Heavy-Duty Vehicle Fuel Efficiency and Greenhouse Gas Emissions: The 2014–2019 Standards and a Pathway to the Next Phase

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December 2011

Report Number T113

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ACKNOWLEDGMENTS

The authors thank Don Anair, Fanta Kamakate, Harvey Sachs, and Ben Sharpe for helpful comments on a draft of this report. The views expressed herein and any remaining errors are the sole responsibility of the authors, however. Thanks also to Renee Nida for report editing.

We appreciate the support of the Energy Foundation and the Kresge Foundation for this work.

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EXECUTIVE SUMMARY

The 2014–2019 Heavy-Duty Rule

In 2011, EPA and NHTSA adopted the first fuel efficiency and greenhouse gas emissions standards for on-road heavy-duty vehicles in the U.S. The rule establishes a program to reduce fuel use and emissions of the full range of on-road heavy-duty vehicles, i.e. vehicles of at least 8,500 lbs. gross vehicle weight, The standards cover vehicles and engines of model years 2014 through 2019 and in the later years require fuel consumption reductions ranging from 5 percent to 24 percent, depending on vehicle or engine class. The program represents a crucial step in reducing fuel consumption and greenhouse gas (GHG) emissions from the second largest energy users in the transportation sector. It offers a workable solution to the difficult problem of creating a regulatory structure for a complex array of products, without interfering with the proper workings of the market. The program will accelerate the adoption of several technologies that are readily available and highly cost-effective. The average buyer of a tractor for hauling box trailers, for example, will earn back through fuel savings the incremental cost of a truck meeting the fuel efficiency targets set by the rule within two years of operation, and net savings over the first ten years of operation will exceed $80,000. The standards for all heavy-duty vehicles will save 370,000 barrels of oil per day nationally in 2030.

At the same time, the standards are not demanding enough to drive all efficiency technologies that will be available in the period covered by the rule. These include advanced transmissions, hybrid vehicles for the vocational segment, and aerodynamic and tire improvements for trailers. The adoption of additional, feasible tractor-trailer technologies alone could increase the rule's oil savings in 2030 by over 50 percent and increase lifetime fuel cost savings to owners. Standards for heavy-duty pickups and vans fall far short of the efficiencies that will be required of similar light-duty pickups and vans in the same years.

The Next Phase

Perhaps the most important aspect of the program to revisit in order to maximize the economic and environmental benefits of the program in the future is the treatment of tractor-trailers and vocational vehicles as collections of components, rather than as integrated systems. In the next phase, the performance of full vehicles, as sold, should be the basis for certification. This is a complex undertaking, however, and extensive data collection and model development will be required to take this step. We offer the following recommendations to policymakers and the relevant agencies.

In the immediate future:

- **Trailer standards:** Adopt trailer standards at the earliest possible date to increase fuel savings and allow integration of tractor and trailer improvements.
- **Data collection, analysis, and dissemination:** Resume and expand the Vehicle Inventory and Use Survey or otherwise establish a federal data collection program for heavy-duty vehicles, including sales, configurations, fuel consumption, and driving patterns. Ensure data is publically available. Collect in-use testing data through manufacturers, fleets, and federal agencies. Prepare annual reports on i) the state of the heavy-duty market and ii) fuel consumption and GHG emissions of new vehicles by vehicle type.
- **Vehicle simulation model:** Develop and maintain a vehicle simulation tool that i) can accurately reflect all vehicle and drive cycle specifications relevant to fuel consumption and ii) is available for general use.

In the next phase of the standards:

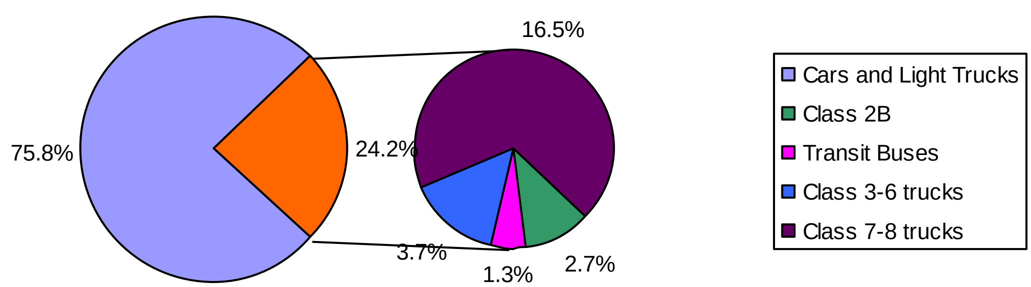
- **Full vehicle standards:** Apply standards to the full vehicle as sold. Evaluate performance of tractor trucks with an appropriate, efficient trailer.
- **Vocational vehicle segmentation:** Further segment vocational vehicles to reflect fundamental differences in duty cycles.

- **Vehicle test cycles and test weights:** Reevaluate the ability of existing test cycles to capture current driving patterns for all vehicle classes, including road grade and driver behavior. Establish appropriate test weights based on vocation and weight class.
- **Test protocol:** Require physical testing (road, track, or chassis dynamometer) for a basic set of well-defined vehicle configurations. Allow variations on these configurations to be tested using a simulation model.
- **Engine standard:** For at least the next round of rulemaking, consider maintaining engine standards along with full-vehicle standards. Develop new test cycles for heavy-duty engines, reflecting real-world driving characteristics.
- **Heavy-duty pickups and vans:** Bring heavy-duty pickups and vans to efficiencies consistent with those of their light-duty counterparts. Consider integrating the standards for heavy-duty pickup trucks and vans with the light-duty program while continuing to recognize the functional requirements of these vehicles.
- **Stringency:** In determining the stringency of standards, consider technologies that deliver large lifetime savings, even if they do not pay back in the ownership period of the initial purchaser.
- **Buyer information:** Put in place a permanent, buyer-oriented label for all covered vehicles, showing both certification values and separate fuel efficiencies for at least two relevant driving modes (e.g., urban and highway). Provide an online simulation tool to allow buyers to compare vehicle performance over drive cycles specified by the user.
- **Standards harmonization:** Seek to achieve consistency with other regions regulating heavy-duty vehicle fuel efficiency or greenhouse gas emissions on program elements such as test cycles, measurement protocols, vehicle segmentation, and standard stringency, and thereby expand the market for efficiency technologies while streamlining manufacturer compliance.

INTRODUCTION

The heavy-duty on-road vehicle sector includes vehicles ranging from pickup trucks with minimum gross vehicle weight (GVW) of 8,500 lbs. to Class 8 tractor trucks with GVW above 33,000 lbs. In 2009, U.S. highway vehicles consumed 21 quadrillion British thermal units (Btus) of energy, or about 11 million barrels of oil per day (MBD) (EIA 2011). The light-duty sector, which includes cars and light trucks, had the major share, about 76 percent of total highway energy use, while the heavy-duty sector consumed 5 Quads or 24 percent of U.S. highway energy, as shown in Figure 1. Heavy-duty vehicle energy use is dominated by large tractor trucks (Class 7&8) engaged in moving freight across the country, consuming 68 percent of heavy-duty energy, 17 percent of total transportation energy, and 12 percent of all U.S. oil consumption (EPA 2011a).

