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Testing the pollutant emissions and fuel efficiency of a commercial bus in India

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Summary

Between fall 2016 and spring 2018, the International Council on Clean Transportation (ICCT) oversaw a two-part testing campaign at the International Centre for Automotive Technology (ICAT) that evaluated the emissions and fuel consumption of a 7.5-tonne Bharat Stage IV (BS IV) diesel bus in India.¹ This is part of ICCT's ongoing effort to better understand the current real-world performance of heavy-duty vehicles (HDVs) in India and to analyze the opportunities and challenges as the country works to bring its HDV fleet up to world-class emission standards.

Regulatory developments in recent years for both pollutant emissions and fuel efficiency are expected to bring about several technological changes to commercial trucks and buses in India. In September 2016, the Government of India finalized a new regulation for vehicle exhaust emissions that called for a leapfrog transition from BS IV to BS VI standards. The BS VI standards took effect throughout the country for all on-road vehicles, light-duty and HDV, manufactured on or after April 1, 2020. In addition, India has been active in developing fuel consumption norms for HDVs. In August 2017, the country's firstever fuel efficiency standards for HDVs with a gross vehicle weight (GVW) of 12 tonnes or greater were published; the norms for the lighter segment of HDVs between 3.5 and 12 tonnes were finalized only in July 2019. The standards include two phases of regulatory compliance, and Phase 1 went into effect on April 1, 2018. However, this was only for HDVs 12 tonnes or more. HDVs weighing between 3.5 and 12 tonnes were only subject to fuel consumption standards starting on April 1, 2020. Given the delay, it is unclear if the original Phase 2 start date of April 1, 2021 will be delayed, also. Nonetheless, all of these policies are intended to improve air quality by reducing real-world emissions from on-road vehicles, and it is useful to assess how the emissions and fuel efficiency performance of vehicles currently in operation compares to regulatory limits. The bus chassis that we tested for this project is a top-seller and its 3.8-liter diesel engine is the second most prevalent engine displacement size in the commercial vehicle market in India.

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^{1 7.5} tonne gross vehicle weight (GVW). GVW is the maximum operating weight of the vehicle as defined by the manufacturer and includes the vehicle body, occupants, and cargo. The ICCT designed the engine and vehicle evaluations, which were carried out by ICAT on behalf of the ICCT at the ICAT facility in Gurgaon, India. ICCT staff were not present when the testing was conducted.

This paper is organized as follows. The next section outlines the motivation for the research and presents some summary statistics of India's heavy-duty engine and vehicle sales market; we also describe the engine and vehicle specifications of the bus chassis tested. The subsequent section summarizes the data and methods from the engine testing phase of the project, which included three main elements: (1) development of a baseline engine fueling map; (2) creation of a comprehensive energy audit of the engine; and (3) testing of the engine over regulatory cycles to determine emission levels of particulate matter (PM), nitrogen oxides (NO_x), carbon monoxide (CO), and hydrocarbons (HC). After that we detail the data and methods for the chassis testing, and then present and compare the emission results from the engine and the chassis tests. We conclude with some policy recommendations and areas for further testing and research.

Project overview

The vehicle acquired for testing was a 7.5-tonne gross vehicle weight (GVW) bus chassis. A previous ICCT study found that of the Indian HDV sales market for new vehicles in fiscal year 2017-18, roughly 60% of commercial buses were less than 10 tonnes GVW (Sharpe & Sathiamoorthy, 2019); of these buses, 3.8-liter buses were the most common weight rating and they represented 13% of all commercial bus sales that year.

The engine of the bus that we acquired for testing is also one of the most popular in the HDV market in India. Figure 1 shows cumulative sales for commercial HDVs in India by engine volume in fiscal year 2013–14. The blue represents all HDVs greater than 3.5 tonnes, and the brown curve only captures bus engines. In both curves, there is a fairly sharp jump at the 3.8-liter level. For all HDVs in India, the 3.8-liter engine accounts for nearly 25% of all sales. For buses, the 3.8-liter is even more popular, representing about 30% of total sales. The 3.8-liter engine is second only to the 5.9-liter engine in terms of sales in the commercial vehicle market.



Figure 1. Cumulative engine sales by displacement in fiscal year 2013-14

Engine and vehicle specifications

In the first phase of the project, the 3.8-liter engine was removed from the bus chassis, which was acquired new from a dealership in Gurgaon, India. The engine had less than 1 operational hour at the time of purchase, and it was removed to facilitate a series of evaluations on an engine dynamometer. The project's second phase involved placing the engine back into the bus chassis and evaluating the emissions and several other operating parameters using a portable emissions measurement system (PEMS).

