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Testing methods for heavy-duty vehicle fuel efficiency: Trends from regulatory programs around the world and implications for India

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1. Introduction

In response to the growing contribution of the trucking sector to global warming and local air quality impacts, many nations and regions around the world have developed programs and policies to improve the environmental performance of heavy-duty vehicle fleets. To date, Japan, the U.S., Canada, and China have enacted mandatory fuel efficiency or greenhouse gas (GHG) standards for new heavy-duty vehicles (HDVs), and many other countries are in various stages of development for their own regulatory measures.

The primary objectives of this paper are to explore methods for testing and certifying the fuel efficiency of HDVs and vehicle components in the established and emerging regulatory programs around the world and the implications for India, as policymakers there deliberate establishing a performance standard of their own. In the India context, one of the key open regulatory design questions is whether a program centered around full vehicle certification or individual engine testing is most appropriate as a first phase regulation. The primary contribution of this paper is to provide an analysis of the advantages and disadvantages of each of these options and present the ICCT's recommended path forward for India.

This paper begins by briefly summarizing the various fuel efficiency and GHG regulations that have been established or are in the process of being developed in Japan, the U.S., Canada, and China as well as the HDV CO_2 certification approach that is being initiated in the European Union. These brief regulatory summaries are followed by more details about the testing and certification methods that are employed or are under consideration in each of these programs. The subsequent section discusses the opportunities and challenges facing India, specifically in terms of the test procedure options in play as policymakers design a HDV fuel efficiency regulation. In the final section, we outline concrete recommendations for test procedure development/adoption in India as well as timelines for implementation. Moreover, we highlight future research that can build on this test procedure assessment and also preview the additional analysis planned by the ICCT that will support fuel efficiency regulatory development for HDVs in India.

This working paper is the first in a series of papers that the ICCT will be releasing that touch on various aspects related to regulatory development for HDV efficiency in India. These analyses will include a market study, industry survey, and a comprehensive technology potential report.

2. Overview of current and developing fuel efficiency regulations for HDVs

Since 2006, Japan, United States (U.S.), Canada, China, and California have adopted some form of fuel efficiency or GHG standard for heavy-duty commercial trucks and buses, while India, Brazil, Mexico, South Korea, and the European Union (E.U.) are in the process of developing such regulations. Combined, these nine regions represent more than three quarters of global heavy-duty vehicle (HDV) fuel consumption, as shown in Figure 1 (Facanha, Miller et al. 2014). The ICCT's best judgment as to the regulatory development timelines in each of these countries and regions is shown in Table 2.

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	HDV efficiency regulation in place	Regulations under consideration
U.S.	✓	✓
China	✓	✓
EU-27		✓
India		✓
Japan	✓	✓
Brazil		✓
Russia		
Canada	✓	✓
Mexico		✓
S. Korea		✓

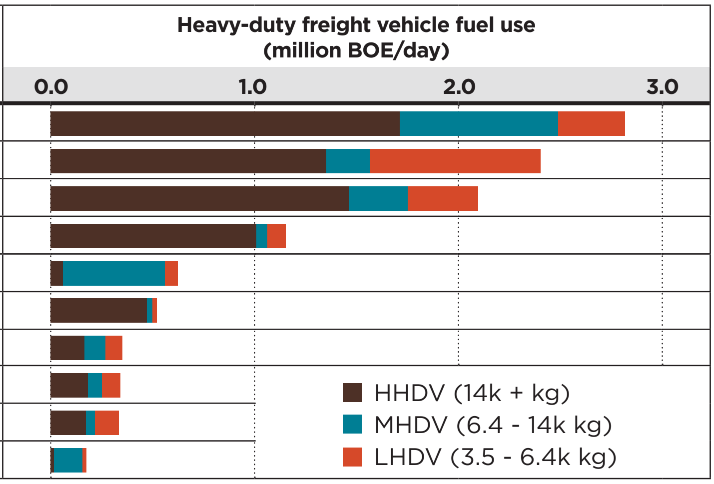

Figure 1: Nations with active or emerging regulatory programs for heavy-duty vehicles
(BOE = barrels of oil equivalent)

Because of the complexities of the HDV sector, designing a regulatory program for HDVs presents unique challenges. For example, measuring the fuel efficiency of a HDV can be quite complicated since a single engine model can be paired with a large number of chassis types and transmissions, with each combination having different fuel consumption characteristics. Furthermore, the fuel efficiency of a given vehicle in use may vary dramatically based upon the duty cycle. Another attribute of the heavy-duty industry that presents challenges from a regulatory perspective is the fact that vehicle manufacturing is often a fragmented and highly customized process. Unlike passenger cars and light-duty trucks, the assembly of HDVs can involve multiple different manufacturers, suppliers, and upfitters. For example, for a particular city delivery truck, one component manufacturer might make the engine; another company might supply the transmission; a separate manufacturer could be responsible for incorporating the engine and transmission and building the rolling chassis; and, finally, an upfitter would be responsible for assembling the body that encapsulates the chassis and carries the cargo. Given that vehicle design and manufacturing are often shared among multiple entities whose individual contributions can all have unique impacts on the ultimate fuel efficiency performance of a vehicle, this can potentially present challenges in terms of identifying a single regulated entity.

The HDV market is so complex and varied that the U.S., Canada, and China have focused the bulk of their regulatory attention on the most energy intensive vehicle types. In these three nations, long-haul tractor-trailers are the top energy consumers. Indeed, as shown in Fig. 1, the heaviest class of commercial vehicles, which includes long-haul tractor-trailers, account for the bulk of fuel consumption for seven out of the nine nations currently considering fuel economy standards. The two important exceptions are Japan and South Korea, where medium-duty trucks and buses dominate heavy-duty vehicle fuel use.

In the remainder of this section, brief program overviews are presented for each of the jurisdictions that have implemented fuel efficiency regulations for HDVs. Though the E.U. has not put a mandatory performance standard in place for commercial vehicles, we provide a summary of their approach for testing and certifying the fuel consumption and CO_2 emissions from HDVs.

2.1 JAPAN

Japan deserves credit as the world's first country to establish HDV fuel economy standards in 2006 as part of the country's commitment to the Kyoto Protocol (Ministry of Economy Trade and Industry (METI) and Ministry of Land Infrastructure Transport and Tourism (MLIT) 2005). Separate fuel economy standards were established for city buses and for heavy-duty trucks, and there are unique stringency requirements that vary by vehicle mass. Truck weight classes ranged from 3.5 to 20 metric tons, while buses ranged from less than 8 to greater than 14 metric tons. On average, the standards required an improvement in fuel economy of 12% by 2015, or a 1.2% annual improvement. These standards were incorporated into Japan's broad Top Runner system for energy efficiency, where the current best performer efficiency is used to set future standards. Each manufacturer is required to meet the fuel economy target in each bin it sells vehicles, based upon a sales-weighted average for that bin, with no opportunities for cross-bin crediting (The International Council on Clean Transportation (ICCT) 2008).

After considering several testing options based upon multiple criteria — equipment and labor costs, accuracy, the ability to account for non-engine efficiency improvements, and overlaps with emissions test cycles — the Japanese government chose to measure fuel economy under its heavy-duty standards through a combination of engine-only fuel consumption testing and simulation modeling of gear shifting and vehicle resistance loads. The test method as designed essentially constrains compliance options for manufacturers to engine efficiency improvements only. Since the simulation model assigns standard values by fuel efficiency category for driving resistance and chassis size, efficiency improvements due to changes in these variables are not counted toward compliance.

Japan's focus on engine efficiency improvements in its regulation aligns well with the technology potential that exists at lower driving speeds. At lower speeds that are typical of urban driving, losses in the engine and transmission tend to dominate, while as speed increases, aerodynamic and rolling resistance drag represent an increasing share of overall energy consumption (Delorme, Karbowski et al. 2009). Given that urban driving accounts for a large percentage of overall HDV fuel consumption in Japan, the regulation's emphasis on engine improvements is a logical point of focus for its first phase regulation.

