WORKING PAPER

Segmentation and Flexibility in Fuel Economy Standards for Tractor-Trailers

Therese Langer
Siddiq Khan

April 2010

30 Years of Energizing Efficiency

American Council for an Energy-Efficient Economy
529 14th Street, NW, Suite 600, Washington, DC 20045
www.aceee.org

AUTHORS: Therese Langer and Siddiq Khan
American Council for an Energy-Efficient Economy

PREPARED BY: American Council for an Energy-Efficient Economy

FOR SUBMISSION TO:

International Council on Clean Transportation
1225 Eye Street Suite 1000 Washington, DC 20005
One Hallidie Plaza Suite 503 San Francisco, CA 94102
www.theicct.org

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ACKNOWLEDGEMENTS:
The authors would like to thank ICCT staff for reviewing and commenting on earlier versions of this report.

April 2010

Executive Summary

The variety of specifications and duty cycles for heavy-duty trucks poses a challenge to the design of fuel efficiency standards for these vehicles. Even within the relatively homogeneous group of tractor-trailers with van-type trailers, there are diverse functional requirements that affect fuel consumption. This paper explores possible approaches to accommodating this diversity in the design of the standards.

Tractor-trailers duty cycles are not uniform. While most tractor-trailers are purchased for long-haul operation, over 10 percent of new tractor-trailers typically travel 100 miles or fewer daily. These trucks have half the annual mileage of long-haul trucks on average and are likely to spend a high percentage of time in stop-and-go traffic, which has major implications for fuel economy. Due to these factors, it is unlikely that any uniform fuel economy standard for tractor-trailers, based on a fixed test cycle, would be equitable. One approach to duty cycle variation would be to classify new trucks based on cab type, given that sleeper cabs are required only for those vehicles that travel long distances. Cab type is not, however, a reliable basis for classification for fuel economy purposes, because trucks having primary trip length of 100 to 200 miles tend to have day cabs, even though their driving patterns are more similar to those of long-haul trucks.

Performance requirements such as the need to pull heavy loads or the need to perform adequately in mountainous terrain are a second reason for the variation in fuel economy across tractor-trailers. While there is no fixed relationship between average fuel consumption and engine rated power, a small engine at appropriate load will tend to consume somewhat less fuel than larger engine will under that same load, due to greater friction losses in the larger engine and a loss of efficiency due to operating at part load. In tractor-trailer engines today, fuel consumption might be expected to vary by over 10% due to horsepower differences alone. Thus a uniform miles-per-gallon standard at fixed load is likely to be substantially more difficult for a truck with higher horsepower. While this may be appropriate to the extent that higher horsepower is used for more aggressive driving, it also could interfere with proper truck specification. In addition, a uniform standard would require that all tractor-trailers be tested at the same load, which could lead manufacturers to optimize fuel economy at the test load, rather than at actual operating loads.

Allowing manufacturers to average fuel economies across their vehicle production would mitigate the problems associated with applying a uniform standard across tractor-trailers with varying duty-cycle and performance requirements. A second approach would be to segment tractor-trailers using one or more parameters that differentiate among them in ways that relate both to fuel economy and to a business necessity. Segmenting by rated power or rated payload would allow testing at payloads reflecting trucks' typical operating weights.

Defining truck standards using a metric such as gallons per ton-mile or gallons per cube-mile may be preferable to a mile-per-gallon standard, given the freight-hauling function of the vehicles. A gallon-per-ton-mile standard, for example, would promote weight reduction by allowing trucks to improve performance by increasing payload while keeping fuel consumption constant. It would not, however, eliminate the difficulties associated with a uniform standard for line-haul tractor-trailers.

The conclusions and recommendations of the paper are:

The variation in fuel economy of tractor-trailers with van-type trailers due to duty cycle and performance-related specifications poses an obstacle to setting a uniform fuel economy standard that is both appropriately stringent and sensitive to the diversity of tractor-trailers. Allowing manufacturers to average fuel economy across their products mitigates the problem to a degree, but functional differences among manufacturers' products may be large enough to raise equity concerns.

- Up-to-date data on the properties and use of new trucks should be gathered to determine whether variations in products across manufacturers are large enough to preclude a uniform tractor-trailer standard, even when averaging is allowed.

Although short-haul tractor-trailers are a small percentage of the new tractor-trailer market, applying the same standard to them as to regional- and long-haul tractor-trailers could make compliance substantially more difficult and costly for some manufacturers. While distinguishing short-haul trucks from regional-haul trucks by physical attributes may not be practical, manufacturers could perhaps be relied upon to classify their own trucks, by virtue of the efficiency technologies they choose to employ to meet the fuel economy standards.

- Separate test cycles should be developed for line-haul vehicles and short-haul vehicles, and regulators should consider allowing manufacturers to choose the test cycle on which a given truck would be certified.

Variations in performance requirements for tractor-trailers, and their effects on fuel economy, also appear sufficient to warrant further segmentation.

- Tractor-trailers should be separated into at least two segments by performance-related criteria, e.g., above and below 400 HP or above and below 60,000 lbs. gross vehicle weight, with a fixed test weight for each segment.

The regulatory challenges associated with the functional diversity of tractor-trailers could also be addressed through an attribute-based standard, rather than by discrete segmentation.

- Regulators should consider defining a miles-per-gallon or gallons-per-ton-mile standard as a function of gross vehicle weight rating, where vehicles are tested at a fixed percentage of rated weight.

Failure to address the variation in tractor-trailer fuel economy, at either the individual truck or the manufacturer average level, could compromise the stringency of the standard. It is therefore important to pursue alternatives to a uniform standard.

Introduction

The variety of specifications and duty cycles for heavy-duty trucks poses a challenge to the design of fuel efficiency standards for these vehicles. Even within the relatively homogeneous group of tractor-trailers with van-type trailers, there are diverse functional requirements that affect fuel consumption. This paper explores possible approaches to accommodating this diversity in the design of the standards. The discussion assumes that vehicle manufacturers will be the regulated entities under the standards.

