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REAL-WORLD EMISSIONS IN CHINA:

A META-STUDY OF PEMS EMISSIONS DATA FROM CHINA 0 TO CHINA 5/V LIGHT- AND HEAVY-DUTY VEHICLES

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EXECUTIVE SUMMARY

Although vehicle emissions standards have been progressively tightened over time, emissions under real-world driving conditions are in some instances found to be substantially higher than laboratory-certified levels. A previous ICCT study based on portable emissions measurement system (PEMS) measurements in Europe and the United States showed that on-road nitrogen oxides (NO_x) emissions from modern diesel passenger cars can exceed the certified emissions limit by a factor of more than 25, with average on-road emissions factors of seven times the Euro 6 limit (Franco et al., 2014). A series of studies based on PEMS measurements in China showed that China III and IV heavy-duty vehicles failed to show a significant reduction in NO_x compared with China 0 vehicles (Wu et al., 2012; Zhang, 2013). The real-world emissions problem is widely attributed to deficiencies of the current type-approval protocols for light- and heavy-duty vehicles (LDVs and HDVs), which include unrepresentative test cycles and procedures, and to weak in-use compliance programs. In response, a new test procedure modeled on the European Real Driving Emissions (RDE) regulation has been introduced in the China 6 LDV emissions standard, and a new full-vehicle real-world emissions testing procedure is likely to be included in the China VI HDV standard. Under the new test protocols, vehicles will have to pass not only the chassis/engine dynamometer emissions test in the laboratory but also an on-road emissions test using a PEMS.

In this meta-study, existing real-world emissions data from multiple sources of vehicle tests in China were collected and analyzed. The data include emissions of NO_x, carbon monoxide (CO), and total hydrocarbons (THC) from 55 LDVs and 67 HDVs tested using PEMS. The vehicle sample covers a wide range of emissions standards—from China 0 to China 5/V—and vehicle types—gasoline private cars, gasoline taxis, diesel heavy-duty trucks, and diesel urban buses. The results add to the growing evidence that vehicle emissions, especially of NO_x, are not properly controlled under real-world driving conditions in China.

For LDVs, emissions standards have played an important role in reducing vehicle emissions in China. NO_x, CO, and THC emissions have declined significantly as vehicle technology has improved since China 4 (see Figure ES1 for NO_x findings). Therefore, accelerating the phase-out of old, high-emitting vehicles would bring a substantial reduction of overall vehicle emissions in China. For some modern China 4 and China 5 gasoline cars, real-world NO_x emissions significantly exceed type-approval limits, while some other models have extremely low NO_x emissions. Some taxis appeared to have removed three-way catalysts (TWCs, the main gasoline exhaust aftertreatment technology). Tests show that average NO_x emissions from these taxis was 72 times that of taxis with functioning TWCs.

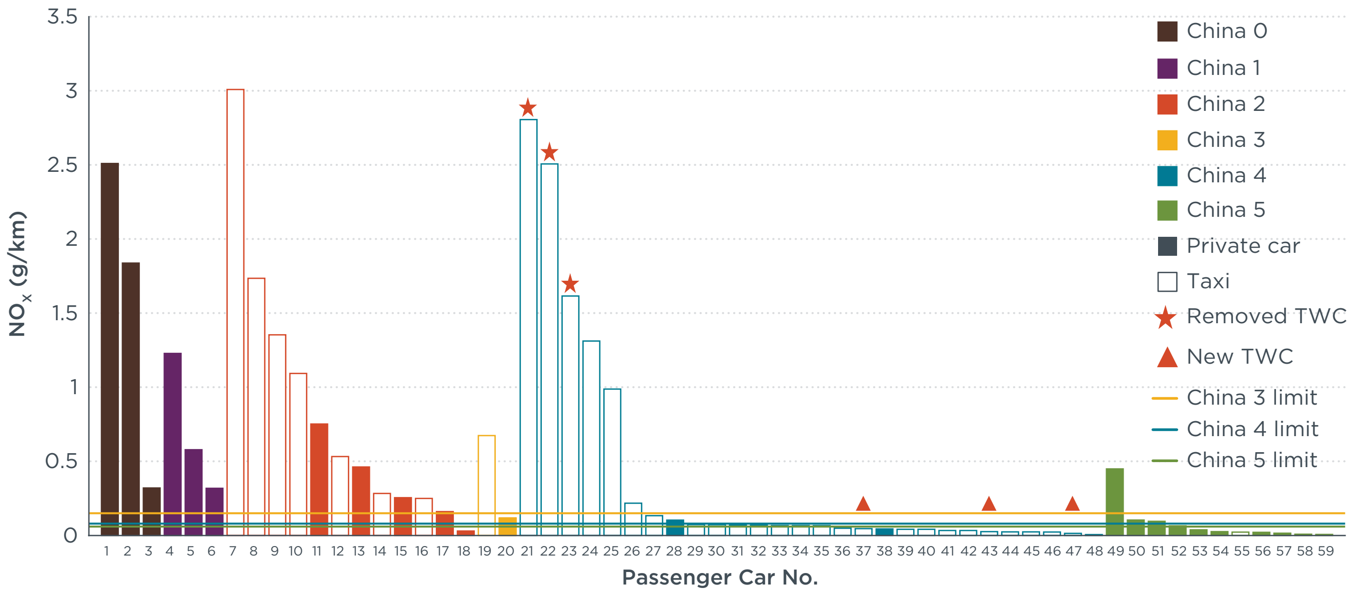

Figure ES1. Real-world NO_x emissions from gasoline cars, by vehicle.

Different colors indicate emissions standards from China 0 to China 5. Solid bars are private cars and open bars are taxis. Stars indicate vehicles with removed TWC. Triangles indicate cars with newly replaced TWC.

For HDVs, no significant improvement in the average ratio of NO_x to CO_2 emissions—a measure of tailpipe NO_x emissions relative to fuel consumption—can be observed as the emissions standard improves (see Figure ES2). Even though NO_x limits decreased by 56% on paper from the China I to the China IV standard, real-world NO_x emissions from modern HDVs are not following the reduction pattern set by the standards. While some of the China III/IV trucks are better than others, even the best trucks are not significantly improved from the best China I truck. Unlike diesel trucks, remarkable differences can be observed in the performance of buses. Surprisingly, some of the best and worst bus performers are from the same model produced by the same manufacturer. This suggests widespread failure to refill urea tanks in use or the removal of selective catalytic reduction (SCR) systems, the aftertreatment device equipped on HDVs since China IV.

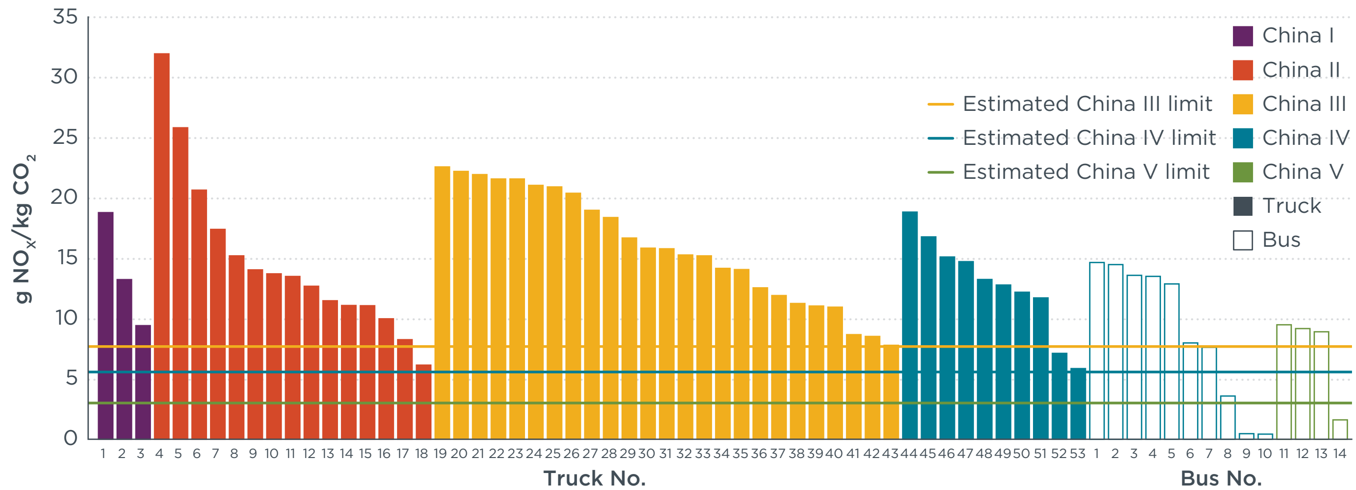

Figure ES2. Real-world NO_x/CO_2 emissions of diesel HDVs, by vehicle.

Different colors indicate emissions standards from China I to China V. Solid bars are diesel trucks and open bars are diesel buses.

In general, the results of our PEMS meta-study indicate that advanced emissions-control technologies already exist on the market, but performance in the real world varies widely. Further, end-users are tampering and disabling emission control devices. Comprehensive testing procedures and robust in-use compliance programs are required to ensure that manufacturers employ these technologies and calibrate them to work properly not only in the laboratory but also under a broad range of in-use operating conditions and that vehicle owners maintain their vehicles properly and do not circumvent emissions control.

The released China 6 LDV emissions standards and the proposed China VI HDV standards both introduce PEMS test procedures and comprehensive in-use compliance programs. These two regulations offer a major step towards effectively controlling real-world emissions. If properly implemented, these standards should bring significant emissions reductions and health benefits in decades to come. At the local level, we recommend that provinces and cities facing severe air pollution implement China 6/VI as early as possible. For in-use fleets, urgent remedial actions are recommended, such as taxi catalyst replacement programs, more intensive and frequent inspection/maintenance (I/M) programs, modification or retrofit programs for urban buses and trucks, and high penalty for non-compliant vehicles.

