# Framework for the Regulation of Greenhouse Gases from Commercial Vehicles

**Cummins Inc.**
**Columbus, Indiana**

**August 6, 2009**

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## Executive Summary

A Framework is described for the regulation of greenhouse gas emissions (GHGs) from commercial vehicles. Commercial vehicles are defined as Class 2b through 8 with a wide range of body types, applications and duty-cycles. Despite this complexity, duty-cycle analysis reveals a natural segmentation into two categories: (1) Line Haul and (2) Vocational, Work Trucks and Buses - noted for brevity as 'Vocational' in the balance of this paper. In the context of this Framework, 'Line Haul' refers to vehicles applied in interstate commerce that spend most of their time in highway transit. This segmentation is helpful for regulating GHGs.

For Line Haul applications, the engine, vehicle and operation all play an important role in reducing fuel consumption and carbon dioxide ($CO_2$) emissions, and the Framework includes regulation of each of these factors for this category of vehicle. Although outside of the scope of this paper, other reductions can be obtained through highway infrastructure improvements, low-carbon-intensity fuels, reduced speed limits and increased gross vehicle weight limits.

For Vocational applications, the engine offers the greatest potential for reducing $CO_2$ emissions with much less opportunity from the vehicle and operations. The Framework focuses regulation on the engine for this commercial vehicle category. The other factors could be regulated as well, but the opportunities for GHG reduction from those effects are smaller for Vocational applications and may not justify the additional regulatory burden. In this category, integrated hybrid powertrains are expected to play a significant role in reducing $CO_2$ emissions. The potential for both conventional drivetrains and integrated hybrid powertrains will be discussed, along with recommendations for their regulation.

Since these are work vehicles, the unit of $CO_2$ emissions for a Line Haul vehicle program should recognize the work performed, for example [$gCO_2$/ton-mile]. Similarly, engine $CO_2$ emissions for Line Haul and Vocational should be measured and reported in the same work units as criteria pollutants, i.e. [g/HP-hr].

In addressing the complexities of vehicle configurations and duty-cycles across this range of applications, this Framework builds on the historical and successful constructs of existing regulatory protocols to address GHGs: the Environmental Protection Agency's (EPA) heavy-duty emissions regulations and the more recent SmartWay program. When the heavy-duty regulations for criteria pollutants were established, EPA faced the same diversity of application and duty-cycle as confronted for GHGs today, and the Agency addressed them in a manner that creates a solid foundation for future GHG regulation. This Framework applies these existing emission regulation protocols to engine GHG regulation. For Line Haul, the EPA heavy-duty engine Supplemental Emission Test (SET) appears to be a good match for predicting in-use $CO_2$ emissions. For Vocational, the Framework applies the EPA heavy-duty engine transient emissions test – Federal Test Procedure (FTP) – for $CO_2$ measurement. Engines in both of these categories would continue to be regulated for criteria emissions against both the SET and FTP as today. Other elements of current regulation under the Clean Air Act, including lead-time and stability, would be applied for GHG regulations as well.

Hybrid and other waste energy recovery technologies must also be recognized in a GHG regulatory structure. The Framework associates all components and subsystems that provide motive power to the vehicle into a 'Power Supply' category. Through some modifications, the existing emission regulations can accommodate the regulation of GHGs from the range of power supply systems.

This regulatory structure would provide for the cost-effective development and deployment of technologies that will significantly reduce fuel consumption and $CO_2$ emissions. It addresses the source of $CO_2$, i.e. the engine, directly while also addressing other opportunities for $CO_2$ reduction from vehicle components and operations where those effects are significant. With regard to timing,

recent experiences highlight the value of providing a phase-in that encourages early adoption as well as a roadmap laying out future requirements.

The independent regulation of the engine in addition to the vehicle for Line Haul is neither intended nor expected to impede the system engineering that is done between engine and vehicle manufacturers in the normal course of business. The optimization for engine performance, size, weight, heat rejection, cost and other factors would continue as is done today. This regulatory structure will drive innovation in a more focused and uniform way at both the engine and vehicle levels. Furthermore, the direct measurement and regulation of engine emissions is more accurate and precise than testing at the vehicle level and can be directly verified for compliance, a key aspect of any effective regulation. Other components may be treated in the same way and will see similar benefits of focused innovation, more precise and accurate test procedures and direct performance verification. Since heavy-duty vehicles are not vertically integrated, this regulatory structure with component standards also aligns with the general business model for the industry

This Framework provides a usable structure for GHG regulation from heavy-duty vehicles from Class 2b through 8. It builds on a natural segmentation of vehicle applications, addressing major factors affecting GHGs directly. The regulations could be implemented expeditiously and feasibly by the industry through the use of existing protocols – which allows for the continuation of flexibility mechanisms. This structure also contains clear lines of responsibility that allow for accurate measurement and verifiable performance.

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## Glossary / Definitions

**GHG**  Greenhouse Gas emissions and specifically $CO_2$ as this paper is written in support of a fuel efficiency study. While other GHGs might be of regulatory interest, the duty-cycle analysis and association with existing emission protocols are focused solely on $CO_2$.

**Line Haul**  Vehicles applied in interstate commerce that spend most of their time in highway transit.

**Vocational**  Shorthand for Class 2b through 8 commercial vehicles - excluding Line Haul trucks as defined above. This category includes many of the vehicles shown in Figure 1 – heavy-duty pick-ups, delivery vehicles, mixers, dump trucks and buses.

**Hybrid**  A vehicle that uses two or more distinct power sources to move the vehicle and incorporates energy storage.

**Hybrid Powertrain**  An integrated powertrain, such as a diesel engine and motor-generator, with electrical storage batteries.

**Criteria Pollutants**  Heavy-duty exhaust emissions controlled under the Clean Air Act – Oxides of Nitrogen (NOx), Particulate Matter (PM), Hydrocarbons (HC) and Carbon Monoxide (CO).

**SET**  Supplemental Emissions Test, which is the EPA heavy-duty engine steady-state emissions test.

**FTP**  Federal Test Procedure, which is the EPA heavy-duty engine transient emissions test.

**SmartWay**  EPA program to incent the design, manufacture and use of energy efficient technologies for Line Haul tractor-trailers and related systems.

**Lead Time**  The minimum time between the date when a new rule comes into effect and the date when standards and other requirements contained in the rulemaking have to be met. Under Section 202(a)(3)(c) of the Clean Air Act, the minimum lead time is 4 years.

**Stability**  The minimum time over which a given standard or other regulatory requirement should apply. The minimum period of stability (also under the Clean Air Act) is 3 years.

**Carbon Intensity**  The ratio of carbon dioxide to usable energy for a given fuel, expressed in terms of grams of carbon dioxide released per megaJoule of energy produced [$gCO_2$/MJ] – usually on a well-to-wheels basis. The analysis here assumes diesel fuel with an intensity of 94.47 [$gCO_2$/MJ].

## Introduction

The commercial transportation system is essential to the health of the US economy [2].

- The trucking industry is a major employer in the United States. In 2007, there were 8.9 million people employed in trucking-related jobs; nearly 3.5 million were truck drivers.
- In 2007, trucks transported 57.8 percent of the value of trade between the United States and Canada, up 3.4 percent from the previous year, and transported 66.2 percent of the value of trade between the United States and Mexico, up 4.8 percent.
- Trucks used for business purposes in 2006 logged 432.9 billion miles.
- Class 8 trucks accounted for 139.3 billion of those miles, up from 130.5 billion in 2005.
- Trucks consumed 53.9 billion gallons of fuel for business purposes and paid $37.4 billion in federal and state highway-user taxes.
- Commercial trucks make up 12.5 percent of all registered vehicles.

Commercial vehicles are diverse in design and application, including: pick-up trucks, delivery trucks, transit buses, school buses, mixers, dump trucks, tankers, bulk haulers, interstate Line Haul and heavy-haul trucks. Figure 1 shows the classification scheme used for commercial vehicles by the Federal Highway Administration (FHWA).
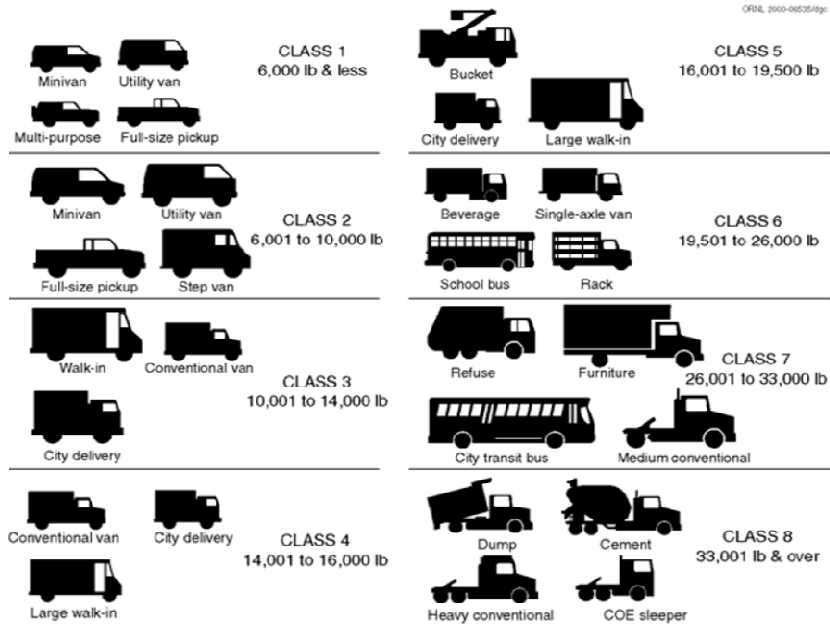
Figure 1    Commercial Vehicle Classes and Applications within Classes [3]. This Framework addresses Class 2b (8500-10,000 lb) through Class 8.