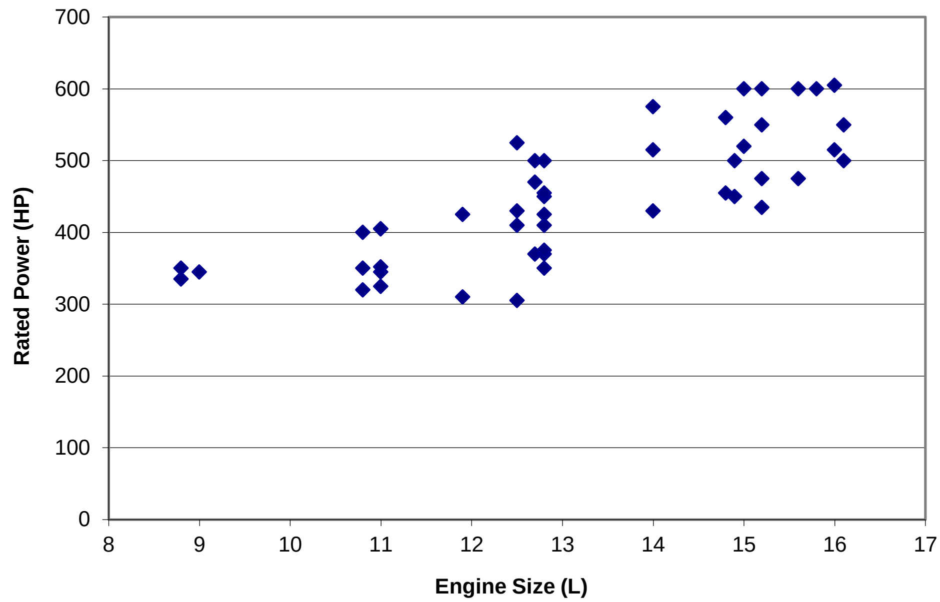
Figure 1: U.S. Transportation Energy Use in 2009 (ACEEE from data in EIA 2011)



Complexity of the Heavy-Duty Sector

The heavy-duty vehicle sector is complex, involving multiple vehicle classes based on gross vehicle weight, as well as diversity in design, manufacture, and usage. For example, Class 7&8 freight trucks may have three distinct manufacturers for their engines, chassis, and trailers. Therefore, regulating these trucks could involve three different manufacturing entities. Some Class 8 trucks regularly carry loads of over 60,000 pounds, while others typically "cube out," i.e., fill the trailer without reaching the weight limit. They may travel fewer than 50 miles or more than 500 miles in a single trip. Fuel economy of these trucks varies widely, from less than 3 miles per gallon (mpg) to as much as 10 mpg (VIUS 2002). They also have numerous designs, including tractors pulling flat-bed trailers, van trailers, or bulk tankers and straight trucks for a variety of vocational uses. Engines used in these trucks have a wide range of power requirements. Engines used in tractor trucks vary in size from 8.8 liters to 16.1 liters, while their rated power ranges from 305 horsepower to as high as 605 horsepower, as shown in Figure 2 (DTI 2010, VTNA 2011).

Figure 2: Size and Power of Tractor Truck Engines (ACEEE from data in DTI 2010, VTNA 2011)



Duty cycle varies widely as well, even within classes. Class 8 tractor-trailers often move into regional or short-haul use after several years of use in the long-haul duty cycle. Even among newly purchased trucks, shorter-haul vehicles constitute a significant percentage, as shown in Table 1. Trucks having primary trip length under 100 miles travel many fewer miles annually than long-haul trucks and are likely to spend a high percentage of time in stop-and-go traffic, which has major implications for their fuel economy.

Table 1: Characteristics of New Tractor-Trailers with Van-Type Trailer (ACEEE, from VIUS 2002)

Primary Trip Length	Percent of Sales	Average Annual Miles
Less than 50 miles	7%	53,705
51 to 100 miles	4%	52,358
101 to 200 miles	7%	96,338
201 to 500 miles	27%	110,746
501 miles or more	55%	113,365

Role of a Greenhouse Gas Regulatory Program

GHG emissions, including carbon dioxide (CO_2), and fuel consumption of heavy-duty vehicles historically have not been regulated in the U.S. Criteria pollutants including carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NOx), and particulate matter (PM) from heavy-duty engines have been regulated since 1988 (Dieselnet 2011), and their levels greatly reduced. Heavy-duty diesel engine NOx emissions were reduced from 10.7 grams per brake horsepower-hour (g/bhp-hr) in 1988 to 0.2 g/bhp-hr in 2010, while PM emissions were reduced from 0.6 g/bhp-hr in 1990 to 0.01 g/bhp-hr during the same time, under the heavy-duty criteria pollution standard set by the U.S. Environmental Protection Agency (EPA) (Dieselnet 2011).

It is frequently argued that, because increasing heavy-duty fuel efficiency serves the business interest of the trucking industry, there is no need to regulate it. Historical data shows, however, that medium- and heavy-duty truck fuel efficiency increased from 5.6 mpg in 1966 to only 5.9 mpg in 2006 (Sivak and

Tsimhoni 2009).[1] By contrast, car and light truck fuel economy, during the same time frame, increased from 13.4 mpg and 9.7 mpg to 22.4 mpg and 18.0 mpg, respectively, under corporate average fuel economy standards first implemented in 1978.

Adoption of fuel efficiency and GHG standards for heavy-duty vehicles is a major step in managing the nation's oil consumption, emissions, and fuel expenditures, and by extension the cost of consumer goods. It also offers the potential for new jobs in the design and production of new vehicle technologies. U.S. manufacturers and suppliers are international leaders in certain advanced technologies for heavy-duty vehicles, and a well-designed regulatory regime can help them consolidate their leadership and thrive in a global market.

THE 2014–2019 HEAVY-DUTY RULE

Summary of the Heavy-Duty Rule

In August 2011, the EPA and the National Highway Traffic Safety Administration (NHTSA) adopted a rule ("the Heavy-Duty Rule") to reduce GHG emissions and improve fuel efficiency of medium- and heavy-duty vehicles in model years 2014–2019 (EPA and NHTSA 2011a). The rule covers three major categories of commercial vehicles: heavy-duty pickup trucks and vans (Class 2b and 3); vocational vehicles (Class 2b-8); and tractor trucks (Class 7&8). It also covers engines used in heavy-duty vocational and tractor trucks. Engine and vehicle manufacturers are the parties to be regulated. Trailers used with tractor trucks are not included.

The agencies set standards for CO_2 emissions and fuel efficiency and also established emission caps for methane (CH_4) and nitrous oxide (N_2O). The EPA program to reduce CO_2 emissions begins with model year (MY) 2014 vehicles and does not have an end date, while the NHTSA's mandatory program to improve fuel efficiency starts with MY 2016 vehicles and ends with MY 2019 vehicles.

Vehicle Standards

Fuel efficiency levels required by the Heavy-Duty Rule are set in gallons per hundred miles for heavy-duty pickups and vans and in gallons per thousand (payload) ton-miles for vocational vehicles and tractor trucks. Table 2 shows the levels of selected standards translated to miles-per-gallon terms using the fixed payload values the rule specifies for vocational and tractor trucks. The baseline values provided are from agency estimates (EPA and NHTSA 2011a).

[1] Load factors and vehicle speeds may have increased substantially during the same timeframe, however, and fuel efficiency may have improved since the 2008 oil price spike. Thus the data cited above gives an incomplete picture of heavy-duty fuel efficiency trends. Lack of comprehensive, up-to-date data on performance of heavy-duty vehicles is in fact a serious obstacle to setting policies to help optimize fuel efficiency for these vehicles.

Table 2: Fuel Efficiency Standards* for Selected Vehicle Classes in 2014–2019 (converted to miles per gallon)

Model Year	Base Line	2014	2015	2016	2017	2018	2019
Gasoline Pickup Trucks and Vans	15.4	15.6	15.6	16.1	16.4	17.2	
Diesel Pickup Trucks and Vans	13.2	13.5	13.7	14.1	14.7	15.6	
Class 8 Vocational Vehicles	5.8	6.0			6.1		
Class 7 High Roof Combination Trucks, Day Cab	5.9	6.6			6.8		
Class 8 High Roof Combination Trucks, Sleeper Cab	5.7	7.2			7.4		

*Figures shown for pickups and vans are agencies' projections of average efficiency attained.