For the next iteration of its heavy-duty standards, Japan's regulatory agencies are researching how to update their testing and simulation methods as well as how best to incorporate a wider range of technology improvements beyond just the engine (e.g., aerodynamics, reduced tire rolling resistance, light-weighting, advanced transmissions, and hybrid powertrains).

2.2 UNITED STATES AND CANADA

Five years after Japan's policy action, the U.S. finalized fuel efficiency and GHG emission standards for medium- and HDVs in the fall of 2011 (The International Council on Clean Transportation (ICCT) 2011, U.S. Environmental Protection Agency 2011). Canada followed roughly a year-and-a-half later with its own rule, which was published in the spring of 2013 and is largely identical to the U.S. regulation (Environment Canada 2013). The U.S. Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) worked collaboratively to deliver these *Phase 1* regulations under their respective authorities. The EPA developed GHG emission standards under the Clean Air Act, and the NHTSA developed fuel consumption standards under the 2007 Energy Independence and Security Act. Environment Canada's authority covers GHG emissions, so its standards are linked to the EPA's GHG regulation. The fuel efficiency and GHG standards are designed to be functionally equivalent, based on carbon dioxide (CO_2) conversion factors for each fuel. In addition, the EPA standard also includes limits on engine nitrous oxide (N_2O) and methane (CH_4), as well as limits on emissions of refrigerant from air-conditioning systems.

The U.S. approach mirrors the Japanese program by adopting a simulation modeling strategy, but the U.S. program is distinct in two important ways. First, the U.S. program sets an engine standard that is separate and unconnected from the vehicle standard. The second major contribution from the U.S. rule proposal is the expansion of the simulation modeling approach to include additional elements of potential efficiency gains from tires, aerodynamics, weight reduction, and other factors as discussed below. As with Japan's fuel economy rule, compliance with the U.S. regulation is based on sales-weighted averaging. Thus each manufacturer's product mix must meet the targets, on average, based on sales-weighting of vehicles that generate credits (i.e., vehicles that perform better than the target) and debits (i.e., vehicles that consume more fuel/emit more CO_2 than the target).

The U.S. rule can be thought of as four rules combined into one regulation. There are distinct provisions for the four primary regulatory subcategories: tractor trucks, pickup trucks and vans, vocational vehicles, and engines of tractor trucks and vocational vehicles.

Tractor trucks account for the largest percentage of fuel consumption and GHG emissions from the HDV sector and thus attract the greatest amount of regulatory attention in the rule. There are nine separate standards for tractor trucks based on combinations of three categories of vehicles (Class 7, Class 8 day cab, and Class 8 sleeper cab) and three roof height categories (low, medium, and high). Regulatory stringency ranges from 9% to 23% for model year (MY) 2017 vehicles compared with the MY 2010 baseline. Table 1 presents a high-level summary of the tractor standards as well as the primary elements of the other three major regulatory categories.

Table 1: Major elements of the U.S. and Canada heavy-duty vehicle regulations

Regulatory Category	Regulatory Subcategories	Compliance Assessment	Stringency versus MY 2010 Baseline
Tractor trucks	Nine subcategories based on weight, cab configuration, and roof height	Greenhouse Gas Emissions Model (GEM) simulation Inputs: aerodynamics, tire rolling resistance, weight reduction, idle reduction, vehicle speed limiter	9% to 23%
Heavy-duty pickup trucks and vans	• Diesel • Gasoline	Chassis dynamometer testing	12% for gasoline 17% for diesel
Vocational vehicles	• Light heavy-duty (Classes 2B-5) • Medium heavy-duty (Classes 6 and 7) • Heavy heavy-duty (Class 8)	GEM simulation Inputs: tire rolling resistance	6% to 9%
Engines for tractors and vocational vehicles	• Light heavy-duty (Classes 2B-5) • Medium heavy-duty (Classes 6 and 7) • Heavy heavy-duty (Class 8) • Gasoline and spark-ignited engines (all classes)	Engine dynamometer testing	5% to 9%

Tractor manufacturers must demonstrate compliance with the tractor standards using the Greenhouse Gas Emissions Model (GEM), a vehicle simulation program that was developed by the EPA and NHTSA. For tractors, inputs to the model include data on aerodynamics, tire rolling resistance, weight reduction, extended idle reduction, and vehicle speed limiting. In addition, there is a separate standard for engines of tractor trucks as discussed below. Notably, transmissions are not included in the suite of technologies that are part of the standard compliance pathway using the GEM program. In the regulation, the EPA and NHTSA explain that transmissions (and axle ratios) were not included in the core set of compliance technologies for tractors and vocational vehicles for two primary reasons: (1) lack of baseline data and (2) the desire to avoid unintended disruptions to the market.

Heavy-duty pickup trucks and vans with a gross vehicle weight (GVW) between 8,500 and 14,000 pounds are often very similar to their counterparts in the light-duty category. Because of the similarities among light- and heavy-duty pickups and vans, the testing and compliance approach is closely related to the program for LDVs. The Class 2B and 3 vehicles are tested on a chassis dynamometer with the stringency of the standards scaled by a newly created “work factor” that reflects the vehicle’s utility (i.e., hauling capacity, payload, and capacity for four-wheel drive). There are separate standards for diesel and gasoline vehicles, and, in MY 2018, the average CO_2 emissions compared with a MY 2010 baseline must be 12% lower for gasoline vehicles and 17% lower for diesel vehicles.

The *vocational vehicle* category is a catchall group for the rest of the HDVs that are not classified as tractor trucks or heavy-duty pickup trucks or vans and includes a vast array of different vehicle configurations (e.g., bucket trucks, refuse vehicles, and buses), duty cycles, and payloads. The regulated entity is the chassis manufacturer. Manufacturers comply with the vocational vehicles standards using the GEM software by inputting tire rolling resistance test data.

The stringency of the vocational vehicle standards is premised solely on improvements in engines (driven by the separate engine standard) and tires rolling resistance and does not incorporate savings opportunities from other areas such as aerodynamics, transmissions and hybrids, and weight reduction. This is not because the agencies have rejected the technology potential across many vocational applications, but rather that there are obstacles to capturing these savings given the structure and protocols of the regulation. For example, the aerodynamic coefficient of drag is not an input parameter in the vocational vehicle module in GEM, since a single chassis may be used with multiple bodies that have vastly different aerodynamic profiles.

Engine testing for compliance with fuel consumption and GHG standards is designed to occur simultaneously with testing for criteria pollutants using the same procedures and test cycles that are currently used. In effect, three more pollutants must be measured and reported: CO_2, CH_4, and N_2O. The procedures to determine which engines must actually be tested will also remain the same as in current criteria pollutant testing. Engines are categorized as light-heavy (Class 2B through 5), medium-heavy (Class 6 and 7), and heavy-heavy (Class 8) based on what vehicle class they are ultimately used in.

2.3 CHINA

Tractor-trailers, dump trucks, and straight trucks account for nearly two-thirds of fuel consumption in the HDV sector in China, and thus represent the categories of HDVs worthy of the initial regulatory focus (Zheng 2013). The composition of the Chinese market is substantially different than that of U.S. and European markets, where tractor-trailers account for greater than half of fuel consumption in the sector. In China, single-unit trucks (e.g., straight trucks, dump trucks) account for the greatest share of fuel consumption (ibid).

The first phase "Industry Standard" was issued in 2011 for implementation in mid-2012 for new models, and mid-2014 for all vehicles. Under the Industry Standard, three HDVs categories are regulated—straight trucks (not including dump trucks), coach buses (not including city buses), and tractor trucks. The currently adopted, second phase "National Standard" went into effect for new HDV models in mid-2014. This regulation tightened the stringency of standards by an average of 10.5% to 14.5% compared to the limits under the Industry Standard. Besides the aforementioned three types of HDVs the standards added in two new categories of vehicles—city buses and dump trucks (Muncrief 2013).