ABBREVIATIONS

v*a	Velocity times acceleration
BJEPB	Beijing Municipal Environmental Protection Bureau
CF	Conformity Factor
CO	Carbon monoxide
CO_2	Carbon dioxide
EGR	Exhaust Gas Recirculation
EPB	Environmental Protection Bureau
ETC	European Transient Cycle
EU	the European Union
I/M	Inspection/maintenance
HDV	Heavy-duty vehicle
LDV	Light-duty vehicle
MEP	Ministry of Environmental Protection of China
MPFI	Multi Point Fuel Injection
NEDC	New European Driving Cycle
NO	Nitric oxide
NO_x	Nitrogen oxides
NTE	Not-to-exceed
OBD	On Board Diagnostics
PC	Passenger car
PEMS	Portable Emissions Measurement System
PN	Particle number
RDE	Real-Driving Emissions
SCR	Selective Catalytic Reduction
THC	Total Hydrocarbons
TWC	Three-way catalyst
U.S.	United States of America
WHTC	World Harmonized Transient Cycle
WLTC	Worldwide Harmonized Light Vehicles Test Cycle

1. INTRODUCTION

Following a series of rapid economic developments, China has been the world's largest vehicle market for the eight years since 2009 (CAAM, 2017). As a result, motor vehicles have become one of the most significant sources of air pollution in China. In some mega-cities, such as Beijing and Shenzhen, vehicle emissions are the greatest local contributor to ambient fine particulate matter pollution (BJEPB, 2014; GDEP, 2015). In response to the severe air pollution problem, China has implemented a series of comprehensive vehicle emissions control measures, including adoption of increasingly stringent emissions standards for new vehicles, scrappage and driving restrictions on high-emitting, in-use vehicles, and improvements in fuel quality requirements. Studies based on emissions inventories have demonstrated that, in general, the vehicle emissions control programs in China have resulted in considerable progress, mainly attributed to the uptake of emissions control technologies driven by increasingly stringent standards as well as improved fuel quality (Wu et al., 2016). Nevertheless, challenges remain regarding the compliance with emissions standards for in-use vehicles under real-world driving conditions. A growing number of studies in China has shown that real-world emissions can be significantly higher than the corresponding certification levels as tested in the laboratory (Huo et al., 2012; Wu et al., 2012; Zhang et al., 2014). In particular, the real-world NO_x emissions from the heavy-duty sector did not improve under real-world operating conditions with more stringent emissions standards (Wu et al., 2012).

There have been plenty of on-road PEMS measurement campaigns deployed in China since 2005 (Chen et al., 2007; Wang et al., 2011; Liu et al., 2011; Huo et al., 2012; Wu et al., 2012; Huang et al., 2013; Zhang et al., 2014; Guo et al., 2015; He et al., 2017, etc.). But those tests were conducted by different research groups, and the data were usually processed using different analysis methodologies. The objective of this project is to collect PEMS data from existing measurement campaigns in China and perform a meta-study using a consistent analytical method. We intend the findings to provide useful information for regulatory agencies in support of the development of future emissions standards, test protocols, and in-use compliance programs. In this study, PEMS emissions data from 55 LDVs and 67 HDVs were collected and analyzed. The data covers more than 210 hours and 6,300 km of second-by-second data. This data also incorporates some recent PEMS test results from China 5/V vehicles tested in 2016 that have not been published before.

The report is organized as follows: Section 2 provides background information on the real-world emissions problem, current regulatory developments around PEMS in China, and the emissions control technologies required for compliance with standards. Section 3 describes the data sources and data analysis methods applied in this study. A detailed analysis of the test results is presented in Section 4, followed by a discussion in Section 5 of the implications of the test findings. The final Section 6 summarizes key findings and provides high-level regulatory recommendations on next steps to establish a robust vehicle emissions compliance program in China.

2. BACKGROUND

2.1 THE REAL-WORLD EMISSIONS PROBLEM

Starting in the 1960s, countries around the world introduced and gradually tightened emissions standards for new motor vehicles. Emissions certification tests are typically carried out under laboratory conditions, either on a vehicle chassis dynamometer for LDVs or engine dynamometer for HDVs. China implemented its first vehicle emissions standard in 2000 (China 1/I, equivalent to Euro 1/I), and progressively strengthened the standards following the European regulatory template. Figure 1 shows the in-use fleet breakdown from China 0 (pre-China 1/I) to China 5/V LDVs and HDVs in China in 2016 (MEP, 2017a).

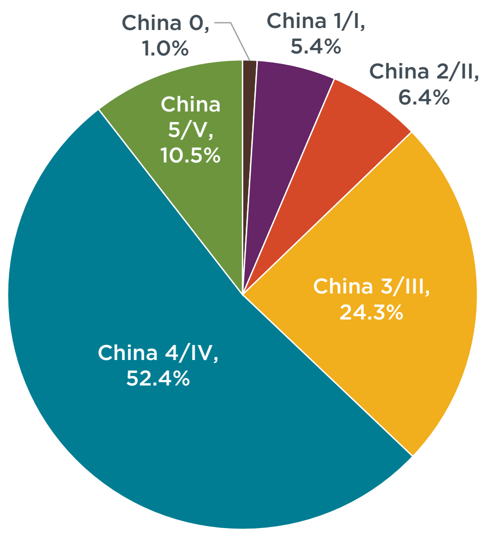

Figure 1. In-use fleet breakdown from China 0 to China 5/V LDVs and HDVs in China in 2016

As new-vehicle standards are tightened over time, the emissions and health benefits can truly materialize only if the emissions control technologies are effective not only in the lab but also in real-world driving throughout the vehicles' useful life. However, emerging studies from the United States and Europe have shown that on-road emissions can diverge significantly from laboratory results. A previous ICCT study based on PEMS measurements in Europe and the United States showed that on-road NO_x emissions from modern diesel passenger cars can exceed the certified emissions limit by a factor of more than 25, with average on-road emissions factors of seven times the Euro 6 limit (Franco et al., 2014). For HDVs, New Euro IV and V heavy-duty trucks and buses equipped with SCR systems recorded significantly elevated NO_x emissions in real-world operation compared with laboratory test results, especially in urban driving (Lowell & Kamakaté, 2012).

Similar results are also found in China. A series of studies based on PEMS measurements in China showed that China II and III trucks and buses failed to show a reduction in NO_x compared with China 0 HDVs (Zhang, 2013). NO_x emissions from China IV buses equipped with SCR systems were similar to those of China III buses (Wu et al., 2012). For gasoline LDVs, the average CO, THC, and NO_x emissions were reduced significantly from China 1 to China 4, whereas a few old gasoline taxis were identified as having emissions equivalent to those of China 0 LDVs (Huo et al., 2012).

High real-world emissions are mostly attributed to shortcomings in the current type-approval protocols for LDVs and HDVs. For LDVs, one major reason is that the New European Driving Cycle (NEDC) test applied at type-approval from China 1 to China 5 does not capture the full range of driving conditions in the real world (Kågeson, 1998; Mellios et al., 2011). For HDVs, the European Transient Cycle (ETC) applied from China III to China V has a higher average engine load and power and less idling time, which does not represent real driving conditions (Lowell & Kamakaté, 2012). This bias would be more significant for urban buses (Wu et al., 2012). In addition, for both LDVs and HDVs, the lack of in-use conformity provisions and enforcement is another major cause for high real-world emissions from in-use vehicles.

2.2 CURRENT DEVELOPMENT OF PEMS REGULATIONS IN CHINA

In the past, vehicles were typically tested in laboratories. In a chassis dynamometer laboratory for light vehicles, a driver operates the auto to match a predetermined time-speed profile and gear change pattern while the exhaust gas is collected in sampling bags for later analysis or processed by on-line chemical analyzers. Because of its high repeatability and reproducibility, laboratory testing is the standard technology for vehicle emissions measurements for regulatory purposes worldwide. However, growing evidence indicates that the chassis/engine dynamometer test does not fully represent real driving situations because of limitations on driving cycles and test procedure, such as road load determination and ambient temperature.

PEMS is a complete set of emissions measurement equipment that can be carried out on a vehicle while driving on normal roads. On-line analyzers can be directly connected to the tailpipe to measure exhaust emissions in real time. The most important advantage of PEMS testing is that it can measure tailpipe emissions during a wide variety of real-world driving conditions (Mock & German, 2015). PEMS has proven to be an effective tool for measuring real-world vehicle emissions, and it has been adopted around the world for research purposes for more than a decade (Franco et al., 2014). In recent years, PEMS has also been introduced for regulatory purposes for both LDVs and HDVs in the United States, the EU, and China.

In January 2011, the European Commission established a working group involving all interested stakeholders to develop a new testing procedure to better control on-road emissions (Mock, 2017). In May 2015, after three years of research and discussion, the European Commission approved the new Real Driving Emissions (RDE) test procedure for type approval of Euro 6 light passenger and commercial vehicles, taking effect in September 2017 (European Commission, 2016a, 2016b). With the new RDE test procedure, LDVs will have to pass not only the chassis dynamometer test in the laboratory but also an on-road test using PEMS. In the EU, RDE is first being used for new vehicle type approval and will eventually be used for in-service conformity testing (Mock, 2017).

The China LDV emissions regulations follow EU regulatory pathways, with the implementation dates of the China LDV standards generally lagging behind the equivalent EU standard by five to eight years. The China 6 standard, first proposed in May 2016 and finalized in December 2016, introduced RDE testing for vehicle type-approval and in-use compliance (MEP, 2016a). The China 6 RDE regulation is primarily based on the Euro 6 RDE Package 2 passed in April 2016 (European Commission, 2016b), with a few enhancements and modifications for the Chinese context. For NO_x

and particle number (PN), only monitoring and recording are required before July 2023, and conformity factors (CF, defined as the ratio of measured on-road emissions factors over the regulated limits) will be enforced starting in July 2023. The CFs of NO_x and PN are temporarily set at 2.1 and will be re-evaluated and determined by July 2022. For passenger cars, for example, this leads to not-to-exceed (NTE) limits of 0.0735 g/km for NO_x and 1.26 x 10^{12} #/km for PN. Although no CF has been set for CO, it will be monitored in RDE tests.

Even though RDE testing is conducted on public roads open to traffic, boundary conditions and criteria have been set to define a valid RDE trip. For instance, the total trip duration, composition of urban, rural, and motorway driving as defined by speed bins, average and maximum speed, ambient temperature, altitude, and dynamic requirements are specified in the RDE regulation. Compared with the EU RDE, China 6 extends the maximum altitude boundary to 2,400 m from 1,300 m, introduces a correction factor of 1.8 for extended high-altitude driving at 1,300-2,400 m, and reduces the maximum speed during motorway driving to 120 km/h from 145 km/h. The data processing method in China 6 follows the moving average window method developed in the EU RDE regulation, and the power binning method in EU RDE is removed. Table 1 provides a detailed comparison of the China 6 and Euro 6 RDE Package 3 requirements.

