WORKING PAPER 2022-33

OCTOBER 2022

Recommendations for the next generation of China's heavy-duty vehicle emission standard based on testing of China VI vehicles

Authors: Tianlin Niu and Felipe Rodríguez

Keywords: heavy-duty vehicles (HDVs), testing, pollutant emissions, greenhouse gases (GHGs)

Background

Heavy-duty trucks (HDTs) generated 79.8% of the emissions of nitrogen oxides (NO_x) and 58.5% of the emissions of particulate matter (PM) from the on-road vehicle fleet in China in 2021, but they were only 4% of the vehicle stock.[1] China has ambitions for much cleaner air and as a result, regulations for HDT emissions control are developing fast and becoming very stringent. The China VI-a emission standard for HDTs was implemented early in some key regions and took effect across the country on July 1, 2021. China VI-b is to fully take effect on July 1, 2023.[2]

China VI-a is largely equivalent to Euro VI, and China VI-b introduces slightly more stringent testing requirements and requires vehicles to be equipped with an on-board remote emissions monitoring system. Though the China VI standard reduces emissions of NO_x and PM from HDTs by around 70% compared to the previous China V standard, there are still opportunities for further emissions reduction from HDTs.[3] The national-level *14th Five-Year Plan for Energy Saving and Emissions Reduction*, published on December 28, 2021, requires the development of a next-generation emission standard

1 Ministry of Ecology and Environment, "China Mobile Source Environmental Management Annual Report - 2021," (2022), https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202109/W020210910400449015882.pdf; and National Bureau of Statistics, "China Statistical Yearbook 2021," (2022), http://www.stats.gov.cn/tjsj/ndsj/2021/indexch.htm.

2 Ministry of Ecology and Environment, "Limits and Measurement Methods for Emissions from Diesel Fuelled Heavy-Duty Vehicles (CHINA VI) (GB 17691—2018)," (2019), https://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/dqhjbh/dqydywrwpfbz/201807/t20180703_445995.shtml.

3 Liuhanzi Yang and Hui He, "China's Stage VI Emissions Standard for Heavy-Duty Vehicles (Final Rule)," (ICCT: Washington, D.C., 2018), https://theicct.org/publication/chinas-stage-vi-emissions-standard-for-heavy-duty-vehicles-final-rule/; and Lingzhi Jin et al., "Opportunities and Pathways to Decarbonize China's Transportation Sector during the Fourteenth Five-Year Plan Period and Beyond," (ICCT: Washington, D.C., 2021), https://theicct.org/publication/opportunities-and-pathways-to-decarbonize-chinas-transportation-sector-during-the-fourteenth-five-year-plan-period-and-beyond/.

Acknowledgments: The authors thank Liuhanzi Yang and Sina Kazemi Bakhshmand from the International Council on Clean Transportation for their guidance and constructive comments on this paper. Thanks also to the consultant team of Sheng Su, Yitu Lai, and Tao Lv of Xiamen Vehicle Emission Testing Center for sharing their expertise on vehicle testing, and to Gang Li of Vehicle Emission Control Center and Liqiang He of Tsinghua University for their support in analyzing the testing data.

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for heavy-duty vehicles (HDVs) that achieves further reductions in pollutant emissions and simultaneously controls greenhouse gas (GHG) emissions.[4]

Evaluating the real-world performance of China VI HDTs and understanding the potential improvements for China VII, the next generation of standards, has become an essential task for regulators. To help, this paper presents analysis of on-road and laboratory testing of two N3 vehicles certified under the China VI standard;[5] the aim is to better understand real-world emissions, the in-use performance of current truck engines and emission control technologies, and to explore policy recommendations for the next generation of HDV standards. The vehicle testing discussed here was conducted by the Xiamen Vehicle Emission Testing Center in the city of Xiamen.

We also examine how to fill the gaps between the current Chinese standards and the latest developments in European standards. Consultants to the European Commission, known as the Consortium for ultra-Low Vehicle Emissions (CLOVE), have developed recommendations for the next generation of Euro emission standards, Euro VII.[6] The official Euro VII proposal is expected to be announced by the European Commission in late October 2022.

Vehicles tested

We selected two HDV models certified to the China VI-b standard that have typical engine displacement and rated power for their category and weight segment.

As shown in Figure 1, Vehicle 1 is a straight box truck with a gross vehicle weight (GVW) of 18 tonnes. The emission control system consists of a high-efficiency selective catalytic reduction (SCR), a diesel oxidation catalyst (DOC), an ammonia slip catalyst (ASC), and a diesel particulate filter (DPF). There is no external exhaust gas recirculation (EGR) loop, and its engine displacement and rated power are 4.5 L and 162 kW, respectively, which place it in the segment of straight trucks with GVWs between 16 and 20 tonnes.

OEM	FOTON	**Vehicle model**	BJ5186XXY-2M
Category	Straight truck (N3)	**Operation**	Express and delivery
Emission standard	China VI-b	**Axis**	4 × 2
GVW	18,000 kg	**Rated load**	9,545 kg
Engine displacement	**4,500 mL**	**Rated power**	**162 kW**
Engine emission control	No EGR	**Aftertreatment system**	DOC*1+ SCR*1 +ASC*1 +DPF*1
Reported fuel consumption	23.1 L/100km	**Odometer**	10,000+

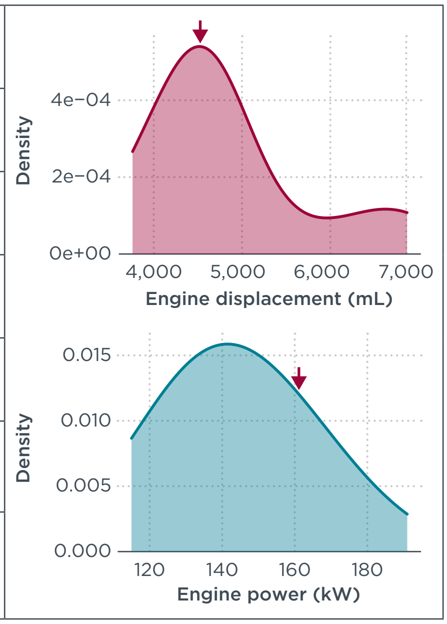


Figure 1. Vehicle 1's technical specifications and how it compares with the other vehicles in its segment.

4 National Development and Reform Commission, "National 14th Five-Year Plan for Energy Saving and Emission Reduction," January 27, 2022, https://www.ndrc.gov.cn/fggz/hjyzy/jnhnx/202201/t20220127_1313521_ext.html.

5 N3 vehicles are freight vehicles (trucks) with gross vehicle weight (GVW) > 12,000 kg.

6 Stefan Hausberger et al., "Supplements to the Scenarios for HDVs Emission Limits and Test Conditions," (Brussels, Belgium, 2021), https://circabc.europa.eu/sd/a/e0063651-4e84-4b95-aac4-edb85a719764/AGVES-2021-04-27-HDV_Exhaust-v6b.pdf.

As shown in Figure 2, Vehicle 2 is a tractor-trailer with a gross combined weight (GCW) of 41.8 tonnes. The emission control system consists of an external EGR loop accompanied by two mid-efficiency SCRs, a DOC, two ASCs, and a DPF. Vehicle 2 also has engine displacement and power of 8.6 L and 283 kW, respectively, which place it in the tractor GCW segment of 40 to 43 tonnes.

