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COMPARATIVE ASSESSMENT OF HEAVY-DUTY VEHICLE REGULATORY DESIGN OPTIONS FOR U.S. GREENHOUSE GAS AND EFFICIENCY REGULATION

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TABLE OF CONTENTS

SUMMARY

As the regulatory agencies in the U.S. work on the second phase of the heavy-duty greenhouse gas (GHG) and efficiency standards, one of the key decisions that will be made concerns the regulatory certification pathways. One of the most hotly debated topics for the upcoming rulemaking is whether to maintain two separate standards, one for the engine and one for the full vehicle, as was done in the first phase of the regulation. In addition, the agencies must decide what upgrades to the testing and certification procedures can be made based on lessons learned from the Phase 1 regulation. In this analysis we develop six possible options for certification, using Phase 1 and publicly expressed industry viewpoints as a guide. We then evaluate these options based on seven criteria that we developed to compare the certification procedures' relative merits.

The findings from this paper are (1) the benefits of maintaining separate engine standards outweigh any potential disadvantages; (2) physical testing of the powertrain (i.e., the engine plus the transmission) in a new test procedure will be necessary in order to capture and promote transmission and engine-transmission integration improvements; (3) some unique inputs about the actual powertrain in a vehicle are necessary in EPA's Greenhouse gas Emission Model (GEM) simulations to ensure that all fuel-saving technologies and approaches are properly incentivized and accounted for; (4) more research is needed to determine the appropriate level of engine information to input into GEM to properly credit all efficiency improvements while balancing resource constraints for both industry and government; and (5) a research plan that tracks and compares real-world engine, truck, and tractor-trailer efficiency with certification values for select, high-volume products in the 2015-2020 time period is warranted.

I. INTRODUCTION

With the second phase of U.S. heavy-duty vehicle greenhouse gas emission (GHG) and efficiency standards currently under development, the timing is ripe to work through various regulatory design and testing protocol issues that have evolved since the initial 2011 rulemaking. There is high motivation to develop impactful, cost-effective standards (White House, 2013). Many critical policy questions about regulatory design, test procedures, and technology inclusion require rigorous technical analysis.

Certification procedures—and, in particular, separate engine standards—were a major point of contention between various stakeholders during the regulatory development of the Phase 1 rule, and this debate continues on as the U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) weigh options for the Phase 2 standards. Namely, the crucial decision is whether or not to maintain the stand-alone program for engines. The market structure in North America in which there are large independent component manufacturers as well as vertically integrated vehicle original equipment manufacturers (OEMs) results in an inherent tension amongst these two types of companies. In general, engine manufacturers prefer a separate engine standard so that they have clarity regarding technology investments. Conversely, vehicle OEMs contend that engine standards disrupt their integrated design process and limit their ability to pursue the most cost-effective means of reducing fuel use and GHG emissions from the vehicles that they produce.

Another prominent question is about how best to design the regulation to promote not only engine and vehicle side improvements, but also credit transmission improvements within the core certification process. Transmission advancements and the benefits of deeper engine-transmission integration were not credited in the Phase 1 rule within the primary testing and certification framework. As a result, the development of updated test procedures and certification methods that are more comprehensive in capturing powertrain technology efficiency benefits is an issue of high importance to all manufacturers.

Yet another key issue is the linkage of GHG and criteria pollutant emissions standards. Eliminating the separate engine standard could divorce the two standards and open the door for the possibility of gaming (e.g., designing an engine control strategy that produces low oxides of nitrogen (NO_x) emissions over the engine cycles (i.e., Supplemental Emissions Test [SET] and Federal Testing Procedure [FTP]) but higher NO_x over vehicle cycles). On the other hand, standards should promote technologies and engine optimization strategies that will translate to real-world fuel savings. This is key for customer acceptance as well as overall societal benefit. In-use data suggests that the SET and FTP engine cycles have poor correlation to the operation of modern engines during real-world driving. These are all important considerations as the Phase 2 regulation is developed.

Table 1 summarizes some of the key arguments posited by both sides of the debate around the existence of separate engine standards. The question of maintaining separate engine standards is inextricably linked to a number of other broader considerations about testing and certification procedures assessed below.

Table 1. Key arguments for and against separate engine standards

For	Against
• Maintains linkage of criteria pollutants with CO_2 — minimizes the potential gaming situation in which an engine might be tuned for low NO_x/high CO_2 emissions during the engine SET and FTP cycles versus high NO_x/low CO_2 emissions over vehicle cycles and in-use operations • Uses existing test procedures — leverages the SET and FTP engine cycles, which industry is very familiar with, in order to minimize the testing burden • Acknowledges the current market structure — allows engines to be certified individually and sold into many different vehicle platforms. • Drives improvements in engine *and* vehicle technologies — provides engine technology investment clarity for both independent engine manufacturers and vertically integrated vehicle manufacturers	• Promotes non-optimal powertrain design — separate engine standards fail to consider the impact of engine requirements on vehicle design and vice versa. • Limits compliance flexibility — vehicle OEMs may not be able to pursue the most cost-effective pathway to compliance • Perpetuates inappropriate test cycles — engines are optimized to the FTP and SET certification cycles, which appear to no longer accurately represent in-use driving • Correlates poorly to in-use results — improved efficiency that is evidenced on the engine test bench may not translate to real-world fuel savings

Recent public comments from several industry stakeholders provided input on their positions on regulatory design. In July of 2014 NHTSA announced their intention to prepare an Environmental Impact Statement for New Medium and Heavy Duty Vehicle Fuel Efficiency Improvement Program Standards and comments were then made publically available on the public docket (Regulations.gov, 2014). Several major manufacturers submitted public comments related to regulatory design. Volvo and Daimler do not support the continuation of separate engine standards into the Phase 2 regulation (Daimler, 2014; Volvo, 2014). Their concerns regarding separate engine standards include the danger of forced implementation of unproven technologies that could cause market disruptions, and that manufacturers should have the flexibility to select the most cost effective approach to meeting the standards. They also highlighted the need to properly credit efficiency improvements and that the standards must drive real-world benefits. As opposed to the stance taken by Volvo and Daimler, Cummins asserted their support of the continuation of separate engine standards (Cummins, 2014). Their reasoning focused on maintaining the link to criteria pollutants and advancing technology in all areas of the vehicle. In addition, similarly to Volvo and Daimler, they discussed the need for the standards to be enforceable and result in verifiable in-use reductions in fuel consumption.

