Trucks and Climate Change

Setting the Stage for Regulation of Heavy-Duty Vehicle Fuel Economy & GHG Emissions: *Issues and Opportunities*

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ABOUT ICCT:

The goal of the International Council on Clean Transportation (ICCT) is to dramatically reduce conventional pollution and greenhouse gas emissions from personal, public, and goods transportation in order to improve air quality and human health, and mitigate climate change. The Council is made up of leading government officials and experts from around the world that participate as individuals based on their experience with air quality and transportation issues.

The ICCT promotes best practices and comprehensive solutions to improve vehicle emissions and efficiency, increase fuel quality and sustainability of alternative fuels, reduce pollution from the in-use fleet, and curtail emissions from international goods movement.

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Executive Summary

This document discusses issues related to the regulation of fuel efficiency of heavy-duty vehicles in the United States. While new U.S. light-duty vehicles (cars and light trucks) are required to meet minimum corporate average fuel economy standards, medium and heavy-duty vehicles (larger trucks and buses) are not. There are currently no federal standards for the fuel economy of large trucks and buses, either for individual models or as a fleet average.

In December 2007 Congress passed, and the President signed, the Energy Independence and Security Act (EISA). This law mandates, among other things, that the Department of Transportation develop, for the first time, fuel economy standards for medium and heavy-duty vehicles. The law requires new standards for both "work trucks" with a gross vehicle weight rating (GVWR) of 8,500 – 10,000 pounds and "medium- and heavy-duty vehicles" with a GVWR over 10,000 pounds.

At the same time, the US Environmental Protection Agency (US EPA) is developing a plan to reduce greenhouse gas (GHG) emissions under the authority conferred by the Clean Air Act. In the agency's Advance Notice of Proposed Rulemaking several options for regulating GHGs from medium- and heavy-duty trucks are described.

The current U.S. heavy-duty vehicle (HDV) fleet is extremely diverse, in terms of vehicle size and configuration, as well as usage patterns. It encompasses everything from 18-wheel combination trucks used to haul freight, to school and transit buses, to numerous "vocational" trucks such as refuse haulers, utility service trucks, and dump trucks. The largest of these vehicles – combination trucks comprised of a truck-tractor pulling a trailer – typically weight 80,000 pounds or more. In 2005 the 8.5 million heavy-trucks registered in the U.S. traveled over 222 billion miles and emitted almost 350 million metric tons of carbon dioxide to the atmosphere - approximately 19% of the CO2 emissions from all transportation sources.

The development of effective fuel efficiency and GHG regulations for HDVs will require attention to numerous technical and policy-related details. Decisions as to the "best" regulatory design must be based on a thorough understanding of existing and future characteristics of the HDV fleet, the structure and characteristics of the HDV manufacturing industry, and potential technology approaches available to reduce HDV fuel use and GHG emissions.

The technical issues that must be addressed range from the metric used to measure fuel economy or GHG emissions, to the format of required improvements, to the test method used to verify compliance. Policy-related issues that can significantly affect the implementation cost and the effectiveness of the regulations include: specific vehicle types to be regulated, companies responsible for compliance, the implementation timeline, provisions for compliance flexibility, and methods of enforcement.

For each technical and policy area there are a number of options available to policymakers. Different approaches will have different potential benefits, costs, and implementation issues. The optimal regulatory design will balance these different implementation issues to achieve cost-effective improvements.

This document is intended to set the stage for an effective and productive dialogue about the optimal regulatory design for HDV fuel efficiency and GHG improvements. The first six chapters provide background information about the composition of the U.S. HDV fleet and the structure of the HDV manufacturing industry; major factors that contribute to fuel use by HDVs; current voluntary efforts and regulatory requirements to increase HDV fuel efficiency in the U.S., Japan, and the European Union; and the technology options available to improve HDV fuel efficiency. The remainder of the document discusses specific technical and policy issues that must be addressed in the design of HDV fuel efficiency and GHG regulations, barriers to implementing these regulations in the U.S., related policy issues, and recommendations for further research and analysis. To address these issues the ICCT has developed a research work plan. The document concludes with a description of recommended research priorities for ICCT to consider in the near term.

1. Purpose

There is considerable interest in the U.S. and internationally in reducing fuel use and green house gas (GHG) emissions from heavy-duty vehicles (HDV). This interest parallels other efforts to reduce fuel use and GHG emissions from the entire transportation sector. Internationally these efforts are primarily related to reduction of GHG emissions, while in the U.S. there is also significant interest in increasing "energy security" by reducing the need to import petroleum and other fuels.

To date most government efforts to improve HDV fuel economy have been voluntary, though Japan has enacted regulations that mandate improvements.

This paper is intended to set the stage for future international regulation of HDV fuel economy and GHGs by providing background information on heavy duty fleets and HDV fuel use, and by identifying and discussing the major topics and issues relevant to design and implementation of fuel economy standards specifically for heavy-duty vehicles. This paper will focus specifically on the U.S. HDV fleet. In addition to regulatory design issues, this paper discusses potential barriers to the implementation of HDV fuel economy regulations in the U.S. context, and provides recommendations on key research required to move any U.S. regulatory effort forward. While the specifics of HDV fleets, and the potential barriers to regulatory implementation, will vary by country the major issues discussed in this paper have general applicability in all countries.

This paper focuses exclusively on on-road heavy-duty vehicles, and does not address non-road vehicles and equipment used for construction, agriculture, forestry, and mining.

This paper is intended as a resource for all parties interested in this subject, including vehicle and technology manufacturers, government agencies, and non-governmental organizations. It is hoped that this paper will begin to frame the debate in a way that will allow all interested parties to productively discuss the relevant issues, and to move cooperatively toward effective and cost-effective solutions.

2. The U.S. Heavy-Duty Vehicle Fleet

The U.S. heavy-duty on-road vehicle fleet is diverse, encompassing everything from 18-wheel combination trucks used to haul freight, to school and transit buses, to numerous “vocational” trucks such as refuse haulers, utility service trucks, and dump trucks.

The U.S. Department of Transportation categorizes trucks into classes based on their gross vehicle weight rating (GVWR)[1]. See Figure 2.1, which illustrates “typical” vehicles that would fall into each class. As shown, Class 1 and 2 vehicles lighter than 10,000 pounds are considered “light trucks” – these would be pick-ups, small vans and sport utility vehicles, most or which are powered by gasoline engines; over 80% of these light trucks are used for personal transportation [2-1]. In the U.S. Class 1 and 2 light trucks up to 8,500 pounds GVWR are currently subject to Corporate Average Fuel Economy (CAFE) standards similar to, but less stringent than, those imposed on cars. These light trucks are also subject to the same emission standards as cars. As a result, Class 2 trucks with GVWR above 8,500 lbs. are more similar to Class 3 trucks than to lighter Class 2 trucks.

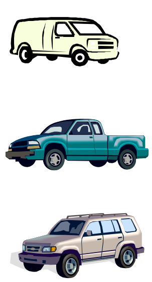
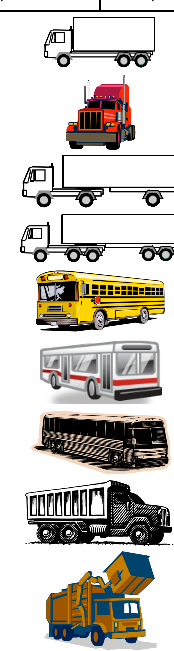
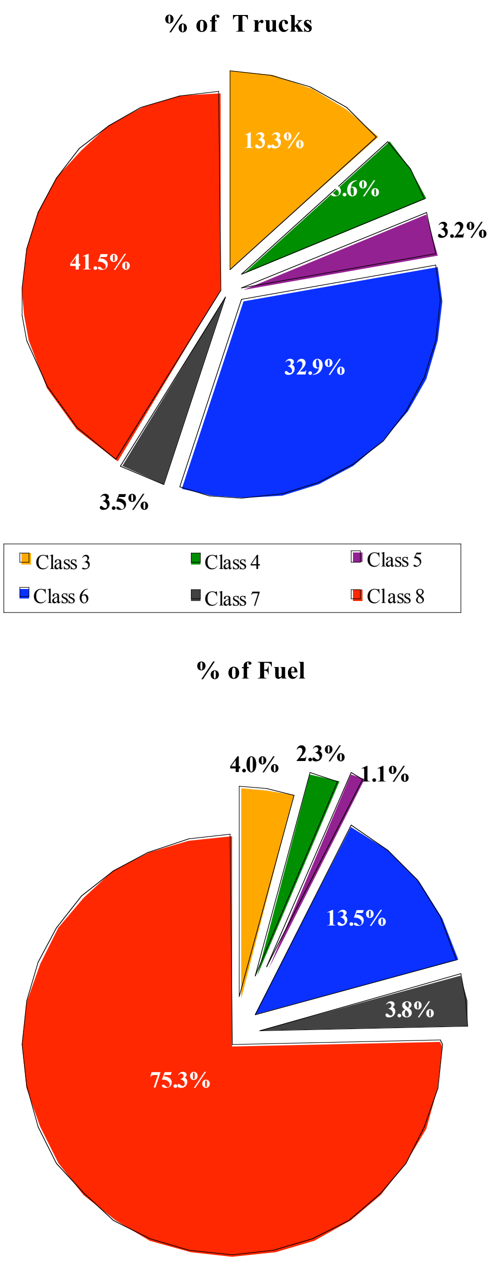
Light-Duty		*Medium Heavy-Duty*				*Heavy-Duty*	
Class 1	**Class 2**	**Class 3**	**Class 4**	**Class 5**	**Class 6**	**Class 7**	**Class 8**
Less than 6,000 lb	6,000 to 10,000 lb	10,000 to 14,000 lb	14,000 to 16,000 lb	16,000 to 19,500 lb	19,500 to 26,000 lb	26,000 to 33,000 lb	Greater than 33,000 lb
							

Figure 2.1 Truck Weight Classes

[1] GVWR is the maximum design weight of the vehicle, including any pay load.

Vehicles in weight class 3 and above are almost exclusively commercial vehicles powered by diesel engines, and are considered to be "heavy-duty vehicles". Class 3 – 6 vehicles are considered medium heavy-duty, and generally have only a single rear axle, while Class 7 and 8 vehicles are heavy heavy-duty and often have two or more rear axles.



Source: DOE

Figure 2.2 Heavy Truck Fleet and Fuel Use, 2002 [2-5]

The largest Class 8 trucks have a GVWR of 80,000 pounds or more, and are exclusively combination trucks composed of a three-axle tractor pulling a trailer with two or more axles.

Vehicles, Mileage, and Fuel Use

In 2005 there were 8.5 million heavy trucks[2] registered in the U.S. [2-2]. These trucks traveled over 222 billion miles that year, consumed 33.5 billion gallons of diesel fuel, and emitted almost 350 million metric tons of carbon dioxide[3] to the atmosphere. This was approximately 19 percent of the CO_2 emissions from all transportation sources in that year [2-3].

Between 1990 and 2005 heavy truck registrations increased by 37 percent and annual fleet vehicle miles traveled increased by 52 percent. Over that period registrations increased at an average annual rate of 2.2%, while mileage increased at an average annual rate of 2.9%. The number of miles traveled annually by Class 8 trucks is expected to continue to increase – by as much as 40 percent through 2020 [2-4].

Since 1990 the average fuel economy of single unit trucks has increased from 6.2 to 8.8 miles per gallon (MPG) while the average fuel economy of combination trucks has only increased from 5.8 to 5.9 MPG [2-2].

See Figure 2.2, which shows the percentage of the truck fleet and fuel usage by weight class in 2002.

Class 3 – 6 medium heavy-duty vehicles are typically used for construction, agriculture, retail trade or for-hire local freight delivery. Larger single-unit freight haulers, most buses, many vocational trucks (refuse haulers, dump trucks), and all combination trucks are Class 7 or 8.

Of those vehicles with more than two axles or more than four tires, 75 percent are single-unit trucks

[2] This includes trucks with more than two axles or more than four tires, generally Class 4 – 8.

[3] Burning one gallon of #2 diesel creates 22.6 pounds of CO_2.

(Class 4 – 8) and 25 percent are combination trucks (Class 8) [2-2].

In 2005 the average single unit truck traveled 12,400 miles while the average combination truck traveled 68,800 miles.

Given their greater weight, lower average fuel economy, and higher usage, in 2005 Class 8 trucks used approximately 75 percent of all fuel consumed by heavy-duty trucks (class 4-8) [2-2].

Heavy-duty Vehicle Use

Heavy-duty vehicles are found in every sector of the economy and are used to perform a wide array of functions, from carrying freight, to carrying passengers, to hauling trash, to mixing and hauling concrete. Different vehicle types can have widely varying duty cycles, including those characterized by mostly high-speed highway operation with few stops, medium-speed suburban operation, and low-speed urban operation with a high number of stops per mile.

The single biggest use of heavy-duty trucks in the U.S. is for hauling goods and materials; over thirty percent of all Class 7 and 8 vehicles are used to provide for-hire transportation of freight [2-1]. Trucks are used to carry 66 percent, by weight, of all goods shipped [2-6].

As noted above the majority of fuel consumed by the heavy-duty fleet is consumed by Class 8 combination trucks. These trucks are used almost exclusively for hauling various types of freight long distance. The trailers that they pull include open flat bed trailers, enclosed box trailers, dump trailers, car haulers, and tanker trailers.

Trucks are also used to haul "intermodal" shipments. These shipments are carried by rail or ship for part of their journey and by truck the rest. Intermodal goods are shipped in standard box-like metal shipping containers that get transferred from rail or ship to the truck without being unpacked. The shipping container rests on a light weight trailer frame that is pulled behind a truck tractor like other combination trailers; the combination of shipping container and trailer look similar to an enclosed box trailer. Approximately seven percent of all goods shipped within the U.S. in

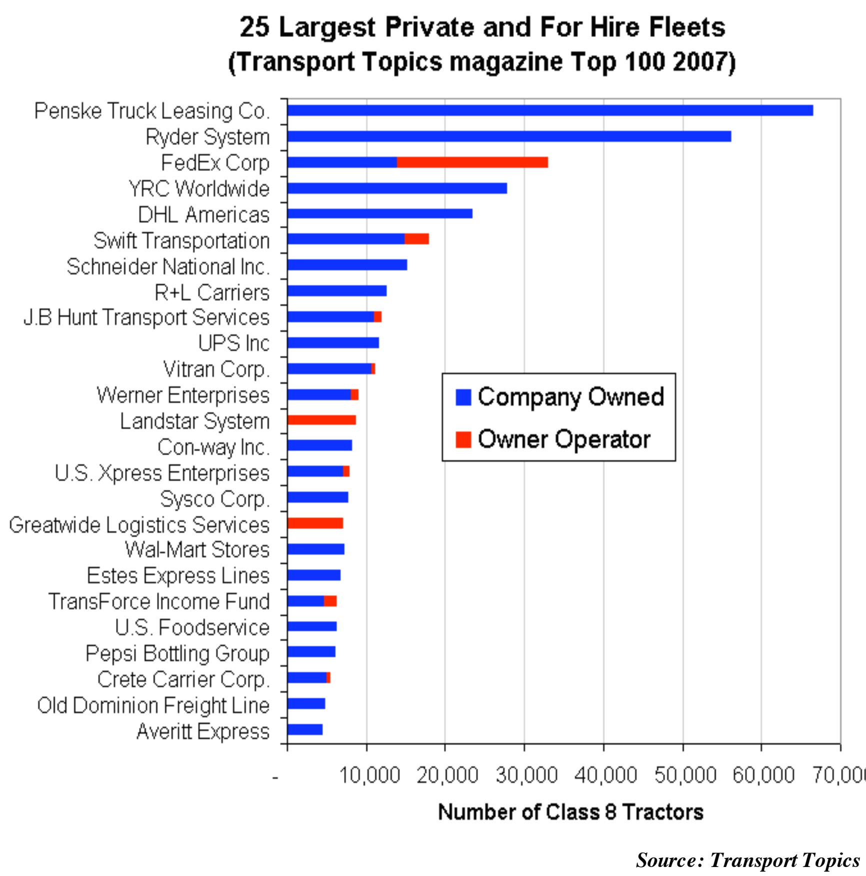


Figure 2.2 25 Largest Private and For-Hire Fleets [2-7]

2006 (by weight) were shipped intermodally [2-8]. Most of this volume was likely shipped in standard intermodal shipping containers.

Typically a specific truck is not used to pull a specific trailer full time. One Class 8 truck will be used to pull multiple trailers over the course of a year.

Most Class 8 combination trucks spend the majority of their time on the nation's highways operating at high, sustained speeds. Some of these trucks are used for local or regional deliveries and experience a greater percentage of suburban or urban driving conditions.

Heavy-Duty Vehicle Ownership

Heavy-duty trucks can be found in the fleets of virtually all local and state governments, and every agency of the federal government. The vast majority, however, are corporately owned and used for commercial purposes.

The largest company-owned fleet of heavy-duty vehicles in the U.S. includes over 60,000 Class 8 tractors. The two hundred largest private and for-hire freight hauling fleets together control over 600,000 Class 8 tractors, and 330,000 Class 4 – 8 single-unit trucks, approximately 11% of registered heavy-duty vehicles [2-7]. Of these Class 8 tractors, 86% are company-owned and 14% are "owner-operator" trucks as shown in Figure 2.3. These fleets also control over 1.1 million trailers.

A large percentage of HDVs are owned and operated by small companies or individuals. Less than two hundred U.S. companies control more than two hundred freight-hauling trucks each. Up to fifty percent of all heavy-duty trucks are in fleets of less than ten trucks, and up to thirty percent of all Class 8 tractors are owned and driven by an owner-operator with only one truck [2-9].

In many cases the truck and trailer that make up a "combination truck" on any particular day will be owned by different companies.

Heavy-Duty Vehicle Manufacturing

Of the Class 7 and 8 vehicles in-use in 2002, over sixty percent had been built by only five truck manufacturers: Freightliner, Kenworth, International, Mack, and Peterbuilt [2-8], and these same five companies accounted for approximately eighty percent of new trucks sold in 2005 [2-10].

Unlike manufacturers of cars and light trucks, not all manufacturers of heavy-duty vehicles produce their own engines. Of new diesel engines sold in Class 8 trucks in 2005, over ninety percent were manufactured by five different engine companies: Caterpillar, Cummins, Detroit Diesel, Mack, and Volvo; only two of these engine manufacturers (Mack and Volvo) also manufacture on-road trucks [2-10].

Many heavy-duty single unit trucks, particularly vocational trucks and school buses, are composed of a body manufactured by one company installed on a chassis[4] produced by another.

The manufacturers of heavy-duty trucks typically do not produce the trailers pulled by combination truck-tractors. These trailers are built by a different set of manufacturers.

See Figure 2.4 for a non all-inclusive list of major HDV manufacturers [2-11].

[4] The chassis usually includes a frame, suspension, engine, drive train, and wheels. It may also include the truck cab.