The rule subdivides tractor trucks into nine regulatory classes depending on weight class, cab type, and roof height. These features correlate with payload, duty cycle, and trailer type, and hence with fuel consumption. Under the rule, fuel consumption of Class 7&8 long-haul tractor-trailers (van type) will decline from estimated 2010 levels by 17 percent in 2014 and 20 percent in 2017, and fuel consumption of Class 7&8 non-van tractor-trailers will decline by 9 percent and 12 percent in 2014 and 2017, respectively. Vocational vehicles are subdivided into three regulatory classes by weight. Class 3-7 vocational trucks fuel consumption will decrease from estimated 2010 levels by 5 percent in 2014 and 9 percent in 2017. Class 8 vocational truck fuel consumption would decline by 6 percent in 2017.

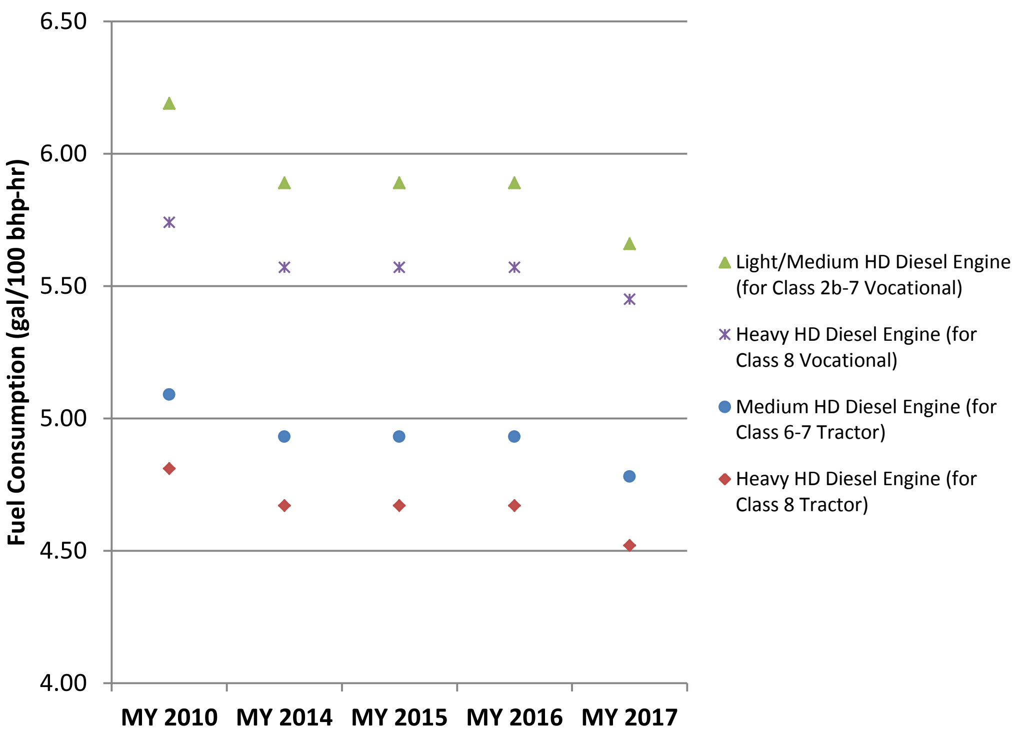
Emissions of vocational vehicles and tractor trucks will be determined using a simulation model, EPA's Greenhouse Gas Emissions Model, or GEM (EPA 2011b). Manufacturers will input certain vehicle specifications, including tire rolling resistance and coefficient of drag (for tractor trucks), but the model assigns many basic features of the vehicle, including engine and transmission properties, by default. The model exercises the resulting vehicles over three test cycles: the California Air Resources Board's (CARB) Transient Cycle (Clark 2004), a 55-mph constant speed cycle, and a 65-mph constant speed cycle. The certified fuel consumption and emissions values for each vehicle will be a weighted average of the three results, where cycle weighting depends on the vehicle type.

The standards for heavy-duty pickups and vans will be implemented in phases from 2014 to 2018 and are based on a "work factor" attribute that combines vehicle payload capacity and vehicle towing capacity with an additional fixed adjustment for four-wheel drive vehicles. The agencies estimate that the average fuel consumption of gasoline and diesel trucks will decline by 11 percent and 16 percent, respectively, in 2018 (NHTSA 2011, EPA and NHTSA 2011b). These vehicles will be tested on a chassis dynamometer for fuel efficiency measurement and compliance. The test cycles will be the same as those used for light-duty fuel economy vehicle testing, and with the same cycle weights: the Urban Dynamometer Driving Cycle (UDDS), weighted 55%, and the Highway Fuel Economy Test (HFET) Cycle, weighted 45% (EPA and NHTSA 2011a).

Engine Standards

The rule divides engines into four categories based on the types of vehicles that will use them. The standards are defined in terms of gallons and grams (CO_2) per brake horsepower-hour, so engine fuel consumption and emissions are regulated on a per-unit-work basis, as vehicles are. Fuel consumption reductions required by 2014 range from 3–6% below 2010 levels, and by 2017, 5–9%. Vocational engines will be tested on the Heavy-Duty Federal Test Procedure (FTP) Cycle, reflecting the prevalence of transient operation in their duty cycles. By contrast, the engines used for Class 7&8 tractor trucks will be tested on the Supplemental Emissions Test (SET) Cycle, reflecting the prevalence of steady operation on highways. Figure 3 shows engine fuel efficiency targets from 2014 to 2017; the 2010 levels are the agencies' baseline estimates for the various engine classes (EPA and NHTSA 2011a).

Figure 3: Heavy-Duty Engine Fuel Consumption Targets from 2014 to 2017



Averaging, Banking, and Trading

Manufacturers' compliance with the standards will be based on average fuel efficiency and emissions for each class of vehicles and engines covered. Averaging will occur only within a weight class in order to avoid i) disadvantaging manufacturers that have limited product ranges and ii) issues arising from differences in lifetime miles and emissions across vehicle and engine classes (EPA and NHTSA 2011a). Manufacturers generating excess credits may bank them for future use or may trade them to another manufacturer, as is the case in the light-duty fuel economy and GHG standards program.

Advanced Technology Provisions

The rule provides credit to manufacturers to promote the implementation of advanced technologies, including hybrid powertrain designs that include energy storage systems, Rankine cycle waste heat recovery systems attached to an engine, all-electric vehicles, and fuel cell vehicles. Hybridization is an important technology for the vocational segment, where the high frequency of stop-and-go driving can result in large benefits from the use of this technology. Hybridization will not be needed to meet the vocational vehicle standard. Rather, the rule is intended to incentivize manufacturer investment in hybrids by providing a credit multiplier of 1.5 for the use of advanced technologies (EPA and NHTSA 2011a).

The rule also provides innovative technology credits that will apply to technologies that are shown to produce emission and fuel consumption reductions that are not adequately recognized by the current test procedures and that are not yet in widespread use in the heavy-duty sector (EPA and NHTSA 2011a). The use of advanced transmissions and drivetrains, use of plastic composites and magnesium for material substitution for weight reduction, predictive cruise control, active aerodynamic features, and air conditioning (A/C) tailpipe emissions reduction can receive innovative technology credits. However, no credit multiplier applies to innovative technologies.