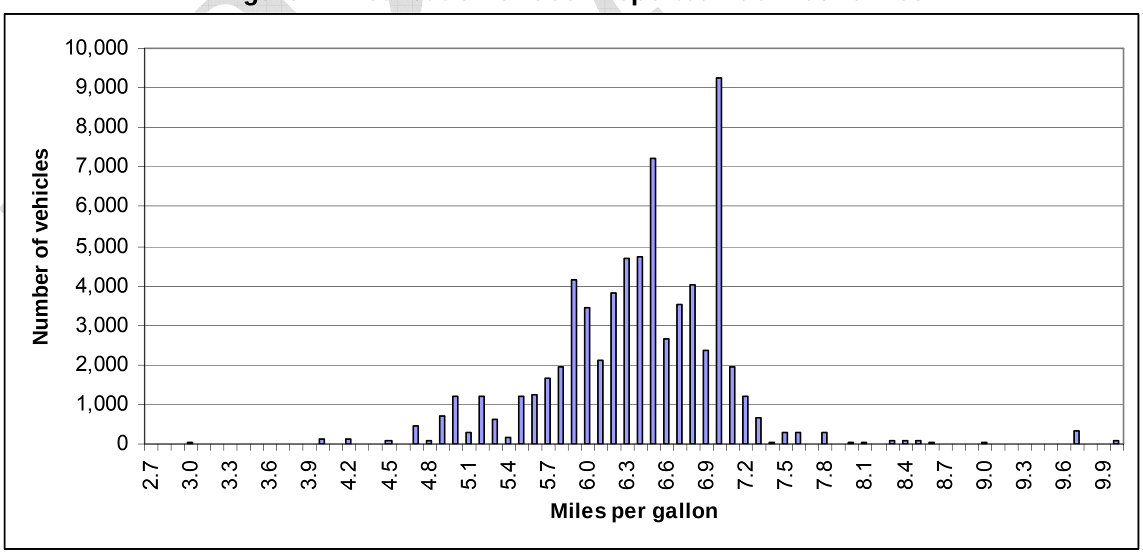
Our starting point is the proposition that all new tractor-trailers with van-type trailer could be subject to the same mile-per-gallon standard. This proposition raises a host of questions: Should there be an allowance for trucks that can carry more weight or travel in mountainous terrain? Should all tractor-trailers be required to meet the standard over the same test cycle, regardless of their actual duty cycles? Even fixing a test cycle and a test weight, functional variations among trucks may mean a uniform standard will be necessarily unfair or, alternatively, too weak to drive technology advances.

If tractor-trailers cannot all meet the same standard, then three possible paths forward are: 1) to allow manufacturers flexibility in meeting the standard, e.g. the ability to average over multiple vehicles; 2) to segment the tractor-trailer population and allow the standard to vary by segment; or 3) to express the standard as a function of truck attributes. To what extent these approaches are necessary and to what extent they can resolve the issues raised by variations among tractor-trailers are the questions considered in this paper.

Fuel Economy Diversity in Tractor-Trailers

The range of fuel economy of new Class 7 (gross vehicle weight 26,000 to 33,000 lbs.) and Class 8 (gross vehicle above 33,000 lbs.) tractor-trailers with van-type trailers is illustrated using data from the *2002 Vehicle Inventory and Use Survey* (VIUS) (U.S. Census Bureau 2004), shown as a frequency plot in Figure 1.[1] The data represents average fuel economy in 2002, as reported by the truck user; spikes in the distribution presumably reflect a tendency to report values rounded to nearest integer or half-integer.

Figure 1: Distribution of User-Reported Fuel Economies



Source: ACEEE, from 2002 VIUS data

[1] Unless otherwise noted, VIUS data referenced in this document is limited to model year 2002–2003 Classes 7 and 8 tractor-trailers with trailers of type “van, basic enclosed,” “van, insulated non-refrigerated,” or “van, insulated.” The VIUS estimates there are 78,519 such trucks.

This distribution reflects trucks using varying levels of efficiency technology. Technological sophistication is by no means the only reason for the variation in fuel economy, however. A standard that fails to take into account these other considerations could interfere with truck functionality.

Duty Cycle

Tractor-trailer duty cycles are not uniform. Long-haul tractor-trailers often move into regional or short-haul use after several years. Even among newly purchased trucks, shorter-haul vehicles constitute a significant percentage, as shown in Table 1.

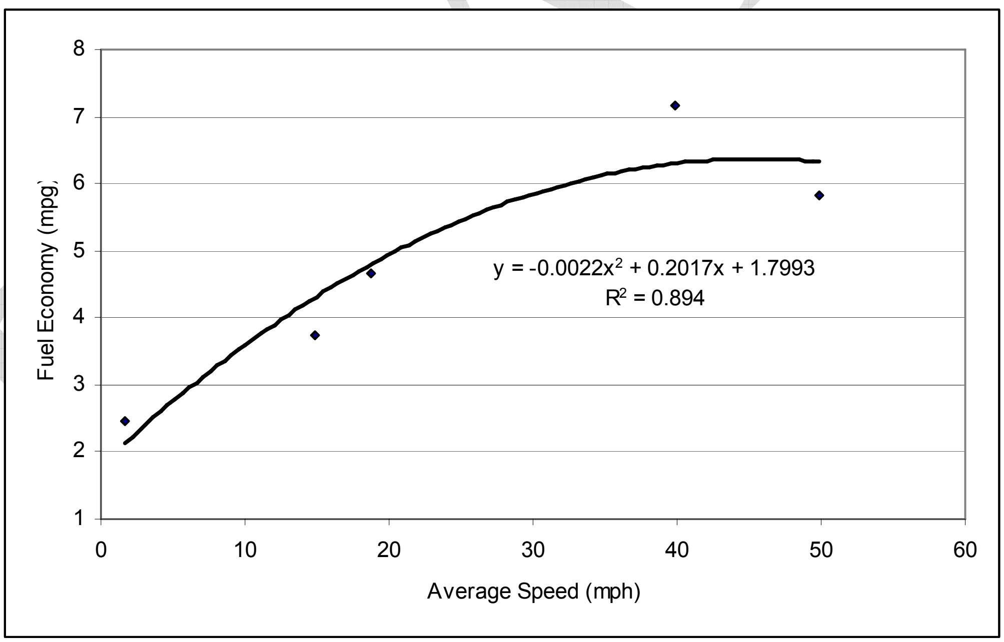
Table 1: Characteristics of New Tractor-Trailers with Van-Type Trailer

Primary Trip Length	Percent of Sales	Average Annual Miles	Percent w/ Sleeper Cab
Less than 50 miles	7%	53,705	16%
51 to 100 miles	4%	52,358	19%
101 to 200 miles	7%	96,338	22%
201 to 500 miles	27%	110,746	72%
501 miles or more	55%	113,365	94%

Source: ACEEE, from 2002 VIUS data

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 fuel economy. As shown in Figure 2, fuel economy declines as average speed decreases from the highway speeds typical of a line-haul drive cycle to the low speeds that characterize an urban drive cycle.

