

Complete Vehicle Standards for Heavy-Duty Trucking: Optimizing Freight Efficiency Benefits to Meet U.S. Greenhouse Gas Emission Standards

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ABSTRACT

For decades, the medium- and heavy-duty ("MD/HD") commercial vehicle industry has focused on improving freight efficiency in order to lower customers' total operating costs. To optimize fuel efficiency, most manufacturers no longer focus on discrete components but instead look at the complete vehicle and operations. The path to future efficiency gains is not sufficiently clear when looking towards 2030; what is clear is that one solution will not work for all manufacturers or vehicle applications. Therefore, fuel efficiency regulations must be sufficiently adaptive to allow a variety of technical approaches to ensure the needs of the commercial truck market are met. This paper explores further the ideas presented in other papers that focus on regulation of engine-only emissions as an approach for HD vehicles. This paper will describe EPA's Phase 1 Greenhouse Gas Emissions Model ("GEM") and discuss technologies expected to be used to improve fuel efficiency in the future and how the next generation of GEM ("NextGenGEM") for Phase 2 should be improved to capture these technologies, including why drive cycles should be revised. This work will also discuss how an improved NextGenGEM simulation can enhance the regulation's ability to be technology-neutral, align with real-world advancements, properly reflect technology penetration with real-world GHG reductions, result in customer acceptance, and maintain a reasonable regulatory burden that works with the product diversity that defines the HD market without compromising emissions compliance. Finally, this paper will evaluate ideas to improve the effectiveness of future GHG regulations for the HD market and ensure regulatory integrity.

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INTRODUCTION

In 2011, the U.S. Environmental Protection Agency and the National Highway Traffic Safety Administration ("the Agencies") promulgated first-ever fuel efficiency regulations for heavy-duty engines and vehicles ("Phase 1") [1]. Phase 1 created two parallel programs for HD engines and vehicles. The engine program credits manufacturers for engine-only CO₂ or fuel consumption savings but not for full powertrain savings nor for savings due to (for example) more efficient engine accessories. The vehicle program credits manufacturers only for vehicle technologies such as aerodynamics and speed limiters but not for powertrain savings nor for engine accessories, engine cooling strategies, transmission shift strategies, nor a host of other technologies that involve engine and vehicle systems integration. Rather, the Agencies' simulation model, GEM, assumes predetermined engine operating "fuel maps" (i.e. engine fuel consumption values based on the demand on the engine at different operating points) and predetermined powertrain characteristics. Therefore, if engine and vehicle manufacturers invest in technologies to improve the efficiency of engine accessories, powertrains, cooling, etc., or if engine manufacturers optimize their engines' fuel maps to improve efficiency over real-world drive cycles, the manufacturers cannot get CO₂ credits for such improvements, even though such a strategy would provide real-world benefits. This could mean having to add additional technologies and cost to the engine and/or vehicle just to meet the

standards while potentially not providing real-world improvement. Phase 1 has already created a divergence between "certified" CO₂ values and real-world fuel economy improvements by separating out components such as engines from the complete vehicle. As the stringency of these standards increase, the risk of this divergence resulting in original equipment manufacturers ("OEMs") being forced to develop technologies that only provide "test-cycle" improvements instead of real-world efficiency improvements greatly increases.

This paper seeks to discuss why it is important for manufacturers to optimize the entire vehicle and why fuel efficiency regulations should use the same approach as manufacturers in order to achieve targeted reductions. This paper also seeks to explain the tradeoffs between test-cycle and real-world efficiency and how the agencies can prevent unintended consequences resulting in test-cycle benefits that do not correspond to real-world benefits.

A Review of Relevant SAE Papers

Numerous SAE papers have been published on the topic of improving fuel efficiency in the commercial vehicle sector. Understanding the work that has been done in the past helps provide insight into the work that is left yet to do. In the 1920's authors explored ideas to improve fuel efficiency such as data collection by fleets to identify opportunities by which to reduce operating costs.