STRAIGHT TRUCKS/CHASSIS		COMBINATION TRUCKS	
Class 6	**Class 8**	**Tractors**	**Trailers**
Daimler Trucks NA	General Motors	Daimler Trucks NA	Fontaine Trailer
Freightliner Custom Chassis	*Chevrolet*	*Freightliner*	Great Dane
Sterling Truck	Daimler Trucks NA	*Sterling Truck*	Hyundai
Navistar Intl.	*Freightliner*	*Western Star*	Stoughton Trailers
International Trucks	*Sterling Truck*	Navistar Intl.	Strick Corporation
Workhorse Custom Chassis	*Western Star*	*International Trucks*	Trailmobile Corporation
General Motors	Navistar Intl.	Paccar	Transcraft Corporation
Chevrolet	*International Trucks*	*Kenworth*	Utility Trailer Manufacturing
GMC	Paccar	*Peterbuilt*	Vanguard National Trailer Corp.
Ford	*Kenworth*	Volvo	Wabash National Corporation
Isuzu	*Peterbuilt*	*Mack*	
Hino Motors	Volvo		
Mitsubishi Fuso	*Mack*		
Paccar			
Kenworth			
UD Trucks			

VOCATIONAL TRUCK/BODY MANUFACTURERS[1]		
Refuse Trucks		***School Buses***
Amrep	Kann Manufacturing Corp.	Blue Bird Corporation
Autocar	Loadmaster	Collins Bus Corporation
Bridgeport Truck Manuf.	Mack Trucks	*Corbeil Bus Corporation*
Crane Carrier	McNeilus Companies, Inc.	*Mid Bus Corporation*
Dempster Equipment Co.	Oshkosh	Daimler Trucks NA
Leach	Pak-Mor Manufacturing	*Thomas Built Buses*
Haul-all Equipment Ltd.	Scranton Manufacturing Co.	Girandin Minibus
Heil Environmental Ltd.	Sterling Truck	Navistar International
Ingold's Hico, Inc.	Wayne Engineering Corp.	*IC Bus*[2]

Companies inset in *italics* are subsidiaries of the company listed above them.

[1] Example only. Other types of vocational trucks are built by different manufacturers. Many of these companies use chassis manufactured by the Truck/Chassis manufacturers.

[2] All Navistar school buses are now sold under the IC Bus brand. Navistar previously sold buses under the International and AmTran brands.

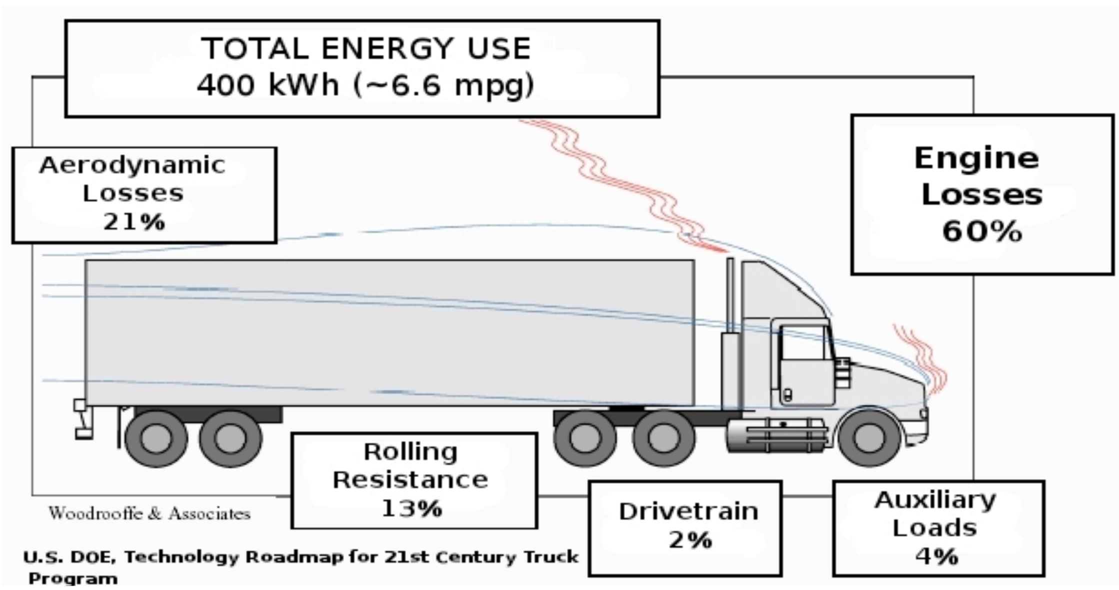
Source: M.J. Bradley & Associates/R.L. Polk & Company

Figure 2.4 Major HDV Manufacturers (non-inclusive list)

3. Components of HDV Fuel Use

The diesel engines used in current heavy-duty vehicles have on average 33% thermal efficiency in-use compared to gasoline engines at approximately 25%. Still only about one third of the input energy in the fuel they burn is turned into useful work as measured at the engine output shaft. The other two thirds of fuel input energy are lost to engine friction, goes out the vehicle tail pipe as heat, or is dissipated as heat by the engine's cooling system.

Of the energy that is turned into useful work by the engine, some is used to power engine accessories (i.e. alternator, air compressor, hydraulic fans) and some is dissipated in the vehicle's transmission and drive train. What is left is used to overcome inertia, gravity, aerodynamic drag, and rolling resistance to accelerate the vehicle and keep it moving down the road and up and over hills. See Figure 3.1, which shows the percentage contribution of various energy uses for a typical combination truck operating at highway speeds on a level road.



Source: USDOE

Figure 3.1 Component of Energy Use on a Class 8 Combination Truck [3-1]

The amount of net energy that goes toward overcoming inertia, versus overcoming aerodynamic drag and rolling resistance, varies significantly based on duty cycle. As shown in Figure 3.1, for a combination truck operating at highway speeds on a level road, more than half of net energy is typically dissipated in aerodynamic losses By comparison, aerodynamic losses are very low for an urban bus in slow, stop-and-go traffic, while the energy required to repeatedly accelerate the vehicle from a stop in that duty cycle could consume significantly more than 50% of net energy delivered by the engine [3-2].

Some vocational vehicles also use some engine power to do work other than driving – for example powering the hydraulic packer on a refuse truck. Other vehicles use a significant portion of total fuel to keep the engine idling while the vehicle is stationary. This is often done to power some relatively small "hotel" loads to provide driver or passenger comfort – for example on a bus that idles the engine to keep the passenger compartment warm in the winter, or a combination truck that idles the engine all night to provide heat or air conditioning, and electricity, to the sleeper berth while the driver is resting.

Each of these uses of fuel energy on a heavy-duty vehicle is discussed further below.

Engine Losses

Lean-burn compression-ignition engines, like those that operate on diesel fuel, are the most efficient internal combustion engines in use today. Even so, potential improvements can be made in net efficiency by modifying current engine equipment and control strategies; more significant gains may also be possible from the use of a completely different combustion cycle.

In recent years achieving efficiency gains in heavy-duty vehicles has been challenging due to more stringent exhaust emission standards that have required changes in the engine itself and/or exhaust after-treatment. In particular, the use of exhaust gas recirculation (EGR) to reduce nitrogen oxide emissions, and the use of diesel particulate filters to reduce particulate emissions, has reduced net efficiency due to higher engine pumping losses, higher engine back-pressure, and diesel fuel required to regenerate active filters. Manufacturers have to date been able to mitigate part or all of this efficiency loss through various engine design improvements. Even more stringent emission requirements that take effect in the 2010 engine model year will require additional changes that might further impact net efficiency.

Drive Train Losses

A heavy-duty vehicle's drive train includes all components which transfer power from the engine to the wheels – it typically includes an automatic or manual transmission, a drive shaft, differentials, and rear axle(s).

Drive train losses result from friction between rotating components and the bearings that support them. In addition, automatic transmissions incur losses in the torque converter used to transfer power between the input and output shafts of the transmission. A manual transmission has no torque converter, so it typically incurs fewer losses than an automatic transmission. Virtually all Class 8 combination trucks currently use manual transmissions, while automatic transmissions are more common in transit and school buses, and some vocational trucks.

Acceleration and Braking

The amount of energy required to accelerate a vehicle from a stop is proportional to the vehicle's mass– the heavier the vehicle is the more energy is required. The rate of acceleration can also affect the net engine and drive train efficiency. Moving a vehicle up a grade at constant speed also requires energy proportional to its mass and to the vertical component of the grade – in order to overcome the effects of gravity.

For most highway vehicles the amount of energy required to overcome inertia, to accelerate the vehicle and climb grades, is a small percentage of the total energy required, because rolling resistance and aerodynamic drag exert much higher forces on the vehicle over an entire day of operation. However, when a conventional vehicle stops, all of its kinetic energy is converted to heat in the braking system[5], which is lost and can not be reused. Additional energy is then required to accelerate the vehicle again from the stop. The percentage of total energy used to accelerate the vehicle, as opposed to overcoming rolling resistance and aerodynamic drag, is

[5] Or is dissipated by aerodynamic loads, rolling resistance, and engine/drivetrain friction/exhaust system pressure if the vehicle coasts to a stop

therefore much higher for urban vehicles that operate in stop-and-go traffic than it is for highway vehicles that operate at near constant speed for most of the day.

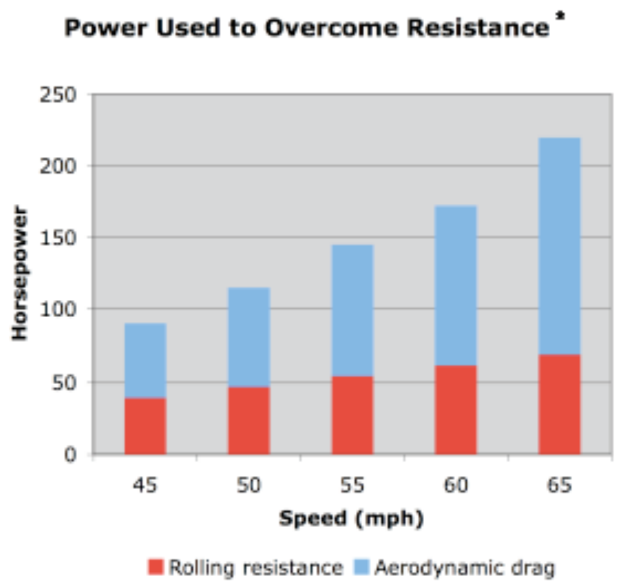
Rolling Resistance

Rolling resistance is the friction exerted on a vehicle's tires by the roadway surface[6]. To keep a vehicle operating at constant speed, even on level ground, engine power is required to overcome this friction. Rolling resistance is proportional to a vehicle's mass, and is also affected by the material, configuration, and air pressure of the vehicle's tires. In general, a tire with low air pressure will have greater rolling resistance than a tire with higher air pressure.

Aerodynamic Drag

Like rolling resistance, the force exerted by the air on a moving vehicle also acts to slow it down, and engine power is required to overcome this force and keep the vehicle moving at constant speed. This force is referred to as aerodynamic drag.

Aerodynamic drag is proportional to the square of the vehicle's velocity – so the amount of energy required to overcome these forces increases faster than the vehicle's speed. See Figure 3.2 which shows the power required to overcome rolling resistance and aerodynamic drag for a typical combination truck at various speeds. As shown, when going from 45 mph to 65 mph the amount of power required to overcome rolling resistance increases from approximately 45 to approximately 60 hp – a 33% increase. By contrast, for the same change in speed the amount of power required to overcome aerodynamic drag increases from approximately 50 hp to over 150 hp – a 300% increase. This is the reason why current highway trucks get better fuel economy at lower speeds.



Source: USDOE

Figure 3.1 Power Used to Overcome Resistance by a Typical Combination Truck [3-1]

Aerodynamic drag is also affected by a vehicle's total frontal surface area and by its shape. A smaller frontal surface area will produce less drag at a given speed. Likewise, sloping shapes that "slice through" the wind produce less drag than flat surfaces directly perpendicular to the direction of travel.

On a heavy-duty combination truck total aerodynamic drag is affected by the size and shape of both the truck tractor and the trailer it is pulling. Issues that can affect total aerodynamic drag include the area and shape of the trailer surface that sticks up above the top of the vehicle cab, the gap distance between the back of the truck cab and the front of the trailer, open space

[6] Some vehicle energy is also dissipated as heat generated within the tires as they flex while rolling over a road surface.

between the bottom of the trailer and the road surface in front of the trailer's wheels, and the shape of the rear trailer surface.

Vehicle Accessory & Hotel Loads

All heavy-duty vehicles include engine-driven components that support various vehicle functions other than propulsion. These typically include an alternator (to provide electrical power for lights, signals, etc), an air conditioning compressor; and air compressor (for air brakes); a fan that is part of the engine cooling system; and oil, coolant, fuel, and power steering pumps.

These components are typically belt- or gear-driven from the engine output shaft, and they absorb some net engine power. The amount of energy used by vehicle accessories depends on the vehicle and duty cycle. For example, urban buses tend to have much higher accessory loads than highway trucks due to their stop and go duty cycle (more air brake use, air operated doors), larger passenger cabin (lights and air conditioning), and rear-mounted engine (greater use of engine cooling fan).

Engine Idling

Heavy-duty vehicles are sometimes left to idle so that the diesel engine can supply a relatively small vehicle accessory or hotel load, often to maintain driver comfort. This is of particular concern for sleeper-cab equipped combination trucks, which often idle for eight hours per day or more while the operator is resting in the sleeper berth. An idling Class 8 truck uses approximately 0.8 gallons of fuel per hour [3-3], and USDOE estimates that idling heavy-duty trucks consume up to 840 million gallons of diesel fuel annually in the US [3-4]. This is about two and one half percent of all fuel used by heavy trucks annually.

While this type of long duration idling is necessary on many current combination trucks, it is inefficient. Total fuel use could be reduced from these vehicles if they were equipped with smaller and more efficient auxiliary engines, or other means of powering accessory loads from external electricity sources while stationary.

Vocational Loads

Some heavy-duty vehicles have significant non-propulsion engine loads that support "vocational" equipment mounted on the vehicle. For example, many refuse haulers use a hydraulic ram to periodically pack collected materials more tightly into the truck body. Similarly, utility service vehicles often have a hydraulic bucket lift used to provide access to overhead lines and structures. To power the hydraulic equipment these vehicles include a large hydraulic pump which is driven by the truck's main engine via a transmission power take-off (PTO).

4. U.S. Efforts to Increase HDV Fuel Economy

To date, U.S. government efforts to increase the fuel economy of heavy-duty vehicles have been voluntary. These efforts include US EPA's SmartWay Program focused on combination trucks, and DOE's 21st Century Truck research and development program.

In response to a state law that mandates reductions in GHG emissions state wide, California regulators have adopted regulations that will mandate improvements in the fuel efficiency of some of the heavy-duty trucks that operate in California. The U.S. Congress also recently passed a law that mandates development of fuel efficiency standards for medium- and heavy-duty trucks for the first time. Finally, the US Environmental Protection Agency (US EPA) is developing a plan to reduce greenhouse gas (GHG) emissions under the authority conferred by the Clean Air Act. In the agency Advance Notice of Proposed Rulemaking several options for regulating GHGs from medium- and heavy-duty trucks are described.

For certain types of vehicles, notably transit buses, more efficient hybrid-electric drive trains are currently being installed on a significant number of new vehicles.

4.1 US EPA SmartWay Transport Partnership

The SmartWay™Transport Partnership program was launched by U.S. EPA in 2004 in order to reduce fuel use, greenhouse gas emissions, and criteria pollutant emissions from the U.S. ground freight system (rail and truck). SmartWay™ is a voluntary public-private partnership program that involves all major stakeholders in the freight industry, including both service providers (carriers) and users (shippers).

SmartWay partners must agree to assess their current environmental performance using EPA's Fleet Logistics Energy and Environmental Tracking (F.L.E.E.T.) performance model, and commit to improving their performance within three years. They also must assess their progress annually using the F.L.E.E.T model, and report their progress to US EPA.

Carriers can meet their SmartWay goals by improving the efficiency of their shipping operations through implementation of various fuel saving technologies on their trucks and trailers. Shippers can meet their SmartWay goals by using SmartWay transport partners for at least 50 percent of their goods shipments, and also reducing the green house gas emissions from their freight facility operations.

SmartWay also has a program to "certify" combination truck tractors and trailers that meet certain minimum requirements for using fuel-saving technologies; equipment that meets these standards can use the SmartWay certified label and SmartWay carriers can use this equipment to help meet their SmartWay goals (see Figure 4.1). Currently six heavy-duty truck manufacturers, including the five who had the highest market share in 2005, produce some SmartWay-certified models. In addition eight trailer manufacturers produce some SmartWay-

Figure 4.1 SmartWay™ Logos ***Source: USEPA***

certified trailer models [4-1]. The use of SmartWay-certified trucks and trailers together is expected to reduce fuel use by 10 -20% compared to non-certified equipment [4-1].

The current SmartWay certification standards are equipment-based and include a specific list of required features as illustrated in Figure 4.2. US EPA intends to move toward a "performance-based" standard for SmartWay certification – instead of requiring a specific list of features, trucks and tractors would receive certification by meeting or exceeding a minimum standard for in-use fuel economy, based on testing using a standard test protocol.

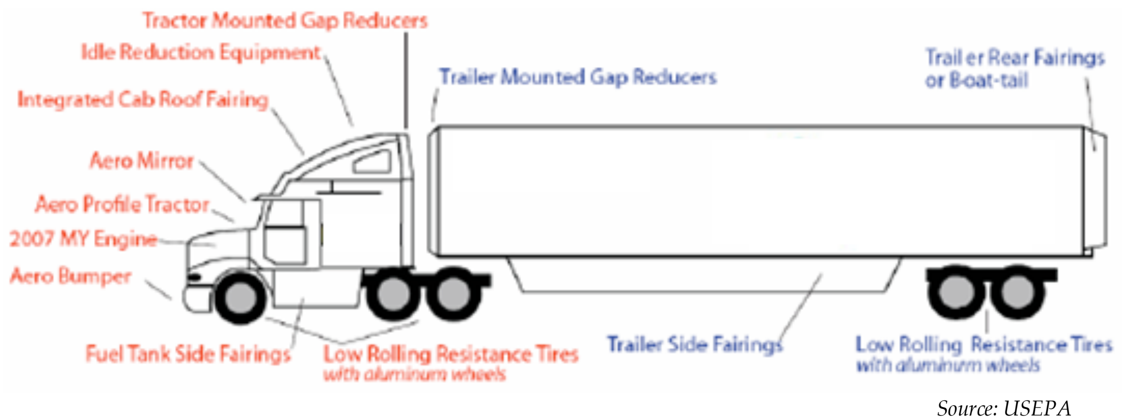


Figure 4.2 SmartWay™ Equipment Standards

US EPA is developing, with industry input, a draft fuel efficiency test protocol for medium- and heavy-duty trucks to be used for SmartWay certification testing. A draft has been published, and EPA convened a public workshop to discuss the draft in March 2008. EPA expects to publish a revised draft protocol in the second half of 2009.