Figure 2: Fuel Economy and Average Speed for a MY2004 Freightliner Truck



Source: ACEEE, from data in Clark et al. (2007)

A fuel economy standard for tractor-trailers could circumvent this problem by requiring that all vehicles be tested over the same drive cycle, regardless of their actual duty cycles. Vehicle specifications reflect the anticipated use of the vehicle, however, so a uniform drive cycle for all vehicles will not result in an equitable standard, as the following example shows.

Example

Suppose a standard of 7.2 miles per gallon (mpg) is applied to all tractor-trailers over a test cycle consisting of 17% city driving and 83% highway driving, corresponding to the transient/high-speed breakdown of the Cruise Cycle in the California Air Resource Board's Heavy Heavy-Duty Diesel Truck Schedule (CARB HHDDTS) (Clark et al. 2004). This hypothetical example considers the implications of the standard for three tractor-trailers: 1) a long-haul truck with limited aerodynamic equipment/design; 2) a regional-haul truck with limited aerodynamic equipment/design; and 3) a short-haul truck with poor aerodynamics. The trucks are assumed to have the same engine. Here long-, regional-, and short-haul trucks are defined per the above discussion as those whose primary trip lengths are over 200 miles, 100–200 miles, and under 100 miles, respectively. All vehicles are tested at 80,000 lbs. GVW.

Table 2 shows the fuel economies, annual miles (from Table 1), and percent city driving might differ for the three trucks. The city and highway fuel economies of the long-haul truck are based on Muster (2000) and are also consistent with the dependence on average speed shown in Figure 2. The fuel economy of the short-haul truck over the highway cycle is assumed to be lower than the highway fuel economies of the other two trucks due to the lack of aerodynamic features. All three trucks as configured fall well short of the 7.2 mpg standard.

Now suppose that, in order to meet the standard, the manufacturers of the long- and regional-haul trucks add equipment or features to the cab and trailer equivalent to the Advanced Aerodynamics package discussed in a recent ICCT-NESCCAF study using modeling conducted at Southwest Research Institute (NESCCAF 2009). The manufacturer of the short-haul truck offers a full hybrid vehicle to take advantage of stop-and-go driving but does not improve aerodynamics, due to the relatively small percentage of miles driven at high speeds (35% by assumption). We chose aerodynamic improvements and hybridization in this example as the principal technologies available in the near term to achieve large reductions in fuel consumption in highway driving and city driving, respectively. Aerodynamics is assumed to reduce highway fuel consumption by 22% and city fuel consumption by 4%. The hybrid is assumed to reduce fuel consumption by 6% in highway driving and 40% in city driving, respectively.

Based on the stated assumptions, the manufacturers' success in complying with the 7.2 mpg standard and the costs the purchasers incur in this hypothetical example are shown in Table 2.

Table 2: Comparison of Tractor-Trailers — Attempted Compliance with Standard

	Long Haul	Regional Haul	Short Haul
Fuel economy — city cycle	4.4	4.4	4.4
Fuel economy — highway cycle	6.5	6.5	6
Av. annual miles — years 1–3	110,000	95,000	55,000
GVW	80,000	80,000	80,000
City share — test cycle	17%	17%	17%
City share — duty cycle	5%	35%	65%
Fuel economy over duty cycle	6.3	5.6	4.9
Fuel economy over test cycle	6.0	6.0	5.7
Fuel economy standard — test cycle	7.2	7.2	7.2
Required reduction in fuel consumption	16%	16%	22%
Equipment added	Aero	Aero	Hybrid
Cost	$20,000	$20,000	$35,000
Reduction in fuel consumption — city	4%	4%	40%
Reduction in fuel consumption — highway	22%	22%	6%
Reduction — test cycle	19%	19%	12%
Meets standard?	Yes	Yes	No
Reduction — duty cycle	21%	16%	28%
Meets std. if test cycle = duty cycle?	Yes	No	Yes
Gallons saved, first 3 years	10,968	8,034	9,554
Cost per gallon saved, first 3 years	$1.82	$2.49	$3.66

In this example, the long-haul truck meets the standard at reasonable cost, in particular at substantially less than the cost of fuel saved over the first three years. The same equipment brings the regional-haul truck into compliance with the standards at a cost slightly less than the price of fuel. The short-haul truck falls short of the standard, and the added technology fails to pay back in fuel savings over the first three years.

Clearly the short-haul truck is disadvantaged by being tested over a drive cycle very different from its actual duty cycle. Maintaining the same assumptions, but instead allowing the test cycle for each truck to match its duty cycle with respect to percent city driving, the short-haul truck easily meets the 7.2 mpg standard and the long-haul truck continues to comply, while the regional-haul truck falls just short. The high cost per gallon saved was already computed for Table 2 over the duty cycle, however, so the standard could still be characterized as quite costly for short-haul trucks.

Thus, the strong dependence of fuel economy on duty cycle and disparities in the cost-effectiveness of achieving a given fuel economy compliance over different usage patterns makes it unlikely that a uniform tractor-trailer standard can be devised. The extent to which manufacturer fleet averaging can address this issue is discussed below.

One approach to duty cycle variation would be to classify new trucks based on cab type, given that sleeper cabs are required only for those vehicles that travel long distances. As Table 1 indicates, however, regional trucks, having primary trip length of 100 to 200 miles, tend to have day cabs, even though their driving patterns are more similar to those of long-haul trucks. Thus, cab type is not a reliable basis for classification for fuel economy purposes, even among new trucks.

Performance Requirements

In the example above, we assumed that the long-, regional-, and short-haul trucks have the same horsepower, in order to eliminate one variable potentially affecting fuel economy. However, tractor-trailer horsepower in fact varies with duty cycle and other factors that influence performance requirements. These requirements, which may include, for example, the need to pull heavy loads or the need to perform adequately in mountainous terrain, help to explain the range in fuel economies that these vehicles display. Such requirements need to be considered in the design of a fuel economy standard in order to avoid interference with the truck specification process.

There is no fixed relationship between average fuel consumption and engine rated power.[2] A small engine at appropriate load will tend to consume somewhat less fuel than a larger engine will under that same load, however, all else equal, due to greater friction losses in the larger engine. In addition, the larger engine will typically experience some loss of efficiency due to operating at part load. In real-world operation, all trucks will operate at a range of loads, and the relative efficiency of two engines will depend on the nearness of overall operating conditions to the ranges of high efficiency for the engines.

