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Real-world emissions performance of a Bharat Stage VI truck and bus

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Introduction and background

In 2015, India ranked second to China in the number of premature deaths attributable to transportation emissions (Miller et al., 2019). Additionally, on-road diesel vehicles have been shown to be the greatest contributor to the overall health burden from transportation-related air pollution (Miller et al., 2019). India has some of the highest population-weighted levels of ambient fine particulate matter ($PM_{2.5}$) and ground-level ozone in the world, and understanding and reducing in-use vehicle emissions is critical for assessing and improving ambient air quality.

The quality of diesel fuel is an important component in improving tailpipe emissions from vehicles. The reduction in sulfur limits in Bharat Stage (BS) VI diesel fuel standards, among limits on other pollutants, is significant because sulfur is known to have detrimental effects on diesel emission control systems that lead to increases in tailpipe emissions of nitrogen oxides (NO_x) and PM. In 2020, the ICCT completed a fuel study that found all samples tested for BS VI fuel standards were compliant with sulfur limits (Sathiamoorthy & Bandivadekar, 2020).

While it is encouraging that the fuel being used in India results in better emissions control, ultimately, real-world tailpipe emissions are what matter. To this end, the BS VI emission standard requires that manufacturers comply at an engine level and at a vehicle level by means of in-service conformity (ISC) testing. ISC tests are on-road and are intended to capture and regulate real-world emissions. ISC testing is being introduced in India for the first time with the BS VI regulation; this study is focused on quantifying the emissions performance of a BS VI diesel truck and bus in real-world operation.

Table 1 shows the timeline in which India has implemented heavy-duty emission standards and the limits for various pollutants over the engine certification cycles. Although the year column refers to the date of nationwide implementation, several cities and states adopted the standards ahead of those dates.[1]

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[1] https://www.transportpolicy.net/standard/india-heavy-duty-emissions/

Table 1. Progression of BS emissions limits

Year	Standard	Tests	CO (g/kW-hr)	HC (g/kW-hr)	CH_4 (g/kW-hr)	NO_x (g/kW-hr)	PM (g/kW-hr)	PN (#/kW-hr)	NH_3
2010	BS III	ESC	2.1	0.66	—	5	0.10/0.13[a]	—	—
		ETC	5.45	0.78	—	5	0.16/0.221[a]	—	—
2017	BS IV	ESC	1.5	0.46	—	3.5	0.02	—	—
		ETC	4.0	0.55	—	3.5	0.03	—	—
2020	BS VI	WHSC (CI)	1.5	0.13	—	0.40	0.01	$8X10^{11}$	10 ppm
		WHTC (CI)	4.0	0.16	—	0.46	0.01	$6X10^{11}$	10 ppm
		WHTC (PI)	4.0	0.16	0.5	0.46	0.01	$6X10^{11}$	10 ppm

[a] For engines with swept volume <0.75 liter per cylinder and rated speed > 3,000 rpm

ISC regulatory requirements

ISC requirements were included in the BS VI emission standards and regulations to make manufacturers more accountable for in-use emissions and to bridge the gap between lab-based emissions and real-world emissions. BS VI took effect on April 1, 2020, but the conformity factors (CF) used to assess ISC compliance were not established at that time because the ISC tests are not mandatory until April 2023. However, the requirements for testing and data processing have been established in Part IV of AIS 137 (MoRTH, 2019). The BS VI in-use portable emissions measurement system (PEMS) test will be performed to demonstrate compliance starting in 2023 and the tests are performed based on a well-defined range of conditions. Standards and provisions for the ISC tests in India were largely derived from Euro regulations, but India's ISC requirements have some large gaps to cover in comparison to the latest, Euro VI-E provisions.

Compliance for ISC tests is evaluated using mass emissions calculated for subsets of a complete data set, and these are called windows. The method used for calculation is called the moving average window (MAW) method. The window size is determined either by the work done over the World Harmonized Transient Cycle (WHTC) cycle (work-based MAW) or the CO_2 mass produced during the WHTC cycle (CO_2-based MAW). In India, the validity of each window is determined by the conditions in Table 3, below. If a window does not meet the requirements in Table 3, it is not considered valid for evaluation. If the average of 90% of all valid windows is less than the ISC limit ($CF_{pollutant}$ proposed in Table 3 x WHTC certification limit), the vehicle is deemed compliant with ISC requirements.

Table 2 details the Euro ISC requirements over time. India's emissions standard and the ISC test requirements proposed in Part IV of AIS 137 are almost the same as what was required in Euro VI-C. In the Euro standards, the engine power and minimum coolant temperature thresholds, which allow for data exclusions during processing, were reduced in the subsequent Euro VI-D and Euro VI-E regulations, respectively, to account for more low-load operation and to include cold-start emissions. CFs for particle number (PN) compliance were also added in Euro VI-E and a weighting factor of 14% was used to include cold-start emissions (30 °C – 70 °C) while calculating CF for compliance. Nonetheless, the Euro VI-E in-use PEMS testing still does not cover all real-world operating conditions.

Table 2. Euro ISC timeline of implementation and requirements

Stage	Implementation date (new types/ all vehicles)	Power threshold for PEMS data (of maximum power)	Minimum coolant temperature for PEMS data	PEMS CF (CO, HC, NMHC, CH_4, NO_x)	PEMS PN CF
A	2013.01/2014.01	20%	70 °C	1.5	—
B (CI)	2013.01/2014.01				
B (PI)	2014.09/2015.09				
C	2016.01/2017.01				
D	2018.09/2019.09	10%			
E	2020.09/2021.09		30 °C		1.63

Tables 3 and 4 below summarize the key requirements for ISC testing in India.

Table 3. India ISC timeline of implementation and requirement

Stage	Implementation date	Power threshold for PEMS data (of max power)	Minimum coolant temperature for PEMS data	PEMS CF (CO, HC, NMHC, CH4, NO_x)	PEMS PN CF
BS VI	April 1, 2023	20%	70 °C	1.5	—

Table 4. India's ISC testing requirements

Testing requirements	3 engines per engine family. First test at 18 months from the date of registration of the vehicle and every 2 years thereafter over its useful life.
Payload	50%–60% of maximum payload.
Trip requirements	20%/35%/45% urban/rural/motorway driving for M3 and N3 category heavy-duty vehicles (HDVs).
Test length	Minimum 5 times the work done over WHTC or minimum 5 times the CO_2 reference mass produced from the WHTC.
Ambient conditions	Temperature greater than or equal to 0 °C and less than or equal to 42 °C. Pressure greater than or equal to 82.5 kPa (~1,600 meters elevation).
DPF regeneration	If regeneration occurs during testing, the manufacturer can request that the trip be voided.

Studies in Europe have found substantial gaps between real-world emissions and those certified through compliance testing (European Commission, 2018). Studies have also found that the real-world performance of Euro VI-C and Euro VI-D trucks leave large gaps that need to be addressed by the regulations, and that even Euro VI-E provisions are not sufficient to bridge those gaps (Giechaskiel et al., 2019; Grigoratos et al., 2019; Vermeulen et al., 2019, Rodriguez et al., 2021). Still, the proposed ISC requirements in India will lag the Euro provisions by 7 years unless additional steps are taken. Currently, there is no public information available about the real-world emissions performance of Indian HDVs and little information available about in-use BS VI HDV emissions overall. This work aims to address that gap by testing two vehicles.

Study objectives

We aim to quantify the real-world emissions performance of two BS VI commercial vehicles with a focus on improving the ISC requirements in future regulations. The analysis additionally does the following:

- Compares BS VI commercial vehicle emission results with the BS VI standards.
- Evaluates in-use, low-load operation, cold-start emissions, and the performance of BS VI vehicles. The study compares results based on different evaluation

techniques by extending boundary conditions. We did this by lowering the engine coolant temperature threshold to include cold-start emissions for compliance evaluation and lowering the engine power threshold to include low-load, low-speed operating conditions.

» Evaluates fuel efficiency by comparing in-use fuel consumption with fuel consumption following the constant speed fuel consumption (CSFC) requirements.

Methodology

We contracted a testing partner, HORIBA India, and chose two test vehicles based on their sales-based market representativeness in the respective truck (N3) and bus segments (M3) of interest. Both test vehicles were model year 2020 and certified to BS VI emission standards.

Table 5. Test vehicle specifications

Segment	Bus (M3)	Rigid truck (N3)
Emissions	BS VI	BS VI
Engine displacement	3.0 L	3.8 L
Model year	2020	2020
Engine power	74 kW	150 kW
Engine torque	300 Nm	450 Nm
Fuel tank capacity (liters)	120	185
Max. GVW (kg)	8,500	16,100
Length (mm)	9,750	5,287
Axle configuration	4x2	4x2
Odometer mileage	750 km	1,600 km

Both vehicles contain the aftertreatment systems package that is most common among all BS VI commercial vehicles sold in FY 2020–21: exhaust gas recirculation (EGR) with a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF), and selective catalytic reduction (SCR).

Figures 1 and 2 show the test truck and the bus, respectively, along with the PEMS and payload setup during the testing program. Also shown are the different sensors used by the manufacturers in the emission control system; these communicate to different controllers as calibrated by the manufacturer. PEMS was used to collect the emissions data from the vehicles, which were driven on different routes. Other parameters broadcast on the controller area network (CAN) bus were captured by an on-board data (OBD) acquisition system connected to the vehicle's OBD port. Data from the PEMS and OBD were merged at both 10 hz and 1 hz resolution for each test. Jerry cans loaded with stones were used to simulate the payloads for the various tests.

