Structural Options for Phase 2 Heavy-Duty Vehicle Fuel Efficiency and Greenhouse Gas Standards

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Abstract

This paper compares two structural options for the next phase of U.S. heavy-duty vehicle fuel efficiency and greenhouse gas standards. The program could regulate engines and vehicles separately, as the first phase did, or it could move to a full-vehicle standard that reflects engine performance. We evaluate these two approaches relative to six criteria, and we conclude by suggesting two further options that incorporate the benefits of each approach while avoiding the pitfalls. For each topic discussed, the paper includes questions to manufacturers and others who can provide additional technical information. We conclude with a preliminary recommendation that the Phase 2 standards combine the two structural options.

Introduction

The Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) ("the agencies") adopted the first standards for the greenhouse gas (GHG) emissions and fuel efficiency of medium- and heavy-duty vehicles in model years 2014–2019 (EPA and NHTSA 2011a, 2011b). For these standards ("Phase 1"), the performance of tractor trucks and vocational vehicles is certified using a simulation model (EPA 2011). The standards for these vehicles are component based, focusing on engines, aerodynamics, and tires. Although the program also sets full-vehicle standards for heavy-duty pickup trucks and vans (generally tested on a chassis dynamometer), these vehicles are not included in the discussion below.

The agencies are now developing the next phase ("Phase 2") of the program, which is expected to apply to vehicles starting with the 2019 or 2020 model year. Further major efficiency gains are possible in Phase 2, including many from technologies already available or now being demonstrated. The program's ability to drive these gains will depend on its structure. Certain features of the Phase 1 program limit its ability to draw technologies into the market. One such feature is the separate standards for engines and vehicles, which effectively ignore potential efficiency gains from integrated engine/vehicle approaches. Whether regulators should retain this structure or switch to full-vehicle standards is a fundamental question for Phase 2 and the subject of this paper.

STRUCTURE OF STANDARDS

In Phase 1, engines are subject to GHG and fuel efficiency standards, expressed respectively in grams of carbon dioxide (CO_2) per brake horsepower-hour and gallons of fuel per brake horsepower-hour. Engines are tested on a dynamometer over the Federal Test Procedure (FTP) and Supplemental Emissions Test (SET) cycles, which are the cycles used for criteria pollutant certification.

Complementing the engine standards are standards for the rest of the vehicle, expressed in grams of CO_2 or gallons of fuel per ton-mile. Vehicle certification is based on a simple simulation in which a fixed engine and transmission are assigned to all vehicles in a given class. Vehicles are simulated over three test cycles: a transient cycle representing city operation (previously developed for the California Air Resources Board), and 55-mph and 65-mph steady-state cycles, representing highway operation.

Standards could be applied instead to the vehicle as a whole. In this approach, the certified fuel consumption and emissions of the vehicle would reflect the specifications and/or performance of the engine and transmission sold with the vehicle. In this case, certified fuel efficiency would generally be a reasonable approximation to actual vehicle performance over the test cycle and with the test load.

Hence there are at least two structural options for the Phase 2 program:

A. Separately regulating engines and the rest of the vehicle, as Phase 1 did
B. A full-vehicle standard

This paper uses six criteria to compare the two options:

- Promotion of advanced technologies
- Reflection of real-world performance
- Compatibility with criteria emission testing
- Practicable compliance and enforcement
- Compliance flexibility
- Low-cost testing

Finally, after comparing the two options using these six criteria, we consider two further structural variations.

While we make a preliminary recommendation on the structure of the Phase 2 program, a full understanding of the issues raised in the paper will require additional data and other detailed information not currently available to us. In an effort to resolve these issues, we pose questions throughout the paper (summarized in Appendix A) to solicit information from manufacturers and others who may be able to provide it.

Criteria for Structure of Standards

PROMOTION OF ADVANCED TECHNOLOGIES

GHG and fuel efficiency standards can encourage the development and adoption of new fuel efficiency technologies. Therefore the standards should be structured to identify and reward the benefits of these technologies. Due to the structure of the Phase 1 standards, they captured only certain categories of efficiency improvements. While the rule did allow manufacturers to claim credits for other types of technologies validated by special testing mechanisms, this approach was burdensome to manufacturers and therefore underutilized. Moreover, the standards did not reflect potential savings from these technology categories, so they were not as strong as they might have been.

