International Alignment of Fuel Efficiency Standards for Heavy-Duty Vehicles

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Contents

Executive Summary

Several regions with large vehicle markets are developing regulatory programs to reduce the fuel consumption and greenhouse gas (GHG) emissions of heavy-duty vehicles. At the same time, manufacturers increasingly are developing global product platforms for the heavy-duty market. This offers an opportunity to accelerate the development and adoption of fuel efficiency technologies. Regulators can facilitate this outcome by coordinating the design of fuel efficiency and GHG emissions reduction programs across regions.

This report compares key features of the heavy-duty fuel efficiency and GHG regulatory programs in place or under development and explores the prospects for aligning them. Table ES-1 summarizes key features of these programs.

Table ES-1. Heavy-Duty Fuel Consumption and/or Greenhouse Gas Emissions Standards by Region

Feature	Japan	U.S.	China	EU
Regulation Timing	Adopted in 2006, effective starting 2015	Adopted in 2011, effective from 2014	Final rule expected in 2013, program to start in 2014	Development and testing of certification procedure
Metric/ Units	Kilometers per liter	Grams CO_2 per payload ton-mile and gallons per 1,000 payload ton-miles (short tons)	Liters per 100 kilometers	NA
Test Cycles	JE05 (transient) and Interurban Mode (80 kph with road grade)	HHDDTS Transient Cycle and 55-mph and 65-mph steady-state cruise cycles	Modified UN World-wide Transient Vehicle (WTVC) Cycle	Multiple mission-based cycles
Cycle Weighting (Tractor-Trailer)	90% JE05 and 10% Interurban Mode for tractor-trailers exceeding 20 tons GVW	5% Transient, 9% 55 mph, and 86% 65 mph for tractor with sleeper cab	10% rural and 90% highways for semi-trailer towing > 25 tons	No weighting necessary for mission-based cycles
Target Fuel Efficiency (Tractor-Trailer)	2.01 km/l by 2015	7.3 gal/1,000 ton-miles by 2014 (short tons)	47 l/100 km (2.13 km/l) by 2014	3.86 km/l deemed cost-effective for long-haul
Test Method	Simulation using engine fuel consumption map and transmission properties; standard trailer	Simulation; standard engine, transmission; standard trailer depending on cab roof height	Basic vehicle is chassis tested; simulation or chassis testing for vehicle variants	Simulation based on actual vehicle values; standard trailer depending on intended use

In February 2013, Canada adopted a heavy-duty vehicle GHG emissions program very similar to the U.S. program. Mexico is considering a similar step, which would result in a very high degree of program alignment across North America. Aside from these examples, however, regulatory programs across the U.S., the EU, and Asia are widely divergent, as shown in Table ES-1 above.

One consequence of the differences among the regulatory programs is that they may drive different fuel efficiency technologies. For example, the basic test protocol for the U.S. does not capture transmission performance, while Japan's program does not capture tire performance. As a result, the programs do little to promote optimal specification or fuel efficiency improvements in those components. In some cases, such features reflect the differing benefits of the various fuel efficiency technologies across countries. Often, however, the fuel efficiency technologies in question would yield benefits in all regions. In such cases, better alignment of regulatory programs could help to spread those technologies.

Aligning programs across regions has potential benefits in terms of both fuel savings and the cost of complying with fuel efficiency regulations. Expanding the market for efficiency technologies spreads development costs over a larger sales base and helps to achieve economies of scale, expediting the adoption of these technologies. Increased alignment could also reduce manufacturer costs by allowing coordinated technological approaches to fuel efficiency improvement and by providing consistent testing protocols across regions.

Based on our assessment, we conclude that foundational steps toward alignment of heavy-duty fuel efficiency and GHG emissions programs would include a common set of test cycles and test payload weights. These elements would serve to define universal measures of vehicle performance, which would permit a standardized calculation of cost-effectiveness of technology improvements as a function of regional conditions. They would also allow comparison of vehicles in a range of driving conditions, and in particular would allow buyers to estimate performance over their own duty cycles. Aligning test methods as well would reduce manufacturer compliance costs, and thus strengthen support for the program. These basic steps regarding testing protocols should precede consideration of alignment of other regulatory elements.

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All remaining errors in the report are the sole responsibility of the authors.

I. Introduction

Japan, the United States, and Canada have adopted standards to reduce GHG emissions and/or raise the fuel efficiency of heavy-duty vehicles,[1] and other countries and regions are on their way to doing the same. These regulatory programs have similar aims and share a number of features. There is also overlap in the vehicle models regulated, and the overlap is likely to grow rapidly in the coming years with increasing globalization of vehicle platforms and components. Yet the differences in the programs are fundamental. This report explores whether and how heavy-duty standards programs could be better aligned across regions.

MOTIVATION FOR ALIGNMENT

The motivation for aligning vehicle standards is two-fold: (1) to expedite and maximize total fuel savings and emissions reductions; and (2) to reduce manufacturers' cost of compliance with the standards. The means by which these goals could be advanced through alignment include:

- Expediting and maximizing fuel efficiency improvements
    - Accelerates development and increases sales of advanced technologies
    - Ensures all promising efficiency technologies and designs are considered for inclusion in increasingly global platforms
    - Facilitates adoption of standards by additional regions
    - Improves vehicle efficiency in regions without standards
    - Promotes technology tailored to users' duty cycles
    - Allows greater stringency of standards
- Minimizing costs
    - Reduces cost of technology development and facilitates globalization of vehicle platforms
    - Minimizes amount and cost of testing needed
    - Permits consolidation of compliance efforts across regions
    - Reduces cost to new regulators relative to developing a program from scratch

Research and development resources for heavy-duty vehicles are limited, and manufacturers seek to expand the sales base over which they can spread such investment. The dynamics of increasing sales base are changing due to dramatic changes in the international vehicle market. Recent commercial vehicle production by region is shown in Figure 1. With China and other rapidly developing countries leading sales growth, global platforms can no longer be designed to the requisites of the historically largest markets (Fleet Owner 2012).

It is worth noting that alignment does not aim to limit the range of available vehicles. Alignment of programs generally will not expand the population of vehicles for which a given technology improves

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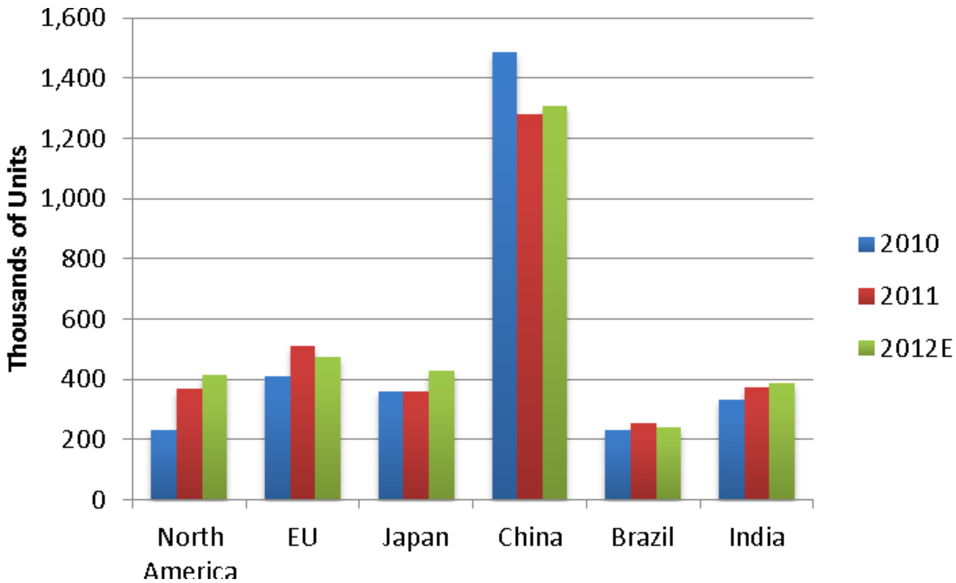
[1] This report is about improving the fuel efficiency of heavy-duty vehicles. Because improving fuel efficiency is at present the primary GHG emissions reduction strategy for vehicles, we treat fuel efficiency and GHG reduction programs largely interchangeably. GHG programs include important non-efficiency considerations, however, including use of alternative fuels and reduction of non-combustion GHG emissions. These are not discussed in this report.

fuel efficiency; that population is determined by the vehicle application. Alignment can, however, help to identify the entire population of vehicles for which the technology provides a benefit.

Figure 1. Heavy Heavy-Duty Vehicle Production, 2010-2012 (Estimated)



Data Source: Baird (2012)

Example: Increased Emissions Reductions

As a concrete (though hypothetical) example of how alignment of programs could allow greater stringency of standards, we consider the treatment of advanced tractor aerodynamics in the U.S. heavy-duty fuel efficiency and greenhouse gas rule (EPA and NHTSA 2011a). The agencies define five increasingly aerodynamic "bins" for tractor trucks, with coefficients of drag (C_d) as shown in Table 1 for the case of high roof sleeper cabs. Also shown is the agencies' assessment of the achievable application rate of the five bins in 2014, leading to an average C_d of 0.59 for such trucks. This is part of the agencies' technological basis for the stringency of the standards for tractors with high roof sleeper cabs in 2014. The rule anticipates no further improvements to aerodynamics through 2017.

At the same time, the rule predicts that technology costs generally will decline with the manufacturer "learning" associated with increasing sales volumes. In particular, the agencies assume that costs of emerging technologies, including advanced tractor aerodynamics, will decline by 20% with each doubling of sales, or every two years (EPA & NHTSA 2011b). If heavy-duty standards programs were aligned across regions so that EPA's and NHTSA's estimates of fuel efficiency gains due to aerodynamic improvements over certain test cycles were considered relevant in some of the other vehicle markets shown in Figure 1, then it is plausible that sales could double twice by 2017, bringing costs down by 36%. Such cost reductions would bring the cost of Bin V aerodynamic improvements below the current cost of Bin IV, while Bin IV would drop to only 10% more than today's Bin III, shifting the distribution of aerodynamic improvements purchased toward the higher bins.[2] As shown in Table 1, the likely result would be a drop in average C_d to 0.53, sufficient to justify an additional 5% reduction in the tractor-trailer GHG emissions standard for 2017, according to the relationship between C_d and CO_2 shown in the rule (EPA & NHTSA 2011b). Other emerging technologies such as hybridization could also be factored into the level of fuel efficiency standards if the relevant vehicle and battery markets were expanded, which program alignment could help to accomplish.

Table 1. Reduction in Coefficient of Drag with Increase in Sales Volume

Bin	C_d	Application rate 2014	Cost 2014	Cost after two doubling cycles	Application rate (hypothetical)
I	0.75	0%	$0	$0	0%
II	0.68	10%	$0	$0	10%
III	0.6	70%	$1,560	$998	0%
IV	0.52	20%	$2,675	$1,712	70%
V	0.47	0%	$3,769	$2,261	20%
		Average C_d w/ 2014 application rates: 0.59			Average C_d w/hypothetical application rates: 0.53

MEANING OF ALIGNMENT

For purposes of this report, alignment of programs is the adoption of similar program features in multiple regions. The nature and extent of any such alignment is yet to be determined. Both European programs for vehicle emissions and U.S. light-duty fuel economy rules have been adopted largely intact by other countries. Given how greatly the heavy-duty vehicle population differs from region to region, in both specification and application, such close alignment of heavy-duty GHG programs may not be feasible in general. Nonetheless, alignment of a more limited scope could provide substantial benefits.

In any case, this is the time to consider alignment opportunities because heavy-duty standards are in the fairly early stages globally and are still subject to structural change. This would contrast with the experience of light-duty vehicles, where fuel economy and greenhouse gas standards regimes have grown in several regions independently. As a result, light-duty standards structure, test cycles, stringencies, and flexibilities are all quite different from region to region.

[2] This example has the advantage of drawing directly from the U.S. heavy-duty rule. It does, however, have the drawback that the particular improvement considered comes not from a freestanding new technology but rather from a suite of design improvements associated with the redesign of a tractor cab. Such changes may be governed more by market acceptance than by cost. Moreover, cab redesign at present typically occurs only once every 15 to 20 years.

II. Heavy-Duty Fuel Efficiency and Greenhouse Gas Regulatory Programs in Place or Under Development

Throughout this report, we will cite the experiences of four regions: Japan, the U.S., China and the European Union (EU). Japan and the U.S. have adopted standards, and China proposed a program in 2012. In the EU, a preliminary certification procedure has been developed, and some parties anticipate an effort to have a regulatory program in place by 2020 (TU Graz 2011; Schuckert 2011). Salient features of the four programs, focusing on their application to heavy tractor trucks, are shown in Table 2.

Table 2. Heavy-Duty Fuel Consumption and/or Greenhouse Gas Emissions Standards by Region

Feature	Japan	U.S.	China	EU
Regulation Timing	Adopted in 2006, effective starting 2015 (Daisho 2007)	Adopted in 2011, effective from 2014, early compliance allowed in 2013 (EPA and NHTSA 2011a)	Proposed in 2012. Program to start in 2014 (AQSIQ 2012)	Development and testing of certification procedure underway
Metric/Units	Kilometers per liter	Grams CO_2 per payload ton-mile and gallons per 1,000 payload ton-miles (short tons)	Liters per 100 kilometers	NA
Reference Fuel Efficiency Level (Tractor-Trailer)	Average for 2002 tractor-trailer with GVW > 20 tons[3] was 1.8 km/l (Daisho 2007)	Average for Class 8 sleeper cab high roof tractor-trailer in 2010 was 9.3 gal/1000 ton-miles (short tons) (2.4 km/l) (EPA and NHTSA 2011a)	1.2, 1.6, and 2.4 km/l for a 49 ton GCW tractor-trailer tested on City, Rural, and Motorway segments (CATARC 2010a)	Average of 3.27 km/l for all long-haul trucks in 2010 (TU Graz 2011)
Target Fuel Efficiency (Tractor-Trailer)	2.01 km/l by 2015 (Daisho 2007) for GVW>20 tons	7.3 gal/1,000 ton-miles (3.06 km/l) by 2014 (short tons) for Class 8 w/ sleeper cab and high roof	42 l/100 km (2.38 km/l) by 2014 for 40-43 tons GCW (AQSIQ 2012)	3.86 km/l found to be cost-effective for long-haul (AEA 2011)

[3] Unless otherwise indicated, "ton" refers to metric ton throughout.

Feature	Japan	U.S.	China	EU
Test Cycles	JE05 (transient) and Interurban Mode (steady state cycle with 80 kph speed and road grade from -5% to +5%)	HHDDTS Transient Cycle and 55-mph and 65-mph steady-state cruise cycles	UN World-wide Transient Vehicle Cycle, modified to match driving patterns in China (CATARC 2010b)	Multiple mission-based cycles; may include road grade, altitude, stops (TU Graz 2011)
Cycle Weighting (Tractor-Trailer)	90% JE05 and 10% Interurban Mode for GVW > 20 tons	Transient 5%, 55-mph cruise 9% and 65-mph cruise 86% for sleeper cab	Road (rural) 10% and highways 90% for semi-trailer towing more than 25 tons	No weighting necessary for mission-based cycles
Test Payload (Tractor-Trailer)	20 tons (half of maximum allowed payload)	19 short tons (17.2 tons)	Maximum allowed payload	Certification testing to be at average payload (TU Graz 2011)
Test Method	Simulation, using engine fuel consumption map and transmission specs; standard trailer	Simulation; standard engine, transmission; standard trailer depending on cab roof height	Chassis testing for basic vehicle; choice of simulation or chassis testing for variants (CATARC 2010b)	Simulation based on actual vehicle values; standard trailer depending on intended use (TU Graz 2011)
Treatment of Aerodynamics and Rolling Resistance	Standard values for C_d and C_{rr}, depending on vehicle category (Daisho 2007)	Manufacturer testing to determine C_d (coastdown preferred); C_{rr} for the steer and drive tire determined per ISO 28580	Manufacturer testing to determine tractive load (coastdown preferred); otherwise standard value used for C_d and standard formula used for C_{rr}	Manufacturer testing to determine C_d (constant speed test preferred); C_{rr} values from tire labels as specified by EC directive No 1222/2009 (TU Graz 2011)
Regulating Agency	Ministry of Economy, Trade and Industry (METI)	National Highway Traffic Safety Administration (NHTSA) for fuel efficiency; Environmental Protection Agency (EPA) for GHG emissions	Ministry of Industry and Information Technology (MIIT)	NA

In February 2013, Canada adopted heavy-duty GHG emissions standards essentially the same as the U.S. heavy-duty GHG standards (Canada Gazette 2012). The point of regulation in Canada will typically be the importer, rather than the manufacturer, however, since most heavy-duty vehicles purchased there are imported. This may lead to compliance strategies that differ from those that will be used in the U.S.