## Scope

The scope of this Framework includes all classes of heavy-duty commercial vehicles from Class 2b through 8. While the paper recognizes the importance of fuels, engines, vehicles, operations and highway regulations and infrastructure, the focus here is squarely on the definition of a Framework for the regulation of GHGs from engines and vehicles. Fuels with reduced carbon intensity can play an important part in the overall reduction of GHGs from commercial vehicles; however, any benefit would have to be realized through the development of engines that can use such fuels and can therefore be accounted for in the $CO_2$ emissions from the engine.

The scope includes all engine and vehicle technologies that can have an impact on GHG emissions, such as more efficient engines and vehicles, advanced conventional transmissions and drivetrains, waste heat recovery systems and hybrid powertrains.

## System Partitioning

It is reasonable to look for natural dividing lines within the system that could form the basis of regulatory or other initiatives aimed at reducing system-wide fuel consumption and $CO_2$ emissions. The partitioning shown in Figure 2 is proposed as a logical and helpful way to think about the system.

In this partitioning, it is useful to consider the engine as the *Power Supply* and the vehicle as the *Power Demand*. As such the power produced by the engine will be equal to the power demanded by the vehicle. Other components and sub-systems that contribute to motive power, including hybrid energy storage and power components and waste heat recovery systems, would be considered with the engine as *Power Supply*. The *Power Supply* system is active, in that it is responsive to operational demands, duty-cycle and ambient conditions, and has complex and active control system that adjusts many parameters dynamically during operation. The components and sub-systems that affect power demand, including payload, aerodynamic losses, rolling resistance, accessory loads and drivetrain friction, are passive in that their operating characteristics are not dynamically adjusted or responsive and can be modeled in a straightforward way.
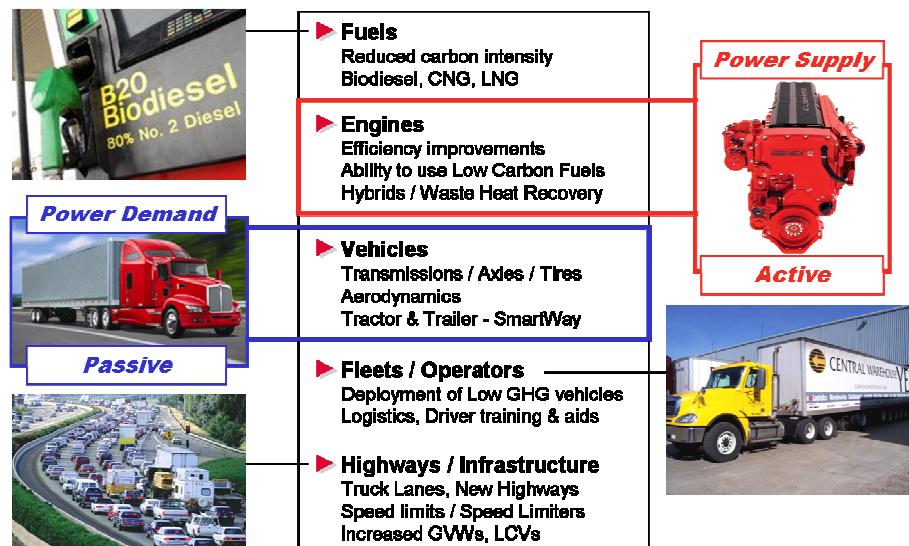
Figure 2    Goods movement system – proposed logical partitioning for control of $CO_2$ emissions. The vehicle provides the **power demand** (payload, aero, rolling resistance, accessories etc) which is met by **power supply** provided by the engine and associated power sub-systems.

This partitioning is employed in Figure 3, to create a formula for $CO_2$ emissions per unit of useful vehicle work [g/ton-mile, in this case] which links together the contributions from fuels, engines, vehicles, operations and highways. In this formula, vehicle efficiency is defined as the useful work done [payload ton-miles] divided by the work input to the vehicle from the engine and drivetrain [HP-hr or MJ].
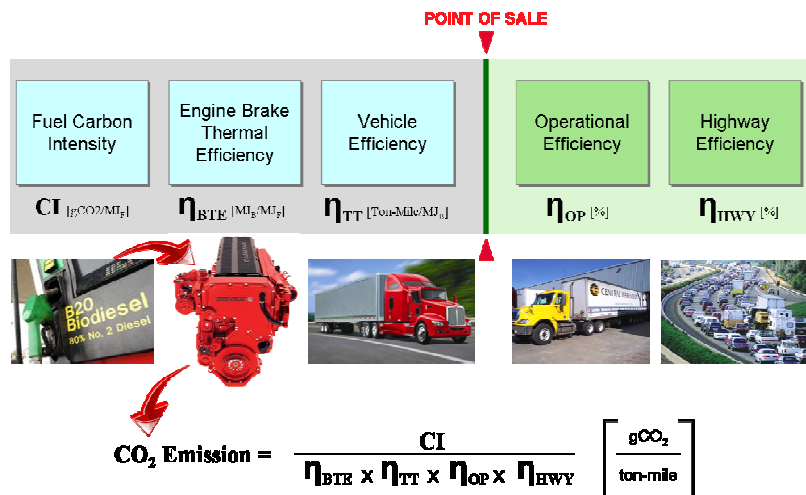


Figure 3,   Conceptual formula for $CO_2$ emissions from commercial vehicles – accounting for fuel carbon intensity, engine efficiency, vehicle efficiency, operational efficiency and highway efficiency.

### Partitioning by Application

Another useful partitioning naturally occurs by duty-cycle, with two major categories:  (1) Line Haul and (2) Vocational, Work Trucks and Buses - noted for brevity as 'Vocational' in the balance of this paper.

Interstate Line Haul trucks are unique in both design and application. Such trucks operate at high average speeds, with high load factors, high annual mileage, high accessory loads and high rolling resistance. For such vehicles, both chassis and engine performance are significant factors for control of $CO_2$ emissions.

Efficient Line Haul trucks have:

–   Highly Efficient Engines,
–   Low Aerodynamic Drag,
–   Low Rolling Resistance, and
–   Low Accessory Loads.

Vocational vehicles typically operate at lower average speeds in and around urban areas.  They have lower rolling resistance, with modest accessory loads and considerably lower annual mileage. Table 1 compares the critical parameters of Line Haul and Vocational applications.

| Parameter | Line Haul | Vocational |
|---|---|---|
| Average Speed | 40-55 MPH | 20-40 MPH |
| Cruise Speed | 60-70 MPH | - |
| Idle Time | 5-35% | 30-55% |
| Annual Mileage | 100-225k | 15-60k |
| Average GVW | 50-80k LBS | 20-40k LBS |
| No. of Wheels | 18 – 26 | 4 – 16 |
| Accessory Loads | Sleeper, HVAC | PTO, HVAC |
| Cruise Power | 180 - 250 HP | - |
| Ave Duty-Cycle Power | 100-200 HP | 20-125 HP |
| Peak Power | 400-500 HP | 200-500 HP |

Table 1, Natural separation of Line Haul and Vocational applications. The table shows factors that largely determine $CO_2$ emissions.

For Line Haul applications, the engine, vehicle and operation all play important roles in reducing fuel consumption and carbon dioxide ($CO_2$) emissions, and the Framework includes regulation of each of these factors for this category of vehicle.  Although outside of the scope of this paper, other reductions can be obtained through highway infrastructure improvements, low-carbon-intensity fuels, reduced speed limits and increased gross vehicle weight (GVW) limits.
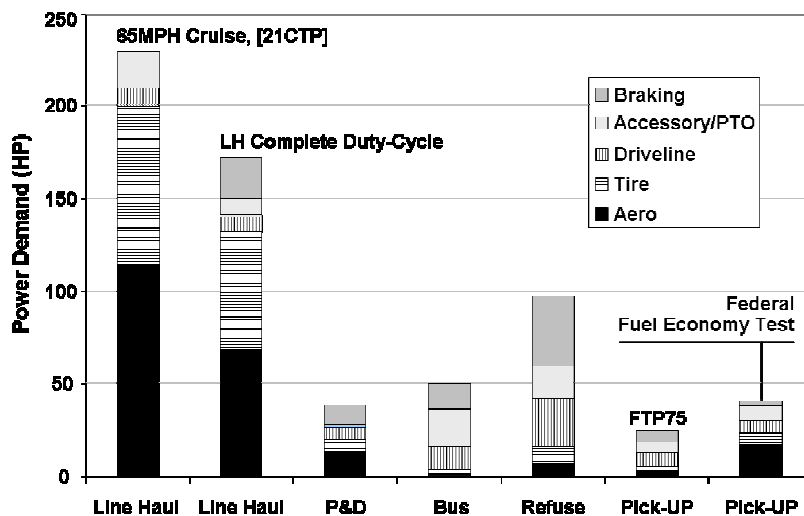


Figure 4, Breakdown of the power demand associated with Line Haul and Vocational applications. Line Haul 65MPH cruise data taken from 21st Century Truck Partnership report [4]

For Vocational applications, the engine offers the greatest potential for reducing $CO_2$ emissions with much less opportunity from the vehicle and operation.  The Framework focuses regulation on the engine for this commercial vehicle category. The other factors could be regulated as well, but the opportunities for GHG reduction from those effects are smaller for Vocational applications and may not justify the additional regulatory burden.

