VIUS, there are 551,205 Class 8a single-unit trucks and 276,930 Class 8a combination trucks, and there are 202,897 Class 8b single unit trucks and 1,074,132 Class 8b combination trucks.

The survey questionnaire contained questions relating to percent of annual miles accounted for by trips in five distance ranges and off-road operation. The five distance ranges were (1) <=50 mi, (2) 51–100 mi, (3) 101–200 mi, (4) 201–500 mi, and (5) >500 mi. The Census Bureau assigned a primary operating range to each truck that corresponded to the largest percentage of annual miles. If the largest percentage occurred in more than one distance range, a distance range was assigned randomly. We removed this random assignment by always assigning the highest distance range when two or more ranges happened to have the same percentage of annual miles.

The 2002 VIUS included information on type of fuel most often used by the truck. In total, fourteen fuels and fuel type combinations were included: (1) gasoline, (2) diesel, (3) natural gas, (4) LPG, (5) alcohol fuels, (6) electricity, (7) gasoline and natural gas, (8) gasoline and LPG, (9) gasoline and alcohol fuels, (10) gasoline and electricity, (11) diesel and natural gas, (12) diesel and LPG, (13) diesel and alcohol fuels, and (14) diesel and electricity. In 2002, only a few selected areas required gasoline to be blended with ethanol, an alcohol. The number of observations that represented trucks operating on a fuel type other than gasoline or diesel was very small. When trucks were classified by GVW class, detailed fuel type, primary operating range, truck type (single unit, combination without a cab sleeper, and combination with a cab sleeper), and body/trailer type, the numbers of observations for fuels other than gasoline and diesel were very low. We combined all fuel types other than gasoline and diesel in one category named "other."

The 2002 VIUS collected information on average weight of each cargo-carrying truck when loaded. This average weight represented vehicle weight plus cargo weight. For a combination truck, this data item represented the sum of tractor, trailer and cargo weights. The survey also collected the empty weight of each cargo-carrying truck. For combination trucks, this weight represented the sum of the tractor and empty trailer weights. Out of 95,432 usable observations, 38,253 observations did not have weight information. A majority of observations without weight data, 21,159, represented trucks used for personal transportation. The remaining cargo-carrying trucks were assigned average values for GVW class and fuel type. Cargo tonnages were estimated by subtracting empty weight from average weight. These tonnages can be used with expanded annual miles and annual fuel consumption to develop estimates of ton-miles per gallon of fuel.

The 2002 VIUS collected data on percentage of annual miles driven when a cargo-carrying truck was empty. We used this data item to develop weighted averages. One of the truck characteristics within the 2002 VIUS is cubic inch displacement (CID) of the truck engine. This data item is in the form of narrow ranges by fuel type. Each observation is assigned a CID code depending on the engine fuel and engine size. We assigned the midpoint of the range to each observation and developed weighted averages.

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APPENDIX C: VIUS-BASED VEHICLE OPERATIONAL CHARACTERISTICS

TABLE C1 Breakdown and comparison of total energy consumption shares, the fuel consumption weighted averages, and the 10th percentiles and 90th percentiles of fleet-average fuel consumption per 1000 ton-mi, fleet-average effective payload, and fleet-average engine displacement of regulatory vehicle categories by engine fuel type, by GVWR class, and by body type, based on 2002 VIUS data

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Diesel	88.90%															
Combination trucks	71.10%	80084	17197	96184	5.8	5	6.3	12	11.3	66.8	15.9	2.5	16.5	12.8	9.9	13.3
Combination long-haul	63.80%	99910	54267	103182	5.9	5.3	6.1	10.6	10.6	60.4	17.2	2.7	17.7	13	12	13.3
Class 7	0.60%	73990	52080	123772	5.9	5.8	6.1	53.5	51.2	66.6	3.2	2.5	3.3	11.9	11.6	12
Trailer: dump >50 miles	2.20%	143393	143393	143393	5.9	5.9	5.9	68.4	68.4	68.4	2.5	2.5	2.5	12	12	12
Trailer: flatbed/platform	31.50%	76132	76132	76132	5.8	5.8	5.8	55.5	55.5	55.5	3.1	3.1	3.1	12	12	12
Trailer: other	13.40%	41772	41772	41772	6.2	6.2	6.2	62.5	62.5	62.5	2.6	2.6	2.6	11.4	11.4	11.4
Trailer: van	52.90%	77991	77991	77991	5.9	5.9	5.9	49.4	49.4	49.4	3.4	3.4	3.4	12	12	12
Class 8a	10.00%	90361	54527	97620	6.2	5.6	6.1	18.7	18.7	25.3	8.7	7	8.8	12.5	12	13
Trailer: dump >50 miles	2.20%	53484	53484	53484	5.5	5.5	5.5	24	24	24	7.6	7.6	7.6	12	12	12
Trailer: flatbed/platform	10.10%	64488	64488	64488	5.9	5.9	5.9	21.7	21.7	21.7	7.8	7.8	7.8	12.1	12.1	12.1
Trailer: other	4.40%	56092	56092	56092	5.9	5.9	5.9	26.2	26.2	26.2	6.5	6.5	6.5	12.4	12.4	12.4
Trailer: tank	1.60%	98561	98561	98561	5.8	5.8	5.8	20.2	20.2	20.2	8.6	8.6	8.6	13.3	13.3	13.3
Trailer: van	81.80%	96208	96208	96208	6.3	6.3	6.3	17.7	17.7	17.7	9	9	9	12.5	12.5	12.5
Class 8b	89.50%	101135	78927	101485	5.8	5.2	5.9	9.4	9.6	11.3	18.3	15.9	18.4	13	12.8	13.4
Trailer: dump >50 miles	1.70%	77295	77295	77295	5.2	5.2	5.2	11.3	11.3	11.3	17.1	17.1	17.1	13.3	13.3	13.3
Trailer: flatbed/platform	11.00%	87826	87826	87826	5.3	5.3	5.3	10.4	10.4	10.4	18	18	18	13.4	13.4	13.4
Trailer: other	4.80%	81375	81375	81375	5.3	5.3	5.3	11.4	11.4	11.4	16.6	16.6	16.6	13.2	13.2	13.2
Trailer: tank	5.60%	95968	95968	95968	5.9	5.9	5.9	11	11	11	15.4	15.4	15.4	12.7	12.7	12.7
Trailer: van	77.00%	105162	105162	105162	5.9	5.9	5.9	9	9	9	18.6	18.6	18.6	13	13	13
Combination short-haul	36.20%	45173	10575	54172	5.6	4.9	6.4	14.4	12.3	76.4	13.5	2.5	14.8	12.6	9.7	13.2
Class 7	1.30%	28428	7674	26821	6.4	3.4	6.8	56.9	47.5	172.6	3.1	2	3.4	9.9	9.2	10

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Trailer: dump <=50 miles	0.50%	6783	6783	6783	5.1	5.1	5.1	54.8	54.8	54.8	3.6	3.6	3.6	8.9	8.9	8.9
Trailer: dump >50 miles	3.60%	20312	20312	20312	1.6	1.6	1.6	247.4	247.4	247.4	2.5	2.5	2.5	9.4	9.4	9.4
Trailer: flatbed/platform	7.00%	8566	8566	8566	5.9	5.9	5.9	67.3	67.3	67.3	2.5	2.5	2.5	10.1	10.1	10.1
Trailer: other	17.60%	19724	19724	19724	7.1	7.1	7.1	46.9	46.9	46.9	3	3	3	9.8	9.8	9.8
Trailer: tank	0.80%	11436	11436	11436	6.4	6.4	6.4	97.7	97.7	97.7	1.6	1.6	1.6	9.9	9.9	9.9
Trailer: van	70.50%	33329	33329	33329	6.5	6.5	6.5	48.1	48.1	48.1	3.2	3.2	3.2	9.9	9.9	9.9
Class 8a	16.60%	30539	18021	30946	6.1	5.3	6.2	20.3	19.4	27.3	8.1	6.9	8.3	11.1	10.6	12.6
Trailer: dump <=50 miles	2.00%	19052	19052	19052	5.8	5.8	5.8	25	25	25	6.9	6.9	6.9	11.9	11.9	11.9
Trailer: dump >50 miles	1.80%	26217	26217	26217	4.9	4.9	4.9	29.6	29.6	29.6	6.9	6.9	6.9	13.1	13.1	13.1
Trailer: flatbed/platform	10.70%	19451	19451	19451	6	6	6	23.4	23.4	23.4	7.2	7.2	7.2	12	12	12
Trailer: other	14.30%	16991	16991	16991	6.2	6.2	6.2	19.4	19.4	19.4	8.3	8.3	8.3	10.2	10.2	10.2
Trailer: tank	2.50%	26153	26153	26153	5.7	5.7	5.7	24.1	24.1	24.1	7.3	7.3	7.3	11.8	11.8	11.8
Trailer: van	68.80%	35675	35675	35675	6.2	6.2	6.2	19.5	19.5	19.5	8.3	8.3	8.3	11	11	11
Class 8b	82.10%	48402	30745	58636	5.4	4.9	5.7	12.5	12	13.7	14.8	14.5	15	12.9	12.6	13.3
Trailer: dump <=50 miles	7.70%	28965	28965	28965	5	5	5	13.9	13.9	13.9	14.3	14.3	14.3	13.2	13.2	13.2
Trailer: dump >50 miles	10.40%	52710	52710	52710	4.9	4.9	4.9	13.5	13.5	13.5	15.2	15.2	15.2	13.3	13.3	13.3
Trailer: flatbed/platform	11.70%	35382	35382	35382	5.5	5.5	5.5	12.2	12.2	12.2	14.9	14.9	14.9	13.2	13.2	13.2
Trailer: other	16.90%	32525	32525	32525	5.1	5.1	5.1	13.2	13.2	13.2	14.8	14.8	14.8	13.2	13.2	13.2
Trailer: tank	16.70%	59688	59688	59688	5.5	5.5	5.5	12.3	12.3	12.3	14.8	14.8	14.8	12.6	12.6	12.6
Trailer: van	36.60%	57584	57584	57584	5.8	5.8	5.8	11.8	11.8	11.8	14.7	14.7	14.7	12.7	12.7	12.7
Heavy-duty pickup trucks and vans	4.00%	20649	17743	21963	12.1	9.6	14.2	8.5	7.1	10.4	0.9	0.7	1.3	6.5	5.7	7
Class 2b	56.40%	22166	18037	22525	13	10.5	13.3	7.8	7.6	9.6	0.7	0.7	0.8	6.7	5.8	6.8
Pickup, mini & lt. van, SUV	83.60%	23086	23086	23086	13.6	13.6	13.6	7.4	7.4	7.4	0.7	0.7	0.7	6.9	6.9	6.9
Van	16.40%	17476	17476	17476	10.2	10.2	10.2	9.8	9.8	9.8	0.8	0.8	0.8	5.6	5.6	5.6