For their certification approach, China has implemented a framework in which "base" vehicles must be evaluated on a chassis dynamometer, but manufacturers have the ability to use an official simulation model to certify "variants" of the base vehicle models. China's primary reliance on chassis testing to determine compliance is particularly noteworthy given that all other nations that have adopted or are considering HDV efficiency standards have designed their test procedure process to feature simulation modeling as the primary means of certification.

2.4 EUROPEAN UNION

The European Commission has been working closely with its domestic HDV industry since the summer of 2007 to develop a new program focused on controlling fuel consumption and CO_2 emissions from HDVs. The collaboration has primarily focused on assessing the technical potential of mitigation options for HDVs, developing a simulation modeling tool, and a set of mission-based test cycles and procedures for each major class or category of HDV.

For the past few years, much of the attention from regulators and industry in Europe has been around developing a simulation-based methodology for testing and certifying the CO_2 emissions of HDVs. The backbone of the European certification process is the Vehicle Energy Consumption calculation Tool (VECTO). VECTO is currently in the proof-of-concept phase and is still being validated before it becomes the official software that manufacturers must use to evaluate each vehicle model's CO_2 emissions and fuel efficiency. As with Japan's model and the GEM tool in the U.S. and Canada, VECTO uses component test data from physical testing (e.g., track testing for determining aerodynamic drag, engine mapping based on dynamometer results, etc.) to create a virtual representation of the vehicle that can then be exercised over mission-specific drive cycles (Fontaras, Rexeis et al. 2013). The key aspect in which the European approach differs from that in North America is that there is no separate engine standard to go along with the VECTO certification process.

The policy outcome for the E.U. has not yet been decided. Two options are currently under consideration. A labeling and information program would provide consumers and HDV purchasers with accurate, detailed information about fuel efficiency across multiple configurations and manufacturers. A central question for European policymakers is whether enhanced consumer information through a labeling and information program will suffice to capture the technological potential for European HDVs. Alternatively, the Commission could develop mandatory performance targets for CO_2/ton-km. These two policy options are not mutually exclusive, but are actually quite complementary.

2.5 CALIFORNIA

As part of the regulatory mandate to reduce GHG emissions from all sectors of the California economy, the California Air Resources Board (ARB) developed a regulation that aims to increase the efficiency of tractor-trailers operating in California. This regulation, which was first proposed in late 2008 and formally finalized in early 2012 (California Air Resources Board (CARB) 2012), has mandatory equipment specification provisions for trucking fleets that affect both tractors and trailers. The reduction in fuel use and GHG emissions will be achieved by requiring the use of aerodynamic tractors and trailers that are also equipped with low rolling resistance tires. The tractors and trailers subject to this regulation must either use U.S. EPA SmartWay certified tractors and trailers or be retrofitted with SmartWay verified technologies. California's program is the first in-use GHG regulation in the world.

Table 2: Regulatory development timelines for heavy-duty vehicle efficiency and GHG regulations around the world

	Regulation Type	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021
Japan	Fuel economy						Phase 1 regulation implemented starting MY 2015						
							Phase 2 under consideration					Phase 2 implementation	
United States	GHG/Fuel efficiency	Standard proposal	Final rule			Regulation implemented starting MY 2014 (mandatory DOT program starts MY 2016)							
					Phase 2 regulatory development		Phase 2 proposal	Phase 2 final rule				Phase 2 implementation	
Canada	GHG			Standard proposal	Final rule	Regulation implemented starting MY 2014 (optional until MY 2016)							
						Phase 2 regulatory development		Phase 2 proposal	Phase 2 final rule			Phase 2 implementation	
China	Fuel consumption	Test procedure finalized	Industry standard proposal	Industry standard implemented	National standard adopted	Final regulation of National standard effective on July 1, 2014 for newly certified vehicles and July 1, 2015 for existing vehicles						Next phase implementation	
European Union	CO_2 test procedure	Technical studies			Impact assessment	Test protocol and simulation model finalization						Policy implementation	
Korea	Fuel efficiency	Technical studies			Impact assessment and test procedure development		Regulatory development and finalization						
California	End-user purchase requirements	Requirements for new tractors, trailers (2011+)			Additional requirements for existing tractors and trailers (< MY 2010)			Additional requirements for existing trailers and reefers (< MY 2010)					

(Text in **orange** represents the ICCT's best estimate as to the timing of these regulatory developments)

3. Testing and certification pathways

Heavy-duty vehicles are produced in a much greater range of sizes and configurations than light-duty vehicles, and have a more diverse range of in-use duty cycles. Also, chassis dynamometers and the associated facilities that can accommodate the significant loads and test apparatus of heavy-duty vehicles are often expensive and much less common than light-duty chassis dynamometers. As such, governments and industry have historically opted for work-specific engine-based standards and engine dynamometer testing for criteria pollutant emissions certification. However, because traditional engine dynamometer testing may not be fully adequate for properly representing vehicle operations, governments and industry have been formulating different strategies for certifying CO_2 emissions and fuel consumption performance. These options include certification pathways based on the following testing methods:

- Chassis dynamometer
- Engine dynamometer
- Powertrain dynamometer
- Simulation modeling
- Closed test track

All of these options are described further below. Following the test procedure descriptions below, Section 3.2 presents a comparison of these options according to a number of criteria as well as how the regulatory programs discussed in Section 2 differ in terms of testing and certification strategies.

3.1 METHODS OF TESTING AND CERTIFYING HEAVY-DUTY VEHICLES

3.1.1 Full vehicle chassis dynamometer testing

In this test method, the full vehicle is mounted on a dynamometer with the drive wheels resting on one or more large cylindrical rolls. The vehicle is stationary during testing, but the drive wheels spin the rolls to simulate driving at different speeds[1]. The dynamometer imparts varying loads to the drive wheels to represent varying vehicle inertial load, rolling resistance, and aerodynamic drag throughout the drive cycle. The vehicle driver follows a specific profile of speed versus time, and is usually given a computerized driver's aid, which shows actual speed versus target speed in real time. The Society of Automotive Engineers (SAE) has developed a recommended practice for conducting emissions and fuel economy tests of heavy-duty vehicles on chassis dynamometers (SAE J2711) (Society of Automotive Engineers (SAE) 2002), and the EPA has detailed procedures for conducting emissions testing (40 CFR Part 86 (U.S. Environmental Protection Agency (EPA) 2015), 40 CFR Part 1065 (U.S. Environmental Protection Agency (EPA) 2015)).

The most significant benefit of this test method is that it effectively brings the entire drivetrain into the test. As such, it can be used to provide a realistic assessment of distance-specific emissions and fuel use for a wide range of advanced vehicle and drivetrain technologies, including all hybrid configurations.

Compared to engine testing, chassis dynamometer testing is time consuming and expensive. In this method the vehicle is stationary during the test, and the aerodynamic load is not imposed on the vehicle surface as it is during driving. Instead, a simulated aerodynamic load is imposed on the vehicle through the tires by adjusting the load on the dynamometer rolls. In effect, the dynamometer uses inertial and electrically generated loads applied through the vehicle's tires to simulate aerodynamic load.

The required load is determined by conducting an on-road coastdown test prior to the dynamometer testing. In a coastdown test the vehicle is accelerated to some speed and then allowed to coast to a stop without applying the brakes, while vehicle speed versus time is recorded. By calculating the varying deceleration rate of the vehicle over time, one can compute the forces (rolling resistance and aerodynamic drag) that were operating on it at each speed. This information is programmed into the dynamometer so that it will impose the appropriate load on the vehicle at each point in the test cycle. The vehicle is then mounted on the dynamometer, and a dynamometer coastdown test is conducted to ensure that the coastdown profile is the same on the dynamometer as it was on the road. An alternative to performing coastdowns is constant speed testing. As the name suggests, constant speed tests derive the total driving resistance by evaluating the vehicle during steady-state operation on a test track.

While this method of evaluating and simulating rolling resistance and aerodynamic drag on a dynamometer is theoretically sound, it is critical that the coastdown (or constant speed) test be conducted correctly. The accuracy of chassis dynamometer testing is limited by the accuracy of the coastdown data used to calibrate the dynamometer for a specific vehicle. The largest constraint on coastdown testing is finding an appropriate location to conduct the test (a straight and level road of sufficient length where the air is relatively still).