Table 1. Comparison of China 6 and Euro 6 RDE requirements

Requirement		China 6	Euro 6
Application	Type Test[1]/Approval	Yes	Yes
	In-service test	Yes	Yes*
Emission standard	Regulated pollutants	NO_x and PN after monitoring period Monitoring for CO	
	Binding limits in Type I Test**	Fuel-neutral NO_x: 0.035 g/km PN: 6 x 10^{11} #/km	NO_x: Diesel: 0.08 g/km Gasoline: 0.06 g/km PN***: 6 x 10^{11} #/km
	Conformity factors****(effective date)	NO_x and PN: All new vehicles: 2.1 (7/1/2023)	NO_x: New types: 2.1 (9/1/2017) All new vehicles: 2.1 (9/1/2019) New types: 1.5 (1/1/2020) All new vehicles: 1.5 (1/1/2021)***** PN: New types: 1.5 (9/1/2017) All new vehicles: 1.5 (9/1/2018)*****
	Cold starts	Excluded	Included

1 Per requirements in China's newly amended Air Pollution and Control Law, starting from the China 6/VI regulation, the regulatory agency no longer type approves new vehicle models. The Chinese MEP used to have a procedure of issuing certification to new vehicle models that are tested to comply with emission standards. This procedure was referred to as vehicle type approval. Under the new law, vehicle manufacturers self-test and self-certify their new vehicle models and need to report to the regulatory agency and publish required information to the public. MEP still establishes the test protocols and emission limits for all required tests. The set of tests are referred to as type tests.

Requirement		China 6	Euro 6
Trip requirement	Total trip duration	90-120 min	
	Minimum distance for each segment	Urban: 16 km Rural: 16 km Motorway: 16 km	
	Trip composition	Urban: 29%-44% of total distance Rural: 23%-43% of total distance Motorway: 23%-43% of total distance	
	Average speed	Urban: 15-40 km/h Rural: 60-90 km/h Motorway: >90 km/h	
	Stop percentage during urban segment	6%-30%	
	Maximum speed during motorway segment	120 km/h (135 km/h for 3% of motorway driving time)	145 km/h (160 km/h for 3% of motorway driving time)
	High-speed duration during motorway segment	At least 5 min driving at >100km/h speed	
Boundary condition	Payload	≤90% of maximum weight	
	Ambient temperature	Moderate: 0°C–30°C Extended: -7°C-0°C, 30°C-35°C	Before 1/1/2020 (for new types), and 1/1/2021 (for all new vehicles): Moderate: 3°C-30°C Extended: -2°C-3°C and 30°C -35°C Afterward: Moderate: 0°C-30°C Extended: -7°C-0°C, 30°C-35°C
	Altitude	Moderate: <700 m Extended: 700 m–1,300 m Further extended: 1,300 m–2,400 m	Moderate: <700 m Extended: 700 m–1,300 m
	Correction factor	Extended: 1.6 Further extended: 1.8	Extended: 1.6
	Altitude requirements	Start and end point shall not differ more than 100 m in altitude Maximum cumulative altitude increase: 1,200 m over a distance of 100 km	
	Dynamic requirements	For each segment, Max. limit is defined as the 95th percentile of v*a (speed * positive acceleration) Min. limit is defined by the RPA (relative positive acceleration)	
	Use of auxiliary systems	Free to use as in real life	
Evaluation methods	Data evaluation methods	Moving average window method	Moving average window method or power binning method
	Verification of test normality in moving average window method	Maximum primary tolerance for the CO_2 characteristic curve: 50%	Maximum primary tolerance for the CO_2 characteristic curve: 30%

**Part of RDE fourth legislative package, currently under technical discussion.*
***The emission limits in this table are for M1 and M2 vehicles in the EU and M1 Category I vehicles in China.*
****Applicable only to vehicles using direct injection engines.*
*****For the whole trip and for the urban segment separately.*
******N1 Classes 2 and 3, and N2 vehicles are always 1 year later than the dates listed above.*

On the HDV side, the China Ministry of Environmental Protection (MEP) released a draft proposal of the China VI HDV emissions standard in October 2016. The document also introduced full-vehicle PEMS testing for HDVs at the national level (MEP, 2016b). The PEMS test provisions in the China VI proposal mainly follow the Euro VI PEMS regulation for in-service vehicles. In addition, the China VI proposal expands the full-vehicle PEMS test to both type test and in-service test. Similar to the LDV RDE, there are specific trip validity criteria in the China VI proposal. For diesel HDVs, the CFs for CO and NO_X are set at 1.5 and for PN at 2. This leads to NTE limits of 6,000 mg/kWh for CO, 690 mg/kWh for NO_X, and 1.2 x 10^{12} #/kWh for PN. The China VI standard was proposed to be implemented starting January 1, 2020, for all sales and registrations. In addition, MEP released a supplemental PEMS testing standard for China V HDVs in September 2017 (MEP, 2017b). The standard is a supplement to all requirements under the existing China V standard. It requires additional on-road PEMS testing for new and in-use China V HDVs. As the China VI HDV standard is not likely to be implemented nationwide until 2020, the supplemental PEMS standard is designed to curb excess NO_X emissions from China V HDVs. In doing so, China became the first country in the world to attempt to solve a known deficiency in the Euro V type-approval process by requiring additional PEMS testing for newly produced vehicles and in-use compliance testing. The standard took effect October 1, 2017. Table 2 provides a detailed comparison of emissions limits and test requirements under the supplemental China V, proposed China VI, and Euro VI PEMS standards.

Table 2. Comparison of requirements under supplemental China V, proposed China VI, and Euro VI PEMS standards

		Supplemental China V	Proposed China VI	Euro VI
Implementation year		2017	2020 for China VI a 2023 for China VI b*	2014
Vehicle tested		Newly produced and in-use	Type test, newly produced and in-use	Type approval and in-use
Mandated test frequency		Every two years with minimum of 10,000 km	18 months with minimum of 10,000 km and then every two years	18 months with minimum of 25,000 km and then every two years
Emission limits for diesel	**NO_x**	4 g/kWh (CF=2.0)	0.69 g/kWh (CF=1.5)	0.69 g/kWh (CF=1.5)
	PN	No	No limit for China VI a 1.2x10^{12} #/kWh for China VI b (CF=2.0)	No
Cold start included		No	No	No
Driving shares (% of time duration)	**Urban**	10%-70%	20%-70%	20%-70%
	Rural	10%-30%	25%-33%	25%-33%
	Motorway	0%-80%	0%-55%	0%-55%
Test length		5x work of WHTC (for urban vehicles) 3x work of ETC (for other categories)	4x-7x work of WHTC	5x work of WHTC (4x-7x work of WHTC beginning 2018)
Payload		50%-100% for bus 75%-100% for truck	China VI a: 50%-100% China VI b: 10%-100%	50%-60% (10%-100% beginning 2018)
Ambient temperature		2 °C - 38 °C	-7 °C - 38 °C	-7 °C - 38 °C
Altitude		<1,000 m	<1,700 m in China VI a <2,400 m in China VI b	<1,700 m
Minimum power threshold		15%	10%	15% (10% beginning 2018)

**The China VI HDV standard is proposed to be implemented in two phases nationwide—China VI a in January 2020 and China VI b in January 2023.*

2.3 EMISSIONS CONTROL TECHNOLOGIES FOR COMPLIANCE WITH STANDARDS

Vehicle emissions are generated in the engine during the fuel combustion process. The approaches to reducing emissions are advanced engine design, which can improve in-cylinder combustion dynamics and minimize the formation of pollutants, and aftertreatment devices, which can reduce engine-out emissions by using catalysts or filters. This section provides an overview of both categories of emissions control technologies as typically deployed to comply with emissions standards for LDVs and HDVs (see Table 3 and Table 4). As China 1/I to China 5/V emissions regulations exactly follow the European precedent, the information from these tables was synthesized from European studies (Posada et al., 2012 & 2016).

For gasoline vehicles, technologies required for compliance with the China 1 standard are electronic ignition and three-way catalysts. TWCs can reduce NO_x, THC, and CO simultaneously. At stoichiometric operations, THC and CO are oxidized into water and CO_2, while NO_x is split into nitrogen and oxygen. China 2 prompts a shift toward multi-point fuel injection (MPFI). Controlling cold-start emissions is the main focus of the China 3 regulation as the warm-up period (40 seconds) was included in the type-approval test. As a result, MPFI is considered the main in-cylinder control technology for complying with China 3, with improved electronic controls for fuel injection and ignition spark timing. In addition, On-Board Diagnostics (OBD) system requirements have been introduced since China 3, prompting the use of secondary oxygen sensors to monitor the performance of TWCs. China 4 limits for NO_x, THC, and CO are reduced by around 50% from China 3 levels. These are met with much improved fueling strategies and TWC systems, as well as calibration strategies to light the catalyst off faster. The 25% NO_x limit reduction in China 5 requires combustion improvements through engine calibration, incremental improvements in air-fuel management, and improved TWC washcoat.

In summary, TWC is the main aftertreatment technology used in gasoline vehicles for controlling tailpipe emissions of NO_x, THC, and CO. However, there could be a deterioration of TWC performance over time. Therefore, proper monitoring of the conversion efficiency of TWCs over their useful life and timely replacement of deteriorated TWCs is crucial for in-use compliance by LDVs.

Table 3. Emissions control technologies for China 1 to China 5 gasoline cars

Emissions standard	In-cylinder control	Aftertreatment
China 1	Electronic ignition	TWC (single oxygen sensor)
China 2	MPFI	TWC (single oxygen sensor)
China 3	MPFI, improved electronic controls for fuel injection and ignition spark timing	Improved TWC (close-coupled catalyst and underfloor catalyst); OBD prompt the use of secondary oxygen sensors
China 4	Improved fueling strategy and faster catalyst light-off	Improved TWC
China 5	Incremental improvements in air-fuel management	Improved TWC washcoat

Table 4 summarizes the strategies for compliance with the China HDV standards. As particle emissions were not measured in this meta-study, only NO_x control technologies are listed in Table 4. For China I and II, mechanical injection is deployed in heavy-duty engines. To meet the China III standard, in-cylinder combustion improvements such as electronic control and variable injection timing are required.