Figure 4 shows a breakdown of the power demand associated with on-highway vehicles - comparing a typical interstate Line Haul truck with typical Vocational applications. The graph

demonstrates clearly the unique nature of the Line Haul truck. The Vocational applications require far less power to overcome aerodynamic and rolling resistances and generally operate with lower accessory loads.

The unit of $CO_2$ emissions for a heavy-duty vehicle program should recognize the work performed, for example [g$CO_2$/ton-mile] for Line Haul vehicles. Similarly, engine $CO_2$ emissions should be measured and reported in the same work units as criteria pollutants, i.e. [g/HP-hr].

## New Technologies and the Potential for GHG Reductions

### Technology – Line Haul

Technologies to reduce diesel fuel consumption in Line Haul applications can be categorized in three areas – engine and drivetrain efficiency, vehicle efficiency, operational and highway efficiency. The potential contributions of technologies in these three categories are similar. In the case of engine efficiency, improvements in all of the key engine subsystems can be leveraged to reduce emission of $CO_2$:

- air handling,
- combustion,
- fuel system,
- aftertreatment, and
- controls.

In addition, conversion of waste heat into useful work (i.e., a thermodynamic "bottoming cycle") may contribute significantly to improved engine efficiency in Line Haul applications. Waste heat recovery is a new technology that is currently being developed to use a closed thermodynamic cycle to produce useful work from the heat otherwise rejected by the engine. The work so produced can be used indirectly by driving an alternator and storing the electrical energy in a battery or directly through a mechanical drive to the engine output shaft. Waste heat recovery is best suited to the high load factor Line Haul operations.

The Line Haul duty-cycle does not lend itself to significant fuel efficiency improvements from hybrid powertrain technologies. The steadier operation associated with extended interstate duty-cycles offers only limited opportunity for recovering braking energy. The scale and cost of heavy-duty hybrid powertrain components is relatively unattractive given the minor efficiency gains. Recovering braking energy and storing it electrically to drive accessories and sleeper cab heating and cooling may be more attractive.

These technologies combined have the potential to improve engine efficiency by greater than 20 percent. Modest improvements in drivetrain efficiency (1 to 2 percent) along with better integration of the engine and transmission controls (2 to 5 percent) are also possible and additive to the engine efficiency improvements.

Vehicle efficiency may be improved through tractor and trailer aerodynamic treatment, tractor-trailer gap treatment, single-wide tires and accessory electrification. These vehicle-level improvements offer opportunities to reduce fuel consumption by 15 to 20 percent.

Operational and highway efficiency can be improved by reducing highway speeds, reducing idling time, increasing the allowable maximum GVW, driver performance and altering driving patterns in anticipation of traffic congestion. These factors are expected to provide at least a 20 percent opportunity for reducing fuel consumption and $CO_2$.

### Technology – Vocational

Vocational applications have a high proportion of stop and go operation and are ideal applications for hybrid powertrains, which recover waste energy from braking and idling and allow greater freedom for engine optimization.

The base engine technologies described for Line Haul also apply to Vocational applications, though the percentage improvements are less because the duty-cycle operates over the full range of engine torque and speed and not predominantly near a "sweet spot" for optimization. Engine efficiency improvements in the 10 to 15 percent range are achievable. Further improvements through hybrid architectures along with transmission enhancements of at least 30 percent are possible. Consequently, engine and powertrain improvements dominate the opportunities to reduce fuel

consumption. Fuel consumption opportunities for vehicle efficiency are in the 10 to 12 percent range while operational and highway efficiency improvements are limited to 3 to 5 percent.

It should be noted that almost all of these opportunities for reduced $CO_2$ emissions are in the early stages of development and are subject to some degree of uncertainty – both for the timing of availability and the precise magnitude of the $CO_2$ reduction that would be realized.

### *Potential CO$_2$ Reductions*

Figure 5 shows the potential for $CO_2$ reduction from Line Haul and Vocational applications – by engine, vehicle and operations. For the engine and the vehicle, these estimates are derived from projected technology improvements. For Line Haul operations, the improvements assume increases in allowable GVW and reduced highway cruise speeds, shown in Appendix D. The total $CO_2$ reduction in these graphs is defined as 100 percent, and contributions from vehicle, engine and operations are shown as a percentage of the total.

For Line Haul applications, it is apparent that vehicle, engine and operations can contribute approximately equally to future $CO_2$ reductions.

For Vocational vehicles, the engine dominates the potential for future $CO_2$ reductions. This analysis is based on aggregate data from a number of applications and is considered to be generally representative of the category. The vehicle does not contribute significantly because the power demanded by the vehicle is very low on average, as shown in Figure 4. For example, there would be little to be gained by improving the aerodynamics of a refuse truck or adding an Auxiliary Power Unit (APU) to a school bus. Similarly, operational factors like reduced highway speed limits will have little impact on vehicles in this category.

Figure 6 shows graphically the potential $CO_2$ reductions from Line Haul applications, categorized by engine (including waste heat recovery and drivetrain optimization), vehicle and operations. The potential improvement in $CO_2$ emissions is very significant with approximately equal contributions from each area. The engine and vehicle estimates are derived from projected technology improvements. For Line Haul operations, the improvements assume increases in allowable GVW and reduced highway cruise speeds.
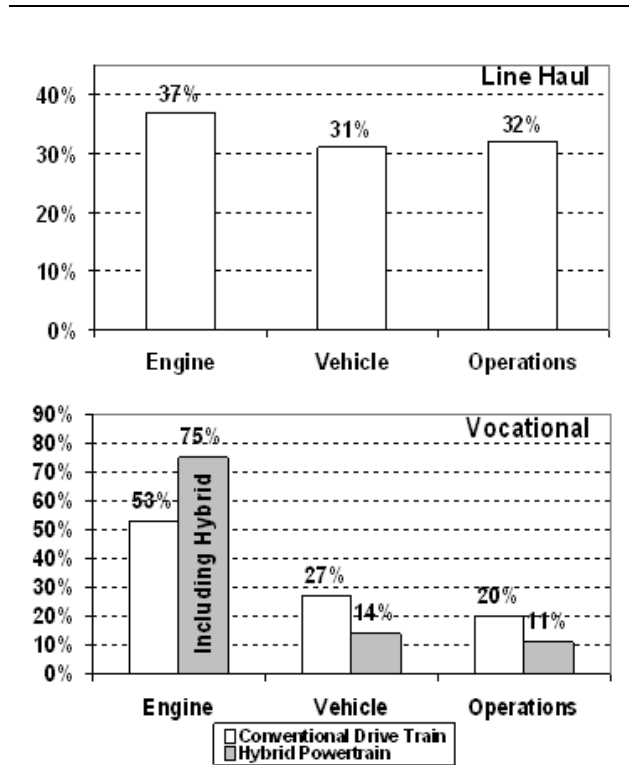


Figure 5, Relative contributions to total potential $CO_2$ savings for Line Haul and Vocational applications, showing the contribution from the vehicle, engine and operations as a percentage of the total $CO_2$ savings. [Source: Internal Cummins Analysis]
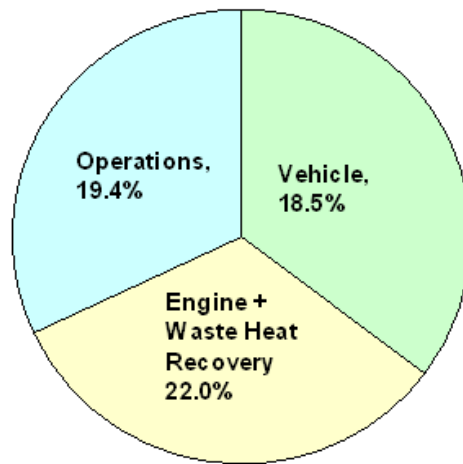
**Line Haul**

Figure 6, Estimated potential $CO_2$ savings from Line Haul applications, showing the contribution from the vehicle, engine and operations as percentage $CO_2$ savings from a 2007 baseline.  *[Source: Internal Cummins Analysis]*

Figure 7 shows the value of a hybrid powertrain for Vocational applications. A hybrid powertrain allows the engine to operate more optimally and recovers braking energy from stop and go operations, thereby reducing fuel consumption.