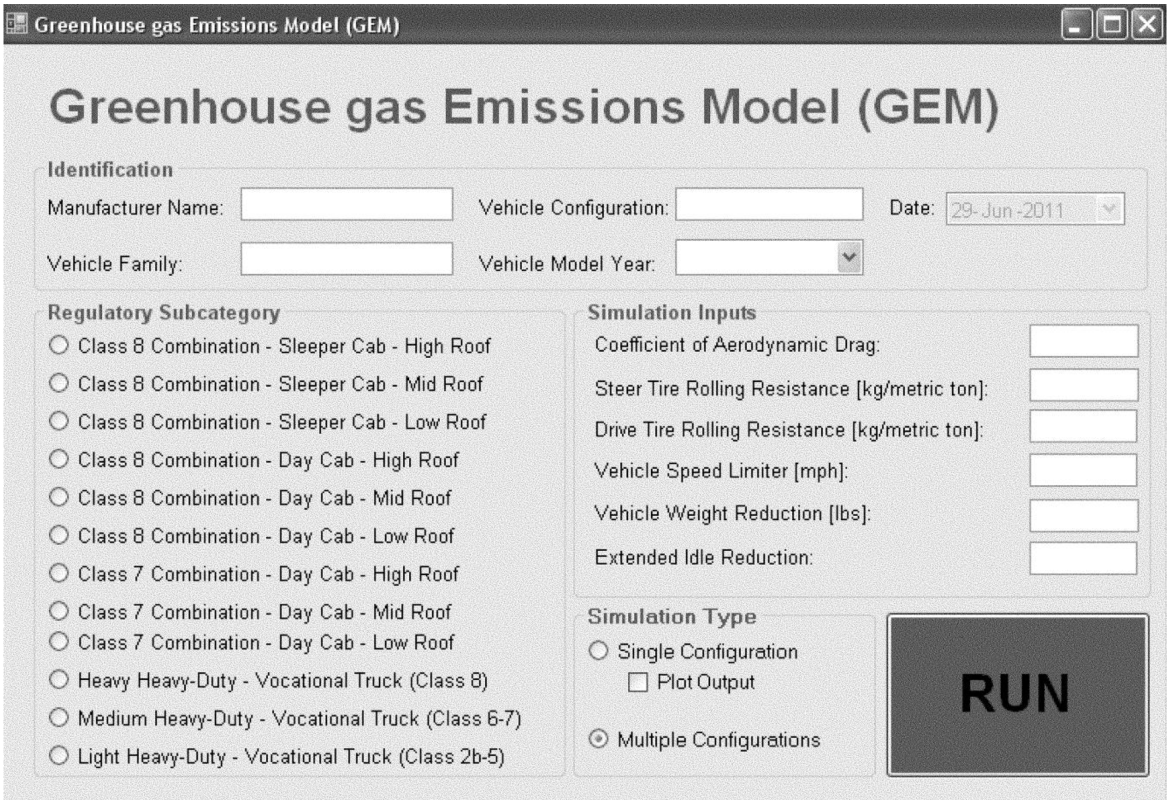
Mexico is developing heavy-duty fuel efficiency standards as well. Ultra-low sulfur diesel and advanced emissions technologies would need to be readily available for Mexico to adopt the same standards as those adopted in the U.S. and Canada, since engine efficiency improvements rely on these technologies. In addition, data on highway driving speeds will be required to determine whether a similar levels of investment in aerodynamic equipment is warranted in Mexico as in the U.S. and Canada. On the whole, however, the long distances covered by over-the-road trucks in the three countries suggest important similarities in driving patterns. This, together with the fact that the same manufacturers produce the vehicles for all three markets, indicate that North America presents an opportunity for a high degree of program alignment.

Vehicle Certification Process

In order to introduce key elements of heavy-duty standards that need to be considered in exploring alignment options, we compare here the steps required to test and certify a tractor truck in various regions, with emphasis on Japan and the U.S. For this purpose we consider a Class 8 (GVW>33,000 lbs., or 14,969 kg) tractor truck with a high roof and a day cab. Under the U.S. program, this is assumed to be a regional-haul truck that will pull a van trailer. In Japan, this vehicle is simply a tractor truck over 20 tons GVWR.

The fuel efficiency test protocols for heavy-duty vehicles in Japan and the U.S. are based on vehicle simulation; neither requires physical testing of the vehicle. The U.S. program will use the EPA's Greenhouse Gas Emissions Model (GEM) (EPA 2011). While in theory GEM accepts a large number of vehicle-specific inputs, including engine fuel consumption map, mechanical attributes, control algorithms, and driver inputs, the majority of the inputs to GEM for purposes of vehicle certification in the current program are default values provided by the regulating agencies (EPA and NHTSA 2011a). The manufacturer will provide only vehicle type and model year, coefficients of drag and rolling resistance, and existence or non-existence of specific weight-reducing components, idle reduction system, and vehicle speed-limiting system, as shown in Figure 2. GEM will calculate CO_2 emissions and fuel consumption over three test cycles: the Heavy Heavy-Duty Diesel Truck Schedule (HHDDTS) Transient Cycle (see Figure), and 55-mph and 65-mph steady-state cruise cycles. To determine overall CO_2 emissions and fuel efficiency, the model applies weightings of 19%, 17%, and 64% (in the case of a tractor truck with day cab) to the results for the three cycles (EPA and NHTSA 2011a, 2011b).

Figure 2. GEM Graphical User Interface

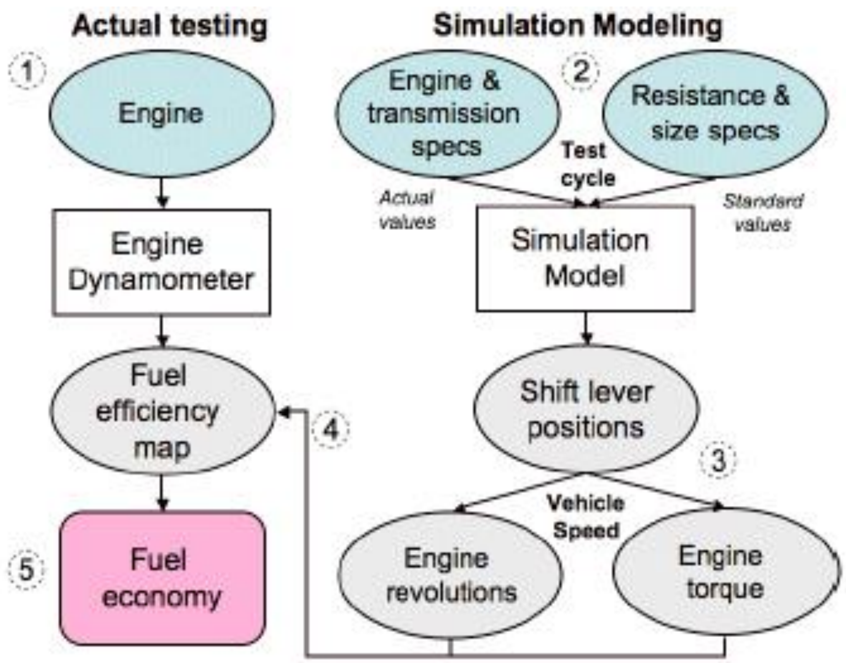


Source: EPA and NHTSA (2011a)

Notably absent from manufacturer inputs to GEM are engine specifications, which in fact do not enter into vehicle certification in the U.S. Engines are subject to separate fuel efficiency and GHG emissions standards. The engine sold in a given vehicle has no bearing on the emissions and fuel efficiency levels to which that vehicle is certified. Fuel consumption and emissions of all Class 8 tractor trucks will be simulated using the fuel map of a fixed, 15 liter, 455 horsepower engine (EPA and NHTSA 2011a). The simulation also uses predefined transmission features, rather than those of the vehicle's actual transmission, and a standard trailer, though the trailer type assumed depends on cab roof height.

In Japan, the test protocol involves translating the prescribed vehicle test cycle into an engine cycle using actual engine specifications together with transmissions specifications representing the manufacturer's "average" transmission in the relevant category (ICCT 2008). The requisite engine specifications include full load torque, idle speed, maximum output speed, and maximum speed with load. Transmission properties used include number of gears, gear ratios, final reduction gear ratio, and shift lever positions. Actual vehicle curb weight is also a required input, and payload is fixed at 20 tons (half maximum payload for a tractor over 20 tons GVW). The conversion to engine cycle uses standard (i.e., not vehicle-specific) driving resistance parameters, including aerodynamic drag coefficient, frontal area, and rolling resistance coefficient (Daisho 2007; Hirai 2011). The manufacturer also must provide an engine fuel map, which permits the calculation of fuel consumption over the constructed engine cycle and therefore over the vehicle test cycle. The test cycle includes a transient portion (JE05) and a constant-speed highway portion (Interurban Mode), weighted 90% and 10%, respectively, for a tractor truck over 20 tons. The vehicle fuel economy simulation from the Japanese rule is shown schematically in Figure 3.

Figure 3. Japan's Heavy-Duty Vehicle Testing Protocol



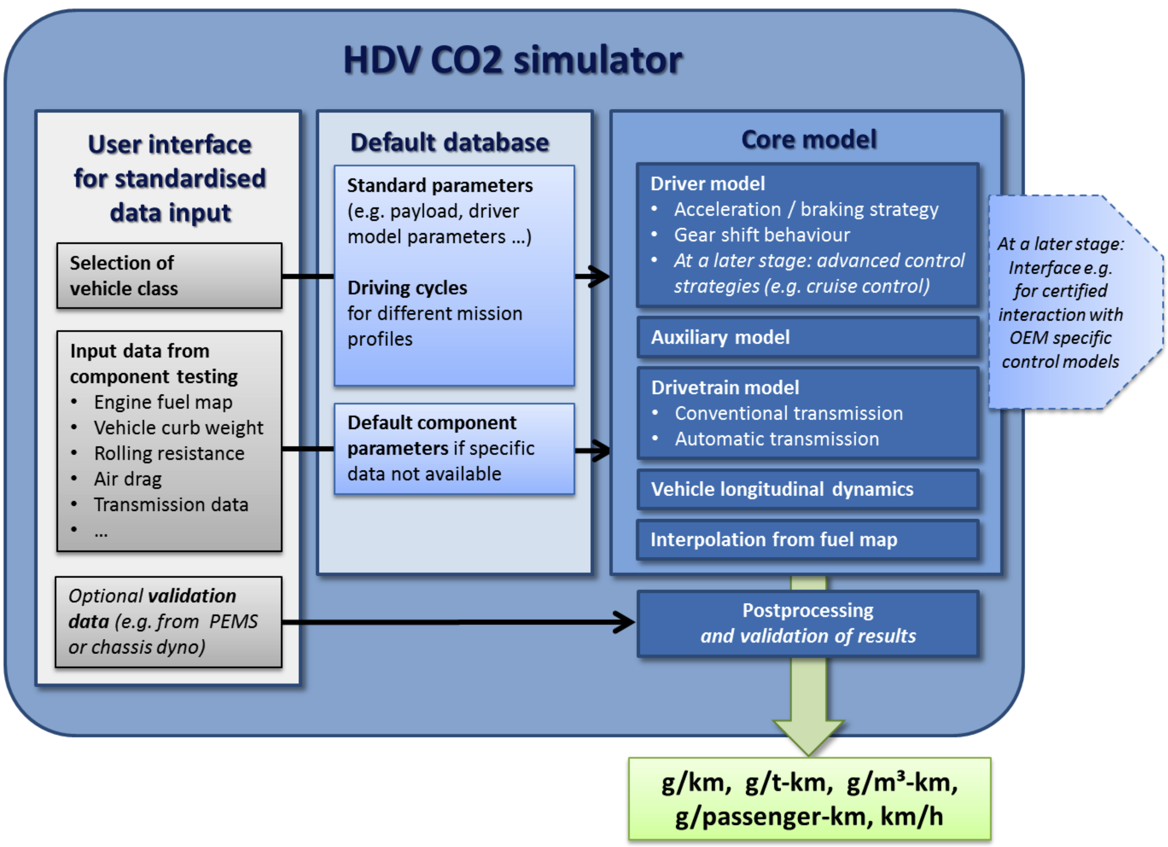
Source: ICCT 2008

Hence Japan's vehicle simulation protocol captures engine and, to a limited extent, transmission features that the U.S. protocol does not. On the other hand, certain vehicle-specific inputs required for the U.S. model are not accounted for in Japan's protocol. These include coefficients of drag and rolling resistance for the tractor and existence of speed limiter, weight reduction, and anti-idle technology. U.S. manufacturers must conduct testing or modeling to determine the vehicle's C_d, and either vehicle or tire manufacturer must test for tire C_{rr}. Neither program can capture the properties of the actual trailer(s) used with the tractor, although the U.S. program assigns a trailer type based on cab features. Both programs assume standard trailers for simulation purposes.

Unlike the programs in Japan and the U.S., China's proposed program requires chassis dynamometer testing. The manufacturer would test the vehicle over a modified version of the World Transient Vehicle Cycle (WTVC; see Appendix A), consisting of 10% rural driving and 90% highway driving. It should be noted that the tractor would not likely come equipped with the same engine in China as in Japan or the U.S., because typical rated power of engines used in those countries is above the top of the horsepower range for engines currently employed in China (ICCT 2011). The chassis test results automatically reflect the performance of certain vehicle components and systems that, in the simulation-based programs of Japan and the U.S., must be input separately. In particular, engine and transmission properties will be reflected by the chassis test results. However, information related to tractive load, such as drag and rolling resistance coefficients, will still be needed as inputs to the chassis test in order to arrive at an estimate of on-road fuel efficiency. Furthermore, manufacturers will still need to supply the full array of engine, transmission and other simulation inputs in China's program, because the fuel consumption of variants of the basic models that will be tested on the chassis dynamometer will still be determined through vehicle simulation.

The certification procedure in the EU also is expected to be based on simulation modeling, so manufacturers would need to provide full vehicle and component specifications, including an engine map. The EU protocol under development appears to maximize the use of actual vehicle specifications. Vehicles pulling trailers will be simulated with a standard trailer of the appropriate type, according to an extensive segmentation of trailers (TU Graz 2011). A schematic of the EU protocol is shown in Figure 4. Many vehicles, including certain tractor-trailers, would be simulated over more than one drive cycle, because test cycles for purposes of certification will be defined not only by vehicle specifications, but also by intended use (TU Graz 2011).

Figure 4. Schematic Diagram of Proposed HDV Simulation for the EU



Source: TU Graz 2011

A comparison of protocols in Japan, the U.S., China, and the EU reveals how structural elements can influence the types of fuel efficiency improvements likely to result from the programs. Table 3 shows which elements are reflected in each program.