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[1] To avoid tire slippage during high torque operations, some heavy-duty chassis dynamometers are designed such that the load-transmitting axle is directly connected to the wheel hubcap.

The accuracy and repeatability of coastdown tests are significantly affected by test track configuration and ambient conditions.

There are several standardized HDV cycles in existence; TransportPolicy.net is an extensive online reference. There are cycles specific to a number of different types of HDV driving patterns, including cycles tailored to tractor-trailers, delivery trucks, transit buses, coach buses, and refuse vehicles. All of these cycles have vehicle speed versus time (in seconds), and the vehicle operator (i.e., the person operating the vehicle on the chassis dynamometer) must following the speed trace as closely as possible. In addition to chassis dynamometer testing, vehicle cycles are also used in simulations models to evaluate vehicle performance.

From a regulatory perspective, China is the only jurisdiction that requires chassis dynamometer testing. The cycle used for evaluating all HDVs in China (on both the chassis dynamometer for "base" vehicles and in the simulation model for "variant" vehicles) is a slightly modified version of the World Harmonized Vehicle Cycle (WHVC), the C-WTVC. As shown in Figure A1, the C-WTVC is very similar to the WHVC. Some of the original WHVC acceleration and deceleration values are reduced in order to reflect Chinese HDVs, which, on average, have lower engine power-to-vehicle weight ratios than HDVs from other major markets (i.e., Europe, North America, and Japan) that were used to develop the WHVC.

Both the WHVC and C-WTVC are comprised of three *mini-cycles*: an urban, interurban, and highway driving portion. In China's regulation, the fuel efficiency for each of these three mini-cycles is weighted according to the type of HDV, and the final certification value for each vehicle model is based on the weighted score. The weighting factors for each of the regulatory subcategories are listed in Table A2, which summarizes all of the engine and vehicle test cycles that are utilized in the regulatory programs in Japan, the U.S. and Canada, and China.

3.1.2 Engine dynamometer testing

Existing engine certification test cycles are designed to offer a reasonable approximation of how an engine installed in a conventional vehicle would operate during in-use driving. In this testing approach, the engine is exercised using a standard engine dynamometer, in which power and torque are measured from the crankshaft of the engine.

One of the most attractive aspects of the engine dynamometer test method is that it is consistent with existing criteria pollutant regulatory programs, which currently use engine dynamometers for all emissions certification testing. For many years, governments and industry have been accustomed to using engine test cycles such as the U.S. Federal Test Procedure (FTP) transient cycle and the European Transient Cycle (ETC) for criteria pollutant certification purposes. Moreover, another advantageous aspect of this test method is the relatively high test-to-test repeatability of the measurements compared to chassis dynamometer results. Unlike the chassis dynamometer procedure, there is no tire slip, no error introduced by human drivers, and most temperatures and pressures can be tightly controlled in a laboratory setting (e.g., air, fuel, engine coolant, oil, etc.).

A key drawback of using engine testing for HDV fuel efficiency testing is that existing cycles are arguably not reasonably representative of how modern engines operate under real-world conditions. Certain stakeholders, including vertically integrated original equipment manufacturers (OEMs), contend that optimizing engine performance to engine cycles leads to sub-optimal fuel efficiency during actual operations (Daimler Trucks North America 2014, Volvo Group 2014).

All of the countries with criteria pollutant regulations have utilized standardized engine cycles for testing and certification for many years. The introduction of the U.S. and Canada's Phase 1 GHG regulations represent the first time that these engine cycles have been used for testing fuel consumption and CO_2 emissions. Some of the key advantages and disadvantages of using engine cycles that were originally derived to test criteria pollutants to evaluate an engine's fuel consumption performance are discussed below in Section 4.1.

3.1.3 Powertrain dynamometer testing

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 torques 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 (i.e., vehicle speed versus time). 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. For more information about powertrain test cycles, see (Andreae and Sun 2012). Of the two methods described here, the PILS strategy generally does a much better job producing results closer to what would be experienced under real-world vehicle operations.

3.1.4 Simulation model-based evaluation

Unlike chassis and engine dynamometer testing, the use of simulation models for heavy-duty vehicle certification is fairly new. Software models vary greatly in complexity and applicability, but, in general, a simulation model uses actual data from physical systems to re-create a virtual vehicle that can mimic, in computational space, its real-world counterpart. Vehicle simulation software can be used for the prediction of fuel consumption and CO_2 emissions from HDVs under various operating conditions, as long as sufficiently detailed models are provided and the necessary input data and parameters are available.

The primary advantage of vehicle simulation tools is the ability to model a large number of vehicle variants and subsystems using less time and resources than the other dynamometer-based methods. However, simulation programs do require physical testing (e.g., engine dynamometer testing, coastdown testing, tire testing, etc.) to create the data inputs that are the backbone of the modeling process. In general, the more representative (or “accurate”) a simulation model is of real-world operations, the more time and resources are required to validate the model and ensure its fidelity (see Figure 3). In addition, another challenge facing simulation models is the increased complexity of modern engine, powertrain, and vehicle control systems. For virtually all manufacturers and component suppliers, sophisticated control algorithms, which are considered confidential business information (CBI), are integral to the proper functioning of all major systems such as engines and transmissions. In a regulatory context, for a single simulation model it is practically impossible to exactly replicate all of the various control strategies for the individual manufacturers, since regulators do not have access to CBI data.

Vehicle simulation has been an indispensible part of the vehicle design process for many years and is now becoming an essential component of regulatory programs as well. As discussed in more detail in Section 3.2, simulation is an integral piece of all of the regulatory certification procedures in existence today (including the E.U., which is developing an official simulation-based certification process but has not indicated that a regulation will be pursued in the future). Vehicle simulation models can provide a relatively inexpensive design platform and valuable source of timely information, particularly in cases where physical testing and experimenting becomes difficult.

3.1.5 Test track evaluation

This test method involves operating the vehicle on a closed test course (typically a one mile or longer circular or oval track with banked corners). For each test the driver is taught how to operate the vehicle for the target test cycle. This includes parameters such as acceleration rates from each stop and target speeds between specific points on the track, braking rates and stopping points, and idle times at each stop. The Truck Maintenance Council (TMC) and SAE procedures for in-service and dynamometer tests can serve as the basis for a test track test protocol (Society of Automotive Engineers (SAE) 1986, Society of Automotive Engineers (SAE) 1986, Society of Automotive Engineers (SAE) 1987, Truck Maintenance Council (TMC) 1996).

The most attractive aspect of this method is the fact that the complete physical vehicle is being tested on the road (albeit, in a controlled test track environment without *normal* traffic conditions). In this sense, this is the most representative of all of the test methods. However, the two major drawbacks are time and resource intensity and poor test-to-test repeatability.

3.2 COMPARISON OF TEST METHODS

There are certain issues and challenges with each of the testing methods that are currently used to certify the fuel efficiency performance of HDVs. As shown in Table 3, none of the methods are clearly superior across all the key regulatory parameters.