II. EVALUATION CRITERIA FOR TEST AND CERTIFICATION PROCEDURES

Prior to describing the set of options that we developed for this analysis, we present our high-level principles by which we evaluate the relative merits of each of the testing and certification alternatives. Table 2 describes the seven criteria that we develop and use for this evaluation to assess the regulatory design options. These criteria, as defined in the table and throughout the discussion below, incorporate what we believe are the highest principles for an optimal regulatory design. The table also provides some additional details about the specific issues that each criteria addresses. It is understood that different stakeholders will value and weight the various criteria differently. But we believe that the criteria taken as a whole represent the features sought in a regulatory certification process from a broader stakeholder, societal, and industry perspective.

Table 2. Criteria for evaluating certification pathways

Criterion	Issues addressed
1. Credit technology improvements. Ensure any efficiency technologies that provide fuel savings and GHG reductions can be accounted for their relative benefits.	• Technologies such as deep engine-transmission integration can allow manufacturers to downsize and downspeed engines for increased efficiency. If certification procedures do not exist that credit these improvements, this could impede such developments as well as lessen the overall benefits of the rule. The Phase 2 rule is an important opportunity to capture, credit, and promote these types of efficiency improvements.
2. Technology investment. Ensure promotion of long-term efficiency investments in the engine, transmission, as well as in vehicle-level systems.	• The structure, stringency, and flexibility mechanisms of the regulation would ideally require manufacturers to invest in efficiency technologies across the entire vehicle. If the regulation procedure (and associated regulatory stringency) do not require development in all areas, innovation and investment toward long-term vehicle efficiency goals could be lost.
3. Acknowledge market structures. Individual engines and powertrains can be sold into multiple different vehicle platforms.	• Heavy-duty vehicles are highly customized to fulfill specific missions, and the strong presence of independent component suppliers in the North American market allows customers to mix/match brands of engines, transmissions, and vehicle bodies. A regulatory process that does not allow individual certification of engines and powertrains could have unintended market consequences.
4. Real-world confidence. End users, society, and regulators have confidence that the efficiency improvements over the regulatory test procedures result in comparable and durable real-world fuel savings and GHG benefits.	• Regulatory engine and vehicle cycles increasingly do not reasonably reflect modern in-use heavy-duty vehicle operation in terms of engine speed/load and grade effects. The perpetuation of non-representative cycles could reduce the value of the certification results to all stakeholders. • The certified fuel efficiency of a vehicle, as calculated in GEM, would ideally reflect comparable efficiency to in-use, real-world operations. This will ensure minimal divergence between manufacturer's new products and end users' expectations and generally greater acceptance of any costs associated with the rule.
5. Cost-effective. Encourage cost-effective technology deployment decisions.	• Manufacturers are able to pursue the unique technology packages for their product lines that are most cost-effective in terms of value proposition to end-users and from a certification perspective.
6. Minimize regulatory burden. Test procedures and enforcement provisions that minimize the burden for government and regulated entities.	• Certification results that are reasonably accurate and representative of real-world operations are balanced with testing and compliance pathways that minimize testing and simulation costs, as well as the verification burden for the regulatory agencies.
7. Accord with criteria emissions. Ensure that fuel consumption and GHG targets are met without compromising very low in-use criteria pollutant emission levels.	• Strategies to reduce NO_x emissions often interact with CO_2 emission performance, and vice versa. As engines and emission control systems become increasingly sophisticated, it is important that the GHG regulation is designed such that both CO_2 and NO_x are reduced during in-use operations.

III. ASSESSMENT OF CERTIFICATION OPTIONS

DESCRIPTION OF SIX OPTIONS FOR CERTIFICATION

For this assessment, we develop a set of six testing and certification pathways that represent potential alternatives for the Phase 2 regulation. A summary illustration of the six options for testing and certification pathways is shown in Figure 1. As shown in the figure, pathways with similar characteristics are grouped by row, column, and color. Options 1 through 4 in the top row outlined in blue include separate engine standards, whereas Options 5 and 6 in the bottom row in yellow do not. In Options 3 and 5 (green), engine mapping is based on the SET and FTP engine cycles. In Options 4 and 6 (red), engine mapping is based on a new, yet-to-be-determined procedure. After describing each of these pathways below, we compare the options according to the criteria that are outlined in the previous section. A summary of the mandatory and optional elements of each Option is found in Table 3.