Table 1 and Figure 2 summarize the key characteristics of the engine and emission control aftertreatment system. This 4-cylinder, 3.8-liter diesel engine is electronically controlled and uses common rail fuel injection. For controlling nitrogen oxide (NO_x) emissions, the engine is equipped with exhaust gas recirculation (EGR). In an engine with EGR, a portion of the combusted exhaust is recycled back into the intake airstream in order to reduce combustion temperatures; this, in turn, lowers NO_x emissions. A notable side effect of lowering the combustion temperature via EGR is reduced combustion efficiency and higher particulate matter (PM) emissions. As shown in Figure 2, two devices—a diesel oxidation catalyst (DOC) and partial flow filter (PFF)—are being utilized in this aftertreatment system. The exhaust first passes through the DOC, where hydrocarbons (HCs), carbon monoxide (CO), and the soluble portion of PM emissions are oxidized. The PFF downstream of the DOC helps to further reduce PM emissions in order to the achieve the Bharat Stage (BS) IV emission levels.

Parameter	Details	
Engine size	3.8 liters, 4 cylinders	
Maximum rated power	92 kW at 2,400 rpm	
Maximum rated torque	400 Nm at 1,300 - 1,500 rpm	
Fuel type	Diesel	
Fuel injection	Common rail fuel injection	
Emission level	Bharat Stage IV	
Aftertreatment system	Diesel oxidation catalyst and partial flow filter	
Gearbox	GBS 40: 5 forward and 1 reverse gear	
Tires	7.5x16 – 16 PR cross ply / bias	
Maximum length and width	Length: 7.75 m Width: 2.14 m	
Gross vehicle weight	7,490 kilograms (kg)	

Table 1. Key engine characteristics



Figure 2. Schematic of the engine and aftertreatment system used in our testing

Data and methods - engine testing

This section outlines the objectives and key results from the three tasks of the engine dynamometer testing phase of the project.

Brake-specific engine fueling map

The first engine testing task was to develop a fuel consumption map for the entire engine operation range. The engine was tested at 100 distinct speed-torque points, and the resulting engine fueling map is shown as a three-dimensional surface in Figure 3. Fuel consumption in terms of grams per kilowatt (g/kW) is shown on the vertical axis, and the speed-torque points are shown on the two-dimensional horizontal plane. As you can see, the majority of the values are between 250 and 350 g/kW, while there are a few points at high speed, i.e., 2,600 revolutions per minute (rpm), and low load, i.e., less than 150 newton-meters (Nm), where fuel consumption exceeds 500 g/kW.



Figure 3. Engine fuel map

Engine energy audit

The second task of the engine testing was to provide a detailed energy audit for the energy losses and loads across a broad range of engine operational conditions. As part of this, the basic flows and losses of energy were analyzed throughout the engine sub-systems.

The portion of the fuel energy that gets converted into indicated work is a direct measure of the engine's fuel conversion efficiency. Factors that affect an engine's fuel conversion efficiency include irreversibilities in the combustion process, the amount of energy leaving the engine cylinder as heat, and the energy remaining in the exhaust at the end of the expansion process. These losses represent energy from the fuel that did not get converted into useful work. Moreover, not all of the energy that was converted into work in the combustion process makes it to the final engine shaft output. Some of the energy is used to overcome friction, some is used to pump air and fuel into the engine and to pump the exhaust gases out of the engine, and some is used to power engine auxiliaries and accessories. The work that makes it to the drive axle is used to overcome vehicle inertia, aerodynamic drag, and tire rolling resistance forces.

In this project, losses were grouped into four categories: losses to (1) the coolant system, (2) exhaust stream, (3) charge air cooler (intercooler), and (4) friction and accessories. Figure 4 summarizes the energy breakdown at four engine speeds and various power settings. After subtracting the losses from the original fuel energy, we are left with useful brake work, which is shown in the bottom blue wedges. As shown, the percentage of fuel energy that results in useful work—i.e., the brake thermal efficiency of the engine—ranges from about 20% at the lower end of the load spectrum up to 35%-40% for the higher loads. Across the various engine speeds, energy lost in the exhaust stream and to the coolant system are the largest loss categories, and combined they represent between roughly 50% and 70% of the total fuel energy lost. The next largest loss area

is to friction and accessories, which accounts for about 10% to 20% of the total energy. Finally, losses to the charge air cooler range from about 2% to 8%.