Any size business can join SmartWay as a partner, from large truck fleets to single owner-operators, and from large chain stores to small local businesses.

Companies that can demonstrate via the F.L.E.E.T model that they have superior environmental performance will qualify to use the SmartWay Transport partner logo in their advertising (see Figure 4.1).

There are currently over 600 SmartWay partner companies, including over 400 truck carriers, over 60 shippers, and over 60 logistics companies [4-2]. By 2012 EPA expects that SmartWay will reduce fuel use from the U.S. freight shipping sector by 3.3 – 6.6 billion gallons per year [4-3].

4.2 DOE 21st Century Truck Partnership

The 21st Century Truck Partnership (21CTP) is a public/private program run by the U.S. Department of Energy which brings together government agencies and members of the heavy-duty vehicle industry to work toward making trucks and buses safer, cleaner, and more efficient.

Announced in April 2000, the program underwent a major revision of its vision, mission, and goals in 2003. The program is intended to be both a coordinated research and development effort, and a forum for information sharing across all government and industrial sectors related to heavy truck research.

Table 4.1 The 21st Century Truck Partnership Technology Goals

Engine Systems	HD Hybrids	Parasitic Losses	Idle Reduction	Safety
▪ Increase thermal efficiency from 42% to 50% by 2010 ▪ Stretch goal of 55% thermal efficiency in prototype engines by 2013 ▪ 10% gain in over-the-road fuel economy by 2013, compared to 2010 goal	▪ By 2012 develop drive unit with 15 year design life that costs <$50/kw ▪ By 2012 develop energy storage system with 15 year design life that costs <$25/ peak kw ▪ Achieve 60% increase in fuel economy on urban drive cycle	▪ Reduce aero drag on Class 8 combination truck by 20% ▪ Reduce auxiliary loads on Class 8 combination truck by 50% ▪ Develop materials and manufacturing that can reduce Class 8 combination truck weight by 15-20%	▪ By 2009 demonstrate add-on idle reduction devices with <2 yr pay back ▪ By 2012 produce a truck with fully integrated idle reduction system ▪ By 2015 demonstrate 5-30 kw fuel cell APU	▪ Reduce stopping distance from operational speeds by 30% ▪ Reduce incidences of HDV roll over ▪ Develop driver aid systems to provide 360° visibility and that promote safe following distance and in-lane tracking

Source: DOE

See Table 4.1 for a list of the major technology goals set by the partnership in each of five critical areas that can reduce fuel use and emissions, while increasing safety [4-4]:

- Engine systems (fuel, engine, and after-treatment)
- Heavy-duty Hybrid drive trains
- Parasitic losses (aerodynamic drag, rolling resistance, drive train losses, and auxiliary loads)
- Idle reduction, and
- Safety

These specific goals are based on a technology research roadmap developed under the partnership.

Program partners include sixteen industrial companies and four U.S. government agencies; the partnership also calls on technical expertise from twelve participating national laboratories. See Figure 4.3 for a list of 21CTP partners. The partners work cooperatively to develop a balanced portfolio of research aimed at achieving their research goals, and coordinate their research activities as appropriate.

The intent is to focus research on selected projects that show the greatest likelihood of near-term success and fleet-wide effectiveness.

21st Century Truck Partners

Industry

Allison Transmission	BAE SYSTEMS
Caterpillar, Inc.	Cummins, Inc.
DaimlerChrysler Corporation	Detroit Diesel Corporation
Eaton Corporation	Freightliner LLC
General Motors Corporation	Honeywell, Inc.
International Truck & Engine Corporation	Mack Trucks, Inc.
NovaBUS	Oshkosh Truck Corporation
PACCAR, Inc.	Volvo Trucks North America, Inc.

Government

U.S. Department of Defense (represented by the U.S. Army)
U.S. Department of Energy
U.S. Department of Transportation
U.S. Environmental Protection Agency

Source: DOE

Figure 4.3 21st Century Truck Partners

The partnership conducts regular public demonstrations of emerging heavy-truck technologies, and provides public data on technologies under development in annual progress reports.

Funding for this effort has dwindled in recent years and a recent review of the program coordinated by the National Academy of Sciences found that "the current level is not in proportion to the importance of the goal of reducing fuel consumption of heavy-duty vehicles" [4-5].

4.3 California AB 32

California Assembly Bill 32 (AB 32), the California Global Warming Solutions Act of 2006, mandates state-wide reductions in green house gas emissions to 1990 levels by December 31, 2020. The California Air Resources Board (ARB) is charged with developing the required implementing rules, including any mandatory reductions by sector and any authorized market mechanisms.

While ARB's major rulemakings are not due to be completed until January 2011, AB 32 requires the agency to develop a list of discrete early-action measures that can be implemented by January 2010.

In California, heavy-duty trucks account for 20 percent of GHG emissions from transportation sources, and almost eight percent of all GHG emissions [4-6]. ARB has identified mandatory reductions in aerodynamic drag and rolling resistance from heavy-duty trucks as a potential early-action measure. The proposal was approved by the agency's board in December 2008.

The regulation requires improvements in aerodynamics and reductions in rolling resistance for both combination trucks (the tractor and trailer) and single-unit trucks. The requirements are based on implementation of technology packages "certified" under EPA's SmartWay™ program, including low rolling-resistance tires and light weight wheels, low-profile aero design for truck cabs, and drag-reducing gap fairings and side skirts for both trucks and trailers.

The rule applies to all new Class 8 trucks, and trailers 53 feet long or longer, beginning with the 2010 model year. It also requires phased retrofits to all 2005 and later in-use trucks between 2010 and 2014 depending on fleet size. Required retrofits would include light weight wheels and low rolling-resistance tires for all trucks, and side skirt- and gap-fairings for all trailers.

As approved the rule applies to all trucks used in California, both those with in-state and those with out-of-state registration.

The ARB also approved in December 2008 the AB 32 Scoping Plan, which outlines the multi-sectoral plan to attain the emission reduction targets set by the bill. The final plan includes a proposal to promote hybridization from medium and heavy-duty vehicles in addition to the early action "SmartWay" measure. An earlier version of the Scoping Plan included a proposal for medium and heavy-duty engine GHG standards. However the agency decided it would consider such standards at a later date if action at the federal level does not provide expected benefits [4-7].

4.4 Energy Independence and Security Act of 2007

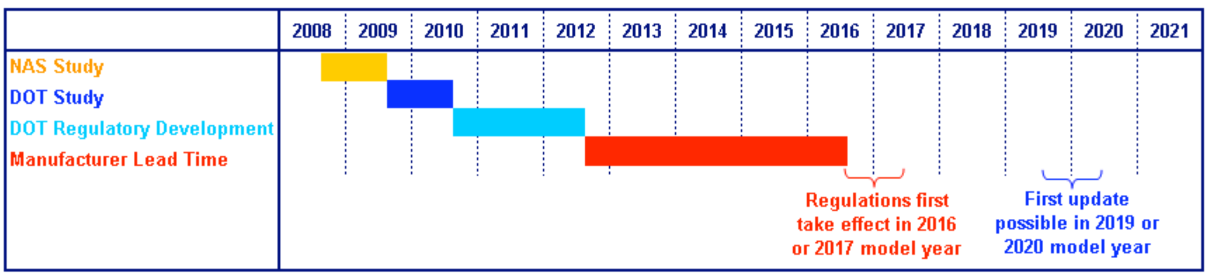
In December 2007 Congress passed, and the President signed, the Energy Independence and Security Act (EISA), which includes a number of provisions intended to reduce U.S. dependence on imported petroleum fuels.

In addition to renewable fuels production mandates, and a significant increase in corporate average fuel economy standards for cars and light trucks (increasing to 35 MPG by 2020), the law also mandates that the Department of Transportation (DOT) develop, for the first time, fuel economy standards for medium and heavy-duty vehicles. The law requires new standards for both "work trucks" with a GVWR of 8,500 – 10,000 pounds and "medium- and heavy-duty vehicles" with a GVWR over 10,000 pounds. The law specifies a lengthy regulatory development process – if DOT takes the maximum time allowed for each step the new standards are unlikely to take effect before the 2016 model year at the earliest.

The specified regulatory development process includes a study by the National Academy of Science of appropriate metrics to measure fuel economy, and available technologies and likely costs to increase fuel economy for the target HDVs. This study must be completed within one year of NAS receiving a contract from DOT. DOT will then undertake its own study of the same issues, to be completed within one year of receiving the NAS study results. Finally, DOT will develop a full regulatory program to prescribe, measure, and enforce fuel economy standards for HDVs, and must issue the regulations within two years of completing their own study.

The statute requires four years of "lead time" for manufacturers to comply after DOT has issued its regulations. It also requires at least three years of "regulatory stability", which means that DOT can not revise the standards more frequently than once every three years.

See Figure 4.4 for a likely time line for development and implementation of the required standards.



Source: M.J. Bradley & Associates

Figure 4.4 Likely Timeline for Development and Implementation of HDV Fuel Economy Standards in Accordance with EISA

4.5 Hybrid-electric Transit Buses & Trucks

Hybrid-electric propulsion systems combine an internal combustion engine with one or more electric motors and an energy storage device (battery pack), to improve over-all vehicle efficiency (see Section 6.2). The first U.S. heavy-duty vehicle sector in which hybrid technology made significant inroads was the transit bus sector. In the last few years hybrid systems have also been developed for medium-duty vocational trucks.

The first commercial hybrid-electric transit buses were put into service by MTA New York City Transit in 1998. Today, transit agencies in over seventy North American cities operate fleets of hybrid buses. More than 1,900 hybrid buses are currently in-service, with an additional 2,000 buses on order with manufacturers [4-8]. The delivered and on-order hybrid buses represent approximately 9% of the U.S. transit bus fleet [4-9]. See Table 4.1 for a list of the largest hybrid bus fleets.

Several companies have developed medium- and heavy-duty hybrid diesel-electric and diesel-hydraulic systems targeted to non-bus vehicle markets as well. Nearly one thousand units of varying sizes are either on the road or on order.

The early market leader is the International Truck and Engine Company, owned by Navistar, which entered early assembly-line production of medium-duty (Class 6/7) hybrid trucks in the fall of 2007. International has teamed with Eaton Corporation for its hybrid-electric system

Table 4.2 Largest Hybrid Transit Bus Fleets

City	Buses		Hybrid Manuf
	In Service	On Order	
New York City, NY	800	850	BAE
Toronto, ON	150	414	BAE
Washington, DC	50	500	Allison
Philadelphia, PA	32	400	Allison
Seattle, WA	235		Allison
Ottawa, ON		200	BAE
Long Beach, CA	77[2]	76[2]	ISE
Houston, TX	50	100	BAE Allison
San Francisco, CA	86		BAE
Montabello, CA	5[2]	46[2]	ISE
Las Vegas, NV		50	ISE
Ann Arbor, MI	20	7	Allison
Newark, NJ [1]	21		BAE
Elk Grove, CA	21[2]		ISE
Pittsburgh, PA	12		Allison
Chicago, IL	10		ISE

1 Used at Newark & NYC airports
2 Gasoline-electric hybrids

Source: M.J. Bradlev & Associates. ICCT

and now has several hundred units on the road, with a current production capacity of approximately one thousand units per year.

PACCAR, Inc. and its Kenworth and Peterbuilt brands have also teamed with Eaton for both hybrid electric and hybrid hydraulic systems. [4-10]. The electric systems are already being offered on a limited basis on Kenworth and Peterbuilt medium-duty trucks targeted for pick-up and delivery and utility fleets. Beginning in 2009 the system will be offered on Peterbuilt Class 8 tractors [4-11].

On Class 8 tractors the system will also include "idle reduction mode" - the hybrid system's batteries will power the heating, air conditioning and vehicle electrical systems while the engine is off, and the engine will only start if the batteries need to be charged. Peterbuilt will also enter production in 2008 on a hybrid hydraulic refuse truck based on its Model 320 chassis and the Eaton HLA™ (Hydraulic Launch Assist) hybrid system. The truck is expected to offer fuel savings of 20-30 percent over conventional trucks.

Mack Truck has delivered to the U.S. Air Force six prototype vehicles that use a "mild" hybrid system which incorporates an electric drive motor attached to the drive line down stream of the transmission. In addition to military vehicles, Mack is contemplating offering the system on refuse haulers, with production as early as 2009 if current field trials are successful [4-10]. The IC Corporation offers a similar hybrid system, built by ENOVA Systems, on their school buses, and Azure Dynamics is entering production with a class 4/5 hybrid shuttle bus.

Arvin Meritor, in a partnership with Wal-Mart and International Trucks, is developing a Class 8 hybrid electric tractor to compete with the Eaton system. The system, still in the prototype phase, would feature a unique dual series-parallel design that would use the engine to generate electricity for electric drive at lower speeds, but shift to a more conventional drivetrain at higher speeds, with the electric motors providing an assist to the main engine.

Hybrid transit buses have been shown to get 20 – 36% better fuel economy than standard diesel buses operated in the same service. The largest benefits were achieved in New York City where buses average only 6-7 MPH in service, and stop as often as 20 times per mile [4-13]. In cities with fewer stops per mile, and therefore higher average speeds, the gains were less [4-14].

The manufacturers of the Mack, Kenworth, and Peterbuilt medium-duty and heavy-duty hybrid trucks claim up to 35% fuel economy improvement in stop-and-go duty cycles and 5-7% fuel economy improvement for long-haul applications, primarily based on reducing over-night idling [4-10] [4-11] [4-12]. Preliminary results from 24 medium-duty hybrid utility trucks built by

International/Eaton, and deployed throughout the country show, a 14-54% increase in fuel economy compared to standard diesel trucks in that application [4-15]

4.6 Hybrid Trucks Users Forum (HTUF)

The Hybrid Truck Users Forum (HTUF) is a program partnership of the U.S. Army's National Automotive Center (NAC) and CALSTART, a non-profit advanced transportation organization. Launched in 2002, HTUF has a goal of commercializing medium- and heavy-duty hybrid vehicles, particularly trucks. The Army participates in and funds the effort due to their tremendous need to reduce fuel use and related supply logistics activities, and to provide greater vehicle capabilities to deployed forces.

HTUF activities initially focused on urban work trucks such as refuse, delivery, and utility service vehicles. These vocational trucks, together with transit buses, provide the best near-term opportunity to demonstrate a business case for hybrids in commercial trucks because of their stop-and-go duty cycles and generally high-idling times. These types of duty cycles can make the best use of a hybrid architecture for saving fuel.

The HTUF program has been successful in helping to speed the assessment, deployment, and early production of Class 6 and 7 hybrid work trucks. Heavier trucks, including Class 8 line haul and heavy regional transport trucks, are also showing potential to benefit from hybridization. While hybrid technologies will likely not be the only, or even the main, strategy to reduce fuel use in heavy trucks, it is emerging as one of the serious options. The same pooled purchase demand and market signals that HTUF has provided for hybrid vehicles can also potentially speed the development of other fuel saving approaches. HTUF is increasingly focusing on overlapping technology approaches, including electrified and efficient components, lighter weight materials, and optimized engines that can lead to both more capable hybrids and more efficient conventional trucks.

5. International Efforts to Increase HDV Fuel Economy

To date there have been limited efforts to mandate increased fuel economy for heavy-duty vehicles in most of the world. This section highlights efforts in Japan and the European Union.

5.1 Japan

In November 2005 the Japanese government introduced minimum fuel economy standards for all new heavy-duty commercial vehicles with a GVWR greater than 3.5 metric tons (7,700 pounds), which will take effect beginning in the 2015 model year. Vehicle manufacturers are required to meet a minimum sales-weighted average fleet fuel economy for each of a number of "bins" aggregated by vehicle class and weight. Manufacturers must meet the target for each bin and there is no flexibility for cross-bin crediting [5-1].

The 2015 fuel economy targets range from 3.57 – 10.83 kilometers per liter[7] of fuel (km/L) depending on the bin. The targets are based on a "top runner" system in that they generally represent an improvement over the "best performer" within each bin from the baseline model year of 2002. Depending on the bin, the 2015 targets represent a fuel economy improvement of 2 – 13% compared to the best 2002 model, and 10 – 13% compared to the average for all 2002 models. There are two bins, urban buses 4,501 – 6,000 kg and 6,001-8,000 kg, for which the 2015 standard is lower than that achieved by the best performing 2002 model.

For each vehicle the regulated fuel economy is a weighted average of the simulated fuel economy achieved on two different test cycles. One test cycle (JE05 Test Cycle) is intended to represent urban driving and includes numerous vehicle stops, and a significant amount of engine idling time. This test cycle has been used in Japan for emissions testing of heavy-duty vehicles since 2005. The second test cycle (Interurban Test Cycle) was developed for this regulation, and it involves steady-state operation at 80 km/hr and 50% vehicle load, but includes the effect of changes in roadway grade. Throughout the test cycle the roadway grade continually changes from -5% to +5%; this profile is based on a scaled-down version of the Tomei expressway, the busiest highway in Japan.

Depending on the vehicle type the weighting used to determine the average fuel economy varies. In general, lighter trucks and buses are assumed to operate almost exclusively in urban areas so the JE05 Cycle fuel economy is weighted at 90 – 100%. When calculating the average for the purposes of meeting the regulation the Interurban Cycle fuel economy is weighted at up to 35% for other types of trucks

To determine the fuel economy of each vehicle on each test cycle the Japanese regulation mandates a combination of engine testing and vehicle simulation modeling.

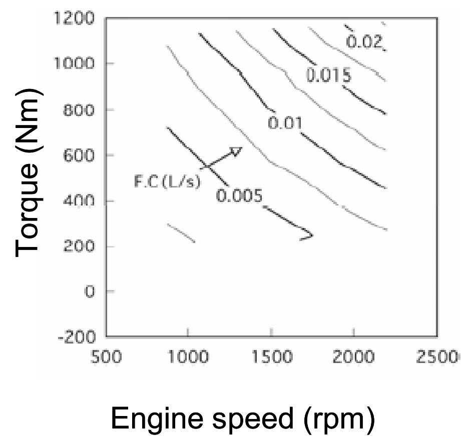
Each engine to be used in a heavy-duty vehicle is mounted on an engine dynamometer and actual fuel use is measured at a minimum of thirty steady-state load points (six engine speed points times five torque points). Based on this testing the manufacturer develops a "map" of fuel use versus speed and torque for the engine. See Figure 5.1 which shows a typical engine fuel use map.

[7] 8.4 – 25.4 miles per gallon.