The major factors that influence the combustion process include air temperature and fuel injection timing and strategy. Electronic injection allows for a more precise and variable fuel injection strategy, which improves combustion efficiency and reduces engine-out emissions.

The China III standard is the last one that can be met without the use of aftertreatment systems. Starting with China IV, HDVs have to be equipped with SCR systems to achieve stringent NO_x emissions reductions. SCR is a catalyst that reduces NO_x to nitrogen and water using ammonia stored on the vehicle in the form of urea as a reductant. SCR systems usually employ a vanadium- or zeolite-based catalyst, and each has its own merits and demerits. SCR has been proven as an effective method for HDV NO_x emissions control, with high NO_x conversion efficiency of as much as 95%. In addition, OBD requirements have been introduced since China IV, intended to identify malfunctions in the emission control system. A few manufacturers rely solely on exhaust gas recirculation (EGR) systems for China IV compliance, recirculating a fraction of exhaust gas to the cylinder to lower the combustion temperature and the formation of engine-out NO_x. Under the China V standard, NO_x reductions can be achieved with improved SCR systems along with enhanced OBD systems to monitor urea level and quality. In 2015, 55% of new rigid trucks and 70% of new tractor-trailers in China were equipped with SCR systems (Rodríguez et al., 2017). Those models relying only on EGR must be supplemented with SCR systems to comply with the China V standard.

Table 4. NO_x emissions control technologies for China I to China V HDVs

Emission standard	In-cylinder control	NO_x Aftertreatment
China I	No (mechanical injection)	No control
China II	No (mechanical injection)	No control
China III	Electronic injection	No control
China IV	Electronic injection	SCR (OBD requirements) (a few manufacturers solely use EGR)
China V	Electronic injection	Improved SCR (enhanced OBD requirements)

3. DATA SOURCES AND ANALYSIS

3.1 DATA SOURCES

The PEMS data in this study were collected from different research institutes in China. The data includes 122 vehicles, including 55 China 0 to China 5 gasoline cars and 67 China I to China V diesel HDVs. The vehicle sample covers a wide range of emissions standards and vehicle types, including private cars, taxis, heavy-duty trucks, and urban buses.[2] Taxis were analyzed separately because they usually operate more extensively than private cars and record as much as 10 times more vehicle kilometers traveled annually. Each vehicle was tested over one PEMS trip, except for two China 5 private cars, which were tested three times. A total of 126 PEMS trips were analyzed in this study. The data covers more than 210 hours and 6,300 km of second-by-second data and incorporates some more recent PEMS test results from modern China 5/V vehicles. The tests were conducted in Beijing, Tianjin, Guangzhou, Zhuhai, Xiamen, Chongqing, and Macau from 2008 to 2016. When tested, the average ages of China 0 to China 5 LDVs were 14 years, six years, three years, two years, two years, and less than one year, respectively. Table 5 and Table 6 give an overview of LDVs and HDVs included in this study.

Table 5. Overview of gasoline LDVs included in the study

	Private cars	Taxis	Total
China 0	3	0	3
China 1	3	0	3
China 2	5	7	12
China 3	1	1	2
China 4	2	26	28
China 5	6	1	7
Total	20	35	55

Table 6. Overview of diesel HDVs included in the study

	Trucks	Buses	Total
China I	3	0	3
China II	15	0	15
China III	25	0	25
China IV	10	10	21
China V	0	4	4
Total	53	14	67

Three sets of PEMS equipment were employed in this study: SEMTECH-DS gas analyzer, SEMTECH-Ecostar, and AVL M.O.V.E. Second-by-second emission rates of NO_x, CO, THC, and CO_2 were collected, and vehicle speed was recorded via GPS. Particle emissions were not measured in this study because of the limitations of PEMS equipment. The

2 The Gross Vehicle Weight of heavy-duty trucks included in this study ranged from 12 to 31 tonnes.

vehicles were driven in normal, real-world conditions following actual traffic. Cold starts were not included, and OBD data was not available. Trip duration, distance, average speed, and raw emissions factors can be found in the Appendix.

3.2 DATA ANALYSIS METHOD

In the China 6 LDV standard and China VI HDV standard proposal, the moving average window method is applied for PEMS data analysis. With this method, the emissions data are integrated over a series of windows. The size of the windows is equivalent to half of the CO_2 emitted over the Worldwide Harmonized Light Vehicles Test Cycle (WLTC) or the total work done by the engine over the transient engine test cycle (World Harmonized Transient Cycle, WHTC). For both LDVs and HDVs, there are some specific requirements for determining whether a window is valid, and only valid windows are included in the emissions calculation. For LDVs, the final CF over a trip is weighted by a given share of urban/rural/motorway. For HDVs, the final CF is the result at the 90th percentile of all the valid windows.

However, the moving average window method is not applicable to this study. This is because, 1) the vehicles were not tested on chassis or engine dynamometer over standard cycle WLTC or WHTC, making the window size difficult to determine; and 2) OBD data including engine power data is not available in this study to calculate brake-specific emissions factors in g/kWh. Therefore, the final emissions factors in this study were calculated directly by dividing the raw cumulative mass emissions by the total distance. For LDVs, emissions factors are directly shown in g/km. For HDVs, NO_X mass emitted per kg of CO_2 mass (g NO_X/kg CO_2, a measure of tailpipe NO_X emissions in proportion to fuel consumption) is used as an additional reference parameter to eliminate the effects of engine size among the HDVs and as a surrogate for the HDV standards, which are in grams per kilowatt hour. Assuming a constant average engine efficiency and fuel consumption, the CO_2-specific emissions factors in g/kg CO_2 can be converted into brake-specific emissions factors in g/kWh. In this study, we apply a typical engine efficiency of 40% (brake specific fuel consumption of 210g/kWh, Vermeulen et al., 2014) to convert the emissions limits in g/kWh into g/kg CO_2. For example, the China V NO_X emission limit of 2.0 g/kWh would be equal to 3.0 g NO_X/kg CO_2.

The experimental data in this report was collected from different institutes, so the test routes and driving conditions may differ from each other. They also could vary greatly in various cities. As on-road emissions are affected by velocity, acceleration, road gradient, and other driving conditions, it is good practice to report the trip profile, such as the time-speed profile, and to develop situation-specific emissions when comparing two trips. Besides reporting raw emissions factors, we applied the same situation-specific emissions analysis method used in the ICCT's PEMS meta-study for the EU and the United States (Franco et al., 2014). The emissions data of each second was binned using instantaneous velocity times acceleration (v*a), which is an approximation of instantaneous mass-specific power. This method allows us to analyze the impact of driving conditions on emissions rates and to compare the emissions performance of two trips with different compositions.

When identifying the causes of high emissions events, it is also useful to look into the second-by-second instantaneous emissions and driving profiles of the vehicle. For example, by plotting the instantaneous emissions rates against the instantaneous velocity, one can easily observe when the emissions peaks occur and the corresponding driving conditions. Also, it can be observed whether the emissions peaks occur only under aggressive driving conditions, such as strong acceleration, or throughout the trip.

In summary, three methods of reporting test results are used in this study: 1) average raw emissions factors of the whole trip; 2) situation-specific emissions analysis; 3) instantaneous emissions analysis.

4. RESULTS

In this section, we present the test results from LDVs and HDVs separately. The final emissions factors by emission standard and by vehicle will be discussed. For situation-specific emissions analysis and instantaneous emissions analysis, we do not report the results for each vehicle. Rather, we focus only on a few representative trips and carefully compare the differences between good and bad performers.

4.1 RESULTS FOR LDVS

4.1.1 Real-world NO_x, CO, and THC emissions by standard and by vehicle

In Figure 2, we show the real-world NO_x, CO, and THC emissions factors for each vehicle by emissions standard and vehicle category. Blue and yellow dots indicate the emissions factor of each vehicle, and the red dots indicate the average number for each emissions standard and vehicle category. Overall, the average emissions factors of the three pollutants decreased from China 0 to China 5. China 0 to China 2 cars had significantly higher NO_x, CO, and THC emissions than China 3 to China 5 cars. Emissions control technologies have evolved significantly since China 3, mainly because the warm-up period of 40 seconds has been included in the type-approval test since China 3.

For THC, the average real-world emissions from China 3 to China 5 private cars and taxis were below the corresponding limits. This indicates that tailpipe THC emissions from gasoline cars have been effectively controlled since China 3. However, it should be noted that cold starts were not included in the PEMS tests in this study. It is widely known that most THC emissions are generated in the first 300 seconds of cold starts. Therefore, the actual real-world tailpipe THC emissions are most likely higher than the results shown in Figure 2 if cold-starts are considered.

For each standard, NO_x, CO, and THC from taxis were always significantly higher than from private cars, with China 5 as the only exception. In this study, the average mileage of old China 2 and 3 taxis when tested was 380,000 km, four times the average mileage of private cars of comparable ages. Therefore, TWCs of these old taxis had more significant deterioration and may lack maintenance, which would lead to the high NO_x, CO, and THC emissions. Anecdotal evidence points to some taxi drivers renting TWCs for annual I/M tests to avoid paying maintenance costs for the catalyst (Beijing Youth Daily, 2015). The daily rental fee for a TWC converter was around 100-300 CNY, much lower than the 2,000-3,000 CNY cost of a replacement converter (Beijing Daily, 2015). Another reason for the taxi drivers to remove the deteriorated TWC is to reduce fuel consumption in real-world driving (Zheng et al., 2017). Generally, TWC converters should not affect fuel economy when working properly, but a clogged or damaged converter can increase fuel consumption. In this study, TWCs from three China 4 taxis were confirmed to have been removed by the drivers. A detailed comparison of emissions by taxis with and without TWCs is in the following section.