[2,3]. Prior to and during World War II, more attention was paid to fuel economy, in large part due to fuel rationing concerns, and attention turned to alternative fuels and engine designs for efficiency improvements [4]. SAE papers in the post-war period focused on saving fuel to decrease fleet operating costs such as “Running a Fleet of Trucks without Cost Records Is Like Using a Clock without Hands” by L.L. Pernot in 1948 [5]. Pernot's paper discusses a cost record system developed over a ten-year span to analyze eight factors that make up the cost of truck operations (e.g. fuel, tires, repair, oil, depreciation, etc.); costs are presented in terms of cost per mile and cost per ton-mile.

In 1949 Carl C. Saal published a highly detailed SAE paper titled “An Evaluation of Factors Used to Compute Truck Performance” [6]. This paper attempted to research factors such as the coefficient of friction, tire rolling resistance, gear efficiencies (for direct drive and other gears), and other inputs to approximate truck performance on the highway and overcome a general lack of agreement on these factors among manufacturers. It is interesting to note that the paper considered the efficiency improvements of 6x2 vehicles compared to 6x4 vehicles.

SAE papers in the 1950's also looked to alternative fuels (e.g. liquefied petroleum gas) and improved engine designs or new engine platforms such as turbines for use in commercial trucks to save fuel [7,8]. For example in a 1962 SAE paper titled “Engines for Economy Plus,” Detroit Diesel Corporation presented the new “N” series engine and described how improvements in fuel injection (such as the use of needle valve injectors) were in large part responsible for a 10 percent reduction in idle fuel consumption, reduced smoke, and the elimination of fuel injection under downhill motoring conditions [9,10].

The 1960's brought new engineering challenges as manufacturers looked ahead to the building of 41,000 miles of interstate highways in the U.S. (actually completed in 1980). A 1965 SAE paper published by Ford titled “A Gas Turbine Super Transport Truck Power Package” looked at optimizing a vehicle for these conditions, stating that fuel consumption was the key factor in powertrain selection due to the operational nature of a long-haul vehicle [11]. Work continued on vehicle optimization into the 1970's as well as work on how to quantify fuel efficiency improvements. For example, General Motors published a detailed paper titled “Commercial Vehicle Performance and Fuel Economy” which sought to improve on Carl C. Saal's 1949 work (discussed earlier) [6,12]. This paper sought to “discuss those aspects of the vehicle's operation that are pertinent to performance and fuel consumption” a prescient topic in 1970 given the energy crisis of 1973.

The energy crisis itself inspired new papers that sought new approaches for fuel economy improvements, such as looking to Europe, Japan, and other countries for ways to optimize fuel efficiency [13,14]. Other papers around this time looked at improvements available from automatic transmissions, and optimizing aerodynamic improvements by looking at the tractor-trailer as a single system [15,16]. Heavy-duty vehicle simulation work was also ongoing such as that presented in “Paper Trucks on

Paper Roads” which discusses computer simulation of heavy-duty truck performance “to satisfy increased interest in vehicle fuel economy” [17]. The recurring theme of optimizing efficiency in trucks continues up through the advent of Phase 1 with the publication of hundreds of papers, many of which also discuss the impact of criteria emissions on fuel efficiency. The fundamental inference of this literature review is that for decades the heavy-duty industry has sought to quantify and solve the same problems and energy losses with newer and different approaches such as technologies enabled by the implementation of electronics.

After the publication of Phase 1, there have been many papers published by suppliers that discuss potential improvements that can be made to specific components such as engine suppliers, transmission suppliers, and even alternative fuel conversion providers [18,19,20]. There have also been papers submitted that support the approach taken in Phase 1 of setting separate engine standards [21]. This paper attempts to fill the gap by discussing the importance of looking at the total vehicle in order to achieve real-world fuel efficiency improvements.