Figure 4. Energy audit at various engine speeds and loads

Engine and vehicle emissions testing

The third and final task of the engine dynamometer testing phase was exercising the engine over a number of regulatory test cycles and evaluating the pollutant emissions species of PM, NO_{v} , HCs, and CO. In addition to these criteria pollutants, carbon dioxide (CO₂) emissions were measured and recorded over each of the regulatory cycles. Dynamometer testing was done using two sets of engine speed-load cycles. The first two test cycles—the European Transient Cycle (ETC) and the European Stationary Cycle (ESC)-are the cycles used for BS IV certification. The engine was thus tested using the same test protocols that are done for type approval. The second set of test cycles-the World Harmonized Transient Cycle (WHTC) and the World Harmonized Stationary Cycle (WHSC)—are the cycles utilized for compliance testing under the BS VI standards that started April 1, 2020. Since the engine tested in this project is certified at the BS IV level, we did not expect it to be able to achieve the more stringent emission limits of BS VI. However, we saw value in testing the engine over the WHTC and WHSC, since these cycles place a much greater emphasis on the low speed and load areas of the engine operating map, where it is generally more difficult to control emissions-particularly NO.. As such, the difference in emissions between the two sets of cycles can be instructive as to the extent to which simply changing the regulatory test cycles will cause emissions to increase.

Data and methods - chassis testing

Following the engine testing, the engine was placed back into the chassis, and then the vehicle was subjected to a two-part testing sequence.

The first task involved coastdown testing, which is required to generate the road load data that must be used in setting the appropriate loading conditions on the chassis dynamometer. In preparation for the coastdown runs, weights were placed on the vehicle to get the total weight to 5,500 kg, to simulate 50% payload. In addition, the chassis was instrumented with all of the requisite gauges for measuring vehicle and wind speed, temperature and humidity, tire pressure, and total weight. Regarding the body configuration, the vehicle was coastdown tested as a rolling chassis. If the chassis were to be upfitted with the body exterior and the interior finishes (e.g., seats, flooring, etc.), that would impact the coastdown results. While it would have been ideal to test the bus in a configuration that closely resembled typical operations, the additional expense associated with upfitting the vehicle to its final design as a bus was beyond the scope of this project. Further testing is required to determine the delta in coastdown results between a rolling chassis and a fully upfitted vehicle, and the degree to which the difference ultimately translates into differences in emissions.



Figure 5. Rolling chassis tested in this project

The coastdown testing was performed on a stretch of the Delhi-Jaipur Expressway (National Highway 8). After a warm-up period, the vehicle was accelerated to a speed of approximately 80 kilometers (km)/hour (hr); then the transmission was placed in neutral and the vehicle was allowed to decelerate to roughly 5 km/hr. The testing was done in both directions to reduce the effects of wind speed. Coastdown runs were performed at least five times in each direction. The results from all of the coastdown tests were averaged to derive the final values that were used to set the loading parameters for the chassis dynamometer testing.

The chassis dynamometer testing, the second major task of the vehicle testing campaign, was carried out at the same facility as the engine testing. At the time that this project was being carried out, lab grade instrumentation was not available. Therefore, a PEMS was used to collect and analyze data on NO_x , PM, HC, CO, and CO_2 emissions. The specific parameters for the PEMS measurement are shown in Table 2.

Parameter	Unit	Source	Measurement principle	
THC concentration(a)	ppm	Analyzer	Flame ionization detector	
CO concentration ^(a)	ppm	Analyzer	Nondispersive infrared detector	
NO _x concentration ^(a)	ppm	Analyzer	Chemiluminescent detector	
CO ₂ concentration ^(a)	ppm	Analyzer	Nondispersive infrared detector	
РМ	grams (g)	Gravimetric		
Exhaust gas flow	kg/hr	EFM	Pilot flow meter	
Exhaust temperature	К	EFM	Temperature sensor at flow meter	
Ambient temperature ^(b)	К	Sensor	External sensor	
Ambient pressure	kPa	Sensor External sensor		
Ambient humidity	%	Sensor	External sensor	
Engine torque ^(c)	Nm	OBD port		
Engine speed	rpm	OBD port	D port	
Engine fuel flow	g/second	Fuel flow meter	el flow meter External fuel measurement equipment	
Engine coolant temperature	K	Sensor	Sensor External sensor	
Engine intake air temperature ^(b)	ake air temperature ^(b) K Sensor External sensor		External sensor	

Table 2. Chassis testing parameters

Notes:

(a) Measured or corrected to a wet basis. Heated lines required for reducing HC condensation.

(b) Use the ambient temperature sensor or an intake air temperature sensor

(c) The recorded value shall be either the net torque or the net torque calculated from the actual engine percent torque, the friction torque and the reference torque, according to the SAE J1939-71 standard

Results and discussion

Engine test results

The engine test results from the four cycles are shown below in Figure 6. The data points for each cycle correspond to a particular color: WHSC is blue; WHTC is brown; ESC is green; and ETC is red. Results from the hot cycles are depicted with circles, and triangles represent the cold test results.