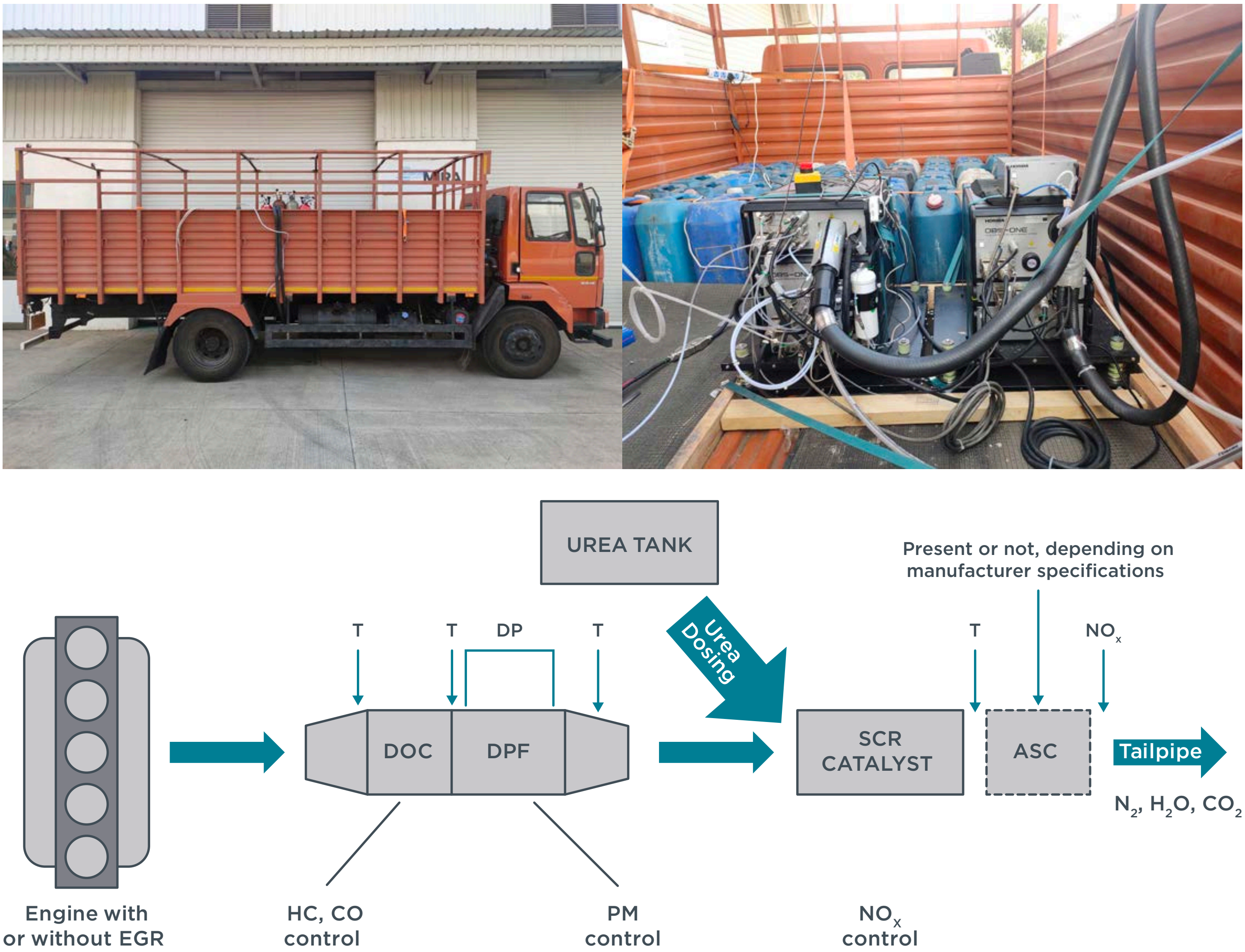

Figure 1. Truck setup and schematic

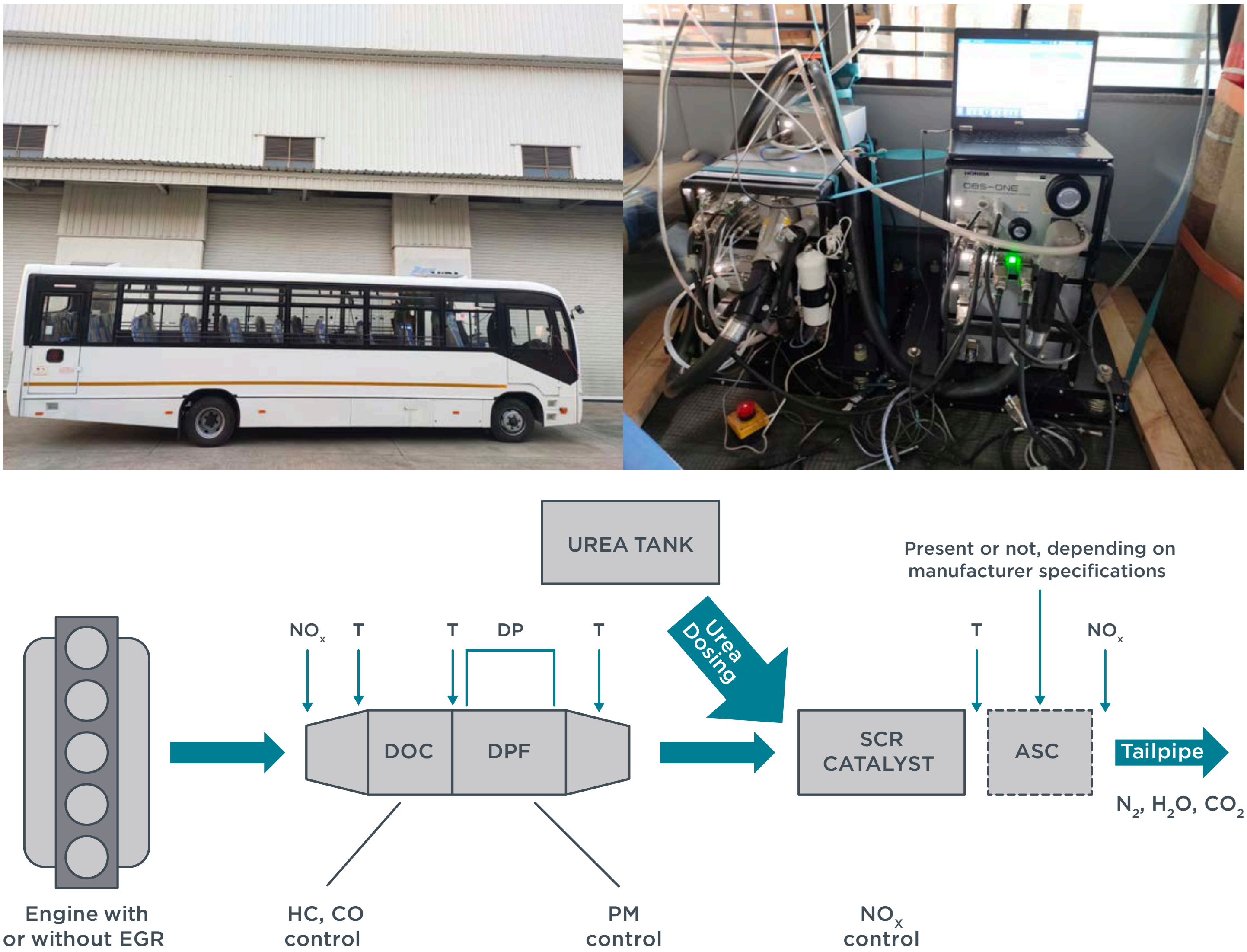

Figure 2. Bus setup and schematic

Each vehicle was tested on three routes and Table 6 summarizes the differences between the routes. One was compliant with the requirements in Part IV of AIS 137, and that is referred to as AIS-ON. The other two routes were not limited by any requirements and ran with increased urban time shares to evaluate the emissions performance over a wider range of conditions typical of normal operations. These two unrestrained routes are referred to as AIS-OFF and AIS-OFFLL.

Table 6. Test summary

Test vehicle/ Route		AIS-ON	AIS-OFF	AIS-OFFLL	WHTC work (kW)	WHTC CO_2 (g)	WHTC certified NO_x (g/kW-hr)	WHTC certified PM (g/kW-hr)
Truck	Payload	55%	55%	5%	13	7,800	0.205	0.0046
	Trip characteristics (urban, rural, motorway)	22%/34%/44%	40%/38%/22%	99.3%/0.6%/0.1%				
Bus	Payload	50%	15%	7%	8.65	6,195	0.028	0.0015
	Trip characteristics (urban, rural, motorway)	24%/34%/42%	41%/32%/27%	100%/0%/0%				

While, as stated above, the AIS-ON tests were carried out fully compliant with the test requirements in Part IV of AIS 137, the other routes had increased urban time shares, and for the bus, the payload was reduced to 15% of maximum allowable payload. The low-load AIS-OFFLL tests were urban-only routes with minimal payload that was limited to essential on-board equipment and personnel on the test vehicles. All tests included cold-start operation. Cold-start phases generally contain high NO_x emissions and we analyzed the data processed both with and without cold-start emissions. The reference work and reference CO_2 from the WHTC certification cycle were used for all data processing. The manufacturer-certified values for NO_x and PM on the WHTC cycle are also listed in Table 6 as WHTC-certified.

Data processing

All the pre-checks, post-checks, calibrations, and post-processing of raw data was carried out for every test following AIS standards. The post-processed test data was additionally subject to different ISC evaluation boundary conditions to understand the emissions performance over a wide range of operating conditions and assess the efficacy of ISC evaluation conditions in capturing real-world emissions over key challenging conditions. The WHTC reference work was used for the MAW processing for the evaluations.

We evaluated the data following provisions in Part IV of AIS 137, for BS VI compliance, and additionally applied the Euro VI-D and E provisions to the same test data. We also conducted a comprehensive, no-exclusions-based assessment of real-world emissions performance at different engine loads and speeds. AIS boundary conditions were also extended to include cold-start, low-load, and low-speed operations, and we evaluated the impact on compliance.

For evaluation of fuel consumption, the data captured from the OBD was used to assess compliance with CSFC standards at 40 km/h and 60 km/h, and to compare the actual, in-use (transient) fuel consumption over the entire cycle for each route with current limits.

Scope of compliance evaluation

We evaluated in-use NO_x emissions against the WHTC and ISC limits by applying AIS provisions and Euro VI provisions. For PN, we evaluated emissions results against laboratory the WHTC PN limit and our recommended ISC limit. The test data was evaluated applying the provisions in Part IV of AIS 137, Euro VI-D, and Euro VI-E for conformity of in-service vehicle testing.