OEM	Faw Jiefang	**Vehicle model**	CA4189P1 K2E6A80
Category	Tractor (N3)	**Operation**	Long-haul Freight
Emission standard	China VI-b	**Axis**	4 × 2
GCW	41,805 kg	**Traction mass**	35,505 kg
Engine displacement	**8,600 mL**	**Rated power**	**283 kW**
Engine emission control	EGR	**Aftertreatment system**	DOC*1+ SCR*2 +ASC*2 +DPF*1
Reported fuel consumption	35.0 L/100km	**Odometer**	24,000+

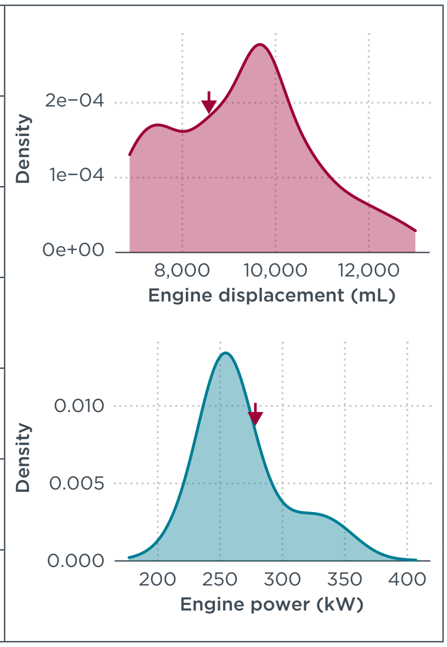


Figure 2. Vehicle 2's technical specifications and how it compares with the other vehicles in its segment.

In the process of selecting the vehicles to test, we found that the engine displacement for China VI HDTs tends to be lower than under previous emission standards in cases of similar GVW and rated power. EGR with SCR is the dominant technology and has been adopted by engine manufacturers including Yuchai, Weichai, and Xichai; high-efficiency SCR is becoming popular and has been adopted by Cummins and Weichai.

Testing methodology

Driving cycles and payloads

Several on-road tests were done for each vehicle. In addition to in-service conformity (ISC) tests following the regulatory requirements of the China VI standard, urban delivery (UD) and low-load tests were conducted to evaluate the emissions performance in urban conditions. The low-load tests were based on the specifications of the Low Load Cycle (LLC) developed by the California Air Resources Board (CARB) in its latest Omnibus regulation addressing NO_x and PM emissions from on-road HDVs.[7] All on-road measurements were done using a portable emissions measurement system (PEMS).

Laboratory tests were also conducted on a chassis dynamometer to measure fuel consumption, GHG emissions and the number of particles larger than 10 nm. See Table 1 for details.

7 Sara Kelly and Benjamin Sharpe, "California's Heavy-Duty Omnibus Regulation: Updates to Emission Standards, Testing Requirements, and Compliance Procedures" (ICCT: Washington, D.C., 2022), https://theicct.org/publication/california-us-hdv-omnibus-reg-jan22/.

Table 1. Details of the tests run and their objectives

Vehicle 1	Vehicle 2	Objective
2 ISC PEMS tests in N3 urban cycles (ISC urban)	2 ISC PEMS tests in N3 urban cycles (ISC urban) 2 ISC PEMS tests in N3 non-urban cycles (ISC non-urban)	To understand compliance with China VI regulations GB 17691-2018, including cold-start measurement
2 urban delivery (UD) PEMS tests	2 urban delivery (UD) PEMS tests	Designed to replicate the typical urban deliveries use case, including frequent stops of adequate duration, operation in rush-hour traffic, and with representative designs of at least 2.5 hours total duration or 40 km total distance.
1 Low Load Cycle (LLC) PEMS test	1 Low Load Cycle (LLC) PEMS test	Based on the LLC developed by the California Air Resources Board (CARB) to represent a worst-case scenario for NO_x emissions.
Chassis tests on C-WTVC[a]: 1 cold start + 4 hot start	Chassis tests on C-WTVC: 1 cold start + 3 hot start	Compliant with China HDV fuel consumption standard GB 27840-2011, to understand the fuel consumption and CO_2 emissions performance

[a] China Adapted World Harmonized Transient Cycle

Figures 3 and 4 show the actual testing speed for the ISC, UD, and LLC PEMS test cycles as a function of distance. To ensure adequate ambient temperature for evaluating cold-start effects, the vehicles were tested in winter, Vehicle 1 in December 2021 and Vehicle 2 in February 2022.

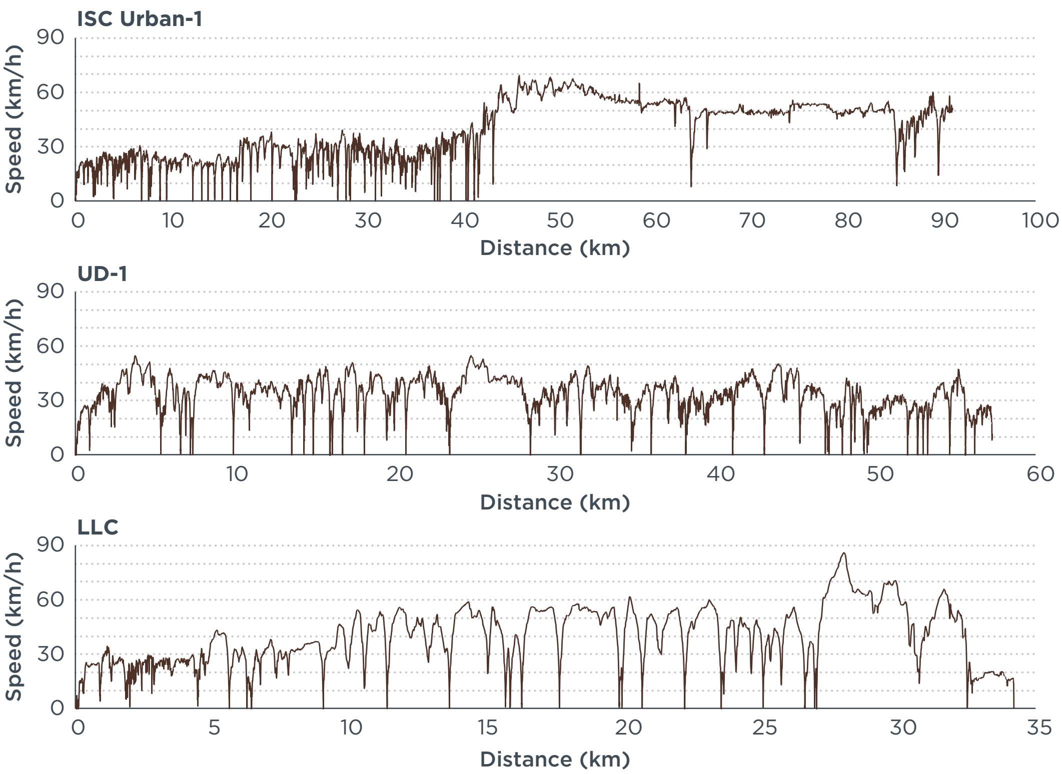


Figure 3. Representative mission profiles for Vehicle 1.