The results shown in Figure 6 and Figure 7 provide direction to any regulatory structure for GHG emissions: Line Haul regulations must address vehicle, engine and operational efficiency, whereas engine regulation will capture most of the opportunity for Vocational applications.



Figure 7, Estimated potential $CO_2$ savings from Vocational applications with conventional and hybrid powertrains, showing the contribution from the vehicle, engine and operations as percentage $CO_2$ savings from a 2007 baseline. *[Source: Internal Cummins Analysis]*

# Regulation of Emissions from Heavy-Duty Engines – A Success Story



Figure 8,   Successful history of emission reductions from heavy-duty on-highway engines.

[Source: Code of Federal Regulations US EPA Standards]
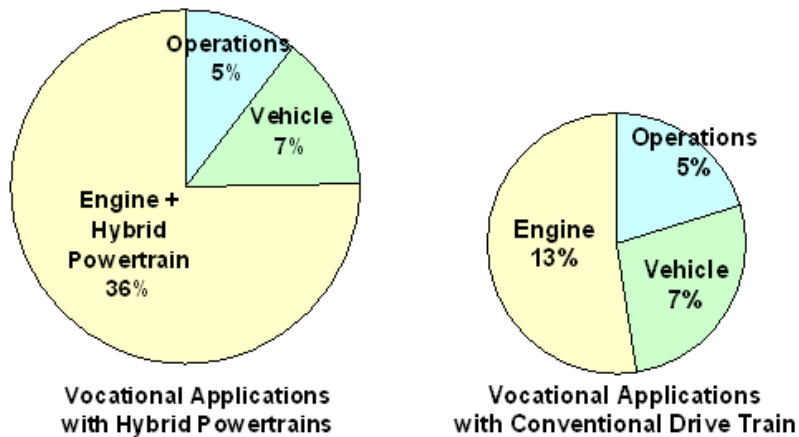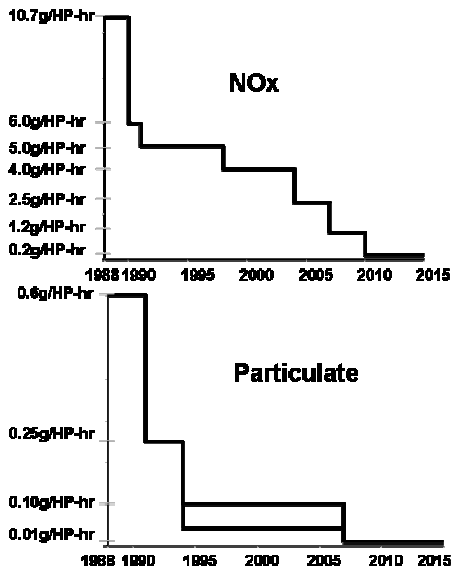
## HD Engine Emissions Program

The regulation of oxides of nitrogen (NOx) and particulate matter (PM) from heavy-duty on-highway diesel engines was first discussed in the late 1970s. Figure 8 shows the successful 30 year history of regulation of criteria pollutants from heavy-duty diesel engines.

At that time, EPA and the industry faced similar complexity in addressing engine emissions across a wide range of vehicle applications, duty-cycles and engine technologies. The issue was resolved by creating a laboratory engine test cycle that was synthesized from actual operating data taken over a number of representative duty-cycles, vehicles and engines. While the Federal Test Procedure (FTP) was not specifically representative of any individual duty-cycle, it was deemed adequately representative of all of them. This approach, essentially 'Engine-in-the-Loop' simulation, has been used to successfully regulate criteria pollutants since the late 1980s. In 2002, a Supplemental Emissions Test (SET), based on European experience, was added. The SET is a steady-state test that examines emissions of NOx, PM, hydrocarbons (HC) and carbon monoxide (CO) over a broad area of the engine operating range from the maximum torque speed to the rated power speed and from full to 25 percent load.

The heavy-duty emissions program may be used almost without change for control of $CO_2$ from heavy-duty engines in Line Haul and Vocational applications.  $CO_2$ can simply be added to the list of controlled emissions ($CO_2$, CO, NOx, PM, HC). The paper presents an analysis of the FTP and SET test cycles for $CO_2$ control from Vocational and Line Haul engines in a later section with encouraging results. Using the existing emissions structure for $CO_2$ control removes the significant overhead associated with developing a new regulation from scratch. It also brings with it a set of provisions such as: test procedures, production line and in-use compliance audits, averaging, banking and trading flexibility, family emission levels, emissions useful life and many others.

## Vehicle Efficiency - SmartWay Transport Partnership

The EPA SmartWay Partnership [1] is also an example of a program aimed at improving fuel efficiency and $CO_2$ emissions, successfully implemented by industry. SmartWay is an innovative public-private partnership to improve the way that companies ship and receive goods and reduce the carbon footprint of the transportation sector. The SmartWay Partnership was launched by EPA in 2004, and there are currently over 2,000 partners, including many large multinational corporations, most of the top motor carriers in the US and all the class I railroads.  The program has now expanded into barge, air and short sea shipping.

Annually, SmartWay partners commit to achieve reductions of 568 million gallons of diesel fuel, nearly 6.3 M tons of $CO_2$, 37,000 tons of NOx and over 2,000 tons of PM, with annual fuel savings of nearly $1.5 billion.

The program has established an international benchmark for freight transportation.  Countries from around the world are using SmartWay for freight excellence, including projects in Mexico, China and Canada.  The European Union and Australia are also considering a SmartWay-like approach. The program offers models, analysis, testing and tools for its partners to quantify the costs and benefits of operational and technology options to reduce GHGs, other emissions and fuel

consumption while improving the efficiency of the global supply chain and saving money. Partners are able to evaluate, track and improve their freight transport performance and receive recognition for these achievements.

Through technology evaluation, SmartWay also identifies the cleanest, most efficient vehicle and equipment options and designates SmartWay-certified vehicles including passenger vehicles and heavy-duty trucks. Using federal funds, SmartWay launched innovative financial programs (including loan and lease programs and bond initiatives) to further accelerate deployment of fuel-saving technologies, especially among smaller fleets that lack sufficient access to capital.

The program has achieved significant, measurable air quality and GHG improvements while maintaining or improving emissions of criteria pollutants. The program encourages the development and implementation of clean technologies for Line Haul trucks, such as:

- – Clean, efficient engines;
- – Qualified tractors and trailers;
- – Idle reduction systems such as APUs;
- – Automated tire inflation;
- – Efficient bunk heaters; and
- – Aluminum wheels and single-wide tires.

The SmartWay Program also includes collaboration with the freight sector and recognizes participating operators and fleets by allowing display of a SmartWay label on qualified Line Haul trucks. The program is driven largely by the improved total cost of ownership associated with the fuel efficient technologies.

## A Framework for Regulation of GHGs from Commercial Vehicles

### *Guiding Principles*

A set of guiding principles has been developed, Table 2, to provide focus on the ultimate goals of a GHG program. The proposals presented in this Framework satisfy these guiding principles.

| Simplicity | Find the right balance between real-world fidelity and regulatory complexity. |
|---|---|
| Speed | Re-use existing vehicle, engine and component regulations and protocols. |
| Incentives | Utilize an incentive program to bring $CO_2$ reduction technologies to the market earlier. |
| Technology | Use regulations to deliver $CO_2$ reductions by driving technology into the vehicle, engine and critical sub-systems. |
| Fairness | Avoid unintended consequences and maintain a level playing field. |
| Compliance | Provide for verifiable procedures and results. |
| Feasibility | Ensure the implementation of best available technology with current lead time and stability requirements. |
| Flexibility | Employ flexibility mechanisms in the current emissions program such as averaging, banking and trading. |
| Phase-In | Provide for a progressive approach to scope and stringency of standards. |

Table 2, Guiding Principles used during this study to retain focus on the goals of a GHG program.

### *Certification Protocol Options*

Table 3 shows a range of protocol options that could be used in a program aimed at reducing GHGs from commercial vehicles. The table is arranged by performance-based and design-based options. A performance-based protocol would involve precise measurement of the controlled parameter (such as $CO_2$ or tire rolling resistance) for comparison with a performance standard. The current heavy-duty engine emissions test methods and standards are an example of performance-based protocols. Performance-based standards can be broken down into test-based, hardware-in-the-loop or simulation-based. Today's heavy-duty transient emissions test or FTP is essentially a hardware-in-the-loop test in which a motoring-absorbing dynamometer is used to simulate a drive cycle.