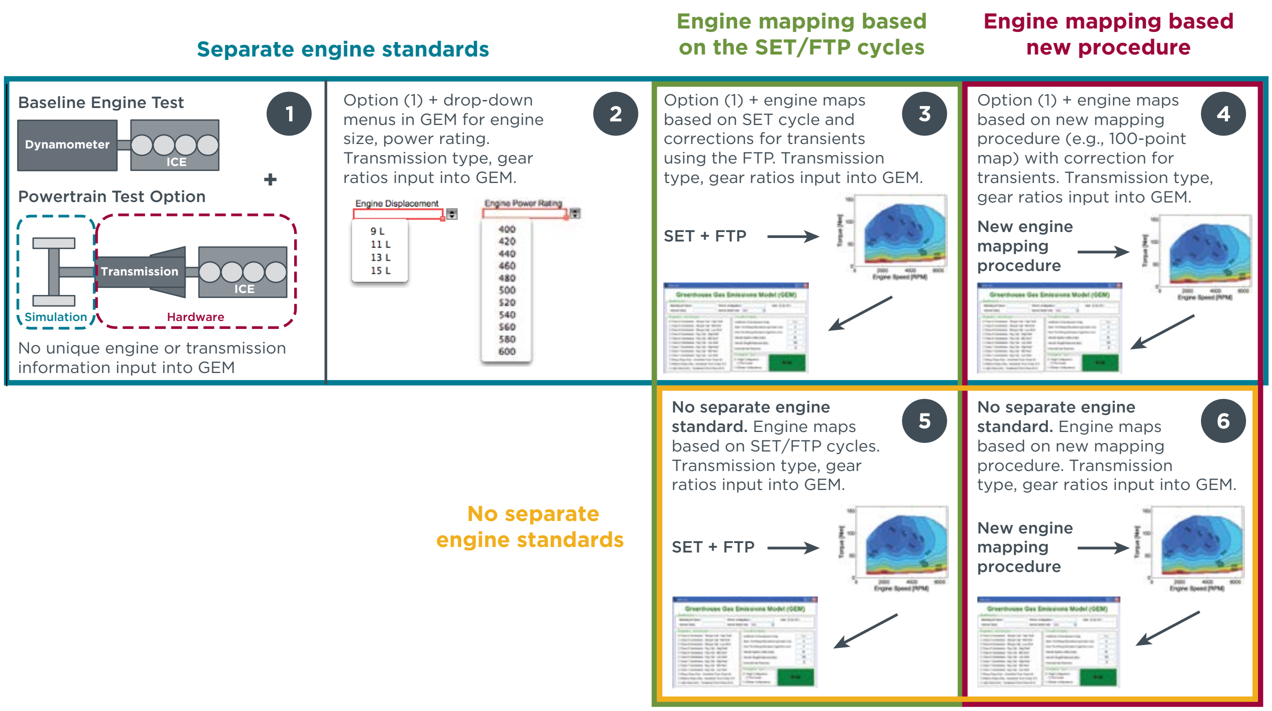

Figure 1. Illustration of six certification pathways considered in this analysis.

Baseline: *Separate engine standards; no unique engine or transmission information input into GEM.* The baseline option, which is not depicted in Figure 1, is equivalent to maintaining the exact same certification pathway as in Phase 1. In the Phase 1 regulation there are separate vehicle and engine standards for Class 7 and 8 tractor trucks as well as vocational vehicles. Engine manufacturers are subject to the engine regulation, and vehicle manufacturers are required to install certified engines in their vehicles. In addition, vehicles manufacturers are required to certify these vehicles using a computer simulation program (the Greenhouse gas Emission Model or "GEM") that evaluates design elements such as the vehicle's aerodynamic features and the rolling resistance values of its tires. The GEM simulation model does not include any information about the vehicle's actual engine or transmission. Standard values are used for engine fueling maps and an optimized manual transmission is incorporated as the shifting model.

Engines are certified using the SET cycle (for tractor trailer engines) and the FTP cycle (for vocational engines). Vehicles are certified in GEM using the steady state 55mph and 65mph cycles and the ARB transient cycle. The simulation results of the three cycles are weighted depending on vehicle type.

Option 1: Separate engine standards; no unique engine or transmission information input into GEM; powertrain testing option; updated engine and vehicle cycles. This option is very similar to the approach taken in the Phase 1 regulation. The engine and vehicle are subject to distinct sets of standards, and GEM utilizes generic engines and transmissions to generate the final fuel consumption and CO_2 results. The two primary departures from the Phase 1 approach is that (1) manufacturers may opt to test the combined engine plus transmission on a *powertrain* dynamometer and use those results to 'correct' the GEM simulation and (2) both engine and vehicle duty cycles will be upgraded to better reflect real-world operations.

As an option for powertrain testing is a key component of all of the options in this analysis, a description of a powertrain dynamometer and the approaches for conducting a powertrain test are useful context. A description of the powertrain testing approach proposed here is detailed in Box 1 and Figure 2. As shown in the figure, the powertrain result would be divided by the GEM result for a given powertrain and vehicle combination to give a dimensionless correction factor. For example, a powertrain test that had a 3% improvement over the respective GEM result would generate a correction factor of 0.97. The correction factor can then by multiplied by the resulting output from GEM simulation modeling for any vehicle utilizing that powertrain in order to credit improvements made by improved powertrain technologies and advanced engine/powertrain integration.

In addition to this voluntary procedure for using powertrain testing to correct GEM results, an additional feature of all of the certification options is updated regulatory test cycles for both engines and vehicles. The SET cycle, which is used for tractor engine certification in the Phase 1 regulation, was developed many years ago to simulate how an engine operates during steady-state (i.e., constant speed) conditions. The cycle is a progression of testing at 13 speed/load points, and each of these points is weighted to yield an overall emissions result. As engines and vehicles have continued to evolve, recent in-use data suggests that the SET cycle weightings are increasingly inaccurate in their representation of the real-world operation of modern tractor-trailer engines, which tend to operate at lower engine speeds. Specifically, it was widely acknowledged by industry stakeholders that many modern engines are operated only a small fraction of the time at or near the 'C' points as compared to these points' relatively heavy weighting in the current SET cycle (Lutsey et al, 2014). To mitigate this issue, one potential solution is to assign new weighting factors for each of the 13 points based on recent in-use engine data. In this approach, the re-weighted SET cycle would be a much better representation of modern engine operation, and the agencies would avoid the arduous task of developing an entirely new cycle and set of test points. As discussed in more detail below, we acknowledge that further research should be conducted to examine how the current SET cycle weightings compare to recent engine data and determine the extent to which new weightings would impact engine CO_2 results.

The current steady state (55mph and 65mph) GEM vehicle cycles are also not fully reflective of real-world driving. The main issue is that the cycles have completely flat road grade profiles, which is not only un-representative of real-world driving, but also leads to the cycles running at only one speed-load point on the engine map during the entire GEM simulation. In addition to more accurately simulating in-use conditions, the introduction of grade into the vehicle cycles would more properly credit technologies that take advantage of and/or anticipate changes in elevation. For example, in tractor certification, hybridization and predictive cruise control would likely have little to no fuel consumption and GHG benefits if the simulation is done using cycles with flat grade. As with engine cycle evaluation, the inclusion of grade in the GEM regulatory cycles is a very important area for research in support of the Phase 2 rulemaking.

Option 2: Separate engine standards; drop-down menus for engine and transmission specifications in GEM. This pathway builds off of Option 1. The key addition is that manufacturers are required to input information about the actual engine and transmission used in the vehicle via drop-down menus in GEM. For engines, this includes the displacement size (e.g., 13 liters) and nominal power rating (e.g., 450 hp). Manufacturers also select the type of transmission (e.g., manual, automated manual, etc.) as well as gear ratios from drop-down menus. The different combinations of inputs from the drop down menus will adjust the fuel map and shifting strategy used during the GEM simulation run for each unique vehicle model.