This study assumes India’s currently proposed CF of 1.5 for NO_x and assumes the same CF for PN, even though a CF for PN is not currently within the scope of ISC under AIS regulations. The window validity criteria differ between AIS, Euro VI-D, and Euro VI-E provisions, and owing to these differences, the results obtained for final compliance are also different.

Results

As shown in Figure 3, below, using AIS provisions, both the truck and the bus were well under the ISC and WHTC limits for NO_x. Using the Euro provisions, the NO_x results increased for both vehicles, but the truck remained well under both the ISC and WHTC limits. The NO_x emissions from the bus, however, were 1.75 to 2.2 times higher than the WHTC limit on the AIS-OFF and AIS-OFFLL test routes.

Regarding PN, when AIS provisions were applied, the truck was nearly 2.2 to 2.5 times higher than the WHTC limit on the AIS-ON and AIS-OFF routes. The bus was within with both laboratory and recommended PN limits on all routes. As expected, the truck also exceeded laboratory and recommended PN limits for WHTC and ISC, respectively, when the Euro provisions were applied. When Euro provisions were applied to the bus, it was within recommended ISC limits on all routes and marginally exceeded the WHTC limit on the AIS-ON route.

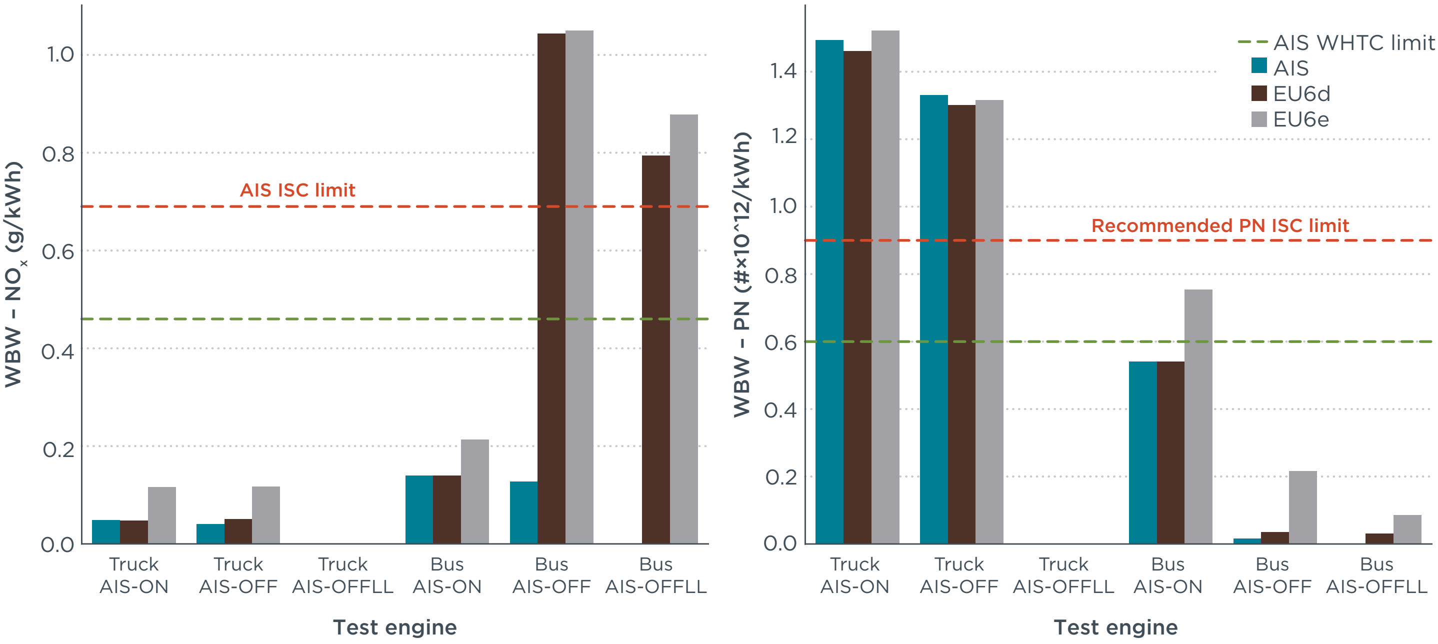

Figure 3. NO_x (left) and PN (right) emissions using AIS and Euro provisions

The low-load test cycle did not have any valid windows after applying AIS or either of the Euro provisions for the truck. For the bus, 75% of windows were valid when Euro VI-E provisions were applied and there were no valid windows otherwise. This is the reason for the absence of some AIS-OFFLL bars in Figure 3—the windows all fell under the 10% average window power criteria used to filter data in the AIS and Euro provisions.

The increase in emissions under Euro VI-D provisions as compared to AIS is due to the inclusion of additional windows with lower power (10%–20% of rated power) and the further increase in emissions under Euro VI-E provisions is due to the inclusion of windows with lower coolant temperatures (30 °C – 70 °C). The difference between the two Euro provisions is relatively inconsequential from a compliance perspective because the windows added to include cold-start are limited by a 14% weighing factor. The remaining 86% weighting factor applied to mass emissions is on the same windows that are processed under Euro VI-D provisions.

The difference in emissions performance between the two vehicles shows the difference in manufacturer calibration strategy, and this is discussed further below. The NO_x emissions from the truck were consistently lower than from the bus and the opposite was found for PN emissions. These results reinforce the importance of carefully monitoring and regulating both NO_x and PN emissions.

The absence of windows in the low-load test routes after applying the different provisions shows the gap in current regulations, which do not capture urban emissions well; examples of urban operations include a city bus or a low-load application like garbage collection, where the trucks are operated at low loads and low speeds. It should also be noted that almost all results reported in Figure 3 are with 90th percentile data only; the exception is Euro VI-E, which includes 14% of 100th percentile cold-start windows. The use of 90th percentile data means that 10% of the worst-performing emissions windows were removed prior to compliance assessment. In summary, although the Euro provisions are an improvement in overall real-world emissions accountability over AIS provisions, the Euro provisions still do not have a measurable impact on improving cold-start and urban operation performance.

Low-load, low-speed, and cold-start conditions

To better understand low-load and low-speed operations and cold-start conditions, we took the same dataset as before, without limiting it by applying the regulatory provisions, and binned it into urban (0–40 km/h), rural (40–60 km/h), and motorway (>60 km/h) groups. Figure 4 illustrates the average brake-specific NO_x emissions for the truck and bus over each test route according to the three bins. NO_x emissions during urban operation were consistently higher than the emissions during rural and motorway operations, between 2 times and 10 times as high. Urban NO_x emissions from the truck complied with both WHTC and ISC limits for all three test routes. Surprisingly, urban NO_x emissions from the truck during the low-load AIS-OFFLL cycle were the least of the three test routes. The urban NO_x emissions from the bus were lower than the limits in only one of the three test routes.

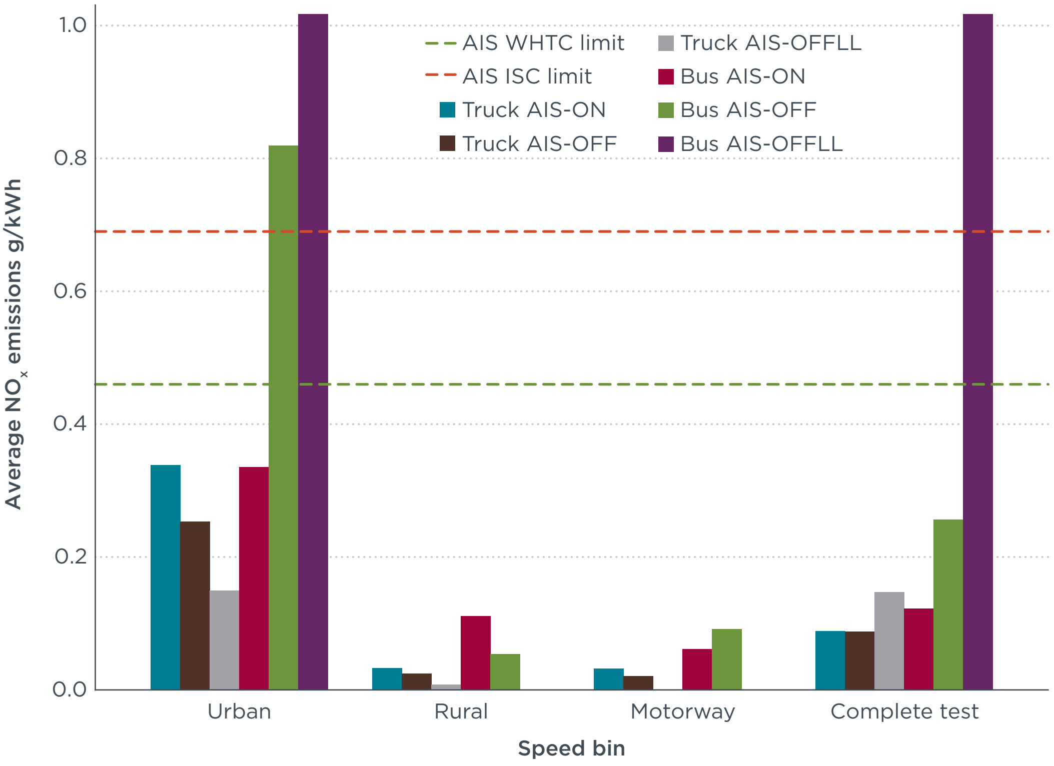

Figure 4. NO_x emissions of the selected vehicles across all test routes

In the AIS-ON test, average urban NO_x from the bus was 0.34g/kWh and compliant with the WHTC limit. For the AIS-OFF route, urban NO_x emissions were 0.82g/kWh and non-compliant, at nearly 2 times higher than the WHTC limit. The urban NO_x from the bus across the three tests ranged from 0.34 to 1.02 g/kWh, and this revealed how engine load affects NO_x emissions. The engine load on the bus for the AIS-ON and AIS-OFF test routes in urban operation were 23% and 14.5%, respectively, and had poor NO_x performance at low-load operations. The low-load test route AIS-OFFLL had an average engine load of 11.9% on the bus and exhibited the worst NO_x performance of all routes.

Since brake-specific urban NO_x values can be skewed or exaggerated by the lower work done during urban operation compared to rural or motorway operation, the mass shares of NO_x emissions were also analyzed. The mass share of emissions only analyzes the cumulative mass of emissions in each bin as a percentage of total emissions over the entire cycle, and the results are shown in Figure 5.