A MILE-PER-GALLON METRIC IS FUNDAMENTALLY INAPPROPRIATE TO MEASURE IMPROVEMENT IN REAL-WORLD FREIGHT EFFICIENCY OF MD/HD VEHICLES

There are many ways to discuss how much fuel a vehicle consumes to perform a certain amount of work. For light-duty vehicles, “fuel economy” or miles per-gallon (“mpg”) is used because these vehicles are similar in size, operations, duty-cycle, and mass and therefore perform similar work. Heavy-duty vehicles use metrics that recognize the work done by the vehicle (“fuel efficiency”) typically measured in “ton-miles.” Fuel consumption is directly proportional to CO₂ through the use of a conversion factor of 10,180 grams CO₂ per gallon for diesel fuel. Therefore, in Phase 1 the agencies measured fuel consumption/CO₂ from a vehicle in grams of CO₂ emitted to move one ton (2,000 pounds) of freight over one mile (g/ton-mile). Consistent with this approach, this paper also uses CO₂ emissions and “fuel efficiency” interchangeably. “Fuel economy” is not used in reference to heavy-duty vehicles as it can be misleading based on the type of freight hauled, route, traffic conditions, speed limits, driver skill, and many other factors. Caution must be given when viewing any mpg value for a heavy-duty vehicle as the value cannot be truly understood without knowing the context of the measurement. The Oak Ridge National Laboratory performed a study in 2011 in partnership with the Department of Energy (“DOE”) and industry to research the impact real-world conditions can have on the fuel efficiency of Class 8 trucks (trucks with a gross vehicle weight rating (“GVWR”) of 33,001 pounds) [22]. Oak Ridge collected data on over 1,000 trips covering some 700,000 miles of primarily highway travel. When looking at the fuel efficiency of Class 8 trucks by weight over flat terrain and traveling 65 miles per-hour (“mph”), the result demonstrates that fuel economy/mpg is not an appropriate measure of fuel efficiency for the heavy-duty industry due to the effects of the weight of the load carried as shown in Figure 1.

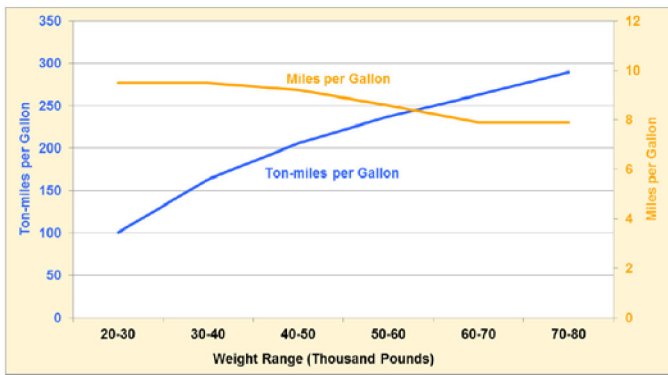


Figure 1. Miles per-gallon compared to ton-miles per-gallon for Class-8 trucks (Source [23])

The Oak Ridge study also monitored the weight, speed, fuel efficiency, and actual road location/grade of certain trucks [22]. When the fuel economy of the same truck carrying the same load over different terrain was analyzed, results show that fuel economy can vary substantially even for the same truck. On severe uphill sections of terrain, fuel economy of the same truck can be 60 percent worse, while on severe downhill grades, the same truck's fuel economy is 221 percent better (as shown in Figure 2) [23]. The opportunities for inappropriate mpg claims to be made for heavy-duty vehicles are almost infinite, especially when operational differences are factored in. For example, using the data from Figure 2 it can be shown that the gain/loss from going uphill or downhill is not equivalent. This means that a truck traveling up and back down a hill with no net elevation change will only get approximately 70 percent of the fuel economy as the truck would on level ground [23].