There are three reasons for including this unique powertrain information in GEM: 1) to credit the manufacturers for any fuel savings that are the product of engine downsizing and downspeeding, 2) to credit any benefits that result from the use of an advanced transmission such as an automated manual transmission (AMT) or dual clutch transmission, and 3) to make the GEM simulation results more accurate.

As with Option 1, manufacturers may choose to physically test the powertrain in a powertrain-in-the-loop configuration and go through the GEM correction process outlined in Figure 2 (See Box 1). For Option 2 to be viable, the results generated using the powertrain drop-down option would likely need to be somewhat conservative. Otherwise, if manufacturers received too much credit from the default engine-transmission in GEM, there is little incentive to conduct powertrain testing to physically demonstrate improvements as compared to these default GEM results.

Option 3: Separate engine standards; engine maps based on simplistic procedure input into GEM along with drop-down menus for the transmission. Building on Option 2, this option forgoes the drop-down menu approach for engine specifications as described in Option 2 and instead relies on engine mapping inputs into GEM. To minimize the testing burden on manufacturers in developing engine maps, one potential approach is to create basic maps based on the steady-state SET cycle (or some simplistic variant of the SET cycle), with corrections for transients based on the FTP cycle. The manufacturers will already be testing their engines over these cycles for compliance with emissions certification, so this option will minimize additional testing for the manufacturers. Due to the relatively limited number of speed and load points in the SET cycle (13 points), this engine map would likely only be a first-order approximation of a unique engine. However, in this analysis we assume that even a simplistic map could provide more accurate results than the default engines employed in Option 2. As with the previous two options, the manufacturer can opt to perform a powertrain test to correct the GEM results, as applicable, for powertrain efficiency technologies.

Option 4: Separate engine standards; engine maps based on sophisticated mapping procedure input into GEM along with drop-down menus for the transmission. As shown in Figure 1, Option 4 is the final pathway in this analysis with a separate engine standard. The only difference from Option 3 is that the method for generating engine maps is now more sophisticated. For this option, the agencies need to create (or adopt) a new engine mapping procedure. For example, a 100-point engine map with rigorous correction method for transients would provide improved accuracy compared to the maps from derived from the SET and FTP cycles. This type of sophisticated mapping approach is currently being developed for the European Commission, which is in the process of establishing test procedures and a vehicle simulation model (the Vehicle Energy Consumption calculation Tool or "VECTO") that will be used to certify heavy-duty vehicle CO_2 emissions as part of the type-approval procedure. As with the previous options, manufacturers choose the transmission type from a drop-down menu and have the choice to conduct powertrain testing at their discretion.

Option 5: No separate engine standards; engine maps based on simplistic procedure input into GEM along with drop-down menus for the transmission. Option 5 is a major departure from the previous pathways in that there is no separate engine standard. Engine information will be included in the GEM certification procedure, but no separate standard will exist for engines. As shown in Figure 1, the approach for developing engine maps is identical to that of Option 3. As before, manufacturers have the option to perform a powertrain test to correct the GEM results, as applicable.

Option 6: No separate engine standards; engine maps based on sophisticated mapping procedure input into GEM along with drop-down menus for the transmission. This final pathway is identical to Option 5, except that, as with Option 4, engine mapping is based on a yet-to-be-determined rigorous test method.

POWERTRAIN TESTING

Background — A powertrain dynamometer test differs from a traditional engine dynamometer test in that it requires a dynamometer that can accommodate the additional rotational inertia and speeds associated with the inclusion of the transmission in the test setup. In practical terms, a powertrain test cell needs to have the power absorption capabilities of a traditional heavy-duty chassis dynamometer, but with the power absorbers connected directly to the transmission output shaft, rather than to rollers that support the drive wheels of the test vehicle. There are typically two strategies for testing a powertrain in a dynamometer test cell. In the first strategy, the physical engine and transmission are linked to computer-simulated models of the remaining vehicle systems. In this *powertrain-in-the-loop* simulation (PILS), the powertrain is exercised using a vehicle duty cycle. In this PILS approach, the engine and transmission operate as if they were in an actual vehicle. This PILS method requires inputs for all of the other non-powertrain components (vehicle weight, aerodynamic drag coefficient, tire rolling resistance, etc.). The second strategy aims at generating speed and torque at the output shaft of the transmission that will cause the engine to mimic the same operation it would experience during a specific engine certification duty cycle. In this setup, there is no need for virtual vehicle parameters since there is only physical hardware being tested. Since the speed and torque used in engine test cycles are not suitable for powertrain testing (because they simulate torque-speed characteristics at the *engine* output shaft), a test cycle that simulates torque-speed characteristics at the *transmission* output shaft is required for this strategy. Of the two methods described here, the PILS strategy will do a much better job producing results closer to what would be experienced under real-world operation. In addition, this technique allows for the GEM vehicle cycles to be utilized as described below. For those reasons, the test procedure proposed below will focus on utilizing the PILS technique.

Test Description — This description covers a voluntary option for evaluating the benefits of enhanced engine-transmission integration and improved powertrain efficiency by physically testing the combined engine and transmission. Figure 2 shows a schematic of how powertrain testing can be used to generate a correction factor, which can then be used to correct the GEM outputs. The test involves an A to B comparison between GEM results (simulated generic vehicle and *simulated* powertrain) and PILS results (simulated generic vehicle and *physical* powertrain). If both tests are run over the same GEM cycles and using the same vehicle characteristics, then the A to B comparison should result a correction factor that corrects for improvements in the powertrain that are not accurately modeled in GEM. As shown in the figure, the powertrain result would be divided by the GEM result for a given powertrain and vehicle combination to give a dimensionless correction factor. For example, a powertrain test that had a 3% improvement over the respective GEM result would generate a correction factor of 0.97.

The Correction Factor — The correction factor that is generated using generic vehicle parameters can then be used to correct GEM results for any vehicle which meets the following criteria: (1) employs that exact powertrain combination and (2) is certified on the same set of GEM test cycles over which the correction factor was generated. The correction factor would by multiplied by the resulting output from GEM simulation modeling in order to credit improvements made by improved powertrain technologies and advanced engine/powertrain integration.