Table 3. Technology Efficiencies Captured in Heavy-Duty Programs

Technology	Japan	U.S., Canada	China	EU[4]
Engine	Yes	Through separate engine standards	Yes	Yes
Transmission	Manufacturer's average manual transmissions simulated; automatics assigned a fixed percent efficiency loss	Optional; by demonstration outside of standard protocol	Yes	Yes
Hybridization	Unclear to what extent hybrid benefits will be captured	By demonstration outside of standard protocol	Yes	Yes
Aerodynamic drag and tire rolling resistance (tractor)	No	Yes	Yes	Yes
Trailers	No	No	No	No

III. Heavy-Duty Program Elements

This section reviews five structural elements of a heavy-duty vehicle rule for fuel efficiency or GHG emissions standards: metrics for the standards, vehicle segmentation, test cycles, test methods, and stringency of standards. Similar treatment of some if not all of these elements would presumably be required to align programs across regions.

METRICS

To achieve its intended outcomes without distorting the vehicle market, any program of heavy-duty fuel efficiency or GHG standards must measure fuel consumption or GHG emissions in a way that reflects the work that vehicles do. Heavy-duty standards to date have been defined in terms of fuel consumption or GHG emissions per unit distance (in the cases of Japan and China proposed) or per unit payload weight-distance (for U.S. vocational vehicles and tractor trucks). If test payload for each vehicle class is fixed, then the difference between these two metrics is essentially a conversion factor.

Payload is a key determinant of a vehicle's fuel consumption, but it is not obvious how payload should be specified for purposes of testing. Maximum rated payload will overstate typical loads, because vehicles often drive part-empty or with loads of low density. While the U.S. and Japan require that tractor-trailers be tested at loads well below the maximum weight, China is proposing full-load testing (CATARC 2010a). Maximum load also varies considerably across regions. A metric could be constructed to factor in performance at various loads, though this adds complexity to the standard.

[4] No regulatory program; based on certification procedure under development.

An alternative approach would be to fix gross vehicle weight for testing purposes. In that case, a metric of fuel use per payload ton-kilometer would give greater credit for vehicle weight reduction than would a fuel-consumption-per-kilometer metric, because reducing vehicle weight would allow increased payload and therefore improved performance under this metric. This approach would be appropriate for vehicles that are constrained by limits on gross vehicle weight. It should be noted, however, that most freight truck miles in the U.S. are driven by "cubed out" vehicles (MJ Bradley 2009; EPA and NHTSA 2011a) for which reductions in tare weight do not permit increased loadings.

SEGMENTATION OF VEHICLES

Central to a program of heavy-duty standards is the way the vehicle market is segmented. A segment is a set of vehicles that, due to similarities in design and/or usage are treated in the same way under the program. More stringent standards will typically call for a higher degree of segmentation so that the standards can be more closely tailored to the vehicles to which they apply. Otherwise, the standard may incentivize suboptimal vehicle specification for some applications. Alternatively, increased stringency can be accommodated through expanded flexibility mechanisms, such as allowing manufacturers to average emissions over groups of vehicles. Allowing averaging often raises questions of fairness with respect to limited-line manufacturers, however.

Regional Comparison

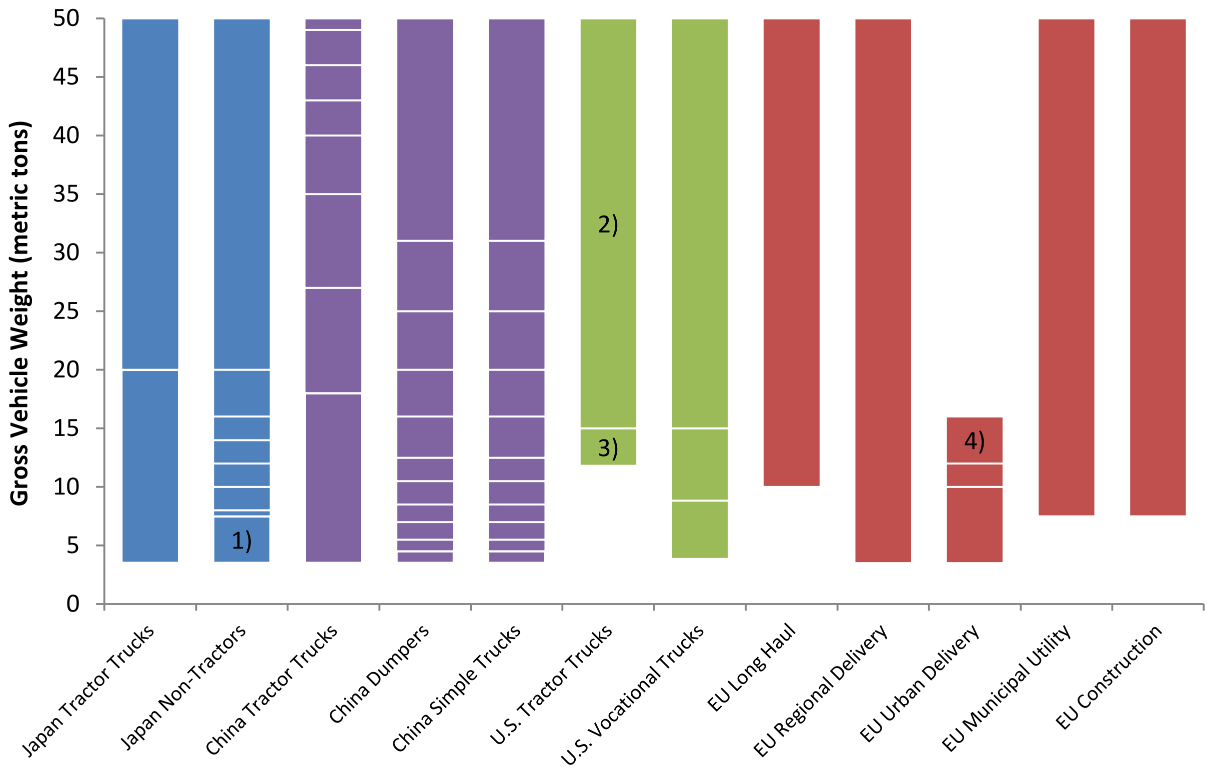
The U.S. heavy-duty rule defines nine types of tractor trucks, each defined by one of three roof heights, and day vs. sleeper cab, with day cab further divided into two weight classes (above and below 15 tons GVW) (EPA and NHTSA 2011a). Vocational vehicles, though a more diverse group, have only three classes: light (below 8.9 tons), medium (8.9 to 15 tons) and heavy (above 15 tons). Buses are included in these classes. The heavy-duty pickups and vans covered by the U.S. rule are treated in a fundamentally different way, and this discussion does not apply to those vehicles.

Japan has only two tractor truck segments, based on GVW. Segmentation of straight trucks is far more extensive and also weight-based. Japan has separate bus segments, defined by weight and type. China has extensive, weight-based segmentation of tractor trucks, as well as straight trucks, dumpers, and buses.

The segmentation under discussion in the EU involves two distinct dimensions, one based on vehicle use patterns and the other on physical characteristics of the vehicle. Vehicles are assigned to one of five drive cycles: long haul, regional delivery, urban delivery, municipal utility, and construction. The second dimension overlays on this a preexisting classification comprising 18 classes based on vehicle weight and axle/chassis configuration. The result is 25 segments in total (TU Graz 2011; see Appendix C).

Segmentation schemes as adopted or envisioned for the four regions are compared in Figure 5.

Figure 5. Heavy-Duty Truck Segments for GHG/Fuel Efficiency Standards



[1)] Further divided into four subsegments by maximum payload
[2)] Further divided into six subsegments by roof height and cab type
[3)] Further divided into three subsegments by roof height
[4)] Each EU segment further divided into two to seven subsegments by axle, chassis, and body configuration and weight

Fineness of Segmentation

Designing a workable program for heavy-duty vehicles requires balancing simplicity with the need to tailor the program to the diverse characteristics and usage patterns of these vehicles. The proper balance must reflect among other things the potential for fuel savings, which in turn relates to the distribution of fuel consumption by vehicle class. Classes of vehicles that consume the most are likely to be of greatest interest, especially in the early stages of a program. This factor is in evidence in the program for the U.S., where Class 8 tractor-trailers account for over two-thirds of heavy-duty fuel use, though only one-third of vehicle registrations (NRC 2010). In Japan, fewer than 10% of trucks with load capacity of 3 tons or more are tractor trucks (JAMA 2011). Furthermore, the highway portion of the fuel efficiency test cycle for tractor trucks is only 10-20% in Japan (Tokimatsu 2007), suggesting that annual kilometers traveled for these trucks is not likely to be much higher than for other trucks. Hence tractor trucks do not dominate heavy-duty fuel consumption in Japan, a fact reflected in their simple segmentation under Japan's fuel efficiency program.

The segmentation of vocational vehicles in the U.S. heavy-duty rule is not fine enough to distinguish among vehicles with very different duty cycles (Eaton 2011; Khan 2011). For example, a transit bus and a utility vehicle of the same GVWR would be tested for certification over the same cycles and be subject to the same standard. In the EU, by contrast, segmentation would take duty cycles into account. In fact, in some cases vehicles there might be differentiated based only on intended duty cycle, so that two virtually identical vehicles could be placed into different segments. Tractor trucks can fall into both regional delivery and long haul segments, for example (TU Graz 2011). While this feature helps to address the problem of setting standards for vehicles that are used in different ways, it raises implementation issues as well.

Test Cycles

A vehicle drive cycle, or operating cycle, is a specification of the conditions of the vehicle at each point along a trajectory. We use the terms "duty cycle" and "test cycle" to mean, respectively, a typical drive cycle for a vehicle in service and a drive cycle over which a vehicle is tested to measure its performance. Vehicles' rate of fuel consumption, as well as the effectiveness of technologies to reduce fuel consumption, varies greatly with drive cycle. Hence choice of test cycles is a crucial component of vehicle standards design.

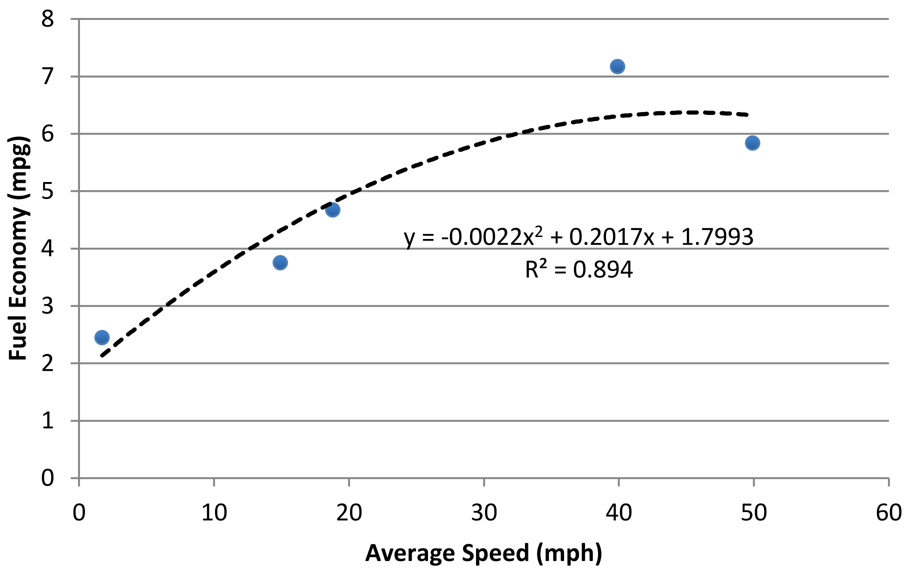
Light-duty vehicle testing in the U.S. involves a city cycle, with relatively low speeds and extensive stop-and-start driving, and a highway cycle, involving higher speeds and relatively steady-state driving. For heavy-duty vehicles, a more refined drive cycle taxonomy may be called for, given the wide variation in duty cycles, the dedicated operation of many vehicles in specific duty cycles, the high sensitivity of fuel efficiency to duty cycle, and the very large per-vehicle fuel expenditures at stake.

The transient operation common to urban driving involves acceleration and deceleration events, which reduces the efficiency of engine operation and results in energy lost in braking. These energy losses are typically much lower in highway driving. On the other hand, highway driving produces other energy losses, because aerodynamic drag increases rapidly with speed. The combined effects of these features of transient and highway driving are illustrated in Figure 6, which shows fuel economy of a 2004 model year Freightliner truck over cycles with a range of average speeds (Clark et al. 2007). The highest fuel economy for this truck was recorded over the HHDDTS Cruise Cycle with a 40 mile-per-hour (64 km per hour) average, above which fuel efficiency declined. Fuel efficiency over a cycle with 50-mph (80 km per hour) average speed (the HHDDTS High Cruise Cycle) was considerably lower, presumably due to high drag. Fuel efficiency over the HHDDTS Transient Cycle, with an average speed of 15 mph (24 km per hour), was far lower still, in this case due to the multiple stops and starts in the cycle.

Test cycles are commonly defined by specifying vehicle speed as a function of time over a fixed time interval (a speed-time "trace"). This practice has major shortcomings, however. First, some vehicles will not be able to follow the given trace due to power limitations and hence will not complete the cycle in the specified time interval, leading to incomparable test results. This problem can be partially addressed by specifying the distance to be traveled by the vehicle rather than fixing the time taken to complete the cycle. A related issue is that in some regions vehicles may be overpowered, which can result in unnecessary fuel consumption. Choosing test cycles based on the driving patterns of such vehicles could have unintended and undesirable consequences. Chinese heavy-duty vehicles at present tend to have substantially lower horsepower than those in Japan, the U.S. or the EU (Fung

2011). Furthermore, China plans to test vehicles at full load. Consequently, their vehicle generally cannot accelerate as quickly as is required by certain segments of the WTVC, leading the government to use a modified version of the cycle for testing.

Figure 6. Average Fuel Economy of 2004 MY Freightliner Truck over Cycles of Various Average Speeds



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

A second shortcoming of specifying test cycles by speed-time trace is that this omits key drive cycle features, including grade. Grade is included in Japan's Interurban Mode (Figure A-6), for instance. It strongly influences fuel consumption and is a major consideration in vehicle specification, as for example in the case of a vehicle to be used on mountainous routes. While grade effects can be captured in chassis testing or simulation, their inclusion adds substantial complexity to the project of identifying a full set of test cycles.

Choice of Test Cycles

The objective of test cycle design is to capture the salient features of actual duty cycles. What those features are warrants careful consideration. While a single test cycle cannot approximate the duty cycles of an entire class of vehicles, too large an array of test cycles yields an unwieldy test protocol. Ideally, test cycle properties would include:

1. Emissions performance of vehicles in the aggregate over the prescribed test cycles will allow a good estimate of real-world aggregate emissions.

2. Results of vehicle testing over the prescribed cycles will allow buyers to compare and optimize vehicles' fuel consumption over their actual duty cycles.

The first property is required to estimate the savings a heavy-duty program will provide, and the second is necessary to ensure that the standard will drive effective technologies in the vehicle market. Achieving the second property poses a big challenge, given the variations in users' duty cycles, but is necessary if the program is to incentivize and facilitate the purchase of appropriate fuel efficiency technologies.

The heavy-duty regulatory programs discussed in this report use one of two approaches to vehicle test cycles. Both involve picking a set of cycles that adequately describes the range of typical driving behaviors and assigning each vehicle segment to a subset of those cycles. The approaches can be described as follows:

- Approach 1: Test cycles represent typical, complete duty cycles, e.g., long-haul truck cycle or refuse truck cycle. Each vehicle is tested over all cycles it might plausibly be used for, and the certified performance of that vehicle then depends upon the vehicle's intended use.

- Approach 2: Test cycles represent common driving "modes," e.g., urban or high-speed highway, and each vehicle is tested over all cycles likely to be part of its duty cycle. In this case, the certified performance of the vehicle is typically defined as a weighted sum of the results over the modal cycles.