Table 3: Advantages and disadvantages of the various methods for testing heavy-duty vehicles

Test Method	Advantages	Disadvantages
Chassis dynamometer	• Ability to test any vehicle configuration, including hybrids and vehicles with advanced transmissions • Ability to test all of the vehicle components as a system • Uses actual production control system algorithms during test	• Limited availability of chassis dynamometers due to high capital costs • Testing is time and resource intensive • Coastdown testing is a required prerequisite for developing road load inputs — limited availability of adequate test facilities, and variability based on ambient conditions • Not consistent with existing criteria pollutant test procedures, which are based on engine dynamometer testing
Engine dynamometer	• Industry and regulators have strong familiarity with engine dynamometer testing — ability to leverage existing engine certification cycles • Consistency with existing criteria pollutant test procedures, which are based on engine dynamometer testing • Uses actual production control system algorithms during test	• Cannot test driveline systems such as the transmission • Existing engine cycles are arguably not representative of how modern engines operate under real-world conditions • May conflict with test procedures for fuel economy/ GHG emissions that are based on vehicle cycles. For example, there is currently no vehicle cycle that is *equivalent* to the heavy-duty FTP engine cycle.
Powertrain dynamometer	• Ability to test any vehicle configuration, including, post-transmission parallel and series hybrids, and advanced transmissions. All driveline components tested as a system. • Uses actual production control system algorithms during test	• Very few powertrain test cells in existence • May conflict with existing criteria pollutant test procedures that are based on engine dynamometer testing
Simulation	• Ability to evaluate a large number of vehicle variants in a timely and cost-effective manner • Minimizes time-consuming and expensive dynamometer testing • Perfect test-to-test repeatability	• Increasing model sophistication and accuracy requires added resources for physical testing and model validation • Very challenging to accurately represent the confidential control strategies of each manufacturer
Test track	• Ability to test any vehicle configuration, including post-transmission parallel and series hybrids, and advanced transmissions • Ability to test all of the vehicle components as a system • Uses actual production control system algorithms during test	• Testing is time and resource intensive • Poor test-to-test repeatability • Appropriate test protocols and data analysis procedures would need to be developed if intended for use in a regulatory context

Because each of the testing options has strengths and weaknesses in terms of cost, complexity, accuracy, and transparency, it is understandable that different governments have developed unique approaches to testing and certification pathways in their HDV regulations. However, as shown in Figure 2, there is certainly a fair amount of overlap in the test procedure approaches in each of the regulatory programs.

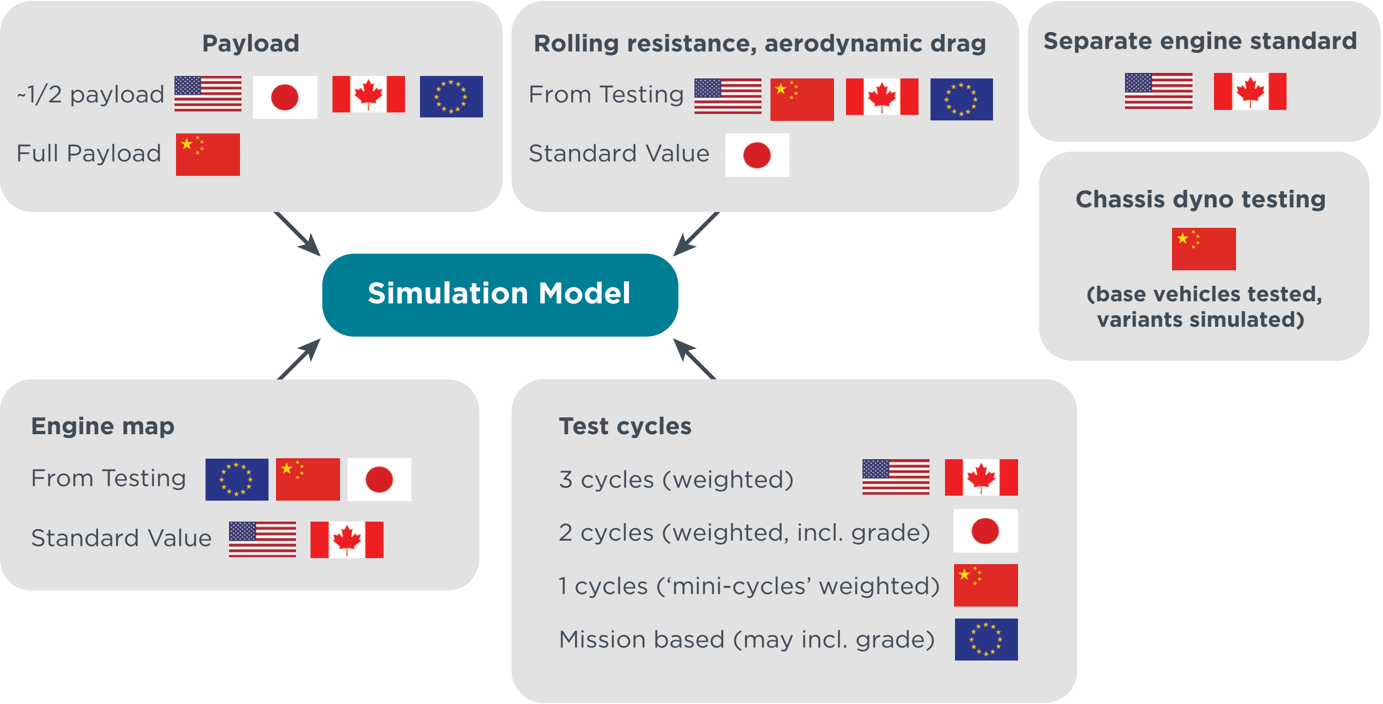


Figure 2: Test procedure comparison across the various HDV regulatory programs

From the figure, the most common element across all of the regulatory programs is simulation modeling. Though the individual certification models in Japan, U.S./Canada, China, and the E.U. are all unique, when we look at the key input requirements and simulation conditions across the five jurisdictions, some important commonalities emerge. Looking at engine data requirements, default engine maps are used in GEM (U.S./Canada), whereas engine dynamometer-derived maps are needed for the models in Japan, China, and the E.U. In their respective Phase 1 programs, both the U.S. and Canada elected to use default engine maps in their certification process primarily based on the fact that engines have their own separate certification process. In other words, the North America agencies were confident that the engine standards based on mandatory engine dynamometer testing would be sufficient to drive engine technologies into the market and did not think that testing-derived engine data was a necessary input to the GEM simulations. Therefore, *Phase 1* GEM is not designed to be as accurate as possible with respect to the powertrain (i.e., engine plus transmission). Furthermore, transmission and improved driveline technologies are not promoted within the standard GEM certification framework, and default values are used for these systems as well. In effect, since the GEM virtual vehicles all have default engines, transmissions, axle ratios, and tire radii, the function of GEM is explicitly limited to evaluating road load-based technologies — namely, aerodynamics, tire rolling resistance, weight and idle reduction, and speed limiting. For the certification programs in Japan, China, and the E.U., the lack of a separate engine standard makes the input of engine-specific data into the model a critical requirement to properly evaluate engine improvements.

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 regulators in the U.S. and Canada weigh options for the Phase 2 standards. Namely, the crucial decision is whether or not to maintain the stand-alone program for engines. The advantages and disadvantages presented by separate engine standards are discussed more in Section 4 in the context of a potential HDV fuel efficiency regulation in India.

Another prominent question that policymakers in the U.S. and Canada face is about how best to design the regulation to promote not only engine and road load 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 many stakeholders in the upcoming Phase 2 rulemaking.

Going back to Figure 2, aerodynamics and tire rolling resistance are key road load inputs in four out of five certification pathways, with Japan being the only exception that uses default values for these parameters. Input data for the aerodynamics of a vehicle is determined by coastdown testing (or constant speed testing in the European process) on a test track. For tires, the rolling resistance coefficient is determined by laboratory testing in the U.S., Canada, and E.U., whereas, for the certification process in China, the tire rolling resistance coefficient is determined using a formula (China Automotive Technology and Research Center (CATARC) 2010, Zheng, Jin et al. 2011).

Some of the standardized test procedures that are most commonly used for component testing input data for aerodynamics, rolling resistance, and powertrains are listed in Table A1 in the appendix.

4. Test procedure challenges and opportunities for India

As policymakers in India consider developing fuel efficiency standards for HDVs, one of the fundamental questions will be how the regulation is designed in terms of testing methods and certification pathways. Figure 3 (adapted from Sanchez 2013) shows how the various certification frameworks around the world compare in terms of the mix of simulation and vehicle testing. On the continuum, the upper left represents one extreme in which simulation is the sole basis for certification. As discussed in the previous section, all of the simulation models require input data derived from physical component testing (e.g., engines, aerodynamics, tires). However, what sets the European and Japanese approaches apart is that there are no separate dynamometer-based standards that go along with the simulation requirement. The lower right-hand corner of the figure represents a scheme solely dependent on physical chassis dynamometer testing. The only country that requires chassis dynamometer testing is China for "base" vehicles; however, "variants" may be certified using the official simulation model.