The vertical axis captures PM. In the BS IV regulation there are separate targets for the engine over the ETC and ESC, and that is shown by the horizontal red dotted lines: 0.03 g/kilowatt hour (kWh) for the ETC and 0.02 g/kWh for the ESC. The three ETC tests (red circles) are all comfortably below 0.03 g/kWh, and the three ESC tests (green circles) are also below the limit of 0.02 g/kWh. The engine was also able to achieve the PM limits over the cold tests. The horizontal axis captures NO_x results. Not only were the cold tests far outside of the NO_x limits for BS IV, but all of the hot tests failed to fall under the limit, as well. Both the ESC and ETC had NO_x emissions around 4 g/kWh, which is about 15% higher than the 3.5 g/kWh regulatory limit. As expected, the WHSC and WHTC NO_y emissions were even higher and ranged from about 4 to 5.6 g/kWh.



Figure 6. Summary of PM and NO_x emissions results over the engine dynamometer cycles

Emissions of CO and total hydrocarbons (THC) were also evaluated over each of the four engine cycles. Table 3 presents the results, along with the limits for BS IV, for the ESC and ETC cycles, and for BS VI, for the WHSC and WHTC cycles. The result columns are the mean of the three test runs that were made after the engine had been sufficiently pre-conditioned (i.e., "hot" cycles). Emissions of CO and THC from diesel engines can generally be reduced to relatively low levels with a DOC (Sharpe & Delgado, 2016a). As shown, CO and THC emissions over the WHTC cycle, where emissions were right at the BS VI limit of 0.16 g/kWh.

	Carbon monoxide (CO) (g/kWh)		Total hydroca (g/k	arbons (THC) Wh)
Cycle	Regulatory limit	Test result	Regulatory limit	Test result
ESC	1.5	0.00	0.46	0.01
ETC	4.0	0.00	0.55	0.02
WHSC	1.5	0.02	0.13	0.05
WHTC	4.0	0.09	0.16	0.16

Table 3. CO and THC results over the engine dynamometer cycles

Figure 7, below, shows the substantial difference in emissions between the cold and hot start tests for each duty cycle. This difference can come about as a consequence of various factors and fundamental differences in the way the system can operate in a cold versus a hot environment. In the 13-mode ESC steady-state test cycle where the engine is operated at a unique speed-torque point in each mode, the NO_x emissions for the cold test were nearly twice those of the hot test. During the cold ESC test, the engine oil/coolant temperature was coldest in mode 1 and gradually increased as the engine warmed up through the 13 modes. However, the engine oil/coolant temperature was hotter in each of the 13 modes of the hot ESC test than it ever was during the cold test. The difference in the temperature during each mode between hot ESC and cold ESC is shown via the black/gray-dashed line in Figure 7.

Note that engine oil/coolant temperature is commonly used by manufacturers in calibration to identify how cold or hot the engine is running. The intake mass air flow (IMAF) for an engine operating at the same mode only changes if the manufacturer has calibrated it differently for hot and cold temperatures. Higher intake air mass leads to higher peak combustion pressure, leaner combustion, and hence higher engine-out NO_x emissions. The difference in IMAF between the hot ESC test and cold ESC test is shown as the purple line in Figure 7. On average, the IMAF is 20% higher in the cold ESC test, and this suggests a manufacturer calibration change at colder temperatures.



Figure 7. NO_x emissions during ESC test cycle

Higher exhaust temperatures favor HC, CO, and soot oxidation, and the improvements in aftertreatment system efficiency during hot starts are attributable to the higher exhaust temperatures. Figures 8 and 9 show substantial differences in the aftertreatment system efficiencies for CO, HC, and PM between cold and hot start tests. The average CO and HC oxidation efficiencies improved by 23% and 13%, respectively, during the hot start ESC test. Most of the improvement between hot and cold start came from mode 1 of the ESC tests, where the difference in exhaust temperature between hot and cold start is largest. Once the engine is in mode 2, the temperature has minimal effect on CO conversion efficiency; still, there is some observed influence on HC efficiencies. Therefore, tuning or calibration of the aftertreatment system for optimal performance under lower exhaust temperatures in applications that involve a lot of stop-and-go driving will be crucial for achieving real-world emissions reductions that meet BS VI emissions limits. Applications that contain a lot of urban-style driving, like transit buses or inter-city cargo moving, will require such tuning at appropriate temperatures.



Figure 8. CO conversion efficiencies during ESC test cycle



Figure 9. THC and PM conversion efficiencies during ESC test cycle

The NO_x emissions during the cold start ETC tests were also higher than the hot start ETC tests. In Figure 10, below, the difference in the cumulative NO_x emissions increase is observed over the test cycle and the cold start ETC NO_x emissions were 75% higher. Engine manufacturer calibrations for higher IMAF, lean combustion mixtures in cold start conditions are key parameters that increase NO_x emissions. The IMAF during the cold ETC tests was 0%-22% higher than the hot start ETC tests. Additionally, the fuel consumption measured over the cold start ETC test cycle was at least 26% lower than any hot start ETC test, and this indicates a leaner combustion mixture during cold start tests.