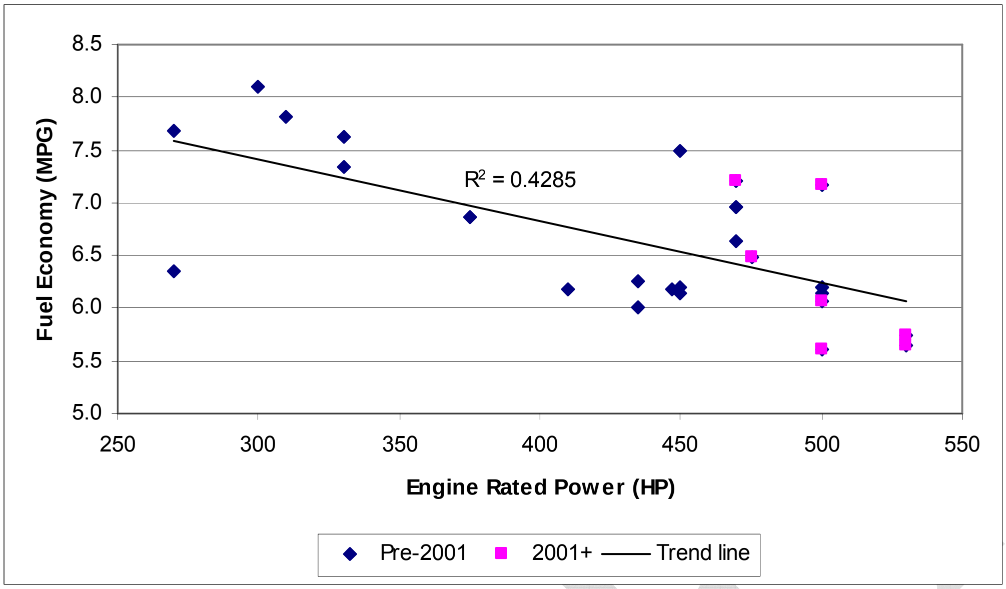
Detroit Diesel's Spec Manager, software designed to help customers specify their trucks appropriately, suggests that any fuel economy/horsepower relationship is not a major consideration. Spec Manager includes three major engine families, collectively ranging from 350 to 560 HP. When these engines are assigned to otherwise identical trucks with air conditioning and full aerodynamic packages and loaded at 80,000 lbs., Spec Manager consistently returns fuel economies between 5.2 and 5.4 miles per gallon in line-haul applications. In fact, within the DDC Series 60, the lower horsepower engines yield lower fuel economy. This counterintuitive result may come about because of the way that engine manufacturers vary performance within a family. Engine size is often constant throughout a family covering a fairly wide horsepower range, with fuel economy variations achieved through changes to the turbocharger and to control algorithms. In this case, engines in the mid-range of horsepower may be the most fuel-efficient (Lowell 2009a).

A more detailed model does show an increase in fuel consumption with a more powerful engine, however. Southwest Research Institute used its RAPTOR vehicle model together with the GT-POWER engine model to calculate that replacing a 500 HP engine with a 600 HP engine in a tractor-trailer would increase fuel consumption by 3.6 to 3.8% over a line-haul cycle (NESCCAF 2009). Given that tractor-trailer engines today range from below 300 HP to 600 HP, fuel consumption therefore might be expected to vary by over 10% due to horsepower differences alone.

Test data supports this relationship. West Virginia University (Clark et al. 2007) tested 27 tractor-trailers on a chassis dynamometer over a number of cycles, including the HHDDTS Cruise Cycle (Clark et al. 2004). These were model year 1990 to 2005 tractor-trailers with electronic fuel injection systems, all at a test weight of 56,000 lbs. Figure 3 plots fuel economy for these trucks against rated power. The trend line fit is not very good (R^2=0.43), but fuel economy of the trucks with rated power less than 400 HP is on average 16% higher than that of the trucks with rated power more than 400 HP.

[2] Rated power is defined as the highest power an engine can deliver in sustained operation.

Figure 3: Tractor-Trailer Fuel Economy vs. Rated Power



Source: Clark et al. (2007)

Thus a uniform miles-per-gallon standard at fixed load is likely to be substantially more difficult for a truck with higher horsepower. While this may be appropriate to the extent that higher horsepower is used for more aggressive driving, it also could interfere with proper truck specification. In addition, a uniform standard would require that all tractor-trailers be tested at the same load, which could lead manufacturers to optimize fuel economy at the test load, rather than at actual operating loads.

Accommodating Tractor-Trailer Diversity

Manufacturer Averaging

The discussion above highlights some of the characteristics of tractor-trailers and their usage that pose an obstacle to a uniform standard. Before considering a more complex standard design, we explore whether allowing manufacturers to average fuel economies across their vehicle production could address those obstacles. Other kinds of flexibility to consider include trading among manufacturers, banking and borrowing of credits, and early action and offsets.

To provide useful flexibility, an averaging scheme should meet some basic criteria:

- *Increases achievable emissions reduction.* Allowing manufacturers to average over their vehicle offerings generally will enable them to meet a standard more stringent than one that can be met by every vehicle they produce.
- *Reduces the cost of compliance.* For a given stringency of the standard, permitting averaging gives manufacturers lower-cost compliance options.
- *Preserves emissions reduction*. Any averaging should be implemented in such a manner as to preserve the emissions reductions provided by the standard. For example, to the extent that averaging occurs across trucks with different average miles driven, the averaging scheme must account for these differences.
- *Treats manufacturers equitably.* Manufacturers must not receive widely disparate benefits from averaging, particularly relative to their direct competitors.
- *Promotes efficiency in all product lines.* There is substantial efficiency gains available for all vehicles subject to the standard, and averaging should not interfere with the realization of those gains.

Real-World Implication of Averaging

To get a sense of whether fuel economy averaging meets the criteria above and makes a uniform standard feasible for tractor-trailers, we consider the impact on real manufacturers. Based on 2002 VIUS data, new Classes 7 and 8 tractor-trailers from the six major manufacturers fall into the three primary trip length categories considered previously, as shown in Table 3. We use the assumptions from Table 2 regarding the properties of long-, regional-, and short-haul trucks. Maintaining also the earlier assumptions regarding the technologies that manufacturers would adopt in response to a 7.2 mpg standard (i.e., aerodynamic improvements for long- and regional-haul trucks and hybridization of short-haul trucks), the effects of the standard on the various manufacturers are as shown in Table 3.