Phase 1 structure

Although rapid growth in emerging markets may shift this dynamic, sales volumes for heavy-duty engines have been too small to spur timely commercialization of all promising technologies. Engine standards create an added incentive. Standards that require a substantial increase in engine efficiency can stimulate the development of advanced engine technologies, which may require major investment over many years. This is the case, for example, for the engine bottoming cycle, which has the potential to reduce fuel consumption by 5-10% (Cummins Inc. 2013; NRC 2010). In the DOE SuperTruck Program, two teams including Cummins and Daimler Trucks North America have used a bottoming cycle to achieve the program's goal of doubling tractor-trailer fuel efficiency.

Although it helps with engines, the Phase 1 approach does not promote transmission improvements, since neither the engine test nor the vehicle test covers the transmission sold with a particular vehicle. Yet advanced transmissions and driveline integration could provide additional fuel savings of up to 10% (ACEEE 2013). Nor can the basic tests measure hybrid performance, although manufacturers may obtain hybrid credits using an alternative test procedure.

In addition, the separation of vehicle and engine means that the program does not incentivize integrated vehicle strategies. For example, aerodynamic improvements in tractor-trailers could permit secondary fuel savings through powertrain downsizing. The Daimler Trucks North America SuperTruck achieved almost 4% fuel savings through engine downsizing (Rotz 2013). But the standards do not stimulate such improvements, because vehicles are tested with a powertrain that is predetermined for each vehicle class.

Question: What percentage of tractor-trailers could get full benefit from a bottoming cycle?

Full-vehicle standards

Since full-vehicle standards would encompass the benefits of all vehicle and engine technologies, they could be more ambitious than the Phase 1 protocol (McLaughlin and Greszler 2013; Christianson 2013). The requirements on the engine to enable a vehicle to achieve a given fuel efficiency level would depend increasingly on the particular features of the vehicle and how the engine interacts with those features. In the absence of separate engine standards, truck manufacturers could choose not to use available engine improvements to meet the standard. This would be appropriate as long as engine improvements were not among the most cost-effective efficiency improvements. However opportunities for new cost-effective engine technologies might be lost if truck manufacturers found it difficult to translate the standard to engine manufacturers in a clear enough fashion to spur their development. This issue would be less likely to arise if the stringency of the full-vehicle standards were sufficient to require adoption of all cost-effective technologies.

Question: How could truck manufacturers translate a full-vehicle standard, defined in terms of grams or gallons per ton-mile, into a performance requirement for the engine manufacturer in such a way as to spur investment in advanced engine technologies?

ABILITY TO REFLECT REAL-WORLD PERFORMANCE

Standards should promote the development and adoption of technologies that will deliver real-world fuel savings. In addition, a vehicle's certified fuel consumption under the standards program should allow a prospective buyer to determine which vehicle will consume the least on his/her duty cycle. Therefore test cycles need to replicate key features of users' actual drive cycles. Phase 1 did not require a sophisticated treatment of test cycles because it did not push any engine or vehicle category close to the limits of cost-effective efficiency improvements. Rather, it relied on technologies that deliver fuel savings broadly across each category. The Phase 2 standards should take advantage of technologies more closely tailored to the intended application.

Phase 1 structure

Engine standards in Phase 1 require bench testing either (1) over a fixed drive cycle (the engine FTP cycle) or (2) on a steady-state test (the SET) that measures fuel consumption at 13 speed/torque points, depending on the type of vehicle in which the engine is to be installed. In both cases, the engine certification values are expressed in brake-specific terms (i.e., per unit of work done by the engine) rather than on a per-mile basis. Engine efficiency measured in this way does not provide direct information about the amount of fuel the engine will consume in use; that information depends on vehicle loads. In fact, brake-specific fuel consumption is an efficiency metric that could favor larger engines, even for applications in which a smaller engine would use less fuel over the appropriate duty cycle.