The first approach is under consideration for the EU program (TU Graz 2011). Japan and the U.S. will use the second approach, with weights adjusted to best represent driving patterns for each vehicle segment. China's approach is a variation on the second approach, in which a single existing vehicle cycle, the WTVC, is adapted to driving patterns in China. The WTVC is essentially a composite of three cycle segments (urban, road and highway); China creates test cycles by applying weightings that vary by vehicle type to the three segments.[5]

While the individual test cycles in Approach 1 will be realistic drive cycles for many vehicles, it is Approach 2 that has the flexibility to represent the full range of duty cycles across applications and regions. Research on U.S. vehicle cycles supports the idea that all real-world driving behaviors, at least insofar as they affect fuel consumption, can be represented as linear combinations of a few basic cycles (Clark et al. 2009).

On the other hand, common modes of driving, such as transient and highway driving, may have important differences across regions. This is evident from research to develop a Worldwide Light-Duty Test Cycle (ACEA 2011). This work demonstrates that speed on a given roadway type (urban, rural, motorway) varies substantially from region to region and concludes that roadway type is therefore not a good basis for defining driving modes. ACEA collected traffic data for each roadway type in several regions and assigned all driving to one of four speed bins (low, medium, high, and extra-high). It then used these bins, characterized by threshold maximum speeds, rather than roadway

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[2] It is not entirely clear how this will be done, given that vehicle speed in the WTVC does not reach zero between the road and highway cycle segments, so the two cannot be separated, strictly speaking.

types, as the basis for defining driving modes. The ACEA work suggests that further consideration of driving modes and further data collection are both prerequisites for developing heavy-duty test cycles that could be used across regions. Nonetheless, the idea that a small number of cycles can adequately represent the full range of driving behaviors is borne out to some extent by comparisons of other parameters such as average speed and idle duration, which have been shown to be predictive of maximum speed (ACEA 2011).

The U.N. has worked toward an international test cycle in developing the WTVC (see Appendix A), which is based upon driving data from several regions. This process sought to facilitate the development of compliant vehicles for a global market. While perhaps appropriate for criteria pollutants, however, this approach is less promising for GHG emissions testing, for which regions will require test cycles that actually represent regional driving. Also, the National Renewable Energy Laboratory has created a tool that, given data collected from in-use vehicles, will create a representative drive cycle for those vehicles, or alternatively will identify an existing industry-accepted drive cycle that provides the best fit for the supplied data (NREL 2011).

Existing Test Cycles

Appendix A discusses several of the principal heavy-duty test cycles in use in the world today. While most cycles included there are vehicle cycles, several have been used to generate companion engine cycles, which are used in criteria pollutant regulatory programs.

Table 4 lists test cycles used for criteria pollutant emissions and for fuel efficiency and GHG emissions by region. Where engine and vehicle cycle names coincide, the engine cycle has been derived from the vehicle cycle of the same name.

Table 4. Test Cycles for Criteria Pollutant Emissions and GHG Emissions/Fuel Efficiency by Region[6]

	Criteria	GHG/Fuel Efficiency
Japan	Engine: JE05	Engine: 30 speed-torque points Vehicle: JE05 and Interurban Mode
U.S.	Engine: FTP and SET	Engine: FTP and SET Vehicle: HHDDTS Transient, 55 and 65 mph steady-state cruise
China	Engine: ETC, ESC, and ELR	Engine: 81 speed-torque points Vehicle: Modified WTVC
EU	Engine: ETC, ESC, and ELR through Euro V; WHTC and WHSC beginning in 2013	Vehicle: Complete, vocation-specific cycles (under consideration)

[6] Several of these cycles are discussed in Appendix A. For additional details, see http://transportpolicy.net.

Table 4 shows some overlap between the cycles used for criteria and fuel efficiency testing. Creating a test cycle is a laborious process involving extensive data collection and analysis. Furthermore, if fuel efficiency and criteria pollutant testing are done on different cycles, it is difficult to verify simultaneous improvement on both. This is a concern particularly because some criteria pollutant reduction strategies adversely affect fuel efficiency, and vice versa. For these reasons, regulators may prefer that existing criteria pollutant testing cycles be used for fuel efficiency testing whenever possible. Manufacturers may take the same view, because they have “fine-tuned” their products to existing criteria emissions cycles. However, existing test cycles for criteria pollutant emissions will not generally be adequate for fuel efficiency testing.

A key difference between GHG emissions or fuel efficiency standards and criteria pollutant emissions standards is that, while criteria pollutant standards to date have sought to dramatically reduce emissions, fuel efficiency and GHG standards aim to reduce fuel consumption and emissions incrementally and by a much smaller percentage. A test cycle that serves to place an upper bound on emissions thus may be adequate for criteria pollutants, while a test cycle for measuring fuel consumption will need to better represent actual operation. In addition, in the case of fuel efficiency testing, the buyer and therefore the manufacturer will be interested in having test results that can be used to predict on-road fuel consumption for individual vehicles with a reasonable degree of accuracy.

TESTING AND MODELING METHODS

There are multiple technical approaches to evaluating vehicle fuel consumption. They generally require physical testing of vehicles and/or vehicle component and systems, together with calculation or modeling to translate the test results into the desired measure of performance. Roughly speaking, the type of testing used can be placed on a spectrum defined by the complexity of the components or systems that are physically tested. At one end of the spectrum is road testing of complete vehicles, which delivers an accurate measure of vehicle performance under the given test conditions, with no need for further calculation. The results are completely specific to the vehicle and conditions, however.

At the other end of the spectrum, individual vehicle components including engine and transmissions parts could be fully specified to generate inputs to a highly detailed model that simulates the vehicle’s fuel consumption given driving conditions and practices. This approach is very flexible, in that, given a perfect model and complete component specifications, one can predict the performance of any vehicle under any conditions simply by running the model. The challenge in this case is building, validating, and updating such a complex model and providing the very detailed inputs required.

Simulation modeling in practice can deliver a very rough or very accurate estimate of vehicle performance, depending on the detail of the component information provided and the sophistication of the model. For example, a simulation model typically requires detailed information on engine fuel consumption as an input. While this is often taken to be a set of fuel consumption rates for an array of engine speed/torque points, full representation of the engine for simulation purposes would also require information such as particulate filter back pressure, engine cooling loads, and the dynamic response of engine controls. The model cannot detect the efficiency gain due to a technology not anticipated in the structure of the model, or applied to a component not fully represented in the model.

In between road testing and pure simulation lies chassis testing, which directly measures the performance of the entire drive train. This approach requires knowledge of the vehicle's tractive load, which is used to generate the appropriate chassis dynamometer settings. Tractive load is in turn calculated from coefficients of drag and rolling resistance (or combined coastdown test results) obtained through additional testing. Due to the huge number of heavy-duty vehicle configurations sold and the varying conditions in which they are driven, chassis testing of every vehicle configuration would also be prohibitively expensive, however. The U.S. rule notes:

> The agencies evaluated the options available for one tractor model (provided as confidential business information from a truck manufacturer) and found that the company offered three cab configurations, six axle configurations, five front axles, 12 rear axles, 19 axle ratios, eight engines, 17 transmissions, and six tire sizes—where each of these options could impact the fuel consumption and CO_2 emissions of the tractor. Even using representative grouping of tractors for purposes of certification, this presents the potential for many different combinations that would need to be tested if a standard were adopted based on a chassis test procedure (EPA and NHTSA 2011a).

The program under development in China is based on chassis testing, but would require testing for only a representative set of vehicles; results for similar vehicles would be generated through simulation.

An approach that plays a role in all of the programs described here is to test the engine on an engine dynamometer and simulate the performance of the entire vehicle based on the engine test results, together with information on aerodynamic drag, rolling resistance, and other vehicle loads. In this approach, the large number of powertrain configurations associated with a single engine or family of engines is handled by the model. This is not adequate to handle a hybrid vehicle, however, and in fact it is not clear that models in use today can properly represent the subtleties of the interplay between engine, transmission, and controls that will be crucial to heavy-duty vehicle fuel efficiency in the coming years. For that reason, some have suggested the use of "power pack" testing, in which the engine and transmission are testing as a unit.

Researchers developing a certification procedure for greenhouse gas emissions and fuel consumption of HDV in the EU noted that a test method should:

- Be repeatable and reproducible;
- Incentivize efficiency technologies and optimize the vehicle as a whole;
- Be highly sensitive to fuel savings;
- Have reasonable cost; and
- Be simple and robust

(TU Graz 2011). With these criteria in mind, we summarize the advantages and disadvantages of the various test methods described above in Table 5.

The method employed to evaluate fuel consumption can influence the technologies and fuel efficiency improvement strategies a program will promote. A program that tests individual components and simply calculates the combined benefits of making those components more efficient will drive improvements in those components alone. As the focus of the program moves to more integrated technologies, such as hybridization or engine downsizing coupled with auxiliary system improvements and weight reduction, an evaluation method that captures the interaction of vehicle components and will be necessary. This can be achieved either through more sophisticated modeling or through testing of the relevant systems.

Table 5. Selected Test Method Pros and Cons

	Pro	Con
Road testing	Measures complete vehicle performance over a given drive cycle Technology advances automatically captured in results Allows for enforcement testing	Separate test needed for every vehicle and drive cycle Results are not repeatable; highly subject to ambient conditions
Chassis testing	Limited space requirements Captures full drive train performance	Must be complemented by testing for aerodynamics and rolling resistance Limited repeatability
Engine/power train testing	Engine dynamometer less costly than chassis dynamometer Fewer distinct configurations to test	Must be complemented by testing for aerodynamics and rolling resistance
Component testing	Testing over multiple cycles as easy as testing over a single cycle Results are replicable	Requires simulation in full detail Model needs extensive and continual updating to capture technology advances and ensure consistency with real-world performance

While the programs in the various regions are diverse, none relies primarily on full-vehicle testing, for the reasons cited above. Hence all use component testing and simulation to some extent. The next section discusses the component test methods in the regional programs. Comments on simulation models follow this discussion.

Component Testing

Testing of components, including engines, will remain an essential element of any test protocol and has consequently received detailed consideration in all regions developing heavy-duty vehicle programs. Component tests have both commonalities and differences across regions, which we summarize below. More detail on component testing is provided in Appendix B.

Engines The U.S. program, which is unique in setting separate engine standards, directly regulates engine manufacturers as well as vehicle manufacturers. This feature is perhaps more important in the U.S. than in other regions such as Europe and Japan, where the heavy-duty industry is more integrated vertically and vehicle manufacturers typically produce their own engines. In the U.S., setting engine standards has the benefit of ensuring a consistent, long-term effort on advanced engine technologies, regardless of the trajectory of fuel consumption reduction on complete vehicles.

While only the U.S. program includes a separate engine standard, engine testing will be needed in all regions. Japan, China and the EU will use fuel consumption maps for individual engines as a crucial input to vehicle simulation. All regions call for steady-state engine emissions data, requiring values at anywhere from 18 (U.S.) to 81 (China) speed-torque points. The U.S. will use a weighted average of emissions at these test points to certify engines (for tractor trucks; vocational engines will be certified based on performance over a transient test cycle), while the remaining regions will use these steady-state data points to generate the full engine GHG emissions map.

A major consideration in establishing engine test protocols in some regions has been that they should match criteria pollutant protocols to the extent possible. The purpose of this is to (i) minimize the testing burden on manufacturers and (ii) ensure that reductions in criteria pollutant emissions and fuel consumption will occur simultaneously, rather than allowing one to be traded off against the other, as has happened in the past (CNRE 2005). In view of the priority placed on maintaining consistency between criteria pollutant and fuel consumption test protocols, we describe briefly the European Union's engine test cycles for criteria pollutants in Appendix A. As noted above, however, programs to improve fuel consumption and reduce GHG emissions can be expected to require more precision in the measurement of performance than criteria pollutant emissions programs have needed to date, so maintaining such consistency in test protocols could in fact prove counterproductive.

Aerodynamic drag and rolling resistance Most programs require or permit the use of certain tests to determine aerodynamic drag and rolling resistance, or tractive load as a whole. The U.S. and China both recommend coastdown testing for this purpose, while the EU has indicated a preference for constant speed testing (TU Graz 2011).

Japan's program uses predefined values for aerodynamic drag and rolling resistance in simulating vehicle performance and therefore will not drive aerodynamic and tire improvements. Tire-specific values for rolling resistance are required in the U.S.; values from tire manufacturers based on established tire test protocols are permitted. China permits the use of default "worst case" values for both drag and rolling resistance coefficients for manufacturers electing not to do physical testing. Further detail is provided in Appendix B.

Transmissions Japan's simulation approach reflects transmission performance, in that the specifications of the manufacturers' average manual transmission are used to translate the prescribed vehicle test cycle into an engine cycle. (CRNE 2005; see Figure 3.) The performance of automatic and automated manual transmissions is represented by substituting in the simulation a manual transmission having the same number of gears and gear ratios. Fuel efficiency is then assumed to be the same for the vehicle with the automated manual as for the manual, while a vehicle with an automatic transmission is assumed to have efficiencies 91% and 96% of the manual transmission efficiencies in the transient and interurban modes, respectively.

The U.S. approach does not capture transmission improvements in the basic protocol. Advanced transmissions can gain credit as an "advanced technology" if manufacturers demonstrate and quantify their efficiency benefits to the satisfaction of the EPA and NHTSA. This may be done through A-to-B chassis testing, for example (EPA and NHTSA 2011a). One transmission manufacturer has raised a question of whether the performance of automatic and automated manual transmissions over a fixed speed-time trace is the appropriate comparison, because real-world drive cycles may vary in duration with the transmission type (Allison 2011).

Transmission performance presumably will be captured in the EU's simulation model approach, although details of the method have not yet been specified (TU Graz 2011). China's protocol based on chassis testing will necessarily capture transmission performance.

Other components Auxiliary loads such as AC, pumps, fans and PTO are often "off-cycle" loads, i.e., not reflected in the test cycles used for certification. Hence if potential fuel savings from improvements in these components are to be captured through the program, testing protocols may need to be improved or supplemented, as has been done, for example, in the light-duty vehicle fuel economy label program in the U.S. Also, U.S. light-duty GHG standards for model years 2012-2016 include credits for certain off-cycle technologies, and such credits will be awarded under both the GHG and fuel economy rules for model years 2017-2025.

Simulation

EU researchers' investigation of the merits of the various test procedures with respect to these criteria led to the conclusion that a simulation-based approach was clearly preferable to other options (TU Graz 2011). The quality of the simulation remains a significant issue, however. Extensive validation of model results against real world performance will be required to gain and maintain the confidence of manufacturers and users, and continual model updates and validation will be essential. Among the critical questions will be how well models can represent advanced technologies; this will vary according to the nature of the technology and the properties of the model. Uncertainty about whether a new technology will receive proper credit in the certification process could discourage development of that technology.

In 2009, Ricardo conducted a review of commercially available software that could be used for heavy-duty vehicle simulation (Fulem 2009). The study identified twenty-three tools, finally considering nineteen of them for evaluation. The majority of these tools were constructed on programming language such as C/C++ or FORTRAN, while eight tools were constructed with MATLAB-Simulink. Ricardo evaluated these tools using multiple criteria, including: complexity, ease of use,cost and customer support. DYMOLA, PSAT, AMESim, and AVL-Cruise were the top four tools according to the Ricardo study. These tools were found to be capable of simulating dynamic behavior and interactions between systems; DYMOLA and AVL-Cruise were able to model the performance of new and alternative designs and technologies. However, the study did not compare model outputs with real-world data.

While having a common simulation model across regions would be convenient, it could be hard to achieve, given historical, competitive, and technical considerations facing participating governments. This becomes an issue to the extent that the models deliver different results from the same inputs, especially if the results vary in unpredictable ways. At the same time, comparing results across models can provide important evidence of the robustness of the simulation model approach (or lack thereof).

STRINGENCY

Typical rates of fuel consumption for a given vehicle may vary greatly across regions due to differences in driving patterns. These differences, as well as differences in fuel prices, mean that the fuel efficiency technologies that are cost-effective for that vehicle vary from region to region as well. The levels of standards set for tractor-trailers in Japan and the U.S. illustrate these considerations.