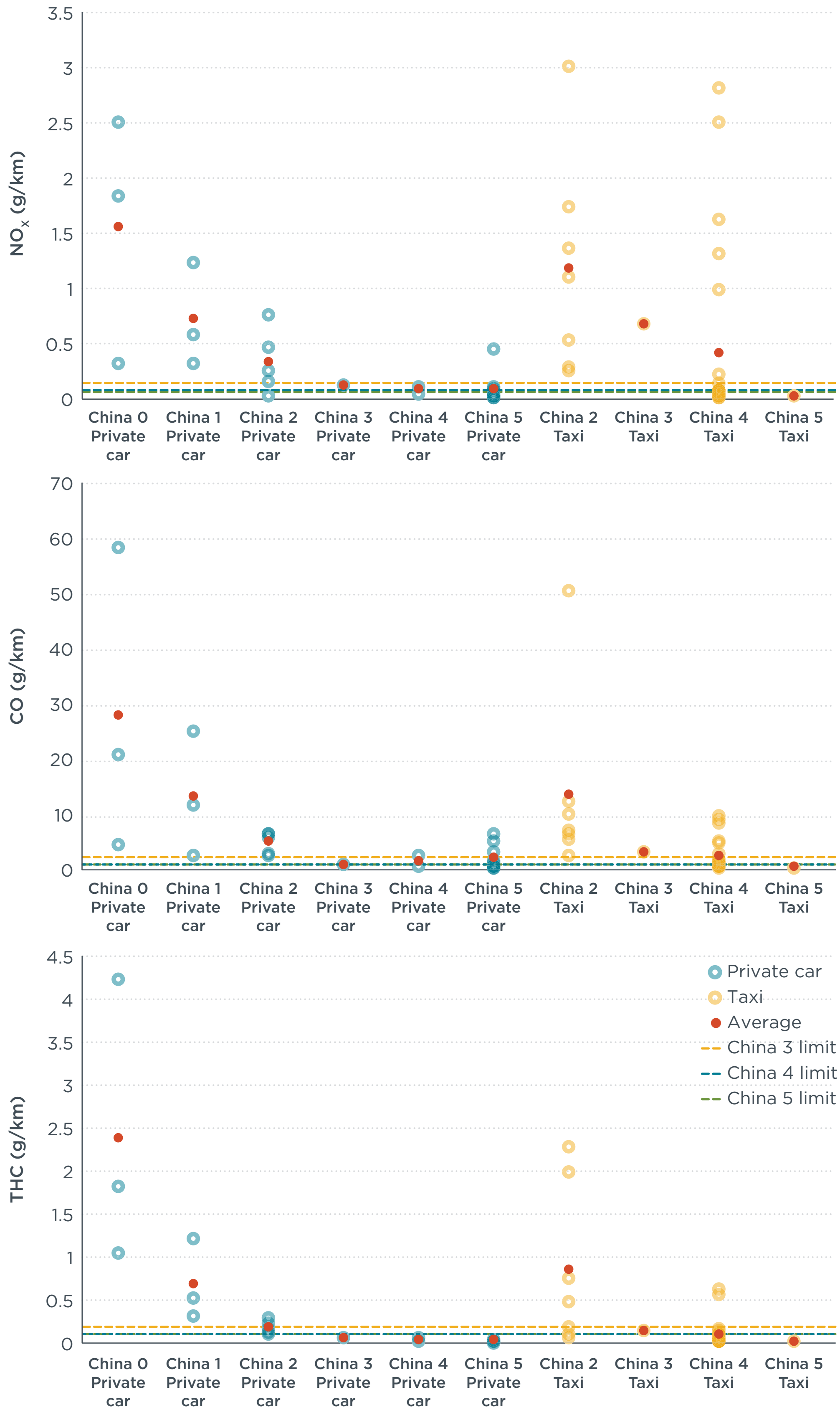

Figure 2. Real-world NO_x, CO and THC emissions factors for gasoline cars, by emissions standard and vehicle category

NO_x, CO, and THC emissions factors for each vehicle are shown in Figure 3. The vehicles were numbered in descending order of NO_x emissions factors for each emissions standard. Besides those high emitters from China 0 to China 2, there are still a few modern vehicles that have higher NO_x and CO emissions than the corresponding limits. For PC 21, 22, and 23—the three highest NO_x emitters among China 4 LDVs—the TWCs had been removed by drivers before the PEMS tests, and OBD malfunction indicator lights were on during the tests. Without the TWCs, the NO_x, CO, and THC emissions of these cars were significantly elevated compared with other China 4 LDVs and were even higher than some of the China 0 and China 1 cars. The NO_x emissions factors of PC 21, 22, and 23 were 20 to 35 times the China 4 limit. The cars' CO factors were eight to 10 times the China 4 limit, and their THC factors were six times the limit. The average emissions of China 4 taxis with removed TWCs were comparable to those of China 1 cars in this study.

To compare the emissions performance of vehicles with removed TWCs against those with new TWCs, three China 4 taxis with newly replaced TWCs (PC 37, 43, and 47) were recruited for this study. The vehicle models of taxis with new TWCs were the same as for those with removed TWCs. The TWCs were replaced by taxi companies just a few weeks before the tests, and the OBD malfunction indicator lights were off during the tests. It can be observed from Figure 3 that the real-world NO_x, CO, and THC emissions factors for the three taxis with new TWCs were below the China 4 regulatory limits, except that the CO emissions factor of PC 37 was 1.6 times of the limit. We classified the rest of the China 4 taxis into two categories, high-mileage and normal TWC. Taxis with mileage of more than 80,000 km were considered high mileage, and those with mileage below 80,000 km were considered normal because the useful life requirement for durability testing is 80,000 km under China 4. Figure 4 presents the average on-road NO_x, CO, and THC emissions factors of China 4 taxis with removed, high-mileage, normal, and new TWCs. All three pollutants increased as TWCs deteriorated. The NO_x CF of taxis with removed TWCs was 72 times that of taxis with new TWCs. For CO, the CF was 10 times and for THC, 39 times those of taxis with new TWCs. Our results indicate that old taxis could be one of the major high-emitter fleets in cities, and compliance and enforcement for in-use taxis should be strengthened. A detailed analysis of on-road performance of taxis with removed, high-mileage, and new TWCs is given in the following section.

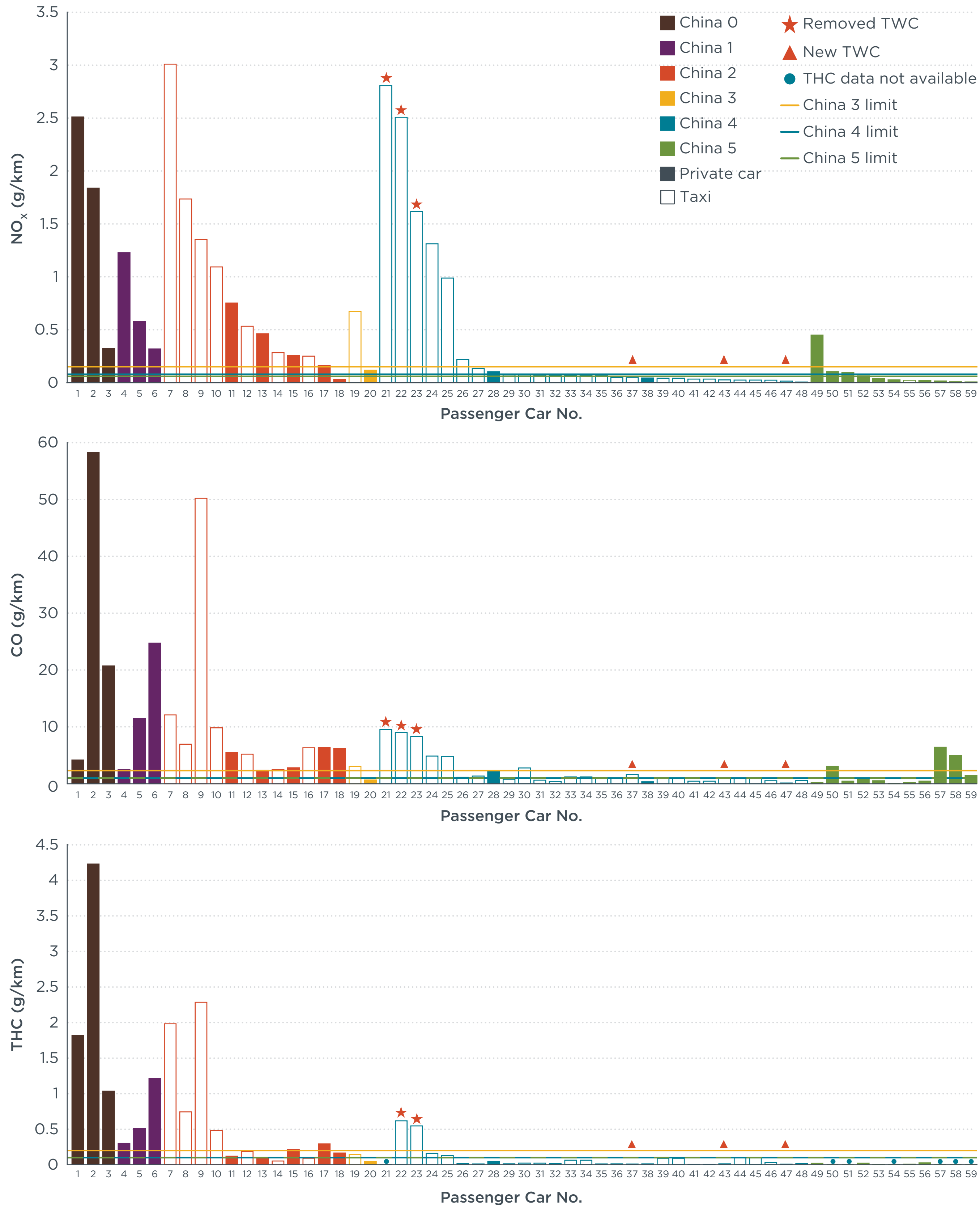

Figure 3. Real-world NO_x, CO, and THC emissions of gasoline cars, by vehicle

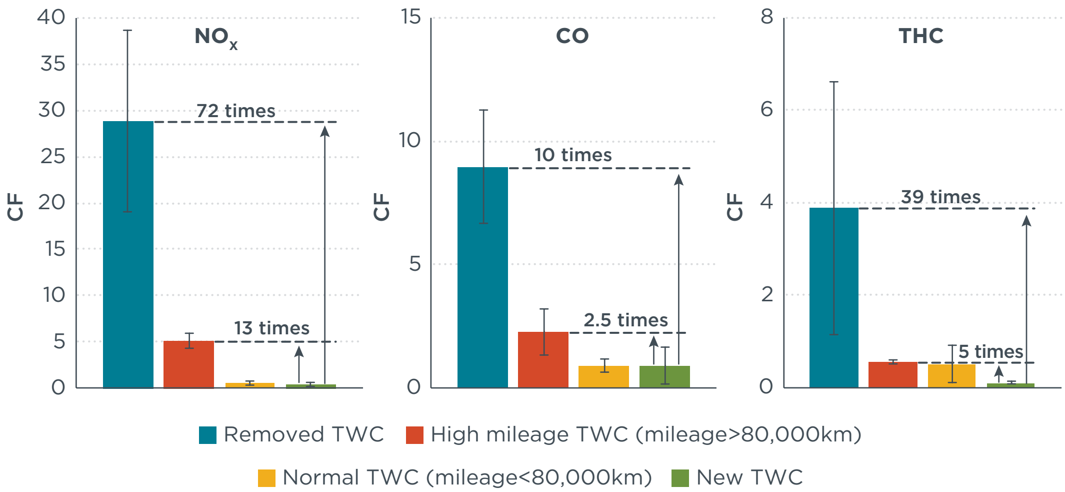

Figure 4. Average NO_X, CO, and THC CFs of China 4 taxis with removed, high-mileage, normal, and new TWCs