Benefits of the 2014–2019 Heavy-Duty Rule; Findings of the NAS Study

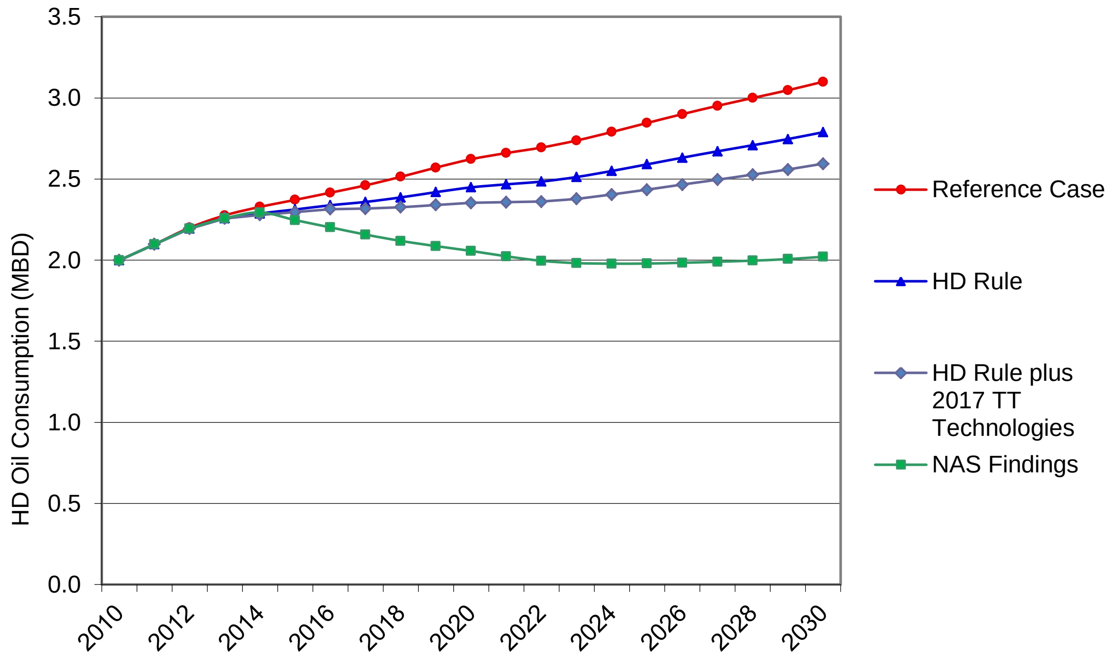
Class 3-8 medium and heavy-duty vehicles and Class 2b trucks at present consume 2.5 million barrels of oil equivalent per day. This number would rise to 3.5 MBD in 2030 if fuel efficiency were to remain at 2011 levels. Using Argonne National Laboratory's VISION 2010 model (ANL 2010), we estimated fuel savings in 2030 relative to the scenario in which fuel efficiency remains flat at 2011 levels. The model uses *Annual Energy Outlook 2010* (EIA 2010) figures as a reference case. Our calculations show that the 2014–2019 Heavy-Duty Rule would save almost 370,000 barrels per day from all covered vehicles except buses. Buses are not included in the VISION model, so we do not include their savings here; they are responsible for only 5 percent of heavy-duty fuel consumption (EIA 2011). They are, however, subject to the vocational standards so presumably will realize fuel savings through improved engines and tires.

The National Academy of Science (NAS) Committee to Assess Fuel Economy Technologies from Medium- and Heavy-Duty Vehicles considered fuel efficiency improvement potential for seven types of heavy-duty vehicles (NAS 2010). The Committee assessed the potential of engine, transmissions, and vehicle technologies to improve the fuel efficiency of these vehicles, and generally found far greater potential for savings than is reflected in the Heavy-Duty Rule. Savings from vocational vehicles and tractor-trailers would exceed one million barrels per day if all technologies considered in the NAS study were included, as shown in Figure 4.

The adoption of trailer standards to take advantage of available improvements to aerodynamics and tires could have reduced fuel use by at least an additional 10 percentage points and allowed manufacturers to optimize the tractor-trailer interface. The operating characteristics of long-haul tractor-trailers would have ensured that the investment was recovered within two years of operation. Trailers stay on the road for a long time, so any delay in regulating them will mean lost savings for many years to come.

The NAS findings for box type tractor trucks in 2015–2020 included technologies that together have the potential to reduce fuel consumption by 46 percent compared to a 2010 baseline. The 2015–2020 package for tractor trucks includes a first generation hybrid system, at a cost of $25,000, that is expected to reduce fuel consumption by 10 percent. It also includes bottoming cycle, a first-generation waste heat recovery system that will cost $7,200 to $15,100 (TIAX 2009). This technology is under development and is estimated to provide 7–10 percent fuel consumption benefit (NAS 2010). The package also included technologies outside the scope of the agencies' rulemaking authority, such as driver training.

Figure 4: Oil Consumption of Heavy-Duty Trucks > 10,000 Lbs. GVW



Limiting the NAS findings to technologies that are available by 2017 and within the agencies' jurisdictions leads to the conclusion that tractor trucks with van trailers can reduce fuel consumption by 35 percent, and other tractor trucks by 20 percent (ACEEE 2010). These technologies would provide an additional savings of 200,000 barrels of oil per day in 2030 beyond what the rule provides. The combined package would integrate fuel efficiency reductions from improving engine and transmission, improving tires and aerodynamics of tractors and trailers, and fuel efficiency gains from weight reduction and idle reduction. Based on the agencies' estimates of the costs of the improvements, we calculate that this tractor-trailer package would pay back the additional costs by the third year of operation and would provide $109,000 in discounted net benefits in the first ten years, compared to $81,000 net savings from the rule, as shown in Table 3. Our calculations considered annual miles traveled and fuel prices as specified in the rule and applied a 5 percent discount rate. Net savings from the rule as calculated by the agencies is somewhat lower, because they include a rebound effect, i.e., a tendency of drivers of more efficient vehicles to drive more miles than they otherwise would have.

Table 3: Comparison of Net Savings for Class 8 Tractor Trucks with Van Trailers

	HD Rule, 2017	HD Rule + 2017 TT Technologies
Fuel consumption reduction from 2010 level	20%	35%
Capital cost	$6,413	$43,950
Payback (years)	1	3
Net savings in the first 10 years of service	$81,000	$109,000

For vocational trucks, the rule captured the benefits only of engine and tire improvements. The omission of advanced transmissions, for instance, was a byproduct of the fact that the standards do not in fact apply to the actual vehicles sold, but only to selected components. The rule's segmentation of vocational vehicles into only three categories, defined by weight alone, means that neither the test cycle nor the value of the standard to which a vehicle is subject reflects the actual vocation of the vehicle. This also severely limits the savings the rule can deliver. Neither test protocols nor standard stringency are adequate to encourage the production of hybrids, which have already been developed for several vocational applications. The NAS also identified a number of efficiency technologies for vocational vehicles beyond engine and tire improvements, including hydraulic hybrid technology and advanced transmissions.

GETTING TO PHASE TWO

The 2014–2019 Heavy-Duty Rule puts in place several essential elements for a strong fuel efficiency and GHG program for heavy-duty vehicles, but there are several opportunities for improvement in the next phase of the program. Most importantly, a full-fledged program must treat a vehicle as an integrated system, rather than as a collection of discrete parts. In particular, the standards need to be applied to full vehicles, configured as sold. This will enable future standards to encourage technologies that the current compliance regime cannot differentiate but that can cut emissions and fuel consumption.

Prerequisites

Proper resolution of a host of issues relevant to the design of the next phase of the program will require extensive data collection on vehicle specifications, duty cycles, and fuel consumption, as well as further work on vehicle simulation.

Data

Balancing accuracy and manageability of the heavy-duty program will require many judgment calls based on characteristics of the heavy-duty market. Much of this work was done by EPA and NHTSA in the first phase of the rule. However, as the program is more closely tailored to actual vehicles sold, further distinctions among the affected vehicles will be necessary. Decisions for the next phase of the program will need to be based on detailed and up-to-date information on matters such as:

- Specifications of the vehicles and engines being purchased;
- Driving patterns and load properties for each vehicle type; and
- Duty cycles and on-road fuel efficiency.

Vehicle and Engine Specifications

The Heavy-Duty Rule requires manufacturers to report sales volumes of each vehicle configuration and "identify the transmission, axle ratio, and engine in addition to subfamily identifiers" (EPA and NHTSA 2011a). Manufacturers will also provide information on the utilization of efficiency technologies. Assuming the vehicle configuration and engine are fully identified, this information will provide a good picture of the current market for purposes of defining market segments and assessing the applicability of efficiency technologies not yet fully adopted. The agencies should produce an annual report summarizing this information for public use.