Additionally, the Phase 1 vehicle test does not produce a real-world fuel consumption value because the protocol tests vehicles with a fixed powertrain rather than with the powertrain sold in the vehicle. Furthermore, the test cycles used in Phase 1 do not adequately represent real driving behavior. The 55-mph and 65-mph steady-state cycles in Phase 1 are not representative of tractor trucks' cruise behavior. Trucks cruising at 65 mph do not actually travel at constant speed; rather, they exhibit some speed variability, which has important implications for fuel consumption (Clark 2013). Road grade, which has a major effect on fuel consumption, is also missing from the steady state test cycles. In the case of vocational trucks, the single transient cycle used in Phase 1 does not adequately represent driving patterns for even the most common applications.

Question: Given two technologically similar engines of different displacements, will the larger be more efficient according to the Phase 1 engine tests?

Full-vehicle standards

Full-vehicle testing or simulation can yield results close to real-world emissions if the test cycle is chosen appropriately. Vehicles' duty cycles vary widely, however, even within a vehicle type, so identifying an adequate set of test cycles is a challenge, particularly for vocational vehicles. In addition, the agencies' vehicle model would have to be enhanced to deliver adequate simulation capability (Sanchez 2013).

Choosing a set of test cycles will require balancing simplicity against accuracy. As noted above, the vehicle cycles used in Phase 1 are not adequate to capture important cycle features. However, introducing a large number of test cycles would complicate the standards without necessarily addressing the fact that the very same vehicle might be used in a variety of ways. One possible strategy to limit the proliferation of test cycles would be to create a small number of cycles that reflect the key features of all relevant driving behaviors including road grade. These cycles could be combined with varying weights to obtain reasonable approximations of a range of drive cycles.

Question: For full-vehicle certification, how many test cycles would be needed for adequate fidelity to real-world performance, and how would vehicles be assigned to those cycles?

COMPATIBILITY WITH CRITERIA EMISSION TESTING

GHG and criteria pollution standards for heavy-duty vehicles should be designed so that steps taken to meet standards for one pollutant do not lead to increased emissions of another pollutant. This is especially a concern for oxides of nitrogen (NO_x) and CO_2 from heavy-duty engines, which in some cases involve control strategies that directly conflict for the two pollutants (Krishnamurthy et al. 2007; ARB 2013)

Phase 1 structure

Engine fuel efficiency and GHG standards can make use of existing criteria pollutant test cycles and protocols, as was done in the Phase 1 program. In fact, Phase 1 requires no testing for engines beyond the testing already done for criteria pollutant emissions certification, because GHG emissions data can be collected at the same time. In addition to minimizing manufacturers' test burdens, this approach ensures that the two types of emissions are reduced simultaneously, at least over the test cycle, so that manufacturers will not meet one standard at the expense of the others.

On the other hand, new engine cycles may be required to adequately reflect the operation of today's vehicles. The FTP cycle represents driving behavior from the 1970s, when most vehicles had engines with lower-rated power than today, and most were equipped with mechanical fuel injection. Maximum vehicle speeds were much lower as well (Zhen et al. 2009). The SET measures steady-state performance, and thus does not capture transient emissions. Modern engines have gone through major changes in their operation, controls, and load patterns since these cycles were created.

Question: How does maintaining an engine GHG standard based on existing engine test cycles control emissions from engines operating in modes and areas of the engine map not fully represented in those cycles?

Full-vehicle standards

A full-vehicle standard would require testing over a vehicle cycle rather than an engine cycle. In that vehicle test cycle, the engine may be operating at points, or using controls, not represented in the existing engine test protocols, and where criteria pollutant emissions may be elevated. While engines are subject to in-use emissions caps (not-to-exceed or NTE levels), these caps do not apply over the entire engine map, and they far exceed emissions levels allowed for criteria pollutant certification.

Question: How can truck manufacturers ensure that the engine of a vehicle optimized to meet a full-vehicle GHG standard will not emit at levels exceeding the criteria pollutant standards in real-world operation?