If we look at the two options in the middle of the figure — those which combine requirements for both simulation and separate dynamometer testing as part of certification process — we find the two regulatory programs in North America. Option (2) represents the Phase 1 regulation in the U.S. and Canada in which both the GEM simulation and engine dynamometer testing are mandatory for tractor trucks and vocational vehicles (heavy-duty pickup trucks and vans must be chassis dynamometer tested, similar to the light-duty vehicle certification process). As discussed in the previous section, regulators in the U.S. and Canada are currently deliberating 1) how to integrate transmissions into the program, and 2) whether or not to require engine-specific data inputs into GEM as part of the Phase 2 regulation. These developments are represented in option (3).

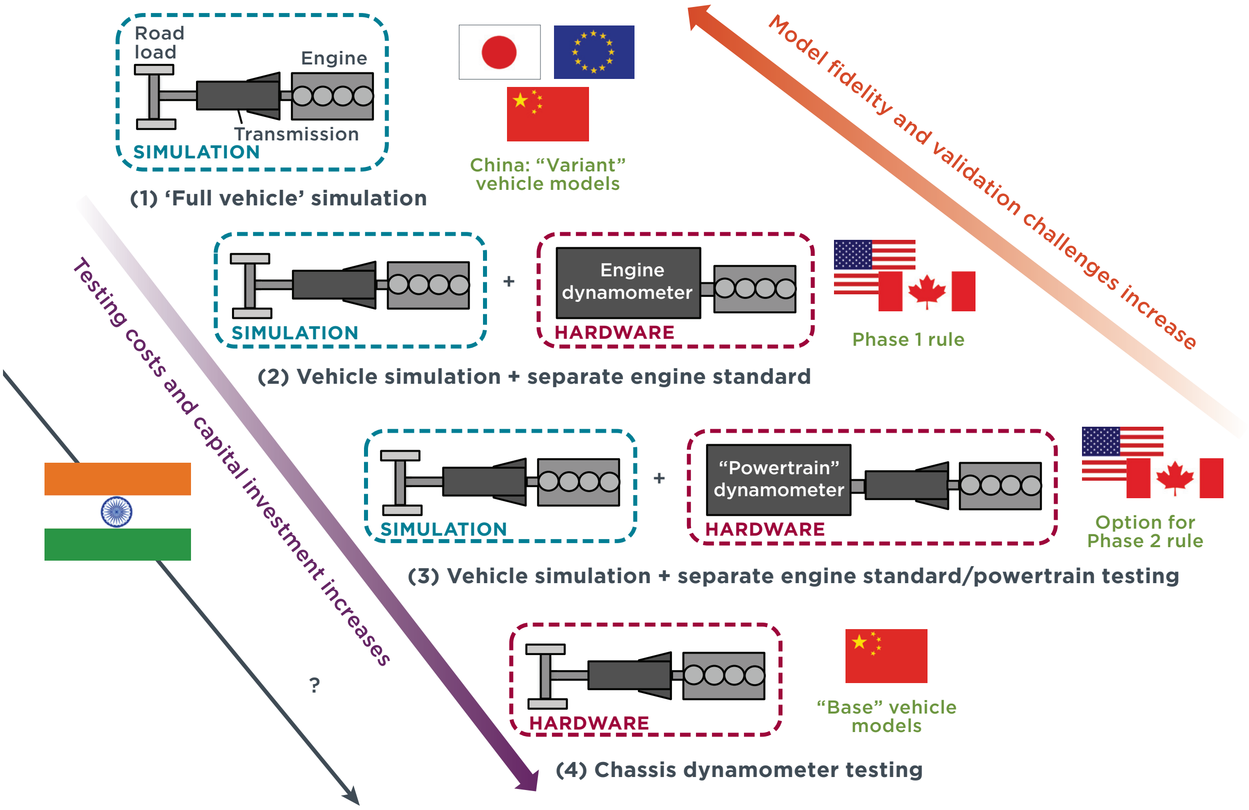


Figure 3: Continuum of certification pathways

As shown by the orange and purple arrows in Figure 3, there is an inherent tradeoff in moving in either direction along the continuum. As we move from the top left to the bottom right, testing costs and capital expenses increase, while the burden of simulation model fidelity and validation decreases (or goes away completely in the case of a regulatory scheme that solely relies on chassis dynamometer testing). Conversely, moving in the opposite direction, the trends reverse for both parameters. Where India falls on this continuum is a critical question that policymakers in India are currently deliberating. We will analyze this issue and provide our recommendations over the remainder of this section.

4.1 SEPARATE ENGINE STANDARDS IN INDIA

The issue of whether or not separate engine standards make sense in the Indian context is perhaps the first fundamental regulatory design question that must be addressed. The HDV market structure in India is similar to North America in that there are large independent component manufacturers (e.g., independent engine and transmission manufacturers) as well as vertically integrated vehicle OEMs. This 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.

Yet another key issue is the linkage of fuel efficiency and criteria pollutant emissions standards. Not having a 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 nitrogen oxide (NO_X) emissions over the engine cycles but higher NO_X over vehicle cycles). It is important to keep in mind that 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.

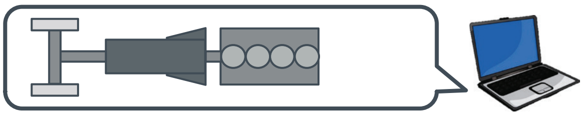
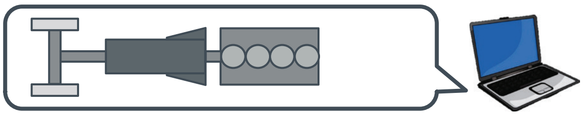
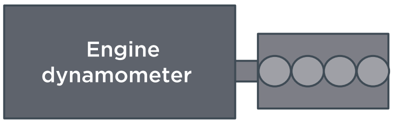
Table 4 summarizes some of the key arguments posited by both sides of the debate around the existence of separate engine standards.

As evidenced in Table 4, there are valid arguments on both side of the debate. By introducing some additional evaluation criteria, we can provide greater clarity as to what testing and certification strategy (or combination thereof) makes the most sense for India's first phase regulation and beyond. The assessment criteria we have chosen and the evaluation matrix are shown below in Table 5.

Table 4: 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 cycles versus high NO_X/low CO_2 emissions over vehicle cycles and in-use operations • Uses existing test procedures — leverages engine cycles, which industry are 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 • Can drive improvements in engine *and* vehicle technologies — provides engine technology investment clarity for both independent engine manufacturers and vertically integrated vehicle manufacturers	• Could promote 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 engine certification cycles, which may not 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, depending on the in-use duty cycle

Table 5: Comparison of test procedure options for India

Certification option	Ability to leverage existing testing facilities	Complexity of certification process	Timeline for regulatory implementation
 **Full vehicle simulation – adapted version of VECTO, GEM, Japan or China model**	🟧	🟧	🟥 **5-7 years**
 **Full vehicle simulation – new India model**	🟧	🟧 **?**	🟥 **5-7 years**
 **Chassis dynamometer**	🟥	🟧	🟥 **5-7 years**
 **Engine dynamometer**	🟩	🟧	🟩 **3-5 years**

🟩 **Favorable** 🟧 **Moderate** 🟥 **Unfavorable**

The top two rows represent certification pathways for full vehicles based solely on simulation modeling. The only distinction between the two options is the simulation program that is employed: a currently existing simulation model such as VECTO or GEM (or a slightly modified version for adaptation in India), or a completely new model that is developed specifically for a regulatory program in India. In both cases, there is somewhat limited ability to take advantage of existing testing facilities. Certainly, manufacturers can utilize existing engine dynamometer capacity for developing engine map inputs, but it is unclear whether or not there are sufficient test track facilities in India to accommodate aerodynamic testing (this is also true for chassis dynamometer testing, which requires coastdown or constant speed testing). Looking at the second criteria, complexity of the certification process, there would likely be a fairly steep learning curve for manufacturers in India to be able to learn an existing simulation model sufficiently enough to successfully navigate the entire certification process. Even if a completely new simulation program is developed for India, no matter how simplistic the model is in terms in inputs and operation, the fact that it is a new tool will mean a certain level of learning is required amongst manufacturers and the regulatory community. Given the long lead-time needed for stakeholders in India to familiarize themselves with simulation modeling and the plethora of other research an engagement required to enact full vehicle standards, it is reasonable to estimate that a regulation in India centered around simulation could not be finalized for another 3 to 4 years. Assuming that the industry needs roughly 3 to 4 years of lead-time after a regulation is codified before actual implementation, our best estimate is that the process of designing, finalizing, and executing a simulation-based full vehicle regulation in India would take roughly 6 to 8 years from now to go into effect.