The information required by the rule will not be sufficient to evaluate the fuel consumption of these vehicles for simulation purposes, however. The MATLAB version of GEM, for example, requires various additional vehicle inputs including chassis and body weight, transmission gear ratios and gearbox efficiency, final drive ratio, frontal area, and electrical and accessory power. A fuel map for the engine also will be needed to simulate vehicle performance. All this data should be publicly available, at least for a large subset of vehicles, to permit transparent deliberation on the next phase of the rule. If manufacturers regard fuel maps as proprietary, they should be built into a publicly available simulation model in such a way as to permit their use in simulation while keeping the maps themselves invisible to the user.

Driving Patterns

The ways in which vehicles are used will determine what savings fuel efficiency technologies can achieve. Test cycles must adequately represent actual usage patterns in order to drive the proper efficiency technologies and achieve the savings anticipated. Representative information on current usage patterns is not readily available, however. The Vehicle Inventory and Use Survey (VIUS), formerly conducted at five-year intervals by the Census Bureau, included much of this information but was discontinued after the 2002 survey due to budget cuts.

Among the data previously collected by the VIUS that will be a prerequisite for sound rule design are annual miles traveled, primary range of operation, average load and percentage time traveling empty, and on-road fuel efficiency. Other data collected by the VIUS that would help to inform standards design include trailer type and specifications, PTO information, business type, fleet size, and ownership status for a representative sample of vehicles. A survey along the lines of the VIUS should be reinstituted as soon as possible.

Fleet Information

In addition to the breadth of information provided by a heavy-duty vehicle survey, the depth of real-world information that could be delivered by fleets would be very useful for developing the next phase of the rule. This information is essential in particular for the laborious process of developing test cycles, helping to determine for each vehicle type the share of transient operation, typical operating speeds, and the incidence of road grade, for example. Fleet participation will also be important to validating any simulation tools used in the program.

Through EPA's SmartWay Program, among other channels, the agencies could develop a voluntary data collection program designed specifically to inform the building of a simulation model and to test real-world benefits of vehicle technologies. Given that SmartWay partners are self-selecting, this data could not be taken as representative of all vehicles on the road, but rather would support the technical work for the rule.

Simulation Tool

Given the very large number of heavy-duty vehicle configurations sold, the cost of physically testing each of them separately would likely be prohibitive. Hence vehicle simulation will be an essential element of the testing program, whatever the protocol chosen for determining vehicle emissions and fuel consumption, and will be important for the development of the program as well. A technically sound, up-to-date, user-friendly, and well-documented simulation tool will be required. GEM, or its replacement, needs to permit inputs from manufacturers and other users for all variables that influence fuel efficiency. At a minimum, the full capability of GEM is needed, which means using the full MATLAB/Simulink version.

The simulation tool should allow the user to input the speed/time trace of any cycle, including grade. The model should also contain an expanded set of fixed cycles that better represents typical duty cycles for common vocational uses such as pickup and delivery, refuse, utility, and transit bus, as discussed below.

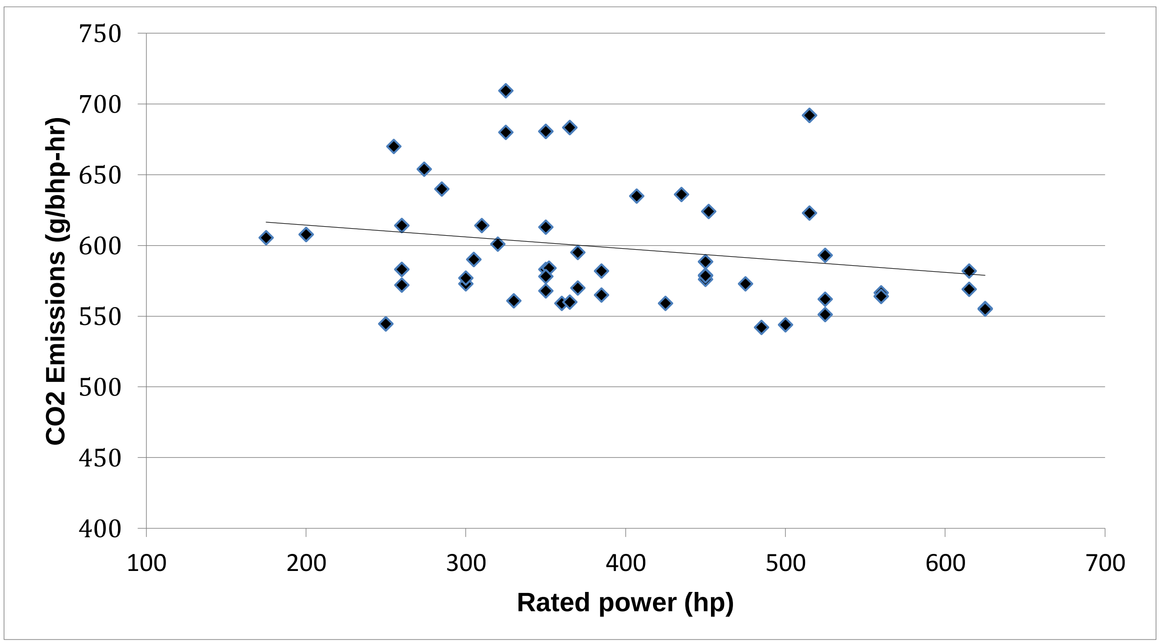
Full Vehicle Evaluation

For heavy-duty vehicles, as for buildings and other energy-consuming products, many of the most important efficiency gains going forward will involve optimized integration of systems, which goes beyond efficiency improvements to individual components. In order to take advantage of opportunities to improve full-vehicle performance, the standard and test protocol must reflect the performance of the real vehicle as sold, and to the extent possible as used. This is the basis on which vehicles will be designed and selected, and the regulatory program should be consistent with that perspective to avoid interference with the market. A program that will promote improvements to driveline efficiency, powertrain integration, cooling optimization, vehicle auxiliary optimization, and trailer gap optimization, for example, will require such an approach (Volvo 2011).

While the Heavy-Duty Rule nominally puts in place full-vehicle standards, the program is in effect a component-based system, with only a subset of components taken into account. In addition to the separate engine standards, credit is awarded separately for low coefficient of drag (tractors only), low rolling resistance tires, weight reduction, idle reduction device, and speed governor. Improvements to transmissions and driveline efficiency, powertrain integration, cooling optimization, vehicle auxiliary optimization, and trailer gaps, While in principle any fuel-saving technology can achieve credit as an "advanced" or "innovative" technology through a direct demonstration of savings, the resources required to make such a demonstration will diminish the incentive to pursue such credit.

A key example of how a full-vehicle approach will drive greater efficiency relates to engine performance. Under the Heavy-Duty Rule, the performance metric for engines is gallons or grams per brake horsepower hour on fixed cycles that are only weakly related to the actual load or duty-cycle of the vehicle in which the engine is installed. Engines' in-vehicle performance is not considered. This could have adverse consequences, including the promotion of oversized engines and higher fuel consumption and GHG emissions. Over a fixed engine cycle, a higher horsepower engine may achieve brake-specific fuel consumption (gallons per bhp-hr) and GHG emissions (grams per bhp-hr) comparable to or lower than those of a lower horsepower engine. This is evident from the limited 2009 EPA engine certification data, shown in Figure 5. Hence, a higher horsepower engine may meet the standard more easily than a lower horsepower engine will.