Table 3: Manufacturer Profiles and Impacts of a Tractor-Trailer Standard with Averaging

	Freightliner	International	Kenworth	Mack	Peterbilt	Volvo
Classes 7&8 vehicles, MY 2002–2003	39,481	11,006	7,170	2,896	4,219	13,389
Primary trip length > 200 mi.	94%	74%	93%	39%	84%	70%
Primary trip length 100–200 mi.	2%	11%	3%	25%	2%	12%
Primary trip length < 100 mi.	4%	15%	4%	36%	14%	18%
Base fuel economy (test)	6.0	6.0	6.0	5.9	6.0	5.9
New fuel economy (test)	7.4	7.2	7.4	7.0	7.3	7.2
Average vehicle improvement cost	$20,635	$22,197	$20,631	$25,457	$22,082	$22,674
Average fuel savings (gal.), first 3 years	10,863	10,433	10,821	9,721	10,721	10,363
Cost per gallon saved, first 3 years	$1.90	$2.13	$1.91	$2.62	$2.06	$2.19

2002 VIUS data (first four rows), ACEEE

Despite the substantially different distribution of long-, regional-, and short-haul truck production among the manufacturers, the differences in the impacts of the standard among manufacturers are relatively modest in terms of ability to comply and cost per gallon of fuel saved in the first three years. All but one manufacturer complies with the hypothetical standard (7.2 mpg), and all experience a cost of fuel saved between $1.90 and $2.62 per gallon. Thus averaging could mitigate substantially the disparate impacts of the standard on long- and short-haul trucks.

It should be noted that fuel economy averaging as reflected in Table 3 does not preserve fuel savings, because it assumes in effect that all vehicles travel the same number of miles annually. This is an added obstacle to a uniform tractor-trailer standard: it cannot distinguish vehicles based on miles driven. Hence, if certain technologies to improve the fuel economy of short-haul trucks were less expensive than those for long-haul trucks (which is not the case in the example given above), a manufacturer could offset a fuel economy shortfall in its long haul-trucks by adopting the short-haul efficiency technology, even though this would save roughly half as much energy as would bringing the long-haul trucks up to the standard.

A similar exploration of the results of averaging can be done with respect to the variation in rated power. Table 4 shows market shares of the highest-selling tractor-trailer models, collectively three-quarters of total sales. It also shows these models' standard engines, which range from 310 HP (International MaxxForce 9.3L) to 455 HP (DDC Series 60 14L). We estimate the variation in fuel economy across manufacturers that is attributable solely to differing horsepower mixes.

Based on the discussion in the preceding section, we assume that each 1% increase in horsepower increases fuel consumption by 0.2%, all else constant.[3] The highest manufacturer average fuel economy would then exceed the lowest by 0.4 miles per gallon, or about 6%, as shown in Table 4. This is much reduced from the fuel economy variation of more than 15% that would be expected among individual models based on variation in rated power.

[3] This is about half the association between fuel economy and horsepower/torque found from historical data for light trucks (Knittel 2009). Diesel engines maintain fuel efficiency better at part load than do the gasoline engines used by most light trucks, so the slower decline of fuel economy with horsepower for trucks is expected.

Table 4: Tractor-Trailer Production by Manufacturer and Estimate of Average Fuel Economy Based on Engine Horsepower

Manufacturer	Model	Standard Engine	Est. Fuel Consumption Relative to Average Engine	Market Share (New U.S. Registrations 2003–2007)	Est. Mfr. Average Fuel Economy
Freightliner	Columbia 120	DDC Series 60 14L, 455 hp	2.4%	21.80%	**5.7**
	Columbia CL 112	MBE 4000 12.8L, 450hp	2.2%	1.10%	
	Century CST 120	DDC Series 60 14L, 455 hp	2.4%	7.80%	
	FLD-120SD	DDC Series 60 14L, 455 hp	2.4%	1.20%	
International	9000 series including	Cummins ISM 10.8L, 320hp (9200I)	-4.6%	2.60%	**5.8**
	9200I, 9400I, 9900I	Cummins ISX 14.9L, 425hp (9900I)	1.0%	8.00%	
	8600 Transtar SBA	International MaxxForce 9.3L, 310hp	-5.2%	2.60%	
Volvo	VNL	Volvo D13 12.8L, 335hp	-3.7%	10.70%	**6.0**
Peterbilt	379/389	Caterpillar C-15, 435hp	1.5%	8.80%	**5.7**
Kenworth	W900	Cummins ISX-330E, 330hp	-4.0%	3.10%	**6.0**
	T800	Cummins ISX-330E, 330hp	-4.0%	5.30%	
Mack	CXN 602/603	Mack AC-310/330, 12L, 310/330hp	-4.6%	2.40%	**6.1**

Sources: Lowell (2009), manufacturer Web sites, and Truck Index (2009)

Segmentation

Another way to address application-related variations in tractor-trailer fuel economy is to segment these trucks to reflect such variations. Segments would be defined using one or more parameters that differentiate among tractor-trailers in ways that relate both to fuel economy and to a business necessity. A standard that reduces purchasers' latitude in truck specification is a problem to the extent that it limits the function of the truck, e.g., carrying heavy loads or driving in mountainous terrain. Segmentation should not result in the manufacture or purchase of vehicles that are poorly suited for their duty cycles or are incompatible with the objectives of the standards. For example, standards based on engine displacement or gross vehicle weight could preclude engine downsizing or vehicle weight reduction, respectively, as compliance strategies and are therefore to be avoided. Based on the discussion above, segmentation by both duty cycle and power requirements warrants consideration.

Duty Cycle

Segments are best defined in terms of vehicles' physical properties, since these are easily verified at the point of sale. Unfortunately, duty cycle cannot be reliably captured by physical attributes, even on a new truck. A sleeper cab is a good indicator of long-haul use, at least on a new truck. A day cab may also be used for long-haul trips, however, if drivers are switched out. Furthermore, day cabs are typical for regional-haul trucks, which tend to be high-mileage, high-speed trucks, as well as for short-haul trucks, which travel fewer miles and in stop-and-go cycles, as shown in Table 1.

One approach to addressing this problem is to allow manufacturers to choose between highway and urban test cycles, and the corresponding fuel economy standard, at the time of certification. The manufacturer could in theory make improvements to the truck that allow it to meet the standard over the chosen test cycle but not over the truck's actual duty cycle, undermining fuel savings from the standard.

In this instance, however, that outcome is implausible because the purchaser will not pay for substantial technology improvements that do not yield savings over the truck's actual duty cycle.