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Class 3	43.60%	18685	18462	19247	11	9.9	13.9	9.5	7.3	10.3	1.2	1.1	1.3	6.3	6.1	6.9
Pickup, mini & lt. van, SUV	32.80%	19345	19345	19345	14.4	14.4	14.4	6.9	6.9	6.9	1.1	1.1	1.1	7	7	7
Van	67.20%	18364	18364	18364	9.4	9.4	9.4	10.7	10.7	10.7	1.3	1.3	1.3	6	6	6
Vocational vehicles	24.90%	21085	8270	32939	6.9	4.9	11.5	41	15.2	154	5.7	0.8	9.6	8.8	6.3	10.8
Heavy heavy-duty vocational vehicles	36.10%	20483	12649	34295	5.3	4.7	8.3	21.6	11.8	27.8	9.7	6.3	14.1	10.9	9.3	12.2
Class 8a	51.90%	14277	12391	17368	5.6	4.8	10.6	26.3	10.7	30.2	7	6.1	9.1	10.2	8.6	10.8
Concrete mixer & pumper	9.60%	14632	14632	14632	4.5	4.5	4.5	34.9	34.9	34.9	6.4	6.4	6.4	10.8	10.8	10.8
Dump <=50 miles	27.30%	12145	12145	12145	5.2	5.2	5.2	26.6	26.6	26.6	7.3	7.3	7.3	10.8	10.8	10.8
Dump >50 miles	11.20%	16706	16706	16706	4.9	4.9	4.9	25.9	25.9	25.9	8	8	8	10.9	10.9	10.9
Flatbed/stake/platform	18.60%	16485	16485	16485	6.2	6.2	6.2	25.8	25.8	25.8	6.3	6.3	6.3	9.3	9.3	9.3
Other	11.50%	14265	12634	14085	6.2	6.8	12.2	28.9	8.9	26.7	5.6	6.2	11.1	9.3	9.3	9.5
Pickup, mini & lt. van, SUV	0.03%	20017	20017	20017	10	10	10	11.8	11.8	11.8	8.5	8.5	8.5	5.9	5.9	5.9
Tank	11.70%	12846	12846	12846	5.4	5.4	5.4	23.3	23.3	23.3	7.9	7.9	7.9	10.2	10.2	10.2
Van	10.10%	14614	14614	14614	6.7	6.7	6.7	19.3	19.3	19.3	7.8	7.8	7.8	9.7	9.7	9.7
Class 8b	48.10%	27173	18100	34741	5	4.7	5.6	16.5	12.8	19	12.5	11.2	14.9	11.8	10.4	12.5
Concrete mixer & pumper	21.10%	17096	17096	17096	4.2	4.2	4.2	23.9	23.9	23.9	10	10	10	11.4	11.4	11.4
Dump <=50 miles	34.60%	27639	27639	27639	5	5	5	15.7	15.7	15.7	12.7	12.7	12.7	12.2	12.2	12.2
Dump >50 miles	16.30%	34042	34042	34042	5.5	5.5	5.5	13.5	13.5	13.5	13.5	13.5	13.5	12.3	12.3	12.3
Flatbed/stake/platform	5.50%	18770	18770	18770	5.6	5.6	5.6	14.8	14.8	14.8	12	12	12	10.8	10.8	10.8
Other	7.70%	29649	29649	29649	5.4	5.4	5.4	15	15	15	12.4	12.4	12.4	12.8	12.8	12.8
Tank	5.90%	35028	35028	35028	5.6	5.6	5.6	11.9	11.9	11.9	15.1	15.1	15.1	11.9	11.9	11.9
Van	8.90%	34549	34549	34549	5	5	5	13.5	13.5	13.5	14.8	14.8	14.8	9.9	9.9	9.9
Light heavy-duty vocational vehicles	22.40%	19993	8063	23765	9.5	6.2	12.6	75.4	43.7	125.2	1.7	0.8	2.5	6.7	6.2	7.4

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Class 2b	10.20%	16147	7964	21115	9.8	6.9	11.5	120.5	100.1	213.4	0.8	0.7	1	6.7	6	6.7
Concrete mixer & pumper	0.20%	26017	26017	26017	5	5	5	302.5	302.5	302.5	0.7	0.7	0.7	5.9	5.9	5.9
Dump <=50 miles	4.50%	8044	8044	8044	9.9	9.9	9.9	126	126	126	0.8	0.8	0.8	6.6	6.6	6.6
Dump >50 miles	0.90%	8986	8986	8986	11.4	11.4	11.4	120.2	120.2	120.2	0.7	0.7	0.7	6.7	6.7	6.7
Flatbed/stake/platform	41.70%	15178	15178	15178	10.1	10.1	10.1	118.4	118.4	118.4	0.8	0.8	0.8	6.6	6.6	6.6
Other	52.20%	17698	8844	16846	9.6	8.4	9.5	121.3	124.2	150.7	0.9	0.8	0.9	6.8	6.6	6.7
Tank	0.50%	15581	15581	15581	11.5	11.5	11.5	72.6	72.6	72.6	1.2	1.2	1.2	6	6	6
Class 3	20.90%	17697	10519	18149	9.5	9.1	10.3	92.8	61.3	105.4	1.1	1	1.6	6.7	6.4	6.8
Dump <=50 miles	9.10%	11026	11026	11026	10	10	10	92.3	92.3	92.3	1.1	1.1	1.1	6.7	6.7	6.7
Dump >50 miles	2.30%	11407	11407	11407	9.1	9.1	9.1	116.2	116.2	116.2	0.9	0.9	0.9	6.8	6.8	6.8
Flatbed/stake/platform	33.60%	15705	15705	15705	10.1	10.1	10.1	94.6	94.6	94.6	1	1	1	6.6	6.6	6.6
Other	54.10%	20419	11071	19535	9.1	9.2	10.1	91.5	73.5	89.8	1.2	1.2	1.4	6.7	6.6	6.7
Tank	0.90%	11453	11453	11453	10.3	10.3	10.3	51.1	51.1	51.1	1.9	1.9	1.9	6.2	6.2	6.2
Class 4	35.70%	21776	8099	25584	9.7	5.4	14.1	73.1	37.3	177.7	1.8	1.3	2.3	6.6	6.3	7.3
Concrete mixer & pumper	2.30%	19376	19376	19376	1.2	1.2	1.2	679.4	679.4	679.4	1.2	1.2	1.2	7	7	7
Dump <=50 miles	2.20%	7731	7731	7731	9.3	9.3	9.3	67.5	67.5	67.5	1.6	1.6	1.6	7.1	7.1	7.1
Dump >50 miles	0.80%	8139	8139	8139	5.9	5.9	5.9	122	122	122	1.4	1.4	1.4	6.8	6.8	6.8
Flatbed/stake/platform	14.30%	17846	17846	17846	9.9	9.9	9.9	62	62	62	1.6	1.6	1.6	6.9	6.9	6.9
Other	23.10%	18620	13047	18059	7.6	7.9	10.2	78.1	42.4	74.5	1.7	1.8	2.4	7	7.1	7.3
Pickup, mini & lt. van, SUV	15.30%	26509	17041	32988	14.6	14.1	15.2	42.3	30.6	50.3	1.8	1.5	2.2	7.2	6.9	7.3
Tank	1.10%	14467	14467	14467	7.7	7.7	7.7	65.1	65.1	65.1	2	2	2	6.3	6.3	6.3
Van	40.80%	24539	24539	24539	9.5	9.5	9.5	50.6	50.6	50.6	2.1	2.1	2.1	6.1	6.1	6.1
Class 5	33.20%	20699	8684	22404	9.2	7.3	13.1	53.1	43	73.4	2.2	1.8	2.6	6.9	6.3	7.5
Concrete mixer & pumper	0.10%	17133	17133	17133	8.4	8.4	8.4	49.8	49.8	49.8	2.4	2.4	2.4	6.3	6.3	6.3
Dump <=50 miles	2.50%	8977	8977	8977	8.1	8.1	8.1	61.2	61.2	61.2	2	2	2	7	7	7

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Dump >50 miles	0.60%	10317	10317	10317	8.9	8.9	8.9	43.6	43.6	43.6	2.6	2.6	2.6	7.6	7.6	7.6
Flatbed/stake/platform	11.00%	14256	14256	14256	9.1	9.1	9.1	55.5	55.5	55.5	2	2	2	7.1	7.1	7.1
Other	22.60%	18598	7310	17383	7.6	7.6	7.8	71.3	53.4	69.4	1.8	1.9	2.4	7.1	7.1	7.4
Pickup, mini & lt. van, SUV	15.60%	31293	13544	35311	13.4	13.1	14.8	41	39.1	49.7	1.9	1.4	2	7	6.4	7.1
Tank	3.30%	17771	17771	17771	4.8	4.8	4.8	91.7	91.7	91.7	2.3	2.3	2.3	7.4	7.4	7.4
Van	44.20%	20668	20668	20668	8.9	8.9	8.9	44.2	44.2	44.2	2.5	2.5	2.5	6.7	6.7	6.7
Medium heavy-duty vocational vehicles	33.00%	21222	8144	44412	7.4	5.6	11.5	41	25.7	197.4	3.6	0.5	4.4	7.4	6.9	9.7
Class 6	67.60%	22949	8539	68601	7.6	5.9	11.5	44.6	32.5	194.8	3.2	0.7	3.5	7.3	7	10
Concrete mixer & pumper	0.10%	15662	15662	15662	8	8	8	162.2	162.2	162.2	0.8	0.8	0.8	8.8	8.8	8.8
Dump <=50 miles	4.70%	9169	9169	9169	6.3	6.3	6.3	52.1	52.1	52.1	3.1	3.1	3.1	7.7	7.7	7.7
Dump >50 miles	1.40%	10040	10040	10040	7.4	7.4	7.4	46.8	46.8	46.8	2.9	2.9	2.9	7.7	7.7	7.7
Flatbed/stake/platform	13.80%	14171	14171	14171	8.3	8.3	8.3	40.6	40.6	40.6	3	3	3	7.2	7.2	7.2
Other	19.10%	18194	9231	17222	7.7	8.1	11.3	46.2	37.4	45.2	2.8	2.4	2.8	7.3	7.3	7.4
Pickup, mini & lt. van, SUV	1.00%	33622	13498	33502	11.7	11.7	13.7	59.1	24.2	58.9	1.6	1.6	3.4	6	6	7.1
Tank	3.30%	12145	12145	12145	6.2	6.2	6.2	46.7	46.7	46.7	3.5	3.5	3.5	7.6	7.6	7.6
Trailer: dump <=50 miles	0.03%	22154	22154	22154	8.5	8.5	8.5	636.1	636.1	636.1	0.2	0.2	0.2	8.6	8.6	8.6
Trailer: dump >50 miles	0.01%	115318	115318	115318	7.6	7.6	7.6	–	–	–	–	–	–	6.8	6.8	6.8
Trailer: flatbed/platform	0.50%	39689	13428	52182	5.4	4.5	7.5	178.4	157.7	188.3	1.1	0.9	1.2	8.8	8.3	9.8
Trailer: other	0.30%	15058	9968	22858	6.4	6.3	6.5	98.5	93.6	105.9	1.6	1.5	1.6	9.7	9.5	9.9
Trailer: tank	0.08%	14484	14484	14484	5.9	5.9	5.9	86	86	86	2	2	2	9	9	9
Trailer: van	3.90%	82144	32761	105774	5.9	5.7	6	127.7	96.4	193.1	1.6	1	1.8	10.5	9.6	11
Van	51.90%	24577	24577	24577	7.7	7.7	7.7	35.7	35.7	35.7	3.6	3.6	3.6	7.1	7.1	7.1
Class 7	32.40%	17617	6757	17590	6.9	5.6	8.8	33.6	24.6	312	4.5	2.8	5.8	7.6	7.2	8.1
Concrete mixer & pumper	0.06%	4993	4993	4993	6.1	6.1	6.1	933.9	933.9	933.9	0.2	0.2	0.2	7.7	7.7	7.7