The chassis dynamometer option is unattractive for India primarily based on the limited number of existing facilities and the significant capital expenditures and time required to construct new facilities.

Introducing engine-based standards in India as a first phase regulation for HDV fuel efficiency is attractive for a number of reasons. This option leverages the strong industry familiarity with engine testing and presents minimal testing and compliance burden to manufacturers. Moreover, a new efficiency improvement requirement based on engine dynamometer testing would not likely require any new testing infrastructure. A list of the accredited organizations in India that do heavy-duty testing is provided in Table 6.

The relatively simplistic nature of engine standards make it such that a regulation could be proposed and finalized within the next 2 years and then implemented by the 2020 timeframe. Thus, electing to pursue engine standards as a first regulatory step maximizes the ability to realize meaningful fuel savings and environmental benefits as soon as possible. The primary downside to engine standards is that they can potentially yield engines that are optimized to the test cycles as opposed to being designed to maximize fuel savings during typical vehicle operations. The extent to which an engine's actual duty cycle in real-world driving differs from the standardized test cycles will dictate the magnitude if this negative impact. However, this issue can be mitigated by introducing weighting factors to the transient and steady-state portions of engine cycles such that engines can be evaluated to better match what the engine will experience in an actual HDV such as a tractor truck or transit bus. This analysis suggests that the benefits of engine standards outweigh the disbenefits, and a first phase regulation in India centered on engine dynamometer testing is the most attractive alternative. Assuming that India develops engine-based standards using existing engine test cycles, there are virtually no technical barriers to finalizing and implementing an engine dynamometer-based regulation by the 2020 timeframe.

Table 6: Accredited organizations in India that perform heavy-duty vehicle testing

Organization	Location(s)
Automotive Research Association of India (ARAI)	Pune, Maharashtra
International Center for Automotive Technology (ICAT)	Gurgaon, Haryana
Vehicle Research & Development Establishment (VRDE)	Vahannagar, Maharashtra
Central Farm Machinery Training and Testing Institute (CFMTTI)	Sehore, Madhya Pradesh
Central Institute of Road Transport (CIRT)	Pune, Maharashtra
Indian Institute of Petroleum (IIP)	Dehradun, Uttarakhand

4.2 TRANSITIONING FROM ENGINE STANDARDS TO A MORE COMPREHENSIVE APPROACH

As engine improvements only represent a subset of the technologies that are available for improving the efficiency of HDVs, India will need to transition from an engine testing-based regulation to a more comprehensive 'full vehicle' approach in order to maximize fuel savings for this sector. This more long-term objective must be able to ensure that technology areas such as aerodynamics, tire rolling resistance, transmissions, and weight reduction are included in the regulatory framework in a manner that makes sense in the Indian context. As discussed in the previous sections, there are a myriad of different regulatory design and test procedure approaches that are available to policymakers in India. Given the challenges and long lead-time needed for deciding amongst these options to create protocols for physical testing and simulation, developing (or adopting) duty cycles, and educating all of the necessary stakeholders about these new procedures, it would be prudent to begin this process as soon as possible. As shown in Figure 4, we recommend that regulators in India actively begin planning the transition to a more comprehensive second phase regulation in parallel to the efforts to design a first phase regulatory program for engines.

If regulatory development for engine standards proceeds such that a proposed rule and then a final regulation can be established over roughly the next 1-2 years, it seems reasonable that implementation can begin in the 2020 timeframe. This would give manufacturers and the industry as a whole approximately three years of lead-time. In addition, as shown in red on the bottom half of the figure, the process for developing full vehicle standards can begin in parallel to the regulatory efforts for engines. Technical studies to support this process would ideally include in-depth analyses in the following areas:

- Market conditions and anticipated impacts
- Vehicle segmentation
- Technology potential
- Test procedures and certification pathways

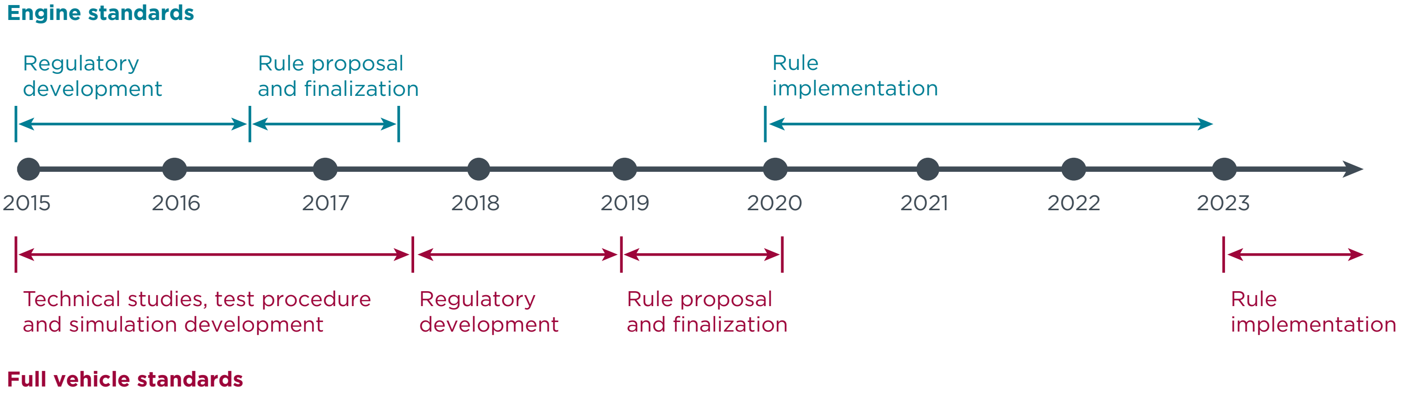


Figure 4: Idealized regulatory timeline for engine and full vehicle standards in India

- Flexibility mechanisms
- Compliance and enforcement

Following these technical studies, regulatory development of this second phase regulation can begin in earnest towards the end of the decade, with a proposed and final rule to be released around roughly the same time that engine standards are commencing implementation in the 2020 timeframe. As with the engine standards, the regulatory program for full vehicles can be implemented starting approximately three years after the regulation is finalized.

5. Conclusions, recommendations, and future work

This study reviewed and summarized HDV fuel efficiency regulations around the world and discussed the pivotal role that test methods and certification pathways play in shaping these programs. Given the complexity of the HDV market and the diversity of commercial vehicle fleet compositions and operations around the world, there has been a proliferation of different regulatory design and test procedure approaches that have been developed in the countries/regions that have established HDV efficiency regulations. A high-level summary of each of these programs is provided in Table 7.

Examining the various options that are available for evaluating the fuel efficiency performance of HDVs, there is no option that is clearly superior in terms of costs, complexity, and accurately representing real-world operations. Each jurisdiction must balance these various criteria in designing a regulation that best suits local conditions.

For India, the ICCT recommends that the first phase HDV fuel efficiency regulation be engine dynamometer-based standards that utilize existing engine test cycles for the following reasons:

- **Leveraging existing testing facilities and expertise:** engine dynamometer testing is well understood within industry and the regulatory community. Piggybacking on existing criteria pollutant testing will minimize the testing and compliance burden.
- **Limiting complexity:** engine testing is relatively straightforward when compared to chassis dynamometer and simulation-based certification.
- **Maximizing fuel savings as soon as possible:** The familiarity and relative simplicity of engine testing makes it such that a regulatory program and certification process centered around engine testing could be established and implemented in the next 4 to 5 years. Conversely, a regulation built upon any of the other test procedure options (i.e., chassis dynamometer, powertrain dynamometer, and/or simulation) would take much longer to develop and fully implement.