Example: Stringency of Japan and U.S. Tractor Truck Standards

Consider once again a high-roof day cab tractor truck with GVW over 15 tons. Under the U.S. standards, the fuel consumption target for this truck in 2014-2016 will be 9.0 gal per 1,000 ton-miles, or 2.49 km/l using the specified test payload of 19 short tons. In Japan, the same vehicle will be required to achieve a fuel efficiency of 2.01 km/l at half maximum payload (20 tons) (CNRE 2005, Daisho 2007). While the level of the U.S. standard is nominally 24% higher than Japan's, this is an apples-to-oranges comparison, because the cycle weightings are very different in the two programs. In Japan, fuel consumption over the JE05 Transient Cycle is weighted 90%, while the Interurban Mode, a constant speed highway cycle, is weighted 10%. In addition, the Interurban Mode includes road grade ranging from -5% to +5% (CNRE 2005). In the U.S. standard, the weightings of transient and highway cycles are essentially reversed, with 19% weighting of the HHDDTS Transient Cycle and 81% combined weighting of the two steady-state cruise cycles (EPA and NHTSA 2011a). The U.S. test cycle does not include the effect of road grade.

We use EPA's GEM to see how the differences in cycle weightings affect the estimated fuel consumption of the given vehicle. Using appropriate inputs to the model, we find that the truck achieves fuel efficiencies of 1.51 km/l, 2.95 km/l, and 2.41 km/l on the HHDDTS Transient Cycle, the 55-mile-per-hour (88.5 km-per-hour) steady-state cruise cycle, and the 65-mile-per-hour (104.5 km-per-hour) steady-state cruise cycle, respectively. This yields an overall average fuel efficiency of 2.23 km/l using the U.S. cycle weights of 19%, 17%, and 64%, just above the fuel efficiency of 10.1 gallons per 1,000 ton-miles (2.21 km/l) the agencies found for an average truck of this type in the rule.

In order to estimate how this truck would perform in Japan's test, we assume that fuel efficiency over the HHDDTS Transient Cycle is the same as fuel efficiency over the JE05 Cycle, and similarly for fuel efficiencies over the 55-mph (88.5-kmph) U.S. and Japan's 80.5-kmph Interurban Cycle. This truck would achieve only 1.59 km/l using Japan's cycle weightings, even ignoring the effect of grade in the Interurban Mode and the 16% heavier test payload (20 metric tons vs. 19 short tons) required for the

Japanese test. In fact, the result is well below the average fuel efficiency of 1.80 km/l found in Japan in 2002 for similar trucks (CNRE 2005, Daisho 2007).

Adding now a U.S. 2015 model year engine and idle reduction technology, improved aerodynamic drag and rolling resistance coefficients, and modest weight reduction, this truck will easily meet the 2015 U.S. standard. According to GEM, it will achieve fuel efficiencies of 1.58 km/l, 3.32 km/l, and 2.78 km/l on the Transient Cycle, the 55 mph steady-state cycle, and the 65 mph steady-state cycle, respectively, giving a combined fuel economy of 2.49 km/l with U.S. cycle weighting. The truck's overall fuel efficiency increases by 12%, primarily due to efficiency improvements on the highway cycles. However, using Japan's cycle weightings, this more efficient truck will achieve a fuel efficiency of only 1.66 km/l, an improvement of 5%, reflecting its modest improvement on the JE05 Transient Cycle. It will fall far short of Japan's 2015 standard of 2.01 km/l.

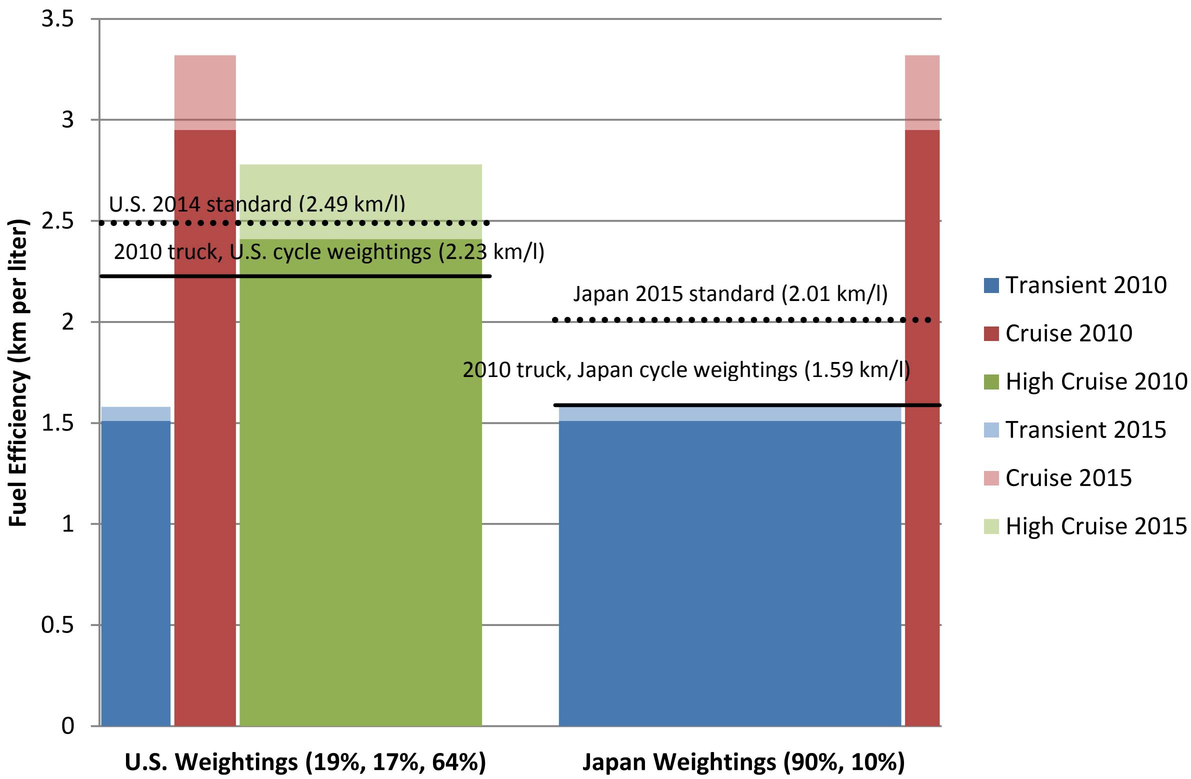
Similarly, a truck designed to meet Japan's 2015 standard would be unlikely to meet the U.S. standard for 2015. Presumably, manufacturers for Japan's market will focus on improving fuel efficiency in urban driving to order to meet Japan's 2015 targets; they are unlikely to invest heavily in the aerodynamic improvements that would be needed to meet the U.S. standard. By contrast, the 2015 improvements assumed above for the U.S. truck are aimed largely at reducing highway fuel consumption.

Figure 7 shows the fuel efficiencies of the given truck before and after the U.S. package of technology improvements, with individual cycle fuel efficiencies shown by color blocks. The solid horizontal lines show the original truck's weighted average fuel efficiency under the two-cycle weighting, while the dotted lines show 2015 fuel efficiency standards for the U.S. and Japan.

The U.S. program sets the 2015 standard 12% above the 2010 baseline, while the Japanese standard requires a 12% increase from the 2002 average to the 2015 target.

One clear implication of this example is that having a single numerical standard across regions for a given truck would not be feasible. The enormous difference between cycle weights for the U.S. and Japan, which reflects fundamental differences in real-world driving patterns, results in a far lower nominal fuel efficiency target for Japan. This discrepancy cannot be addressed simply by adjusting the cycle weights to match, because that could drive efficiency technologies inappropriate for one region or the other. For example, increasing the weight of the interurban mode in Japan would incentivize aerodynamic improvements to tractor-trailers. While these are highly cost-effective in the U.S., such improvements would not necessarily make sense for tractor-trailers in Japan. Any viable program of standards will necessarily reflect these region-specific conditions.

Figure 7. Fuel Efficiency of Tractor-Trailer, GVW>20 tons, with U.S. and Japan Cycle Weightings



Flexibility Mechanisms

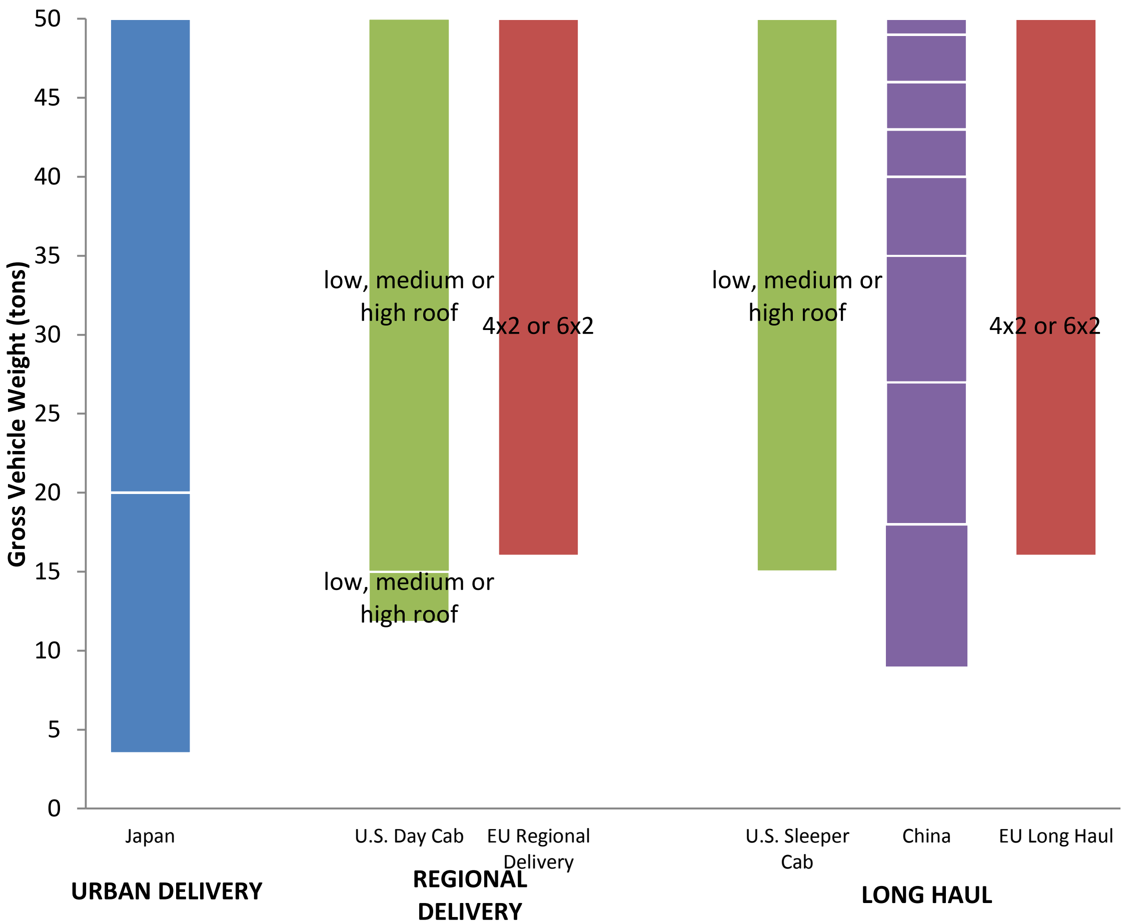
The stringency of a standard is determined not only by the numerical performance levels assigned to each vehicle, but also by flexibilities that may be put in place to facilitate compliance with the standard. For example, the programs in Japan and the U.S. permit manufacturers to comply with the standard on average within in each vehicle class, rather than requiring that vehicles must achieve the standard individually. Inclusion of such mechanisms in principle can reduce manufacturers' compliance costs without reducing the fuel savings and emissions reduction benefits of the program. On the other hand, averaging raises issues of fairness, especially when the classes over which performance can be averaged are large. In that case, manufacturers whose products do not cover the full range of vehicles in the class may be unable to take advantage of the flexibility of averaging.

Alignment Considerations

Aligning heavy-duty fuel efficiency standards in different regions presents fundamental challenges. In particular, a fuel efficiency level that is achievable for a given vehicle in one region may not be achievable for the same vehicle in a different region, given differences in driving patterns and other regional conditions. There are less restrictive ways in which regulatory programs could be aligned, however, that would contribute to achieving the objectives of maximizing fuel savings and minimizing manufacturer compliance costs associated with meeting the standards. This section considers which of the program elements discussed above might be amenable to alignment.

Segmentation The vehicle segmentation schemes in use have important features in common; but there are also major disparities, as shown in Figure 5. Even for tractor trucks, the programs have adopted diverse segmentation schemes, as shown in Figure 8. On top of the variations in number of segments, weight class boundaries, and application that arise for all vehicle types, the U.S. and EU tractor segmentation schemes add roof height and axle configuration, respectively. These factors present a major barrier to a common system of segmentation.

Figure 8. Tractor Truck Segments



Test cycles As discussed above, all programs to date follow one of two approaches to vehicle test cycles: Approach 1, which defines an array of complete duty cycles, or Approach 2, which defines a set of modal cycles. Both approaches could assign multiple cycles to a single vehicle, which is exactly the feature that allows the possibility of using the same set of cycles in all regions. Under Approach 1, the fuel efficiency of a vehicle in a given region would be evaluated over the cycle or cycles relevant to that region. In Approach 2, the vehicle would be evaluated over all modal cycles, and its fuel efficiency would be defined as a weighted sum of the results, where the weights would be region-specific.

Advantages and disadvantages of the two approaches are shown in Table 6. Assuming typical duty cycles in all regions can in fact be represented adequately for fuel consumption purposes as linear combinations of a few modal cycles, Approach 2 would likely require a much smaller number of cycles than would Approach 1. Approach 2 is also more flexible, because it can represent a continuum of duty cycles through variation in the weightings of the modal cycles. On the other hand, in Approach 1, a vehicle would have a well-defined fuel efficiency for a given use, regardless of the region.

Table 6. Pros and Cons of Two Approaches to Test Cycles

	Pro	Con
Approach 1 (Typical duty cycles)	• For each intended use, tested fuel efficiency is a single number, same in all regions	• Large number of cycles • Fuel efficiency depends on intended use, not just vehicle properties
Approach 2 (Modal cycles)	• Relatively few cycles • Set of fuel efficiency values the same in all regions • Allows customized fuel efficiency estimates	• Fuel efficiency not represented by a single number

Under either approach, each vehicle is assigned fuel efficiencies over a fixed set of test cycles. These values would be the same for all regions involved, resulting in universal, well-defined measures of vehicle performance. This information would permit a standardized calculation of cost-effectiveness of technology improvements as a function of regional conditions. This in turn would help to establish a global market for efficiency technologies. It would also allow comparisons of vehicles in a range of driving conditions, and in particular would allow buyers to estimate performance over their own duty cycles.

In the U.S. program, the compliance model GEM reports out the vehicle's compliance fuel efficiency and CO_2 emissions, but does not provide results for the three test cycles individually. This prevents vehicle buyers from customizing the calculation of fuel efficiency. In Japan, by contrast, manufacturers will be required to display test results for each cycle separately, in addition to the combined value, for all vehicles (CNRE 2005).

Testing and modeling methods Establishing common testing and modeling methods would entail agreement on the roles and protocols for vehicle, system, and/or component testing, and on the role of simulation. It would also be important to have agreement on how to define test families of similar vehicles, engines, or components so that not every variation of the tested item requires a separate test.

In addition to any technical obstacles that may arise to adopting a common test method across regions, institutional obstacles could be significant. For physical testing, resources are an issue, especially the availability of test facilities and personnel. While the impediment to common test weights and cycles is the variation in the way vehicles are used across regions, impediments to common test methods are more likely to be differences among implementing agencies. Such institutional issues may be amenable to resolution through cooperative agreement, for example by formation of an international testing oversight body.