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Dump <=50 miles	7.80%	7514	7514	7514	5.6	5.6	5.6	45.4	45.4	45.4	3.9	3.9	3.9	8	8	8
Dump >50 miles	2.00%	13136	13136	13136	5.5	5.5	5.5	42.2	42.2	42.2	4.3	4.3	4.3	8.3	8.3	8.3
Flatbed/stake/platform	16.60%	14629	14629	14629	7.6	7.6	7.6	31.2	31.2	31.2	4.2	4.2	4.2	7.6	7.6	7.6
Other	18.10%	12684	8483	12238	6.9	7.3	11.1	37.6	15.4	35.2	3.9	4.1	6.4	7.6	6.7	7.5
Tank	13.80%	13264	13264	13264	6.3	6.3	6.3	29.6	29.6	29.6	5.4	5.4	5.4	8	8	8
Van	41.70%	24497	24497	24497	7.2	7.2	7.2	30.2	30.2	30.2	4.6	4.6	4.6	7.5	7.5	7.5
Refuse trucks	8.50%	25999	17072	27093	4.7	4.5	7.5	33.1	27.8	137.2	7.6	1.1	8.7	10.2	6.2	10.7
Class 2b	0.03%	18861	18861	18861	8	8	8	100.2	100.2	100.2	1.2	1.2	1.2	9.9	9.9	9.9
Trash/garbage/recycling	100.00%	18861	18861	18861	8	8	8	100.2	100.2	100.2	1.2	1.2	1.2	9.9	9.9	9.9
Class 3	0.40%	23175	23175	23175	7.2	7.2	7.2	166.7	166.7	166.7	0.8	0.8	0.8	6.2	6.2	6.2
Trash/garbage/recycling	100.00%	23175	23175	23175	7.2	7.2	7.2	166.7	166.7	166.7	0.8	0.8	0.8	6.2	6.2	6.2
Class 4	0.60%	17086	17086	17086	4.8	4.8	4.8	124.5	124.5	124.5	1.7	1.7	1.7	6.1	6.1	6.1
Trash/garbage/recycling	100.00%	17086	17086	17086	4.8	4.8	4.8	124.5	124.5	124.5	1.7	1.7	1.7	6.1	6.1	6.1
Class 5	1.00%	20746	20746	20746	5.5	5.5	5.5	119.4	119.4	119.4	1.5	1.5	1.5	6.9	6.9	6.9
Trash/garbage/recycling	100.00%	20746	20746	20746	5.5	5.5	5.5	119.4	119.4	119.4	1.5	1.5	1.5	6.9	6.9	6.9
Class 6	2.60%	17037	17037	17037	7.3	7.3	7.3	59.9	59.9	59.9	2.3	2.3	2.3	7.4	7.4	7.4
Trash/garbage/recycling	100.00%	17037	17037	17037	7.3	7.3	7.3	59.9	59.9	59.9	2.3	2.3	2.3	7.4	7.4	7.4
Class 7	7.10%	21332	21332	21332	5.6	5.6	5.6	49.5	49.5	49.5	3.6	3.6	3.6	7.8	7.8	7.8
Trash/garbage/recycling	100.00%	21332	21332	21332	5.6	5.6	5.6	49.5	49.5	49.5	3.6	3.6	3.6	7.8	7.8	7.8
Class 8a	68.00%	25690	25690	25690	4.6	4.6	4.6	32	32	32	6.9	6.9	6.9	10.3	10.3	10.3
Trash/garbage/recycling	100.00%	25690	25690	25690	4.6	4.6	4.6	32	32	32	6.9	6.9	6.9	10.3	10.3	10.3
Class 8b	20.40%	30367	30367	30367	4.3	4.3	4.3	18	18	18	12.8	12.8	12.8	11.6	11.6	11.6
Trash/garbage/recycling	100.00%	30367	30367	30367	4.3	4.3	4.3	18	18	18	12.8	12.8	12.8	11.6	11.6	11.6
Gasoline	10.50%															
Combination trucks	0.60%	47196	1283	49331	5.3	4.3	6.3	17.5	10.3	52.1	14.3	3.1	18.4	6.4	6.2	6.6

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Combination long-haul	56.60%	72009	59232	77718	4.9	3.4	5.5	15	11.3	23.3	15.9	13.4	17.1	6.4	6.2	6.4
Class 8b	100.00%	72009	59232	77718	4.9	3.4	5.5	15	11.3	23.3	15.9	13.4	17.1	6.4	6.2	6.4
Trailer: other	34.70%	56921	56921	56921	3.1	3.1	3.1	24.8	24.8	24.8	12.9	12.9	12.9	6.2	6.2	6.2
Trailer: van	65.30%	80029	80029	80029	5.8	5.8	5.8	9.9	9.9	9.9	17.6	17.6	17.6	6.4	6.4	6.4
Combination short-haul	43.40%	14844	1074	13292	5.9	4.5	6.4	20.7	11.6	54	12.3	3	18.6	6.4	6.2	6.6
Class 7	8.50%	7061	459	5908	6.4	6	6.4	45.7	47.4	58.1	3.4	2.9	3.3	6.6	6.4	6.6
Trailer: dump >50 miles	0.50%	331	331	331	6.2	6.2	6.2	55	55	55	2.9	2.9	2.9	6.3	6.3	6.3
Trailer: flatbed/platform	0.80%	970	970	970	6	6	6	58.8	58.8	58.8	2.8	2.8	2.8	6.6	6.6	6.6
Trailer: other	98.70%	7142	7142	7142	6.4	6.4	6.4	45.5	45.5	45.5	3.4	3.4	3.4	6.6	6.6	6.6
Class 8a	33.90%	23897	2214	23565	5.8	4.6	6	30.8	22.4	31.5	5.8	5.5	9.7	6.2	6.2	6.4
Trailer: dump <=50 miles	6.60%	2013	2013	2013	5.6	5.6	5.6	26.8	26.8	26.8	6.7	6.7	6.7	6.4	6.4	6.4
Trailer: flatbed/platform	7.10%	2684	2684	2684	4.2	4.2	4.2	22.1	22.1	22.1	10.7	10.7	10.7	6.2	6.2	6.2
Trailer: other	13.80%	4767	4767	4767	6	6	6	23.1	23.1	23.1	7.3	7.3	7.3	6.4	6.4	6.4
Trailer: van	72.50%	31621	31621	31621	6	6	6	33.5	33.5	33.5	5	5	5	6.2	6.2	6.2
Class 8b	57.60%	10669	2809	11525	5.8	4.5	7.2	11	8.3	17.1	17.3	12.3	19.3	6.4	6.2	6.7
Trailer: dump <=50 miles	3.00%	2560	2560	2560	5.1	5.1	5.1	16	16	16	12.2	12.2	12.2	6.2	6.2	6.2
Trailer: flatbed/platform	31.90%	7991	7991	7991	8.5	8.5	8.5	6.2	6.2	6.2	18.8	18.8	18.8	6.3	6.3	6.3
Trailer: other	55.10%	13881	13881	13881	4.6	4.6	4.6	13.2	13.2	13.2	16.6	16.6	16.6	6.5	6.5	6.5
Trailer: tank	1.80%	7312	7312	7312	4.5	4.5	4.5	17.8	17.8	17.8	12.5	12.5	12.5	6.2	6.2	6.2
Trailer: van	8.20%	3182	3182	3182	4.5	4.5	4.5	11.4	11.4	11.4	19.6	19.6	19.6	6.8	6.8	6.8
Heavy-duty pickup trucks and vans	54.60%	15615	13400	16800	11.6	8	12.8	9.1	7.9	12.5	1	0.9	1.3	5.7	5.6	6
Class 2b	71.50%	16289	16170	17009	12.4	8.4	13	8.5	7.9	12.2	0.9	0.9	1	5.6	5.6	5.7
Pickup, mini & lt. van, SUV	78.60%	16065	16065	16065	13.6	13.6	13.6	7.4	7.4	7.4	0.9	0.9	0.9	5.5	5.5	5.5
Van	21.40%	17114	17114	17114	7.8	7.8	7.8	12.7	12.7	12.7	1	1	1	5.7	5.7	5.7