While cold start emissions only account for a fraction of the BS VI tailpipe emission standards, there are several vocational duty cycles that could operate predominantly within the cold range of calibrations for a specific engine. This means the engine temperature might always be in the lower range while in operation. In such cases, the manufacturer's calibrations would always recognize the engine as cold and operate cold calibrations that might lead to high tailpipe NO_x emissions.



Figure 10. NO_x emissions during ETC test cycle

Although pre-catalyst HC emissions during the hot start ETC tests were 10% higher than in the cold start ETC tests, the tailpipe HC emissions during the cold start test were five times higher than that of hot start tests. Much of this is attributable to the DOC HC oxidation efficiency, which was 25% lower in the cold start test, as shown in Figure 11. The transient nature of the duty cycle magnifies the significance of aftertreatment system efficiencies at lower temperatures as compared to steady state conditions. Since all on-road in-use operation is transient, it is critical that manufacturers calibrate aftertreatment systems to optimize system efficiency for transient response.



Figure 11. PM, HC, and CO conversion efficiencies during ETC test cycle

As expected, the NO_x emissions from the BV VI WHSC test cycle were substantially higher during cold and hot start tests in comparison with the BS IV-equivalent ESC test cycle. Figure 12, below, shows that the WHSC operates the engine at lower engine speeds and the NO_x emissions at these points are much higher than comparable ESC points. This indicates that a carryover BS IV engine might need both NO_x aftertreatment systems and major revisions to base engine calibrations to meet BS VI standards.





Figure 13 shows the DOC conversion efficiency during the WHSC cycle and reveals characteristics similar to the ESC as far as improved HC and CO conversion efficiencies during the hot start tests. However, the PM filtration efficiency is higher during cold start tests. A 14% variance in PM filtration efficiency was observed between the three hot start WHSC tests. Such large variations between runs can be expected in applications using partial flow filters (PFF) that rely only on passive regeneration once the filter is saturated. So, in the event that the PFF reaches its maximum soot capacity, in the absence of regeneration, PM emissions would be allowed to pass through the structure. It is expected that diesel particulate filters (DPFs) with active and passive regeneration capabilities will be used in all BS VI diesel commercial vehicles. This highlights the importance of aftertreatment system status at the time of certification tests. A clean DPF will have lower filtration efficiency than a DPF filled at maximum capacity; as such, it is important to understand the amount of time a vehicle will spend with a full DPF versus a clean DPF over its lifetime. This can inform discussion about how much the DPF should be loaded at the time of a certification test.





The comparison between the WHTC and the BS IV-equivalent transient cycle, ETC, revealed that the tailpipe NO_x emissions from the WHTC hot start tests were higher by at least 18% and were about 9% lower at cold start. However, a potential tailpipe (post-catalyst) sample leak was identified during the WHTC tests. This implies that the tailpipe WHTC emissions values reported in this paper are likely lower than what was actually emitted by the vehicle. Even so, the engine-out NO_x and PM emissions were about 21% and 35% higher than the ETC tests. Similar to the findings from the WHSC-ESC test comparison, this is evidence that carryover BS IV engines would need major revisions to base engine calibrations in order to meet BS VI limits.

Chassis test results

The vehicle was tested over three distinct chassis test cycles, which are shown in Figure 14.² Derived from the WHVC, the WHVC-India cycle, the blue curve in Figure 14, was created by the ICCT to account for the fact that HDV speeds on highways in India are typically much slower than in other major markets such as the United States and the European Union. In ongoing research to assess the fuel efficiency technology potential of commercial vehicles in India, we have used the WHVC-India cycle in simulation modeling (Sharpe, Garg, & Delgado, 2018; Karali, Gopal, Sharpe, Delgado, Bandivadekar, & Garg, 2017). As such, we wanted to use the WHVC-India cycle in the chassis dynamometer testing to help validate our simulation modeling.

In addition, the vehicle was exercised over the ARB Transient cycle (the green curve) and a constant speed fuel consumption (CSFC) cycle (the purple curve). We selected the ARB Transient cycle to evaluate the vehicle in highly urban, stop-and-go driving conditions. In contrast, the CSFC cycle represents steady-state conditions that are typical of highway driving in India. Another added value of chassis dynamometer testing over the CSFC cycle is that in the first phases of fuel efficiency regulations for HDVs greater than 12 tonnes and between 3.5 and 12 tonnes in India, trucks and buses are evaluated on a test track at constant speeds—40, 50, and/or 60 km/hr, depending on the type and size of vehicle.