PRACTICABLE COMPLIANCE AND ENFORCEMENT

Compliance and enforcement mechanisms are key elements of standards design. Compliance with the standards must be defined for the service life of the vehicle. Compliance verification must be robust, practicable, and repeatable, and it must not create an excessive burden on manufacturers, end-users, or the agencies.

Phase 1 structure

Certification of engines for CO_2 in Phase 1 follows the same process that is used for criteria pollutant emissions. However in-use compliance for GHG does not follow criteria pollutant protocols. For criteria pollutants, manufacturers test their engines using portable emission measurement systems (PEMS). The engines are tested in the vehicles, which drive over typical routes rather than a prescribed test cycle. Engine-out emissions must remain within the NTE limits established for each pollutant (EPA and NHTSA 2011a).

An NTE standard makes little sense for GHG, however, because the GHG standards seek to reduce emissions by percentages much smaller than the several-fold reductions typical of criteria pollutant standards. Manufacturers are required to submit CO_2 data from in-use testing, in both gallons per brake horsepower-hour and gallons per ton-mile, but these data are used for reference purposes only (EPA and NHTSA 2011a).

The in-use compliance mechanism for vehicle fuel efficiency and GHG standards in Phase 1 consists of verifying that GHG emissions technologies are installed and in service throughout the life of the truck (EPA and NHTSA 2011a). For tires, however, rolling resistance of replacement tires does not have to match that of the tires used to certify the vehicle.

Full-vehicle standards

It is unclear how in-use compliance would work for full-vehicle standards, given that such standards would be performance based rather than component based. Road testing could yield GHG values very different from the certified values, and, again, an NTE standard would not be useful. In addition, engine in-use compliance testing would not be available if engine standards were no longer in place. As one possible solution, in-use compliance might consist of verifying the validity of the inputs used to simulate the vehicle throughout its useful life.

Question: What in-use compliance mechanism could ensure that fuel consumption reductions measured during vehicle certification would persist throughout the life of the vehicle?

COMPLIANCE FLEXIBILITY

In the Phase 1 rule, the agencies showed how vehicles and engines of each type could achieve the standards cost effectively using available technologies. However manufacturers are free to use other technologies to meet the standards, and they will typically do so if they find technologies that achieve the standards at lower cost. However Phase 1 limits this flexibility in that the test protocols recognize only a subset of available efficiency improvements. Furthermore, engines and vehicles have to meet separate standards, which precludes balancing the improvement in each.

Phase 1 structure

Maintaining separate engine standards requires vehicle manufacturers to adopt new engine technologies even if available vehicle technologies deliver comparable fuel consumption reductions at lower cost. On the other hand, the Phase 1 standards for both engine and vehicle have been shown to be highly cost effective.

Question: How can a separate engine standard be justified if the out-year standard for the vehicle can be achieved less expensively using engines not meeting the engine standard?

Full-vehicle standards

Full vehicle standards will give vehicle manufacturers maximum flexibility in choosing the least expensive technologies to achieve a given fuel efficiency target.

Question: If engine improvements are not explicitly required through a standard, how could continuing investment in engine efficiency improvements be ensured?

LOW-COST TESTING

Costs associated with a change in the standards are an important consideration. We need information from both engine and truck manufacturers to compare the testing burden they would carry under each approach.

Phase 1 structure

The Phase 1 program was developed to minimize its cost burden.

Full-vehicle standards

Using simulation modeling instead of chassis testing to certify vehicle performance would substantially bring down the cost of implementing full-vehicle standards. Nevertheless full-vehicle simulation requires testing of components or systems that the model does not adequately represent based on specifications alone. Test results will have to be validated using on-road testing and other methods. Moreover, detailed performance information for engines, transmissions, and other complex components that might be used as inputs to a simulation model might be confidential business information that component manufacturers would be reluctant to release.

Question: What is the cost of providing the full range of input values for full-vehicle simulation? Is an engine fuel map good enough for high-quality simulation, especially given the importance of controls and transients in today's engines?

Additional Options

INTEGRATED ENGINE PLUS TRANSMISSION STANDARDS

A critical shortcoming of the Phase 1 structure is its inability to drive transmission improvements and the integration of engine and transmission. Instead of making a wholesale change to the program structure, this shortcoming might be addressed by replacing engine standards with standards for the engine and transmission together. In this scenario, integrated testing of engine and transmission in a test cell would replace engine bench testing. This approach would also capture hybrid benefits to a significant extent, although not entirely.