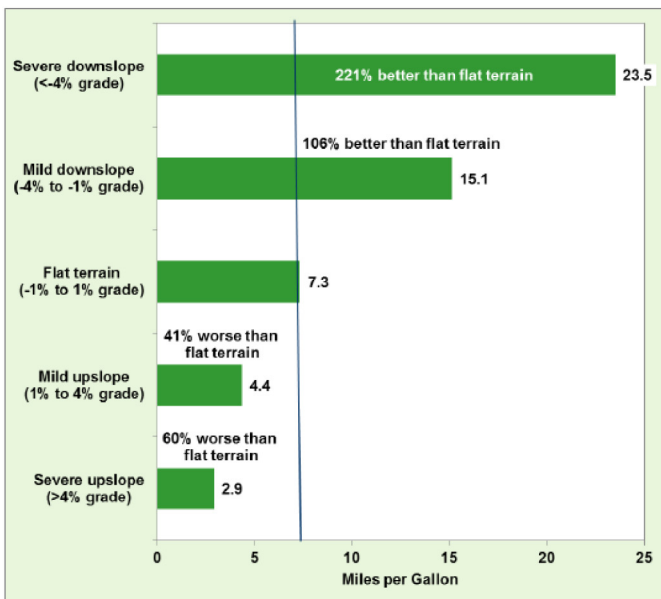


Figure 2. How roadway grade can affect fuel economy of Class 8 trucks (Source [23]).

The Agencies' are required to apply metrics consistent with direction given by Congress to use test methods and measurement metrics that are appropriate for the commercial work truck industry. The agencies' selection of metrics was also supported by the work of the National

Academy of Sciences ("NAS") in their report published in 2010 and cited by the Phase 1 rule [24]. NAS concluded that measuring mpg is an inappropriate metric to use for heavy-duty and recommended the use of fuel consumption. In the Phase 1 rulemaking, NHTSA states "in the context of 49 U.S.C. 32902(k), NHTSA interprets "fuel economy standards" as referring not specifically to miles per-gallon, as in the light-duty vehicle context, but instead more broadly to account as accurately as possible for MD/HD fuel efficiency," and further states that the metric must recognize the work these commercial vehicles are designed to do. EPA said in Phase 1, "the CO₂ and fuel consumption metric should reflect what we wish to control (CO₂ or fuel consumption) relative to the clearest value of its use: In this case, carrying freight." Fuel efficiency remains the correct metric by which to judge fuel efficiency improvements.

HISTORICAL FOCUS ON FUEL EFFICIENCY AND CONSTRAINTS ON IMPROVEMENTS RESULTING FROM CRITERIA EMISSIONS REGULATIONS

Daimler Trucks North America ("DTNA") is a vertically integrated manufacturer of HD vehicles and powertrains. DTNA is headquartered in Portland, Oregon, and produces Class 4-8 vehicles under the Freightliner, Western Star, and Thomas Built Bus nameplates. DTNA employs computerized fluid dynamics modeling to simulate shapes, test, and analyze them in a company-owned wind tunnel. Daimler's global technology and experience in passenger cars and commercial vehicles is applied to its North American products to incorporate a myriad of fuel efficiency features and safety options, including anti-lock brakes, obstacle detection systems, and lane departure warnings which ultimately improve efficiency by reducing congestion through improved safety. DTNA's subsidiary, Detroit Diesel Corporation ("DDC") offers fuel efficient engines and powertrain components that provide owners lower total operating costs.

Like other HD manufacturers, DTNA focuses heavily on achieving fuel efficiency gains through both technological advancements and by optimizing the entire vehicle. By designing and engineering highly efficient components such as engines, transmissions, and axles as well as the vehicles these powertrain components go into, DTNA is able to use a total system approach to optimize for fuel efficiency.

For decades the HD diesel industry has worked to improve engine and freight efficiency while complying with ever more stringent emission standards which often have required efficiency compromises. This effort and progress has been largely dismissed by many environmental groups. For example in a recent article the Union of Concerned Scientists [25] opined that:

"Unlike passenger cars and other light-duty vehicles, the fuel economy of heavy-duty vehicles has been largely unregulated for decades. Tractor trailers, delivery vans, and other heavy-duty trucks have kept roughly the same fuel economy since the 1970s—just 6 miles per gallon. Years of non-regulation and slow investment now mean that heavy-duty vehicles consume 25 percent of all fuel, despite only accounting for 7 percent of vehicles on the road."