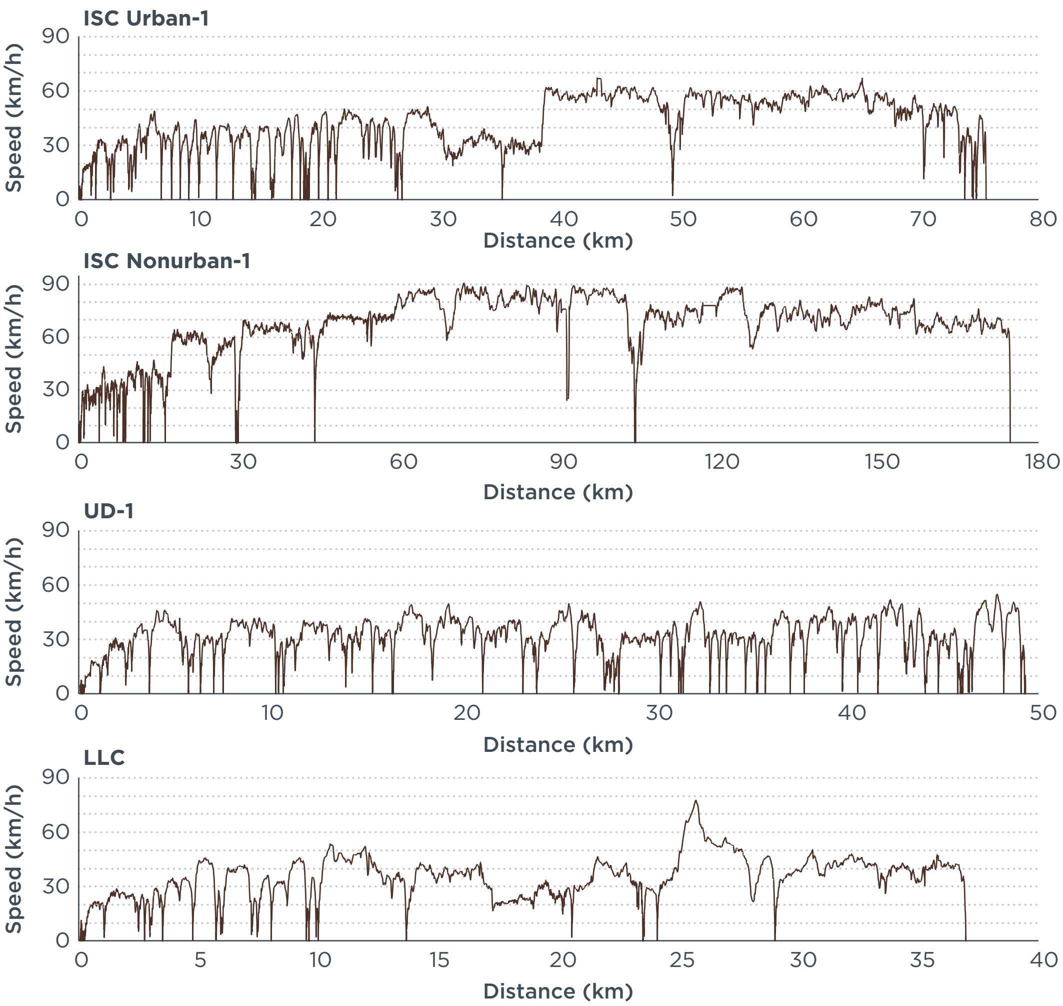


Figure 4. Representative mission profiles for Vehicle 2.

Pollutants and testing facilities

The exhaust constituents regulated in China VI are carbon monoxide (CO), NO_x, and the number of particles larger than 23 nm (PN_{23}). The currently unregulated pollutants are ammonia (NH_3), an important precursor to fine particulate matter;[8] nitrous oxide (N_2O), a gas species with a high global warming potential (GWP) of 273 over both a 20-year and 100-year time period;[9] and the number of particles larger than 10 nm (PN_{10}), which captures particles smaller than 23 nm and larger than 10 nm. The testing of Vehicle 1 and Vehicle 2 covered all five of these plus CO_2.

Measurement of CO, NO_x, PN_{23}, and CO_2 was done with HORIBA OBS ONE PEMS analyzers. Measurement of NH_3 and N_2O was done with a HORIBA QCL device. PN_{10} was only measured on the chassis dynamometer tests and it was done with a full stream dilution sampling system, AVL's CVS i60 tunnel.

Emissions performance

All PEMS tests data were analyzed using the moving average window (MAW) methodology. This was so we could evaluate and compare the emissions performance

8 Junsu Park et al., "Contributions of Ammonia to High Concentrations of $PM_{2.5}$ in an Urban Area," *Atmosphere* 12, no. 12 (December 2021): 1676, https://doi.org/10.3390/atmos12121676.

9 Intergovernmental Panel on Climate Change, "Climate Change 2021: The Physical Science Basis," in *Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, (Cambridge University Press, Cambridge, United Kingdom and New York, 2021), https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter_07_Supplementary_Material.pdf.

with respect to the limits stipulated in both the China VI regulation and the aforementioned CLOVE proposal for Euro VII.

For all regulated emissions, we compared the 90th percentile MAW value (MAW 90%) with China VI on-road limits. While the MAW 90% calculation was done with and without the inclusion of cold-start emissions, we used the results excluding cold-start emissions to assess compliance with China VI.

We also evaluated MAW 100% and MAW 90% following the CLOVE proposal for Euro VII and compared the emissions levels to the limits proposed (CLOVE-100 and CLOVE-90, respectively).

The MAW results for all valid windows and the trip average results without any MAW analysis are shown in Figure 5, which contains the following:

» Boxplots of all MAW results for CO, NO_x, PN_{23}, N_2O, and NH_3 emissions, with and without engine cold start[10]

» Key MAW results for CO, NO_x, PN_{23}, N_2O, and NH_3 emissions:

  » The 90th percentile window value of all MAW results (MAW 90%), marked as a rhombus

  » The 100th percentile window value of all MAW results (MAW 100%), marked as a circle

» Trip average results, without any MAW post-processing, of CO, NO_x, PN_{23}, N_2O, and NH_3 emissions, marked as blue crosses.

» Regulatory limits for:

  » CO, NO_x, and PN_{23} under China VI, marked with a red solid line (recall that N_2O and NH_3 are not regulated).

  » CLOVE's proposed Euro VII limits for CO, NO_X, N_2O, and NH_3. The CLOVE 100th percentile limit (CLOVE-100)—in other words, the worst window from the MAW analysis—is marked as green dashed lines. The CLOVE 90th percentile limit (CLOVE-90) is marked with an orange dashed line.

10 Cold start is defined as a vehicle start when the engine coolant temperature equals the ambient temperature. The cold-start period ends when the engine coolant temperature reaches 70 °C.