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Class 3	28.50%	13924	12975	14676	9.6	8.7	10.8	10.6	9.3	11.6	1.2	1.1	1.4	6	5.9	6.1
Pickup, mini & lt. van, SUV	45.40%	12762	12762	12762	11.1	11.1	11.1	9	9	9	1	1	1	6.1	6.1	6.1
Van	54.60%	14889	14889	14889	8.4	8.4	8.4	11.9	11.9	11.9	1.4	1.4	1.4	5.9	5.9	5.9
Vocational vehicles	44.80%	8260	3059	11310	7.9	4.9	10.8	–	–	–	2.8	1.1	8.8	6.3	5.9	6.6
Heavy heavy-duty vocational vehicles	5.50%	5055	3032	10766	6	3.3	8.6	21.9	6.5	26.5	9.1	6.9	22.4	6.3	6	6.6
Class 8a	88.60%	4518	3072	8389	6	4.5	8.3	23	15.4	32.4	7.4	6.8	8.6	6.3	6.1	6.9
Concrete mixer & pumper	0.30%	3194	3194	3194	2.7	2.7	2.7	45.8	45.8	45.8	8.2	8.2	8.2	7.7	7.7	7.7
Dump <=50 miles	24.70%	3620	3620	3620	5.3	5.3	5.3	24.8	24.8	24.8	7.6	7.6	7.6	6.3	6.3	6.3
Dump >50 miles	3.20%	3112	3112	3112	6.6	6.6	6.6	21.9	21.9	21.9	6.9	6.9	6.9	6.2	6.2	6.2
Flatbed/stake/platform	23.70%	3826	3826	3826	5.5	5.5	5.5	26.7	26.7	26.7	6.8	6.8	6.8	6.2	6.2	6.2
Other	14.90%	8055	8026	8582	6.5	6.4	8	22.8	14	23.3	7	6.9	9.2	6.5	6	6.5
Tank	7.90%	8276	8276	8276	8.6	8.6	8.6	16.5	16.5	16.5	7	7	7	6.3	6.3	6.3
Van	25.30%	2979	2979	2979	6.2	6.2	6.2	19.8	19.8	19.8	8.2	8.2	8.2	6.3	6.3	6.3
Class 8b	11.40%	9208	4000	13762	5.6	3.2	8.8	13.2	5.6	24	22.1	15	23.8	6.1	6	6.4
Concrete mixer & pumper	0.04%	150	150	150	4.2	4.2	4.2	22.4	22.4	22.4	10.7	10.7	10.7	6.2	6.2	6.2
Dump <=50 miles	5.60%	7974	7974	7974	8.9	8.9	8.9	6.2	6.2	6.2	17.9	17.9	17.9	6.1	6.1	6.1
Dump >50 miles	7.10%	6566	6566	6566	6.4	6.4	6.4	7.2	7.2	7.2	21.7	21.7	21.7	6.2	6.2	6.2
Flatbed/stake/platform	24.60%	9170	9170	9170	7.3	7.3	7.3	6.9	6.9	6.9	19.7	19.7	19.7	5.9	5.9	5.9
Other	6.10%	16661	16661	16661	5.6	5.6	5.6	8.3	8.3	8.3	21.8	21.8	21.8	6.6	6.6	6.6
Tank	34.60%	7007	7007	7007	1.7	1.7	1.7	26.3	26.3	26.3	22.9	22.9	22.9	6.1	6.1	6.1
Van	21.90%	11830	11830	11830	8.6	8.6	8.6	4.6	4.6	4.6	25.1	25.1	25.1	6	6	6
Light heavy-duty vocational vehicles	58.30%	9417	4635	12655	8.9	6.4	12.3	89.3	31.5	138.9	1.6	0.9	2.6	6.3	5.9	6.7
Class 2b	21.90%	9409	3592	18058	9	6.3	10.5	130.6	74.9	152.8	0.9	0.8	1.5	6.1	5.6	6.2
Concrete mixer & pumper	0.50%	26681	26681	26681	5	5	5	138.9	138.9	138.9	1.4	1.4	1.4	5.4	5.4	5.4

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Dump <=50 miles	7.50%	4635	4635	4635	10.5	10.5	10.5	118.1	118.1	118.1	0.8	0.8	0.8	6.1	6.1	6.1
Dump >50 miles	2.60%	4279	4279	4279	7.2	7.2	7.2	164.3	164.3	164.3	0.8	0.8	0.8	6.3	6.3	6.3
Flatbed/stake/platform	39.40%	7162	7162	7162	8.3	8.3	8.3	145.2	145.2	145.2	0.8	0.8	0.8	6.1	6.1	6.1
Other	49.60%	12035	3537	11334	9.4	9.5	10.5	119.6	68	115.4	0.9	0.9	1.5	6.2	5.9	6.1
Tank	0.60%	6616	6616	6616	7.7	7.7	7.7	83.4	83.4	83.4	1.6	1.6	1.6	5.8	5.8	5.8
Class 3	28.60%	9133	5907	10472	9.2	8.9	10.3	94	60.2	98.8	1.2	1.1	1.6	6.3	6.1	6.3
Dump <=50 miles	10.40%	4776	4776	4776	9.6	9.6	9.6	97.1	97.1	97.1	1.1	1.1	1.1	6.3	6.3	6.3
Dump >50 miles	4.70%	8164	8164	8164	9.1	9.1	9.1	90.6	90.6	90.6	1.2	1.2	1.2	6.3	6.3	6.3
Flatbed/stake/platform	36.00%	8280	8280	8280	9.4	9.4	9.4	90.5	90.5	90.5	1.2	1.2	1.2	6.3	6.3	6.3
Other	47.60%	10883	10093	10851	8.9	9	10.8	97.1	55.8	95.4	1.2	1.2	1.7	6.3	6.1	6.3
Tank	1.30%	7038	7038	7038	9.5	9.5	9.5	69.5	69.5	69.5	1.5	1.5	1.5	6.3	6.3	6.3
Class 4	26.90%	9963	5300	12924	8.9	6.6	12.6	81.6	30.7	133.7	2	1.8	2.6	6.3	5.8	6.5
Dump <=50 miles	9.80%	5539	5539	5539	7.9	7.9	7.9	59.6	59.6	59.6	2.1	2.1	2.1	6.3	6.3	6.3
Dump >50 miles	8.20%	5033	5033	5033	1.3	1.3	1.3	378	378	378	2	2	2	6.4	6.4	6.4
Flatbed/stake/platform	16.50%	6610	6610	6610	7.9	7.9	7.9	64.9	64.9	64.9	1.9	1.9	1.9	6.4	6.4	6.4
Other	18.20%	12474	7159	12045	8.1	8.4	11.8	71.4	35.7	68.5	1.8	1.8	2.5	6.7	5.7	6.6
Pickup, mini & lt. van, SUV	30.30%	12890	11268	13696	12.4	11.9	13.6	36.7	28.9	40.5	2.3	2.1	2.6	6.3	5.9	6.4
Tank	0.80%	5367	5367	5367	8.2	8.2	8.2	66.1	66.1	66.1	1.8	1.8	1.8	6.3	6.3	6.3
Van	16.20%	10474	10474	10474	8.9	8.9	8.9	57.6	57.6	57.6	2	2	2	6.1	6.1	6.1
Class 5	22.70%	9134	4358	12500	8.3	6.2	13.5	52.6	28.9	73.5	2.5	2.1	3.2	6.5	6.1	7.1
Dump <=50 miles	5.90%	4639	4639	4639	7.8	7.8	7.8	62.7	62.7	62.7	2.1	2.1	2.1	6.5	6.5	6.5
Dump >50 miles	2.40%	5192	5192	5192	6.4	6.4	6.4	71.8	71.8	71.8	2.2	2.2	2.2	6.7	6.7	6.7
Flatbed/stake/platform	12.80%	5217	5217	5217	8.5	8.5	8.5	56.4	56.4	56.4	2.1	2.1	2.1	6.4	6.4	6.4
Other	21.20%	10626	5649	10227	7.2	7.3	9.2	67.4	34.5	64.8	2.1	2.2	3.3	6.9	6.4	6.9
Pickup, mini & lt. van,	14.50%	9382	8230	18073	13.4	13.3	14.6	32.6	23.2	33.9	2.3	2.3	3	7.3	6.1	7.5

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
SUV																
Tank	1.00%	3235	3235	3235	5.5	5.5	5.5	80.3	80.3	80.3	2.3	2.3	2.3	6.4	6.4	6.4
Van	42.10%	10490	10490	10490	7.3	7.3	7.3	47.6	47.6	47.6	2.9	2.9	2.9	6.1	6.1	6.1
Medium heavy-duty vocational vehicles	35.40%	6840	1014	9344	6.7	5	9.9	–	–	–	3.9	1.1	5.1	6.2	6	6.5
Class 6	76.40%	7134	548	9198	6.7	5.3	10.3	–	–	–	3.6	0.6	4	6.1	5.9	6.4
Concrete mixer & pumper	0.00%	100	100	100	4.5	4.5	4.5	–	–	–	0	0	0	6.1	6.1	6.1
Dump <=50 miles	11.40%	3168	3168	3168	5.9	5.9	5.9	51.2	51.2	51.2	3.3	3.3	3.3	6.2	6.2	6.2
Dump >50 miles	3.30%	4295	4295	4295	6.2	6.2	6.2	43.5	43.5	43.5	3.7	3.7	3.7	6	6	6
Flatbed/stake/platform	25.10%	5026	5026	5026	6	6	6	49	49	49	3.4	3.4	3.4	6.1	6.1	6.1
Other	16.10%	8705	3365	8226	6.5	6.6	7.7	48.2	26	46.2	3.2	3.4	5.2	6.2	6	6.2
Pickup, mini & lt. van, SUV	2.70%	4490	4147	5266	10.7	9.7	11.1	24.6	23.3	27.5	3.8	3.8	3.9	5.9	5.8	6
Tank	3.50%	4324	4324	4324	5.3	5.3	5.3	51.3	51.3	51.3	3.7	3.7	3.7	6.2	6.2	6.2
Trailer: dump <=50 miles	0.00%	60	60	60	5.9	5.9	5.9	157	157	157	1.1	1.1	1.1	6.1	6.1	6.1
Trailer: flatbed/platform	0.50%	25155	8750	32887	6.4	5.6	8	131.1	113.8	139.3	1.2	1.1	1.3	6.2	6.1	6.5
Trailer: other	0.10%	5638	5638	5638	6	6	6	118.4	118.4	118.4	1.4	1.4	1.4	6.6	6.6	6.6
Trailer: tank	0.00%	997	997	997	11	11	11	32.2	32.2	32.2	2.8	2.8	2.8	6.1	6.1	6.1
Trailer: van	0.01%	1054	1054	1054	6.1	6.1	6.1	2151	2151	2151	0.1	0.1	0.1	5.7	5.7	5.7
Van	37.30%	9563	9563	9563	7.4	7.4	7.4	33	33	33	4.1	4.1	4.1	6.1	6.1	6.1
Class 7	23.70%	5893	3727	8687	6.7	4.9	8.9	32.4	22.1	41	4.8	4.1	6.1	6.3	6.3	6.7
Dump <=50 miles	17.90%	3844	3844	3844	6.2	6.2	6.2	36.2	36.2	36.2	4.5	4.5	4.5	6.3	6.3	6.3
Dump >50 miles	3.70%	3454	3454	3454	4.7	4.7	4.7	43.9	43.9	43.9	4.8	4.8	4.8	6.4	6.4	6.4
Flatbed/stake/platform	23.70%	5671	5671	5671	7	7	7	29.1	29.1	29.1	4.9	4.9	4.9	6.3	6.3	6.3
Other	17.10%	9690	5119	9339	7.1	7.2	8.3	32.9	16.1	31.6	4.4	4.6	8	6.4	6.3	6.4
Pickup, mini & lt. van, SUV	2.90%	8181	8181	8181	10	10	10	25.4	25.4	25.4	3.9	3.9	3.9	7.4	7.4	7.4