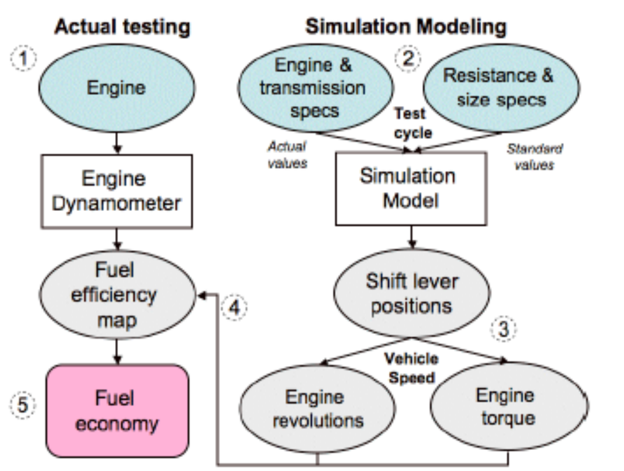
Next, all technical specifications for the vehicle (i.e. engine, transmission, rolling resistance, aerodynamic drag) are entered into a simulation model which determines the shift lever positions required to drive the vehicle over the JE05 and Interurban test cycles. For each test cycle these shift lever positions are combined with test cycle speed to determine the engine speed and torque at each point in the cycle. For each point in the cycle engine speed and torque are then used to access the engine fuel use map, to determine simulated fuel consumption over the test cycle. The total fuel consumption is then used to calculate vehicle fuel economy (km/L) over the test cycle. See Figure 5.2 for a schematic of how fuel economy is determined for the Japanese regulations.

Figure 5.1 Fuel Use Map for a Diesel Engine

Source: NTSEL, Japan



This method of determining vehicle fuel economy allows a large number of vehicle models/configurations to be "tested" in a cost-effective manner, reducing the burden of compliance for vehicle manufacturers. This method could also allow a large number of test cycles to be simulated with minimal cost and effort.



Source: ICCT

Figure 5.1 Schematic of Fuel Economy Determination for Japanese Regulations

As currently configured this test method also has significant limitations. Currently it is primarily a test of engine and drive-train efficiency, and does not account for differences in rolling resistance or aerodynamic drag that can significantly affect fuel use (see Section 3). While these factors are included in the vehicle simulation model used to determine required engine speed and torque, the Japanese regulations currently mandate the use of standard values for these parameters based on vehicle category, rather than vehicle-specific values. Likewise the model does not fully account for differences between different transmission types, and does not allow a hybrid vehicle to take "credit" for lower net fuel use based on regenerated braking energy and/or idle stop.

Conceptually, many of these limitations could be at least partially alleviated by allowing for the use of vehicle-specific parameters in the simulation model, based on additional component or vehicle testing. This would add complexity and cost for regulatory compliance, but would significantly increase the technical options available to manufacturers to achieve compliance.

5.2 European Union

The European Commission commissioned a study investigating the policy options available to reduce GHG emissions from the heavy-duty sector in Europe [5-2]. This report will in part inform the Commission's strategy for heavy-duty vehicles in the coming years.

The consultant team led by Faber Maunsell reviewed mandatory and voluntary programs proposed and in place in Europe and elsewhere. They conducted a "reality check" with various industry stakeholders to assess the potential real-world costs and benefits of these measures as well as to identify obstacles to their implementation. The study recommends several programs for further consideration by the European Commission including a European Heavy-Duty Vehicle Operational Efficiency Programme to promote fleet best practices and a labeling program for engine, vehicles, tires, and trailers. The authors encouraged the review of weight and size limits of vehicles as well as the use of market-based instruments such as taxation, road user charges, and the inclusion of trucks in the Emission Trading Scheme to achieve further emission reductions from the heavy-duty sector.

The recently adopted conventional pollutant emissions standards for heavy-duty vehicles (Euro VI) lays the regulatory groundwork for a vehicle CO_2 labeling program in Europe. The final text of the regulation instructs the Commission to "study the feasibility and the development of a definition and methodology of energy consumption and CO_2 emissions for whole vehicles and not only for engines." [5-3]. The regulation also requires that once a methodology is established, fuel consumption and CO_2 emission for each vehicle types be made available to the public.

6. Technology Options to Increase HDV Fuel Economy

There are several ways that fuel use can be reduced from heavy-duty vehicles:

- increase engine thermal efficiency so that more of the energy in the fuel is converted to useful work by the engine, and less is dissipated as waste heat in the exhaust and by the cooling system,
- recover some thermal energy from the engine exhaust, and put it to use to power the vehicle,
- recover some of the vehicle's kinetic and potential energy during braking (normally dissipated as heat in the braking system) and put it to use to power the vehicle,
- reduce friction losses in the drive train,
- reduce engine accessory loads, or
- reduce the vehicle's weight, frontal area, aerodynamic drag, and/or rolling resistance so that the engine will have to produce less net energy to accelerate and move the vehicle.

There are numerous technologies currently available, or under development, that can be used to achieve the above objectives. Some of the most significant are listed below. Obviously, these technologies are not completely independent of one another – in some cases diverse technologies can be combined in ways which will achieve greater savings than if implemented independently.

6.1 Engine Technologies

Engine efficiency can potentially be increased by making the following types of changes; these generally involve only marginal modifications to existing diesel engine designs:

- Reduce internal engine friction
- Improve the handling of intake air
- Refine fuel injection strategies
- Improve turbocharger efficiency and energy recovery
- Improve thermal management/heat transfer within the engine

More radical modifications to traditional diesel engine design that are under development, and which might significantly increase engine efficiency and reduce emissions, include:

- Homogeneous Charge Compression Ignition (HCCI) or Pre-mixed Charge Compression Ignition (PCCI)[8]
- Sturman digital engine[9]

[8] An HCCI engine is an Otto-cycle engine in which a pre-mixed fuel-air mixture is compressed in the cylinder to achieve auto-ignition. As such it combines aspects of a gasoline engine (homogenous charge spark ignition) and a diesel engine (stratified charge compression ignition). The potential benefits include diesel-like thermal efficiency combined with better fuel combustion for inherently low particulate emissions. A PCCI engine is a variant of the concept in which the pre-mixed fuel-air mixture may be somewhat stratified.

- Cam-less engine

Other approaches to increasing net engine efficiency involve the use of devices which can extract thermal energy from the engine exhaust and put it to use for vehicle propulsion, or to power vehicle accessory loads. These approaches include:

- Mechanical turbo-compounding
- Electrical turbo-compounding
- Diesel bottoming cycle[10]

6.2 *Drive-train Technologies*

One approach to reducing drive-train losses is to reduce friction in existing drive train components by using improved low-viscosity lubricants.

Net vehicle efficiency can also be increased by optimizing gear ratios throughout a vehicle's drive cycle and/or by reducing the losses from traditional automatic transmissions. Potential approaches include:

- Use of a continuously variable transmission (CVT), or
- Use of an automated manual transmission (AMT) in lieu of a traditional automatic transmission[11]

For some vehicles and some duty cycles significant reductions in net fuel use can be achieved by using an electric-hybrid or hydraulic-hybrid drive train. In an electric hybrid system the diesel engine is supplemented by one or electric motor/generators and a battery pack; in a hydraulic hybrid system the diesel engine is supplemented by a hydraulic motor/pump and a hydraulic accumulator.

In either case the main benefit of the hybrid system for most vehicles is that during braking the vehicle's kinetic energy can be recovered and stored (as electrical energy in the battery pack or as high-pressure mechanical energy in the hydraulic accumulator). During subsequent accelerations this stored energy can be used by the electrical or hydraulic motor to help accelerate the vehicle, reducing net energy required from the diesel engine. In some instances additional efficiency gains can be achieved by down-sizing the vehicle's diesel engine.

Some vocational vehicles, for example utility trucks, can also use the stored energy to power vocational loads, thus reducing net engine idling. The ability to reduce engine idling using a hybrid system may also be important for some heavy-duty line haul and drayage trucks. These types of vehicles typically idle for long periods, both over night (line haul) and during warehousing operations (drayage), using the large main engine to power very modest "hotel" loads on the vehicle. By providing a different power source (battery pack) for these hotel loads a hybrid system can significantly reduce or eliminate engine idling.

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[9] A cam-less engine concept incorporating digital valves to achieve better fuel injection control and hydraulic valve actuation.

[10] A Rankine cycle system that uses waste heat from the engine to produce super-heated vapor, which then drives a turbine to produce electricity. The resulting electricity can be used to support engine/vehicle accessory loads or propulsion.

[11] CVT and AMT are best suited for vocational trucks and buses that are typically used in stop and go applications

In general, the benefits of a hybrid drive train will be greater for vehicles with a slow-speed, stop-and-go duty cycle. These typically include transit and school buses, urban pick-up and delivery vehicles, and some vocational trucks. The potential drive cycle benefits of a hybrid system are lower for combination trucks that operate primarily in a line haul application, but even these trucks may benefit from the ability of a hybrid system to reduce or eliminate engine idling.

6.3 Vehicle Technologies

Vehicle technologies that can be used to reduce fuel use include those that reduce vehicle weight, rolling resistance, aerodynamic drag, or vehicle accessory loads.

Approaches to reduce vehicle weight include:

- Use of alternative materials (i.e. aluminum, composites, light weight steel)
- Use of super-single wheels

Approaches to reduce a vehicle's rolling resistance include:

- Use of low rolling resistance tires (new and aftermarket)
- Use of super-single wheels and tires
- Use of automatic tire inflation systems

Approaches to reduce vehicle accessory loads include:

- Improved cab thermal insulation
- Electric accessories (air compressor, cooling fan, fuel pump, air conditioning)

With respect to reducing aerodynamic drag, significant improvements are available from changes to single-unit trucks and combination truck tractors, as well as from changes to combination truck trailers.

Truck modifications to reduce aerodynamic drag include:

- Low-profile cab
- Integrated cab-high roof fairing
- Fuel tank side fairings
- Aerodynamic bumper and mirrors
- Tractor-mounted gap reducers (combination trucks)

Trailer modifications to reduce aerodynamic drag include:

- Low profile or "low-boy" trailers
- Side skirts
- Trailer-mounted gap reducers
- Trailer rear-end fairings or boat tail

7. Design of HDV Fuel Economy Regulations

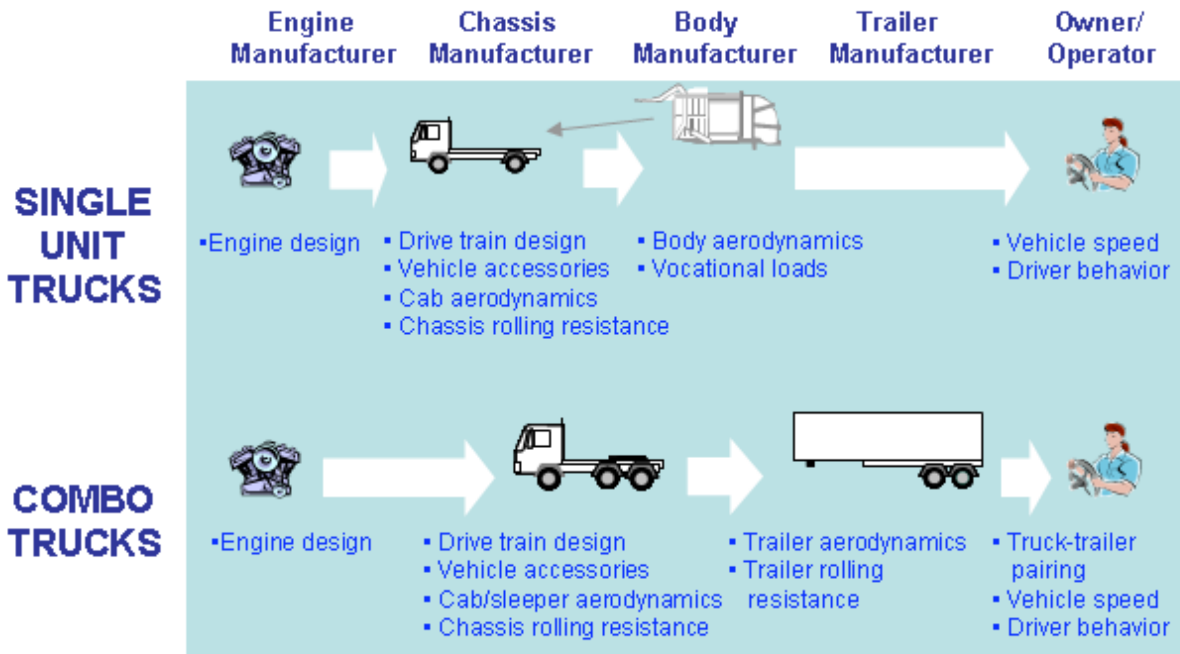
There are a significant number of technical issues that must be addressed when designing fuel economy regulations for heavy-duty vehicles. These range from the metric used to measure fuel economy, to the format of required improvements, to the test method used to verify performance. In addition, there are a number of policy-related issues that can significantly affect the implementation cost and the effectiveness of the regulations. These issues include: which specific vehicle types will be regulated, which companies will be responsible for compliance, the implementation time line, provisions for compliance flexibility, and methods of enforcement. Each of these issues is discussed below.

For each subject area there are a number of options available to policy makers. Different approaches will have different potential benefits, costs, and implementation issues. The optimal regulatory design will balance these different implementation issues to achieve cost-effective improvements.

7.1 Regulated Entity or Entities

Current fuel efficiency and emission standards for cars and light trucks are imposed on the car manufacturer. This is logical since for virtually all cars and light trucks both the engine and the rest of the vehicle are designed, manufactured, and sold by a single company. The heavy duty vehicle market is more complicated, since for any particular HDV the engine, chassis, and body might each be designed and manufactured by different companies. For Class 8 combination trucks it is even more complicated since a truck designed and manufactured by one company is paired with a trailer designed and manufactured by a different company. Furthermore, tractors are routinely paired with different trailers.

For an HDV the engine, chassis, body, and trailer (combination trucks) all influence fuel use. As such, for any particular HDV responsibility for design and operating decisions that affect fuel efficiency are shared by as many as five different entities: the engine manufacture, the chassis manufacturer, the body manufacturer, the trailer manufacturer, and the fleet owner (see Figure 7.1 for an illustration of this shared design responsibility).



Source: M.J. Bradley& Associates

Figure 7.1 Shared Responsibility for Major Elements that Effect HDV Fuel Efficiency

To be fully effective fuel efficiency regulations must apply to the entiti(es) that have control over the major decisions that affect fuel efficiency – which as noted in some cases may be five different entities for a particular HDV.

Current emissions regulations for heavy-duty diesel engines apply to the engine manufacturer only. HDV vehicle manufacturers have no responsibility for meeting emission standards. Since the engine is the only component that actually consumes fuel, one possibility would be to apply HDV fuel efficiency standards to the engine manufacturer as well, particularly since the same engines are used in multiple vehicles from different vehicle manufacturers. To do so might forego significant opportunities for improvements in vehicle efficiency based on different drive train technologies and improved vehicle aerodynamics.

Since the drive train and cab/body shape have such a significant effect on over-all fuel use, another approach would be to apply HDV fuel efficiency standards to the vehicle manufacturer, not the engine manufacturer. While there is a trend toward greater vertical integration and preferred partnering in the truck industry, it is still true that for many single-unit trucks the chassis (including operator cab) is produced by one manufacturer and is sold to a second manufacturer, which adds a body and sells it to the fleet customers. In this case responsibility for design decisions that affect fuel efficiency are shared by two different vehicle manufacturers, though the major responsibility generally falls to the chassis manufacturer. The chassis manufacturer typically controls engine and drive train choice, major vehicle accessory loads, tire configuration, and cab aerodynamics. The body manufacturer generally controls body aerodynamics and vocational loads. In addition, essentially the same chassis design is often used for multiple vehicle models produced by different body manufacturers.

As such it might be more efficient to apply fuel efficiency standards primarily to the chassis manufacturer. This would cover most of the major design decisions that would affect fuel use, while minimizing compliance costs. This could be done by requiring chassis to be tested for compliance with a "reference body" of a standard size and shape installed (likely a worst-case box shape).

For some vehicle types it might also be advisable to apply a second, more stringent standard to the final vehicle with the actual body installed. This would likely only be worthwhile for vehicles that operate primarily at highway speeds in a line haul cycle, where the aerodynamics of the actual installed body could significantly affect actual fuel use. Given that the installed body would primarily affect vehicle aerodynamics, compliance testing of the final vehicle might be able to be effectively conducted using wind tunnel tests and vehicle simulation modeling, rather than requiring additional chassis dynamometer or test track testing (see Section 7.4.1).

To be fully effective, fuel efficiency regulations for Class 8 combination trucks must cover both the truck tractor and the trailer. One standard could apply to the truck manufacturer, with compliance testing conducted using a "reference trailer". A separate, more stringent, standard could apply to the trailer manufacturer. There are three options for trailer compliance testing: 1) in-use, test track, or dynamometer (coast down) testing conducted using the trailer matched with a compliant "reference truck" (see section 7.4.4) 2) wind tunnel (aerodynamic drag) and rolling resistance tests of the trailer, in conjunction with vehicle simulation modeling to calculate an expected combination fuel efficiency if the trailer were paired with a compliant truck, or 3) setting maximum values for trailer rolling resistance and aerodynamic drag, to be confirmed using wind tunnel and other tests, but without converting this data into an expected "fuel efficiency rating". See Section 7.4.1.

Another approach would be to regulate fleet owners, rather than HDV vehicle and trailer manufacturers, since they can make decisions to purchase or not purchase fuel efficient equipment, and they may be in a position to ensure that combination trucks and tractors are paired in a way that minimizes fuel use. This approach was chosen by the California Air Resources Board, which has mandated aerodynamic and rolling resistance-related retrofits for part of the HDV fleet operating in the state (see Section 4.3).

Such an approach would rely more heavily on market forces to effect change in the HDV fleet, but would almost certainly still require a mandatory fuel efficiency testing requirement for truck and trailer manufacturers. Mandatory testing using a consistent test protocol would be required to provide fleet owners with the necessary information to make smart purchasing decisions. Confirmation of fleet compliance with a fuel efficiency standard could be based on either 1) a weighted average fuel efficiency rating for their fleet based on manufacturer test data, or 2) actual in-use fuel and mileage records for the fleet. In either case there would be a significant reporting burden for fleet owners, with a parallel burden on government to review and analyze the fleet-supplied data.

See Table 7.1 for a comparison of the different entities that HDV fuel efficiency regulations might apply to.