Segmentation by duty cycle also allows the assignment of different annual miles traveled to short- and long-haul trucks, which would be necessary to ensure that any averaging preserves fuel savings.

Rated Power and Gross Vehicle Weight Rating

Rated power is a well-defined physical property of a truck, so in that respect is a good basis for segmentation. Dividing engines into two groups by horsepower would serve, at a minimum, to effectively halve disparities among manufacturers based on differing distributions of horsepower among their vehicles. If, as suggested by the standard engines and sales figures listed in Table 4, engines largely fall into two clusters (roughly 310–335 HP and 425–455 HP), dividing them into above- and below-400 HP groups in fact goes much further to eliminate the disparities. Drawbacks of rated horsepower as a segmentation parameter are that it has only an indirect relationship with functionality and that it could promote the trend towards higher horsepower.

A more direct indicator of truck function is rated payload, i.e., the difference between gross vehicle weight rating and curb weight.[4] Trucks could be segmented by either rated payload or, as Japan has done for its heavy-duty truck standards, by gross vehicle weight rating. In the U.S., Class 8 trucks could be subdivided by the EPA weight classifications 8a and 8b, where Class 8a comprises those up to 60,000 lbs. GVW and Class 8b, 60,000 lbs. GVW and over. Using gross vehicle weight has the disadvantage of lessening manufacturers' incentive to reduce (empty) vehicle weight, however. Because both tractor and trailer offer substantial opportunities for weight reduction, undermining weight reduction as a strategy to save fuel is ill-advised.[5]

Whether gross vehicle weight rating or rated payload is used, a system like Japan's, which divides tractor-trailers into two weight classes, is worth considering. Japan's program requires tractors weighing 20 tons (44,000 lbs.) or less to achieve 3.09 km/liter (7.3 miles per gallon) over a test cycle that is 20% highway driving and 80% on JE05, Japan's emissions test cycle. Those over 20 tons must achieve 2.01 km/liter (4.7 miles per gallon) over a test cycle that is 10% highway driving and 90% on JE05 (Tokimatsu 2007). The tractor-trailers are tested at half-load: the lighter ones are tested at 22,580 kg (49,780 lbs.), and the heavier ones at 39,083kg (86,162 lbs.) (Tanishita 2009).

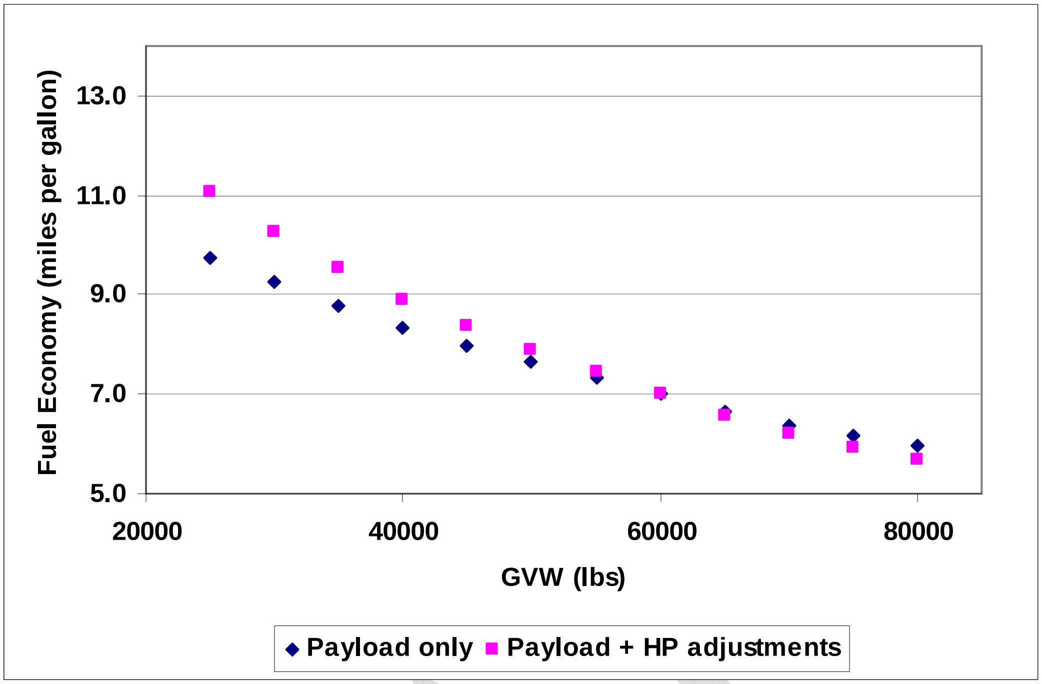
Dividing tractor-trailers into two weight classes has the benefit of allowing testing at appropriate payloads. That is, Class 8b would be tested at a payload higher than the test payload for Class 8a, better capturing typical operating weights of the vehicles.

In order to assess the potential benefit of segmenting trucks by a weight parameter, we consider the dependence of fuel consumption on weight. The Road-Load Equation (see the Appendix) shows the contribution of weight (or inertial load), wind drag, and rolling resistance to the total load on an over-the-road truck at any given moment. Applying the Road-Load Equation over an entire drive cycle gives the contribution of inertial load to total load, which in turn shows how fuel consumption varies with weight. Taking as reference point a 60,000-lb. tractor-trailer achieving 7 MPG over the HHDDTS Cruise Cycle, fuel economies at other weights are shown in Figure 4.

[4] Manufacturers' specification of gross vehicle weight may introduce an element of subjectivity to this parameter.

[5] According to the 2002 VIUS, 88% of new, Classes 7 and 8 tractor-trailers with van-type trailer have average gross weight in the 60,000 to 80,000 lb. range. The small percentage under 60,000 lbs. calls into question the utility of dividing these trucks into above-60,000 lb. and below-60,000 lb. weight classes. VIUS data also imply that 78% of Class 7 tractor-trailers operate at average weights exceeding 60,000 lbs. GVW. Given that Class 7 trucks are only rated up to 33,000 lbs., this result is puzzling.

Figure 4: Weight-Dependence of Fuel Economy — CARB HHDDTS Cruise Cycle



These calculations show the effect of weight on fuel economy, all else equal. In reality, a truck that typically carries a high payload is likely to have a high horsepower engine, further affecting fuel economy. Using the maximum total load over the HHDDTS Cruise Cycle to scale engine rated power, and assuming the same relationship between rated horsepower and fuel consumption used earlier (1% increase in rated horsepower increases average fuel consumption by 0.2%), we arrive at a second estimate of fuel economy as a function of gross vehicle weight rating, also shown in Figure 4.