² The World Harmonized Vehicle Cycle (WHVC) is shown for reference. The WHVC-India cycle is identical to the WHVC for roughly the first 1,200 seconds, and then afterward the speeds of the WHVC are multiplied by 0.7 to produce the speeds for the WHVC-India.



Figure 14. Cycles used for the chassis dynamometer PEMS testing

To assess the accuracy of both our simulation modeling and our chassis testing results, we created a vehicle model in Autonomie to match the real-world bus chassis as closely as possible. We calculated the aerodynamic drag and rolling resistance coefficients for the virtual vehicle by using the road load data that was generated during coastdown testing. In addition, we matched the total vehicle weight, axle ratios, transmission gear ratios, and tire size. In a previous study (Sharpe et al., 2018), we created a virtual model of the 3.8-liter engine by using the engine fuel consumption map and energy balance data that was generated during the engine testing campaign.

Figure 15 shows the fuel consumption results from the chassis testing on the x-axis and from the simulation modeling on the y-axis. The measured fuel consumption values for the two WHVC chassis dynamometer runs are shown in the blue circles, and the ARB Transient data points are the orange triangles. For the WHVC-India and ARB Transient cycles, the fuel consumption values generated in Autonomie are lower than the average of the two sets of chassis testing results by 6% and 10%, respectively. Further comparison of real-world testing results with simulation results is necessary over a wider range of vehicle types, sizes, and drive cycles to better assess if the simulation modeling is systematically underestimating fuel consumption and the factors driving these differences.



Figure 15. Comparison of fuel consumption results from chassis dynamometer testing versus simulation modeling

The fuel consumption results over the constant speed test cycle, shown in Figure 16, are quite relevant from a regulatory perspective. The blue and orange data points are the results from only the constant speed portions of the cycle at 40 km/hour and 60 km/ hour, respectively; the acceleration and deceleration portions of the CSFC are ignored, as is the case in the official test procedure for India's HDV fuel consumption regulation. In addition, the maximum fuel consumption levels for this vehicle segment are shown with the corresponding blue and orange dashed lines. With a value of 8.4 I/100 km at 40 km/hour, this bus is well below the limit of 10.3 I/100 km. At 60 km/hour, the fuel consumption result of 12.7 I/100 km is just below the regulatory limit of 13.0 I/100 km.





Comparison of engine and chassis results

Recall from above that NO_x emissions during engine testing were roughly 15% higher than the regulatory BS IV limit value of 3.5 g/kWh. In order to compare the engine and vehicle results, some post-processing of the raw chassis dynamometer data was required to calculate total engine work performed during each vehicle cycle.³ Then, by dividing the total grams of NO_x by the amount of work performed by the engine during the vehicle cycles, we arrive at the g/kWh values that can be used for comparison with the engine dynamometer results. The NO_x results from the vehicle PEMS testing are presented in Figure 17. As you can see, NO_x emissions over the vehicle cycles were fairly comparable to the engine-based results for all of the runs except WHVC1.



Figure 17. Engine and chassis dynamometer NO_x emissions over the various cycles

³ Engine work is expressed in kilowatt hours (kWh).

Regarding the results from WHVC1 and WHVC2, further analysis was needed to determine why NO_x emission rates were nearly 2.5 times higher during WHVC2. Analysis of that testing run indicated that although the speed traces for the two cycles remained identical, the operating points on the engine map significantly varied. To show the fundamental difference between the two cycles, 4 load bins, as shown in Table 4, were created to indicate where the engine operated predominantly between the two cycles. As can be seen in Figure 18, WHVC1 operated in Bin 3 (~35%) predominantly while WHVC2 operated in Bin 2 (~40%).

Table 4. Bins associated with engine loads

Bin	Load %
1	0-25
2	25-50
3	50-75
4	75-100

High engine speeds increase in-cylinder temperatures, and that consequently drives higher NO_x emissions. Further investigation of the data from WHVC1 and WHVC2 revealed that both cycles operated predominantly in Bin 1 or Bin 2. Figure 18 groups the amount of time the engine spent at each RPM during WHVC1 and WHVC2. The blue columns indicate the time spent at each RPM, the red line traces cumulative percentage of total cycle time, and the dashed black box represents 80% coverage of total cycle time. The time spent and the groupings for WHVC2 were longer at higher RPMs, indicating the vehicle operated at a higher RPM in both Bins 1 and 2 compared to WHVC1.