Similarly, while having a common simulation model across regions would be convenient, it could be hard to achieve given historical, competitive, and technical considerations facing participating governments. This becomes an issue to the extent that the models deliver different results from the same inputs, especially if the outputs vary in unpredictable ways. Furthermore, models will need to evolve over time, as when a new technology emerges or problems arise, and agencies likely will want to make changes to their models unilaterally. On the other hand, a common model is not essential if the models used in the various regions are sound. In fact, comparing results across models can help to evaluate the robustness of the simulation model approach.

Stringency Diversity of driving conditions and other regional differences will preclude adoption of standards of the same stringency globally, although common stringencies may be possible across some regions, as in the case of North America. Moreover, the approaches to test cycles described above would permit the definition of fuel efficiency and GHG emissions performance levels that would be meaningful in all regions.

APPROACHES TO ALIGNMENT

The above considerations suggest that a common set of vehicle test cycles and test weights is fundamental to alignment. These elements can be used to define a measure of a vehicle's fuel efficiency that would be meaningful in all regions. This in turn would facilitate the sale of efficiency technologies globally and thereby accelerate the rate of fuel efficiency increases.

A uniform test method, by virtue of its ability to reduce compliance costs, would be useful to increase alignment's appeal to manufacturers. In particular, common component test methods would be relatively straightforward to develop, since component testing typically provides information about performance that is applicable over a wide range of operating conditions and thus does not require test cycles that reflect specific real-world duty cycles.[7]

Given the importance of gaining the support of all stakeholders, an approach to alignment might therefore best be characterized as a choice of a set of test cycles and weights, together with a choice of test method.

While uniform stringency might appear at first glance to be the defining feature of program alignment, this will not generally be feasible, as observed through the comparison of tractor truck standards in Japan and the U.S. Supporting evidence for this conclusion is the fact that international appliance standard alignment to date has focused on the areas of test protocols and methods (Waide 2011).

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[7] An important exception is an engine cycle for transient operation.

Data and Research Needs

Data limitations have proven to be a challenge in establishing sound heavy-duty vehicle fuel efficiency or GHG emissions regulations. In the U.S., for example, the primary source of national data on the heavy-duty vehicle stock, the Vehicle Inventory and Use Survey (VIUS), was last conducted in 2002. It was discontinued due to federal budget constraints in 2006 and has not been reinstated. As a result, much of the analysis done for the U.S. is based on data now a decade old. For the EU, researchers have done extensive data collection and analysis for member countries, but they also highlight data gaps as an obstacle to program development (AEA 2011).

Developing an aligned program will require not only solid data for all participating countries but also extensive cross-regional analysis, including:

- *Comparative market assessment.* A comparative assessment should be undertaken of regional heavy-duty vehicle markets, including aspects such as dominant manufacturers and degree of vertical integration in the industry, customer vehicle specification practices, vehicle financing options, and fuel availability. Manufacturers marketing internationally would be well positioned to provide much of the necessary information.

- *Duty cycle analysis.* A comparison of duty cycles for each major heavy-duty vehicle application, including not only speed but also grade and payload, will be needed to determine whether global driving behavior can be captured by a manageable set of cycles. Work similar to that done to develop the WTVC and other international cycles oriented toward criteria pollutant emissions testing could be used to develop candidate drive cycles for an aligned program. As is evident from ongoing work toward an international light-duty vehicle cycle for fuel consumption and GHG emissions (ACEA 2011), development of heavy-duty cycles will require extensive new data collection and analysis relating to in-use behavior. Fleet participation will be valuable in this effort.

- *Simulation model review.* A follow-up to the Ricardo survey of simulation tools (Fulem 2009), focused specifically on the suitability of models for purposes of fuel efficiency and GHG standards, would be useful at this stage. The study should review such questions as: whether the accuracy of the models is sufficient to measure all significant fuel efficiency improvements; whether the models can easily use and supplement data generated through chassis and component testing; the extent of validation using real-world data; and which types of technological advances the models are well-suited to represent. Models adopted or contemplated for the four regional programs should be reviewed and compared.

Manufacturer participation will be essential to the entire process of developing test protocols. As EU researchers note in particular, "several data necessary as input to the test procedure cannot be gained by independent consultants in a cost efficient way (e.g., engine map, gear box efficiency maps, data on auxiliary efficiencies etc.)" (TU Graz 2011).

Conclusions and Recommendations

Regulation of fuel efficiency and greenhouse gas emissions of heavy-duty vehicles is new but bound to develop rapidly now that the biggest heavy-duty vehicle markets have adopted their first programs or are well along in designing them. There are important benefits of aligning these programs going forward, in terms of maximizing the cost-effective fuel savings and emissions reductions such programs bring and minimizing manufacturers' costs to meet the new standards. Alignment must be approached with flexibility, however, because certain aspects of these programs do not lend themselves well to a uniform treatment. The idea of a standards program that is essentially identical in all regions is not realistic.

From the perspective of a manufacturer participating in more than one market, each element of the program that is aligned across sales regions implies reduced costs. From both manufacturing and regulatory perspectives, it may be tempting to seek standards that apply the same stringency across regions so as to be able to minimize the variations in vehicles across markets and to ensure the largest market for efficiency technologies. However, uniform stringency appears not in fact to be a feasible or even desirable objective, given the differences in operating conditions across regions. A prime example is the reversal of urban and highway driving shares for large tractor-trailers in Japan and the U.S., a fact reflected in the very different fuel efficiency targets set for the two countries. This suggests the need for a broader notion of alignment, which aims to increase the effectiveness of the individual programs by demonstrating the benefits of fuel efficiency technologies for the entire population of vehicles to which these technologies will bring real-world savings.

The basic structural elements of heavy-duty fuel efficiency and GHG standards programs raise a variety of issues with respect to the feasibility and value of alignment. The following conclusions and recommendations regarding those elements arise from the discussion in previous sections.

Metric

- Program alignment will require the use of fuel efficiency or GHG emissions metrics that are readily convertible across programs. Liters (or grams CO_2) per payload ton-kilometer or an equivalent appears to be the best choice.

- Test payloads must be specified for the metric to be meaningful as well as to define equivalence with a liters-per-kilometer metric. Typical payloads vary from region to region, however. Hence testing should be done with multiple payloads, e.g., empty, full, and regionally appropriate payload.

Vehicle Segmentation

- Due to differences in existing class definitions, distribution of fuel use, and ways in which certain vehicles are used, uniform segmentation across regions would be difficult. Nonetheless, for vehicle categories such as line-haul tractor-trailers that are important in many regions, it would be useful to develop global characterizations and weight thresholds to facilitate discussion and comparison of programs.

Test Cycles

- While various engine test cycles exist for criteria pollutant testing, and several have vehicle versions, fuel efficiency and GHG emissions programs will require additional data points and cycles. At a minimum, a complete engine fuel map will be needed. Additional information relating to engine cooling, transient operation, and response to ambient conditions may be required as well.

- Two approaches to accommodating the variety of duty cycles for heavy-duty vehicles are: (1) developing a wide array of test cycles representing typical complete duty cycles, e.g., long-haul truck cycle or refuse truck cycle; and (2) choosing cycles to represent common driving modes, e.g., urban or highway, and defining vehicle performance as a weighted sum of the results over the modal cycles. Either of these approaches could be used in an aligned program. This would involve either use-dependent certification of vehicles (first approach) or weightings that vary from region to region (second approach).

Testing and Modeling Methods

- Component testing will be a necessary part of any test protocol. Alignment of test protocols for components, including engines, across regions would be relatively easy and could contribute substantially to both expanding the market for efficiency technologies and reducing manufacturer testing costs. Component testing is not, however, sufficient basis for a program of standards that seeks to recognize the full range of potential efficiency improvements. Full-vehicle evaluation will be required to capture the benefits of advanced technologies and the interactions of vehicle systems.

- Simulation modeling will also be an important element of any heavy-duty test protocol. Any model adopted for this purpose should be fully documented and use open source software to allow for evaluation and improvement.

- In addition, some amount of physical testing will be needed to validate the results of simulation modeling and to capture the benefits of technologies not anticipated in the model.

- Differing test methods do not preclude program alignment but may reduce the validity of cross-region comparisons. Uniform test methods also reduce manufacturer costs and hence will increase the appeal of standards to manufacturers.

Stringency

- Due to cross-regional differences in driving patterns, fuel prices, typical payloads, and other conditions, it will not generally be feasible to set a given vehicle's fuel efficiency or GHG emissions standard at the same level in all regions.

Data and Research

- Region-specific and cross-region analysis will both be needed; early efforts to coordinate could greatly reduce duplication of effort.

- Development of modeling tools sufficient for evaluating heavy-duty vehicles' fuel efficiency and GHG emissions will require detailed information on engines and other components and systems from manufacturers. A survey should be conducted of simulation models in use, with a focus on suitability for fuel efficiency and GHG emissions prediction.

- For heavy-duty vehicle duty cycles and other information about driving patterns, participation of fleets will be essential. Data collection similar to that done by participants in EPA's SmartWay program would be useful in all regions.

In view of these conclusions, we recommend approaching alignment of heavy-duty fuel efficiency and GHG emissions programs by establishing a common set of test payload weights and test cycles satisfying the requirements of one of the two approaches described above. This would result in universal, well-defined measures of vehicle performance. This information would permit a standardized calculation of cost-effectiveness of technology improvements as a function of regional conditions, which would help to establish a global market for efficiency technologies and thereby accelerate the rate of fuel efficiency increases. It would also allow comparison of vehicles in a range of driving conditions and in particular would allow buyers to estimate performance over their own duty cycles. Aligning test methods as well would reduce manufacturer compliance costs and thus strengthen support for the program.

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Appendix A: Survey of Heavy-Duty Cycles

Below we describe a number of heavy-duty cycles from various regions that are potentially relevant to greenhouse gas emissions and fuel efficiency testing for heavy-duty vehicles. The list is by no means comprehensive. A more extensive "library" of test cycles is referenced in materials of the National Renewables Energy Laboratory (NREL), for example, with primary focus on vocational cycles (O'Keefe and Kelly 2006).

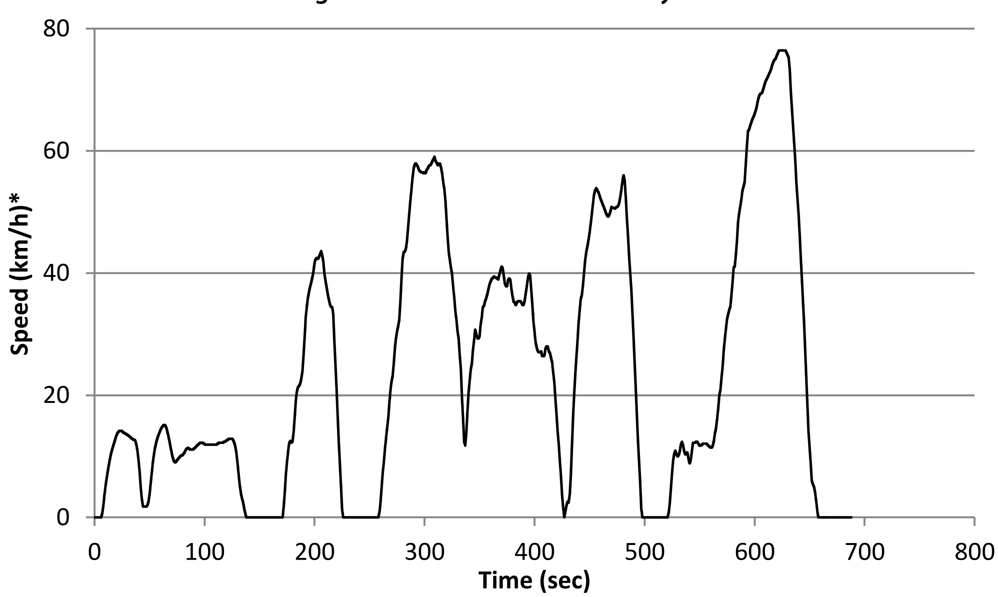
URBAN CYCLES

Heavy Heavy-Duty Diesel Truck Schedule (HHDDTS) – Transient Cycle

The Heavy Heavy-Duty Diesel Truck Schedule (HHDDTS) is a set of diesel truck cycles developed by West Virginia University and the California Air Resources Board (CARB) for trucks over 26,000 lbs. GVW. It is comprised of three cycles (Creep, Transient, and Cruise) preceded by an idle mode (Gautam et al. 2002). These four modes together represent wide-ranging truck activities including stationary, delivery, non-freeway, and freeway operations. West Virginia University recently developed an engine version of this schedule, called the Advanced Collaborative Emissions Study (ACES) Cycle, which represents updated truck usage patterns (Bedick et al. 2009).

The HHDDTS Transient Cycle has an average speed of 24 km/hr and maximum speed of 77 km/hr. It is one of three test cycles used in the EPA/NHTSA GHG and fuel efficiency program to test vocational trucks and tractor-trailers. The Transient Cycle is presented in Figure A-1.

Figure A-1. HHDDTS Transient Cycle



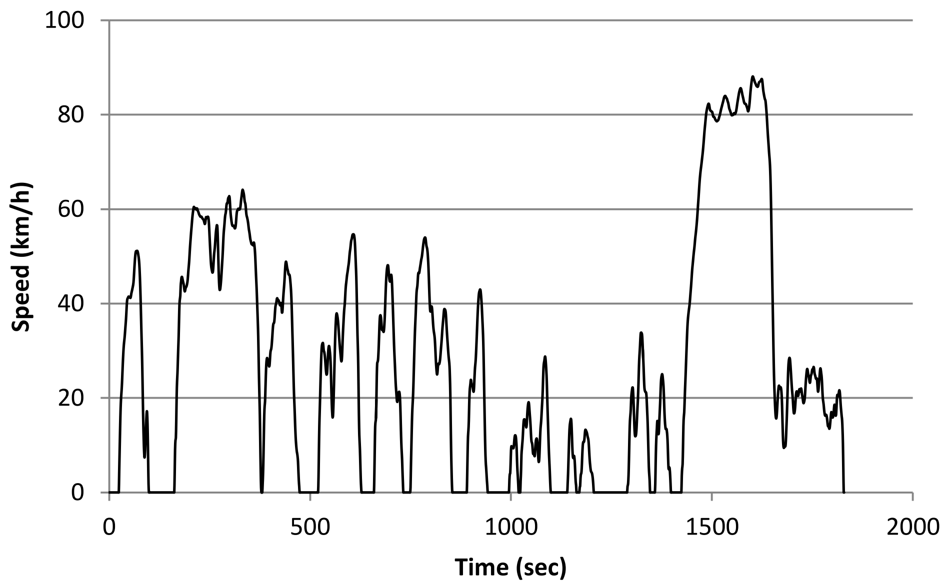
*Actual speed units are miles per hour

JE05 Cycle

Japan's fuel efficiency standards use the JE05 test cycle for heavy vehicles, defined as those of GVW above 3.5 metric tons. The JE05 cycle is a transient cycle based on the typical driving pattern in Tokyo

City (Rakpoulos and Gaikoumis 2009). It covers almost 9 miles in its 1829 seconds of duration. The cycle has an average speed of 27 km per hour and maximum speed of 89 km per hour. Figure A-2 shows the speed-time trace of the JE05 Cycle.