A design-based protocol would require that trucks be assembled from qualified sub-systems and components that meet individual efficiency or $CO_2$ standards or a tractor unit that meets aerodynamic standards. SmartWay is an example of such a design-based protocol. Note that a design-based protocol for the vehicle does not preclude performance-based protocols and standards for the sub-systems, such as engines or tires.

| | | | Vehicle | Engine & Drive Train |
|---|---|---|---|---|
| PROTOCOL OPTIONS | Performance Based | Test / Experiment | ▪ Vehicle road / track test<br>▪ Fleet-Level Fuel Efficiency<br>▪ Sub-system tests – tires, transmissions, aerodynamics | ▪ Steady-state engine dynamometer testing<br>▪ Rig testing |
| | | Hardware-in-the-Loop | ▪ Vehicle Chassis Dynamometer<br>▪ Engine-in-the-Loop, simulated vehicle<br>▪ Controller-in-the-Loop (HILS) | ▪ Engine-in-the-Loop Testing – simulated vehicle, duty-cycle, powertrain, route & driver<br>▪ Controller-in-the-Loop (HILS) |
| | | Computer Model / Simulation | ▪ Dynamic Drive-cycle models<br>▪ CFD Chassis Aerodynamics<br>▪ Sub-system simulation models | ▪ Engine simulation models<br>▪ Sub-system simulation models |
| | Design Based | Feature-Based | Aero Cabs (v. Conventional), Tractor / Trailer Fairings, Trailer End Caps, Tractor to Trailer Gap Fairings, Anti-Idling APU, High Efficiency Cab Heating / Cooling (Example - EPA SmartWay Partnership) | |

Table 3, Options for regulating GHGs from commercial vehicles, ranging from testing, through hardware-in-the-loop, through computer simulation models.

### Regulatory Framework

The Framework for regulations is shown in Table 4. It has a relatively simple structure in which two vehicle classes are defined: *Line Haul* and *Vocational*. The program for Line Haul applications has both vehicle and engine requirements. The vehicle standard could be either design-based or performance-based, as discussed earlier.
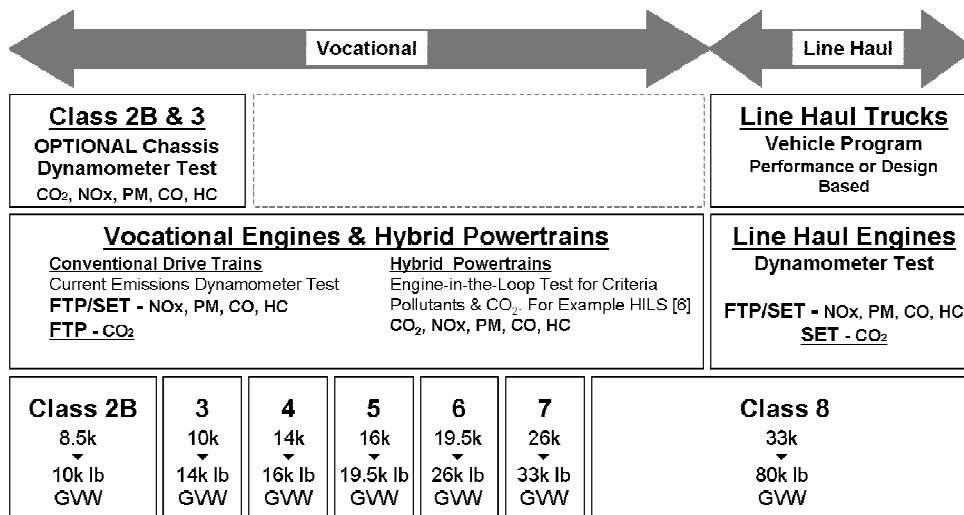


Table 4, Outline of the Framework for regulating GHGs from commercial vehicles from Class 2b through Class 8.

For Vocational applications, the vehicle offers much less opportunity for $CO_2$ reduction and the emphasis should be placed on the engine and hybrid power systems. Engine regulation for both Line Haul and Vocational should be performance-based and leverage existing emissions protocols and procedures [5].

The independent regulation of the engine in addition to the vehicle for Line Haul is neither intended nor expected to impede the system engineering that is done between engine and vehicle manufacturers in the normal course of business. The optimization for engine performance, size, weight, heat rejection, cost and other factors would continue as is done today. This regulatory structure will drive innovation in a more focused and uniform way at both the engine and vehicle

levels.  Furthermore, the direct measurement and regulation of engine emissions is more accurate and precise than testing at the vehicle level and can be directly verified for compliance, a key aspect of any effective regulation.

Other components may be treated in the same way and will see similar benefits of focused innovation, more precise and accurate test procedures and direct performance verification. Since heavy-duty vehicles are not vertically integrated, this regulatory structure with component standards also aligns with the general business model for the industry.

Figure 9 summarizes the Framework in simple form.

### Line Haul Applications - Options for a Vehicle Program

No attempt is made in this paper to define or recommend vehicle regulations or protocols, rather some options are presented for consideration. A number of options exist – from computer simulation models of complete vehicles through to testing of the complete vehicle on a chassis dynamometer or over the road. The following options will be discussed briefly.

– Option 1: A design-based program, such as the EPA SmartWay Partnership
– Option 2: A program based on a computer simulation model representing the complete vehicle
– Option 3: A performance-based program of the complete vehicle

Option 1 could be based on component verification under which trucks are allowed into commerce if they meet a set of efficiency or GHG requirements, such as: having a certified engine, a qualified tractor and trailer, qualified tires and qualified anti-idling technologies. Performance categories ("A, B, C …") might be defined to indicate the level of GHG reduction expected for specific groupings of component technologies. In this scenario, the truck would be expected to be sold, operated and maintained according to the requirements of the program. In this option, the engine would be certified against a $CO_2$ [g/HP-hr] standard in accordance with current EPA procedures as described in this Framework. Other components (e.g., tires, transmissions, axles, aerodynamic aids) would be certified against similar component standards. This would allow production line and in-use audits and provide a pathway for compliance and enforcement.

Option 2 would require the development of a computer model that could be used across the industry to determine the $CO_2$ emissions [g/ton-mile] of a given vehicle, at the point of sale. Unlike Option 1, this approach attempts to determine and track $CO_2$ by vehicle and as such would require extensive, high quality data input from each of the critical sub-systems to allow compliance to be verified and enforced:

– Engine $CO_2$ emissions for the intended use
– Tractor-trailer aerodynamics
– Tractor-trailer optional treatments such as fairings and boat tails
– Transmission and rear axle ratios and parasitic losses
– Accessory loads, APU performance, etc.
– Rolling resistance, wheel and tire information

The computer model would then exercise the given vehicle over a prescribed route, with prescribed driver characteristics, load factor and assumptions regarding vehicle speed.

While this approach has some attractiveness in that it reduces the need for vehicle testing and deals with the proliferation of vehicle configurations and options, it also has challenges:

**Line Haul Applications - Vehicle & Engine CO2 Program**

**Vehicle-Level Program**
Build on the SmartWay Partnership

**Other Sub-Systems**
Build on SAE, SmartWay & other existing protocols
• Tires
• Aero Features
• Axles and Transmissions

**Engine CO2 Regulation**
Build on the HD Emissions Program
• CO₂, CO, NOx, PM & HC Standards
• Existing Protocols – SET & FTP
• Averaging, Banking & Trading

**Vocational Applications – Engine CO2 Regulation**

**Engine Regulation**
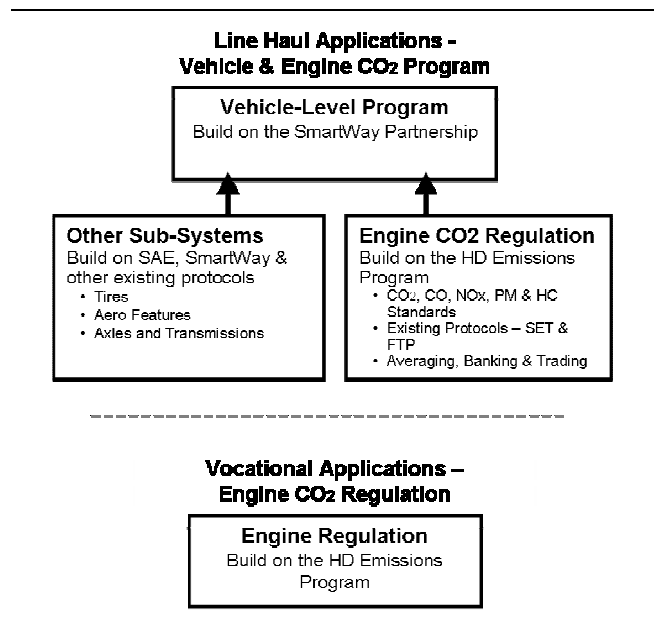Build on the HD Emissions Program

Figure 9, Programs for regulating $CO_2$ emissions from Line Haul and Vocational applications

– Lead time to develop the vehicle model
– Development of the supporting program and rulemaking
– Creation and maintenance of sub-system and component data needed to support an accurate model
– Enforcement, compliance and accountability
– Verifiability for the sub-system and component data that underpins the vehicle simulation

Preliminary analysis indicates that Option 2 might be feasible with a simple vehicle model when specific component performance criteria are available.