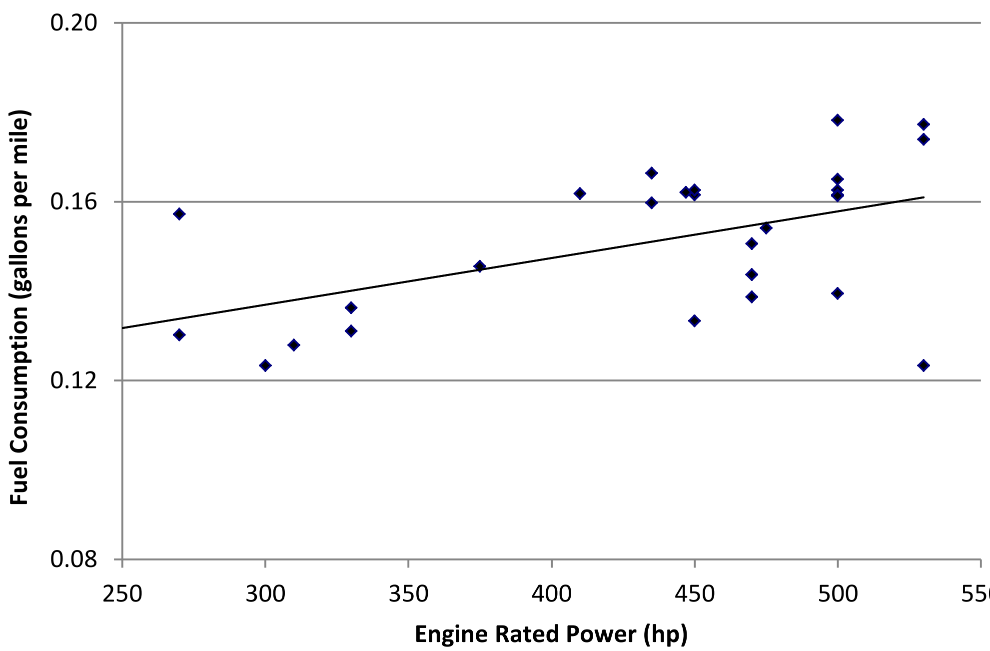
Figure 5: CO_2 Emissions vs. Power for MY2009 Engines (ACEEE from EPA certification data at EPA 2011c)



While this may suggest a fuel consumption and GHG emissions benefit from increasing engine horsepower, this is not generally the case, for two reasons. First, an engine is most efficient at or near full load. An oversized engine spends more time at lower percent load and consequently achieves a lower efficiency. The SET and FTP measure emissions at points on the engine map that are normalized to engine peak torque and speed, and hence do not permit a comparison of how two engines of different power ratings would perform under the same absolute load. Second, a vehicle with an overpowered engine is likely to be driven in a manner different from a vehicle with lower rated power; in particular it may accelerate and climb hills faster, increasing fuel consumption. These differences will not be reflected in engine test results either, because the drive cycle does not capture grade effect and is fixed across vehicles. Also, idle emissions of a bigger engine will be higher. The bigger engine also increases vehicle curb weight and consequently reduces payload for a weight-limited vehicle, which in turn increases fuel consumption per ton-mile.

Real-world data supports these concerns. For example, the CRC Study E-55/59 tested more than 40 Class 8 tractor trucks carrying a fixed load of 56,000 pounds (CRC 2007). These trucks had engines ranging from 7.6 liter (L) to 15 L in size and from 215 hp to 530 hp in rated power. The wide range of rated horsepower contributed to a wide range of fuel consumption, varying from 0.12 gallons per mile to 0.18 gallons per mile (see Figure 6). The trend is the opposite of what Figure 5 suggests.

Figure 6: Tractor-Trailer Fuel Economy vs. Rated Power (ACEEE from CRC 2007)



Transmission provides another example of the drawback of the approach taken in the Heavy-Duty Rule. Vehicles are evaluated using a predefined transmission (a 10-speed manual transmission for Class 7 and 8 tractor trucks) and there is no separate efficiency or technology requirement for transmissions. There is therefore little incentive for manufacturers to use technologies such as automated manual or dual clutch transmissions. According to one manufacturer, these transmissions can reduce fuel consumption and GHG emissions of vocational vehicles by 8 to 22 percent, depending on the truck type and the driver, when compared to torque converter automatic transmission (Eaton 2011). The rule also misses out on the ability to downsize an engine due to chassis weight reduction.

Design of Standards for Tractor-Trailers and Vocational Vehicles

For a program regulating the full vehicle as sold, the structure of the standards will need to be reconsidered. It must be determined to what extent the standards can and should be tailored to the diverse collection of vehicles in the market and their duty cycles. This determination should be made in keeping with the purpose of the program, namely to accelerate the use of efficiency technologies in such a way as to maximize fuel savings, and without interfering with the heavy-duty market.

Vehicle Segmentation

For purposes of the program, segments are groups of vehicles subject to the same standard and tested over the same cycle. It is possible that the standard within a segment would best be specified as a function of vehicle attributes, rather than as a fixed value, though we make no such recommendation here. Such "attribute-based" systems are exemplified by the standards for heavy-duty pickups and vans, which vary with payload and towing capacities and presence of four-wheel drive, and light-duty vehicle fuel economy and greenhouse gas standards, which vary with vehicle footprint. Test weight within a segment should similarly be a fixed number, or be defined as a function of a vehicle parameter such as maximum payload.

The nine tractor truck segments defined under the Heavy-Duty Rule were chosen to address some of the most important distinctions among these trucks: type of trailer pulled (as indicated by roof height); whether the trailer must accommodate hoteling loads (sleeper cab vs. day cab); and how heavy a payload the truck will pull (Class 7 vs. Class 8). This segmentation of tractors may prove adequate for the net phase, although the question should be revisited in light of current, representative data once that is available.

The rule's segmentation of vocational trucks, by contrast, is tailored to weight class only and does not reflect vehicle use. That this very diverse collection of vehicles was divided into fewer segments than the more homogeneous set of tractor trucks may reflect the fact that vocational vehicles are responsible for a smaller share of total heavy-duty fuel consumption than tractor truck are, and therefore fine-tuning the rule to vocational trucks was less critical to achieving fuel savings in the first phase of the program.

This segmentation will not be adequate as the program seeks to capture more of the available savings, however. Vocational vehicles comprise a broad array of vehicles that vary by purpose, duty cycle, and annual miles, even within a weight class. For example, Class 7 and 8 vocational vehicles include dump trucks, refuse trucks, concrete mixers, furniture trucks, city buses, tow trucks, fuel tankers, and fire engines, which have a wide array of payload weights, duty cycles, and rates of fuel consumption, all related to their very different functions. Class 4–6 vocational vehicles include city pickup and delivery trucks, school buses, and bucket trucks, while vocational vehicles in Classes 2b and 3 include pickup and delivery vans, utility vans, and step vans (NAS 2010). At the same time, some duty cycles are common to vehicles in multiple weight classes. For example, there are transit buses in Classes 6 to 8 and delivery vans from Class 2b to Class 6, and cycles within either vocation are similar.

As an example of insufficient segmentation of vocational vehicles in the Heavy-Duty Rule, the Class 8 payload of 15,000 lbs. is not appropriate for all vehicles in this segment. To reach this payload, a transit bus would need to have about one hundred passengers, though it would typically have only 35 seats (NTD 2008). On the other hand, some vocational vehicles, including refuse trucks, are designed to carry far more than the predefined payload. The efficiency technologies appropriate for such a disparate set of vehicles will also differ widely and cannot be incentivized by a program that views them as similar. Hence vocational vehicles should be segmented further in the next phase of the program.

Much of the work necessary for the further segmentation of vocational vehicles has already been initiated by EPA's SmartWay Program. SmartWay identified major categories of vocational vehicles and developed duty cycles for each category (EPA 2007). Major categories identified to date are: pickup and delivery trucks, utility trucks, refuse trucks, and buses. Segmenting vocational vehicles in this way would allow the tailoring of baseline and target fuel consumption values, and hence would lead to greater technology uptake and greater fuel and emissions reductions. Test cycles would be determined by vehicle category, while the value of the standard would be determined by both weight class and standard.