The choice of what vehicle parameters to use in the GEM and PILS test to generate the correction factor, as well as further specifying the testing protocol are important issues that require further exploration.

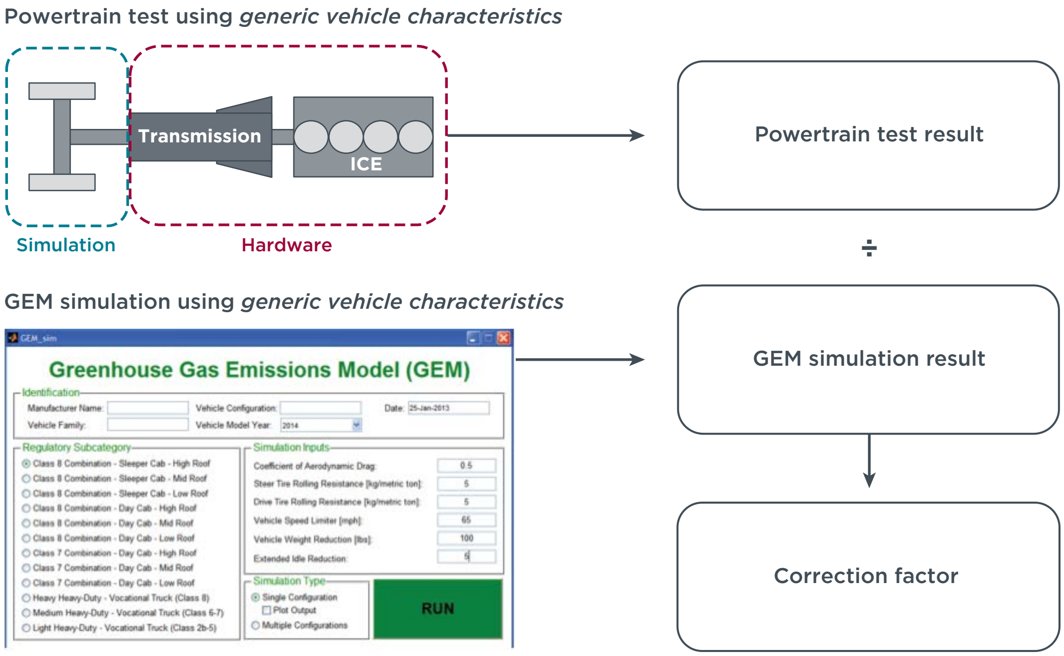

Figure 2: Using powertrain and engine tests as a voluntary procedure to obtain a correction factor for GEM results to account for efficiency improvements due to advanced powertrain technology and integration

Table 3. Mandatory and optional elements of each option

Option	Mandatory elements	Optional elements
Baseline	• Engine certification • GEM certification	Innovative Technology Credit using agency-approved test method
1	• Engine certification • GEM certification	Powertrain test — Correction factor for GEM result
2	• Engine certification • GEM certification	Powertrain test — Correction factor for GEM result
3	• Engine certification • GEM certification • Basic engine map	Powertrain test — Correction factor for GEM result
4	• Engine certification • GEM certification • Advanced engine map	Powertrain test — Correction factor for GEM result
5	• GEM certification • Basic engine map	Powertrain test — Correction factor for GEM result
6	• GEM certification • Advanced engine map	Powertrain test — Correction factor for GEM result

EVALUATION OF TESTING AND CERTIFICATION OPTIONS

It is difficult to compare the six testing and certification options on a rigorous quantitative basis. To compare the options we develop a evaluation framework based on the criteria outlined earlier in the paper. As described above these criteria are defined to incorporate the highest principles for an optimal regulatory design. In this approach, we assign each of the six options a score according to their merits on each criterion. Given the qualitative nature of this scoring system, the overall purpose of this comparison is not to identify a single 'winner,' per se. Rather, the objective of this analytical framework is to identify a set of *preferred* options that score well on a range of criteria and then qualitatively assess the merits of this sub-set of preferred options.

The system of symbols for the scoring system to evaluate the six options for the seven criteria is defined as follows —

- Option does not fulfill criterion at all: **—** ("*one-minus*")
- Option is sufficient in satisfactorily addressing the criterion, but there could potential be issues: **~** ("*neutral*")
- Option addresses the criterion well, and there is less opportunity for issues or uncertainty: **+** ("*one-plus*")
- Option addressed the criterion very well, and there is little opportunity for issues or uncertainty: **++** ("*two-plus*")

Table 4 summarizes the scoring for each of the six certification pathways. As shown, none of the options are clearly superior across all of the parameters, which attests to the difficulty that the agencies face in making a decision about certification pathway(s) for the Phase 2 regulation. We take each of the criteria in turn, moving from left to right in the table.

Table 4. Comparison of options for certification pathways in the Phase 2 regulation based on seven criteria

Test procedure and certification pathway option†	Properly credits all efficiency improvements	Promotes improvements in all technology areas	Acknowledges market structures	Provides confidence of real-world savings	Encourages cost-effective technology investment	Minimizes compliance burden	Linked to criteria pollutant standards
Baseline: Phase 1	–	–	+	–	~	+ +	+ +
1. Engine test + powertrain test option*	~	+	+	~	~	+	+
2. Option (1) + drop-down menus for engine size and power in GEM**	+	+	+	~	~	+	+
3. Option (1) + engine maps derived from SET/FTP input into GEM**	+	+	+	+	~	+	+
4. Option (1) + engine maps derived from new mapping procedure input into GEM**	+ +	+	+	+ +	~	~	+
5. Full simulation with engine maps derived from SET/FTP input into GEM**	+	~	–	+	+ +	+	~
6. Full simulation with engine maps derived from new mapping procedure input into GEM**	+ +	~	–	+ +	+ +	~	~

† For all of the options manufacturers have the ability to perform a powertrain dynamometer test and use these results to 'correct' the GEM results to properly account for the efficiency improvements due to engine-transmission integration. See Figures 2 and 3.
* No unique engine or transmission information entered into GEM
** Manufacturers choose transmission type from a drop-down menu and enter transmission gear ratios