Table 7.1 Comparison of HDV Fuel Efficiency Regulated Entities

Regulated Entity	Pros	Cons
Engine Manufacturer	▪ In line with current responsibility for compliance with exhaust emission standards ▪ One set of engine test(s) required for numerous vehicle models	▪ Would not encompass significant vehicle parameters that affect fuel efficiency: drive train, rolling resistance, aerodynamics, vehicle accessories
Truck/Chassis Manufacturer	▪ Would encompass virtually all vehicle parameters that affect fuel use for most single-unit HDVs ▪ Engine manufacturers would contribute to improvements through commercial relationships with Truck/Chassis Manufacturers	▪ Would not cover trailer aerodynamics for combination truck trailers ▪ Would not cover body aerodynamics and vocational loads for some single-unit HDVs ▪ Would likely require testing of single unit HDVs with "reference body" installed
Truck/Body Manufacturer *(if different than chassis manuf)*	▪ Would encompass all vehicle parameters that affect fuel use for single-unit HDVs ▪ Testing of multiple vocational configurations on the same chassis might be accomplished using a simulation model rather than additional track or dynamometer tests	▪ Increased compliance costs as virtually identical chassis must be tested in multiple vocational configurations
Trailer Manufacturer *(Combination Trucks)*	▪ Would include in the regulations equipment that has significant impact on fuel efficiency of combination trucks, especially at highway speeds ▪ To minimize compliance costs trailer testing might be accomplished using wind tunnel and rolling resistance tests combined with simulation modeling	▪ No precedent for fuel efficiency or emissions regulation of non-powered equipment ▪ More complicated since trailers would likely need to be tested with a "reference truck"
Fleet Owner	▪ Relies on market forces to meet compliance goals ▪ Potentially allows a greater range of operational changes to achieve compliance	▪ Significant reporting/review burden on fleets and government to judge compliance ▪ Would still require mandatory fuel efficiency testing of HDVs to provide fleet owners with information required to make smart compliance decisions

7.2 *Regulated Vehicles*

As discussed in Section 2, the U.S. HDV fleet is extremely diverse, with a wide range of vehicle sizes and configurations. As such, a fuel efficiency standard that applied to all HDVs would of necessity be complex, with a wide range of test cycles and numerical standards required (see Sections 7.3 and 7.4).

In order to reduce regulatory complexity one could more narrowly apply fuel efficiency requirements to some sub-set of all HDVs, or could phase-in regulation to different types of HDVs over time. For prioritization the most logical way to parse the HDV fleet is by weight class and/or vehicle type.

As discussed in Section 2, Class 8 trucks comprise only 40% of the HDV fleet, but they consume 75% of the fuel used by HDVs. As such it might be logical to focus fuel efficiency regulations on these large vehicles first, in order to maximize fuel savings resulting from the regulations. The Class 8 HDV fleet itself is quite diverse, encompassing single-unit freight hauling trucks, buses, vocational trucks, and combination trucks. Of these sub-fleets, a typical Class 8 combination truck uses on average eight times as much fuel annually as the various types of Class 8 single-unit trucks and buses. While comprising about 25% of the heavy-duty fleet, combination trucks use 65% or more of the fuel consumed by all U.S. HDVs. Class 8 combination trucks are therefore logical place to focus initial HDV fuel efficiency regulation in order to maximize initial benefits.

Class 8 combination trucks present a particular challenge for fuel efficiency regulation since they are composed of a powered truck tractor pulling an unpowered trailer, but both truck and trailer can significantly affect fuel use, particularly at highway speeds. Since the truck and trailer are typically not manufactured, sold, or used as sets, to be fully effective any fuel efficiency regulation for Class 8 combination trucks must regulate both the truck and the trailer separately.

See Section 7.4.4 for a discussion of how Class 8 combination truck tractors and trailers could be separately tested to measure compliance with a fuel efficiency standard.

Another approach to prioritizing fuel efficiency regulation would be to focus not on total or initial benefits (fuel, CO_2 savings), but rather on some other factor such as ease of implementation or cost-effectiveness. If this approach is taken it is possible that trucks smaller than Class 8 would be a better target for initial regulatory efforts.

7.3 Fuel Economy/Efficiency/GHG Metric

For most heavy-duty onroad vehicles their main purpose is to move goods or people over a distance[12]. For the purpose of fuel economy regulation it is therefore appropriate to measure fuel or energy use relative to accumulated mileage – i.e. miles driven per gallon of fuel used (MPG), or inversely, gallons used per mile driven.

The use of a volume measurement for fuel (gallons), however, can be mis-leading when comparing results from trucks operated on different fuels - not all grades of diesel fuel have the same energy content per gallon and some heavy-duty vehicles are gasoline fueled. This metric is also not appropriate when using gaseous fuels (i.e. natural gas), without making a conversion to "equivalent gallons" based on energy content. To overcome this limitation a regulatory program could require the use of a "reference fuel" with constant energy density for all testing, or compliance could be evaluated by adjusting measured results to what they would have been using a reference fuel, based on the measured difference in energy density of the actual fuel used versus the reference fuel.

[12] The exception is some vocational vehicles, for which fuel use per unit time might be a more appropriate metric.

A more universal metric would be based not on the volume of fuel used per mile driven, but rather the energy content of the fuel used per mile driven – i.e. British thermal units (btu) per mile, or kilowatt-hours (Kwh) per mile. Such a metric would allow direct comparison of test results using different fuels, without requiring an adjustment based on measured energy density.

An energy per mile metric will suffice if the main purpose of the regulation is to promote efficiency and reduce the need to import transportation fuels. However, if the purpose of the regulation is to reduce the amount of greenhouse gases released to the atmosphere from transportation sources, then a different metric might be preferred.

The main green house gas (GHG) produced by heavy-duty vehicles is carbon dioxide (CO_2). An appropriate metric to capture the effect of heavy-duty vehicles on global warming would therefore be grams CO_2 emitted per mile driven. This metric relates to fuel economy by virtue of the fact that reducing the amount of diesel fuel used per mile will reduce the amount of CO_2 released per mile. However, this metric can also capture CO_2 reductions based on switching to lower carbon fuels assuming there is a single point of regulation, and as such is a better metric if GHG reductions are the primary goal of regulation.

Another GHG-related metric that could be used is grams CO_2-equivalent[13] (gCO_2-E) per mile driven. CO_2-E captures the effects of all GHGs emitted by a vehicle, not just CO_2. Black carbon, a sub-set of particulate matter, is another diesel truck emission with significant climate impact in the near term. SCR controlled engines may emit excess N_2O if the ammonia ($NH_{3)}$ slip catalyst is not appropriately formulated. Lean-burn natural gas engines may also emit a significant amount of methane (CH_4) unless equipped with an appropriate oxidation catalyst.

As discussed in Section 2, heavy-duty vehicles come in a wide range of sizes – with GVWR from 10,000 to over 80,000 pounds. In general the heavier a vehicle is the more fuel it will burn for every mile it drives – but the more cargo it will/can carry. Regardless of whether one uses fuel volume, fuel energy content, CO_2 emissions, or CO_2-E emissions as the basis of a fuel economy metric, if referenced to miles driven there will need to be a different regulatory standard for different sized vehicles (i.e. it would make no sense to mandate that a 10,000 pound truck and an 80,000 pound truck both must achieve at least 10 miles/gallon – the smaller truck could easily achieve this target while it might be impossible for the larger one).

Specifically for heavy-duty vehicles it might therefore be appropriate to use a fuel economy metric based not on miles driven, but rather ton-miles. A ton-mile is defined as miles driven times vehicle pay-load weight expressed in tons (2000 lbs/ton). For example, a truck with a 10,000 lb pay-load driven one mile would equal 5 ton-miles, while a truck with a 40,000 lb pay-load driven one mile would equal 20 ton-miles).

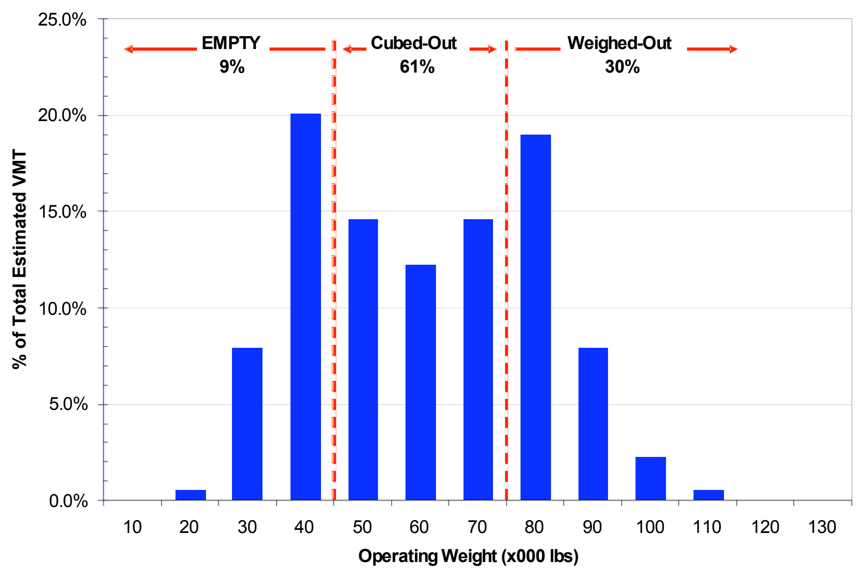
The use of a ton-mile based fuel-economy metric for heavy-duty vehicles would simplify fuel economy regulations because a single numerical standard could be applied to a wider range of vehicle sizes. This type of metric would also explicitly acknowledge the main purpose of most heavy-duty vehicles, which is to move freight. When regulating the efficiency of the freight system it is appropriate to mandate the maximum amount of energy (or resulting CO_2 or CO_2-E emissions) allowed per ton-mile of freight moved.

Another approach that might be appropriate for freight vehicles would be to reference a fuel efficiency standard to cubic-volume miles rather than ton-miles, in recognition of the fact that some freight fills up the available cargo space ("cubes-out") in an HDV before the vehicle reaches its maximum GVWR ("weighs-out"). A cubic volume-mile is defined as miles driven times vehicle cargo capacity, in cubic feet or cubic yards (i.e. a truck with a cargo box 8 ft x 8 ft

[13] For any GHG, CO_2-E is calculated by multiplying the mass (grams) of the GHG by its global warming potential (GWP), as defined by the Intergovernmental Panel on Climate Change.

x 20 ft would have 1,280 ft^3 [47.4 yd^3] of cargo capacity; if this truck were driven one mile it would equal 1,280 ft^3-miles [47.4 yd^3-miles]).

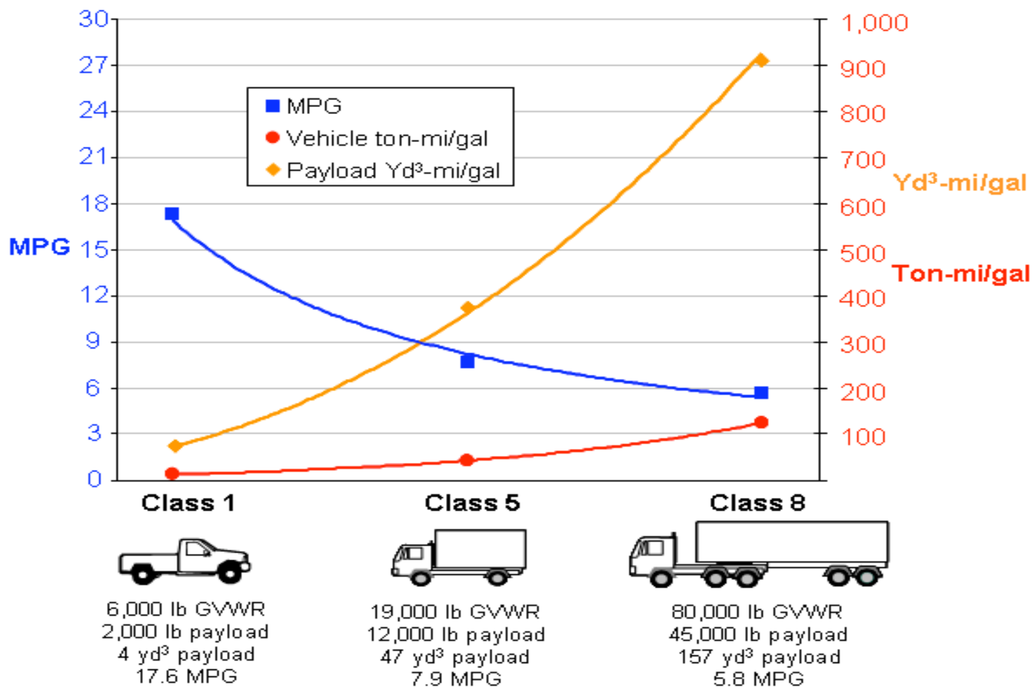
An analysis of operating weight data from the U.S. Census Bureau's 1992 Truck Inventory and Use Survey (TIUS) indicates that as many as 70 percent of vehicle miles traveled by five-axle combination trucks are accumulated at operating weights significantly below this type of vehicle's typical gross vehicle weight rating of 80,000 pounds [7-1]. Some of those miles are traveled with the trailer empty (below about 35,000 pounds operating weight) or with only a part load. However, a significant portion of them – perhaps the majority of all miles traveled – are accumulated with the trailer "cubed-out" as shown in Figure 7.2. A cubic volume-mile fuel economy metric might provide trailer manufacturers with an incentive to increase trailer volumes (for example by using smaller tires to lower the trailer's floor height while keeping the roof height the same). This could significantly increase the efficiency of the over-all freight system by allowing more freight to be loaded before cubing-out the trailer. A mile per gallon or ton-mile per gallon metric would not provide any incentive for increasing trailer volumes.



Source: U.S. DOT, FWHA

Figure 7.2 VMT of Five-Axle Combination Trucks, by Operating Weight Range (1992 TIUS)

See Table 7.2 for a comparison of fuel efficiency/GHG metrics, and Figure 7.3 for an illustration of the difference between an MPG, ton-mile, and cubic volume-mile metric as applied to vehicles of various sizes.



Source: M.J. Bradley & Associates

Figure 7.3 Illustration of Different Fuel Efficiency Metrics as Applied to Cargo Vehicles of Different Sizes

Table 7.2 Comparison of Fuel Efficiency / GHG Metrics

Basis	Metric	Pros	Cons
Fuel Volume	miles/gallon	▪ Understandable to most people due to common usage	▪ Can not capture differences in fuel energy or carbon content ▪ Different vehicle sizes need different numerical standards
	gal/mile	▪ A reduction in the value of the metric is equivalent to reduced fuel use	▪ Same as miles/gallon
	gal/ton-mile or gal/cube-mile	▪ Directly related to the purpose of most HDVs ▪ Same numerical standard can be used for different sized HDVs	▪ Can not capture differences in fuel energy or carbon content
Fuel Energy Content	BTU/mile	▪ Efficiency of vehicles operated on different fuels can be directly compared	▪ Can not capture differences in fuel carbon content ▪ Different vehicle sizes need different numerical standards
	BTU/ton-mile or BTU/cube-mile	▪ Same as BTU/mile, plus ▪ Directly related to the purpose of most HDVs ▪ Same numerical standard can be used for different sized HDVs	▪ Can not capture differences in fuel carbon content
CO_2 Emissions	gCO_2/mile	▪ Captures differences in vehicle fuel use as well as energy or carbon content of fuel ▪ Measures vehicle impact on global warming	▪ Unfamiliar as an "efficiency" or "fuel economy" metric
	gCO_2/ton-mile or gCO_2/cube-mile	▪ Same as gCO_2/mile, plus ▪ Directly related to the purpose of most HDVs ▪ Same numerical standard can be used for different sized vehicles	▪ Unfamiliar as an "efficiency" or "fuel economy" metric
GHG Emissions	gCO_2-E/mile	▪ Captures effect of non-CO2 GHGs	▪ Additional emissions must be measured during testing
	gCO_2-E/ton-mile or gCO_2-E/cube-mile	▪ Same as gCO_2-E/mile, plus ▪ Directly related to the purpose of most HDVs ▪ Same numerical standard can be used for different sized vehicles	▪ Additional emissions components must be measured during testing

7.4 *Test Procedures Used for Verification*

As discussed in Section 3, there are numerous factors that can affect fuel use for HDVs, including engine and vehicle design, but also driver behavior, vehicle condition (i.e. tire pressure) and duty cycle (speed, number of stops, etc). Any numerical standard for HDV fuel economy or fuel efficiency must therefore be supported by a specific and detailed test procedure to ensure that test results are repeatable, are comparable from vehicle to vehicle, and result in a reasonable approximation of what most vehicle owners will experience in-use.

U.S. EPA has developed a detailed test procedure for evaluating the fuel efficiency of cars and light trucks [7-2]. This method is used to test every new car model sold in the U.S., and the results must be published by the manufacturer. This procedure uses a chassis dynamometer and five different drive cycles to produce three fuel economy ratings (miles per gallon – MPG): one for slow-speed city driving, one for high-speed highway driving, and a "combined" rating intended to represent a typical average duty cycle. The same test data is also used to evaluate compliance with EPA exhaust emission standards for these vehicles.

U.S. EPA does not currently have a similar detailed test procedure for evaluating the fuel efficiency of HDVs, though there are a number of industry-developed test protocols that might serve as the basis of such a procedure (see below). As noted in Section 4.1 EPA is currently developing a draft fuel efficiency test protocol for medium and heavy-duty trucks to be used for SmartWay certification testing, which is based on prior industry-developed protocols.

Fuel economy testing of HDVs is significantly more complicated than fuel economy testing of cars for a number of reasons:

- The much larger size of most HDVs requires much larger equipment and facilities, which are expensive and currently in limited supply
- The HDV fleet is much more varied (size, configuration, vocational equipment), and
- There is a much wider range of "typical" duty cycles applicable to specific HDV vehicle types, but not others.

In addition, EPA emission standards for HDVs apply to the engine, not the vehicle. Emissions certification testing for heavy-duty diesel engines is done using an engine dynamometer, and does not evaluate the effect on emissions and fuel efficiency of other vehicle components and parameters (i.e. drive train, accessory loads, vehicle weight, vehicle aerodynamics, etc.).

The major issues related to development of a test procedure to evaluate HDV fuel efficiency are discussed below.

7.4.1 Test Equipment/Test Method

Evaluating fuel use involves measuring the amount of fuel that a vehicle consumes while it operates over a specific, repeatable, test cycle intended to represent "typical" vehicle behavior in-use. Fuel use can be measured directly (by using a portable fuel tank that is weighed before and after the test run) or indirectly (by measuring cumulative carbon emissions from the tail pipe throughout the test and imputing fuel use based on fuel carbon content).

There are well-developed procedures available for gravimetric fuel measurement (SAE J1321) and tail-pipe emissions measurement (40 CFR Part 86, 40 CFR Part 1065) – determining the amount of fuel used on a particular test run is not difficult. What is more difficult is ensuring that each test run is conducted over the same test cycle.

There are three basic test methods that can theoretically be used to test a vehicle:

- **In-use Test:** operate the vehicle on public roads over its normal route. This method is often used by vehicle manufacturers and truck fleets to conduct comparison tests between two different trucks. In a comparison test the two trucks would follow each other on the route and the drivers would be in constant contact. At the half way point the drivers would change vehicles, and for combination trucks the trailers would also be switched. In these tests each truck typically logs 400 miles or more for each test run.