There is no known reliable way to look back at truck fuel economy data from past decades, and unlike the light-duty industry the heavy-duty industry is commercial and seeks to use the fewest number of trucks to haul the most freight. In 2014, heavy-duty vehicles moved nearly 70 percent of all domestic freight some 168 billion miles [26]. Another key aspect of the heavy-duty commercial market is the low sales volume, for example in 2014 Class 8 sales were approximately 220,000 compared to light duty vehicle sales in 2014 of 6.7 million units [27,28]. Further, assessing fuel efficiency of trucks is very different than judging fuel economy of trucks on a mile per-gallon basis due to the commercial operation of the trucking industry, as explained above. Fuel usage is the largest operating expense in trucking and has always been a focus of purchasers who continuously demand improvements in order to be able to compete in the highly competitive freight hauling business [29]. DDC, has always placed priority on increasing market share by providing the best real-world fuel efficiency as shown in DDC's 1958 ad presented in Figure 3 below (when Detroit Diesel was a separate division of General Motors). Throughout the energy crisis of the 1970's and 1980's fuel efficiency remained top priority as DDC sold its "Fuel Pincher" and "Fuel Squeezer" engines which were advertised as being almost twice as efficient as gasoline spark-ignition engines. The reason it is important to recognize that manufacturers have continually sought to increase fuel efficiency is to recognize that engineers have explored and continue to explore physical and theoretical limits of achievable efficiency and have in many respects developed nearly to the limits of what's possible. The heavy-duty trucking industry shares the agencies' fundamental goal to deliver real value to customers and to society through reduced fuel consumption and reductions in greenhouse gas emissions. A Phase 2 program with complete vehicle standards that is based on proven, commercially viable technology, and sets reasonable stringency is the real key to a successful Phase 2 program that allows manufacturers to meet customers' needs and has the best chance of achieving real-world success.



Figure 3. General Motors 6-71E Diesel Ad from 1958 "Leading all others in economy as well as performance."

In 1987, DDC released the first production engine with integrated electronic controls, the Series 60. DDC published at least one SAE paper describing the new Series 60 diesel engine [30,31]. As the first electronically controlled engine in the HD market, the Series 60 leveraged electronics to improve fuel efficiency. The paper states that "the 1988 engines are a minimum of three percent more fuel efficient than other production heavy-duty truck engines" [30]. DDC described this revolutionary engine as "designed to set new world class standards in areas of primary importance to heavy-duty engine users, which include fuel economy, reliability, durability, noise level, and exhaust emissions" [31]. These goals remain consistent in today's heavy-duty engine design, except the order has changed such that fuel efficiency can only be optimized after near-zero emission standards are met.

In support of Phase 1, NAS published data highlighting the overall trend in fuel efficiency improvements in the HD industry, shown in Figure 4, which lines up well with the brake-specific fuel consumption ("BSFC") data provided in DDC's 1987 SAE paper (achieving rated brake-specific fuel consumption of 0.315 pounds per brake horsepower-hour [24, 30, 31]. One of the important concepts in the chart is how this trend in fuel efficiency improvements was interrupted by NOx regulations.

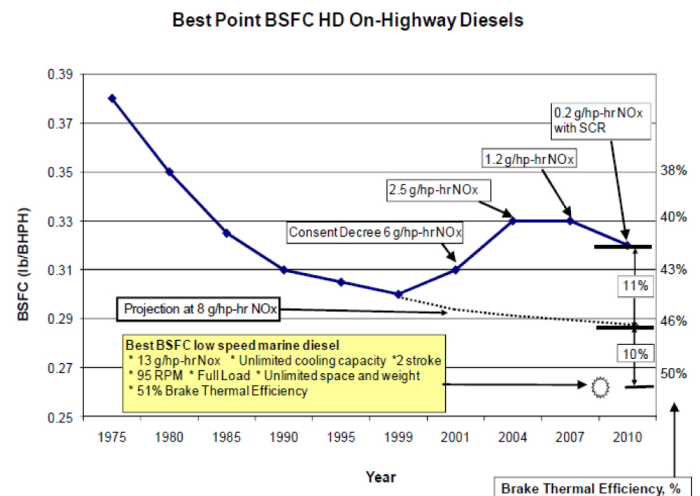


Figure 4. Brake-specific fuel consumption improvements over time in HD engines (Source [24])