Although experiments are currently proceeding on testing engines and transmissions together, the cost and technical suitability of this approach are not fully understood. Modifications of the existing test cells could be costly and time consuming. A recent report by the International Council for Clean Transportation (ICCT) highlights the potential technical difficulties of such testing. The ICCT report observes that "engine test cell would require an electric alternating current dynamometer to accommodate the additional rotational inertia and speeds associated with the inclusion of the 'transmission' in the test setup" (Sharpe and Lowell 2012). On the other hand, one powertrain company reports having upgraded an engine test cell recently by replacing existing motors to accommodate the transmission in engine testing. They accomplished this upgrade in a short period without major capital investment (M. Dorobantu, senior manager, Eaton Corp., pers. comm., November 8, 2013).

Another complication is that, if the engine standards and testing are expanded to encompass transmissions, simultaneous certification for criteria pollutant emissions and CO_2 emissions will no longer be possible. The test cycles and protocols will need to be modified since the load on the engine and transmission together will be different from the load on the engine. Demonstration and validation of cycles for engine plus transmission will be a significant undertaking.

Integrated engine and transmission bench testing is not applicable to vehicles with manual transmissions, since an operator is needed to shift a manual. However, if the manufacturer could provide an automated manual version of its transmission, that should reflect transmission performance with an excellent driver. A standard loss of efficiency could be applied to reflect performance with an average driver.

Finally, the engine-plus-transmission approach does not fully address the need for an integrated full-vehicle test. Vehicle load reductions such as aerodynamic improvements and light-weighting could permit engine downsizing and other powertrain refinements, but the standards cannot drive these advances if the test protocols do not detect their benefits.

At the same time, engine-plus-transmission testing could prove essential if the test protocol does turn to full-vehicle simulation. It is unlikely that a simulation model used for regulatory purposes will be able to capture the increasingly fine-tuned engine/transmission interactions that are emerging today. Thus, simulation that permits a hardware-in-the-loop approach to the engine and transmission should be an option in a full-vehicle scenario.

Question: What are the costs associated with integrated engine plus transmission testing? What test cycles would be used?

COMBINED APPROACH

Because the strengths and weaknesses of engine testing and full-vehicle testing generally fall in different areas, it is worth considering whether using the two approaches together might constitute a viable option, one that addresses the shortcomings of each of the approaches used separately. This combined option would maintain separate engine standards as in Phase 1 while redefining vehicle standards to reflect the actual powertrain sold in the vehicle. A variation on this option would be to replace the engine standard with an engine plus-transmission-standard as described above, and to combine this measure with a full-vehicle standard.

One objection to a combined option is that it might result in double counting, because the efficiency of the engine would enter into both vehicle and engine standards. However the measures of efficiency reflected in the two standards are in fact quite different. Engine testing measures efficiency under a load normalized to the engine's rated torque and speed. Vehicle testing measures the efficiency of the engine (and other components and systems) under the load conditions imposed on the engine by the vehicle. Thus right-sizing of the engine and its efficiency at absolute load values enter into the vehicle test result.

In summary, a combined option would build on the Phase 1 approach, integrate actual engine, transmission, and vehicle parameters, and provide a path forward for engine manufacturers. On the other hand, it would limit truck manufacturers' compliance flexibility.

Conclusions

This paper has compared two options for structuring Phase 2 of federal heavy-duty GHG emissions and fuel efficiency standards:

- Option A. Continuing with the separate engine and vehicle standards of Phase 1
- Option B. Moving to an integrated full-vehicle standard

We also considered:

- Option C. An extension of the Phase 1 structure that replaces engine standards with standards for engine plus transmission
- Option D. A combination of Options A and B

Table 1 below summarizes the advantages and disadvantages of these four options. All of these options involve substantial and unresolved issues, and additional technical information will be required to determine how and if they can be resolved. This is the purpose of the questions we have asked manufacturers and others throughout the paper and consolidated in Appendix A.