The use of paired trucks allows better control of independent variables that can affect fuel use, and the results are typically reported as a % difference in fuel use for one truck compared to the other, as opposed to an absolute value for fuel use. The Society of Automotive Engineers and the Truck Maintenance Council have developed detailed test procedures for conducting these types of tests (SAE 1264, SAE 1321, SAE 1526, RP 1109) [7-3]

- **Test-track**: operate the vehicle over a closed test course (typically a one mile or longer circular or oval track with banked corners). For each test the driver is instructed how to operate the vehicle for the target test cycle (i.e. acceleration rate from each stop and target speed between specific points on the track, braking rates and stopping points, idle time at each stop). The TMC and SAE test procedures for in-service and dynamometer tests can serve as the basis for a test track test protocol.
- **Chassis Dynamometer:** mount the vehicle on a dynamometer with the drive wheels resting on one or more large cylindrical rolls. During testing the vehicle is stationary, but the drive wheels spin the rolls to simulate driving at different speeds. The dynamometer can impart to the drive wheels a varying load to represent varying vehicle inertial load, rolling resistance, and aerodynamic drag throughout the drive cycle. The vehicle driver is instructed to follow a specific profile of speed versus time, and is usually given a computerized drivers aid which shows actual speed versus target speed in real time. The Society of Automotive Engineers has developed a recommended practice for conducting emissions and fuel economy tests of heavy-duty vehicles on chassis dynamometers (SAE J2711) and EPA has detailed procedures for conducting emissions testing (40 CFR Part 86, 40 CFR part 1065) [7-4].

Each of these methods has pros and cons. In-use testing requires no specialized equipment or facilities, but it is difficult to get good test cycle repeatability from run-to-run or truck-to-truck. In addition, for a regulatory program each tested truck would need to be tested over the same section of road, or different test routes would have to be carefully compared to ensure sufficient similarity of road profile, road surface, traffic conditions, etc. Because this method is best suited for comparing one truck to another it might also require the use of a “reference truck”, with results reported as a percentage difference from the reference, rather than as an absolute number.

Testing on a test track is more repeatable than in-use testing, but the complexity of the test cycles are limited by what it is practical for a driver to follow. A heads-up display drivers aid might increase the complexity of practical test cycles, but might introduce concerns about driver distraction and safety. Test tracks are perhaps best suited to testing on high-speed highway test cycles with relatively few stops, and limited speed changes. They are less suited to more dynamic urban test cycles with frequent speed changes and a greater number of stops per mile.

Test tracks are also affected by ambient weather conditions such as temperature, humidity, precipitation, and wind, which could severely limit in the possibility of testing under standardized conditions in some locations. Test tracks are also generally constructed to be flat, and can not incorporate changes in grade as part of the test cycle. There are currently a limited number of test tracks that would be suitable for testing HDVs, and development of additional facilities would be expensive.

Chassis dynamometer testing is the most repeatable of the test methods, and is generally minimally affected by ambient weather conditions. Relatively few heavy-duty chassis dynamometers exist today, and developing new ones would be expensive, but not as expensive as development of new test tracks.

With respect to HDVs, the most significant limitation of chassis dynamometer testing is its method of simulating vehicle aerodynamic loads. Since the vehicle is stationary during the test the aerodynamic load is not imposed on the vehicle surface as it is in-use. Instead, a simulated aerodynamic load is imposed on the vehicle through the tires, by adjusting the load on the dynamometer rolls. In effect, the dynamometer uses inertial and electrically generated loads applied through the vehicle's tires to simulate aerodynamic load.

The required load is determined by conducting an on-road coast-down test prior to the dynamometer testing. In a coast-down test the vehicle is accelerated to some speed and then allowed to coast to a stop without applying the brakes, while vehicle speed versus time is recorded. By calculating the varying deceleration rate of the vehicle over time, one can impute the forces (rolling resistance and aerodynamic drag) that were operating on it at each speed.

This information is programmed into the dynamometer – so that it will impose the appropriate load on the vehicle at each point in the test cycle. The vehicle is then mounted on the dynamometer and a dynamometer coast down test is conducted to ensure that the coast-down profile is the same on the dyno as it was on the road.

While this method of evaluating and simulating rolling resistance and aerodynamic drag on a dynamometer is theoretically sound, it is critical that the coast-down test be conducted correctly. The largest constraint on coast-down testing is usually finding an appropriate location to conduct the test (straight, level, with sufficient length).

In addition to the above vehicle test methods, engine dynamometer testing in conjunction with vehicle simulation modeling could also be used for regulatory certification of HDV fuel efficiency. This is the approach taken in Japan (see section 5.1 for a detailed description of this methodology). Such an approach would be the least costly method of conducting fuel efficiency tests of new HDVs since one laboratory engine test could be used to model multiple vehicles. To a certain extent the required engine tests are already conducted in the context of emissions certification, and the additional testing requirements would be minimal. The use of a simulation model would also allow manufacturers to cost-effectively estimate fuel efficiency for each vehicle on a large number of different test cycles using data from a single engine test.

The "accuracy" of resulting fuel efficiency ratings from such a method would be limited by the "accuracy" of the vehicle simulation model used. To achieve a high degree of accuracy the simulation model would need to be highly detailed and sophisticated, and appropriate vehicle-specific factors would need to be developed for all parameters that might affect vehicle fuel use, including rolling resistance, aerodynamic drag, drive train losses, accessory and vocational loads, and engine idling (see Section 3).

One existing simulation model that could be evaluated for use in a regulatory program for HDV fuel efficiency is the Powertrain System Analysis Toolkit (PSAT) model developed by Argonne National Laboratory. PSAT is a "forward-looking" model that simulates fuel economy and performance in a realistic manner — taking into account transient behavior and control system characteristics. This model is used by vehicle manufacturers during design development, and was chosen by DOE as the primary vehicle simulation tool to support 21st Century Truck Partnership activities [7-5].

To develop accurate vehicle-specific factors for simulation modeling additional laboratory testing of vehicles or vehicle components would likely be required. For example, wind-tunnel testing could be conducted to determine the aerodynamic drag created by different vehicle configurations.

Vehicle simulation modeling could also be used in conjunction with in-use, test-track, or chassis dynamometer testing to minimize the testing burden on HDV vehicle manufacturers.

Under such a scenario a full-vehicle test would have to be conducted on a "base model" of a particular truck, while a simulation model would be used to develop a fuel efficiency rating for vehicles with "minor" changes to the base configuration – for example a different transmission or rear-end gear ratio, or a different style of body attached to the same vehicle chassis.

See Table 7.3 for a comparison of the different test methods.

Table 7.3 Comparison of HDV Fuel Efficiency Test Methods

Method	Equipment	Pros	Cons
In-Use Test	400 – 600 mile test course(s) on public roads	▪ Easy to conduct ▪ Relatively in-expensive ▪ Well-developed procedure in place ▪ Familiar to HDV fleets	▪ High test-to-test variation ▪ Best for comparing one truck to another ▪ May require the use of a "reference truck"
Test Track Test	Closed, 1-5 mile oval or circular test track	▪ Easy to conduct ▪ Good repeatability	▪ Facilities are limited and expensive ▪ Complexity of test cycles limited ▪ Best for high-speed steady-state test cycles ▪ Can not incorporate changes in grade to test cycle ▪ Affected by ambient conditions
Chassis Dynamometer Test	Heavy-duty chassis dynamometer Coast-down test track	▪ Well-developed procedure in place ▪ Computerized drivers aids ensure very good compliance with transient test cycles ▪ Very good repeatability	▪ Facilities are limited and expensive ▪ Accuracy depends on accurate coast-down test
Engine Test plus Vehicle Simulation Modeling	Engine dynamometer Vehicle simulation model	▪ Well-developed test procedure in place ▪ Minimal additional testing burden ▪ Lowest total cost to vehicle manufacturer of available options ▪ Ability to run large number of test cycles off single engine test.	▪ Accuracy depends on complexity of simulation model and "accuracy" of model inputs ▪ Development of vehicle-specific modeling parameters likely to require additional vehicle/component testing (i.e. wind tunnel tests of aerodynamic drag)
Simulation Modeling for Changes to Base Model	Vehicle simulation model	▪ Can minimize over-all testing burden to manufacturers	▪ Accuracy depends on complexity of simulation model and "accuracy" of model inputs ▪ Requires careful definition of "major" change that triggers need for additional base vehicle testing

7.4.2 Test Cycle(s)

Regardless of the test method used, HDV fuel efficiency testing will require development and use of appropriate test cycles. For any HDV an "appropriate" test cycle must accurately model the "typical" in-use duty cycle seen by the vehicle. Relevant aspects of a vehicle's duty cycle that can significantly affect fuel use include acceleration rates, vehicle speed, number and severity of engine transients (changes in speed), changes in roadway grade, number of stops per mile, percent engine idling time, and vocational loads.

Different HDVs have significantly different duty cycles – for example a transit bus is used very differently than a refuse truck or a Class 8 combination truck. Any one type of HDV may not have a single "typical" duty cycle either. For example, Class 8 combination trucks often operate for long periods at sustained high speeds on interstate highways (line haul cycle), but they can also operate in slow speed stop-and-go urban traffic (urban cycle). Even line haul vehicles may have significantly different fuel use when operating on generally flat terrain as opposed to hilly or rolling terrain.

One approach to HDV fuel economy testing would be to use the same test cycle(s) to test all HDVs, regardless of type. This would be similar to current EPA fuel economy and emissions testing of light duty vehicles, which uses five different test cycles to determine City, Highway, and Combined fuel economy ratings for every vehicle model (see Section 7.5). While such a test protocol is appropriate for light duty vehicles, and would be relatively simple to implement, it would be unlikely to produce satisfactory results for HDVs for two reasons.

First, there is no way that even five test cycles could be representative of "real world" operating behavior for all HDVs. Testing on an unrepresentative test cycle for a particular type of HDV might lead vehicle manufacturers to make changes that would allow them to meet the regulatory efficiency standard, but which would have little actual benefit in-use. For example, if all testing was done on a slow-speed urban test cycle manufacturers would have little incentive to improve vehicle aerodynamics , but would have a large incentive to incorporate a hybrid drive train. If the resulting vehicle were then operated exclusively at high sustained speeds the expected benefits from the hybrid drive train would be largely unrealized and a significant opportunity to reduce real-world fuel use based on improved aerodynamics would be missed.

Second, vehicle users are likely to use the fuel efficiency ratings developed during certification testing as a guide when making purchasing decisions. If these ratings are based on an unrepresentative test cycle for a particular vehicle type they will have little correlation with the purchaser's in-use experience, and they will quickly be discredited as a reliable source of information.

In order to adequately cover the complexity and variety of the HDV fleet another approach would be to use different test cycles for each type of HDV during fuel efficiency testing. In this approach each major category of HDV (transit bus, refuse truck, utility truck, single-unit freight hauler, combination freight hauler, etc) would require two to five different test cycles to cover the range of typical operation for that type of vehicle, and these cycles would be different for each vehicle type.

A third approach would be to use a limited number of test cycles to test all HDVs, but to mathematically combine the fuel economy results from these cycles in different ways depending on the type of HDV – to use the measured results to "predict" fuel use on a more representative cycle or cycles for each HDV type. In this scenario all HDVs would be tested on the same test cycles, but the weighting of fuel economy results from each cycle would be different depending on the type of HDV. As a simple example, consider a case where testing was done on a slow speed urban cycle and a high speed line haul cycle. The predicted regulatory fuel economy for a transit bus and a Class 8 combination truck might be calculated as follows:

Transit bus = (URBAN CYCLE FE x 80%) + (LINE HAUL CYCLE FE x 20%)

Combination Truck = (URBAN CYCLE FE x 20%) + (LINE HAUL CYCLE FE x 80%)

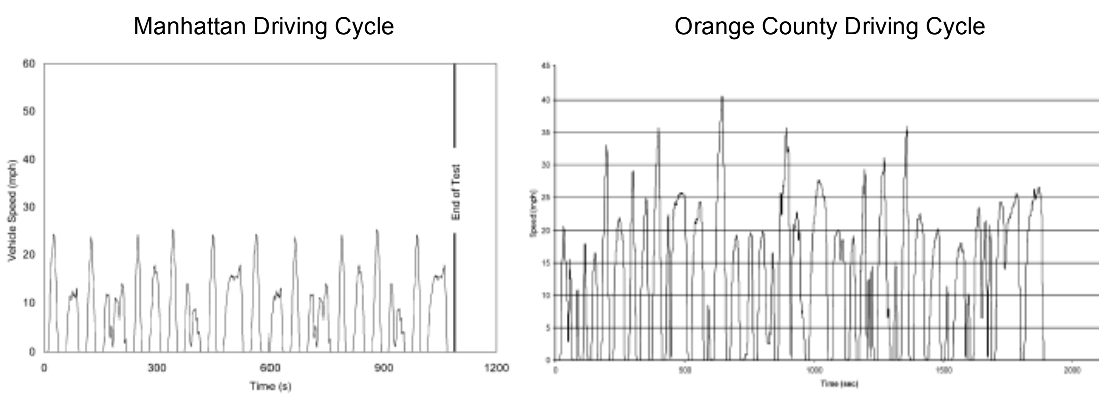
This approach has preliminarily been demonstrated by West Virginia University (WVU) to predict exhaust emissions (including CO_2) on an "unseen cycle" based on the measured results from some number of "standard cycles" [7-6]. In WVU's methodology the required weighting factors for measured emissions from each test cycle are determined based on the statistical characteristics of the cycle (average speed, idle time, average change in speed, etc.) compared to the same metrics for the target "unseen" cycle. In order to adequately characterize the dynamic behavior of HDVs (including engine idle time) a minimum of three widely variant test cycles will probably be required. Every additional independent variable (i.e. geography, vehicle weight, vocational PTO load, etc) would require another test cycle.

This approach would simplify actual fuel economy testing, but would still require prior knowledge of "typical real world" duty cycles for the various major types of HDV, in order to develop appropriate type-specific weighing factors. These type-specific weighing factors would be used to calculate the regulatory fuel economy value for each HDV, based on the measured fuel economy on the test cycles.

For some HDVs (for example transit buses) a number of chassis dynamometer test cycles have already been developed that might be appropriate for fuel efficiency testing. See Figure 7.4 for two of many examples. Preliminary work has also been done to develop appropriate test cycles for highway line haul vehicles, local pick-up and delivery vehicles, neighborhood refuse trucks, utility service trucks, and intermodal drayage trucks [7-7]. For some of these vehicle types additional cycles will likely be required in order to cover the full range of in-use operation.

Some of these dynamometer test cycles may also be appropriate for use on a test track, while others may be too complex to produce consistent test track results.

Specifically for sleeper cab-equipped combination trucks it might also be desirable to include long duration idling as part of the certification test, with appropriate cabin hotel loads included. This could be handled in a separate test, in addition to the baseline drive cycle(s).



Source: SAE

Figure 7.4 Transit Bus Test Cycles: Manhattan Cycle and Orange County Cycle

7.4.3 Test Conditions

In addition to specifying the testing method and test cycles, a fully developed fuel efficiency test protocol must specify mandatory testing conditions. This is required in order to control for all of the major variables that might affect vehicle fuel use. Some of the test conditions that must be specified include:

- The acceptable range of ambient weather conditions (temperature, humidity, wind speed)
- Vehicle test weight/payload
- Vehicle accessory loads (i.e. air conditioning on/off)
- Vehicle vocational loads
- Tire pressure and tread depth
- Vehicle pre-conditioning
- Test fuel specification

Defining an appropriate vehicle test weight is of particular concern for many HDVs, especially single-unit and combination freight haulers. One approach would be to test at a vehicle's maximum GVWR (worst case) while another would be to test at some percentage of GVWR which is representative of the "average" load carried by this type of vehicle in-use, taking into account that in the real world it is not always possible to maximize vehicle payload on every trip.

Vehicle accessory loads will be relatively insignificant for some HDVs (for example combination trucks on a line haul cycle) but much more important for others (for example transit buses). Likewise, the importance of vocational loads will be dependent on vehicle type.

7.4.4 Combination Truck-Trailer Testing

Specifically for Class 8 combination trucks, an important consideration will be how truck/trailer combinations will be tested for fuel efficiency. Especially on high speed line haul cycles the characteristics of both the truck and trailer will significantly affect fuel use.

As discussed in Section 2, heavy-duty truck tractors and the trailers that they pull are manufactured by different companies and are generally not sold as sets. In fact the truck tractor and trailer that make up a specific combination truck on a specific day are often owned by two different companies, and the tractor may be paired with a different trailer the following day or week.

In this situation it will be necessary to conduct fuel efficiency testing of combination truck tractors while paired with a "reference trailer" of standard size and configuration. All aspects of this reference trailer will need to be defined, including the exterior dimensions, shape, and materials as well as the specifics of the axles, wheels, and tires. The distance between the rear of the truck cab and the front of the trailer during testing will also need to be specified since it can significantly affect aerodynamics.

There are two approaches that could be taken to specification of a reference trailer. The first would be to specify a standard box-type trailer with relatively poor aerodynamics and standard tire configuration, which would result in fuel use generally representative of what is seen today. The second would be to specify a "best-in-class" trailer design with improved aerodynamics and low rolling resistance tires, which would result in lower fuel use for every tractor with which it was paired.

If separate trailer testing is required (see Section 7.2) it could be accomplished by testing trailers while paired with a "reference truck". The reference truck could be a specific vehicle, or could be any vehicle which achieves a specific fuel efficiency rating when tested paired with the reference trailer. It is also worth exploring the possibility of developing a trailer standard and test procedure independent from the truck.

7.5 Form of Required Fuel Efficiency "Improvement"

Regardless of the metric used (see Section 7.3) regulation of HDV fuel efficiency will require that a minimum standard be set for all vehicles of a specific type. There are two options for how to define the minimum standard: 1) by setting an absolute value for the chosen metric, or 2) by mandating a percentage improvement from some baseline value.

In order to set a meaningful but realistic goal for improved efficiency, defining an absolute value goal (i.e. maximum of 500 BTU/ton-mile = ~7 MPG for a fully-loaded Class 8 combination truck) will require good information about the fuel efficiency of existing vehicles, as well as the potential of various technology options to reduce fuel use. A separate absolute value goal will have to be set for a number of different HDV types, based on the chosen test cycles (i.e. each test cycle will require a separate value for the fuel efficiency standard).

Mandating a percentage improvement from a baseline does not necessarily require definitive information on the fuel efficiency of existing vehicles, nor does it necessarily require a separate goal for each type of HDV. For example, one could mandate that beginning in 2015 all HDVs be tested using the regulatory protocol (including using different test cycles for different vehicle types) to develop a baseline fuel efficiency rating for each vehicle type, and that beginning in the 2017 model year all new vehicles must have at least 10% lower fuel use than the measured 2015 baseline.