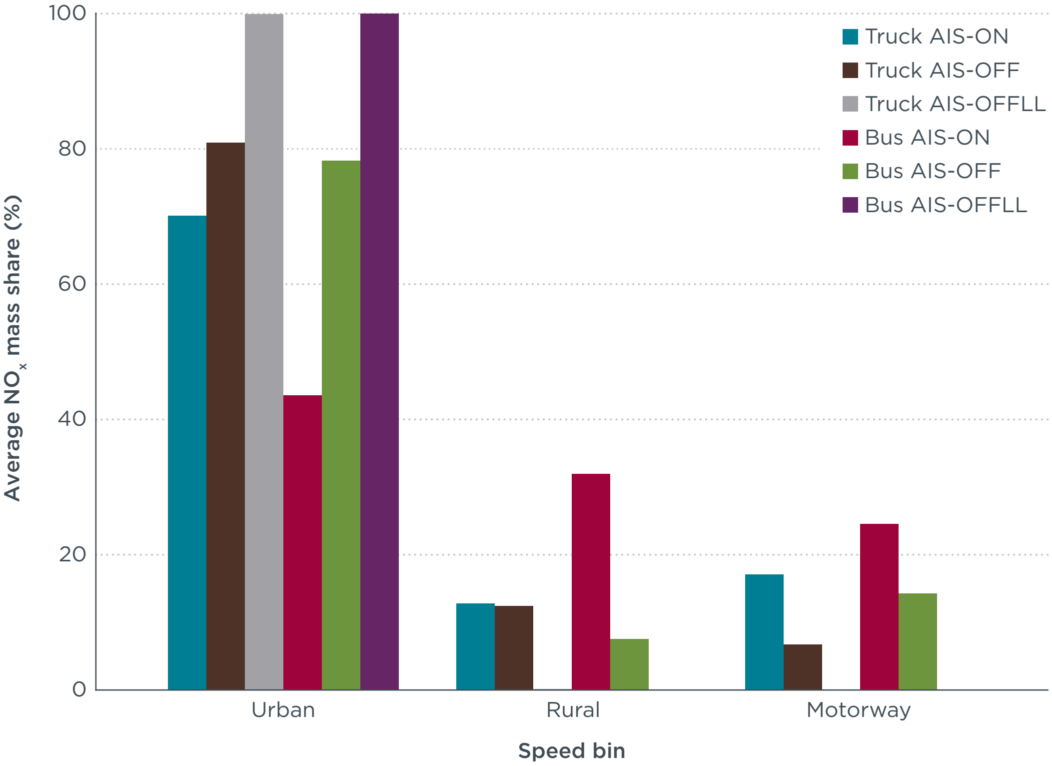

Figure 5. Mass share comparison of NO_x emissions from both vehicles across all test routes

The mass share in the truck and bus AIS-OFLL routes is 100% urban because these ran only in urban speed ranges. The other tests had urban NO_x mass shares between 44% and 81% of total NO_x. The mass shares in the AIS-ON routes were 70% and 44%, and the urban composition of the trips was just 24%. In the AIS-OFF routes, the urban composition increased to 40% and the urban NO_x mass shares increased to nearly 81%.

Figure 6 shows the average brake-specific urban PN emissions for the truck and bus across all test routes. Urban PN emissions were highest in almost all cases. Four out of the six tests had higher urban PN than the recommended ISC limit and five out of six were found to be higher than WHTC limits. The truck exceeded the WHTC limit and the recommended ISC limit on all completed test routes and emitted urban PN three times higher than the WHTC limit during the AIS-ON test. Urban PN from the bus, for two out of three tests, was nearly four times higher than the PN emissions over the complete tests. Urban PN from the bus during AIS-ON was two times higher than the WHTC limit.

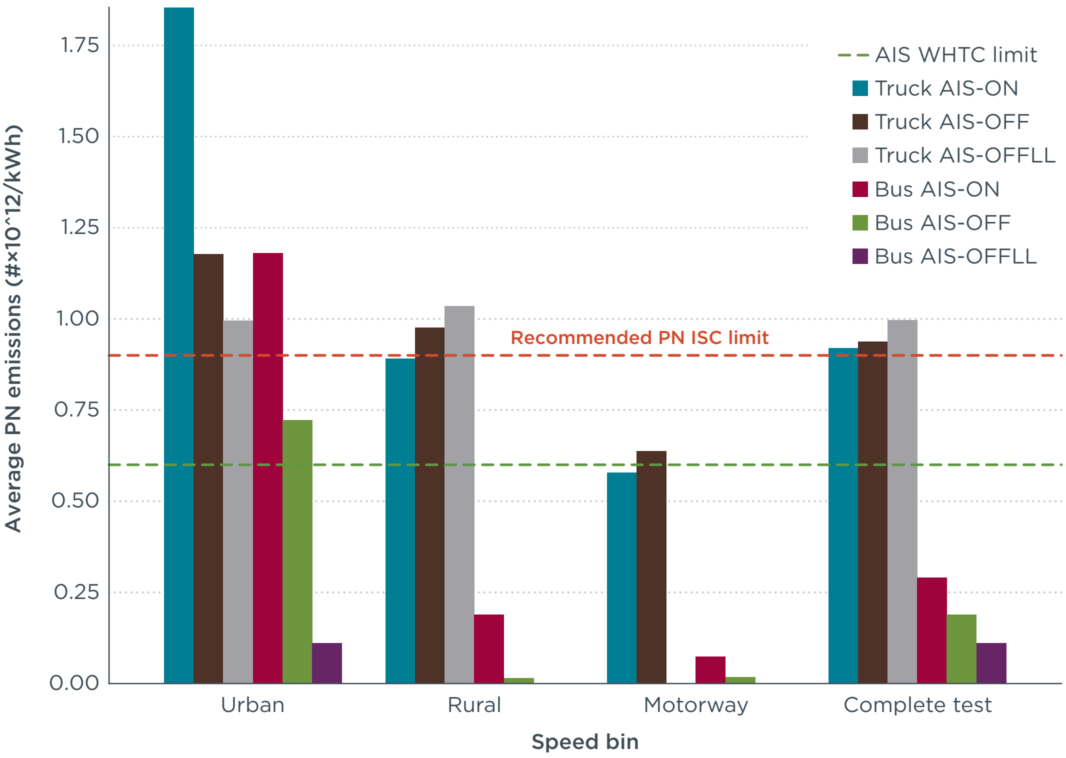

Figure 6. Comparison of the average brake specific PN emissions of both vehicles across all test routes

Figure 7 presents the PN mass shares. Excluding the AIS-OFFLL routes from the analyses, the urban PN mass share ranged between 38% and 94%. The bus had an urban PN mass share of 66% and 94% for the AIS-ON and AIS-OFF routes, respectively. The truck's mass share was more evenly spread out across urban, rural, and motorway.

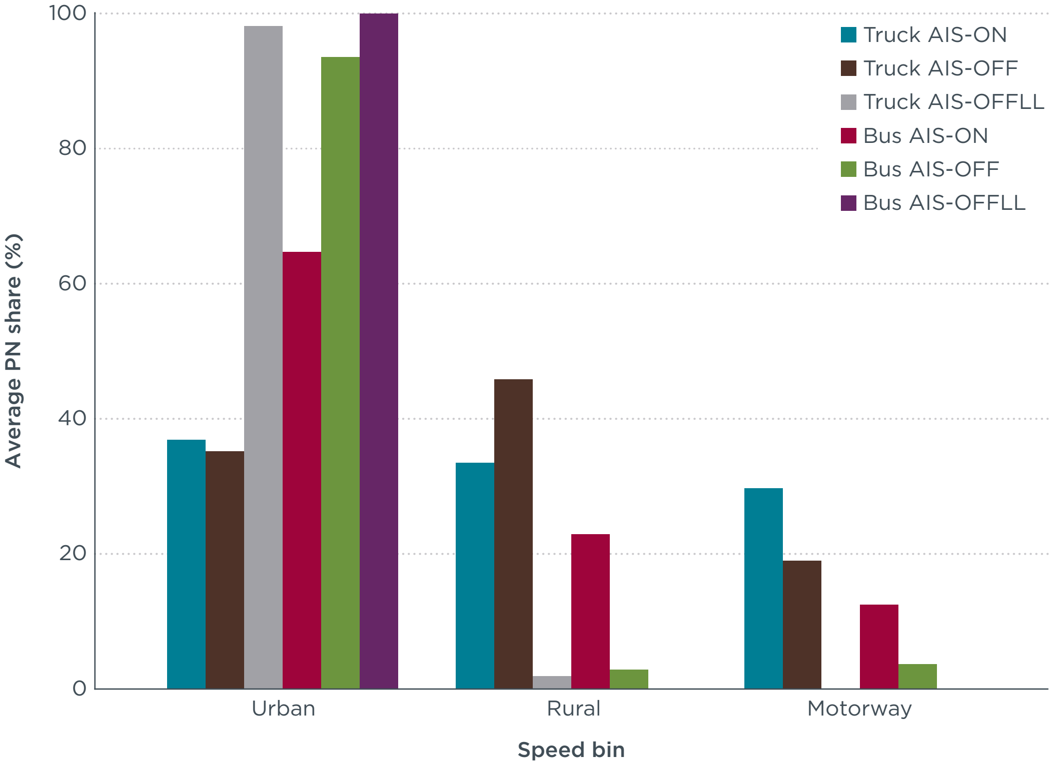

Figure 7. Mass share comparison of PN emissions from both vehicles across all test routes

Overall, the share of urban emissions in terms of work-specific and mass-share was very high on the complete test results. While the truck's NO_x emissions performance was very good over all the test routes and individual operating bins, the overall PN, and more significantly the urban PN emissions, were very high and exceeded the recommended ISC limit. For the bus, while PN emissions over complete tests and in rural and motorway operating bins were good, urban PN emissions were substantially high and exceeded the WHTC limits and the recommended ISC limit. Similarly, NO_x performance in rural and motorway operation was good but urban NO_x emissions were significantly higher than the ISC and WHTC limits. In sum, the vehicle tests showed poor performance in low-load, urban conditions compared to higher load operations like rural and motorway. From a compliance perspective, this makes capturing low-load emissions critical for true representation of in-use vehicle emissions.