Option 3 requires complete vehicle testing for vehicles greater than 14000 lbs GVW and may be problematic as a primary regulatory approach. Full vehicle testing is costly with regard to test facilities and vehicle proliferation, and it is not likely to be accurate enough for development, certification and compliance for Class 4 through 8 vehicles. For Class 2b and 3, the optional chassis dynamometer test should be retained and adapted for $CO_2$ regulation of vehicles (mostly heavy-duty pick-ups) with conventional and hybrid powertrains.

From technical as well as regulatory perspectives, vehicle-level certification and compliance pose significant challenges. While it is common industry practice to measure vehicle-level fuel economy using standardized tests, such as SAE Type-II, the uncertainty in this measurement would make it difficult to quantify small differences at the component level (e.g., tire rolling resistance) for development, certification and compliance. This would drive a large number of replicate tests to establish reliable statistics or would force large design margins into component performance targets to ensure compliance. Either (or both) of these effects would drive considerable increases in development cost and time. From a regulatory perspective, a vehicle-only standard would likely result in a highly non-uniform cascade of component performance targets into the supply base as each OEM would set component targets based on their own experience and perspective. This would result in the inconsistent development and application of technologies and would add considerable cost and complexity to development, certification and compliance.

For these reasons, this Framework builds up from component-level standards that could be aggregated at the vehicle level by simple association into performance categories (Option 1) or used to predict vehicle-specific $CO_2$ emissions based on component certification data and vehicle simulation (Option 2). Full vehicle testing (Option 3) may be appropriate for Class 2b and 3 vehicles, but it does not lend itself to regulation or align with the overall industry business model for Class 4 and above. The SmartWay Partnership gives useful guidance at the vehicle level for Line Haul.

### Line Haul and Vocational Applications - Engine Protocols

The existing regulatory structure for controlling the emissions of criteria pollutants from heavy-duty engines can be used to control $CO_2$. The test cycles used for emissions certification – the FTP transient test cycle and the SET steady-state supplemental emissions test – are designed to represent real-world operations for the range of vehicle applications and duty-cycles.

Table 5 compares real-world emissions of $CO_2$ from Line Haul and Vocational vehicle duty-cycles with $CO_2$ emissions measured in the emissions engine certification test cell, using standard emissions protocols. Because of its more steady-state nature, Line Haul $CO_2$ is compared to SET $CO_2$. Similarly, the transient nature of Vocational operation is associated with FTP $CO_2$. These correlations are described in more detail in Appendices A and B. The preliminary results are encouraging and indicate that the existing emissions protocols may be used in this way for regulation of $CO_2$.

| Line Haul – CO2 Emissions Test | % Difference |
|---|---|
| Full 13 Mode SET Emissions Results with ESC Weighting Factors | 3.7% |

| Vocational – CO2 Emissions Test | % Difference |
|---|---|
| Full FTP Transient Test - Cold & Hot Cycle Composite | 4.0% |

Table 5, Comparison of real-world, in-use $CO_2$ emissions with certification test cycle results:

Upper: Average of 8 Line Haul duty-cycles compared with the steady-state emissions test – using the standard 13 modes.

Lower: Average of 9 Vocational duty-cycles compared with results from the FTP transient engine test procedure.

The Framework considers the existing EPA test cycles for heavy-duty engines. As future regulatory protocols emerge, e.g., the World Harmonized Test Cycle (WHTC), they may be considered in the same way for GHG regulation as well as criteria pollutants. However, duty-cycles and test protocols other than current EPA practices are outside the scope of this paper.

### *Hybrid Powertrain Protocol*

A hybrid powertrain is an integrated engine and secondary power source (such as a motor-generator) with energy storage typically in the form of electrical batteries. While existing engine emissions protocols could be used for now, new test procedures should be developed for these hybrid powertrains to allow the full benefits of hybridization to be realized – namely: recovery of braking energy, reduced engine idling through engine shut-down and better engine optimization and down-sizing.

Alternative test procedures could be developed where the engine is tested using a transient dynamometer with torque and speed inputs derived from a simulation of the vehicle and hybrid powertrain. Such an approach is favored by the Japanese [6], as it gives a direct measurement of both criteria emissions and $CO_2$ from a test that can also be used to demonstrate compliance with performance standards. For Class 2 and 3 heavy-duty pick-up trucks, testing the complete vehicle for $CO_2$ emissions using the optional chassis dynamometer test would be an attractive option.

### *Defining the Baseline*

It is important to establish a baseline from which to set future progressive $CO_2$ standards for vehicles, engines and potentially other sub-systems and components. Considerations for setting the baseline include: product that is in the market at volume, represents the state-of-the-art and for which $CO_2$ data is readily available.

For Line Haul and Vocational engines, the 2007 US EPA generation of product should be used as the baseline by which future improvements be established. This generation of product is in volume production currently, represents the most advanced design practice for low emissions and fuel efficiency and has freely available data. Establishing the baseline $CO_2$ emission level [g/HP-hr] for engines may be relatively straightforward, since engines are already subject to emissions regulations. These regulations require definition of critical parts lists, tightly controlled test procedures, well defined compliance audits and many other controls.

For vehicles, it will be more challenging to set a baseline and would depend on the choice of protocol (design-based or performance-based), metrics and structure of the regulation, in particular the role of sub-systems and components. The degree of diversity within Line Haul tractor-trailer models and options suggests the need to define a 'reference Line Haul truck' with known $CO_2$ performance from which a standard could be derived.

### *Phased Introduction of GHG Regulation for Commercial Vehicles and Engines*

A phased introduction of GHG regulation for commercial vehicles is recommended, primarily to spread the work load over time and allow industry to successfully implement the new regulations. A phased introduction can also provide the necessary lead time for the development and introduction of new technologies being proposed, which in many cases are in the early stages of development. Such a phase-in of $CO_2$ standards could commence with an incentive program to encourage early introduction of technologies, as shown in Figure 10. The feasibility of an incentive program is greatly enhanced if the existing emissions protocols and procedures can be adapted for the control of $CO_2$.

Beyond an incentive program, standards would be set for $CO_2$ emissions from both Line Haul engines and vehicles and Vocational engines.
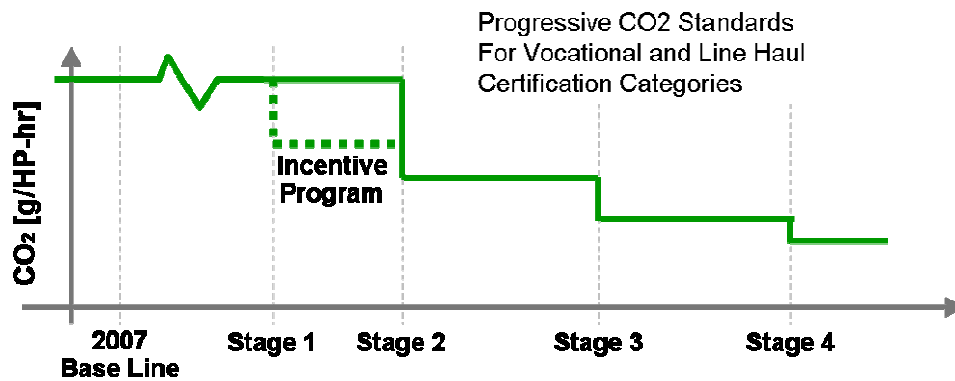
Figure 10, Schedule for regulation, showing the progressive phase-in of $CO_2$ standards. An optional incentive program is shown, starting ahead of the regulation. Parallel activities are envisioned during the phase-in period – such as establishing baselines for engines and vehicles, vehicle simulation model development, vehicle protocol development, etc.

## Conclusions

A Framework for the regulation of GHGs from commercial vehicles from Class 2b through 8 has been described. It utilizes the natural separation that exists between Line Haul and Vocational applications. It recommends both engine and vehicle regulation for Line Haul and engine regulation for Vocational vehicle classes. While all components of the goods movement system can make a contribution to $CO_2$ reduction (fuels, engine, vehicles, operations and highways), this paper focuses on the regulation of vehicles and engines.

The Framework provides for a program that:

– Significantly reduces emissions of GHGs (primarily $CO_2$) from commercial vehicles;
– Drives innovation in a uniform way at vehicle, engine and other component levels;
– Aligns with the overall business model of the industry;
– Minimizes regulatory complexity; and
– Can be successfully implemented by industry and government.

The Framework incorporates existing regulatory and administrative programs wherever possible – such as the EPA heavy-duty emissions program for engines and the SmartWay Partnership [1] for Line Haul tractor-trailers. While this paper does not preclude a vehicle program for Vocational applications, the supporting data suggests only minor benefits are achievable beyond the application of more efficient engines and hybrid technology.

New technologies are described which will provide significant reduction of $CO_2$ from both engines and vehicles. For Line Haul applications, efficiency improvements can be made to engines, tractor-trailer aerodynamics, rolling resistance, drivetrain efficiency and hotel and accessory loads. For Vocational applications, base engine improvements and hybrid powertrains will be key contributors. Engine and hybrid components should be considered as the vehicle's *Power Supply.* Hybrid powertrains should be regulated as a single unit – either as part of the vehicle for Class 2b and 3 (8500-14000 lbs GVW) using the existing optional heavy-duty chassis certification procedure or as a power system using an engine-in-the-loop test procedure based on the existing emission test. Engines for Vocational applications with conventional drivetrains would be certified under the existing emissions test procedures.