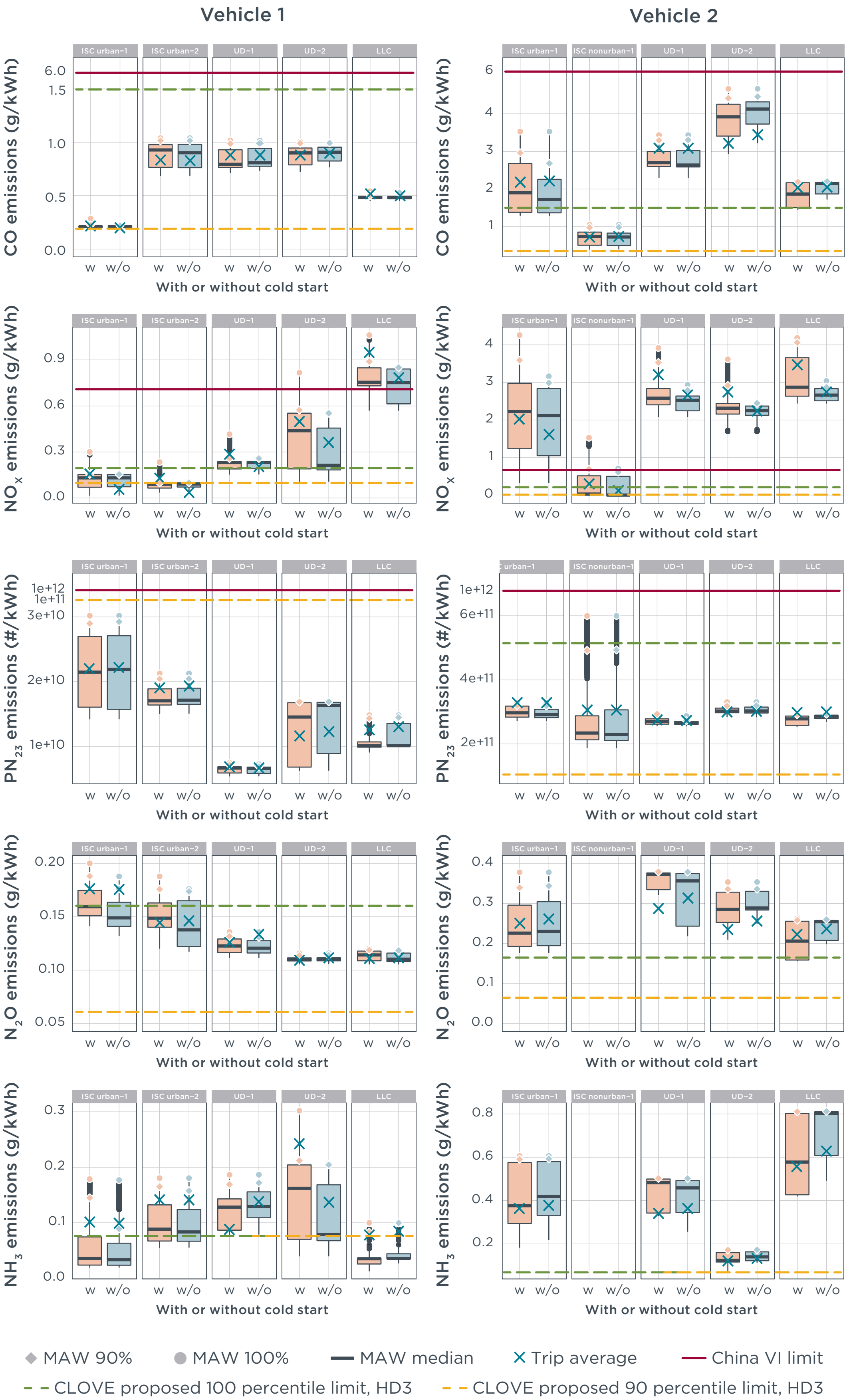


Figure 5. Emissions performance over all valid PEMS tests, both the MAW and trip average analyses. *Note:* The CLOVE limits shown in the boxes for PN_{23} results are the limits proposed for PN_{10} and they are provided for illustrative purposes.

China VI compliance analysis

A comparison of the MAW 90% emissions over the ISC cycles without cold start and the China VI on-road limit in Figure 5 shows that both Vehicle 1 and Vehicle 2 are compliant with the on-road emissions limits set by China VI for CO, NO_x, and PN_{23}. Compliance was evaluated over the ISC urban test for Vehicle 1, the 18-tonne straight truck, and over the ISC non-urban test for Vehicle 2, the 42-tonne tractor-trailer, following the ISC route requirements set by China VI, which are without cold start.

The requirements set by China VI apply, in principle, at the engine level, not at the vehicle level. The same 8.6 L diesel engine that is in Vehicle 2 could be used in a smaller straight truck, and that would make the ISC urban cycle the appropriate cycle for compliance testing. Thus, the emissions performance of Vehicle 2 over the ISC urban test is discussed in this section.

Both vehicles complied with the CO emissions limit by a large margin, with the MAW 90% emissions in the range of about 3 to 20 times lower than the China VI limit of 6 gCO/kWh. Note, though, that the CO emissions of Vehicle 2 over the ISC-urban cycle were 2.7 gCO/kWh, 10 times higher than Vehicle 1 over the same cycle.

Regarding NO_x emissions, Vehicle 1's MAW 90% emissions were 0.10–0.15 gNO_x/kWh, well below the China VI on-road limit of 0.69 gNO_x/kWh. Vehicle 2, in contrast, barely met the China VI on-road limit over the ISC non-urban test and exhibited MAW 90% emissions of 0.62 gNO_x/kWh. If cold start emissions were included, Vehicle 2's MAW 90% emissions would just hit the 0.69 gNO_x/kWh target. Further, if the engine in Vehicle 2 were to be evaluated over the ISC urban test, it would fail to be compliant by a large margin: the MAW 90% emissions are 3.0 gNO_x/kWh, approximately 4.4 times higher than the China VI on-road limit.

While both trucks had PN_{23} well below the China VI limits, Vehicle 2 exhibited emissions 10 times higher than Vehicle 1. Vehicle 2's emissions were 2.93×10^{11} #/kWh over the ISC urban test and 4.94×10^{11} #/kWh over the ISC non-urban, compared to the China VI on-road limit of 1.2×10^{12} #/kWh.

The next sections provide an in-depth analysis of the emissions performance for all pollutants and conditions, including those that fall outside of the scope of China VI's ISC provisions.

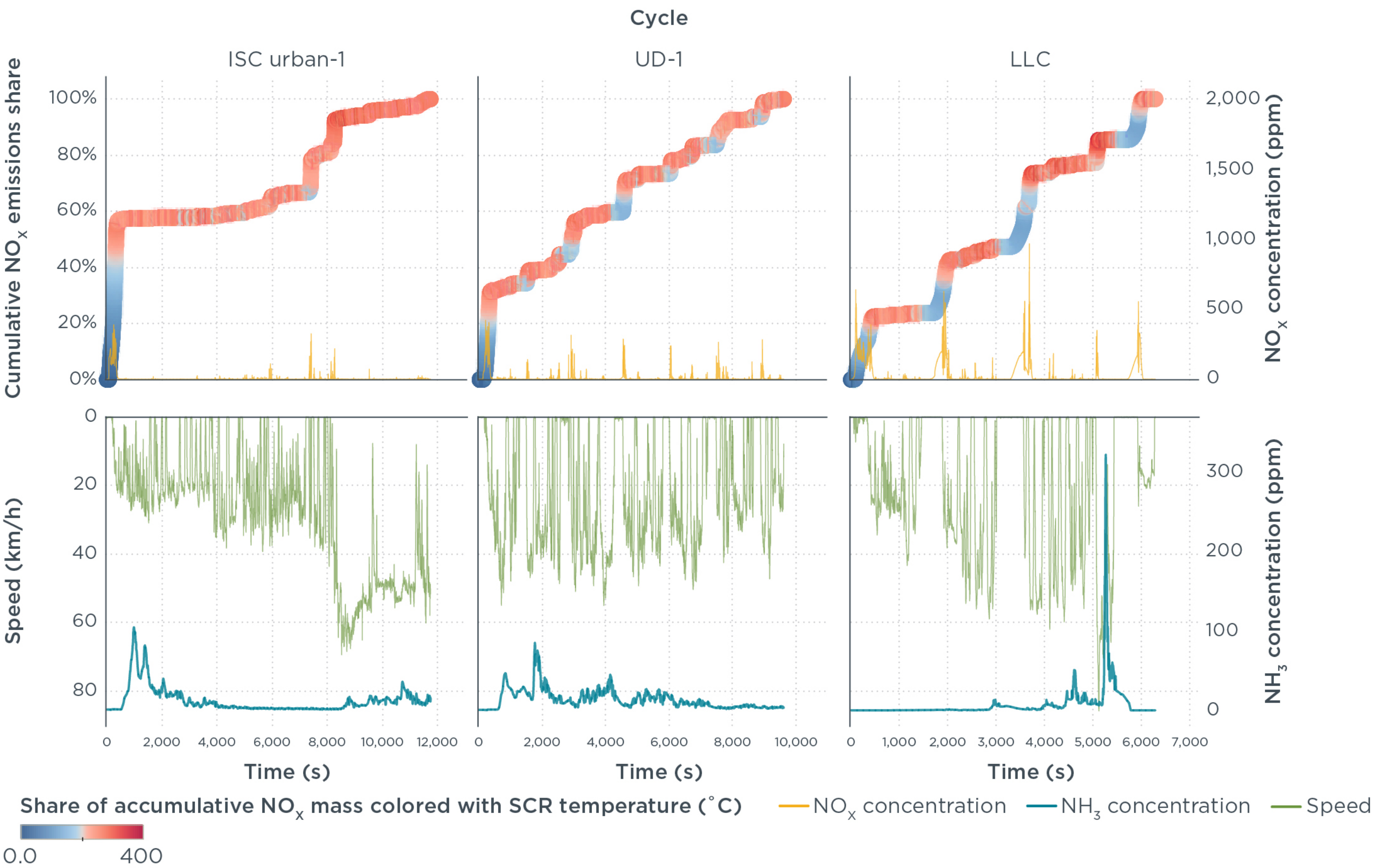
NO_x and NH_3 emissions analysis

Fixed nitrogen in the exhaust gas of diesel engines comes in the form of NO_x and NH_3 emissions. Fixed nitrogen emissions react in the atmosphere to form particulate matter ($PM_{2.5}$), the ambient air pollutant with the most detrimental impacts on human health. Most of the $PM_{2.5}$ in China comes from emissions from vehicle tailpipes. Therefore, pollutant emission regulations must ensure that the technologies deployed for NO_x control, which are SCR systems in most cases, do not lead to higher NH_3 emissions.