Taking 40,000 lbs. and 70,000 lbs. as representative of Classes 8a and 8b (below 60,000 lbs. and 60,000 lbs. and above), respectively, this leads to an estimate that the fuel economy of the higher GVW truck, with horsepower adjustment, would be 30% lower than the fuel economy of the lighter class, with nearly three-quarters of the reduction due to the increased weight and the remainder to the higher horsepower.

The difference between these two fuel economies is substantial. This may raise concerns that vehicles close to 60,000 lbs. GVW would be pushed over to the heavier class to be eligible for a less exacting fuel economy standard. However, given that a heavier vehicle would be tested with a greater payload, which accounts for the majority of the difference in fuel economy between the two classes, the incentive to push lighter vehicles into the heavier weight class would be minimal.

Japan's program addresses both weight and duty cycle distinctions between its two segments by using different percentages of urban and highway miles in the test cycle for the two weight classes. Absent evidence that the attributes of weight and duty cycle correlate well among U.S. tractor-trailers, however, four bins would be required to implement the two segmentation proposals made here.

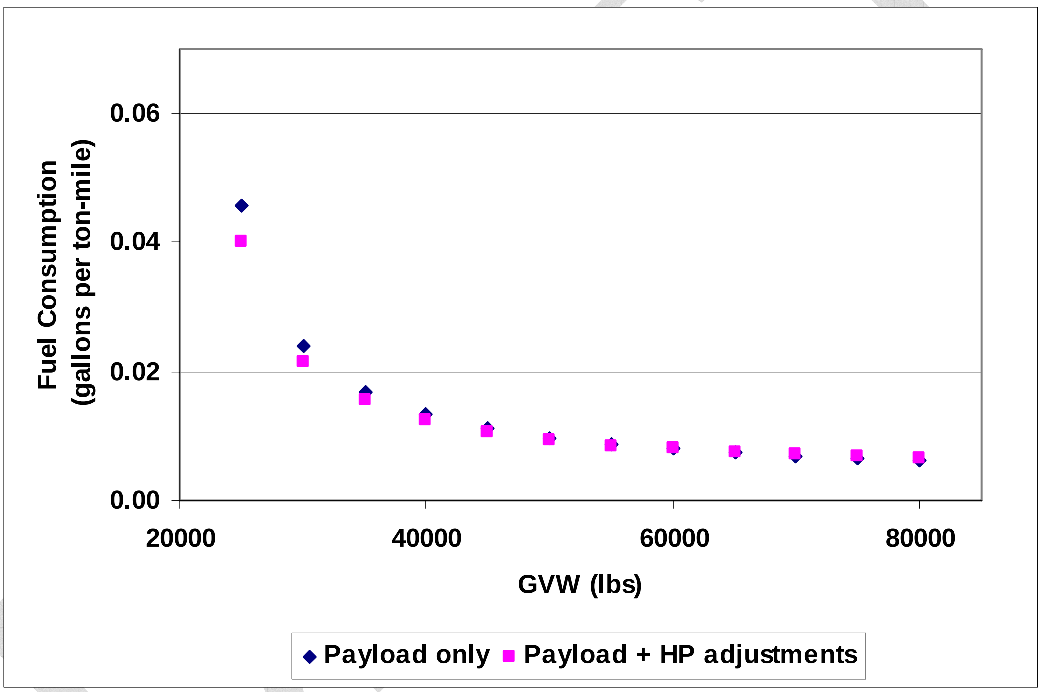
It should be noted that segmentation is unlikely to eliminate the need for averaging. Well-chosen segments will reduce the disparities among vehicle types and among manufacturers with regard to how costly it is to meet the standard, but no manageable segmentation scheme can treat every truck fairly in this regard. Allowing manufacturers to average fuel economies across their products within segments would increase the flexibility of the standard.

Metrics and Functional Form

The discussion of fuel economy to this point has been in terms of miles per gallon. Defining standards using other metrics such as gallons per ton-mile or gallons per cube-mile may be preferable, given the freight-hauling function of the vehicle. A gallon-per-ton-mile standard, for example, would promote weight reduction by allowing trucks to improve performance by increasing payload while keeping fuel consumption constant. A gallon-per-ton-mile standard could also permit each truck subject to a given standard to be tested at an appropriate load. Thus it is worth considering whether the use of other metrics could better address the difficulties of a miles-per-gallon standard.

Using a gallon-per-ton-mile metric converts the fuel economy-weight relationship shown in Figure 4 into the relationship shown in Figure 5. The heavier vehicle does better than the lighter vehicle in this metric. In this case, the horsepower adjustment serves to reduce slightly the performance differential between heavier and lighter vehicles, but the heavier vehicle nonetheless uses 43% less fuel per ton-mile. Hence the variation of fuel consumption with weight persists under a gallon-per-ton-mile metric.

Figure 5: Weight-Dependence of Gallons per Ton-Mile — CARB HHDDTS Cruise Cycle



This discussion indicates that switching to a gallons per-ton-mile metric will not eliminate the difficulties associated with a uniform standard for line-haul tractor-trailers. However, a fuel economy or consumption standard could perhaps be expressed as a simple and continuous function of some parameter, such as payload, for example, as the relationships shown in Figures 4 and 5 suggest. This approach could eliminate the discontinuity and imprecision associated with a segmentation approach as described above.

Conclusions and Recommendations

The fuel economy of tractor-trailers with van-type trailers varies substantially with both duty cycle and performance-related specifications. This variation poses an obstacle to setting a uniform fuel economy standard that is both appropriately stringent and sensitive to the diversity of tractor-trailers. Allowing manufacturers to average fuel economy across their products mitigates the problem to a degree, but functional differences among manufacturers' products may be large enough to raise equity concerns.

- Up-to-date data on the properties and use of new trucks should be gathered to determine whether variations in products across manufacturers are large enough to preclude a uniform tractor-trailer standard, even when averaging is allowed.

Although short-haul tractor-trailers are a small percentage of the new tractor-trailer market, applying the same standard to them as to regional- and long-haul tractor-trailers could make compliance substantially more difficult and costly for some manufacturers. While distinguishing short-haul trucks from regional-haul trucks by physical attributes may not be practical, manufacturers could perhaps be relied upon to classify their own trucks, by virtue of the efficiency technologies they choose to employ to meet the fuel economy standards.

- Separate test cycles should be developed for line-haul vehicles and short-haul vehicles, and regulators should consider allowing manufacturers to choose the test cycle on which a given truck would be certified.