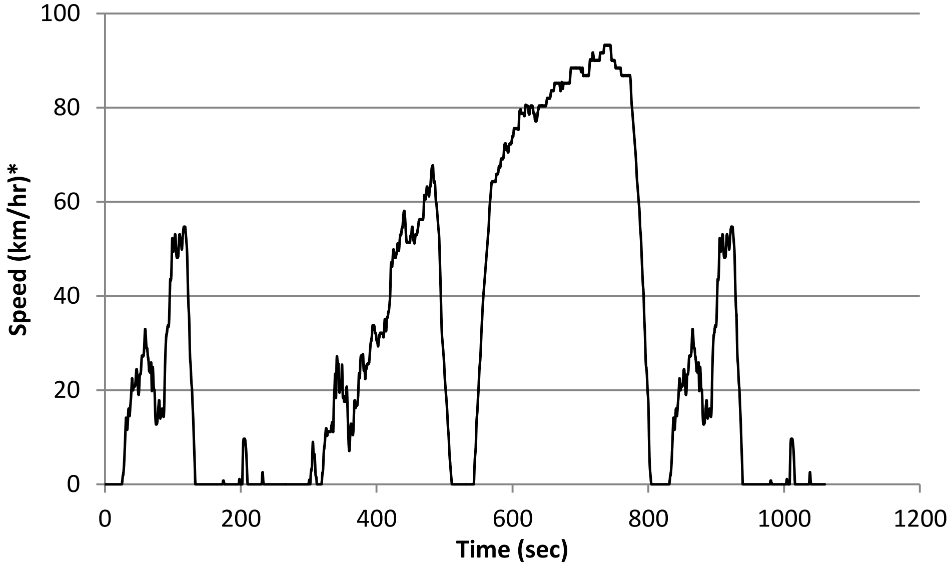
Figure A-2. JE05 Cycle



UDDS Cycle

The Urban Dynamometer Driving Cycle (UDDS), also known as the Federal Test Procedure (FTP) Heavy-Duty Transient Test Cycle, was developed in the U.S. from traffic data in the 1970s for use in chassis dynamometer testing of heavy-duty vehicles (France 1978). It was designed to capture freeway and urban operations without separation into activity types, as shown in Figure A-3. The cycle covers 5.5 miles (8.9 km) at an average speed of 19 mph (30.6 km/hr) and a maximum speed of 58 mph (93.3 km/hr). The engine version of this cycle is used for heavy-duty engine certification for both criteria pollutants and GHG.

Figure A-3. The UDDS Cycle

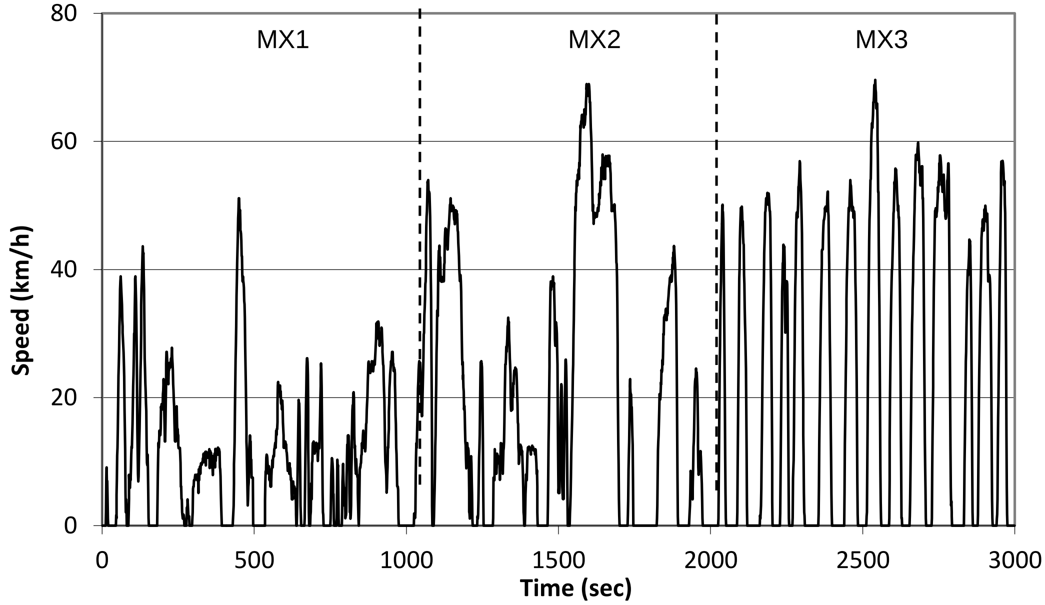


*Actual speed units are miles per hour

Mexico City Cycle

The Mexico City Cycle (MCS) was developed by West Virginia University for bus emissions testing in Mexico City. Like the ETC, the MCS has three segments. The segments, MX1, MX2, and MX3, have average speeds of 11, 21, and 23 kilometers per hour, respectively. The MX1 has a maximum speed of 51 km per hour, while the MX2 and MX3 have maximum speeds of 68 and 71 km per hour, respectively. The cycle covers approximately 14.9 kilometers. The cycle is presented in Figure A-4. Mexico has no program in place for heavy-duty fuel efficiency or GHG emissions at this time but is considering aligning with the U.S. program.

Figure A-4. The Mexico City Schedule (MCS)

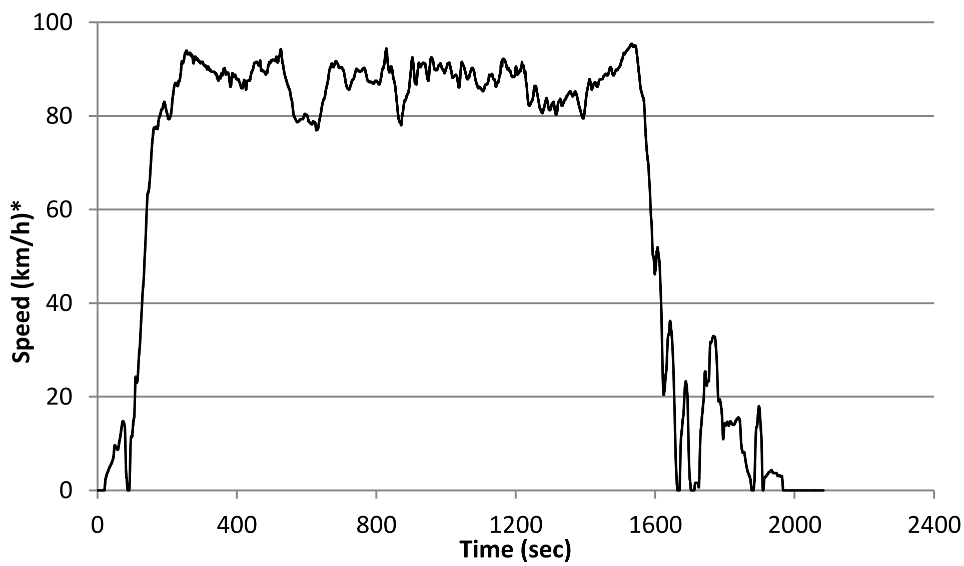


Highway Cycles

Heavy Heavy-Duty Diesel Truck Schedule (HHDDTS) – Cruise

Figure A-5 shows the Cruise cycle of the HHDDTS, described above. This highway cycle has average speed of 64 km/hr and maximum speed 95 km/hr.

Figure A-5. HHDDTS Cruise Cycle

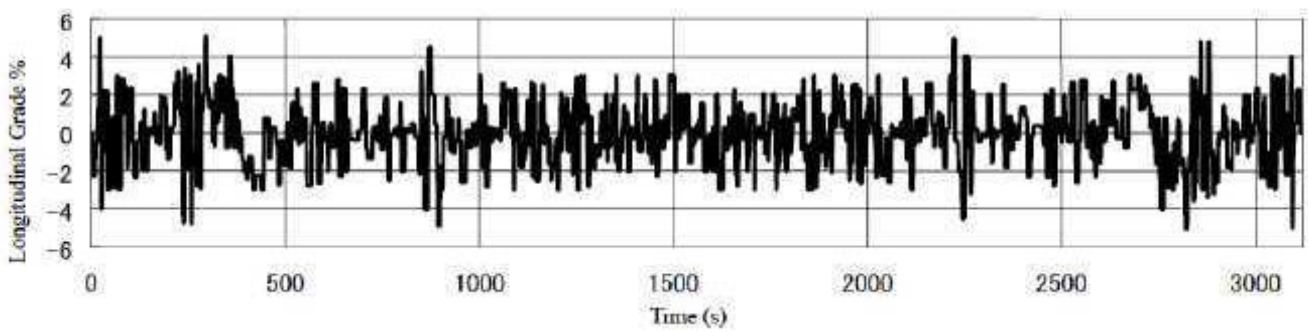


*Actual speed units are miles per hour

Interurban Mode

Japan's heavy-duty fuel consumption test includes an Interurban Mode, in addition to the transient JE05 shown above. The Interurban Mode has a constant vehicle speed of 80 km per hour but varying grade. The grade profile of the Interurban Mode is shown in Figure A-6.

Figure A-6. Japan Interurban Mode (constant vehicle speed of 80 km/h)

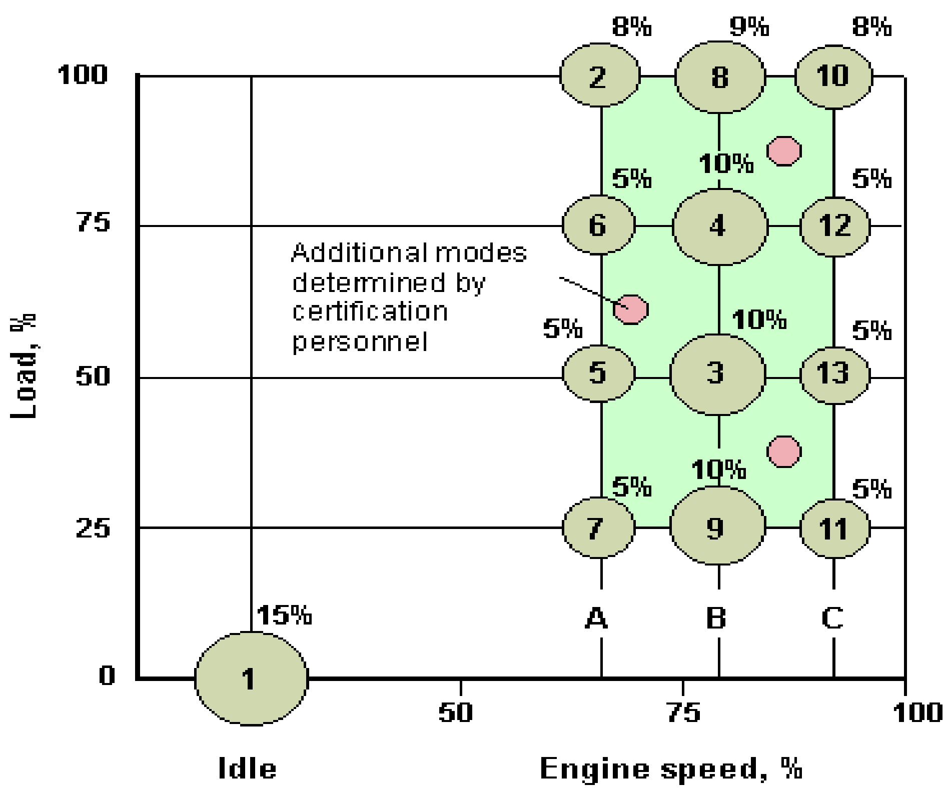


Source: Daisho (2007)

Supplemental Emissions Test (SET)

The SET (Figure A-7) is an engine test used for criteria pollutant testing to supplement the FTP.

Figure A-7. Supplementary Emissions Test for Heavy-Duty Engines



Source: DieselNet.com

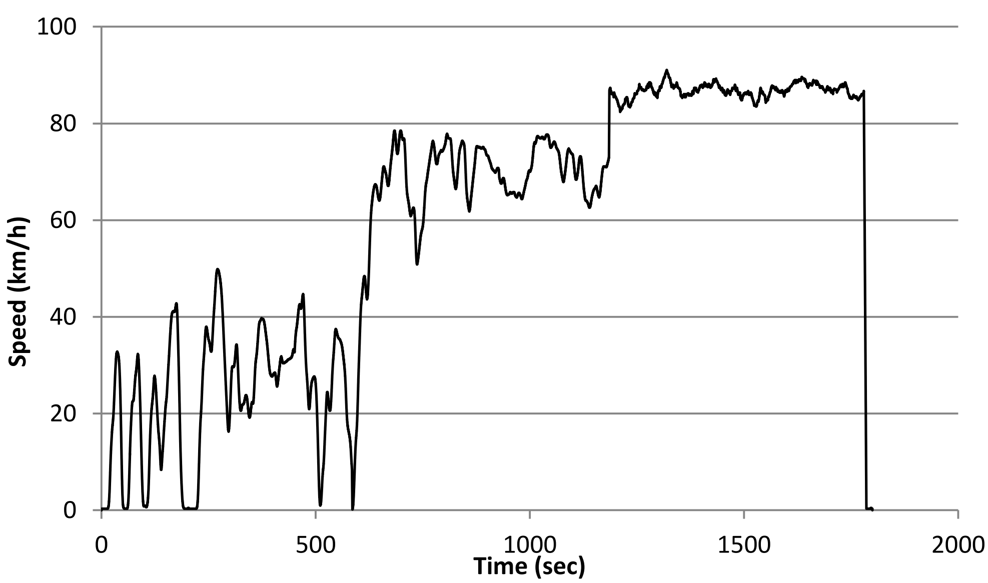
Combined Cycles

European Transient Cycle (ETC)

The FIGE Institute of Germany developed the European Transient Cycle (ETC) from real-world data on heavy-duty vehicles (Ahlvik 2008). The cycle, shown in Figure A-8, has three segments, representing urban, rural, and motorway driving, each running for 600 seconds. The vehicle does not come to a stop between the rural and motorway segments, so these cannot be used independently without modification. The cycle covers 29 kilometers. The maximum speeds for the urban, the rural, and the motorway segments are 23 km/hr, 72 km/hr, and 89 km/hr, respectively.

The FIGE Institute also developed an engine dynamometer version of this cycle, which has been used for the certification of diesel engines since 2000 (Ahlvik 2008, Zhen et al. 2009). The EU heavy-duty diesel engine program regulates gaseous pollutants, including carbon monoxide (CO), hydrocarbons (HC), methane (CH4), and oxides of nitrogen (NOx) as well as particulate matter (PM) and smoke opacity. The Euro VI regulation specifies that carbon dioxide (CO_2) emissions and fuel consumption must be measured during the emissions tests, although no limits are specified (EC 2009). Emissions of CO, HC, NOx, and PM will be measured on the European Steady State Cycle (ESC) as well as the engine ETC for Euro V, while smoke opacity will be measured on the European Load Response (ELR) test. However, beginning with Euro VI standards, emissions and fuel consumption will also be evaluated on the World-wide Harmonized Steady State Cycle (WHSC) and the World-wide Harmonized Transient Cycle (WHTC) (cf. Figure A-9 for corresponding vehicle cycle) (EC 2009). However, emission standards are expressed on the basis of the ESC and the ETC engine cycles. The European Commission is working to establish correlation factors between the European and Worldwide harmonized drive cycles and to specify their equivalent values. The U.S. SET coincides with the European Stationary Cycle (ESC) (DieselNet.com).