The results in Figure 5 indicate that the inclusion of cold-start emissions has the largest impact on the NO_x emissions performance. This does not come as a surprise, as SCR systems must achieve their activation temperature—typically 200 °C—to be able to efficiently reduce NO_x emissions.[11] Similarly, NH_3 emissions are a consequence of ammonia, the SCR reducing agent, slipping through the SCR system. The ability of the SCR system to store ammonia on its surface is temperature dependent.

11 Xinmei Yuan, Hongqi Liu, and Ying Gao, "Diesel Engine SCR Control: Current Development and Future Challenges," *Emission Control Science and Technology* 1, no. 2 (May 2015): 121–33, https://doi.org/10.1007/s40825-015-0013-z.

Figures 6 and 7 show the cumulative NO_x emissions over three different test cycles, color-coded as a function of the SCR upstream temperature. The curve is white at the SCR activation temperature, then turns blue where the SCR temperature is lower than 200 °C and turns red when the temperature is higher than 200 °C.



The trends of Acc NO_x share, sum of NO_x conc, sum of Speed and sum of NH_3 conc for Time broken down by Cycle on page Model1. For pane Acc NO_x share: Color shows sum of SCR Temp. The view is filtered on Cycle, which keeps ISC Urban-1, LLC and UD-1.

Figure 6. Cumulative NO_x emissions, NO_x concentration, NH_3 concentration, and speed profile for the ISC-urban, UD-1, and LLC tests for Vehicle 1.

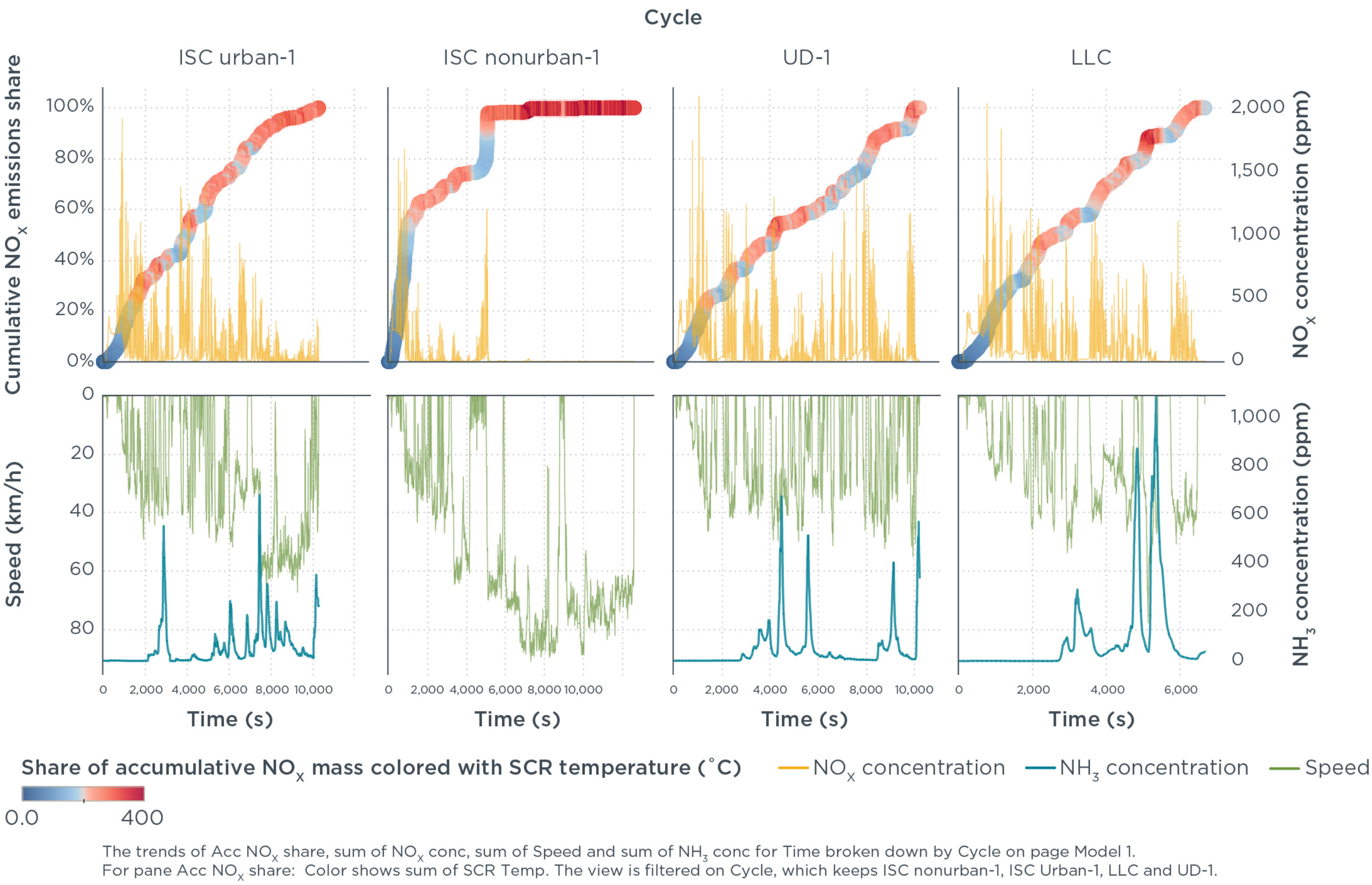


Figure 7. Cumulative NO_x emissions, NO_x concentration, NH_3 concentration, and speed profile for the ISC-urban, UD-1, and LLC tests, for Vehicle 2.

For both Vehicle 1 and Vehicle 2, the largest portion of NO_x emissions happens at the start of the test, when the SCR system is cold. Additional NO_x emissions spikes—reflected as step-like increases in the cumulative curve—occur every time the SCR temperature drops below 200 °C. The frequent stops in the UD tests and the long idling time in the LLC tests cause NO_x emissions peaks as the SCR system cools down during stops and idling. Especially for the long idling time in LLC tests, the impact was of the same order of magnitude as cold-start emissions. These results, which comport with what is already well known in the industry, unambiguously highlight the need for active thermal management of the SCR system to achieve a rapid warm-up and ensure that the SCR stays warm during operation.

Figure 8 shows the SCR activation time for both vehicles.[12] The SCR activation time for Vehicle 2 was much longer than for Vehicle 1. In all three tests, the SCR for Vehicle 2 needed more than 1,000 s to work after the vehicle started and in the LLC test in particular, it needed over 1,600 s to work. In contrast, the SCR of Vehicle 1 only took 100 to 300 s to warm up. These findings illustrate the great variability present in the SCR thermal management in China VI trucks and thus the latent potential for improvements of the SCR technology applied, including things like rapid warm-up and stay-warm strategies to further control NO_x emissions.

12 SCR activation time is defined in this study as the time that elapses between when the vehicle first moves (GPS speed > 1 km/hr) and when the SCR upstream temperature first reaches 200 °C.