Error bars indicate standard deviation

It is also worth noting that PC 49, a modern China 5 private car, had unusually high NO_X emissions. PC 49 is a China 5 gasoline car produced in 2014, and its mileage was 900 km before the test. The NO_X emissions factor for PC 49 was eight times the China 5 limit, whereas the car's CO and THC emissions were both far below the limits. Even though NO_X, CO, and THC are concurrently taken care of by the TWC, it is possible for a vehicle to have high emissions of just one of those pollutants. A detailed analysis of the instantaneous emissions of this and other high emitters is provided in the following section.

By looking at CO emissions, we can observe that some modern China 5 cars (PC 50, 57, and 58) had significantly high CO emissions during real-world driving. Under the current China 6 emissions standard, CO limits are set for the chassis dynamometer test but are not included in the RDE test. It should be noted that the results for PC 50, 57, and 58 all reflect valid RDE tests, meaning that the test route, trip dynamics, and trip normality of the tests all met the criteria set out in the China 6 RDE regulation. Therefore, the high CO emissions from these trips are not attributable to aggressive driving. The test results add to evidence that real-world CO emissions from modern gasoline cars should get special attention.

4.1.2 Situation-specific emissions and instantaneous emissions analysis

In this section, we give two analysis examples of situation-specific emissions and instantaneous emissions. The first example is a comparison of three China 4 taxis that are of the same model, one without TWC, one with a high-mileage TWC, and a third with a newly replaced TWC. The second example is a comparison between two China 5 private cars of different models.

Table 7 summarizes the emissions factors and trip characterizations of PC 22, 25, and 47. As Table 7 shows, the three vehicles are all China 4 Beijing Hyundai Elantras. The TWC of PC 22 was removed by the driver before the test, and the TWC of PC 47 was replaced with a new one by the taxi company just a few weeks before the test. The TWC of PC 25 was considered high mileage given that the mileage when tested was 314,000 km, much higher than the 80,000 km useful life requirement under the China 4 regulation.

Table 7. Emissions and trip summary of PC 22, 25, and 47

	PC 22	PC 25	PC 47
Emission standard	China 4		
Model	Beijing Hyundai Elantra		
Production year	2009	2011	2012
Mileage	653,000 km	314,000 km	195,000 km
Aftertreatment	Removed TWC	High mileage TWC	New TWC
Average NO_x EF	**2.5 g/km**	**0.98 g/km**	**0.014 g/km**
Average CO EF	**9.0 g/km**	**4.8 g/km**	**0.12 g/km**
Average THC EF	**0.6 g/km**	**0.13 g/km**	**0.008 g/km**
Average CO_2 EF	182 g/km	165 g/km	178 g/km
Average speed	34 km/h	38 km/h	37 km/h
Total trip distance	50 km	52 km	48 km

As Table 7 presents, the average NO_x, CO, and THC emissions factors of PC 22 with removed TWC were significantly higher than for PC 25 and 47. Emissions from PC 47 with a new TWC were excellently controlled in real driving conditions. In Figure 5, we compare the situation-specific emissions categorized by v*a (velocity times acceleration, a common approximation of the power demands on the engine). We classified v*a into four categories: strong negative, mild negative, zero or mild positive, and strong positive. We selected 9.2 W/kg as a threshold between mild and strong v*a because it is the maximum v*a value for the standard NEDC. As Figure 5 illustrates, the trip composition, or the time share and distance share of four driving categories, was similar. However, the NO_x emissions factors of PC 22 were significantly higher than those of PC 25 and 47 at all four situation categories. By looking at the instantaneous NO_x emission rates and velocities of these three vehicles (Figure 6), it is apparent that PC 22 emitted more NO_x than PC 25 and 47 under all circumstances. It is also worth pointing out that all three pollutants from PC 47, with a new TWC, stayed below the laboratory limits, especially under aggressive v*a. The results provide further evidence that TWC plays an important role in controlling emissions from gasoline cars, and gasoline emissions can stay at very low levels under real-world driving as long as the TWC is working effectively.

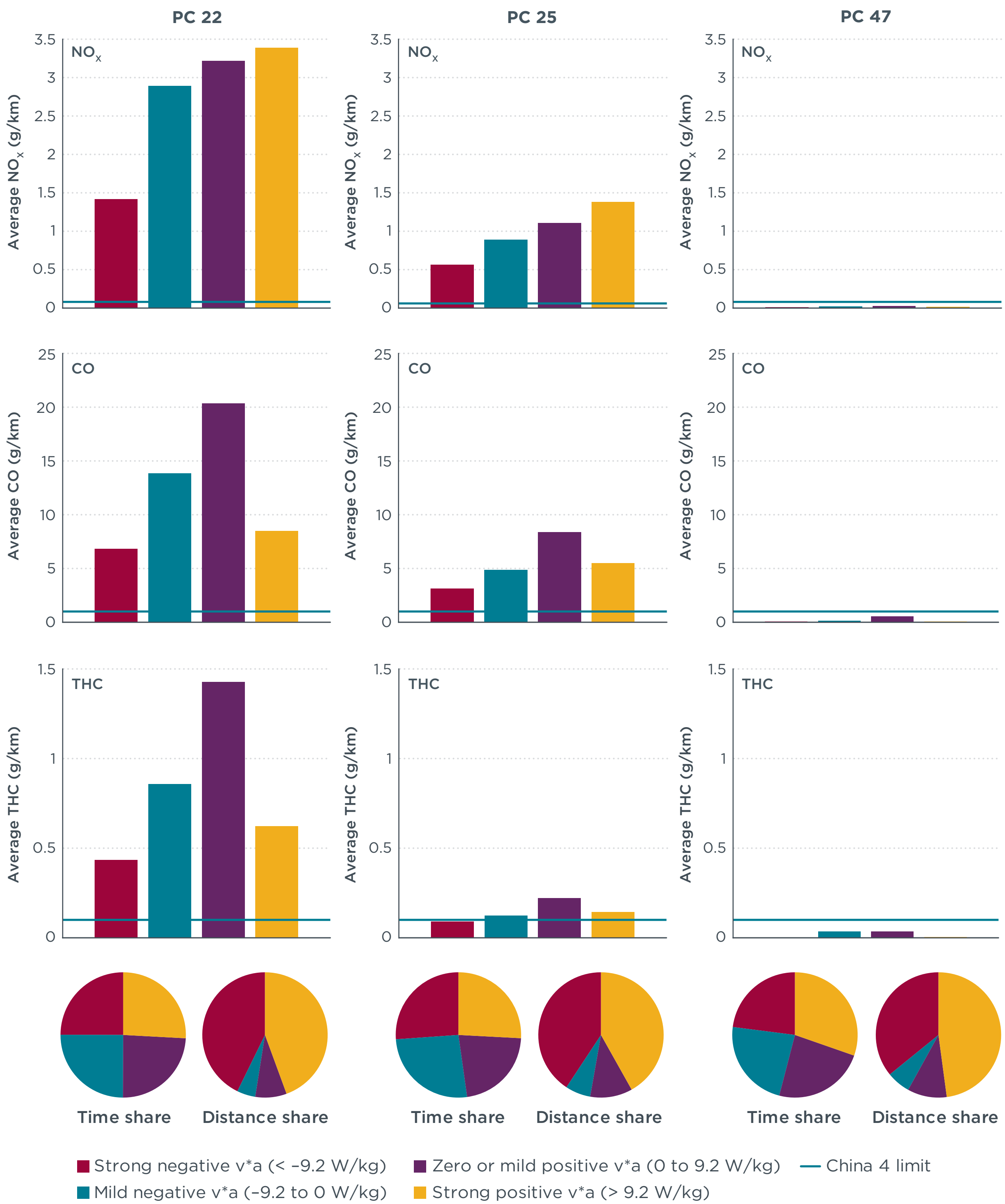

Figure 5. Situation-specific emissions analysis of PC 22 (removed TWC), PC 25 (high-mileage TWC) and PC 47 (new TWC)