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Tank	13.10%	5987	5987	5987	4.9	4.9	4.9	39.7	39.7	39.7	5.1	5.1	5.1	6.3	6.3	6.3
Van	21.60%	4875	4875	4875	7.3	7.3	7.3	26.8	26.8	26.8	5.1	5.1	5.1	6.2	6.2	6.2
Refuse trucks	0.80%	8919	5467	9749	5.7	4.3	8.4	118.8	45.8	193.4	2	0.8	3.6	6.5	6.2	6.7
Class 2b	2.00%	5531	5531	5531	9	9	9	218.4	218.4	218.4	0.5	0.5	0.5	6.6	6.6	6.6
Trash/garbage/recycling	100.00%	5531	5531	5531	9	9	9	218.4	218.4	218.4	0.5	0.5	0.5	6.6	6.6	6.6
Class 3	19.10%	9689	9689	9689	8	8	8	116.2	116.2	116.2	1.1	1.1	1.1	6.6	6.6	6.6
Trash/garbage/recycling	100.00%	9689	9689	9689	8	8	8	116.2	116.2	116.2	1.1	1.1	1.1	6.6	6.6	6.6
Class 4	26.80%	9839	9839	9839	3.8	3.8	3.8	176.7	176.7	176.7	1.5	1.5	1.5	6.5	6.5	6.5
Trash/garbage/recycling	100.00%	9839	9839	9839	3.8	3.8	3.8	176.7	176.7	176.7	1.5	1.5	1.5	6.5	6.5	6.5
Class 5	18.90%	8995	8995	8995	4.6	4.6	4.6	139.1	139.1	139.1	1.6	1.6	1.6	6.8	6.8	6.8
Trash/garbage/recycling	100.00%	8995	8995	8995	4.6	4.6	4.6	139.1	139.1	139.1	1.6	1.6	1.6	6.8	6.8	6.8
Class 6	18.60%	9212	9212	9212	7.2	7.2	7.2	51.4	51.4	51.4	2.7	2.7	2.7	6.3	6.3	6.3
Trash/garbage/recycling	100.00%	9212	9212	9212	7.2	7.2	7.2	51.4	51.4	51.4	2.7	2.7	2.7	6.3	6.3	6.3
Class 7	3.10%	5371	5371	5371	5.6	5.6	5.6	154.8	154.8	154.8	1.2	1.2	1.2	6.2	6.2	6.2
Trash/garbage/recycling	100.00%	5371	5371	5371	5.6	5.6	5.6	154.8	154.8	154.8	1.2	1.2	1.2	6.2	6.2	6.2
Class 8a	11.60%	6468	6468	6468	5.3	5.3	5.3	37.5	37.5	37.5	5	5	5	6.1	6.1	6.1
Trash/garbage/recycling	100.00%	6468	6468	6468	5.3	5.3	5.3	37.5	37.5	37.5	5	5	5	6.1	6.1	6.1
Other fuels	0.60%															
Combination trucks	2.80%	44452	518	67692	5.2	4.7	8	15.1	6.9	161.6	15.9	1.4	25.2	7.9	6	8
Combination long-haul	29.60%	91990	17195	102402	5.9	5.7	7.4	9.5	7.4	135.9	19.7	5	23.6	8	7.9	8.1
Class 7	0.40%	3659	3659	3659	8	8	8	189.2	189.2	189.2	0.7	0.7	0.7	7.9	7.9	7.9
Trailer: other	100.00%	3659	3659	3659	8	8	8	189.2	189.2	189.2	0.7	0.7	0.7	7.9	7.9	7.9
Class 8b	99.60%	92306	53507	106685	5.9	5.7	5.9	8.9	7.2	11.1	19.7	15.8	24.3	8	7.9	8.1
Trailer: other	23.70%	72420	72420	72420	5.7	5.7	5.7	6.8	6.8	6.8	25.6	25.6	25.6	8.2	8.2	8.2
Trailer: tank	19.30%	48779	48779	48779	5.7	5.7	5.7	11.6	11.6	11.6	15	15	15	8	8	8

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Trailer: van	57.10%	115251	115251	115251	6	6	6	8.8	8.8	8.8	18.9	18.9	18.9	7.9	7.9	7.9
Combination short-haul	70.40%	24455	348	26023	4.9	4.4	8.7	17.4	7.3	176	14.4	3.5	24.1	7.9	5.7	8
Class 7	0.30%	1844	1844	1844	8	8	8	674.8	674.8	674.8	0.2	0.2	0.2	7	7	7
Trailer: flatbed/platform	100.00%	1844	1844	1844	8	8	8	674.8	674.8	674.8	0.2	0.2	0.2	7	7	7
Class 8a	1.10%	594	191	874	8.9	5	10.7	24.8	12.7	45.9	7.1	4.6	8.2	6.4	5.7	7.3
Trailer: dump <=50 miles	34.60%	992	992	992	4.5	4.5	4.5	51.3	51.3	51.3	4.3	4.3	4.3	7.7	7.7	7.7
Trailer: other	4.30%	139	139	139	7.1	7.1	7.1	24	24	24	5.9	5.9	5.9	5.8	5.8	5.8
Trailer: van	61.00%	400	400	400	11.6	11.6	11.6	9.8	9.8	9.8	8.8	8.8	8.8	5.7	5.7	5.7
Class 8b	98.60%	24796	16718	26772	4.9	4.7	6.2	15.3	6.8	16.4	14.5	13.4	25.8	7.9	7.9	8
Trailer: dump <=50 miles	0.90%	12540	12540	12540	5.7	5.7	5.7	7.5	7.5	7.5	23.3	23.3	23.3	8	8	8
Trailer: dump >50 miles	58.30%	24007	24007	24007	4.2	4.2	4.2	18.7	18.7	18.7	12.7	12.7	12.7	7.8	7.8	7.8
Trailer: flatbed/platform	15.90%	25648	25648	25648	6.4	6.4	6.4	9.4	9.4	9.4	16.5	16.5	16.5	8	8	8
Trailer: other	19.60%	27522	27522	27522	5.4	5.4	5.4	12.9	12.9	12.9	14.4	14.4	14.4	8	8	8
Trailer: tank	5.20%	22984	22984	22984	5.7	5.7	5.7	6.4	6.4	6.4	27.4	27.4	27.4	8	8	8
Heavy-duty pickup trucks and vans	13.50%	13418	7120	13332	12.3	9.1	13.7	8.3	7.3	11	0.7	0.5	1.1	5.9	5.9	6.6
Class 2b	88.70%	13987	9412	14216	12.6	9.3	12.7	8.1	8	10.9	0.7	0.6	1	5.8	5.8	6.1
Pickup, mini & lt. van, SUV	86.20%	14817	14817	14817	13.2	13.2	13.2	7.6	7.6	7.6	0.6	0.6	0.6	5.8	5.8	5.8
Van	13.80%	8811	8811	8811	8.9	8.9	8.9	11.2	11.2	11.2	1	1	1	6.1	6.1	6.1
Class 3	11.30%	8966	6743	9521	10.6	9.9	13.5	9.7	7.5	10.2	0.9	0.5	1	6.6	6.4	6.7
Pickup, mini & lt. van, SUV	26.00%	6396	6396	6396	13.9	13.9	13.9	7.2	7.2	7.2	0.5	0.5	0.5	6.3	6.3	6.3
Van	74.00%	9868	9868	9868	9.5	9.5	9.5	10.6	10.6	10.6	1.1	1.1	1.1	6.7	6.7	6.7
Vocational vehicles	83.70%	14031	1642	16225	5.5	4.2	9.3	–	–	–	4	0.8	9.6	6.8	6.3	8
Heavy heavy-duty vocational vehicles	7.20%	9563	1739	15773	5.6	4.2	5.7	25.5	14.6	29.7	7.3	6.7	13.9	7.2	6.6	8.1

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Class 8a	81.50%	9434	1389	10247	5.7	4.7	6.1	26.1	21	27.5	6.9	6.4	9.7	7	6.4	7.3
Concrete mixer & pumper	2.70%	5284	5284	5284	3.4	3.4	3.4	26.8	26.8	26.8	10.9	10.9	10.9	6.9	6.9	6.9
Dump <=50 miles	2.90%	1785	1785	1785	5.6	5.6	5.6	23.7	23.7	23.7	7.5	7.5	7.5	6.9	6.9	6.9
Dump >50 miles	22.20%	6781	6781	6781	5.3	5.3	5.3	26.8	26.8	26.8	7.1	7.1	7.1	7.5	7.5	7.5
Flatbed/stake/platform	27.90%	8324	8324	8324	7.1	7.1	7.1	22.9	22.9	22.9	6.1	6.1	6.1	6.4	6.4	6.4
Other	9.00%	6753	1258	6149	5.2	5.3	5.6	24.5	19.7	24	7.8	7.9	9	7.2	6.5	7.1
Tank	32.30%	14734	14734	14734	5.2	5.2	5.2	29.3	29.3	29.3	6.5	6.5	6.5	7.2	7.2	7.2
Van	3.10%	1707	1707	1707	5.3	5.3	5.3	21.7	21.7	21.7	8.8	8.8	8.8	6.8	6.8	6.8
Class 8b	18.50%	10131	3480	26622	4.9	4.2	5.4	23	12.7	30.2	9.3	7.9	16.3	8.1	7.9	8.2
Concrete mixer & pumper	26.40%	8346	8346	8346	4.2	4.2	4.2	30	30	30	8	8	8	8.2	8.2	8.2
Dump <=50 miles	4.80%	41855	41855	41855	5	5	5	19.1	19.1	19.1	10.5	10.5	10.5	8.1	8.1	8.1
Dump >50 miles	38.60%	7912	7912	7912	5.2	5.2	5.2	20.9	20.9	20.9	9.2	9.2	9.2	8.1	8.1	8.1
Flatbed/stake/platform	18.80%	7452	7452	7452	5.7	5.7	5.7	17.1	17.1	17.1	10.4	10.4	10.4	8	8	8
Other	0.90%	2672	2672	2672	5.2	5.2	5.2	12.1	12.1	12.1	15.9	15.9	15.9	8.1	8.1	8.1
Tank	8.20%	16466	16466	16466	4.2	4.2	4.2	30.7	30.7	30.7	7.8	7.8	7.8	7.8	7.8	7.8
Van	2.30%	4019	4019	4019	4.6	4.6	4.6	13	13	13	16.8	16.8	16.8	8	8	8
Light heavy-duty vocational vehicles	27.70%	16880	1638	18475	6.5	5.3	9.8	84.6	55.7	183.4	2	0.8	2.7	6.5	6.1	7.3
Class 2b	4.70%	11990	586	11215	9.1	6.4	9.5	133.8	113	913.5	0.9	0.3	1	6.1	5.8	7.2
Dump >50 miles	1.20%	1489	1489	1489	9.7	9.7	9.7	135.8	135.8	135.8	0.8	0.8	0.8	7.6	7.6	7.6
Flatbed/stake/platform	21.40%	3345	3345	3345	9.2	9.2	9.2	231.1	231.1	231.1	0.5	0.5	0.5	6.5	6.5	6.5
Other	77.40%	14541	1638	13149	9.1	5.6	8.7	106.9	213.5	1095.7	1.1	0.3	1	6	5.7	6
Class 3	16.70%	13556	2821	17390	9	8.6	10.4	106.6	82.7	121.7	1.1	0.9	1.2	6.7	6.1	6.9
Dump <=50 miles	1.80%	2490	2490	2490	11	11	11	71	71	71	1.3	1.3	1.3	6.2	6.2	6.2
Dump >50 miles	2.20%	3152	3152	3152	9.7	9.7	9.7	105.8	105.8	105.8	1	1	1	6.6	6.6	6.6
Flatbed/stake/platform	15.00%	5169	5169	5169	8.5	8.5	8.5	100.8	100.8	100.8	1.2	1.2	1.2	6.4	6.4	6.4