Figure 18. Speed distribution for WHVC1 and WHVC2

The two ARB test cycles that have repeatable values of NO_x emissions operated with similar weightage across the load bins. The speed distribution within their predominant Bins 1 and 2 (together weighing approximately 75% of the test cycle) were also similar, as seen in Figure 19. This suggests that operator influence, even in driving the same

test cycle, can substantially impact where the engine operates under the engine power curve. Even in a controlled test environment where the operator is asked to match target wheel speed, substantial differences in emissions are revealed between cycle repeats. Chassis dynamometer tests were originally incorporated into standard emissions testing requirements to closely mimic in-use conditions. But as large deviations between emissions from chassis tests and in-use tests were identified, requirements evolved to adopt on-road in-use testing using PEMS equipment. BS VI is one step closer in the ongoing effort to get closer to in-use representation. While BS VI does not include chassis testing requirements, these results raise an important discussion around the repeatability of in-use testing results where conditions can be more dynamic just depending on the time of day, due to weather and traffic differences, operator acceleration and deceleration profiles, and how off-cycle emissions (OCE) test cycles would capture such variance to represent in-use emissions.



Figure 19. Speed distribution for ARB1 and ARB2

Engine temperatures and exhaust flow rates change as a result of operating at different engine speed and load conditions. Figure 20 compares the exhaust flow rate, exhaust temperate, and NO_x emissions between WHVC1 and WHVC2. Areas of higher NO_x emissions marked by the red circles correspond to areas of higher exhaust temperatures marked by yellow circles.



Figure 20. NO_x emissions, exhaust flow rate, and exhaust temperature over WHVC1 (top) and WHVC2 (bottom)

The NO_x emission rates from the other three chassis dynamometer runs ranged between 4.3 and 5.4 g/kWh, which is very similar to what was observed from all the engine-based results (3.9 to 5.6 g/kWh). Overall, the NO_x levels from both the engine and chassis testing provide evidence that this vehicle's real-world NO_x emissions are up to 55% higher than what would be expected if the engine was fully compliant with BS IV standards. The average of the fuel consumption rates from the transient WHVC tests was about 15.7 I/100km—that is at least 23% higher than the fuel consumption rates obtained from the CSFC tests and at least 24% higher than the regulatory limit.

That the emissions from a new engine were found to be out of compliance during the chassis and engine tests raises concerns over what the in-use emissions might be like at mid-life and near end of useful life, after several hours of engine and aftertreatment system deterioration. Furthermore, the difference between the ARB and the WHVC test results shows the effect that in-use dynamic vehicle operation has on tailpipe emissions and aftertreatment system efficiency.

Figure 21 presents the PM results from engine testing and the total engine work performed during each vehicle cycle. Ranging between 0.02 and 0.03 g/kWh, the results from the two ARB vehicle cycles are similar to the values from the engine testing. In contrast, the two runs over the WHVC cycle resulted in PM emissions between 0.11 and 0.13 g/kWh, which is roughly five times the results from any of the other engine or vehicle tests. Recall that Figures 18 and 19 showed the weighting factor of the ARB 1, 2 and WHVC 1, 2 test cycles across the four load bins in which the engine operated. This shows how the difference in test cycles led to differences in exhaust temperatures and exhaust flow rates.





Conclusion and policy recommendations

The ICCT designed and managed a testing program of an HDV engine and chassis at the International Centre for Automotive Technology in Gurgaon, India, between fall 2016 and spring 2018. The 7.5-tonne commercial bus selected is a top-seller in its segment, and the vehicle's 3.8-liter diesel engine is the second-most prevalent engine displacement size in the on-road commercial vehicle market in India.

The first phase of the project involved a three-part engine dynamometer evaluation. Following the successful development of an engine fuel map and after conducting an energy audit, we created and validated a virtual engine model that we have used for simulating the performance of a 12-tonne rigid truck and 7.5-tonne bus (Sharpe et al., 2018). The energy audit concluded that only 20%-35% of fuel energy results in useful work with 50%-70% of energy lost in the exhaust and coolant system as heat.

The engine testing over the cycles used for type approval revealed that NO_x levels are roughly 15% higher than the BS IV limits. Given that we only tested this single engine, it is unclear whether all of the models sold in this engine family would have NO_x emissions that exceed the BS IV limit. Moreover, it is important to note that the engine used for all testing and evaluation was new and had fewer than 10 operational hours at the start of the program. This raises concerns about this engine's emissions range near the end of its useful life. While the vehicle was expected to perform sub-optimally since it was not degreened per manufacturer recommendations, the vehicle was still run for 20 hours prior to any data collection and tailpipe emissions are still expected to be within BS IV limits at all stages of the engine's useful life.