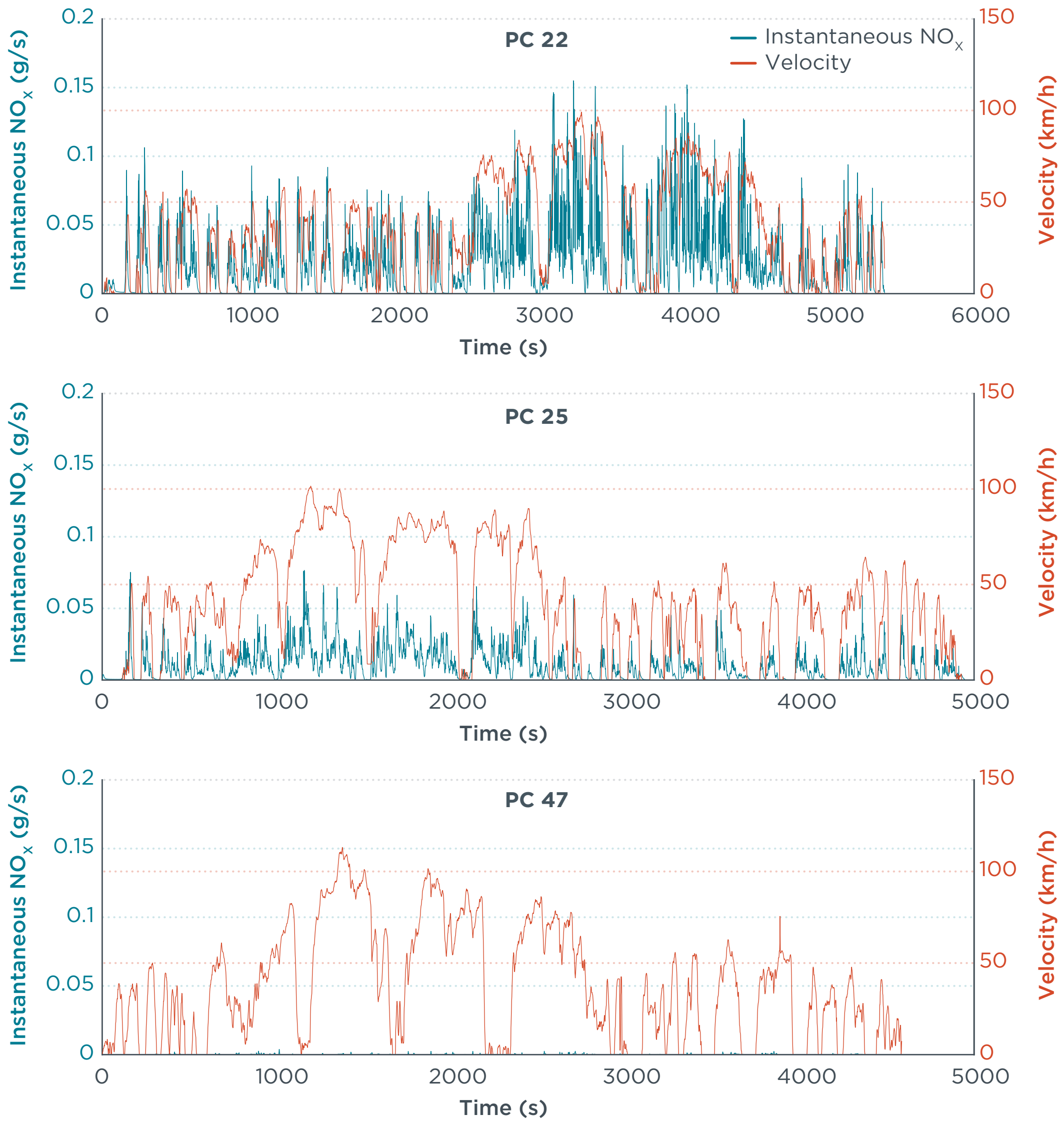

Figure 6. Instantaneous NO_x emissions and velocity profiles of PC 22, 25, and 47

In the second example, we compared the situation-specific and instantaneous emissions of two China 5 private cars with port fuel injection. As Table 8 shows, PC 49 was produced in 2014 and PC 52 in 2013. The mileage of PC 52 was more than 22 times that of PC 49. However, the NO_x emissions factor of PC 49 was 0.45 g/km, eight times the regulated limit, while NO_x from PC 52 was below the limit. Figure 7 presents the situation-specific emissions analysis of these two trials. Under all driving circumstances, NO_x emissions rates from PC 49 were higher than from PC 52. Unlike the situation in the first example, CO emissions from PC 49 were much lower than the other, which can hardly be seen on the instantaneous emissions profiles (see Figure 8). High NO_x but low CO emissions indicate that PC 49 might have been running lean with excess air in the air-fuel mix during the test. In this case, OBD data is not available to further investigate the actual cause of lean operation, but it is likely that the engine calibration or electronic control of PC 49 might not be robust.

Table 8. Emissions and trip summary of PC 49 and PC 52

	PC 49	PC 52
Emission standard	China 5	
Production year	2014	2013
Mileage	900 km	20,000 km
Aftertreatment	TWC	TWC
Average NO_x EF	**0.45 g/km**	**0.06 g/km**
Average CO EF	0.19 g/km	0.95 g/km
Average THC EF	0.02 g/km	0.02 g/km
Average CO_2 EF	172 g/km	201 g/km
Average speed	42 km/h	40 km/h
Total trip distance	44 km	48 km