The concept that fuel efficiency was ignored by manufacturers absent regulation mistakenly ignores the fundamental tradeoff between criteria emissions control and achievable fuel efficiency. Historic levels of investment were required to meet stringent criteria emissions standards which has forced increasingly complex technology over the past decade, resulting in severe impacts to the industry including one engine manufacturer leaving the heavy-duty on-highway market. It is more important than ever to recognize the tradeoff between NOx and CO₂ emissions, especially as the California Air Resources Board ("ARB") is considering mandates for additional NOx reductions of up to 90 percent, which if technically feasible, will have negative impacts on achievable fuel efficiency improvements [32].

The net result of the existing near-zero NOx and PM emissions standards has also been a much higher permanent cost than EPA predicted in their rulemaking to set lower NOx. The EPA estimated approximately \$2,000 per truck whereas the cost actually approaches \$20,000 per truck [33]. This higher cost of trucks due largely to regulation makes it difficult if not impossible for manufacturers to focus on reducing cost given the constant engine regulation over the past decade, including most recently: 2010 near-zero NOx regulations, 2013 onboard diagnostics regulations (“OBD”), 2014 GHG regulations, 2016 OBD regulations, and 2017 GHG regulations. In addition to these engine regulations, there are numerous vehicle-side regulations that can add weight and complexity that can also work counter to fuel efficiency.

REAL-WORLD IMPACTS OF PHASE 1

Implementing GEM

While the Phase 1 mandate went into effect in 2014 and data as to its effects is largely limited, some successes and failures have already been identified. The largest success of Phase 1 was the fact that it recognized the highly diverse nature of the HD industry. The program has, however, taken considerable effort on the part of OEMs to design and implement systems to handle the compliance and data requirements of Phase 1.

To understand just how important simulation is to achieving a regulatory program that OEMs can actually comply with, DTNA looked at the avoided testing burden in Phase 1. Analyzing all GHG14-compliant vehicles sold by Daimler (approximately 300,000 units) we first analyzed the different build variables utilized by GEM, including: regulatory subcategory, coefficient of rolling resistance for drive and steer tires, aerodynamics, weight reduction, and whether or not a vehicle used regulatory vehicle speed limiters or automatic engine shutdown timers. The actual number of combinations built results in over 11,000 unique GEM configurations; with each configuration needing be run through GEM simulations. As the complexity of the program increases through Phase 2 and assuming more components are pulled into NextGenGEM as recommended by many stakeholders (e.g. some OEMs and NAS), Daimler estimates the number of unique GEM simulations required will increase by some 400 percent. It is simply not feasible for OEMs to run tens of thousands of unique tests when sales volumes are numerically small. Simulation provides a sound and auditable methodology to comply with the Phase 1 program, and will be even more important in Phase 2.

The diversity of heavy-duty vehicles is the one constant in the heavy-duty industry. While the industry does manufacture a large number of vehicles for fleets that engage in over-the-road transport, looking at the production volume of GHG14 vehicles, Daimler built trucks for nearly 18,000 unique customers, with over 99.9 percent of these customers representing less than one percent of total sales. Many customers buy more than just one type of vehicle, from line-hauls to heavy-hauls. Heavy-haul vehicles can range from GVWRs of 52,000-105,000 pounds, and typically work in severe-duty operations. One technology will not work for all applications,

and some may interfere with the job the commercial truck is designed to do as demonstrated by the heavy-haul truck in [Figure 5](#).