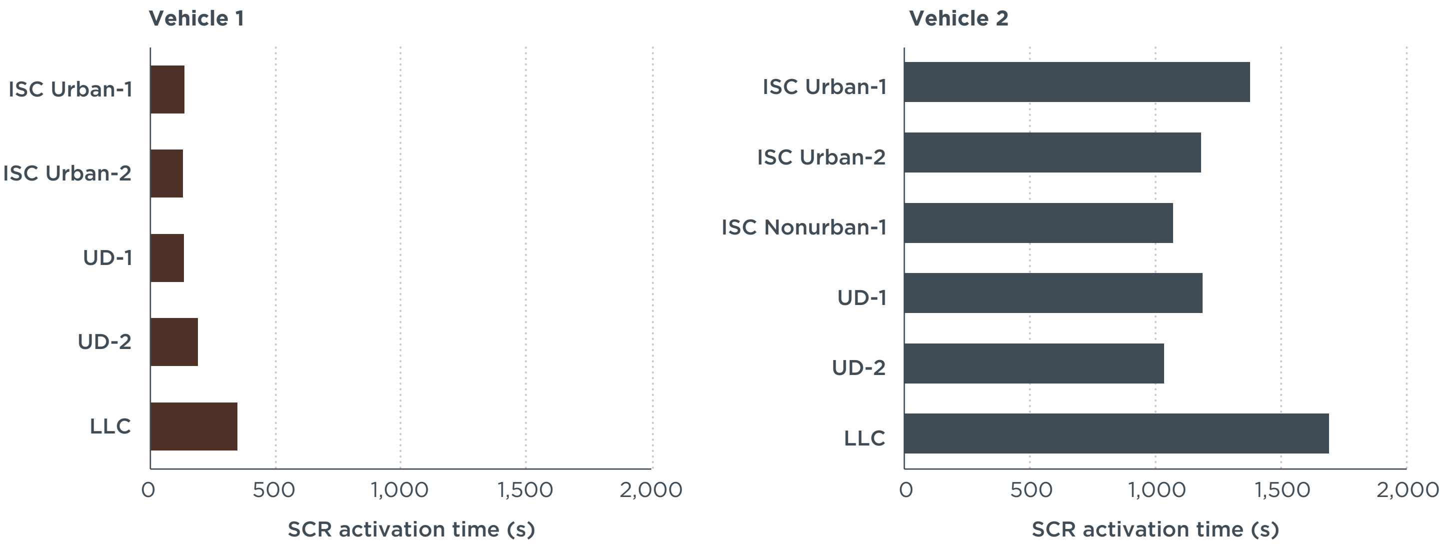


Figure 8. SCR activation time after vehicle start for both vehicles.

Figures 6 and 7 also show instances of NH_3 concentration in the tailpipe exhaust. Sharp acceleration events, particularly when the SCR is not warm enough, can lead to NH_3 slip. NH_3 in the tailpipe can also be a consequence of ammonia desorption from the SCR surface at high SCR temperatures. SCR and ASC systems must be properly calibrated to avoid ammonia slip. Heated urea dosing, dual SCR systems, and model-based control strategies provide additional ways to prevent ammonia slip.

The results indicate that the high-efficiency SCR of Vehicle 1 performs better than the mid-efficiency SCR with EGR of Vehicle 2 in terms of controlling both NO_x emissions and NH_3 slip. This is particularly evident when comparing the emissions performance against the Euro VII limits proposed by CLOVE. Both vehicles tested would fail to meet CLOVE-90 and CLOVE-100 limits, set at 0.09 gNO_x/kWh and 0.175 gNO_x/kWh, respectively. But while Vehicle 1 exceeded those emissions levels by 12%–888% in the MAW 90% calculation and by 160%–1,080% in the MAW 100% calculation, Vehicle 2 exceeded the proposed Euro VII limits by 667%–4,410% and 773%–2,339%, respectively. The results are all including cold start, and the range is across the different test cycles.

For NH_3 emissions, Vehicle 1 is also significantly closer to meeting the CLOVE Euro VII targets—set at 65 $mgNH_3$/kWh—than Vehicle 2. While Vehicle 1 exceeded those NH_3 emissions levels by 27%–154% in the MAW 90% calculation and by 54%–178% in the MAW 100% calculation, Vehicle 2 exceeded the proposed Euro VII limits by 166%–1,146% and 171%–1,149%, respectively, depending on different test cycles.

PN_{23} and PN_{10} emissions analysis

China VI sets limits on emissions of PN_{23}, that is, for solid particles larger than 23 nm. Volatile, semi-volatile, and solid particles smaller than 23 nm are currently not regulated. Still, these unregulated particles can have detrimental effects on human health, not only through direct exposure but also because of their role in the formation of secondary aerosols and $PM_{2.5}$.

Lowering the size threshold in China's regulations from 23 nm to 10 nm (in other words, measuring PN_{10}) for solid particles can be done without making a large investment or significant modifications to existing measurement systems. Indeed, PN_{10} counting techniques are now mature enough to warrant their inclusion in pollutant emission regulations. This section assesses the filtration efficiency of current DPF systems for PN_{10} and the additional filtration challenges that will be imposed if the regulatory requirements are extended to particles smaller than 23 nm and larger than 10 nm.

Since PN_{10} measurement equipment was not available for the on-road tests conducted, PN_{10} emissions were evaluated on a chassis dynamometer over the C-WTVC cycles. PN_{23} was measured in both on-road and laboratory tests. Figure 9 shows the trip average emissions of PN_{23} and PN_{10} for both vehicles.

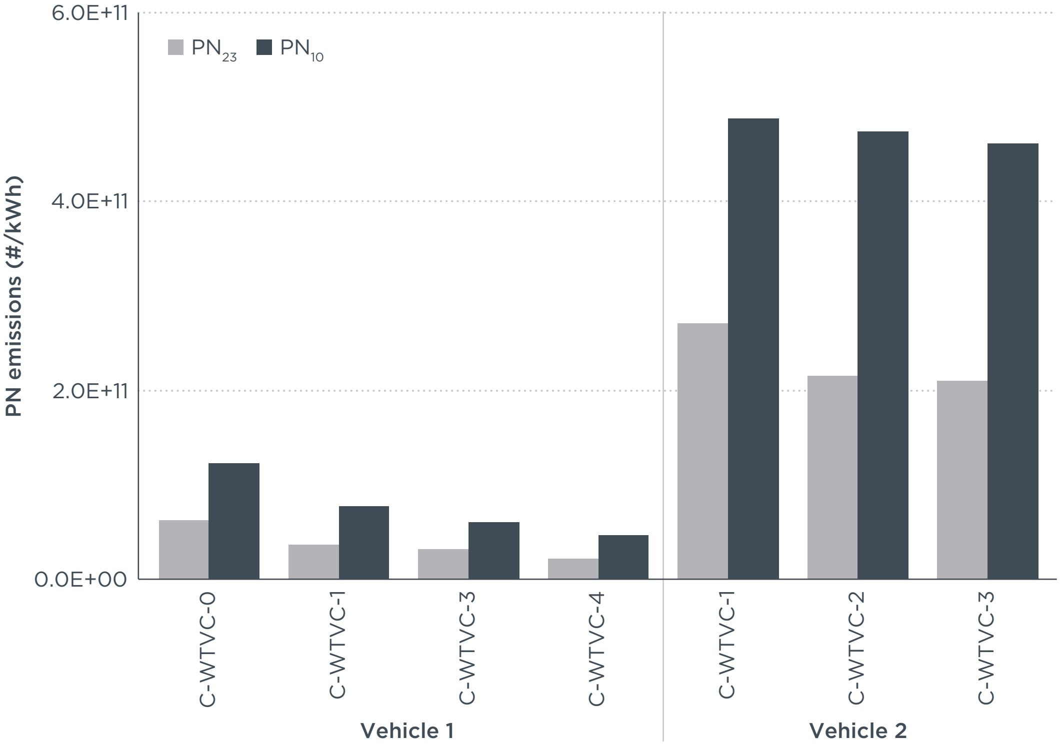


Figure 9. PN_{23} and PN_{10} results from chassis dynamometer tests over the C-WTVC for both vehicles.