Test Cycles and Test Weight

The segmentation of vehicles discussed above assumes that all vehicles within a segment will be tested over the same cycle or cycles. While segments will be defined to ensure a large degree of similarity in the usage of the vehicles within them, duty cycles will nonetheless vary from vehicle to vehicle. Percentage of transient operation or typical highway speeds, for instance, is not constant within segments but substantially influences fuel consumption. Consequently test results will not accurately predict the fuel consumption of any particular vehicle. To be effective, however, the segments and test cycles must be selected so as i) to incentivize the adoption of technologies that will achieve real-world savings for vehicles in the given segment and ii) to allow estimates of fuel consumption of the segment in the aggregate.

The Heavy-Duty Rule did not require great precision in establishing test cycles because it did not push any vehicle category to the limits of cost-effective efficiency improvements. In the future, however, technologies will need to be increasingly tailored to the intended application. The rule uses three basic test cycles for all tractor-trailers and vocational vehicles: a transient cycle, with 15.2 mph average speed and 47.7 mph maximum speed, and two constant speed cycles of 55 mph and 65 mph. Vehicles will be simulated over these cycles and the results weighted to give the final emissions and fuel consumption levels.

Using data gathered as recommended above, the agencies will be able to give an up-to-date description of driving patterns of the various vehicle types and determine whether these cycles adequately capture these patterns. While this may be the case for tractor-trailers, the vocational cycles will need to be refined in the next phase.

Gross weight has a substantial effect on vehicle fuel consumption, so testing a vehicle at its actual weight is preferable. A given model and indeed an individual vehicle might carry a wide range of payload weights, however, and in particular vehicles typically travel a substantial amount of time empty. Vehicle survey data can be used to determine typical payloads for each vehicle type, as well as deviation from that typical payload. While one cannot hope to differentiate new vehicles' fuel consumption in anticipation of their likely loads, at least simulation can be used to estimate the impact of the variation in load on real-world fuel use.

Test Protocol

Given the large number of heavy-duty vehicle configurations sold, requiring physical testing of each distinct model would be onerous. Hence vehicle simulation will continue to play an important role in testing in the next phase of heavy-duty standards. Simulation can be used not only to test many vehicle variations at relatively low cost, but also to test sensitivity of fuel consumption to variations in duty cycles and driving conditions. Only physical testing, however, will inspire confidence that the protocol captures how vehicles will actually perform, particular those adopting new technologies involving system integration. Hence both physical testing and simulation will be essential elements in the testing program for the next phase. Chassis testing should be required for a representative set of vehicles and complemented by simulation testing for similar vehicles. Defining the appropriate representative set is not a straightforward task, but at a minimum any significant change in powertrain would call for additional chassis testing.

Engine Requirements

The stringency of engine standards for 2014-2017 in the Heavy-Duty Rule does not reflect certain technological improvements that are expected to be available before 2020, including elements of DOE's SuperTruck Program, such as waste heat reduction, parasitic load reduction, engine downsizing, and turbocompounding (DDC 2011). Given the long lead times needed to develop advanced engine technologies, the rule at a minimum should have sent a clear signal that substantial additional improvements would be required for the next phase to ensure manufacturers' continued investment in engine technologies.

For GHG and fuel consumption certification, the engine is exercised through a speed-torque schedule on an engine dynamometer while emissions are collected and analyzed. The FTP and the SET cycles used for engine testing follow EPA's existing heavy-duty test procedures for criteria pollutants. The agencies selected this path to streamline testing, reduce the time to develop an engine program, and limit the possibility of gaming between the efficiency and conventional pollutant programs. However, the FTP test cycle was developed from driving behavior of trucks in the last century, some of which had gear ratios limiting maximum vehicle acceleration. It also was based on engines with lower power density and lower turbocharger boost than current diesel engines, and therefore cannot represent today's complex engines and their application (Zhen 2009). Existing chassis cycles that better reflect today's driving behavior and engines offer a better basis for developing engine cycles for certification purposes.

The FTP and the SET test the engine over predetermined torque-speed points, scaled to the engine's maximum load, that may not adequately cover its actual operating range in use. This could lead manufacturers to optimize engine performance for testing rather than for real-world driving. Moreover, a test that does not reflect actual loading may help to perpetuate the trend toward higher horsepower engines by understating their in-use fuel consumption.

Once the heavy-duty program makes the transition to evaluation of full vehicles, the need for separate engine standards will be less clear. Absent engine standards and direct involvement of engine manufacturers, however, vehicle manufacturers might opt for improvement in vehicle technologies alone to meet the target, forgoing engine improvements. Yet there is considerable potential for further gains in engine efficiency in the somewhat longer term, as evidenced by the objectives for DOE's SuperTruck Program, and having a clear long-term target for engines will support engine manufacturers' decisions to invest consistently in advanced technologies. It will be essential to ensure sufficient consistency between the engine and vehicle tests so that engine manufacturers will have an incentive to optimize their products for the vehicle tests as well as the engine tests.

The agencies' clear preference, and in fact the preference of regulators around the world, is to use the same engine tests for criteria pollution and greenhouse gas emissions/fuel consumption. This serves not only to minimize the work needed for manufacturers to comply, but also to ensure consistency across the rules. Especially given that, historically, criteria pollutant reduction for heavy trucks has sometimes occurred at the expense of fuel efficiency and vice versa, using the same test cycles for both types of emissions may be necessary to ensure simultaneous progress on both fronts. Existing criteria pollutant test cycles are not adequate for this purpose, however, since the speed-torque points of greatest interest may differ for GHG and criteria pollutant emissions. In addition, while criteria pollutant standards aim to bring emissions down by large amounts in a single step, fuel consumption reductions occur more incrementally and require measurements over the full cycle of operations. Extensive work will be needed to develop test cycles appropriate to both criteria pollutant and GHG testing, and to adjust standards accordingly.

Heavy-Duty Pickups and Vans

Heavy-duty pickups and vans trucks using engines and transmissions similar to light-duty trucks will have much lower fuel efficiency targets under the rule than their light-duty counterparts will have under the light-duty fuel economy program. An ACEEE analysis found that fuel economy targets for the light-duty pickups will be 35–50% higher than the fuel economy targets for their heavy-duty counterparts in 2016, even after adjustment for differences in curb weight and payload. It is not clear that such a gap is warranted. A discrepancy in the stringency of standards for two contiguous segments of the vehicle market could produce distortions in the market, with adverse effects on the consumer and a loss in fuel savings.

Fuel efficiency requirements for heavy-duty pickups and vans should be strengthened to be more consistent with standards for their light-duty counterparts. The manufacturers, duty-cycles, buyers, available technologies, and vehicles themselves have much more in common with light-duty than with heavy-duty vehicles. Consideration should be given to integrating standards for these vehicles with the light-duty program. The work requirements for heavy-duty pickups and vans should continue to be recognized in the program. In particular, the current attribute of work factor could remain the basis for the targets for heavy-duty pickups and vans, while footprint would remain the attribute for light-duty vehicles. With these vehicles properly placed within a common context with light-duty, however, the "boundary issue" described above, in which standards for very similar vehicles are far apart, could be mitigated. At the same time, a host of other issues, including technological assessment, manufacturer considerations, real world vs. laboratory performance, and labeling, could be handled consistently and efficiently.

It should be noted, however, that the proposed standards for light-duty vehicles in 2017–2025 do not fully reflect the technological improvement potential for large pickups; the agencies increased the slope of the CO_2 emissions-vs.-footprint curve in response to concerns that large pickups would lag other vehicles in adopting improvement technologies (EPA and NHTSA 2011c). The theoretical advantages of integrating the heavy-duty pickup and truck standards with the light-duty program must be weighed against this reality in deciding how to proceed in the 2020–2025 period.

Stringency Considerations

As noted earlier, the standards set in the Heavy-Duty Rule can be met for the most part with efficiency improvements that will pay back buyers in fuel savings within two years. Moving into the next phase, as the program aims to capture more of the savings available, payback periods for technologies used to meet the more stringent standards may increase. Indeed, fuel costs are so great for many heavy-duty vehicles that technologies paying back only after many years can still deliver enormous net savings over their lifetimes.