Variations in performance requirements for tractor-trailers, and their effects on fuel economy, also appear sufficient to warrant further segmentation.

- Tractor-trailers should be separated into at least two segments by performance-related criteria, e.g., above and below 400 HP or above and below 60,000 lbs. gross vehicle weight, with a fixed test weight for each segment.

The regulatory challenges associated with the functional diversity of tractor-trailers could also be addressed through an attribute-based standard, rather than by discrete segmentation.

- Regulators should consider defining a miles-per-gallon or gallons-per-ton-mile standard as a function of gross vehicle weight rating, where vehicles are tested at a fixed percentage of rated weight.

Failure to address the variation in tractor-trailer fuel economy, at either the individual truck or the manufacturer average level, could compromise the stringency of the standard. It is therefore important to pursue alternatives to a uniform standard.

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Appendix: The Road-Load Equation and Truck Operating Weight

Total power needed at the wheels at a given time t is expressed by the road-load equation (Khan 2009) applied to a highway vehicle as:

$P_t = mv(dv/dt) + 0.5\, C_D \rho A v^3 + \mu mgv + mgvZ$

where, m is mass of the vehicle, v is its speed, A is frontal area, g is acceleration due to gravity, C_D is aerodynamic drag coefficient, μ is tire rolling resistance coefficient, ρ is air density, and Z is road gradient (%). P_t is the total power needed at the wheels and is expressed in kilowatts (kW). In this equation the first term is referred to as the Inertia Load, the second term as the Wind Drag, the third term as the Rolling Resistance, and the last term as the Grade Load. The sum of these loads is the "total load" or total power demand.

We apply the Road-Load Equation, with road grade set to zero, to a Class 8 tractor-trailer over EPA's Highway Fuel Economy Test (HWFET) Cycle, shown in Figure 6.

Figure 6: Speed-Time Trace of CARB HHDDTS Cruise Cycle

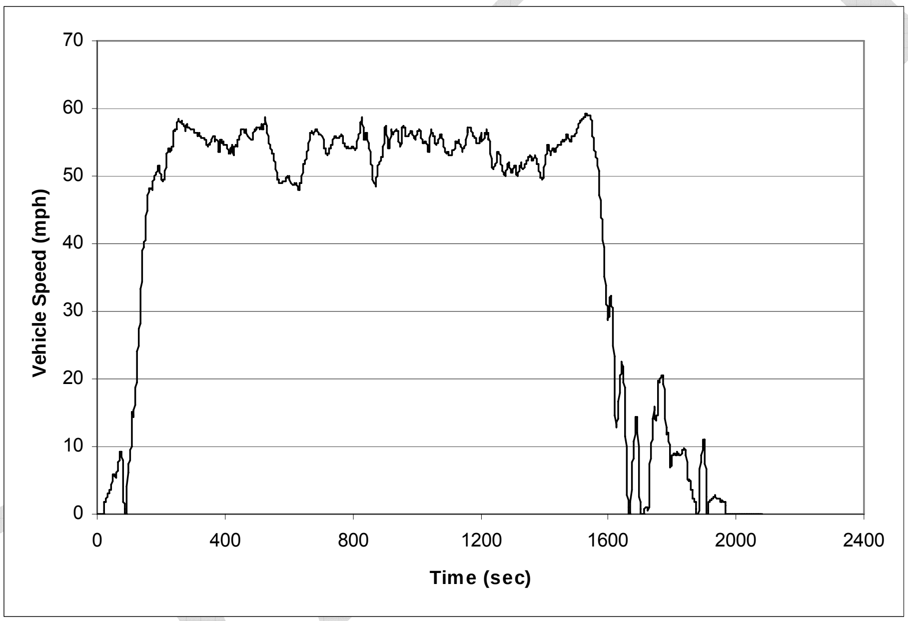

Figure 7 shows aerodynamic drag, rolling resistance, inertia, and total load over the CARB HHDDTS Cruise Cycle for a truck at 80,000 lbs.

Figure 7: Load Variation for 80,000 lbs. Test Weight over CARB HHDDTS Cruise Cycle — First 400 Seconds

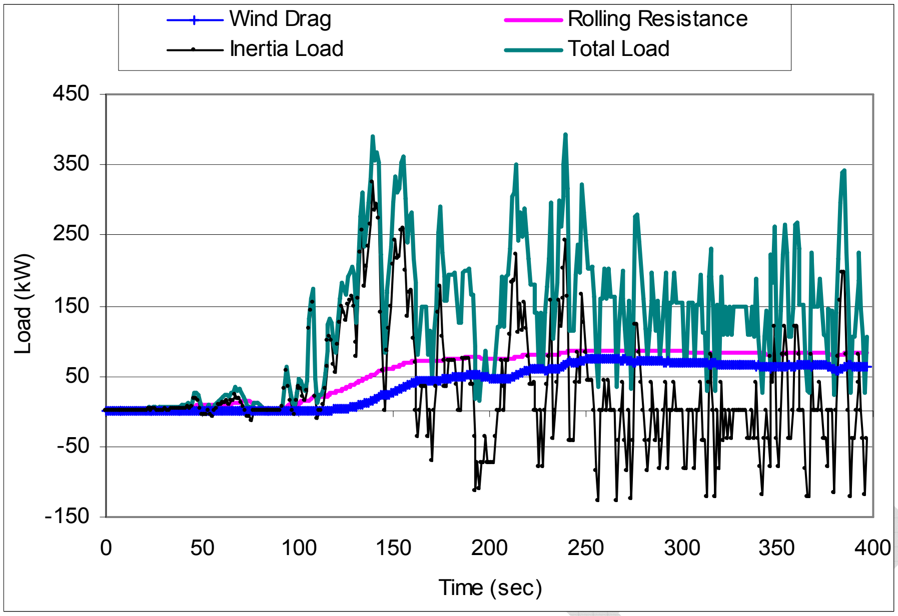

Figure 7 illustrates the fact that total load over the cycle is dominated by inertia load, followed by rolling resistance and aerodynamic load. Note that, over the Cruise Cycle, the truck operates about 96% of the time below 300 kW (about 400 HP) and 87% of the time below 215 kW (280 HP).

Next we consider truck operation at three test weights: 33,000, 50,000, and 80,000 lbs weight. Figure 8 shows how total load and rolling resistance vary with operating weight.

Figure 8: Difference in Total Load for Three Operating Weights on CARB HHDDTS Cruise Cycle — First 400 Seconds