Extended ISC boundary conditions

The provisions specified within ISC requirements in AIS, Euro VI-D, and Euro VI-E apply several thresholds to exclude data for compliance assessment using minimum power and coolant temperature and by removing the worst performing 10% of emissions data for regulated pollutants. The extension of these thresholds will allow more real-world data to be used for compliance evaluation.

In this section, we investigate extensions to the current provisions to include cold-start operation, low-load driving, and low-speed driving. The same test data was used for the analyses. A sensitivity analysis was conducted applying extensions of thresholds separately and together to see the independent and compounded effect on emissions performance.

Raw data without any weighting factors were used in the calculation of mass emissions in Figures 8 and 9 such that:

» The average window power threshold was lowered to 5% and compared to assessments at 10%, per Euro provisions, and 20%, per AIS.

» No data exclusions for coolant temperature thresholds were considered and this was compared to the assessments considering exclusions at coolant temperatures of 30 °C (per Euro VI-E) and 70 °C (per Euro VI-D and AIS).

» No data exclusions per percentile thresholds was considered and this was compared to the assessments at the 90th percentile (per AIS and Euro provisions) and 95th percentile.

The data is presented using three separate plots for each power threshold and the coolant temperatures are distinguished by different sets of bars. The color of each bar shows the percentile of data used for the analyses.

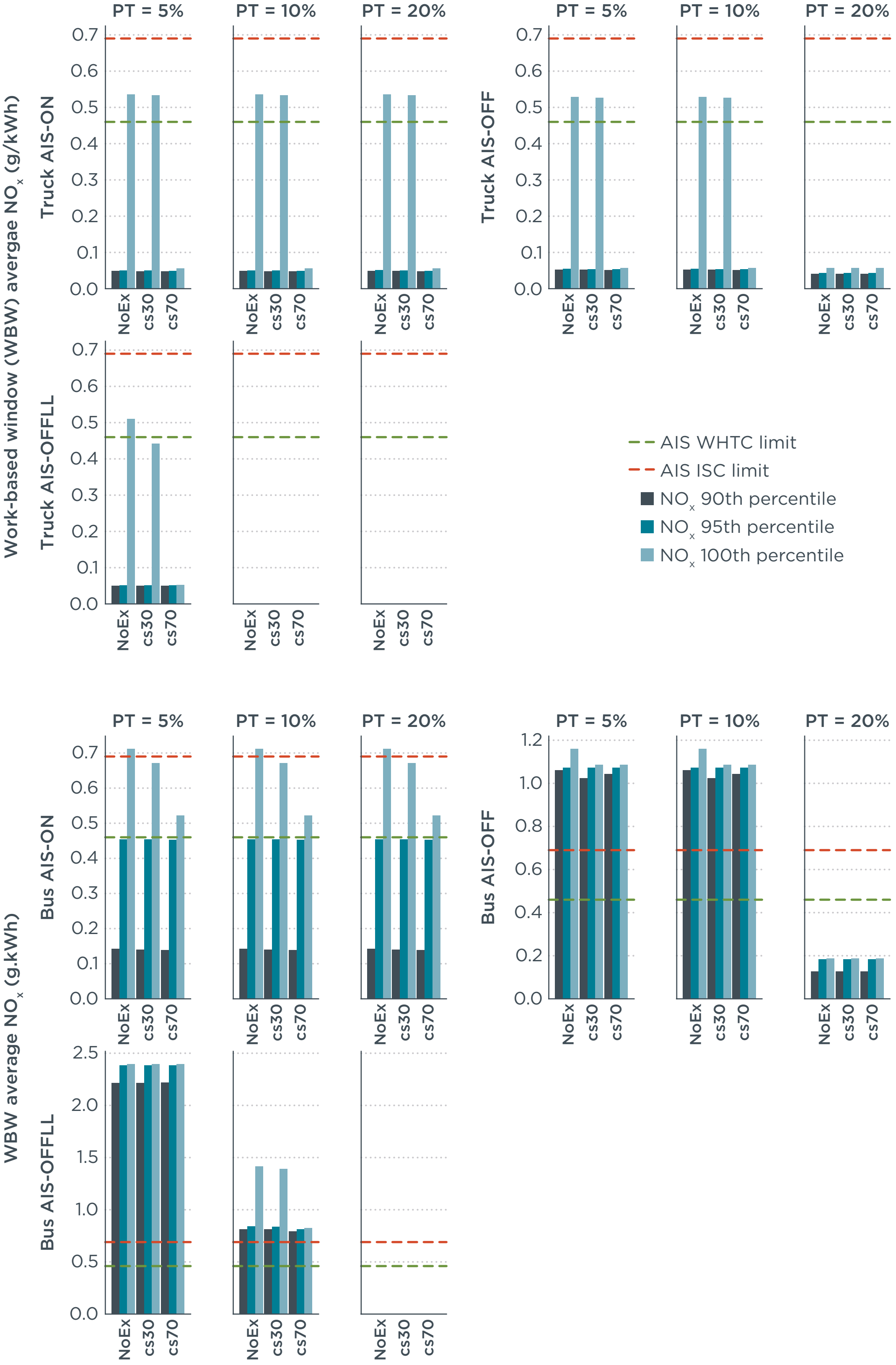

Figure 8. Sensitivity analysis of boundary condition extensions on NO_x emissions for truck (top) and bus (bottom).

The following inferences were made from the sensitivity analysis on NO_x emissions:

- The threshold used for coolant temperature to include cold start had no impact on NO_x emissions at the 90th and 95th percentile regardless of the power threshold applied. So, lowering the coolant temperature threshold to include cold start can only have an impact if applied in combination with a reduced power threshold and increased evaluation percentile (to 100%).

- Lowering the power threshold to 10% and 5% did not by itself have any significant impact on the NO_x emissions from the truck. Substantial impact was only seen when integrated with lower coolant temperatures and increased percentile (to 100%) for data evaluation. High NO_x events were contained at low power, cold-start conditions and these are excluded when 90th percentile exclusions are applied.
- Lowering the power threshold to 10% and 5% on the bus had significant impact on NO_x emissions in two of the three routes. A further increase in emissions was observed when coupled with lower coolant temperatures and increased percentile (to 100%) for data evaluation.
- Under current AIS provisions, NO_x emissions from the truck and bus are compliant with India's ISC and WHTC limits. However, when the power threshold was lowered to 10%, coolant temperature threshold was lowered to 30 °C (as in Euro VI-E), and percentile for evaluation was increased to 100%, five of the six tests exceeded WHTC limit and two of the six exceeded ISC limits.
- When no exclusions were applied and the data was evaluated at 5% power threshold, the bus exceeded the ISC limit for NO_x on all tests, and NO_x emissions were 1.65 to 5.2 times higher than the WHTC limit.

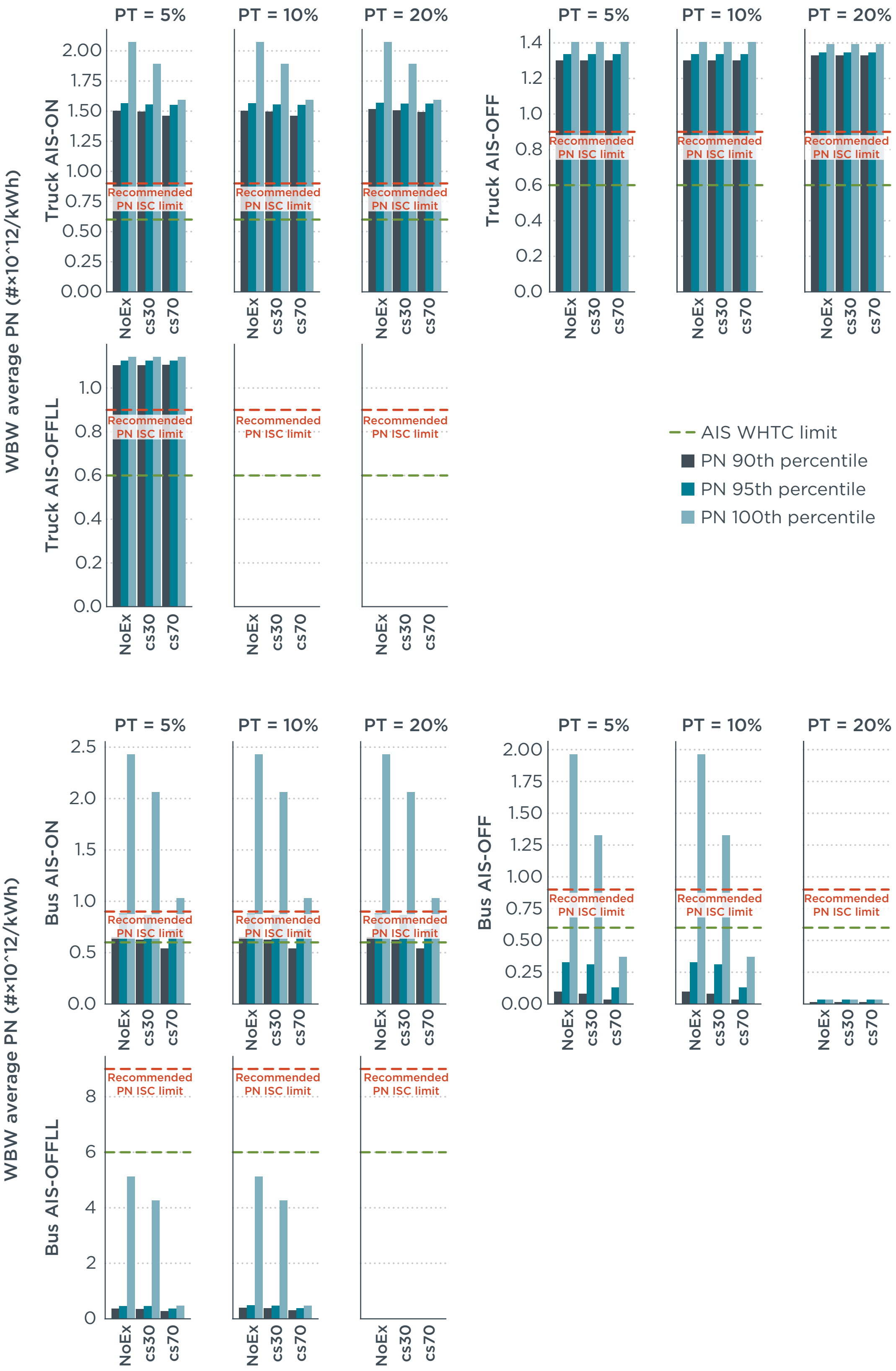

Figure 9. Sensitivity analysis of boundary condition extensions on PN emissions for truck (top) and bus (bottom).