Buyers may be reluctant to accept such large increases in upfront costs, even given the long-term benefits. One reason for this is that the buyer may sell the vehicle long before the incremental cost has been recouped and savings begin to accrue. This is especially true, for example, for large fleet buyers of long-haul trucks, which often sell their vehicles within three years and look for a payback in under two. Owner turnover does not present a barrier to purchase of high-efficiency vehicles if the efficiency improvements are valued appropriately in the used vehicle market, but this is not necessarily the case. There may be no clear evidence of the vehicle's superior fuel economy when it is resold. In addition, the more closely tailored efficiency improvements become to the truck and its user, the smaller the pool of potential buyers in the used market whose duty cycles are sufficiently like those of the original owner to benefit from the same technologies. These problems could be mitigated to a large degree if detailed, standardized information about vehicles' fuel efficiency were consistently available in the aftermarket.

Buyer Information

The vehicle and engine labels required by the Heavy-Duty Rule are an enforcement mechanism and are not intended to provide information to buyers. Surprisingly, the rule does not even require consumer fuel efficiency labels for heavy-duty pickup trucks and vans, for which a label similar to the light-duty vehicle label would be appropriate. Better information for heavy-duty vehicle buyers is an important aspect of the effort to improve fuel efficiency, and should be fully developed in parallel with the next phase of the standards. EPA and NHTSA expressed concerns that a consumer-oriented label would provide misleading information, especially given how far removed vehicle certification values might be from performance of the actual vehicle (EPA and NHTSA 2010a). Moving to a full-vehicle testing protocol based on the performance of the vehicle as sold will mitigate that problem to a large degree, removing what has been perceived as an obstacle to a heavy-duty label.

Due to the great importance heavy-duty vehicle owners attach to fuel expenses, manufacturers already have tools to demonstrate to clients the expected fuel consumption for any given vehicle over a given route, and the effects of changes in specifications on fuel consumption. There is no uniform, industry-wide information of this sort available, however, so buyers cannot easily compare the full range of options in the market, including new technologies and equipment. A labeling system would help to address this need, as would an annual buyer's guide similar to the Fuel Economy Guide that EPA and DOE issue for light-duty vehicles. The guide should list, for each vehicle and engine subject to the heavy-duty standards, fuel consumption and GHG emissions rates, along with other information helpful for comparing and understanding the performance of these vehicles and engines.

As noted previously, test cycles used for each vehicle segment cannot properly represent the duty cycles of all vehicles in that segment. As a result, certification values may not provide a projection of a vehicle's fuel consumption that is adequate for heavy-duty purchase decisions. Hence, in addition to the certified levels of fuel consumption and GHG emissions, the label should display results for certain common modes of operation (e.g., urban and highway) separately, as the light-duty fuel economy label does. This would help buyers assess the suitability of a given vehicle or specification for their particular duty cycles.

Research indicates that fuel consumption and GHG emissions over any heavy-duty drive cycle can be reasonably well approximated as a weighted sum of fuel consumption and GHG emissions over certain standard drive cycles (Clark 2009; Taylor 2004). The weightings are determined by certain parameters associated with the drive cycle, such as average speed, average acceleration, percent time at idle, and stops per mile. Various combinations of three drive cycles, including some similar to the cycles proposed in the Heavy-Duty Rule, have been shown to produce good results. Hence a buyer in principle could use fuel consumption values from at most three cycles to estimate the fuel consumption of a given vehicle knowing the characteristics of his or her own duty cycle.

Buyers should also have online access to the simulation model used for the regulatory program and the ability to input their own duty cycles, as discussed above, and complete specifications for the vehicles on the market. This would provide a still better basis for a customized comparison of vehicles.

Harmonization

The heavy-duty vehicle market is small compared to the light-duty market in the U.S. This presents an obstacle to innovation among manufacturers, who may find it too costly to invest in technologies purchased in such small numbers each year. At the same time, several regions are developing heavy-duty vehicle standards that could require similar efficiency improvements, and drive the same technologies, outside the U.S. If some degree of consistency is achieved in the standards across these regions, both manufacturers' costs of compliance and the costs of the technologies required to meet the standards will decline. While fundamental differences exist in the specifications and usage patterns of heavy-duty vehicles across regions, it is important to understand, and take advantage of, the commonalities to the greatest possible degree.

Conclusions and Recommendations

The 2014–2019 Heavy-Duty Rule represents an important step toward managing fuel consumption and greenhouse gas emissions of the transportation sector. The program will promote adoption of several efficiency technologies that will provide rapid payback to buyers through fuel savings, and does so without interfering in the heavy-duty market. Many efficiency technologies are not incentivized by this first rule, however, in large part because the program does not regulate full vehicles.

The next phase of the program, to begin in 2020 or before, should be based on evaluation of the full vehicle. This has major implications for tractor-trailers and vocational vehicles, and will allow the program to drive greater savings than the current program structure permits. Questions of vehicle segmentation, test cycle, test protocol, and stringency of standards will need to be rethought in the design of this next phase. Prerequisites for this work include more complete and up-to-date data on medium- and heavy-duty vehicles than is available today, as well as an enhanced simulation model.

In view of these considerations, we offer the following recommendations to policymakers and the relevant agencies.

In the immediate future:

- **Trailer standards:** Adopt trailer standards at the earliest possible date to increase fuel savings and allow integration of tractor and trailer improvements.
- **Data collection, analysis, and dissemination:** Resume and expand the Vehicle Inventory and Use Survey or otherwise establish a federal data collection program for heavy-duty vehicles, including sales, configurations, fuel consumption, and driving patterns. Ensure data is publically available. Collect in-use testing data through manufacturers, fleets, and federal agencies. Prepare annual reports on i) the state of the heavy-duty market and ii) fuel consumption and GHG emissions of new vehicles by vehicle type.
- **Vehicle simulation model:** Develop and maintain a vehicle simulation tool that i) can accurately reflect all vehicle and drive cycle specifications relevant to fuel consumption and ii) is available for general use.

In the next phase of the standards:

- **Full vehicle standards:** Apply standards to the full vehicle as sold. Evaluate performance of tractor trucks with an appropriate, efficient trailer.
- **Vocational vehicle segmentation:** Further segment vocational vehicles to reflect fundamental differences in duty cycles.
- **Vehicle test cycles and test weights:** Reevaluate the ability of existing test cycles to capture current driving patterns for all vehicle classes, including road grade and driver behavior. Establish appropriate test weights based on vocation and weight class.
- **Test protocol:** Require physical testing (road, track, or chassis dynamometer) for a basic set of well-defined vehicle configurations. Allow variations on these configurations to be tested using a simulation model.
- **Engine standard:** For at least the next round of rulemaking, consider maintaining engine standards along with full-vehicle standards. Develop new test cycles for heavy-duty engines, reflecting real-world driving characteristics.
- **Heavy-duty pickups and vans:** Bring heavy-duty pickups and vans to efficiencies consistent with those of their light-duty counterparts. Consider integrating the standards for heavy-duty pickup trucks and vans with the light-duty program while continuing to recognize the functional requirements of these vehicles.
- **Stringency:** In determining the stringency of standards, consider technologies that deliver large lifetime savings, even if they do not pay back in the ownership period of the initial purchaser.
- **Buyer information:** Put in place a permanent, buyer-oriented label for all covered vehicles, showing both certification values and separate fuel efficiencies for at least two relevant driving modes (e.g., urban and highway). Provide an online simulation tool to allow buyers to compare vehicle performance over drive cycles specified by the user.
- **Standards harmonization:** Seek to achieve consistency with other regions regulating heavy-duty vehicle fuel efficiency or greenhouse gas emissions on program elements such as test cycles, measurement protocols, vehicle segmentation, and standard stringency, and thereby expand the market for efficiency technologies while streamlining manufacturer compliance.

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