The difference between PN_{10} and PN_{23} emissions is similar for both vehicles. The PN_{10} emissions of Vehicle 1 were 87%–112% higher than PN_{23} across the different tests and the same range was 80%–120% higher for Vehicle 2. This means that, if the next-generation emission standard continues to ignore particles smaller than 23 nm and larger than 10 nm, about 50% of PN emissions in the most critical size range will remain unregulated. Hence, setting a PN_{10} limit is critical for achieving robust control of PN emissions.

As was the case with NO_x and NH_3 emissions, Vehicle 2 showed worse PN emissions performance than Vehicle 1. Therefore, Vehicle 1 is closer to meeting the CLOVE Euro VII limits than Vehicle 2.

Assuming that PN_{10} emissions are twice as high as PN_{23} emissions, as assessed above, Vehicle 1 would already meet the CLOVE Euro VII targets, set at $1{\times}10^{11}$ #/kWh and $5{\times}10^{11}$ #/kWh for CLOVE-90 and CLOVE-100, respectively. As shown in Figure 5, Vehicle 2 would need to reduce its PN emissions by 85%–90% and 25%–60% to meet the recommended CLOVE-90 and CLOVE-100 limits, respectively.

GHG emissions analysis

CO_2 emissions are a direct and unavoidable consequence of combusting diesel fuel. N_2O emissions, on the other hand, are formed inside the emission control systems of vehicles during the catalytic reduction of NO_x to nitrogen. SCR systems can produce N_2O at temperatures around 250 °C through the decomposition of ammonium nitrates. At temperatures above 500 °C, the primary mechanism for N_2O formation is NH_3 oxidation in the ASCs.

At present, CO_2 is the only GHG that must be measured and reported under China VI, but there are no regulatory limits on it. N_2O is not regulated in any form under China VI.

CO_2 emissions are reported from PEMS and chassis tests in a work-specific metric (g/kWh). CO_2 emissions are also estimated from fuel consumption performance as a distance-based metric (g/km).[13] Table 2 shows the CO_2 emissions results for both vehicles from all tests. Generally, the work-based CO_2 emissions of Vehicle 2 were lower than Vehicle 1. This result is expected because larger engines tend to have better thermal efficiency.

Despite testing at 10% of the maximum payload, the C-WTVC CO_2 emissions of Vehicle 1 are higher than the certified CO_2 emissions of that truck model, which are determined at 100% payload.

Table 2. CO_2 emissions for Vehicle 1 and Vehicle 2 in all tests

Test	Cycle	Vehicle 1		Vehicle 2	
		Power-based (g/kWh)	Distance-based (g/km)	Power-based (g/kWh)	Distance-based (g/km)
On-road PEMS	ISC urban	910.1	405.6	753.8	722.8
	ISC non-urban	—	—	671.8	764.4
	Urban delivery	882.1	544.7	773.1	830.7
	LLC	871.0	553.8	785.6	787.8
Chassis test	C-WTVC	737.4	629.2	750.1	663.0
	C-WTVC (Certified)	—	600	—	910

The results indicate that N_2O emissions are not a negligible component of the GHG emissions of the tested vehicles. Figure 10 shows the tailpipe GHG emissions from both vehicles considering CO_2 and N_2O as CO_2 equivalent, using GWP-100. N_2O emissions contribute an average of 5% of total tailpipe GHG emissions from Vehicle 1, and 9% for Vehicle 2. Given this, regulating N_2O emissions in addition to CO_2 emissions is critical for reducing total GHG emissions from HDVs and must be considered.

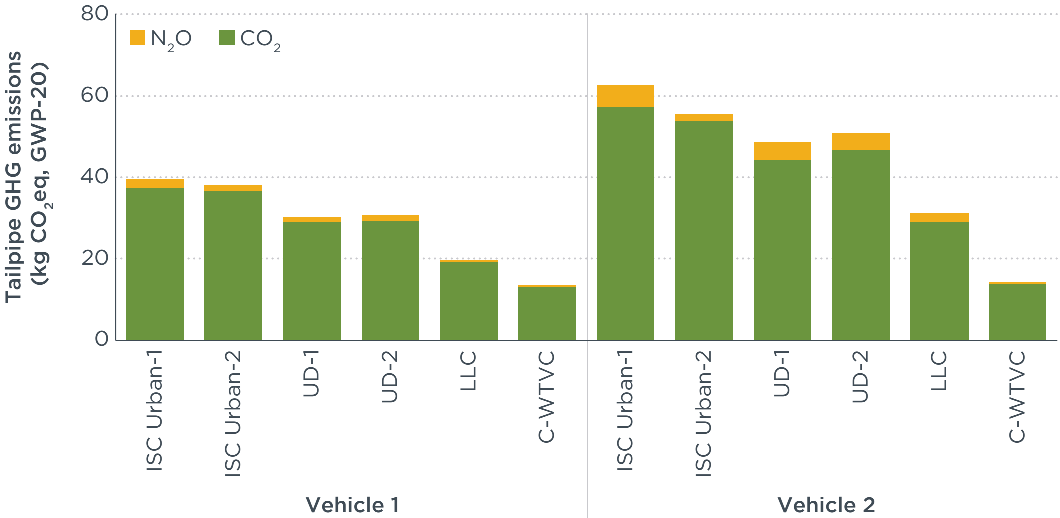


Figure 10. Tailpipe CO_2 and N_2O emissions from both vehicles in all PEMS and laboratory tests.

Both vehicles would fail to meet CLOVE-90 and CLOVE-100 limits for N_2O, set at 0.06 gN_2O/kWh and 0.160 gN_2O/kWh, respectively. Recall from Figure 5, above, that Vehicle 1 exhibited better performance; it met the CLOVE-100 limit in some tests but exceeded the CLOVE-90 limit by 90%–191% in the MAW 90% calculation. Vehicle 2 exceeded the

13 The conversion rate of diesel fuel consumption to CO_2 emissions is assumed as 2,600 g/L.

CLOVE-90 limits by 330%–531% and exceeded the CLOVE-100 limit by 64%–139%. All ranges are the result of different test cycles.

Key findings and policy recommendations

While both vehicles showed adequate compliance with the China VI emission standard, both are far from meeting the Euro VII limits proposed by CLOVE. Both vehicles complied with the China VI standard for emissions of regulated pollutants in the standard ISC test, and the CO and PN emissions in particular were far below the limits.[14] However, their performance would be worse if they were subject to the CLOVE proposal for Euro VII, especially the CLOVE-90 limits. For almost all regulated pollutants, emissions for the two vehicles were higher than CLOVE-90 limits; the exception was the PN emissions from Vehicle 1's chassis tests. Further, tests showed that for both unregulated pollutants, NH_3 and N_2O, neither vehicle would comply with the proposed emission limits in CLOVE.

FAW Jiefang's tractor-trailer (Vehicle 2) tended to have higher air pollutant and GHG emissions than FOTON's straight truck (Vehicle 1) in all the parallel PEMS test cycles (ISC urban, urban delivery, and LLC) and the same chassis dynamometer test cycle (C-WTVC). Potential reasons for this include differences in engine technology such as engine design and power and differences in the emission control system technology, including differences of SCR and DPF.

NO_x emissions control is not performing well in certain circumstances and China's regulations need to be improved. Cold-start procedure, low-load and long-idling driving cycle, and SCR technology all have major impacts on NO_x emissions. Cold-start procedure can contribute to over 20%–60% of total NO_x emissions in real-world driving, and the NO_x emissions in LLC tests for Vehicle 1 and Vehicle 2 were 1.3 and 4 times higher, respectively, than the China VI regulation, mostly because of cold start and long idling time. Further, the efficiency and activation time for Vehicle 2's SCR led to significantly higher NO_x emissions compared with Vehicle 1.