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Other	65.40%	14572	7016	13828	8.7	8.8	9.6	111.8	113.6	129.8	1	0.8	1	6.6	6.1	6.6
Tank	15.60%	20102	20102	20102	9.9	9.9	9.9	94.4	94.4	94.4	1.1	1.1	1.1	7.1	7.1	7.1
Class 4	17.70%	15839	2151	14714	6.1	5.1	8.7	93.1	68.6	177.5	2	0.9	2.7	6.7	6.2	7.1
Dump <=50 miles	0.50%	2497	2497	2497	6.5	6.5	6.5	189.3	189.3	189.3	0.8	0.8	0.8	6.1	6.1	6.1
Dump >50 miles	3.40%	2262	2262	2262	5.7	5.7	5.7	169.6	169.6	169.6	1	1	1	6.5	6.5	6.5
Flatbed/stake/platform	15.90%	6292	6292	6292	10.4	10.4	10.4	108.3	108.3	108.3	0.9	0.9	0.9	6.3	6.3	6.3
Other	18.70%	10212	2812	9416	7.6	7.5	7.5	89.6	49.3	85.3	1.5	1.6	2.8	7.2	7.1	7.1
Tank	58.90%	21423	21423	21423	4.6	4.6	4.6	84.5	84.5	84.5	2.6	2.6	2.6	6.7	6.7	6.7
Van	2.70%	8717	8717	8717	5.5	5.5	5.5	101.4	101.4	101.4	1.8	1.8	1.8	6.6	6.6	6.6
Class 5	60.90%	18474	4996	14831	5.8	5.3	8.3	72.2	49.3	75.9	2.4	2.2	2.7	6.4	6.3	7.6
Dump <=50 miles	0.50%	10974	10974	10974	9	9	9	40.4	40.4	40.4	2.8	2.8	2.8	7.8	7.8	7.8
Dump >50 miles	1.00%	1454	1454	1454	7.9	7.9	7.9	55.2	55.2	55.2	2.3	2.3	2.3	6.5	6.5	6.5
Flatbed/stake/platform	4.90%	8253	8253	8253	7.6	7.6	7.6	57.1	57.1	57.1	2.3	2.3	2.3	6.7	6.7	6.7
Other	2.30%	7487	7373	7498	7.3	7.2	7.7	62.3	58.6	62.7	2.2	2.2	2.2	7.3	6.6	7.3
Tank	8.60%	8860	8860	8860	4.6	4.6	4.6	80.4	80.4	80.4	2.7	2.7	2.7	6.3	6.3	6.3
Van	82.80%	20617	20617	20617	5.7	5.7	5.7	72.9	72.9	72.9	2.4	2.4	2.4	6.4	6.4	6.4
Medium heavy-duty vocational vehicles	61.60%	12513	1403	12001	5.1	4.4	7.3				4.2	2.4	5.1	6.8	6.4	7
Class 6	57.00%	10827	880	11652	5.4	4.7	6.8				3.6	1.9	4.9	6.7	6.3	6.8
Dump <=50 miles	0.20%	1029	1029	1029	5.5	5.5	5.5	63.7	63.7	63.7	2.8	2.8	2.8	6.7	6.7	6.7
Dump >50 miles	1.20%	2671	2671	2671	6.3	6.3	6.3	59.7	59.7	59.7	2.7	2.7	2.7	6.6	6.6	6.6
Flatbed/stake/platform	16.60%	10108	10108	10108	8	8	8	51	51	51	2.4	2.4	2.4	6.2	6.2	6.2
Other	15.90%	11028	11066	11432	4.6	4.8	6.3				4.8	0.5	4.4	7.1	6.6	7
Tank	45.00%	12351	12351	12351	4.8	4.8	4.8	56.4	56.4	56.4	3.7	3.7	3.7	6.8	6.8	6.8
Trailer: other	0.00%	281	281	281	5.9	5.9	5.9	33.1	33.1	33.1	5.1	5.1	5.1	6.3	6.3	6.3
Trailer: van	0.20%	7095	7095	7095	5.9	5.9	5.9	70.5	70.5	70.5	2.4	2.4	2.4	6.6	6.6	6.6

	Fuel Consumption (%)[a]	Annual VMT			MPG[b]			Fuel Consumption (gal/1000 ton-mi)[a]			Effective Payload (tons)			Engine Displacement (L)		
		Wtd. Avg[c]	P10[d]	P90[e]	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90	Wtd. Avg.	P10	P90
Van	21.00%	8547	8547	8547	5.4	5.4	5.4	51.2	51.2	51.2	3.6	3.6	3.6	6.4	6.4	6.4
Class 7	43.00%	14747	2698	12840	4.6	4.2	7.2	44.2	28.1	52.7	5	3.8	5.5	7	6.8	7.1
Dump <=50 miles	0.40%	1963	1963	1963	4.2	4.2	4.2	57.4	57.4	57.4	4.2	4.2	4.2	6.9	6.9	6.9
Dump >50 miles	2.10%	4124	4124	4124	5.6	5.6	5.6	48	48	48	3.7	3.7	3.7	7.2	7.2	7.2
Flatbed/stake/platform	2.10%	3432	3432	3432	7.1	7.1	7.1	36.5	36.5	36.5	3.9	3.9	3.9	6.8	6.8	6.8
Other	1.10%	8268	8268	8268	7.4	7.4	7.4	23.4	23.4	23.4	5.8	5.8	5.8	6.8	6.8	6.8
Tank	83.50%	16121	16121	16121	4.3	4.3	4.3	45.9	45.9	45.9	5.1	5.1	5.1	7	7	7
Van	10.90%	9560	9560	9560	6	6	6	32.7	32.7	32.7	5.1	5.1	5.1	6.8	6.8	6.8
Refuse trucks	3.60%	27129	8562	27516	3.8	2.9	5.4	92.4	29.4	635	8.7	1.7	10.2	7.8	7	8
Class 2b	7.30%	11983	11983	11983	5	5	5	890	890	890	0.2	0.2	0.2	7.1	7.1	7.1
Trash/garbage/recycling	100.00%	11983	11983	11983	5	5	5	890	890	890	0.2	0.2	0.2	7.1	7.1	7.1
Class 7	4.20%	7096	7096	7096	5.6	5.6	5.6	35.3	35.3	35.3	5.1	5.1	5.1	6.9	6.9	6.9
Trash/garbage/recycling	100.00%	7096	7096	7096	5.6	5.6	5.6	35.3	35.3	35.3	5.1	5.1	5.1	6.9	6.9	6.9
Class 8a	69.60%	33826	33826	33826	4	4	4	26.8	26.8	26.8	9.3	9.3	9.3	7.9	7.9	7.9
Trash/garbage/recycling	100.00%	33826	33826	33826	4	4	4	26.8	26.8	26.8	9.3	9.3	9.3	7.9	7.9	7.9
Class 8b	18.90%	12792	12792	12792	2.4	2.4	2.4	39.8	39.8	39.8	10.6	10.6	10.6	8.1	8.1	8.1
Trash/garbage/recycling	100.00%	12792	12792	12792	2.4	2.4	2.4	39.8	39.8	39.8	10.6	10.6	10.6	8.1	8.1	8.1

[a] Diesel gallons for diesel vehicles and gasoline gallons for gasoline vehicles.
[b] The unit for heavy-duty pickup trucks and vans is expressed in gal/100 mi.
[c] Fuel consumption-weighted average.
[d] 10th percentile.
[e] 90th percentile.

APPENDIX D: DRIVING CYCLES OF HEAVY-DUTY VEHICLES

This section summarizes the characteristics of typical driving cycles of the HDVs.

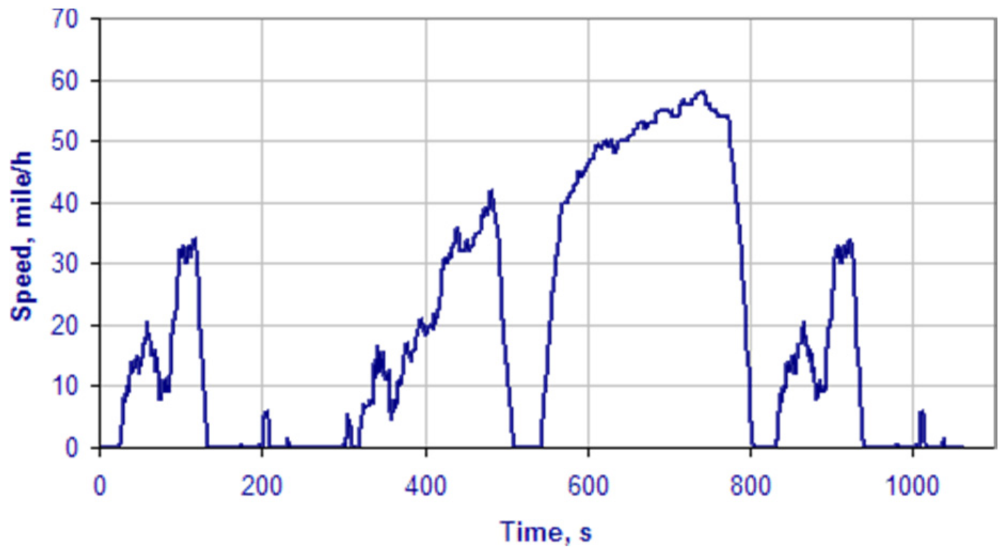

FIGURE D1 Heavy Duty Urban Dynamometer Driving Schedule Drive Cycle (DieselNet, 2015)

The Heavy Duty Urban Dynamometer Driving Schedule (HD-UDDS) cycle is a U.S. chassis dynamometer test procedure for heavy-duty vehicles. This cycle is different from the light-duty Urban Dynamometer Driving Schedule (UDDS) cycle developed for passenger cars and trucks.