Scoring system:

» Option does not fulfill criterion at all: – ("*one-minus*")

» Option is sufficient in satisfactorily addressing the criterion, but there could potential be issues: ~ ("*neutral*")

» Option addresses the criterion well, and there is less opportunity for issues or uncertainty: + ("*one-plus*")

» Option addressed the criterion very well, and there is little opportunity for issues or uncertainty: ++ ("*two-plus*")

1. Ensure any efficiency technologies that provide fuel savings and GHG reductions can be accounted for their relative benefits. In Phase 1, there is no mechanism for accounting for the benefits from a number of efficiency technologies (e.g., transmission technologies) aside from pursuing "innovative technology" credits, which are outside typical certification test, require additional work, and involve uncertainty. In Phase 2, ideally the addition of an optional powertrain test with clearly defined certification procedures would directly capture transmission-related benefits. Although the powertrain testing would still be optional, the test could be integrated into the rule in such a way that it would be utilized on a more regular basis than the innovative technology credits allowed in Phase 1. In addition, an ideal regulatory design would involve a series of options that require varying levels of powertrain information to be directly input into the GEM simulation. The scores in Table 4 reflect the level of engine and transmission detail that are required to be input into GEM. All of the options are identical in terms how vehicle-level technologies (e.g., aerodynamics, tire rolling resistance, weight reduction, etc.) are evaluated in GEM.

In Option 1 no information about the actual engine and transmission is entered into GEM, and thus this option cannot easily credit and promote manufacturers' powertrain advancements. However, manufacturers have the option to perform a powertrain test in order to receive any credit for powertrain improvements. For that reason, this option is given a *neutral* score for this criterion. Looking at the remaining five options, the two options (Options 4 and 6) that utilize a sophisticated engine fuel map are scored *two-plus*, with the remaining three options as *one-plus*. Presumably, a more rigorous method for engine mapping will yield simulation model results that more closely match actual engine operations, and thus, will do a better job of accurately crediting the benefits of fuel-saving technologies.

2. Ensure promotion of long-term efficiency investments in the engine, transmission, as well as in vehicle-level systems. Again, since all of the options are more-or-less interchangeable in terms of the evaluation of vehicle-level technologies, the focus of this criterion is the extent to which each option promotes efficiency improvements in engine and transmission technologies. It should be noted that the stringency level of the rule will be the ultimate driver of technology promotion, but that separate engine standards are a critical subpart of the stringency question. As shown in Table 4, Options 1 through 4—that is, the options with a separate engine standard—score *one-plus* whereas the remaining two options are given a *neutral* score. A separate engine standard provides a clear market signal and roadmap for engine efficiency improvements, and it ensures that engine technologies will be developed and deployed. Without an engine program, there is no such certainty that manufacturers will invest in long-term engine technology research and development due to the fact that they may be able to select vehicle (i.e., non-engine) technologies that could meet the standard (again, this depends on stringency). For this reason, Options 5 and 6 are designated as *neutral*.

3. Acknowledges current market structures. Without a separate engine standard, an engine is tied to a specific vehicle, since the fuel consumption and CO_2 for that vehicle are intrinsically dependent on both the engine and vehicle specifications. This causes difficulties when engines are sold separately from vehicles (for example, to be used to repower existing chassis). In addition, the HDV OEMs in the US are not all vertically integrated. End users are able to purchase a truck chassis from one manufacturer with an engine and a transmission manufactured by separate companies. There are chassis manufacturers who do not produce engines and engine manufacturers who do not produce chassis. If the final vehicle OEM is the only regulated entity it could limit the recourse that the vehicle OEM might have if the engine does not perform as expected during certification testing. As such, Options 5 and 6, the two options without an engine standard, are given *one-minus* scores.

4. End users, society, and regulators have confidence that the efficiency improvements over the regulatory test procedures result in comparable and durable real-world fuel savings and GHG benefits. For this criterion, we seek to differentiate the options based on their ability to accurately represent the benefits of fuel-saving technologies. As before, the focus is on engine and transmission technologies. Among the six options, Options 1 and 2 are scored *neutral* since these options rely on default powertrain inputs, though in Option 2, these defaults are based on drop-down menus and could be made to represent the powertrain more accurately. Options 3 and 5, which have some level of unique powertrain information, are assigned *one-plus* scores, whereas Options 4 and 6, which employ detailed engine mapping methods, are scored *two-plus*.

5. Encourages cost-effective technology deployment decisions. For this criterion, we distinguish the six pathways by the manufacturer's ability to pursue whatever combinations of technology packages for their product line that provides them with the necessary efficiency improvements to achieve overall compliance with the rule. This comparison is similar to the 'acknowledges the current market structure' criterion in that there is a polarity between the sets of options that have and do not have separate engine standards. In this case, the options without the separate engine standards are scored *two-plus,* while those options with an engine standard are *neutral*. From the point of view of a vertically integrated manufacturer, an engine standard limits their compliance flexibility, since it imposes compulsory engine improvements. Even if the manufacturer would actually prefer to seek a lower level of engine efficiency improvements for its product line, an engine standard requires a manufacturer to achieve a sales-weighted average level of engine improvements over the course of the regulation. However, there are competing industry statements about which technologies — engine or otherwise — are the most cost effective (e.g., in terms of incremental technology cost per percent fuel use reduction), but there is a lack of new transparent public research on the subject. More research is needed to properly assess the cost-effectiveness of the wide range of technologies under consideration for the post-2020 timeframe, but available data indicates that there is significant overlap in available engine and vehicle technology improvement cost-effectiveness (e.g., see NRC, 2010). For this reason, Options 1 through 4 are given *neutral* instead of *one-minus* scores.