The following inferences were made from the sensitivity analysis on PN emissions:

- Lowering the coolant temperature threshold (to 0 °C and 30 °C) had little to no impact on PN emissions by itself. However, substantial impact on PN emissions was observed when this extension was applied with increased percentile (to 100%) for data evaluation and reduced threshold for average window power.

- Except for the AIS-OFFLL, which is a low-load test, reducing the power threshold to 10% and 5% did not have an impact on PN emissions.
- Under the current AIS provisions, PN emissions from the bus were lower than the WHTC limit and the recommended ISC limit. However, when Euro VI-E provisions with an increased percentile (to 100%) for data evaluation were applied, two of the three tests exceeded the recommended ISC limits and PN emissions were 2.1 to 3.5 times higher than the WHTC limit.
- The truck exceeded the WHTC and the recommended ISC limits for PN under current AIS provisions. When Euro VI-E provisions were applied with increased percentile (to 100%) for data evaluation, the results increased to as high as 2.3 to 3.1 times the WHTC limit in two out of three tests.
- When no exclusions were applied, PN emissions in five out of six tests exceeded the WHTC and recommended ISC limits, and these emissions ranged from two to four times higher than the WHTC limit on most tests.

In summary, the results from all the tests increased dramatically when one or more extensions to the current provisions were applied. When extensions were applied to NO_x emissions for all tests, the truck marginally exceeded WHTC limit and NO_x emissions from the bus were 1.6 to 5.2 times higher than the WHTC limit. Similarly, when extensions were applied to PN emissions, in five out of six tests, PN emissions were between two and four times higher than WHTC limit. For compliance evaluations to be more representative of real-world emissions by capturing these high-emitting events, the results suggest the following:

- The minimum average power threshold should be lowered to at least 5%
- Constraints on minimum coolant temperatures should be removed to include cold-start conditions
- Compliance must be assessed on 100% of valid windows

Transient emissions analyses

The two test vehicles chosen are BS VI-certified. Because they are in the top five best-selling models in their respective vehicle categories, the emissions performance of these vehicles is reflective of a fairly large share of the market for commercially sold BS VI vehicles. As mentioned in the previous section, cold NO_x and low-load NO_x are clearly important factors to consider when assessing overall NO_x performance. Figure 10 presents a window-based analysis wherein each window is equal to 1xWHTC work done. The cold NO_x from the bus was, on average, twice as much as the cold NO_x from the truck. All of the non-compliant NO_x events for the truck were contained within the cold-start period, while the bus had several high-emitting, non-compliant events even after the engine had warmed up.

Note that raw data without any weighting factors were used in the calculation of mass emissions in Figures 10 and 11. This is different from the mass emissions presented earlier in Figure 3.

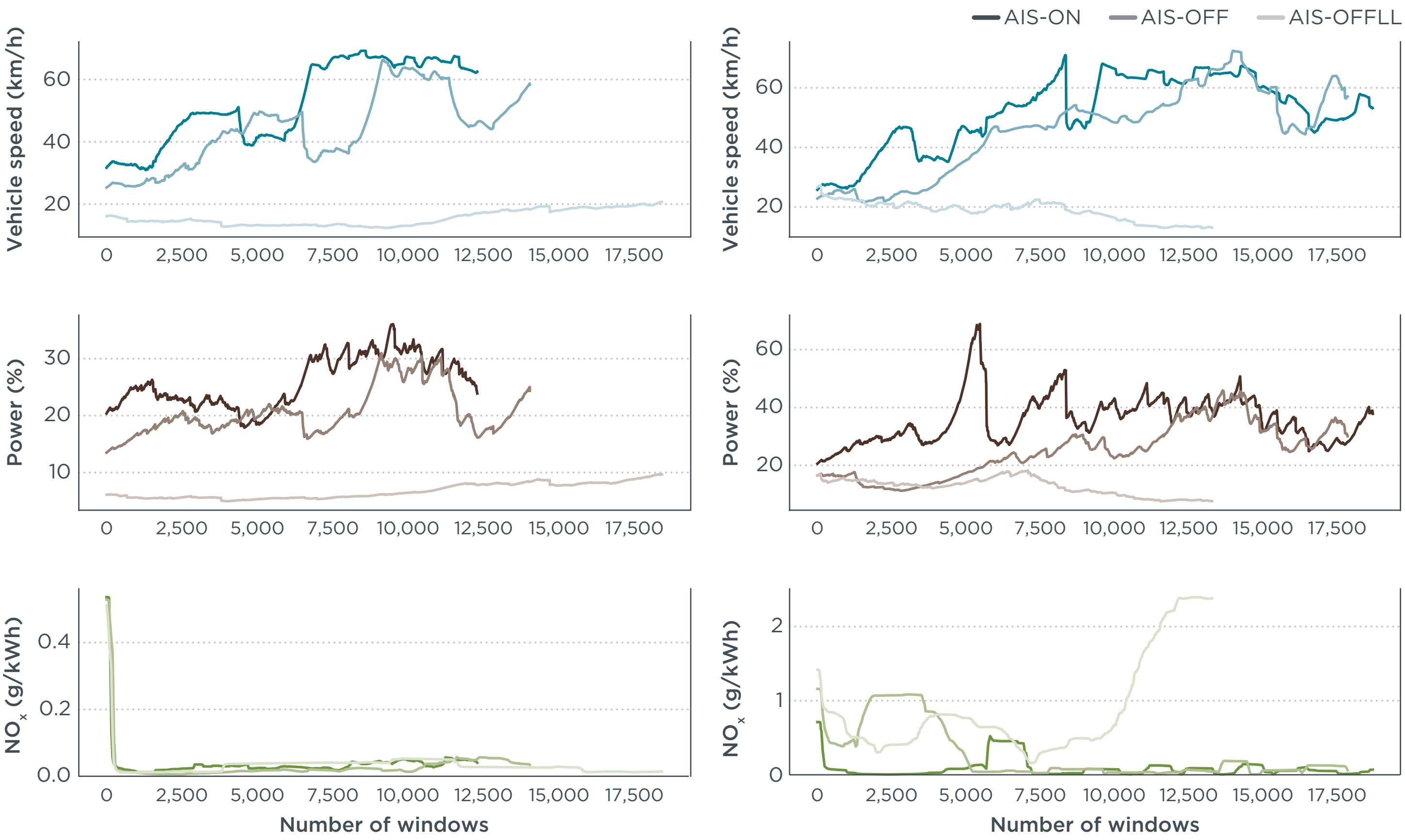

Figure 10. Window-based NO_x emissions for truck (left) and bus (right) over entire test cycles

In the AIS-OFFLL test, when the engine load fell below 10%, the NO_x emissions from the bus climbed steeply to as high as 2.4 g/kWh; that is 5.2 times the WHTC limit. Meanwhile, NO_x emissions from the truck remained relatively flat over the entire cycle, even at lower loads. The diesel exhaust fluid (DEF) consumption over the AIS-OFFLL tests was roughly the same for the truck and bus at 0.016 l/kWh. The fuel consumption was 0.31 l/kWh and 0.38 l/kWh for the bus and truck, respectively, over the AIS-OFFLL cycles. Given that the duty cycles for the two vehicles were the same, either or both of these two deductions is possible:

> Assuming the aftertreatment system NO_x efficiency is similar given similar DEF consumption rates, the engine-out NO_x from the bus is substantially higher than from the truck, thereby resulting in higher tailpipe NO_x.
>
> Assuming both the engine-out NO_x and aftertreatment system NO_x efficiency are similar, the EGR rates on the truck are higher than the bus, thereby decreasing tailpipe NO_x but increasing fuel consumption.

An inverse pattern emerged for PN emissions between the two vehicles, and that is seen in Figure 11. The bus had better PN emissions than the truck on all routes. Most of the bus's high-emitting events that exceeded laboratory and recommended limits were contained within the cold-start period, and in one instance, increased PN emissions were seen close to when the engine load increased to greater than 50%. PN emissions remained relatively low during the remainder of all test routes for the bus and no direct correlations were observed between load and PN emissions.