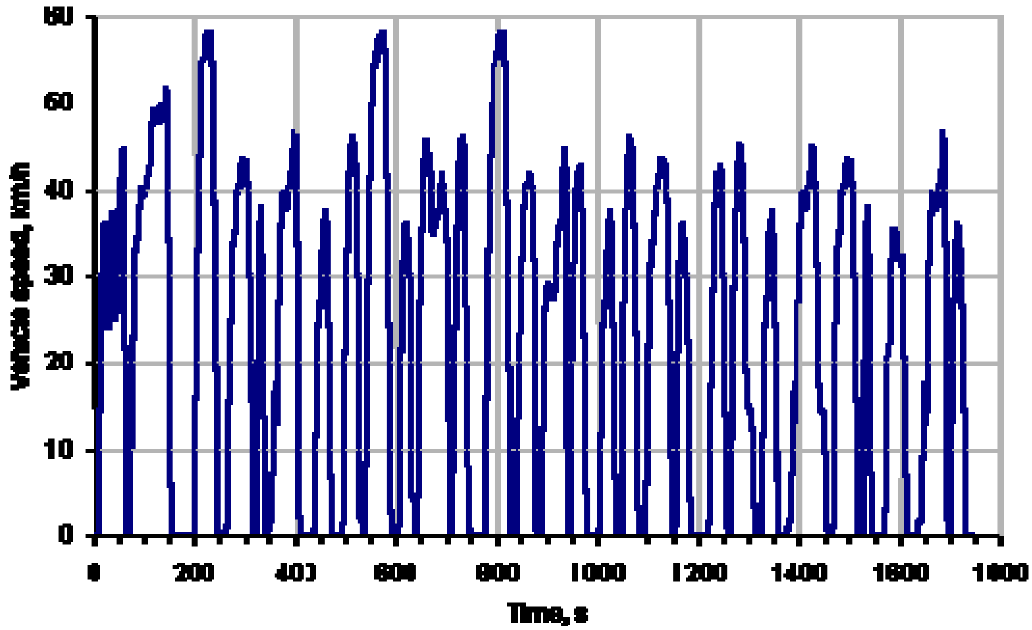

FIGURE D2 Braunschweig Drive Cycle (DieselNet, 2015)

The Braunschweig cycle is a European chassis dynamometer test procedure that simulates urban bus driving with frequent stops. The drive cycle was based on the driving patterns of buses in Braunschweig, which is a mid-sized European city.

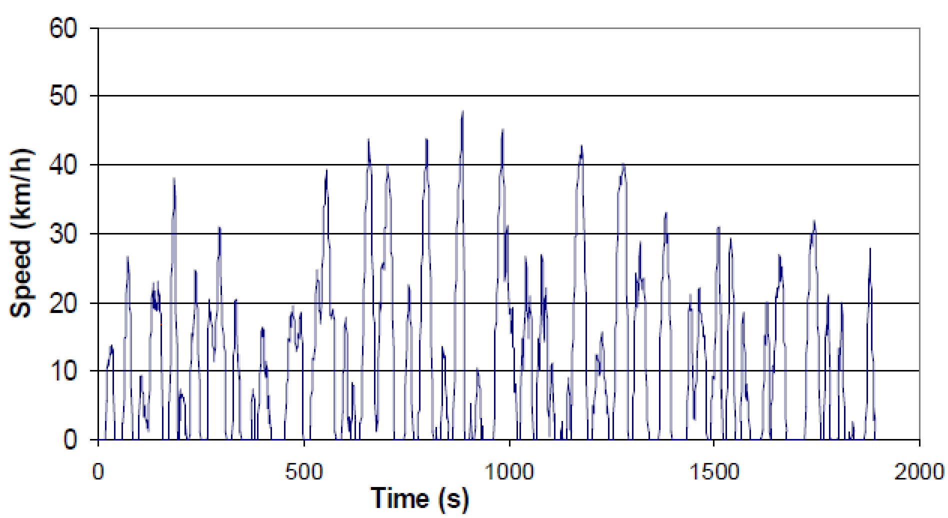

FIGURE D3 ADEME Drive Cycle (Nylund, 2011)

The ADEME-RATP cycle is a European chassis dynamometer test procedure that simulates urban bus driving with frequent stops. The drive cycle was based on the driving patterns of buses in Paris.

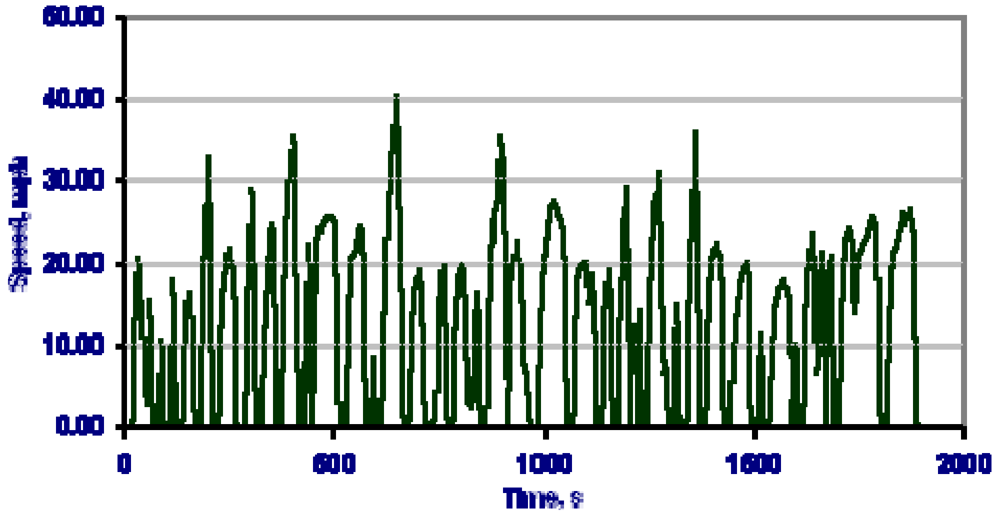

FIGURE D4 Orange County Transit Authority Drive Cycle (DieselNet, 2015)

The Orange County Transit Authority (OCTA) cycle is a U.S. chassis dynamometer test procedure that simulates urban bus driving. This drive-cycle was based on the driving patterns of Los Angeles buses.

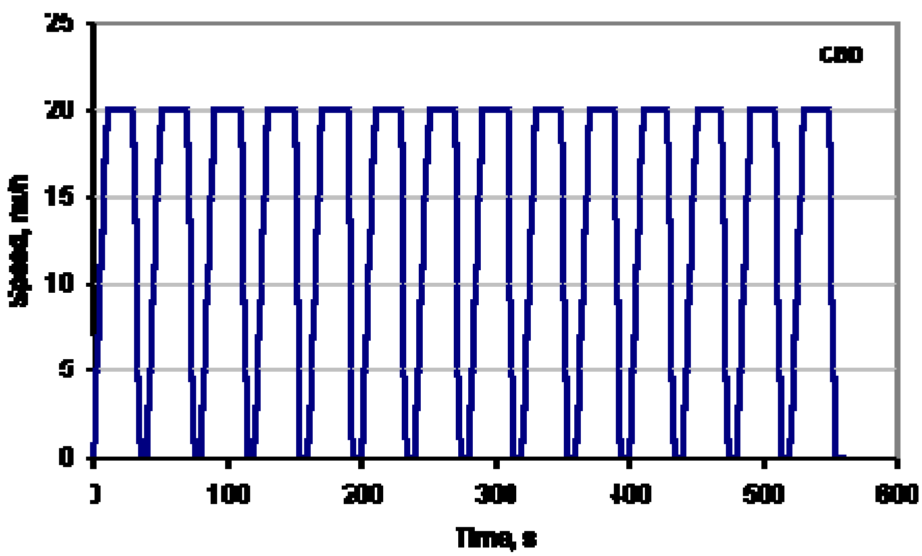

FIGURE D5 Central Business District Drive Cycle (DieselNet, 2015)

The Central Business District (CBD) cycle is a U.S. chassis dynamometer test procedure designed to assess transit buses. This cycle has repetitive acceleration, cruise, deceleration, and idling segments.

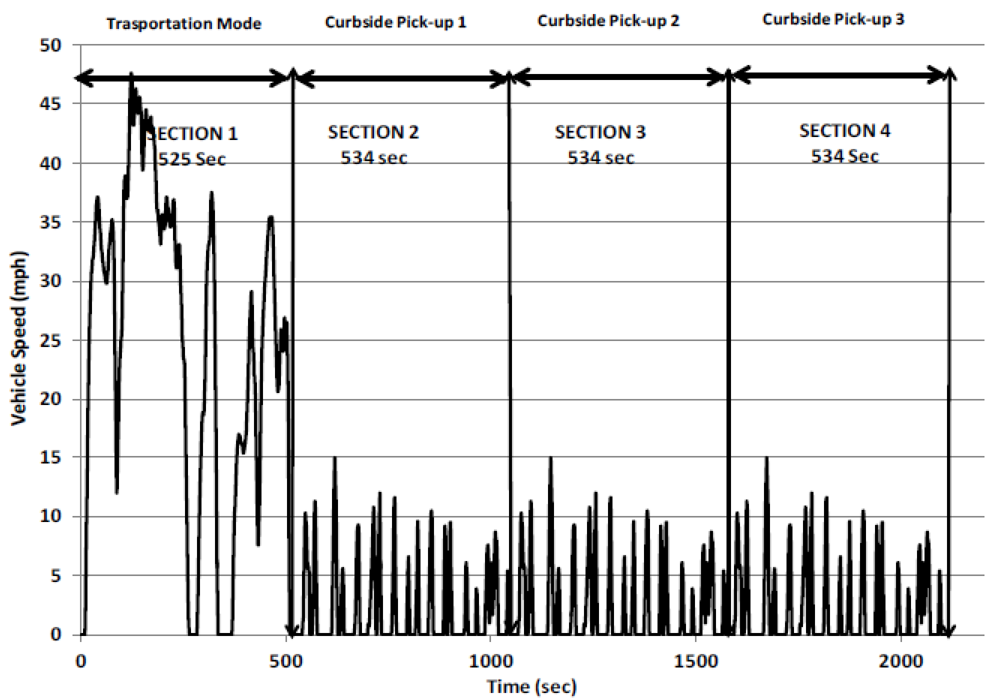

FIGURE D6 SCAQMD Refuse Truck Cycle (DieselNet, 2015)

The South Coast Air Quality Management District Refuse Truck Cycle (SCAQMD-RTC) is a U.S. chassis dynamometer test procedure designed to assess refuse trucks. This cycle has two modes: a transportation mode that represents the operation from the depot to the refuse collection area and a curbside pick-up mode that represents the operation of collecting garbage in a community.