6. Minimizes the compliance burden for government and regulated entities. Here, we compare each of the pathways by the estimated burden imposed by testing and certification activities. In progressing from Option 1 to 3, there is presumably additional effort required as incremental information about the powertrain is needed for input into GEM. However, since these options require little (i.e., Option 3) or no (i.e., Options 1 and 2) additional physical testing, all three options are scored *one-plus* as a simplification. Option 5 employs an identical fuel mapping procedure to Option 3, and therefore is assumed to require a comparable amount of resources for testing and certification. Even though Option 3 has a separate engine standard and Option 5 does not, since the engine CO_2 testing is currently carried out simultaneously during criteria pollutant measurement, Option 5 does not represent significant resource savings in terms of test procedure costs. As such, Option 5 is also scored as *one-plus*. We assume that the detailed engine fuel maps needed for Options 4 and 6 will require additional engine dynamometer time as compared to the other options, so these two options are scored *neutral*.

7. Ensure that fuel consumption and GHG targets are met without compromising very low in-use criteria pollutant emission levels. In this final point of comparison, we assess the extent to which the options require manufacturers reduce CO_2 and criteria pollutants simultaneously. As with the ‘acknowledges market structure’ and ‘cost-effectiveness’ criteria, the analysis here splits cleanly according to the existence of an engine standard. Our analysis assumes that the agencies will be updating the engine regulatory cycles for CO_2 certification to better reflect real-world operations. Because the criteria pollutant program is a separate regulation, there is a chance that in updating the cycles for the Phase 2 rule, there could be a temporary disconnect between the engine cycles used in the GHG and criteria pollutant regulations. As such, Options 1 through 4 are scored *one-plus* instead of *two-plus*. Though Options 5 and 6 do not have an engine standard, there are engine CO_2 provisions that could be added to these options to help to retain a linkage to the criteria pollutant standards. For example, requiring each engine class to achieve at least a minimum level of CO_2 emissions (i.e., a separate “backstop” regulation for engine CO_2 within the overall Phase 2 program) is a stipulation that could augment Options 5 and 6 in this area. As such, these two options are scored *neutral*.

SUMMARY OF ASSESSMENT

Overall, when looking at the distribution of scores across the Table 4, Options 2, 3, and 4 have the largest number of advantages (i.e., plus signs) and least potential disadvantages (i.e., no minus signs). Since the objective of the exercise is to determine the preferred set of options rather than a single winner, Options 2, 3, and 4 seem to emerge as the preferred tier of regulatory design pathways in this analysis. These three are the options that have a separate engine standard and also require data inputs about the actual engine and transmission in the GEM simulations. Looking at these three options, it is difficult to assess the marginal benefits of increasing levels of sophistication with regard to representing the engine in GEM. Further recommendation according to modeling complexity, the accommodation of engine map inputs, and the accuracy of results with respect to powertrain improvements between Options 2, 3, and 4 would require further analysis.

In summary, we recommend that the Phase 2 regulation maintain a separate program for engines and that the GEM model require some level of input about the unique engine and transmission used in the vehicle. We also recommend that a method for physical testing of advanced powertrains be integrated into the rule as an option, yet in such a way that it will be utilized extensively. By continuing their efforts to analyze the costs and benefits of increasing the complexity in GEM with respect to representing the actual engine and transmission, the agencies can design a powertrain modeling approach in GEM and an overall certification approach that properly balances complexity, accuracy, and the overall burden for both manufacturers and the regulatory agencies.

IV. ADDITIONAL CONSIDERATIONS

In addition to the above comparison based on our foundational principles stated in the development of the seven primary criteria above, there are some further criteria that are important in the analysis of certification pathways. In the discussion of the seven additional issues below, we assume that there is a separate engine standard and that unique powertrain inputs are required in GEM.

Stringency. As with the Phase 1 program, the overall stringency of the Phase 2 regulation as well as the relative stringency of the engine and vehicle standards are pivotal decisions. The agencies, along with a number of diverse stakeholders, are engaged in technology potential and cost analyses that will help to inform the set of technology packages that will ultimately be promoted in this rulemaking. The agencies, and other research groups like the ICCT, are developing modeling tools that will allow further investigation into technology efficacy and the interactions between technologies across a range drive cycles. A very strict engine standard and relatively modest vehicle standard could lead to a deficiency in investment in vehicle technologies, and vice versa. A review of various studies (e.g., NRC, 2010), as well as private communications with industry representatives, indicates that the incremental costs and benefits of technologies for the Phase 2 timeframe suggest that various engine- and vehicle-level technologies have overlapping ranges of cost-effectiveness (e.g., cost per fuel saved). There are vehicle technologies that are more cost-effective than engine technologies and engine technologies that are more cost-effective than vehicle technologies. As such, well-designed and balanced stringency targets for both the engine and vehicle standards will drive technology development and deployment across all technology areas, powertrain and vehicle alike.

Confidentiality. To properly credit all efficiency improvements and better represent real-world operations, we recommend that in addition to a separate engine standard, the GEM simulations require some level of input for the unique engine and transmission used in a given vehicle model. Two of the options we evaluated with a separate engine program require that manufacturers provide engine fuel maps as a GEM input. There are concerns that this is proprietary information, and requiring these fueling maps would prompt the need for the necessary controls and software infrastructure to ensure that this confidential business information (CBI) is properly secured. For managing CBI data, the agencies can draw on the experiences from both the Phase 1 regulation as well as the criteria pollutant emission program. By designing a robust interface for manufacturers to input unique powertrain information and adequate controls to ensure confidentiality, the agencies can mitigate stakeholder concerns of using CBI engine fuel map data.

Hybrids. Advanced technology heavy-duty vehicles such as hybrids present unique regulatory challenges. Hybrids employ an additional energy source in conjunction with an internal combustion engine for motive power, and the interactions between the engine and the hybrid components affect criteria pollutant emissions and fuel consumption. Often, an engine installed in a hybrid vehicle will operate very differently from the same engine installed in a conventional vehicle driven over the same route. One of the difficulties in integrating vehicles such as hybrids into regulatory programs is developing the proper certification test procedures for criteria pollutant and greenhouse gas (GHG) emissions so that these advanced technologies and vehicles are evaluated fairly and consistently as compared to their conventional counterparts.

Given the difficulty of evaluating hybrid systems in an accurate and equitable manner in simulation, hybrids are a good candidate for PILS testing. In this PILS set-up, the engine, hybrid components (e.g., the energy storage systems, motors/generators, controllers, etc.), and transmission are all tested as hardware.