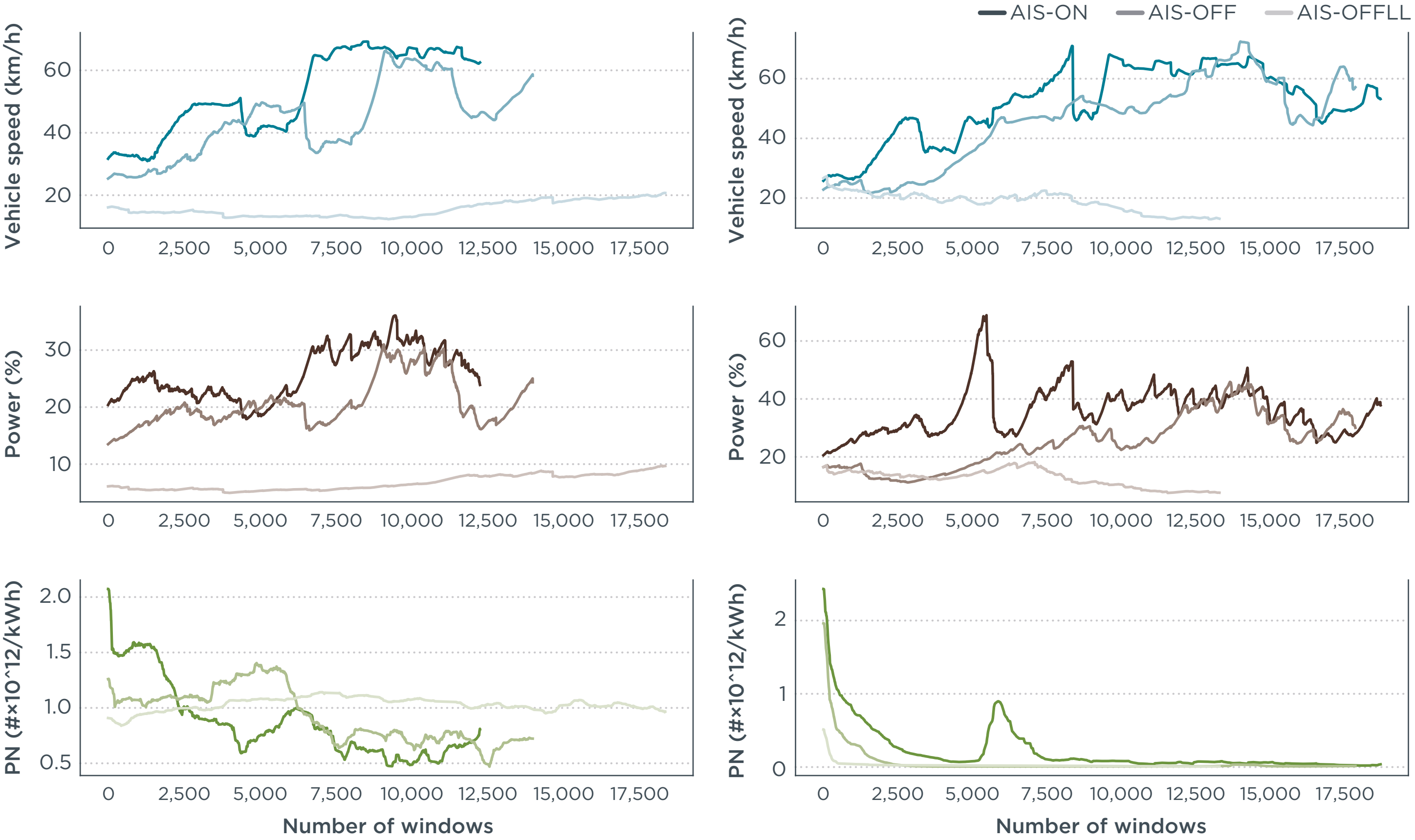

Figure 11. Window-based PN emissions for truck (left) and bus (right) over entire test cycles

The truck, on the other hand, had high-emitting events for large portions of the test cycles. High emitting events occurred during cold start and remained elevated in the AIS-ON and AIS-OFF test cycles when engine load was less than 20%. Lower PN emissions were observed when the engine had warmed up and the load remained greater than 28%, as in motorway operation. During the AIS-OFFLL test, where the truck operated at less than 10% load during the entire cycle, the PN emissions remained elevated between 1.5 and 2 times the WHTC limit through the entire route. Cold-start PN emissions from AIS-OFF and AIS-OFFLL were lower than AIS-ON for truck and bus, and this correlates with lower engine load at cold-start during those cycles. These substantial differences between NO_x and PN emissions performance, where a vehicle has good NO_x emissions but poor PN emissions, are why there is a critical need to have ISC CFs for both NO_x and PN.

Individual, time-based emissions performance over each window wherein emissions were averaged over 300-second windows, for all tests, can be found in Figures A1 and A2 in the Appendix.

In-service fuel consumption versus CSFC

Fuel efficiency standards for commercial vehicles in India were finalized in August 2017 for vehicles with gross vehicle weight (GVW) greater than 12 tonnes. Later, in 2019, the notification was updated with standards for commercial vehicles between 3.5 and 12 tonnes; another update in 2020 amended them to create two new vehicle categories for GVW and axle configurations. The current standards are based on constant speed tests at 40, 50, and 60 km/h depending on vehicle segment, GVW, and axle configuration. Steady-state tests are generally not effective in representing real-world operating conditions for a variety of reasons and this is why most certification test cycles now include transient tests based on real-world conditions. The study conducted by ICCT on a BS IV commercial bus engine and vehicle reported "the results from the CFSC tests showed that the vehicle met the regulatory standards for fuel economy at 40 km/hr and 60 km/hr. However, the fuel consumption over the transient WHVC test cycle was 15.7 l/100km, or 24% higher than the regulatory limit" (Sathiamoorthy et al., 2020, p.22). This revealed the significant difference in fuel economy that operators would realize in real-world, transient conditions as opposed to the vehicle's regulatory limits.

While running the AIS-OFF tests, both vehicles were operated at steady-state speeds for extended timings at 40, 50, and 60 km/h to simulate CSFC tests. The fuel consumption during these steady-state intervals was obtained from the OBD's instantaneous broadcasting and was averaged over the interval. The limits at these speeds for the truck and bus were calculated per equations corresponding to the vehicle and weight categories. Figure 12 shows the CSFC limits represented by circles for the truck and bus at 40 km/h and 60 km/h along with the actual fuel consumption reported by the OBD represented by bars at those speeds for the vehicles. Both vehicles complied with the CSFC limits.

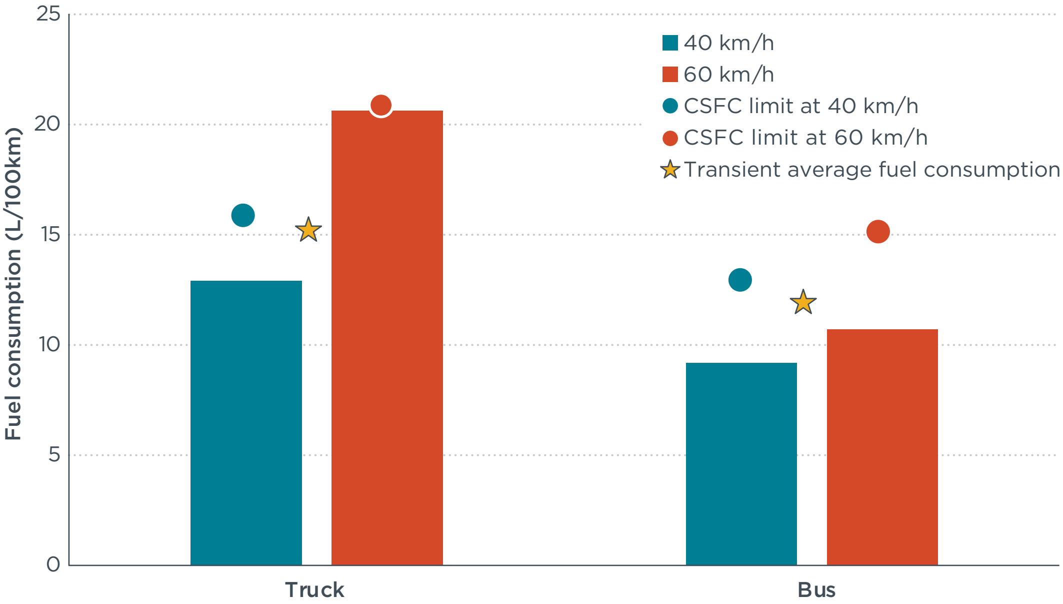

Figure 12. Fuel consumption of truck and bus to CSFC limits at 40 km/h and 60 km/h

The CSFC for the bus and truck at 40 km/h was about 25% and 20% lower than the limit, respectively. The CSFC at 60 km/h was about 31% and 5% lower than the limit for the bus and truck, respectively. The average vehicle speeds over the AIS-OFF test cycles were 40 km/h and 41 km/h for the bus and truck, respectively. The transient average fuel consumption represented by stars in Figure 12 was only lower by about 14% and 5% than the limit at 40 km/h. This increase in fuel consumption can be attributed entirely to the transient operation during real-world operation. If current vehicle technologies can comply with the CSFC standards with such comfortable margins, improvements to fuel savings cannot be expected without tightening the standards.

The CSFC values from a similar BS IV vehicle from an earlier ICCT study (Sathiamoorthy et al., 2020) also complied with the current (2020) CSFC limits. This shows that the current CSFC standards add no value in the betterment of the vehicle segments' fuel economy. In order for the standards to have meaningful impact on improving fuel economy and CO_2 emissions, they need to be tightened to bridge the gap with real-world fuel consumption. The testing requirements need to include transient operation to be representative of real-world operation.

Conclusions and recommendations

This study investigated real-world emissions from a BS VI bus and truck over three test routes that covered a wide range of real-world operating conditions. We also assessed different extensions to India's proposed AIS provisions. The selected truck and bus both complied with India's proposed ISC limits for NO_x emissions according to AIS provisions. The Euro VI-E provisions, meanwhile, include additional windows for evaluation, and when these were applied, the NO_x emissions from the bus were at least two times higher than the WHTC limit. With Euro VI-E provisions, the NO_x emissions from the truck continued to comply with both ISC and WHTC limits.

India's current AIS standard does not propose a CF for PN emissions, but this study assumed the same CF as is currently proposed for NO_x. While the bus met the recommended PN ISC limits and was below the WHTC limit following AIS provisions, the truck failed to meet the ISC limit for PN emissions for all routes which had at least 50% valid windows. Additionally, PN emissions from the truck were more than two times higher than the WHTC limit. When Euro VI-E provisions were applied, the bus exceeded the WHTC limit marginally on one route but overall, Euro VI-E provisions did not impact the overall PN results significantly.

Additionally, the study found:

- The AIS-OFFLL, which was a low-load test route, did not have any valid windows when AIS provisions were applied and could not be included in AIS compliance evaluation.
- Urban NO_x emissions were significantly higher than rural and motorway for both vehicles, contributing between 44% to 81% of total NO_x for AIS-ON and AIS-OFF routes. Urban NO_x emissions from the truck were compliant with ISC limits and lower than the WHTC limit, but urban NO_x emissions from the bus were only compliant in one test route. Urban NO_x from the bus in the AIS-OFF and AIS-OFFLL were 2 and 2.5 times higher than the WHTC limit.
- Urban PN emissions ranged from 38% to 94% of total PN for AIS-ON and AIS-OFF routes between the two vehicles. Urban PN from the truck exceeded WHTC and recommended ISC limits for all tests and was 1.6 to 3 times higher than the WHTC limit.
- India's current AIS provisions do not capture cold-start emissions for compliance evaluation. Even lowered thresholds for coolant temperature to 30 °C and 0 °C had no meaningful impact on emissions and these changes were still unable to capture low-load and cold-start operations. Applying Euro VI-D and Euro VI-E provisions had no meaningful impact on four of the six routes. AIS and Euro provisions are still largely not capable of capturing real-world low-load, low-speed, and cold-start emissions.
- When data evaluation was extended to the 100th percentile and included all cold-start emissions with a lower power threshold at 5%, both AIS compliant vehicles exceeded the WHTC limit on five of the six tests. In five of the six tests, PN emissions were 2 to 4 times higher than the WHTC limit. In three of the bus tests, NO_x emissions were higher than the WHTC limit, by as much as five times.