Figure 5. Western Star heavy-haul vehicle example

Engine Test-Cycle Divergence from Real-World

One of the failures of the Phase 1 program is the divergence that exists between real-world operation and operation over the test-cycle that is used to measure compliance with the separate engine standards. Daimler engineers have done benchmarking studies to identify any fuel efficiency advantages of DTNA products as well as to gain understanding of how real-world fuel consumption compares to certified fuel consumption (CO₂) levels. In one such case, Daimler compared two engines in two separate (but identical) vehicles: engine A, a 2013 DD15AT installed in a Freightliner Cascadia with a 72 inch raised-roof sleeper, automated manual transmission, and a vehicle test weight of 73,500 GVW; engine B, a 2013 concurrently sold competitor engine also installed in a Freightliner Cascadia with a 72 inch raised-roof sleeper with the same rear axle ratio as the other vehicle, 73,500 GVW test weight, and mated to the same automated manual transmission as engine A.

The engines were configured to be as close as possible in specification given the different manufacturers. Displacement was within 0.1 liters, compression ratios were nearly identical, and both engines had a fleet rating of 455hp @ 1,800 rpm and 1,500 ft-lb at 1,100 rpm. DTNA tested these two vehicles over a real-world route using a modified ‘Technology & Maintenance Council Type IV’ fuel economy test procedure (adopted by SAE).

Tests were performed on these two trucks over the same route. Trailers and drivers were swapped at mid-point to minimize potential driver and/or trailer influence on the test. Driver impact was also minimized by using predetermined shift strategies and cruise control. Both engines meet EPA's Phase 1 CO₂ standards [37]. The result was that the engine certified by EPA to have lower CO₂ over the engine dyno certification test-cycle, actually had higher fuel consumption during real-world testing as shown below in [Figure 6](#).

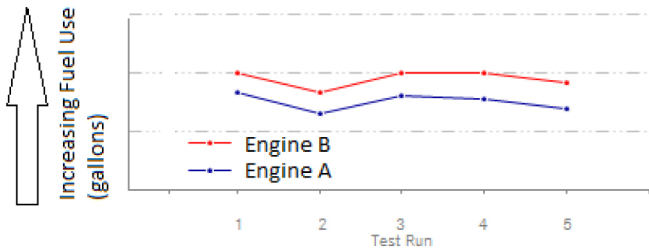


Figure 6. Results of fuel use from engine benchmark testing (Note: while absolute fuel efficiency varied from day to day due to ambient conditions, relative fuel efficiency remained consistent)

The difference between the test-cycle fuel consumption values and real-world values approached six percent. Although a single digit difference may be perceived by some as negligible, it is in fact of a magnitude equal to the entire engine CO₂ reduction required through 2017 by the Phase 1 program and represents a tremendous improvement on today's diesel engines. Such a divergence between metrics of the certification process and real-world results should be corrected by eliminating the separate engine standard.

The problem stems essentially from the adoption of test procedures that integrate CO₂ emissions over test-cycles originally designed to ensure criteria pollutant emissions are met across a wide range of engine speeds and loads. In particular, the Ramped Modal Cycle ("RMC") which is used to measure compliance of line-haul engines is not representative of how engines operate in powertrains designed for today's vehicles. The RMC was based on the European steady state test-cycle that was designed to ensure that emissions are controlled over an engine's potential operating range but without emphasis on weighting operating modes that might be the most important emissions contributors in actual operation. While this approach may suffice for criteria pollutants, the emphasis of the test-cycle on covering a broad range of operation is disconnected from today's need for regulatory procedures that accurately capture fuel consumption in specific applications. The RMC is particularly problematic in its divergence from operation in the line-haul application. An example of how today's engine operation in this application has diverged from the test-cycle is illustrated by comparing past and present driveline gearing recommendations. For example, in the 1980's it was recommended that the Series 60 be geared to run in line-haul applications between 1,600-1,800 rpm (depending on the displacement) near peak power engine speed. This is in drastic contrast to today's recommendations for drivetrains to be geared for engine operation at or below 1,200 rpm. The divergence becomes clearer upon evaluation of operating points recorded on vehicles in real-world operation. Figure 7 shows that while the test-cycles serve their purpose of ensuring criteria emissions are met everywhere the engine operates; the percentage of time the engine operates at certain speeds does not match real-world operations. This means that the CO₂ certification value for an engine overemphasizes operation at high speeds and loads on the test-cycle that seldom occur in the real world. Daimler is not the only manufacturer to identify this divergence. In SAE paper 2013-24-0094, Cummins highlights their downspeeding goals, and notes that engines rarely operate at 75-100 percent of rated speed anymore [18].