The Working Party on Pollution and Energy (GRPE), which is an entity of the United Nations Economic Commission for Europe (UNECE), has an Informal Group on Heavy-Duty Hybrids that is in the process of developing an amendment to Global Technical Regulation No. 4, which established a harmonized type-approval procedure for heavy-duty engine exhaust emissions. The amendment will provide a test procedure and harmonized technical requirements for certifying pollutant emissions and carbon dioxide (CO_2) from heavy-duty hybrid vehicles. This GRPE group is currently in the process of finalizing a procedure based on Japan's hardware-in-the-loop certification procedure for heavy-duty hybrid systems in which the physical hybrid control unit (HCU) is linked to simulation models of the engine, hybrid system, and vehicle components. As an alternative to this controller-in-the-loop method, the group is considering allowing full testing of the physical hybrid powertrain with the vehicle components simulated (i.e., PILS).

The development of a *world-harmonized* test procedure for heavy-duty hybrids that includes PILS as a testing pathway has important implications for countries such as the U.S. and Canada that are currently deliberating certification options for their GHG regulatory programs. Because a powertrain test cell can be used to test any type of hybrid system (pre- or post-transmission parallel hybrid, or series hybrid) as well as advanced transmissions, a PILS testing method is a very attractive option that would allow hybrid vehicles to be subject to the same certification process as non-hybrid vehicles. By requiring that hybrids be certified using a combination of PILS testing and GEM simulation in the Phase 2 regulation, hybrids can be brought into the fold along with conventional vehicles. This approach is more advantageous than the provisions in the Phase 1 regulation, where hybrids have their own unique set of test procedures and are not certified within the GEM framework.

Design of credit program. As with the Phase 1 rule, a key question that emerges is whether or not credits from the engine program and vehicle program will be interchangeable. If credits are allowed to freely flow between the two programs, there is a risk that vertically integrated manufacturers will avoid engine technology improvements by supplying credits from over-compliance in the vehicle program. To avoid this situation, we recommend that credits *not* be fungible across the engine and vehicle programs, as is the case in the Phase 1 regulation.

Engine families. One area for future research is the method in which engine and powertrains are grouped into families for the certification process. In the engine provisions of the Phase 1 regulation, manufacturers are allowed to use identical families as are used for criteria pollutant emission certifications. The general principle of the criteria pollutant emission certification process is to test the worst performer within the family, and, presumably, all of the other engines in the family will fall within the standard. This logic may not necessarily hold true for CO_2 emissions. Moreover, the criteria by which manufacturers decide how to group engines into families are somewhat nebulous. We believe that family definitions deserve investigation as part of Phase 2 regulatory development process, particularly when considering that a procedure for defining powertrain families could be required as well.

Technology reliability and sensitivity to duty cycle. Technology reliability and sensitivity to duty cycle are important in the longevity and the ultimate extent of the real-world reductions that are obtained through the rule. It is important to consider the three distinct pathways through which engine and vehicle technologies lead to lower fuel consumption. Vehicle-side technologies, such as those that reduce aerodynamic drag and rolling resistance, reduce the required load on the engine and allow the engine to operate in a new, lower fueling rate location of the engine map. In contrast, engine-side technologies, such as those that reduce pumping and heat loses, actually work to lower the fueling rate at a certain location (or locations) in the engine map. Energy recovery technologies, such as hybrid and waste heat recovery systems, work by recovering thermal or braking losses and utilizing the recovered energy to offset required engine operation. Of the three pathways, it is important to note that vehicle-side technologies and energy recovery technologies typically show a high sensitivity to duty cycle, whereas engine-side technologies tend to promote improvements across the engine map and therefore have the potential to be less sensitive to a range of real-world operational conditions. Further analysis is required to quantify this issue, yet it is important to note when thinking about the real-world implications of enacting a standard that does not specifically promote engine technology improvements.

V. CONCLUSIONS AND NEXT STEPS

Based on this assessment of testing and certification pathways, the U.S. Phase 2 heavy-duty vehicle regulation would benefit from maintaining separate engine standards but requiring that manufacturers input information about the actual engine and transmission into GEM. In addition, a method for physical testing of advanced powertrains is integrated into the rule as an option, yet in such a way that it will be utilized extensively would also be highly beneficial. From our comparison of alternatives across a number of criteria, the three pathways (i.e., Options 2, 3, and 4) that have both engine standards as well as powertrain inputs in GEM emerge as the superior options. Our analysis suggests that the reduced compliance flexibility imposed by engine standards is outweighed by other benefits—namely, driving engine technology improvements, acknowledging the current heavy-duty engine and vehicle market structure, and the strong linkage to criteria pollutant standards.

The findings from this paper are:

(1) The benefits of maintaining separate engine standards outweigh any potential disadvantages.

(2) Physical testing of the powertrain (i.e., the engine plus the transmission) in a new test procedure will be necessary in order to capture and promote transmission and engine-transmission integration improvements.

(3) Some unique inputs about the actual powertrain in a vehicle are necessary in the GEM simulations to ensure that all fuel-saving technologies and approaches are properly incentivized and accounted for.

(4) More research is needed to determine the appropriate level of engine information to input into GEM to properly credit all efficiency improvements while balancing resource constraints for both industry and government.

(5) Based on the complexity of any laboratory-plus-simulation testing procedures, it would be suitable for EPA and NHTSA to integrate a research plan that tracks and compares real-world engine, truck, and tractor-trailer efficiency with certification values for select, high-volume products in the 2015-2020 time period.

This assessment reveals several areas for continued research for the agencies and other stakeholders. Among the areas for ongoing technical and policy analyses are the engine modeling approaches and user input requirements in GEM, integration of hybrids into the overall GEM certification framework, and re-weighting of the SET cycle points. An assessment of the viability and fuel-saving potential of all the various efficiency technologies across the engine, powertrain, and vehicle areas in the 2020-2030 timeframe is also a critical factor that plays into regulatory design and regulatory stringency discussions. In addition, the associated incremental costs and cost-effectiveness of each of these technologies should also be more closely examined as part of the deliberations over the design and stringency of the engine and vehicle standards. Finally, although this study discussed elements of the regulatory design in relation to ensuring real-world technology benefits, exploring how to modify the particular regulatory test cycles to best reflect real-world conditions is also critical.

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