As discussed in Section 7.4.2, most HDVs will not have a single "typical" duty cycle that adequately covers the full range of in-use fuel use over the vehicle's lifetime. As such, it is likely that for most vehicle types it will be advisable to test on more than one test cycle. From a regulatory perspective one must decide how the test results from the different test cycles will be used to evaluate compliance with the regulatory standard. There are two options: 1) mathematically combine the results from the separate test cycles to create a "combined" rating used for regulatory compliance, or 2) set a separate regulatory standard for each test cycle which must all be met.

The first option is analogous to what is currently done for cars and light trucks. These vehicles are tested on five different test cycles[14] and the city, highway, and combined fuel economy ratings posted on window stickers are calculated based on different weighting of results from each test cycle. Compliance with corporate average fuel economy standards (CAFE) is based on a combined MPG rating derived from only the city and highway test cycle results[15] [7-8].

The formula used to combine test results from different HDV test cycles could be simple or complex, but in general would be designed to represent over-all fleet average fuel efficiency for each vehicle type, based on the relative percentage of time that typical vehicles spend in each duty cycle.

The second option is analogous to current emission standards for locomotive engines. Unlike other heavy-duty diesel engines that are tested on only one test cycle, locomotive engines are

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[14] The test cycles are: Federal Test Procedure, FTP (stop-and-go city driving), Highway Fuel Economy Test, HFET (rural driving), US06 (high speeds and aggressive driving), SC03 (air conditioner operation), and Cold FTP (cold temperature operation)

[15] While the test data used are the same, the cycle weightings used to calculate MPG for compliance with CAFE and for the fuel economy ratings posted on window stickers are different. For any individual vehicle the fuel economy ratings on the window sticker may therefore not match exactly the fuel economy rating used for CAFE compliance calculations.

tested on two different test cycles – the line haul and switcher cycles – that represent the extremes of typical locomotive in-use duty cycles. There is a separate numerical standard for emissions as tested on each cycle, and every engine must meet both standards. For example, since 2005 new locomotive engines have been required to emit no more than 5.5 g/bhp-hr NOx when tested on the line haul cycle, but they are allowed to emit up to 8.1 g/bhp-hr NOx when tested on the switcher cycle [7-9].

7.6 Choice of Baseline

If the regulatory standard for HDV fuel efficiency is defined as a percentage improvement from some baseline, the baseline against which regulatory compliance will be measured must be defined. The baseline will typically be defined as the measured efficiency from some sub-set of vehicles of each type from a specific model year, as tested using the regulatory protocol.

An appropriate choice of baseline year might be one or two model years prior to implementation of fuel efficiency regulations. EPA emissions standards for onroad heavy duty diesel engines that take effect in the 2010 model year will require an 80 percent reduction in NO_x emissions. The changes required to meet this standard may negatively affect net engine efficiency. As such the baseline year for any HDV fuel efficiency standards should be the 2010 model year or later.

Given the volatility in diesel fuel prices truck owners and fleets have increased incentive to voluntarily adopt technologies that will reduce fuel use. If the recent high prices ($3.50+ per gallon) had been sustained there would likely be significant vehicle and fleet changes over the next few years, and a fleet fuel efficiency baseline defined for the 2012 model year or later would likely be higher than a baseline defined for earlier model years.

Which ever model year is chosen as the baseline year, there are several options for defining the numerical standard for baseline fuel efficiency based on available vehicles from that model year. These choices include: 1) the average fuel efficiency of all models sold that year (model average), 2) the sales-weighted average fuel efficiency of all models sold that year (fleet average), 3) a fuel-weighted average calculated based on the sales of each vehicle, their fuel economy ratings, and their "expected" annual mileage (fuel-weighted average) or 4) the fuel efficiency of the best performer of all models sold that year (top runner).

7.7 Implementation Timeline & Flexibility Provisions

There are several options for a regulatory time line for implementation of HDV fuel efficiency standards. The first is to set a specific fuel efficiency standard for each HDV vehicle type, to take effect for vehicles sold beginning in a specific vehicle model year (i.e. beginning in model year 2015 HDVs must get 5% better fuel efficiency than the 2012 baseline). A second approach would be to set a specific standard for each HDV vehicle type, to take effect for vehicles sold beginning in a specific vehicle model year, and to periodically tighten the standard every few years (i.e. beginning in model year 2015 HDVs must get 5% better fuel efficiency than the 2012 baseline, beginning in model year 2017 HDVs must get 10% better fuel efficiency than the 2012 baseline, etc.).

Under this second scenario the initial standard might be "easy" to reach using off-the-shelf technology, while later more stringent standards would require new technology development or maturation. The lag for application of more stringent standards would be designed to allow time for the required technology development.

Whichever of these methods is chosen, it is not a given that the standard must apply to all HDVs sold in the first model year to which they apply. It might be advantageous to allow manufacturers compliance flexibility by phasing in the requirements over several model years. There are several options for a phase-in, including:

- % **of Models**: phase-in the requirement on a percent-of-models basis (i.e. in the first year 25% of each manufacturer's models must meet their target, in year two 50%, etc).
- % **of Sales:** phase-in the requirement on a percent-of-sales basis (i.e. in the first year 25% of all vehicles sold by each manufacturer must meet their target, in year two 50%, etc).

Another approach that would allow manufacturers flexibility would be to set a fleet average fuel efficiency standard, rather than requiring every HDV model to meet a specific standard. Under fleet averaging the sales-weighted or fuel-weighted average[16] of all vehicles sold by each manufacturer must meet a specific fuel efficiency standard, while individual vehicle models would be allowed to be less efficient. Obviously, to meet the fleet average standard some models would also have to be more efficient, and the net effect would be the same as if every model exactly met the standard. A fleet average requirement could also be periodically tightened over some range of model years to allow for technology development required to meet the final, most stringent standards.

U.S. Class 8 combination trucks typically burn eight times as much fuel per year as other HDVs because they are heavier and typically travel many more miles. In this situation, sales-weighted fleet averaging across all HDV types would not be optimal. Fleet averaging would have to be done for each separate type of HDV sold by each manufacturer, or a fuel-weighted fleet average would have to be used, which takes into account the amount of fuel that each truck typically uses in a year in addition to the number of trucks sold.

An approach that would give manufacturers additional compliance flexibility is the use of averaging, banking, and trading. "Averaging" is often used to mean that manufacturers are given "credit" for over-compliance in one area, which they can use to off-set under-compliance in another area. "Trading" is often used to describe the sale of a "credit" from one company to another. "Banking" would allow manufacturers to over-comply in earlier years, in exchange for lesser reductions in following years. Averaging, banking and trading could be used to ease compliance across vehicle types within a single model year, or across model years. One advantage is the ability to potentially set tighter limits at equal or possibly even lesser cost than standards that must be met by each and every unit.

For example, let's say that a fuel efficiency regulation requires a separate fleet average fuel efficiency rating for each type of vehicle sold by a manufacturer (i.e. combination trucks, single-unit freight trucks, buses). Cross-vehicle banking and trading would allow a manufacturer to get credit for over compliance by their buses and apply that to offset under compliance for the combination trucks they sell. Likewise, under a scenario in which the fleet average standard gets more stringent over time, a manufacturer could be given credit for over compliance in the early years through "banking", which would allow them to take more time to meet the more stringent standards required in later model years.

Averaging, banking and trading schemes can be complex, and must be carefully crafted to ensure that the reduction in fuel use of over-complying vehicles is at least as great as the increase in fuel use from non-complying vehicles that are allowed to be sold under the averaging, banking and trading scheme. For the U.S. HDV fleet, careful attention must be paid to the relative "worth" of an over- or under-complying Class 8 combination truck compared to other HDV types which typically burn much less fuel annually.

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[16] Due to the fact that different types of HDVs have significantly different annual usage, the sales-weighted average and the fuel-weighted average will not be the same. For example, if 75% of trucks sold are single-unit trucks that get 8 MPG and 25% are combination trucks that get 6 MPG, the sales-weighted average fuel economy will be 7.5 MPG. However, if single units trucks average 12,000 miles per year and combination trucks average 60,000 miles per year the fuel-weighted average fuel economy will be 6.6 MPG.

7.8 Compliance/Enforcement

The most significant issue for compliance and enforcement of a U.S. HDV fuel efficiency/GHG regulation is the agency of the federal government that would be responsible to promulgate and enforce the rules. The two most likely candidates would be the Environmental Protection Agency (EPA) and the Department of Transportation (DOT).

EPA has responsibility for regulation of exhaust emissions from new light-duty vehicles and new heavy-duty engines. DOT has responsibility for regulation of new vehicle safety requirements (both light duty and heavy duty), commercial vehicle operations, and for the current fuel economy standards for light duty cars and trucks (Corporate Average Fuel Economy, CAFE)[17]. While DOT is responsible to develop and implement the CAFE standards, the corporate average fuel economy for each manufacturer is calculated by EPA based on test data collected during emissions certification testing [7-10]. Congress has tasked DOT with the responsibility for HDV fuel efficiency standards, given their technical responsibility for new vehicle safety and their current responsibility for light duty fuel economy standards.

EPA would also be in a good position to develop and implement HDV greenhouse gas regulations given their technical familiarity with fuel economy and heavy-duty emissions testing, as well as the technical efforts currently being undertaken under their SmartWay program, including current efforts to develop a heavy-duty vehicle fuel efficiency test protocol.

In April 2007 the U.S. Supreme Court ruled that the Clean Air Act gives EPA the authority to regulate carbon dioxide emissions from vehicles, in the context of efforts to protect human health by reducing global warming. Further, the Court ruled that "under the Act's clear terms, EPA can avoid promulgating regulations only if it determines that greenhouse gases do not contribute to climate change or if it provides some reasonable explanation as to why it cannot or will not exercise its discretion to determine whether they do."

The decision recognized that an EPA effort to regulate CO_2 emissions from vehicles would overlap with DOT's mandate to promote energy efficiency by setting mileage standards, but affirmed that these two goals were not in conflict. The court said that "The fact that DOT's mandate to promote energy efficiency by setting mileage standards may overlap with EPA's environmental responsibilities in no way licenses EPA to shirk its duty to protect the public health and welfare." Protecting public health and welfare is a duty mandated by the Clean Air Act.

Another important compliance issue for any HDV fuel efficiency standard would be labeling requirements. The measured fuel efficiency of every HDV subject to regulation should be available to the public to help inform their equipment buying decisions. How best to disseminate this information might be open to debate. Some issues to consider include the required location for fuel efficiency "labels" to be posted (i.e. on a window sticker as with current cars and light trucks), the format for reporting fuel efficiency (see Section 7.1), and how test results from different test cycles will be reported (see Section 7.2.2).

Non-compliance with any HDV fuel efficiency regulation will require penalties. Some issues to consider with respect to non-compliance penalties include the form of the penalty, the value of the penalty, and who will be required to pay it.

In accordance with the Clean Air Act penalties for non-compliance with heavy duty engine exhaust emission standards are based on the expected average cost of compliance and the degree of non-compliance for the engine. They are specifically designed to erase any

[17] The agency of DOT responsible for CAFE is the National Highway Traffic Safety Administration (NHTSA)

competitive disadvantage for manufacturers that are complying. There is also an upper bound on allowable emissions from non-compliant engines – those whose emissions exceed the upper limit can not be sold at all.

Based on penalty formulas in the Clean Air Act and EPA's assessment of the average cost of compliance, in 2001 EPA proposed non-compliance penalties of $4,680 per engine for model year 2004 and later heavy-duty diesel engines with a NO_x emissions rate of 3.0 g/bhp-hr, compared to the regulatory limit of 2.5 g/bhp-hr. For engines emitting 4.5 g/bhp-hr NO_x the proposed penalty increased to $11,342 per engine [7-11]. These penalties were for the first year that the non-compliant engine model was sold, and they increased in subsequent years.

Penalties for non-compliance with the CAFE standards for cars and light trucks are a fine levied against the vehicle manufacturer of $5.50 per tenth of a mile per gallon below the standard, times the manufacturer's sales volume[18].

Another approach would be to levy a "gas guzzler" tax or duty on each non-compliant vehicle, to be paid by the purchaser. While not levied directly against the vehicle manufacturer such a tax would provide an indirect incentive to the manufacturer to comply, by making their vehicles more expensive compared to compliant vehicles, and would directly discourage the purchase of non-compliant vehicles. To be effective the value of the tax would need to be greater than the per vehicle differential cost of manufacturer compliance.

One might also impose a non-monetary penalty by refusing to allow non-compliant vehicles to be registered by the user. This option might not be practically available to the federal government, but could be implemented by the individual states.

[18] For a corporate average fuel economy of 20 MPG compared to a CAFE standard of 20.5 MPG, and an annual sales volume of 500,000 vehicles, the non-compliance fine would be $13.75 million.

8. Barriers to Implementation of HDV Fuel Economy Standards

There are a number of factors specific to the U.S. HDV market that make HDV fuel efficiency regulations more difficult and complicated to design and implement than fuel efficiency regulations for cars and light trucks. The most significant of these are discussed here.

8.1 HDV Fleet Diversity

As discussed in Section 2, the U.S. HDV fleet is extremely diverse, with a wide range of vehicle types, sizes, and typical duty cycles. To effectively cover the entire HDV fleet any fuel efficiency regulation will of necessity be complex.

While the same basic test protocol can be used to measure the fuel efficiency of virtually all HDVs, different types of HDVs may require different test cycles to replicate typical in-use behavior. Even a single type of HDV will likely require several different test cycles to adequately cover the range of typical in-use duty cycles. For any particular HDV type this is no different, or more difficult, than current fuel efficiency regulation of light duty vehicles, which uses five different test cycles. However, the greater diversity of vehicle types in the HDV fleet will add complexity to the over-all regulatory scheme.

Depending on the fuel efficiency metric used, and the form of any required improvement, separate numerical standards for fuel efficiency may also be required for each type/size of HDV.

8.2 Shared Responsibility for Components of Fuel Use

HDV manufacturing is more complicated than manufacturing of cars and light trucks. For a typical HDV the engine, chassis, and body may have been produced by three different manufacturers. In addition, Class 8 combination trucks are composed of a truck-tractor paired with a trailer. The truck and trailer are typically manufactured by different companies, and are often owned by different companies as well for in-use vehicles. Trucks and trailers are typically not paired long term either – a specific truck may pull a number of different trailers over the course of a month or a year.

For a typical HDV no single entity controls all design decisions that affect fuel use, making it difficult to determine where best to assign responsibility for complying with fuel efficiency regulations.

For HDVs the engine manufacturer has responsibility to comply with current EPA exhaust emission standards. While the engine in an HDV affects fuel efficiency, so does the drive train, vehicle accessories, and vehicle aerodynamics - which are determined by the vehicle manufacturer. As such, it might be better to assign primary responsibility for complying with fuel efficiency standards to the vehicle manufacturer (i.e. the vehicle would be regulated, not just the engine).

That being said, many HDVs are produced by two different vehicle manufacturers – the producer of the chassis, and a second manufacturer that buys the chassis, adds a body, and ultimately sells the vehicle to the user. For most of these vehicles the chassis manufacturer likely has greater impact on fuel use than the body manufacturer does, and the same basic chassis will be used for a number of different vehicle types. As such, it might be more efficient to assign primary responsibility for complying with fuel efficiency regulations to the chassis manufacturer, but it may also make sense to apply a second set of standards to some finished vehicles, with the final body attached.

Because they have such a significant impact on fuel use, particularly at highway speeds, to maximize the effectiveness of any HDV fuel efficiency regulations the trailers used with Class 8 combination trucks should also be regulated. Since they are manufactured by different companies they will have to be regulated separately from the Class 8 truck tractors that pull them. This significantly complicates regulatory fuel efficiency testing, and will likely require the use of "reference trailers" for truck testing and "reference trucks" for trailer testing.

8.3 Vehicle Ownership Patterns

A high percentage of Class 8 combination trucks and other HDVs are owned by small businesses and independent owner/operators that own only one or a few trucks.

Many of these owners may be resistant to the imposition of HDV fuel efficiency standards due to concerns about the affect on truck prices, and new technology risk aversion.

8.4 Financing & Access to Capital

The imposition of fuel efficiency standards will almost certainly increase prices for new HDVs based on the incremental cost of compliance. Because more efficient vehicles will use less fuel to do the same amount of work, or to carry the same amount of cargo, there will be an off-setting savings in annual fuel costs for the vehicle owner.

In some cases the pay-back period of the incremental purchase cost, based on annual fuel savings, may be quite short[19]. Even so, independent owner/operators and small businesses may be constrained in their ability to purchase new, more efficient, trucks due to limited access to low cost capital funds.

8.5 Lack of HDV Fuel Economy Test Protocol

There is currently no well-established, accepted test protocol that could be used to test the fuel efficiency of HDVs to judge compliance with a regulatory fuel efficiency standard. There are a number of industry-developed fuel efficiency and emissions test procedures that could be used as the basis of such a protocol, but significant work is required to develop them into a comprehensive procedure.

EPA has developed a draft fuel efficiency test protocol intended to be used for certification of medium and heavy duty vehicles under their SmartWay™ program. This protocol currently envisions the use of chassis dynamometer and/or track testing to evaluate the fuel efficiency of various types of HDVs. Many aspects of the draft protocol are well developed, but the following areas need significantly more work to be useful for regulatory testing:

- specification of drive cycles for various types of HDVs
- specification of test weight/payload for various types of HDVs
- specification of vehicle accessory and vocational loads for various types of HDVs
- specification of required tire condition for testing (tread depth, tire pressure)
- management of engine cooling load during dynamometer testing

[19] An average Class 8 combination truck logs 69,000 miles per year, gets 5.9 MPG, and burns 11,600 gallons of diesel fuel annually. A ten percent increase in fuel economy would reduce annual fuel use by 1,000 gallons. At $3.50 per gallon the vehicle owner would save $3,500 per year, $10,500 over three years, and $17,500 over five years.

- accounting for fuel used to regenerate active diesel particulate filters
- evaluating and accounting for the effect of cross-winds on aerodynamic drag

In addition, while the draft SmartWay™ protocol currently envisions allowing both chassis dynamometer and test track testing, there is relatively little information currently available to evaluate the correlation of results from these two test methods for the same vehicle, or the correlation of results from either method to "typical" in-use results.

Companies that own large fleets of HDVs, particularly Class 8 combination trucks, regularly conduct formal in-use fuel economy tests to evaluate the effect on fuel use of different truck models and configurations, different components and tires, and after-market devices. These tests are usually conducted in accordance with TMC RP1109, *Type IV Fuel Economy Test Procedure.* This procedure is a paired-truck test, and testing is usually conducted on public roadways over the actual in-service routes used by the fleet. Results are reported as a percentage change in fuel use for one truck compared to the other (control) truck. The use of a control or reference truck allows for control of many independent variables, but this type of test may not be practical for testing under a regulatory program due to concerns about duty cycle repeatability, and the need to specify and maintain a fleet of reference trucks to maintain an appropriate control.