In conjunction with the regulatory development process for engines, it is imperative that policymakers in India also embark on the many technical and policy analyses that will be required to move beyond engine-only standards to a regulatory approach that promotes improvements across the entire range of technologies available for HDV fuel savings. By beginning the long-term undertaking of establishing full vehicle standards in parallel to rulemaking activities for engine standards, the transition from an engine-only regulation to a more comprehensive approach can be as streamlined as possible.

Future work for the ICCT will include assessing the HDV market India as well as the technology potential of both trucks and buses. In addition, we will be conducting interviews with a broad cross-section of stakeholders in the HDV industry in India to learn about attitudes, experiences, and expectations about fuel-saving technologies and practices in the sector.

Table 7: Regulatory design summaries for Japan, the U.S. and Canada, China, and the European Union

	Regulatory Categories	Certification Test Procedures	Metric		
Japan	• Other Truck (11 subcategories) • Tractor (2 subcategories) • Route Bus (5 subcategories) • Other Bus (8 subcategories)	Simulation modeling + engine dynamometer testing	Fuel economy (km/L)		
U.S. and Canada	• Tractors • Vocational vehicles • HD pickup trucks and vans • Engines (tractors, voc. vehicles)	Vehicles → simulation model Engines → dynamometer testing	Tractors, Vocational	HD Pickups	Engines
			gal/1,000 ton-mi	gal/100 mi	gal/100 bhp-hr
			g/ton-mi	g/mi	g/kWh
China	• Tractors • Dump trucks • Rigid trucks • City buses • Other buses	"Base" vehicles → chassis dynamometer "Variant" vehicles → simulation modeling	Fuel consumption (L/100 km)		
European Union*	Truck and bus categories based on GVWR, chassis configuration, and axle configuration	Simulation modeling	GHG (g/tonne-km)		

* Regulatory design is currently under development in the EU. This information represents an upcoming certification program, not necessarily a standard.

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Appendix

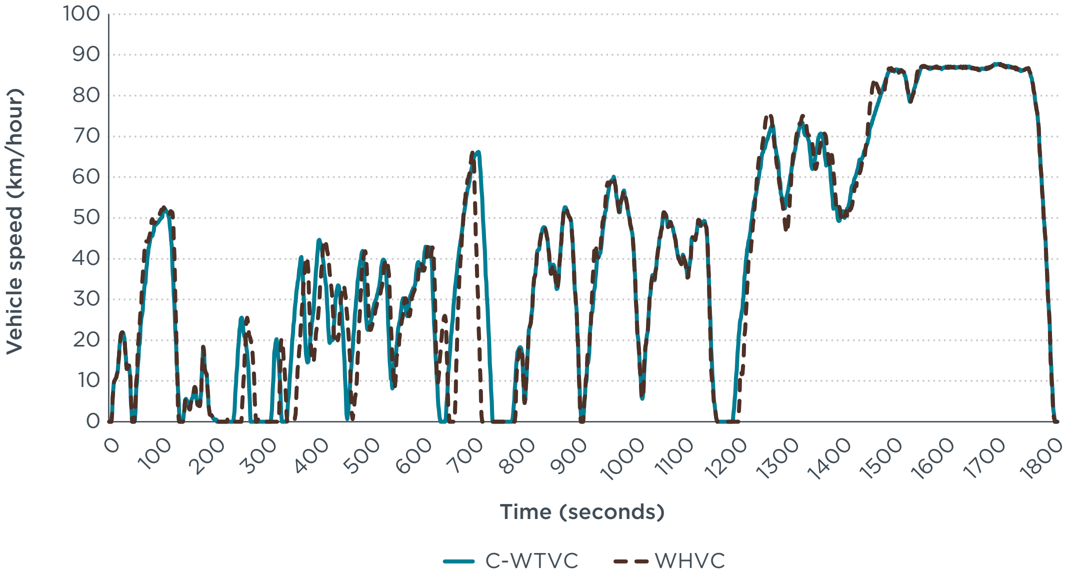

Figure A1: The World Harmonized Vehicle Cycle (WHVC) and the China-World Harmonized Vehicle Cycle (C-WTVC)

Table A1. Commonly used test procedures in the trucking sector

Technology area	Metric	Test method	Example test procedures
Aerodynamics	Fuel savings	Track test, on-road test	SAE J1321, SAE J1526
	Coefficient of aerodynamic drag (Cd) reduction	Wind tunnel	SAE J1252
		Computational fluid dynamics (CFD)	SAE J2966
Tire rolling resistance	Fuel savings	Track test, On-road test	SAE J1321, SAE J1526
	Coefficient of rolling resistance (Crr) reduction	Laboratory drum test	ISO 28580:2009
Powertrain and driveline	Fuel savings	Track test, on-road test	SAE J1321, SAE J1526
		Chassis dynamometer	SAE J2177
		Engine dynamometer	40 CFR 1065

Table A2. Regulatory test cycles in Japan, the U.S. and Canada, and China

Country	Type	Cycle name	Description	Comments and cycle weightings
Japan	**Vehicle**	Heavy-Duty Urban Test Cycle (JE05 mode)	Designed to simulate stop-and-go urban driving	**Cycle weightings (% urban, interurban)** Tractor trucks < 20 tonnes GVW: 80%, 20% Tractor trucks > 20 tonnes GVW: 90%, 10% Other trucks < 20 tonnes GVW: 90%, 10% Other trucks > 20 tonnes GVW: 70%, 30% Transit buses: 100%, 0% Other buses < 14 tonnes GVW: 90%, 10% Other buses > 14 tonnes GVW: 65%, 35%
		Heavy-Duty Interurban Test Cycle	Designed to simulate highway driving at a maximum of 80 kph (includes +/- 5% grade)	
U.S. and Canada	**Engine**	Federal Test Procedure (FTP) heavy-duty transient cycle	Transient cycle that includes segments designed to simulate both urban and highway driving	Vocational vehicle engines tested using the FTP only
		Supplemental Emissions Test (SET)	13-mode steady state test	Tractor truck engines test using the SET only
	Vehicle	Heavy Heavy-Duty Diesel Truck (HHDDT) transient cycle	Designed to simulate stop-and-go urban driving	**Cycle weightings (% transient, 55 mph, 65 mph)** Sleep cab tractor trucks: 5%, 9%, 86% Day cab tractor trucks: 19%, 17%, 64% Vocational vehicles: 75%, 9%, 16%
		55 mph cruise	Designed to simulate highway driving at a maximum of 55 mph	
		65 mph cruise	Designed to simulate highway driving at a maximum of 65 mph	
China	**Vehicle**	China-World Harmonized Vehicle Cycle (C-WTVC)	Slightly modified version of the World Harmonized Vehicle Cycle. Meant to better reflect the duty cycles of Chinese commercial vehicles.	**Cycle weightings (% urban, interurban, highway)** Tractor trucks < 25 tonnes GVW: 0%, 40%, 60% Tractor trucks > 25 tonnes GVW: 10%, 90% Dump trucks > 3.5 tonnes GVW: 0%, 100%, 0% Other trucks < 5.5 tonnes GVW: 40%, 40%, 20% Other trucks 5.5-12 tonnes GVW: 10%, 60%, 30% Other trucks 12.5-24.5 tonnes GVW: 10%, 40%, 50% Other trucks > 24.5 tonnes GVW: 10%, 30%, 60% Transit buses > 3.5 tonnes GVW: 100%, 0%, 0% Other buses 3.5-5.5 tonnes GVW: 50%, 25%, 25% Other buses 5.5-12.5 tonnes GVW: 20%, 30%, 50% Other buses > 12.5 tonnes GVW: 10%, 20%, 70%