Based on our analysis, Option D (separate engine and full-vehicle standards) looks the most promising. The primary purpose of the standards is to drive efficiency technologies for heavy-duty vehicles, and Option D’s superior performance on that criterion must be given extra weight. Option D also does as well as any in its ability to reflect real-world performance, another key criterion. Although the remaining criteria are important and could even pose insuperable obstacles to Option D and to some of the other options, the issues they raise are largely technical rather than fundamental, so it may be possible to solve them.

Table 1. Performance of structural options relative to six criteria

Criterion	A. Separate engine standards	B. Full-vehicle standards	C. Integrated engine + transmission standards	D. Separate engine and full-vehicle standards
Promotion of advanced technologies	+ Promotes engine technologies - Does not advance transmissions, hybrids, or integrating technologies	+ Promotes technology advances and integration throughout the vehicle + Promotes right-sizing of engine - Difficult to ensure progress on the engine or other components not produced by the truck mfr. - Allows backsliding on engine fuel efficiency and GHG emissions	+ Promotes engine and transmission technologies - Does not promote engine downsizing or integration of powertrain and vehicle	+ Advantages of A and B
Ability to reflect real-world performance	- Certification values do not relate directly to vehicle performance. - Current test cycles do not reflect operation of today's vehicles.	+ Certification values approximate actual performance over an appropriate cycle. - Unclear how test cycles could be chosen to capture range of real-world operation	- Disadvantages of A	+ Advantages of B - Disadvantages of B
Compatibility with criteria emissions testing	+ Uses criteria pollution certification testing	- No assurance of compatibility with criteria pollutant emissions reductions	- Simultaneous certification for criteria pollutant and CO_2 emissions no longer possible	+ Advantages of A

Criterion	A. Separate engine standards	B. Full-vehicle standards	C. Integrated engine + transmission standards	D. Separate engine and full-vehicle standards
Practicable compliance and enforcement	- Unsatisfactory in-use compliance mechanism for engines - Tire efficiency not assured for life of vehicle	- Protocol for in-use compliance undefined	- Disadvantages of A	- Disadvantages of A and B - Potential double counting of benefits from engine
Compliance flexibility	- Limits flexibility of vehicle manufacturers in choosing technologies to reduce fuel use	+ Allows vehicle manufacturers full flexibility to choose technologies to meet standard at lowest cost	- Disadvantages of A	- Disadvantages of A
Low-cost testing	+ No increase in cost	- Requires additional testing of components and systems to provide detailed simulation model inputs	- Modification of existing dynamometer testing is required to accommodate transmissions.	- Disadvantages of B

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Appendix A: Questions to Manufacturers and Others

What percentage of tractor-trailers could get full benefit from a bottoming cycle?

How could truck manufacturers translate a full-vehicle standard, defined in terms of grams or gallons per ton-mile, into a performance requirement for the engine manufacturer in such a way as to spur investment in advanced engine technologies?

Given two technologically similar engines of different displacements, will the larger be more efficient according to the Phase 1 engine tests?

For full-vehicle certification, how many test cycles would be needed for adequate fidelity to real-world performance, and how would vehicles be assigned to those cycles?

How does maintaining an engine GHG standard based on existing engine test cycles control emissions from engines operating in modes and areas of the engine map not fully represented in those cycles?

How can truck manufacturers ensure that the engine of a vehicle optimized to meet a full-vehicle GHG standard will not emit at levels exceeding the criteria pollutant standards in real-world operation?

What in-use compliance mechanism could ensure that fuel consumption reductions measured during vehicle certification would persist throughout the life of the vehicle?

How can a separate engine standard be justified if the out-year standard for the vehicle can be achieved less expensively using engines not meeting the engine standard?

If engine improvements are not explicitly required through a standard, how could continuing investment in engine efficiency improvements be ensured?

What is the cost of providing the full range of input values for full-vehicle simulation? Is an engine fuel map good enough for high-quality simulation, especially given the importance of controls and transients in today’s engines?

What are the costs associated with integrated engine plus transmission testing? What test cycles would be used?