The paper has evaluated the application of existing test procedures for criteria pollutants (NOx, PM, HC, CO). The preliminary results suggest that the SET represents real-world $CO_2$ emissions from Line Haul trucks within 4 percent over a range of duty-cycles, engines and truck models. Similarly, for Vocational applications, preliminary results suggest that the FTP represents real-world $CO_2$ emissions also within 4 percent.

The Framework includes a phased introduction of $CO_2$ regulations under which both scope and stringency would increase over time to allow industry to develop new technologies and to complete the first phase of new product development across the full range of vehicles and engines. This phase-in of regulatory standards would be preceded by an incentive program that would cover vehicles and engines and incent early introduction of new technologies.

Other elements of current regulation under the Clean Air Act, including lead-time and stability, would be applied for GHG regulations as well.

It is recommended that the current commercial vehicle fleet – i.e. those compliant with the 2007 EPA Heavy-Duty Engine and Vehicle Standards – be used to establish a baseline against which standards for $CO_2$ can be set.

### *Future Work*

This Framework satisfies the Guiding Principles outlined in Table 2. It provides a basis for a relatively simple and understandable set of regulatory and administrative programs for vehicles and engines that can be implemented expeditiously and with maximum leveraging of existing procedures. The Framework provides a clear path to enforcement and compliance, which will allow greater certainty for manufacturers and regulators alike.  However, the Framework described here is incomplete for effective regulation. Future work includes:

1. Detailed definition of Line Haul and Vocational vehicles, especially dealing with Class 8 day cab tractor units and other vehicle types that fall between these segments;

2. Alignment of Line Haul and Vocational certified engines and other components with the intended vehicle applications – i.e. how to avoid misapplication across categories;

3. Development of $CO_2$ standards for Line Haul and Vocational categories;

4. Development of component-level regulations and performance standards for other Line Haul vehicle components, including tires, transmissions, axles, and aerodynamic devices;

5. Development of a phase-in schedule, including an early incentive program; and

6. Development of engine-in-the-loop protocols for hybrid powertrains, as an extension of existing steady-state and transient test procedures.

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5. EPA, 40 CFR Parts 69, 80, and 86, 'Control of Air Pollution from New Motor Vehicles: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements', Final rule. http://www.epa.gov/fedrgstr/EPA-AIR/2001/January/Day-18/a01a.htm

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7. Cooper, K R, 'Full-Scale Wind Tunnel Tests of Production and Prototype, Second-Generation Aerodynamic Drag-Reducing Devices for Tractor-Trailers', SAE 2006-01-3456 (National Research Council Canada)

## Appendix A – SET as a Model for Line Haul $CO_2$ Emissions

A comparison is made between the in-use operation of 8 Line Haul trucks and the EPA supplemental emissions test (SET). The SET is normally used to test the engine at 13 defined test points for criteria pollutants – NOx, PM, CO and HC. In this case the SET is being used to predict the in-use fuel consumption (as a surrogate for $CO_2$) of typical Line Haul trucks.
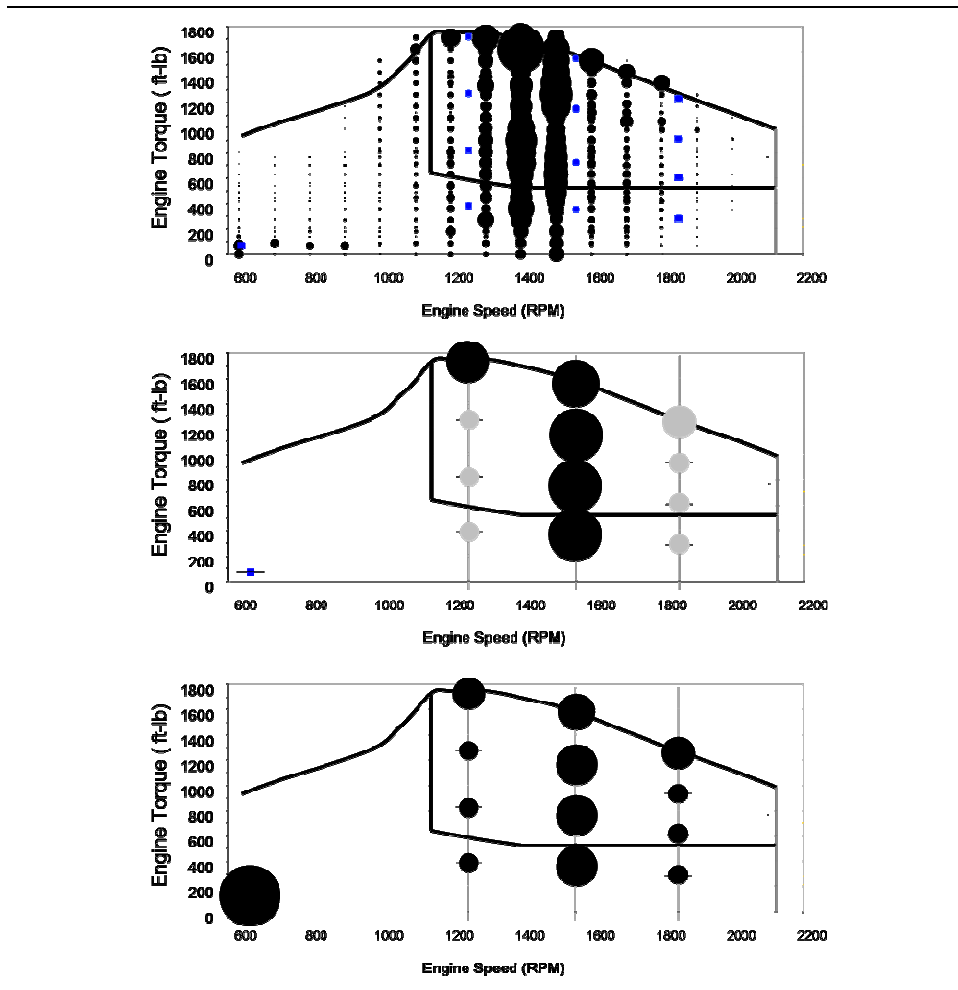


Figure 11, Field data from 8 Line Haul trucks and SET emissions test points.

Upper: Duty-cycle data from 8 Line Haul trucks running a variety of routes and GVWs. Circle diameter represents fuel used by engine speed and load.

Middle: Top 5 modes from the SET 13 Mode steady-state emissions test - circle diameter proportional to mode weighting factors

Lower: Standard SET steady-state emissions test – circle diameter proportional to mode weighting factors

Figure 11 (upper) shows duty-cycle fuel consumed (or $CO_2$), from 8 Line Haul trucks. The trucks were equipped with data acquisition systems to allow fuel to be tracked at 1 second intervals during normal operation. Also shown in Figure 11 (lower) is the standard SET steady-state emissions test points with weighting factors represented by the diameter of the circles at each of the 13 test points. The diameter of the circular dots represents fuel used at each of the engine speed and torque points in the graph. Figure 11 (Center) also shows a sub-set of the 13 modes (A100, B100, B75, B50 and B25). These 5 modes are the most highly weighted of the 13 modes and were used to evaluate a simpler 5 mode representation of the engine's fuel consumption.

In this assessment, a comparison is made between the $CO_2$ emissions of the 8 Line Haul trucks in the field and that predicted from a steady-state (SET) emissions test – using both the standard emissions weighting factors and the simplified 5 mode cycle described above. The results, shown in Table 6, indicate that the SET can be used to represent real-world emissions of $CO_2$ from Line Haul trucks. Table 7 shows further detail of the 8 Line Haul trucks tested, including the engine rating, average power produced during the test and in-use, and the specific $CO_2$ emission in-use and over the test cycle.

| Line Haul – CO2 Emissions Test | % Difference |
|---|---|
| Full 13 Mode SET Emissions Results with ESC Weighting Factors | 3.7% |
| 5 Modes from the SET 13 Modes, Weighting Factors recalculated to 100% (A100, B100, B75, B50, B25) | 6.7% |

| Vocational – CO2 Emissions Test | % Difference |
|---|---|
| Full FTP Transient Test - Cold & Hot Cycle Composite | 4.0% |

Table 6, Comparison of real-world, in-use $CO_2$ emissions with certification test cycle results:

Upper: Average of 8 Line Haul duty-cycles compared with the steady-state emissions test – using the standard 13 modes, and a simplified 5 mode model (A100, B100, B75, B50, B25).