8.6 Lack of Baseline Data

Large HDV fleets typically keep very detailed records on the usage patterns and fuel use of their vehicles. These fleets also regularly conduct formal in-use paired-truck fuel economy tests (see Section 8.5). Many of these fleets consider this data to be proprietary, and there is relatively little published, peer-reviewed information about these fleets. In addition, many trucks are owned by small businesses and owner/operators that do not keep formal or comprehensive records. It is therefore impossible to create a comprehensive picture of the ownership and usage patterns, and fuel efficiency, of the current U.S. HDV fleet.

The best, though limited, information currently publicly available comes from the *Vehicle Inventory and Use Survey* that has been conducted by the U.S. Census Bureau every five years since 1963. The latest survey was completed in 2002, but this program has been discontinued and no more surveys will be conducted.

In order to develop effective HDV fuel efficiency regulations the following types of information about the current HDV fleet would be useful:

- fleet ownership and use patterns for various types of HDVs
- typical duty cycles for various types of HDVs
- truck model-specific fuel economy data
- potential fuel efficiency improvements from various technology combinations

8.7 Changes in Ownership Over a Vehicle's Life

As with other vehicle types, HDVs typically have multiple owners throughout their life. To a greater extent than with cars and light trucks, however, a change in ownership of an HDV might also bring a significant change in duty cycle.

Different sized fleets have different purchasing patterns for HDVs. For line haul trucks, larger fleets with more than fifty trucks tend to buy vehicles new, and to keep them for a relatively short time, while smaller fleets with less than ten trucks purchase a much higher percentage of their trucks used, and keep them for longer periods [8-1]. Heavy vocational trucks tend to be held longer by their first owner – seven to eleven years – even when purchased by larger fleets.

New trucks, particularly Class 8 combination trucks, also typically see more annual use than older trucks. While the average Class 8 combination truck travels 68,800 miles per year, approximately 50 percent of trucks less than two years old travel more than 100,000 miles per year, and some of them can travel over 200,000 miles per year [8-2].

Over it's life time a "typical" Class 8 combination truck might be purchased new by a large national fleet and used for long-distance hauling for three to five years, after which it might be sold to a small- or medium-sized fleet and used for local or regional hauling for another five to eight years. It might pass through several more owners, and ultimately end up as a drayage truck making short local runs in and around a port or international border crossing.

With respect to fuel efficiency regulation, this complexity of usage patterns over the life of an HDV might affect the choice of test cycle(s) used for compliance testing, and/or the weighting of results from different test cycles, when developing a combined fuel efficiency rating (see Sections 7.2.2 and 7.3).

9. Related Issues

The bulk of this document discusses issues related to regulation of fuel efficiency from new heavy duty vehicles. There are a number of other factors that might affect fuel use and GHG emissions from the entire transportation sector. Some of these are briefly discussed here.

9.1 Complementary In-use Standard

As with current exhaust emission standards for light duty vehicles and heavy duty engines, and current fuel efficiency standards for light duty vehicles, any new fuel efficiency regulations for HDVs would presumably apply only to *new* vehicles.

Opportunities exist to also improve the fuel efficiency of existing HDVs. Standardizing rolling resistance measurement methods and labeling aftermarket tires with their rolling resistance, for example, would enable vehicle owners to select low rolling resistance tires. Additional improvements can be achieved through the application of after-market retrofit technologies and/or engine upgrades. In conjunction with the imposition of fuel efficiency standards for new HDVs one could contemplate the imposition of complementary in-use standards. This is the approach that California has adopted as one early-action measure to reduce GHG emissions state-wide (see Section 4.3).

Other states could follow California's lead and impose in-use retrofit requirements as a condition of annual vehicle registration. At a federal level, engine upgrades to reduce CO_2 emissions could be mandated in conjunction with engine overhaul/rebuilding, but since current emission standards do not apply to the entire vehicle it is likely that the mandates on engine upgrades could not include retrofits to other vehicle systems.

9.2 The Role of Non-standard Fuels

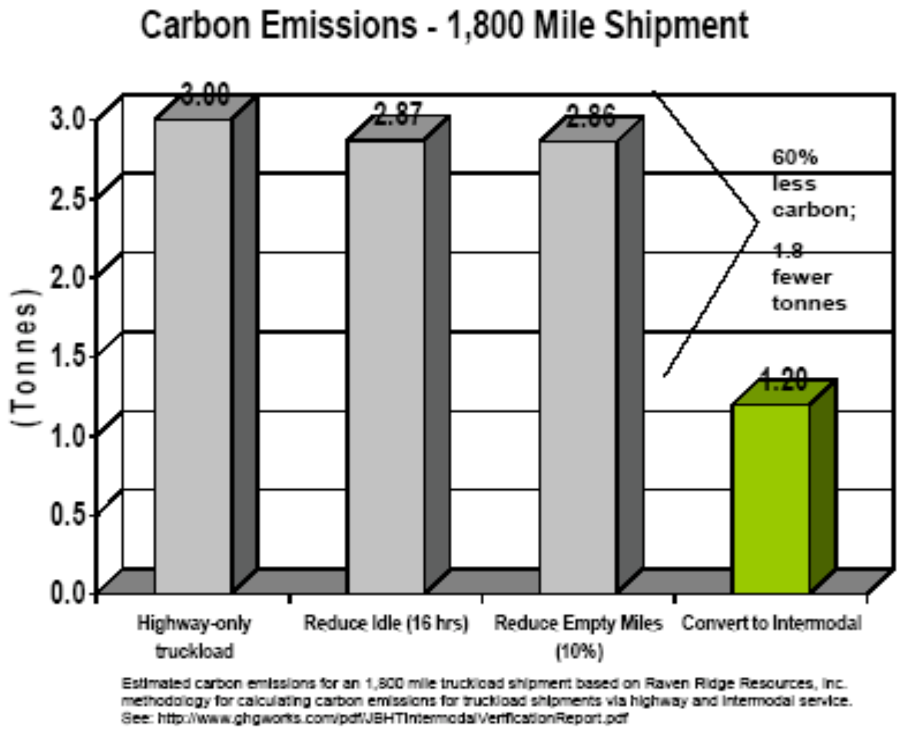
Some non-standard fuels that can be used in HDVs produce lower net CO_2 and GHG emissions than standard diesel fuel, either directly from the tailpipe (i.e. natural gas, hydrogen) or from the entire wells-to-wheels fuel cycle (i.e. biodiesel). Defining the actual wells-to-wheels benefits from some agriculturally-derived fuels has proven problematic, but if an appropriate standard can be developed, "low carbon fuels" might play a role in meeting fuel efficiency/GHG standards for some HDVs.

The test protocols discussed in this document focus on measurement/calculation of vehicle fuel use and tailpipe CO_2 emissions. Depending on the metric chosen for a fuel efficiency regulation the CO_2 reduction benefits of non-standard fuels could be captured directly during testing, or could be easily calculated using adjustments based on measured fuel parameters.

Any "upstream" benefits from other parts of the fuel cycle would have to be measured/calculated separately and subtracted from the tail pipe CO_2 emissions measured during regulatory vehicle testing.

9.3 Incentives for Modal Shift/System Efficiency

This document focuses on regulations to improve the efficiency of individual heavy duty trucks, many of which are used for goods movement. Improvements in HDV fuel efficiency will reduce over-all fuel usage and GHG emissions from the freight sector, but larger benefits could also accrue from modal shift of some shipments to other transportation modes. On a ton-mile basis rail and water-borne freight shipments generally use less fuel than shipments by truck, though total transport time may be longer. See Figure 9.1 for an illustration of the reductions in CO_2 emissions possible from changes in freight strategies [9-1]



Source: J.B. Hunt

Figure 9.1 Relative Carbon Emissions Using Different Freight Strategies

In 2006, approximately 75% of goods carried domestically (by weight) were carried exclusively by truck, and only 9% were carried intermodally [9-2]. While approximately 58% of the weight of exported goods and 79% of the weight of imported goods moved by intermodal shipment, just over one percent of purely domestic shipments moved intermodally.

Any national policy focused on reducing fuel use from the freight sector must address and encourage modal shift to more efficient freight modes, as well as improvements in efficiency of the individual modes themselves.

9.4 HDV Weight and Length Restrictions

One way to reduce per ton-mile fuel use and GHG emissions from Class 8 combination trucks would be to allow them to be bigger and/or heavier than they currently are. Current restrictions on combination truck size and weight are based on existing roadway dimensions (height, width), safety considerations (length, GVWR), and a desire to limit the damage that HDVs cause to roadway pavement, substructures and bridges (GVWR, axle weight).

Current federal law limits vehicle width to 102 inches, and limits axle weights for trucks used on the interstate system to 20,000 pounds for single axles and 34,000 pounds for tandem axles. Total GVWR for a truck-trailer combination is also limited to 80,000 pounds.

Most states have been allowed to adjust these federal limits for certain roadways based on "grandfather rights", and only seven states have adopted them state-wide without adjustment. All states also issue routine permits to exceed these limits. Only New Mexico (86,400 pounds) and Wyoming (117,000 pounds) allow virtually all trucks on the interstate system to exceed the federal GVWR limit, but thirteen states allow trucks on other state roadways to exceed the federal limit, and virtually all states issue routine permits that allow a GVWR of 120,000 pounds or more. Most states have adopted the federal axle weight limits, but issue routine permits for tandem axles weighing 48,000 pounds or more [9-3].

Federal law sets a minimum length of 48-feet for single trailers used in combination trucks and 28-feet each for trailers used in a twin trailer combination on the interstates. Most states have adopted a length limit on the interstates of 53 feet for single trailers, while four states only allow trailers up to 45 feet, and ten states allow longer trailers (up to 60 feet). Hawaii is the only state that has no limit on the length of trailers that can be used on interstate highways. Nine states limit the length of trailers used on other state roads to less than 53 feet, while nine have no limit on the length of trailers that can be used on state highways [9-2].

Over half of the states allow a truck to haul a two-trailer combination, and twelve states allow three trailers. However, federal law limits the GVWR of two- and three-trailer combinations to less than 130,000 pounds in most states.

Fuel use per ton-mile could be reduced from Class 8 combination trucks by allowing higher GVWR, higher axle weights, longer trailer length, or greater use of two- and three-trailer combinations. The benefits of such a policy change would need to be weighted against potential dis-benefits from reduced safety and increased damage to roadways. Such a policy might also provide a dis-incentive for shifting more freight volume away from trucks to more efficient modes such as rail and water transport.

9.5 Reductions in Highway Speed Limits

Aerodynamic drag increases as a square of vehicle speed – the faster a vehicle goes the more fuel it uses to push through the air and maintain its speed. The impact of speed on fuel economy depends on a number of factors, but a general rule of thumb indicates that increasing the speed of a Class 8 combination truck by one mile per hour will decrease fuel economy by 0.1 miles per gallon [9-4].

Reducing average highway speeds from 70 miles per hour to 60 miles per hour might increase fuel economy for a typical Class 8 combination truck by one mile per gallon or more, and save over 1,200 gallons of fuel annually[20] per truck. For the 2 million combination trucks on the road the potential annual fuel savings could total 2 billion gallons or more, approximately six percent of the fuel currently used annually by heavy-duty trucks.

A national policy to reduce maximum allowable highway speeds, implemented and enforced by the states, could significantly reduce fuel use from the freight sector without any changes in new vehicle standards. With such a policy average transit times would increase, which would affect driver hours, productivity, and shipper costs and revenue. Any potential fuel efficiency benefits would need to be weighted against these factors.

9.6 Driver Training

Driver behavior can significantly increase or decrease fuel use for a heavy-duty vehicle regardless of the engine or vehicle technology. A few simple changes in driving habits can reduce fuel use by five percent or more. A Canadian study estimates that many fleets could

[20] Based on 5.9 MPG baseline fuel economy, 69,000 miles per year, and 75% of mileage on the highway.

achieve an average ten percent fuel economy improvement through driver training and monitoring [9-5].

Common habits that can increase fuel use include driving with engine RPM too high, frequent or improper shifting, too-rapid acceleration, too-frequent stops and starts from failing to anticipate traffic flow, and excessive engine idling. Proper driving habits that help to save fuel can be taught. A study for the European Commission estimated that an annual one-day driver training course will improve truck fuel efficiency by five percent [9-4].

Annual or bi-annual refresher training on fuel saving driving techniques for commercial vehicle operators could be enforced by the states as a condition of renewal for commercial drivers licenses.

10. Key Research Areas

As discussed in the previous chapters of this report, the development of effective fuel efficiency regulations for HDVs will require attention to numerous technical and policy-related details. Decisions as to the "best" regulatory design must be based on a thorough understanding of existing and future characteristics of the HDV fleet, the structure and characteristics of the HDV manufacturing industry, and potential technology approaches available to increase HDV fuel efficiency. While much of the required information is known, additional research and analysis is required to further develop and elucidate key areas of interest. The most important research areas are discussed briefly here. These areas will form the basis of the ICCT's research work plan in the near term.

10.1 Technology Options to Increase HDV Fuel Efficiency

In order to set appropriate regulatory targets for improvements to HDV fuel efficiency, more must be known about both the benefits and the costs of the various technology options available to achieve improvements. While it is appropriate for fuel economy regulations to be "technology forcing", they must also be realistic, in terms of what is achievable and in terms of how much regulatory compliance will cost vehicle manufacturers.

Given the complexity of the HDV fleet – the variety of vehicle types and their duty cycles - modeling will likely be required to fully evaluate this issue. Different technologies will have significantly different effects depending on the type of vehicle, as well as how it is used. Different technologies can not necessarily be viewed in isolation either, as there may be complex interactions that increase effectiveness in one type of application but not another. Modeling of multiple scenarios will provide an understanding of the envelope of potential improvements, the sensitivity of the results to various factors, and the relative ease of achieving various levels of improvement for different types of HDVs.

The modeling should include a realistic assessment of the time frame and cost for development and implementation of the modeled technologies, taking into account purchase costs, incremental maintenance costs, and resultant fuel cost savings. A joint project by the Northeast States for Clean Air Future and the ICCT to be completed in early 2009 has been exploring these questions for Class 8 trucks. The modeling performed by the Southwest Research Institute and the cost analysis by TIAX will provide an estimate of the potential fuel use and emission reduction offered by a range of technology packages and their associated cost effectiveness.

10.2 HDV Fleet & Industry Characteristics

While much is known about the composition and characteristics of the existing U.S. HDV fleet and the HDV manufacturing industry, important gaps exist in the data which is publicly available. More information is required about the following issues:

- Segmentation of the existing HDV truck fleet by vehicle type and weight class, including better information on the number of in-use vocational trucks of different types.
- Segmentation of the existing commercial trailer fleet (combination trucks) by length and configuration.
- Data on manufacturer and model market share for different types of trucks.
- Data on manufacturer and model market share for different types of commercial trailers

- Ownership patterns for different types of trucks, including what percentage of each truck type is owned and operated by fleets of various sizes
- Typical duty cycle(s) for various types of HDV, including combination trucks and vocational trucks. Duty cycle information should include speed versus time, as well as change in grade versus time, and engine accessory load/PTO load versus time.
- In-use fuel economy for all models of current HDV in a range of duty cycles.

10.3 Test Cycle(s) & Methodology

For ease of implementation there will be a strong desire to minimize the number of test cycles required for any HDV fuel economy regulation. On the other hand, the over-all regulatory regime must be robust (and complex) enough to handle the real world complexity of the HDV fleet and produce meaningful results. Ideally, regulatory HDV fuel economy testing should:

- accurately predict real-world differences in fuel economy due to the application of different technologies to different types of HDVs
- be insensitive to "gaming" by vehicle manufacturers, and
- provide consumers (truck owners) with relevant information to guide their purchasing decisions for different types of HDVs

The issue of the number and complexity of required test cycles for regulatory HDV fuel economy testing needs to be further explored, through modeling and/or analysis of existing test data. The issues that need to be addressed in this analysis include:

- The relative effect of different technologies (i.e. engine improvements, aerodynamic improvements, hybrid drive train, etc) on fuel use when an HDV operates on different duty cycles
- The relative effect of duty cycle on fuel use for different HDV types (size and vocation).
- The ability to effectively "model" multiple in-use duty cycles for a particular HDV by different weightings of results from a limited set of test cycles
- The ability to effectively "model" real world fuel use from different types of HDVs by different weightings of results from one set of test cycles used for all vehicle types.
- The most important factor(s) in the duty cycle of different HDVs in determining fuel use (i.e. speed vs. topography vs. vocational load, etc.)
- The potential for "gaming" by a vehicle manufacturer on any specific test cycle.

The specific questions that should be answered by the analysis include:

- How important is it to have different test cycle(s) for different types of HDVs?
- For any one type of HDV, what is the minimum practical number of test cycles required for effective fuel economy testing?
- Can one set of test cycles be used to effectively test the fuel economy of all HDVs? If so, what are the trade-offs involved? If not, why not?
- If one set of test cycles can not be used to test the fuel economy of all HDVs, which characteristic(s) are most important in determining that a particular type of HDV needs its own test cycles (i.e size, weight, vocation)?

- Will testing all HDVs using a single set of test cycles provide meaningful data that can be used by consumers making buying decisions? How should this data be presented?

In order to reduce compliance costs it is also likely that there will be strong interest in the use of modeling to determine regulatory fuel economy compliance for some or all HDVs, either as a replacement for actual vehicle testing or in combination with limited vehicle testing.

There are a number of different vehicle simulation models used by various organizations that might be used in a regulatory program to simulate HDV fuel efficiency. In order to evaluate the efficacy of modeling in the regulatory context, as well as to determine which specific model would be "best" for this purpose, a neutral, third-party review of the various available models is required. The specific issues to be addressed in this review for each model include:

- Current users, cost, and computing requirements
- Structure of the model, and required inputs
- Ease of use
- Complexity, and ability to model all parameters that effect HDV fuel use
- Strengths and weaknesses for predicting fuel use for specific vehicles/technologies/duty cycles
- Additional testing required to develop appropriate vehicle-specific parameters to be used in the model
- Correlation among models and/or calibration of models to measured data

10.4 Choice of Fuel Efficiency Metric

As discussed in Section 7.1, it may be appropriate to regulate the "fuel efficiency" of HDVs not in terms of gallons of fuel per mile driven, but rather gallons of fuel per ton-mile or per cubic volume-mile driven. These metrics explicitly acknowledge the main function of the majority of HDVs (to haul freight) and potentially open up additional avenues for regulatory compliance that would make any HDV fuel economy regulation more effective in reducing net fuel use from the transportation sector.

However, ton-mile and cubic volume-mile metrics are unfamiliar, and might be conceptually challenging to many people. In order to justify the use of these less familiar metrics, an analysis of the potential net benefit of such an approach is required. This scenario analysis would use known characteristics of the existing freight system (current HDV vehicle miles traveled segmented by average trucks weights and typical volumes) as well as realistic options available to increase cargo capacity per truck (weight and volume) to identify the incremental reductions in net fuel use that might be available if a ton-mile or cubic volume-mile metric were used instead of a gallons/mile metric.

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