Unregulated pollutants including NH_3, N_2O, and PN_{10} are very important in vehicle emissions. NH_3 is already known as an important precursor to $PM_{2.5}$ pollution and neither vehicle showed good compliance with the proposed Euro VII standard. Results showed that N_2O is contributing an additional 3%–9% of GHG emissions above the CO_2 emissions and that considering PN_{10} can catch about 44%–55% more PN emissions beyond what is captured when only PN_{23} is regulated.

Policy recommendations

Based on the key findings, the following are proposed for China's next-generation emission standard:

China VII should tighten pollutant emission limits. Future limits, particularly for NO_x emissions, should force the adoption of technologies currently available and accelerate the commercialization of those under development. Technology packages that reduce NO_x emissions by 90% from current values have been demonstrated by CARB in its Omnibus rulemaking.

Emission limits should drive the adoption of technologies that simultaneously reduce NO_x and CO_2. Any potential trade-off between pollutant and CO_2 emissions has been overcome in recent years. Many technologies exist that can simultaneously reduce NO_x and CO_2 emissions, and many more can reduce NO_x without increasing CO_2. Applications

14 The standard ISC test cycle for Vehicle 1 is the ISC urban test and for Vehicle 2, the standard ISC test is the non-urban test.

of rapid warm-up and stay-warm strategies are limited to cold-start and low-load operation and have limited impact on the vehicle's overall fuel efficiency. China VII standards can incentivize the adoption of technologies that simultaneously reduce NO_x and CO_2 emissions in a synergistic manner.

China VII should focus on cold-start emissions and low-load operation. To close the gap between regulatory emission limits and the real-world emissions measurements highlighted in this paper, new technologies and thermal management strategies are needed. China VII should include clear regulatory provisions that target cold-start and low-load NO_x emissions.

New standards should lower the size cutoff for particle counting from 23 nm to 10 nm. This lowering of the size threshold for solid particles is possible without making large investments or significant modifications to existing measurement systems. Future China VII standards should also consider including volatile and semi-volatile particles by developing the right regulatory framework and forcing the development of a suitable methodology for measuring the emissions and compliance.

Introduce stringent on-road limits for NH_3 and N_2O. The former is a strong precursor to $PM_{2.5}$ and the latter is a potent GHG. The United States has already set limits for N_2O, and the European Union plans to do so with Euro VII. While NH_3 limits already exist under China VI as an average concentration limit over the WHTC engine cycle, the inclusion of this pollutant in the in-service conformity provisions will lead to better calibrations of emission control systems.

Widen the scope of on-road in-service conformity (ISC) testing. The China VI ISC methodology to assess compliance does not capture performance in cold-start conditions or in low-load or low-speed operations, even though these conditions are encountered under real-world operation. China VII provides an opportunity to ensure that all driving conditions—including low-load and cold-start—are captured.

Introduce strict idling NO_x limits. Setting an idling limit of 5 g/hr or below can drive the adoption of technologies that prevent idling, such as automatic shutdown systems and stop-start, and of technologies that make idling unnecessary, such as battery-driven auxiliary power units and off-board power capabilities. Such limits were already adopted by CARB in its Omnibus regulation.

Appendix. Summary of results over all cycles tested

Table A1. Results from on-road PEMS testing

	Name	Cold start[a]	Avg. temp	Avg. speed	Fuel economy	CO	CO_2	NO_x	N_2O	NH_3	PN_{23}	Total work
	Cycle & test number	**With (w) or without (w/o)**	**°C**	**km/h**	**L/100km**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**×10^10 #/kWh**	**kWh**
Vehicle 1	**ISC Urban-1**	w	22.6	28.0	15.6	0.231	897.4	0.156	0.175	0.097	2.12	41.6
		w/o				0.214	870.7	0.066	0.174	0.098	2.13	40.4
	ISC Urban-2	w	22.1	27.8	15.6	0.845	951	0.130	0.143	0.143	1.80	38.5
		w/o				0.830	921.4	0.059	0.143	0.146	1.82	37.4
	UD-1	w	25.2	21.4	19.2	0.882	858	0.295	0.125	0.090	0.63	33.8
		w/o				0.883	841.5	0.209	0.130	0.137	0.64	31.7
	UD-2	w	21.4	18.5	22.7	0.880	922.9	0.493	0.109	0.245	1.11	31.7
		w/o				0.890	905.8	0.369	0.113	0.136	1.16	29.3
	LLC	w	26.9	19.5	21.3	0.539	892.7	0.927	0.111	0.067	1.20	21.4
		w/o				0.511	849.2	0.773	0.112	0.073	1.25	19.7
Vehicle 2	**ISC Urban-1**	w	30.4	26.4	28.6	2.217	741.4	2.051	0.248	0.361	30.7	77.3
		w/o				2.238	727.9	1.670	0.257	0.376	30.7	74.0
	ISC Urban-2	w	30.1	26.5	27	—[b]	778.6	2.334	0.098	0.638	20.3	69.1
		w/o				—	767.3	1.979	0.102	0.675	19.9	65.1
	ISC Nonurban-1	w	26.7	49.9	29.4	0.779	678.2	0.260	—	—	31.8	200.0
		w/o				0.778	672	0.118	—	—	31.8	195.6
	ISC Nonurban-2	w	26.6	54.3	29.4	—	—	—	—	—	—	—
		w/o				0.382	665.1	0.194	—	—	64.6	180.5
	UD-1	w	21.1	17.3	34.5	3.146	791.5	3.202	0.286	0.342	27.6	55.9
		w/o				3.204	774.8	2.699	0.302	0.365	27.3	52.2
	UD-2	w	24.8	18.6	33.3	3.328	770.8	2.788	0.238	0.116	29.3	60.7
		w/o				3.532	755.3	2.313	0.256	0.126	29.2	56.2
	LLC	w	23.3	19.8	30.3	2.078	796.1	3.430	0.221	0.566	28.8	36.4
		w/o				2.193	775	2.741	0.234	0.623	29.2	33.0

[a] This column indicates whether the MAW results are with or without the windows for the cold start period.

[b] The cells marked as '—' indicate the data was not measured or was deemed invalid for some reason.

Table A2. Results from chassis dynamometer testing

	Name	Cold start	Avg. temp	Avg. speed	Fuel economy	CO	CO_2	NO_x	N_2O	NH_3	PN_{23}	PN_{10}
	Cycle & test no.	**Cold or hot start**	**°C**	**km/h**	**L/100km**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**g/kWh**	**×10^10 #/kWh**	**×10^10 #/kWh**
Vehicle 1	**C-WTVC-0**	cold start	20.0	40.2	24.6	0.427	745.7	0.087	0.087	0.341	6.30	12.3
	C-WTVC-1	hot start	19.9	40.6	23.4	0.375	719.8	0.066	0.066	0.037	3.70	7.78
	C-WTVC-2	hot start	20.1	40.6	27.3	0.468	834.6	0.106	0.106	0.008	59.3[a]	1420[a]
	C-WTVC-3	hot start	19.9	40.4	24.4	0.665	743.1	0.115	0.115	0.003	3.24	6.07
	C-WTVC-4	hot start	19.7	40.6	24.5	0.734	740.8	0.118	0.118	0.001	2.24	4.74
Vehicle 2	**C-WTVC-0**	cold start	16.8	40.4	27.2	0.449	767.1	2.543	0.106	0.187	—	—
	C-WTVC-1	hot start	23.0	40.6	25.5	0.361	760.5	1.663	0.128	0.381	27.2	48.8
	C-WTVC-2	hot start	23.0	40.6	24.7	0.343	742.1	1.592	0.110	0.200	21.6	47.4
	C-WTVC-3	hot start	23.1	40.6	24.6	0.37	730.6	1.196	0.109	0.300	21.0	46.2

[a] A DPF regeneration event occurred in the C-WTVC-2 test and it caused 16- and 180-times higher emissions of PN_{23} and PN_{10}, respectively.