CSFC for the truck and bus were about 20% and 25% lower, respectively, at 40 km/h, and 31% and 5% lower at 60 km/h than the limits in the standard. The average transient fuel consumption over the whole route at an average speed of about 40 km/h was higher than the measured CFSC for both vehicles, but still lower than the limit at 40 km/h.

- The CSFC values measured in this study show that BS VI vehicles comfortably met the 2020 CSFC limits. Previous work indicated that even a similar BS IV vehicle in this category had met the CSFC standard. The comfortable margins with which current vehicle technologies comply with CFSC limits show that no impactful standards have been implemented towards fuel economy betterment, and no significant fuel benefits can be expected without a tightening of standards.

Policy recommendations:

- For ISC compliance evaluation to capture the emissions that result from real-world urban driving, the power threshold must be lowered to 5%, all cold-start emissions must be included, and the percentile for data evaluations must be increased to 100%. India should look to proactively improve the ISC standards and aim to avoid the gaps identified in Euro VI provisions that are discussed in Rodriguez and Badshah (2021).
- India should also consider adopting the Euro VI-E provisions as an immediate, transitory step while AIS provisions are still being phased in. Stakeholders can then formulate improved provisions and specifics for the next regulatory standard, BS VII, and a timeline of implementation.
- To improve real-world fuel economy and CO_2 emissions, fuel consumption limits need to be lower and the testing requirements need to include transient operation, as this would make them more representative of real-world operation. This would bridge the gap between real-world fuel consumption and current CSFC-based fuel consumption.

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Appendix

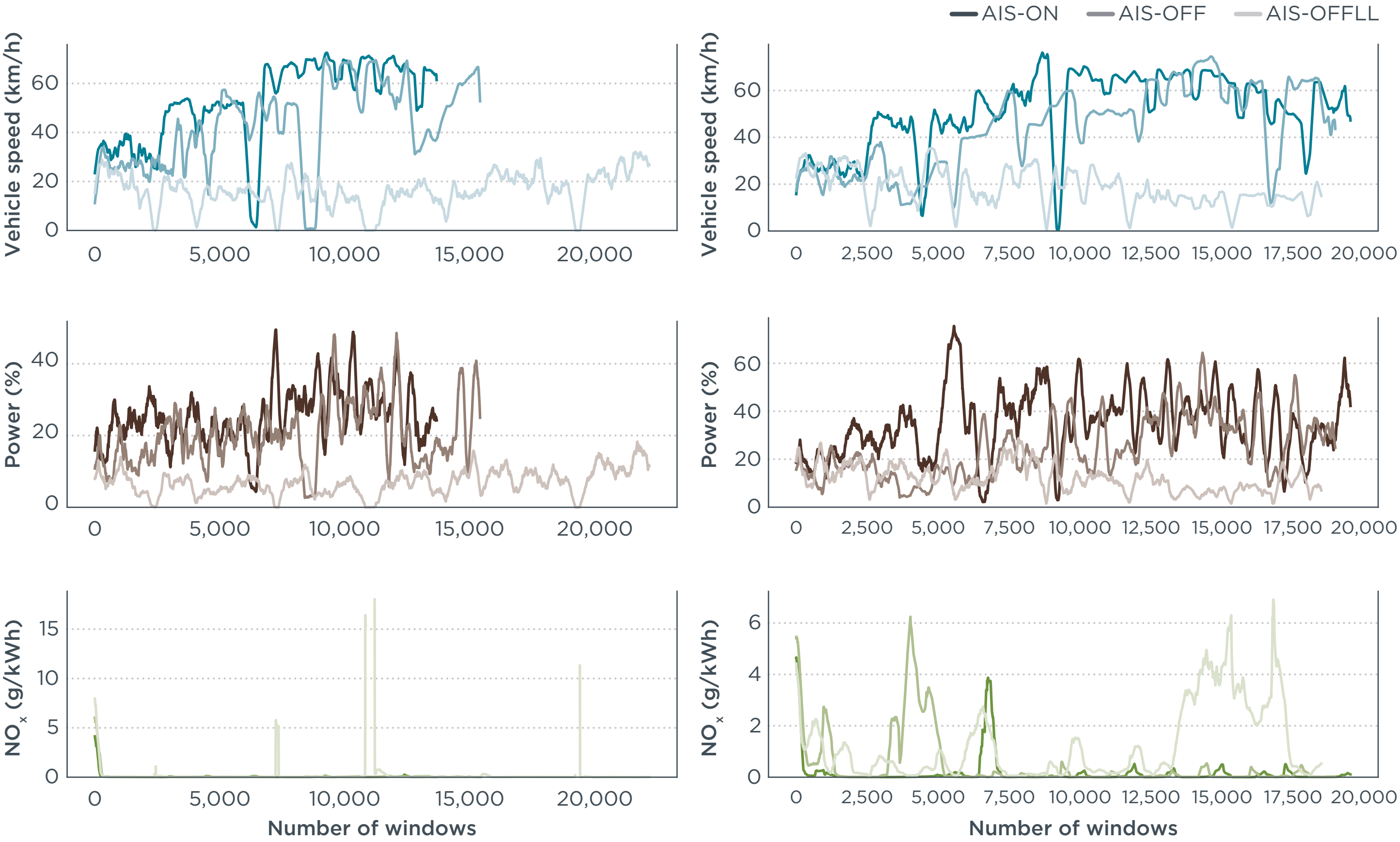

Figure A1. Time-based (300-second window) NO_x emissions performance over each window for truck (left) and bus (right)

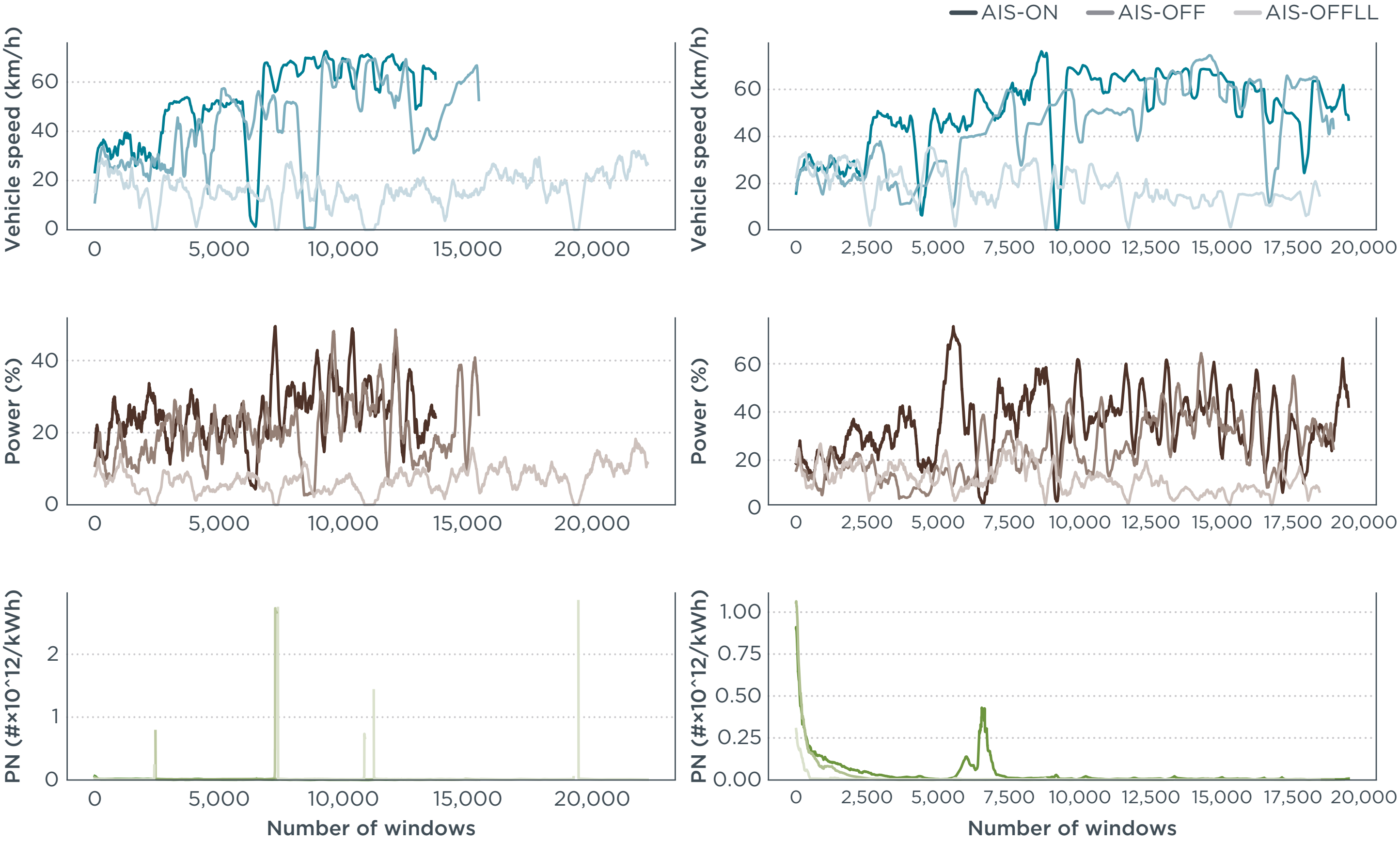

Figure A2. Time-based (300-second window) PN emissions performance over each window for truck (left) and bus (right)