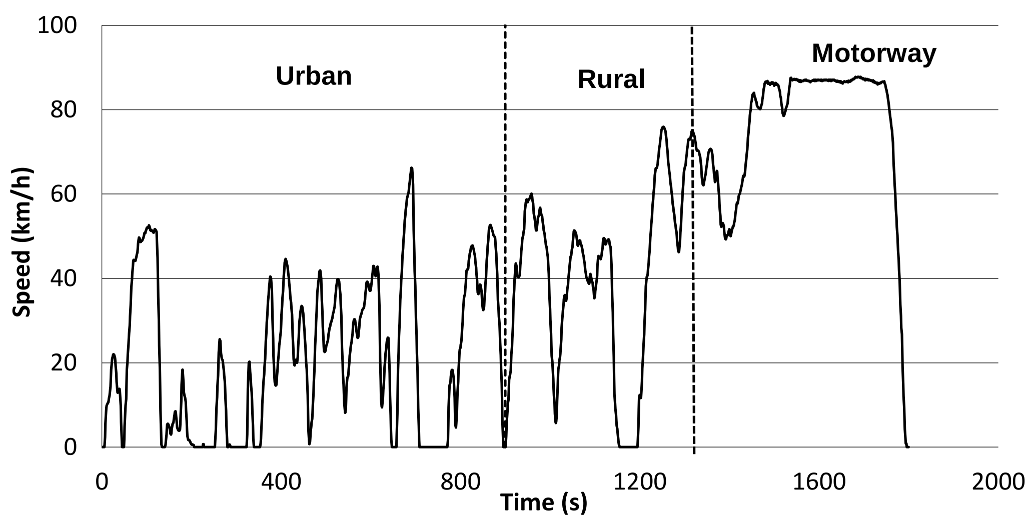
Figure A-8. ETC Cycle



World-Wide Transient Vehicle Cycle (WTVC)

The World-wide Transient Vehicle Cycle (WTVC) was developed by the Working Committee of Pollution and Energy of the United Nations Economic Commission for Europe (UNECE 2005). The cycle was based on heavy-duty vehicle data collected from Australia, the European Union (EU), Japan, and USA (Heinz 2001). The total duration of this cycle is 1800 seconds, and it is divided into three segments: Urban, Rural, and the Motorway, similar to the ETC and the MCS. However, the Urban Segment is long compared to the Rural and the Motorway segments. The Urban, the Rural, and the Motorway segments run for 900 seconds, 500 seconds, and 400 seconds, respectively, as shown in Figure A-9. Although the Urban segment can be treated as an independent cycle, the Rural and the Motorway segments are connected similar to the ETC Cycle. The average speeds for the Urban, the Rural, and the Motorway segments are 13.3 mph, 27.3 mph, and 47.9 mph, respectively, while their maximum speeds are 41 mph, 47 mph, and 55 mph, respectively. The cycle also was used to create an engine cycle for criteria pollutant emissions testing, which is expected eventually to replace the ETC Cycle for certification of diesel engines in the EU for Euro VI (Ahlvik 2008).

Figure A-9. World-Wide Transient Vehicle Cycle



China proposes to use a slightly modified version of this cycle for its heavy-duty vehicle fuel consumption program (CATARC 2010a). The modifications entail a small reduction in peak power demand at some points in the cycle, reflecting the lower horsepower of trucks in China (ICCT 2011). In addition, China would weight the three cycle segments to better reflect commercial driving patterns there (CATARC 2010b). The weightings would vary with vehicle class.

Selected properties for the cycles in our survey are shown in A-1. While the cycles have significant differences, all have maximum speed in the range of 88-95 km per hour with the exception of the Mexico City Cycle, which was developed from transit bus operating data rather than truck operating data. Average speed and maximum speed for transient and cruise operations are fairly consistent across the HHDDTS, the ETC, and the WTVC, while the two single-mode cycles UDDS and JE05 have similar average speeds and maximum speeds. That raises the prospect that vehicle behavior across these regions could be sufficiently similar to permit the creation of common test cycles.

Table A-1. Properties of Selected Heavy-Duty Vehicle Test Cycles

Driving Cycle	Duration (seconds)	Average Speed (km per hour)	Maximum Speed (km per hour)	Regulatory Application
Urban				
HHDDTS Transient	668	24	77	US fuel efficiency and GHG rule, along with two steady-state cycles
JE05	1829	27	89	Japan's heavy duty vehicle fuel economy program (engine version for criteria pollutant emissions program)
UDDS (also known as heavy-duty FTP)	1059	30	93	Engine version used for certification of heavy-duty engines in U.S.
MCS (MX1/MX2/MX3)	1000/1000/1000	11/21/23	51/68/71	None
Highway				
HHDDTS Cruise	2083	64	95	None
Interurban Mode		80	80	Japan's heavy duty vehicle fuel economy program
Combined				
ETC (Urban/Rural/Motorway)	600/600/600	23/72/89	50/79/93	Engine version used for criteria pollutant emissions program in the EU
WTVC (Urban/Rural/Motorway)	900/500/400	21/43/77	66/76/89	Proposed with modification for China's HDV fuel consumption program
ACEA long-haul prototype (Urban/Rural/Motorway)	2%/13%/85%	78	85	Under development for EU HDV GHG Program

Appendix B: Component Testing

ENGINE TESTING

A brief description of each region's engine test protocol is provided below.

Japan

Japan's heavy-duty program does not regulate the engine separately. The engine fuel map is an essential input for vehicle simulation, however. Each engine intended for use in heavy-duty application will be tested on an engine dynamometer to generate fuel consumption data at a minimum of thirty speed-torque points (six engine speeds and five torque values), chosen by the manufacturer. The manufacturer will use these results to develop an engine map (MJ Bradley 2009).

For testing vehicles in transient operation, engine speed and torque vs. time data must be generated based on the vehicle speed points in the JE05 Transient Cycle and applying a suitable drivetrain model (Rakopoulos and Gaikoumis 2009). For each engine, manufacturers will have to supply full load engine torque, idling engine revolution, maximum output engine revolution, and maximum engine revolution with load, among other inputs to the drivetrain model.

U.S.

Engines are regulated separately in the U.S. heavy-duty GHG and fuel efficiency program. Engines are grouped in families; an engine family "consists of several ratings having slightly different horsepower and/or torque characteristics but no differences large enough to require a different engine family designation" (EPA 2009). Only one engine per family will be tested (EPA and NHTSA 2011b). For regulatory purposes, all engines in a family are assumed to have the same emissions performance as the parent engine in terms of grams or gallons per brake horsepower hour. Thus manufacturers do not need to test every engine for vehicle fuel economy and GHG emissions compliance.

In practice, two engines in the same family may differ by more than 100 HP in engine power and more than 200 lb-ft in engine torque. A single engine family can also include more than one engine model (CARB 2011). The size of engine families warrants further analysis in the U.S. For criteria pollutant emissions, the parent engine in a family is by definition the highest-emitting engine. These engine families and parents are preserved under the fuel consumption and GHG emissions rule, so there is no guarantee that the parents will be the highest consuming engines in the family. Hence an engine may have fuel consumption well in excess of its certification value. The EPA asserts that this is unlikely to occur, however (EPA and NHTSA 2011a).

Testing is conducted on the steady-state Supplemental Engine Test (SET) (Figure A-7) and/or transient Federal Test Procedure (FTP) Engine Cycle, depending on whether the engine is used for long-haul operation and in vocational applications, or both. The FTP is the engine version of the UDDS vehicle cycle shown in Figure A-3.

China

China does not propose to regulate engines for fuel consumption, but engine parameters as well as engine fuel consumption maps are key inputs to the vehicle simulation model. The fuel consumption map will be based upon at least 81 speed-torque data points. These data points are to be selected as uniformly as possible from the point of 10% engine load to the point of the maximum torque within the normal range of engine speed (CATARC 2010b). Several additional engine characteristics will need to be specified as inputs to the simulation as well, including reverse drive torque, engine speed and fuel consumption during idling, rated and maximum engine speed, and maximum torque (CATARC 2010a, 2010b). Manufacturers will need to test every engine that will be used in a heavy-duty vehicle.

EU

The EU program will require an engine fuel map as an input for simulation modeling. The engine fuel map will be based on fuel consumption rates at more than 80 test points (Schukert 2011), defined by 10 engine speeds at equal intervals and 10 engine load levels (TU Graz 2011). The existing steady-state and transient engine cycles (World Harmonized Stationary Cycle and World Harmonized Transient Cycle) are viewed as inadequate, because they do not cover all engine operating conditions (TU Graz 2011).

Aerodynamics and Rolling Resistance

This section provides details of each region's handling of coefficients of drag (C_d) and rolling resistance (C_{rr}), followed by a description of four methods of measuring C_d.

US

The U.S. program adopts a coastdown test as the primary method for measuring aerodynamic drag coefficient, C_d. However, alternative methods including wind tunnel testing and computational fluid dynamics can be used with preliminary approval from the agencies. In that case, C_d values determined from the alternative method must be corrected by a constant adjustment factor, as outlined in the rule (EPA and NHTSA 2011a).

The overall tire C_{rr} will be calculated by the equation:

$$C_{rr} = 0.425 \text{ x Trailer } C_{rr} + 0.425 \text{ x Drive } C_{rr} + 0.15 \text{ x Steer } C_{rr}$$

The C_{rr} for trailer tires is specified as 0.006, but C_{rr} for the steer and drive tires is determined by the vehicle or tire manufacturers per ISO 28580.

Japan

Japan's vehicle simulation uses standard values for the coefficients of aerodynamic and rolling resistance, depending on vehicle category. They are computed as follows:

$$C_d{*}A = 0.00299\ B{*}H - 0.000832$$

$$C_{rr} = 0.00513 + 17.6/W$$

where A = frontal area, B = full width, H = full height, and W = vehicle curb weight are values fixed for each regulatory class (based on a "standard plain body") (CNRE 2005).

China

In China, coastdown testing is recommended to determine tractive load. The test is to be conducted at full load (CATARC 2010b). For trucks for which manufacturers do not provide coastdown results, a C_d value of 0.8 will be used, and C_{rr} for bias and radial tires for trucks with 14 tons or more design mass will be determined by the following equations:

$$\textbf{Bias Tires: } C_{rr} = 0.0066+0.0000286v$$

$$\textbf{Radial Tires: } C_{rr} = 0.0041+0.0000256v$$

where v is the speed of the testing vehicle in km/h (CATARC 2010b).

EU

The product of drag resistance coefficient and cross sectional area (C_d*A) will be determined by constant speed testing, but coastdown testing may remain as an alternative option for OEMs (TU Graz 2011). Regulators may be satisfied with the labeled rolling resistance coefficient provided by tire manufacturers.

AERODYNAMIC DRAG TESTING

This section describes the various means of determining aerodynamic drag, all of which play a role in one or more of the regional programs discussed in this report.

Coastdown Testing

The EPA and NHTSA have largely adopted the Society of Automotive Engineers (SAE) Surface Vehicle Recommended Practice SAE J1263, Road Load Measurement and Dynamometer Simulation Using Coastdown Techniques (SAE 2010), with some adjustment required due to the fact that the existing coastdown protocols were established primarily for light-duty vehicles (EPA and NHTSA 2011b).

In coastdown testing, the vehicle is driven on a dry, clean, smooth road not exceeding 0.02% grade. If grade is greater than 0.02% then its effects should be incorporated into the calculation of road load (EPA and NHTSA 2011b). A minimum of 10 valid runs, 5 in each direction, must be made (SAE 2010). For each run, the vehicle is accelerated 5 mph above the high point of coastdown speed range, the transmission is shifted to neutral gear and measurements of speed are taken until the vehicle reaches a speed less than the lower point of the coastdown speed range. The range of speed over which the vehicle is tested should be as large as possible considering the length of the straightaway (SAE 2010). The speed data points collected must range from 70 mph down to 15 mph and must include 50 mph (EPA and NHTSA 2011b). The coefficients of the road load equation are determined for each individual valid coastdown run and are then averaged over all pairs of coastdown results (i.e., one in each direction) in each data set. Corrections are applied for the wind, temperature, and air density. Finally, the drag area C_d*A is calculated, from which the drag coefficient C_d is determined, since frontal area of the vehicle is known (EPA and NHTSA 2011b).

This method is simple and is already used by light-duty manufacturers for vehicle certification. Replicability of the coastdown result is not high, however, and the effect of variable wind direction on the drag coefficient cannot be captured (EPA and NHTSA 2011b).

Wind Tunnel Methods

A wind tunnel provides a stable test environment in which a full-scale vehicle or a model can be tested to determine the aerodynamic drag. This method also allows the introduction of positive or negative yaw angle in order to capture the effect of non-uniform direction of wind on drag coefficient. This method saves time and helps ensure repeatability of data. However, building a full-scale wind tunnel is time consuming and costly, and existing facilities in North America are limited. Manufacturers often use a reduced scale wind tunnel where the scale is reduced to 40% or 12.5% (DTNA 2011).

The U.S. heavy-duty rule requires the use of procedures specified in SAE Wind Tunnel Test Procedure for Trucks and Buses, SAE J1252 (SAE 1981). SAE J1252 specifies that the tunnel test section size and speed be determined by a Reynolds number of at least $0.7x10^6$, but recommends that a higher value be used whenever possible. Researchers from Daimler Trucks North America argue that the minimum number should be 3 to 4 times higher than the SAE recommended value (DTNA 2011).

The testing protocol consists of multiple baseline runs with full yaw sweep regardless of tunnel type (SAE 1981). Testing may be performed for C_d measurements with yaw angles 0, +1, +3, +6, +9, 0, -1, -3, -6, -9, and 0 (SAE 1981), although results from zero yaw angle will be used for compliance (EPA and NHTSA 2011b).

Computational Fluid Dynamics

This method models the effect of wind drag on the vehicle using either the Navier-Stokes equations or the Boltzman equation. The Navier-Stokes equations relate the physical law of conservation of momentum to the flow relationship of a dynamic object when the vehicle is moving through the airflow or of a static body when air is moving around the static vehicle. It can be termed a “macro” approach. The Bolzman equation takes a “micro” approach, in which the characteristics of discrete, individual particles within a fluid are determined to model the overall dynamics and behavior of the fluid, in this case the airflow (EPA and NHTSA 2011a).

Given the drag coefficient of one vehicle, CFD can easily calculate the drag of variants of that vehicle, thus saving time and money. However, the accuracy of the result is largely dependent on the assumptions made for the basic vehicle. (EPA and NHTSA 2011a).

Constant Speed Test

Constant speed testing is an alternative method for measuring C_d, or more properly C_d*A. This is the recommended method for the EU program (TU Graz 2011). Since the vehicle is driven at constant speed, the acceleration/deceleration is zero and therefore the tractive force at the wheel is the sum of drag, rolling resistance, and grade force. Determination of tire rolling resistance coefficients, vehicle frontal area, and the altitude profile will provide all unknown parameters and thus C_d can be readily calculated. The final value should also be normalized to ambient temperature and pressure (TU Graz 2011).

Appendix C: EU Segmentation

Table C-1 shows the full segmentation proposed for heavy-duty vehicles in the EU.

Table C-1. Proposed EU Segmentation of Heavy-Duty Vehicles

	Identification of vehicle class				Segmentation (vehicle configuration and cycle allocation)					Norm-body allocation		
Axles	Axle configuration	Chassis configuration	Maximum GVW [t]	<-- vehice class	Long haul	Regional delivery	Urban delivery	Municipal utility	Construction	Standard body	Standard trailer	Standard semitrailer
2	4x2	Rigid	>3.5 - 7.5	0		R	R			B0		
2	4x2	Rigid or Tractor	7.5 - 10	1		R	R			B1		
		Rigid or Tractor	>10 - 12	2	R	R	R			B2		
		Rigid or Tractor	>12 - 16	3		R	R			B3		
		Rigid	>16	4	R+T	R		R		B4	T1	
		Tractor	>16	5	T+S	T+S						S1
	4x4	Rigid	7.5 - 16	6						B1		
		Rigid	>16	7					R	B5		
		Tractor	>16	8								W1?
3	6x2/2-4	Rigid	all weights	9	R+T	R		R		B6	T2	
		Tractor	all weights	10	T+S	T+S						S2
	6x4	Rigid	all weights	11					R	B7		
		Tractor	all weights	12					R			S3
	6x6	Rigid	all weights	13						W7		
		Tractor	all weights	14						W7		
4	8x2	Rigid	all weights	15		R				B8		
	8x4	Rigid	all weights	16					R	B9		
	8x6 & 8x8	Rigid	all weights	17					R	W9		

R = Rigid & Body

R+T = Rigid & Body & Trailer *)

T+S = Tractor & Semitrailer

*) Whether it is sufficient to simulate the truck-trailer combination based on cd*A for Rigid & Body or the full-vehicle test for aerodynamic drag has to be performed additionally with Rigid & Body & Trailer has to be clarified

Source: TU Graz (2011)