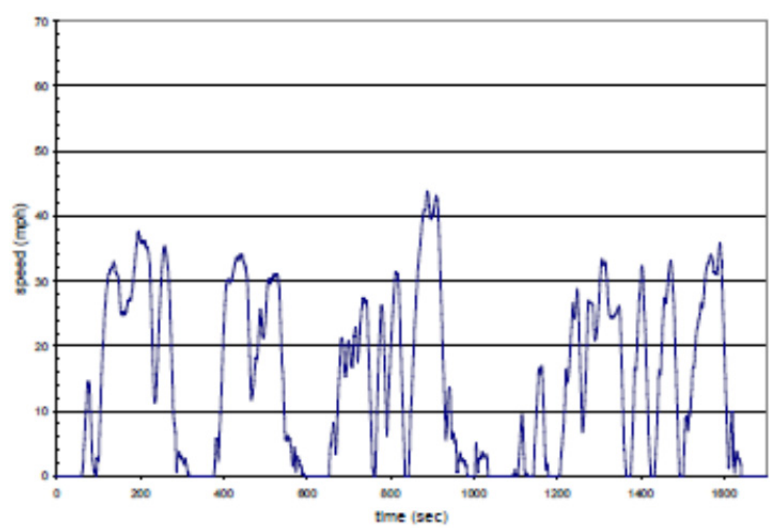

FIGURE D7 City-Suburban Heavy-Vehicle Cycle (McCormick et al., 2006)

The City-Suburban Heavy-Vehicle Cycle (CSHVC) has an average driving speed of 18.4 mi per hour, in comparison to the 29.6 mi per hour on the HD-UDDS driving cycle.

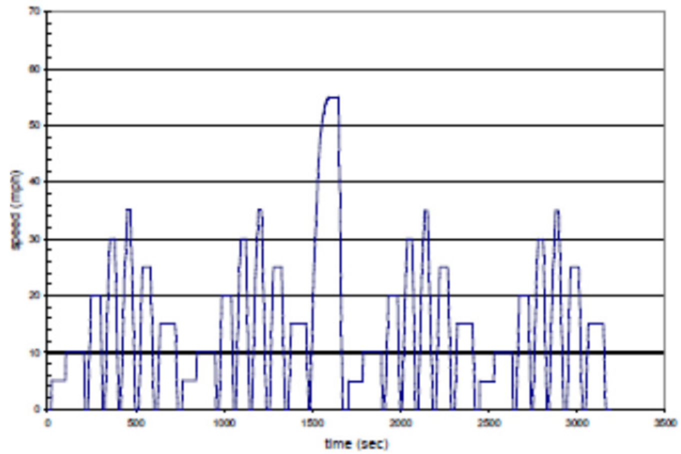

FIGURE D8 Combined International Local and Commuter Cycle (McCormick et al., 2006)

The Combined International Local and Commuter Cycle (CILCC) was developed by NREL for testing Class 4 to 6 hybrid electric delivery vehicles.

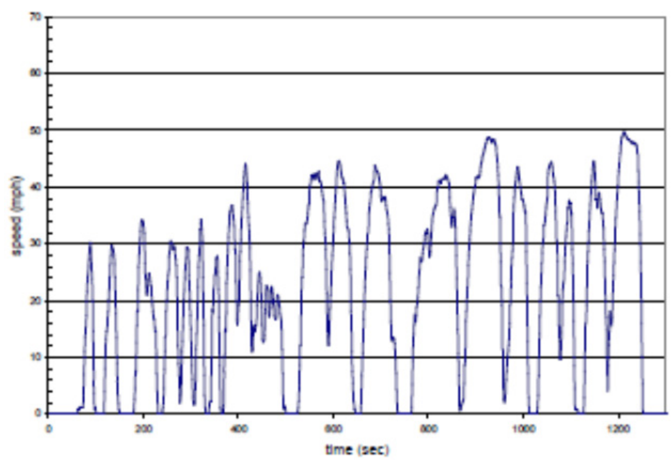

FIGURE D9 Rowan University Composite School Bus Cycle (McCormick et al., 2006)

The Rowan University Composite School Bus Cycle (RUCSBC) is an aggressive cycle that has high average speed and acceleration rates.

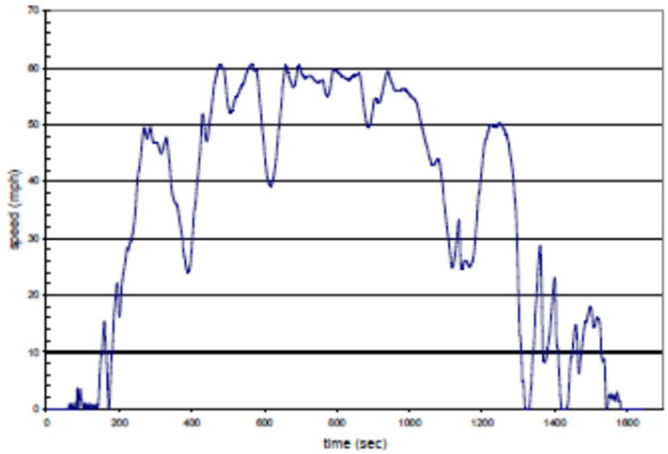

FIGURE D10 The Freeway Cycle (McCormick et al., 2006)

The Freeway cycle has an average and maximum speed of 34.0 and 37.5 miles per hour, respectively, about 0.6 stop per mile, representing high speed interstate driving.

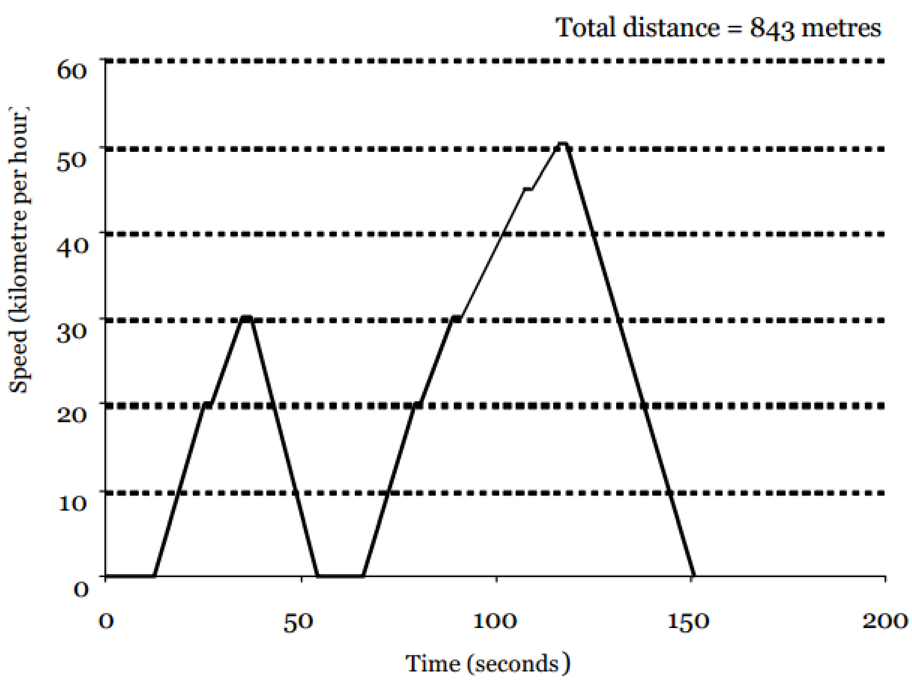

FIGURE D11 Mumbai Drive Cycle (Sundar et al., 2004)

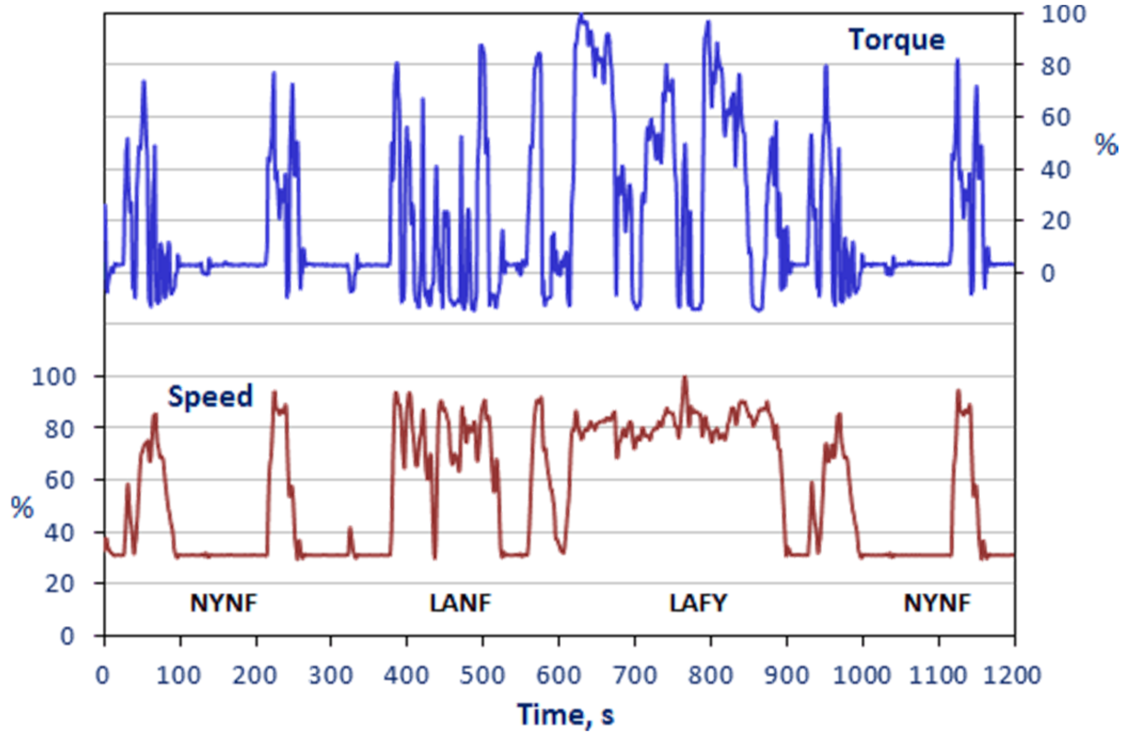

FIGURE D12 Federal Test Procedure heavy-duty transient cycle (DieselNet, 2015)

The FTP heavy-duty transient cycle is based on the HD-UDDS cycle and includes four phases to incorporate different HDV driving patterns. The four phases include the New York Non Freeway phase to simulate light urban traffic with frequent stops and starts at the beginning and end of the cycle; Los Angeles Non Freeway phase to simulate crowded urban traffic with few stops; and Los Angeles Freeway phase to simulate crowded freeway traffic.

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