Overall, we observed lower aftertreatment system efficiencies for HC, CO, and PM conversion during the cold start tests. These characteristics are mostly attributable to manufacturer calibration strategy and that strategy is expected to change significantly when vehicles are calibrated for BS VI. The analyses of individual engine test runs also sheds light on the substantially higher emissions during all cold start tests as compared to hot start tests. While this was not a concern for BS IV vehicles, even using a 10% weighting factor like in WHTC, the NO_x emissions increase to 23% from 15% over the

BS IV limit. It is very likely in real-world conditions, especially in colder regions of the country, that cold start and cold engine operation could contribute to at least 10% of daily operation.

The NO_x emissions rates from the transient chassis dynamometer runs ranged from between 4.3 and 5.4 g/kWh, which is very similar to what was observed from the engine-based results (3.9 to 5.6 g/kWh). Overall, the NO_x levels from both the engine (ESC and ETC only) and chassis testing provide evidence that this vehicle's real-world NO_x emissions are up to 15% and 55% higher (respectively) than what would be expected if the engine was fully compliant with BS IV standards. Given the variability observed between repeated transient tests on the chassis dynamometer on a new, low-hour engine, there are concerns about the effects of the in-use dynamic conditions such as grade, weather, and traffic.

Owing to driver influence, the engine operating points vary greatly even while repeating the same vehicle speed profile in WHVC1 and WHVC2. This leads to different combustion strategies, exhaust flow rates, and temperatures, and that, in turn, results in different NO_x emissions for the same test cycle. The difference in PM emissions between the WHVC and ARB cycles further shows how changing vehicle speed profile and transience can have major effects on vehicle emissions.

The results from the CSFC tests showed that the vehicle met the regulatory standards for required fuel economy at 40 km/hr and 60 km/hr. However, the fuel consumption over the transient WHVC test was 15.7 l/100 km, or 24% higher than the regulatory limit. This leads us to believe that the fuel economy numbers from CSFC tests underestimate in-use fuel consumption and suggests that modification of testing requirements and regulatory standards to more appropriately represent in-use driving is necessary.

Recommendations to policymakers

BS IV engines do not have to meet any regulatory requirements for cold start emissions, and results from engine tests in this study suggest poor manufacturer calibrations for cold start engine conditions. While BS VI emission standards do treat cold starts, they place a 14% weightage on cold start emissions; it is likely that in several stop-and-go applications an engine will operate cold for longer than 14% of its daily operational hours, especially in winter months. Policymakers should therefore consider increasing the weightage on cold start emissions to improve manufacturer accountability in engine tests and/or in-use tests designed to capture cold engine emissions.

In the transition to BS VI, most manufacturers will be introducing entirely new aftertreatment technologies for controlling NO_x and PM emissions, including SCRs, lean NO_x traps, and DPFs, and this makes the need for independent testing that much more acute. The tests need to examine a wide range of engine models and sizes across the heavy-duty spectrum in India to better understand the distribution of emission levels and how emission control systems are performing under real-world conditions—especially concerning NO_x . Moreover, as efforts are made to improve testing requirements to resemble in-use activity, it is important over the next few years to check in-use emissions compliance in order to realize the gains from tighter emission standards.

Although BS VI standards include both in-service conformity (ISC) tests and PEMS tests for compliance, results from the vehicle tests in this study show the influence of driver behavior on emissions. Driver influence combined with other in-use dynamics like traffic, grade, and weather need to be factored in when assessing results from in-use tests. Current ISC and PEMS test requirements only warrant one valid test, and this will not accurately capture the wide variability of conditions in which the vehicle might operate during its regular operation. This warrants multiple runs from the same vehicle, even along the same route, at various times of the day, week, and even month. Furthermore, we see from cycles like ARB and WHVC in this study that the vehicle operated for significant portions in low load, low RPM ranges; it is important to account for these operating points to get a representative in-use emissions value. The current data evaluation method allows for 10% of the valid dataset collected to be out of compliance and low load/low speed operation to be excluded from evaluation. The method should be revised to instead require 100% compliance and evaluation of data all the way to idle, and this should be mandatory as part of both in-service and PEMS testing.

While India made efforts in 2017 to include testing requirements as part of HDV fuel consumption standards, there is good reason to consider replacing the two steady state tests currently used with a representative duty cycle for each vehicle class. Results from CSFC evaluations are far from the real-world fuel consumption values and this highlights the need to develop new maximum fuel consumption levels based on representative test duty cycles.

Since BS VI is largely adopted from Euro VI, lots of lessons can be drawn from past studies (Posada & Rodriguez, 2019; Yang, Muncrief, & Bandivadekar, 2017) that have identified gaps in Euro VI; these offer Indian policymakers an opportunity to revise standards and correct course in the early stages of BS VI. Finally, this is just one part of a suite of policies that India can use to improve the real-world emissions performance of its vehicle fleet. Other options include conducting reliable testing and checks at all stages of production and vehicle use, prioritizing data and information transparency, and creating a penalty system and corrective actions when problems are identified.

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