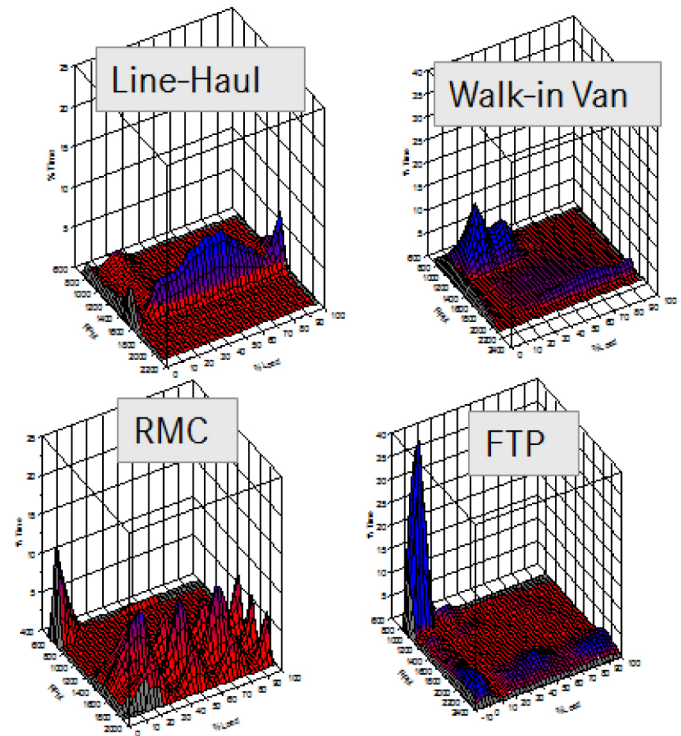
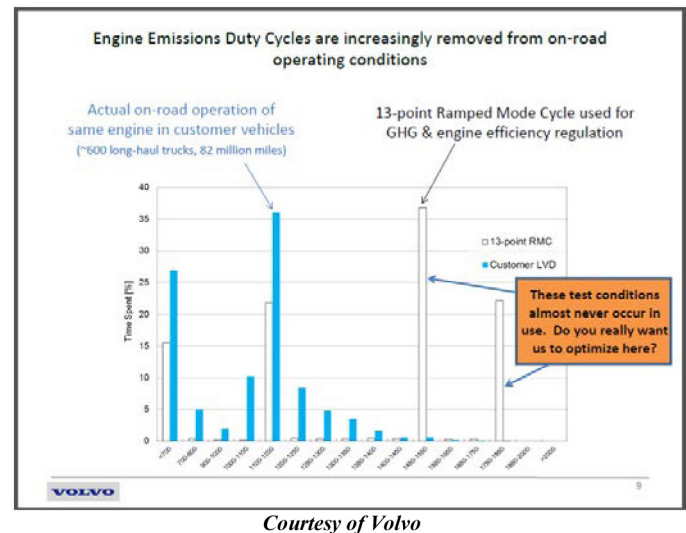


Figure 7. Test-cycle v. real-world operations



Courtesy of Volvo

Figure 8. Volvo's data on engine speed divergence between real-world and test-cycle speeds (Source [34])

In a presentation given at the "Workshop on Emerging Technologies for Heavy-Duty Fuel Efficiency" hosted by the American Council for an Energy-Efficiency Economy and the International Council on Clean Transportation, Volvo presented data on the observed mismatch between real-world engine operation and EPA's test-cycle operational profile [34]. Their data are based on the actual on-road operation of the same engine model in over 600 line-haul customer vehicles representing operation over 83 million miles (see Figure 8). Volvo's presentation also states that engine operation has changed since the time the cycle was developed, primarily to provide fuel savings, and while there is some overlap between the test-cycle and actual operation resulting in an opportunity for fuel savings to be measured