Lower: Average of 9 Vocational duty-cycles compared with results from the FTP transient engine test procedure.

| Application | Engine / Rating [HP], [FT-LB] | SET Average Power [HP] | SET CO$_2$ [g/HP-hr] | Duty-Cycle Average Power [HP] | Duty-Cycle CO$_2$ [g/HP-hr] |
|---|---|---|---|---|---|
| Line Haul #1 | 15L 450,1650 | 245 | 646 | 184 | 641 |
| Line Haul #2 | 15L 400,1650 ST | 245 | 646 | 143 | 676 |
| Line Haul #3 | 15L 450,1650 | 245 | 646 | 120 | 660 |
| Line Haul #4 | 15L 400,1650 | 245 | 646 | 139 | 717 |
| Line Haul #5 | 15L 450,1750 ST | 245 | 646 | 194 | 641 |
| Line Haul #6 | 15L 450,1750 ST | 245 | 646 | 184 | 655 |
| Line Haul #7 | 11L 450,1450 | 204 | 669 | 115 | 729 |
| Line Haul #8 | 11L 370,1350 | 204 | 669 | 120 | 704 |

Table 7, Field data taken from 8 Line Haul trucks used to produce Table 6.

Note: ST = Smart Torque – an engine feature designed to restrict available torque until needed, typically an additional 100 FT-LB of torque is available for hill climbing or other high torque demand situations.

## Appendix B – FTP as a Model for Vocational $CO_2$ Emissions

Figure 12 shows duty-cycle data from a variety of Vocational applications – including school bus, refuse trucks and pick-up and delivery applications. The diameter of the circular dots represents fuel used at each of the engine speed and torque point in the graph. In contrast to the data shown in Figure 11, where the data shows Line Haul trucks cruising at steadier vehicle speeds, here the engine is operated more transiently across the operating range of the engine.
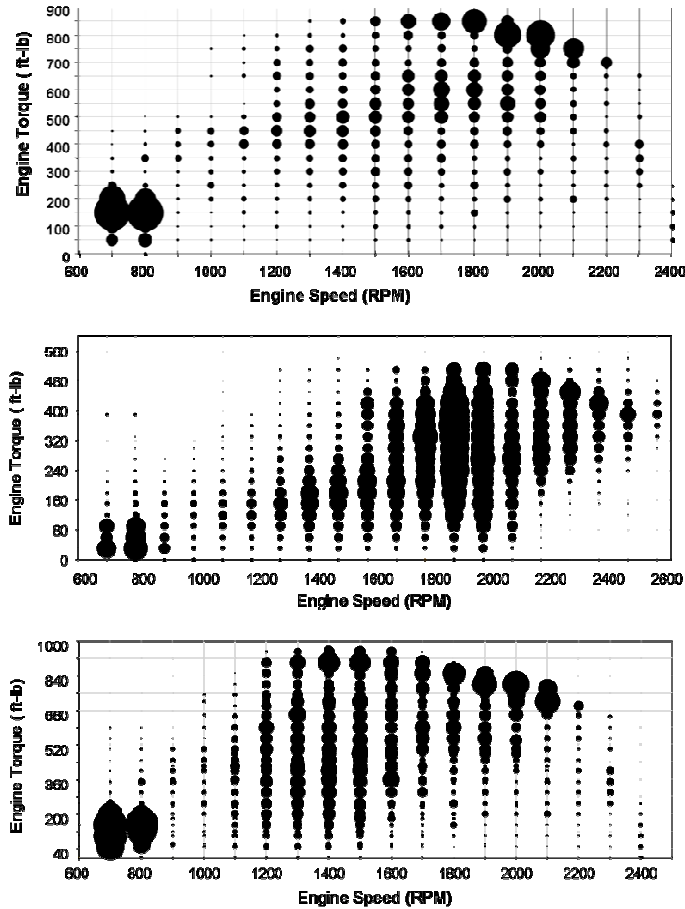


Figure 12, Field data taken from 9 Vocational applications used to produce Table 6. Fuel used is plotted on engine speed and torque axes.

| | |
|---|---|
| Upper: | 11L engine, refuse truck with PTO |
| Middle: | 8.3L engine, school bus and refuse truck overlaid |
| Lower: | 6.7L engine, pick-up and delivery |

Similar to the analysis described in Appendix A, a comparison is made between the $CO_2$ emissions of 9 Vocational vehicles in the field and that predicted from the transient (FTP) emissions test. The results, shown in Table 6 in Appendix A, indicate that the FTP can be used to represent real-world emissions of $CO_2$ from Vocational vehicles.

Table 8 shows further detail from the 9 Vocational vehicle duty-cycles and includes duty-cycle and emissions test (FTP) average power and $CO_2$ emissions [g/HP-hr].

| Application | Engine / Rating | FTP Average Power [HP] | FTP $CO_2$ [g/HP-hr] | Duty-Cycle Average Power [HP] | Duty-Cycle $CO_2$ [g/HP-hr] |
|---|---|---|---|---|---|
| Concrete Mixer | 11L 350HP | 68 | 716 | 54 | 782 |
| Concrete Mixer | 11L 425HP | 76 | 722 | 59 | 775 |
| Dump Truck | 11L 425HP | 76 | 722 | 125 | 730 |
| Refuse Truck | 11L 320HP | 61 | 721 | 111 | 724 |
| Refuse Truck | 8.3L 300HP | 61 | 765 | 54 | 768 |
| School Bus | 8.3L 300HP | 61 | 765 | 61 | 751 |
| Local P&D | 6.7L 200HP | 33 | 718 | 91 | 737 |
| Local P&D | 6.7L 200HP | 33 | 718 | 39 | 820 |
| Transit Bus | 11L 280HP | 53 | 720 | 46 | 765 |

Table 8, Field data taken from 9 Vocational vehicles used to produce Table 6

## Appendix C – Commercial Vehicle Classification

**Vehicle Classification**

| Vehicle Type | GVWR[a] (lb) | Vehicle Type | GVWR[a] (lb) |
|---|---|---|---|
| Passenger cars | 0 – 6,000 | Class 2b – 4 trucks | 8,501 – 16,000 |
| Class 1 trucks (LDT1) | 0 – 6,000 | Class 5 – 6 trucks | 16,001 – 26,000 |
| Class 2a trucks (LDT2) | 6,001 – 8,500 | Class 7 trucks | 26,001 – 33,000 |
| | | Class 8a trucks | 33,001 – 60,000 |
| | | Class 8b trucks | > 60,000 |
| | | School buses | 21,000 – 31,000 |
| | | Transit and commercial buses | 26,001 – 60,000 |

[a] Gross vehicle weight rating.

Table 9, Vehicle classification system – including Class 2a and 2b definitions and Class 8a and 8b.

## Appendix D – Potential Efficiency Measures for Line Haul Tractor-Trailers and Operations

The data contained in Table 10 is intended to give an indication of the value of various features that improve the efficiency of Line Haul tractor-trailer performance and operational efficiency. Some of these features are in production currently, either as retro-fit or first fit.

| Technologies | Baseline | Details | Fuel Consumption Reduction | | |
|---|---|---|---|---|---|
| | | | Low | High | Source |
| Tractor Treatment | Base Non-Aero Tractor | ● Aero bumper<br>● Fuel tank fairing<br>● Cab side extender fairing<br>● Sleeper cab with high roof integrated fairing<br>● Aero Mirror | 7.00% | | SmartWay |
| Trailer Treatment | No Trailer Treatment | ● Rear trailer deflector or Boattail, 2~3.5%<br>● Trailer side skirt 1~2% | 3.00% | 5.50% | SAE 2006-01-3456 |
| Wide-based Single Tire | Conventional dual tires | ● Super Single<br>● Central Tire Inflation System | 3.00% | | Fleet Input |
| Trailer Gap Treatment | No Gap Treatment | ● Trailer leading edge fairing,<br>● Reduce gap,<br>● Roof deflector filler | 1.50% | 2.50% | SAE 2006-01-3456 |
| Transmission | Transmission 2007 | ● Synthetic transmission & axle lube<br>● Dry Sump lube system ~0.5% | 1.50% | 5.00% | General Industry Assessment |
| Accessory Electrification | Base | ● Electrical air compressor / air conditioner | 2.00% | | Ref. Public 2007 DEER |

| Measure | Baseline | Details | Fuel Consumption Reduction | | |
|---|---|---|---|---|---|
| | | | Low | High | Source |
| Cruise Speed Reduced to 60 MPH | 65MPH | ● Route Simulation - Mixed Flat and Hilly<br>● 2007 Line Haul Truck | 5.60% | | Cummins Vehicle Route Simulation |
| GVW | 80K LB, 5 axles 53' trailer | ● 92,000 to 97,000 LB - 6 axles | 6.00% | | American Truck Research Institute (ATRI) |
| Idle Reduction | Overnight Idle Main Engine | ● APU<br>● Fuel Fire Heater (FFH)<br>● Electrification: HVAC<br>● Shore Power | 3.00% | 6.50% | Cummins Assessment |
| Driver Behavior | Base | ● Progressive shifting<br>● Anticipating traffic change | 2.00% | 5.00% | Industry assessment, but assume that Vehicle speed has been lower from 65MPH to 60MPH |
| Traffic Flow Improvement | Base | ● Truck lane to reduce traffic congestion<br>● GPS assisted truck maneuver optimization<br>● Real time route optimization | 2.80% | 4.50% | Cummins simulation |

Table 10, Line Haul Tractor-Trailer partial list of potential efficiency measures

Upper: Vehicle options

Lower: Operational options