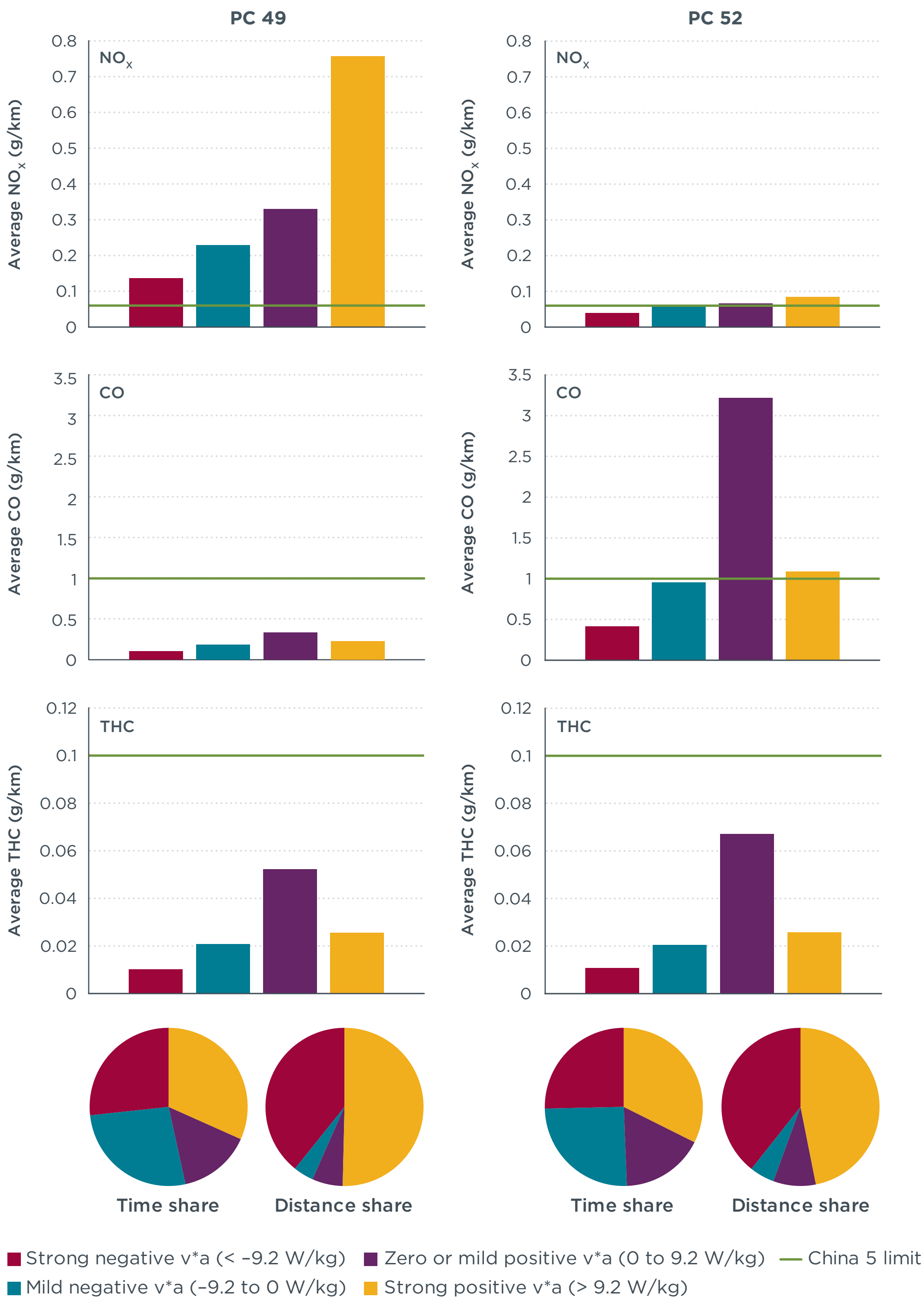

Figure 7. Situation-specific emissions analysis of PC 49 and PC 52

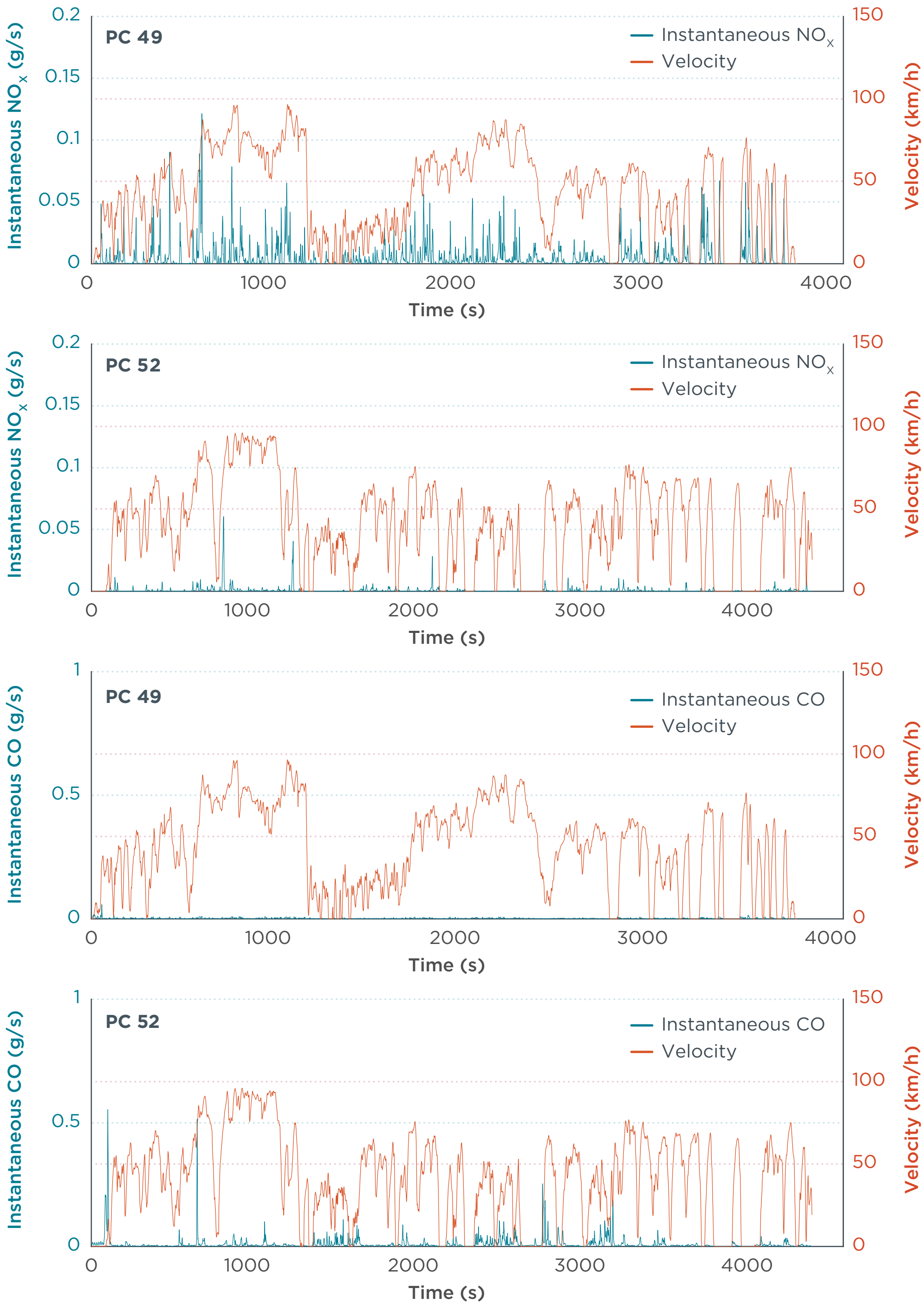

Figure 8. Instantaneous NO_x and CO emissions and velocity profiles of PC 49 and PC 52

In the previous section, we identified three high emitters (PC 22, 25, and 49) and performed a detailed analysis of them. There were four other China 3 and China 4 taxis (PC 19, 21, 23, and 24) that had high NO_x and CO emissions and three China 5 private cars (PC 20, 57, and 58) that had high CO emissions. For PC 21 and 23, it was confirmed that TWCs were removed by drivers, which led to high on-road emissions. For PC 19, the mileage when tested was nearly 80,000 km and for PC 24, almost 350,000 km. The TWCs were confirmed as installed on these vehicles, so it is likely that the high emissions were due to deterioration of the TWCs. PC 50, 57, and 58 had high CO but relatively low NO_x emissions, which might be attributed to poor engine calibration or control.

4.2 RESULTS FOR HDVS

In this section, we present the results for HDVs. The operating characteristics of heavy-duty trucks and urban buses are significantly different, so we report the results for trucks and buses separately. Engine size is one of the major factors affecting emissions levels, so the standards are set as a function of engine energy output (g/kWh). We use NO_x mass emitted per kg mass of CO_2 (g NO_x/kg CO_2) to eliminate the effects of engine size among the HDVs.

4.2.1 Real-world NO_x emissions by emission standard and by vehicle

Figure 9 presents the average real-world g NO_x/kg CO_2 emissions of diesel heavy-duty trucks and buses. The China III, IV, and V NO_x limits in g/kg CO_2 are estimated based on an average engine efficiency of 40%. In this figure, no significant improvement in average NO_x emissions can be observed from China I to China IV trucks. The results point to a serious compliance problem for NO_x control on HDVs in China. The NO_x limit was reduced by 56% from 8 g/kWh under China I to 3.5 g/kWh under China IV. However, the average real-world NO_x/CO_2 ratio of China IV trucks decreased by only 7% compared with China I trucks. It should be noted that there were both good and bad performers among the China IV vehicles tested, which we will discuss in the following section.

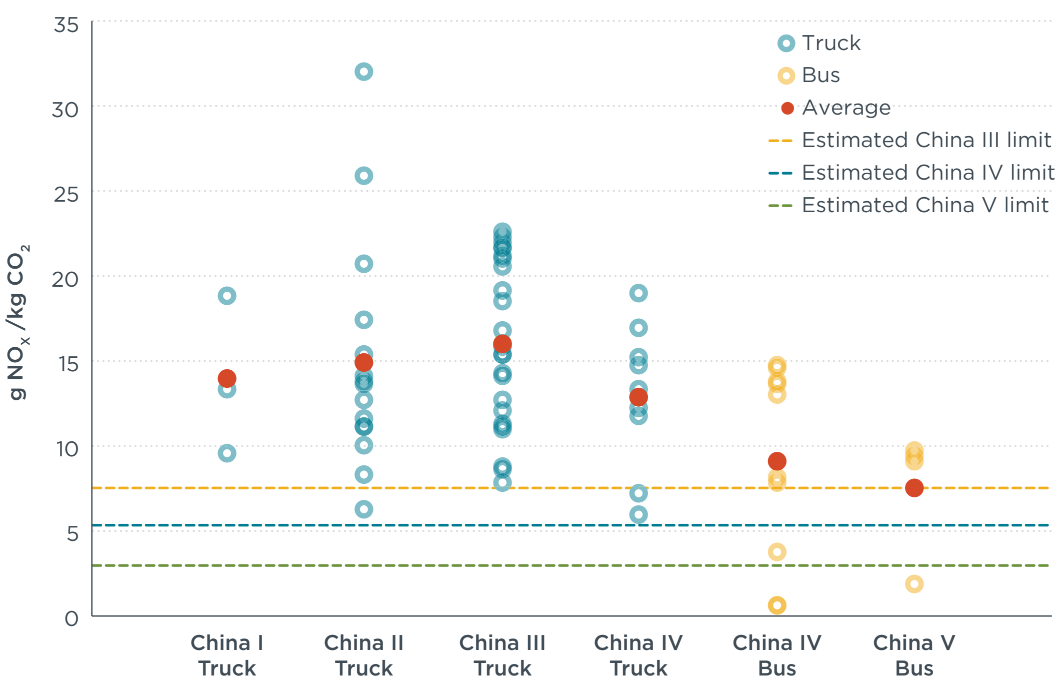

Figure 9. Average real-world NO_x/CO_2 emissions of HDVs, by emissions standard and vehicle category

As discussed in Section 2.3, HDVs should be equipped with electronic injection starting with China III and should be deployed with SCR systems starting with China IV. However, fake China III/IV HDVs were reportedly widespread in the market in 2014 (Economic Information, 2014). Some vehicles manufactured under the China III/IV standard actually used technologies typical for China I/II trucks. In addition, China Central Television (CCTV) reported that in some truck sales markets in Hebei, Guangdong, and Shanghai, newly produced China IV trucks offered for sale were not equipped with SCR systems (CCTV, 2014).

In this study, not all institutes checked the engine type and aftertreatment devices before the tests, so it is possible that some of the China III/IV trucks included in this study were not in compliance with the corresponding standards. Moreover, a previous ICCT study of urban off-cycle NO_x emissions from Euro IV/V HDVs found that Euro IV/V trucks and buses in the EU equipped with SCR had significantly elevated NO_x emissions during urban driving (Lowell & Kamakaté, 2012). This is mainly attributed to the fact that the NO_x conversion efficiency of SCR systems is poor when exhaust temperature is low. The root causes are the unrepresentative test cycle and the weak in-use conformity provisions in Euro IV/V standards. As China followed the European precedent before China V, this further explains why no significant real-world NO_x improvement for China IV trucks can be observed in Figure 9. In this study, China IV buses are observed to have lower average NO_x emissions than China IV trucks. This is mainly because a few buses performed extremely well under real driving conditions, as discussed in detail in the following section.

Figure 10 gives an overview of the real-world g NO_x/kg CO_2 ratio of diesel HDVs by vehicle. It can be observed that a range of performance can be found for each emissions standard. Truck 53, a China IV truck, was the best NO_x performer among the 53 trucks tested, whereas another China IV truck, Truck 44, emitted even more NO_x than some China I and II trucks.

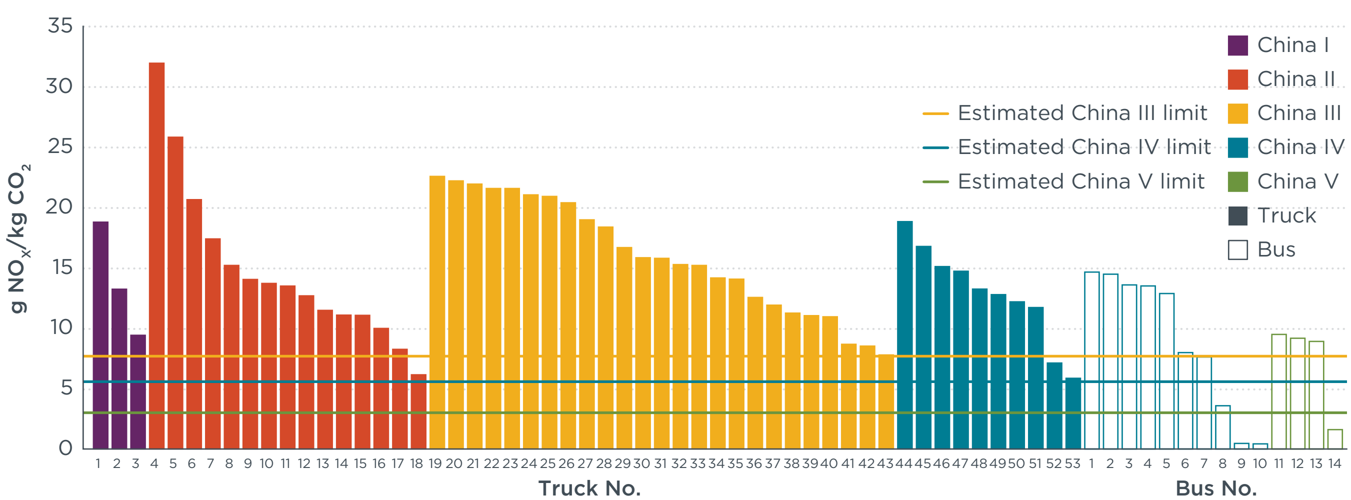

Figure 10. Real-world NO_x/CO_2 emissions of diesel HDVs, by vehicle

Unlike the diesel trucks, remarkable differences can be observed in the performance of buses, with a few buses of China IV and China V that performed substantially better than the others. As presented in Figure 10, the NO_x/CO_2 ratios from Buses 9, 10, and 14 were much lower than from the other buses—and were an order of magnitude lower than the NO_x/CO_2 ratio of all of the HD trucks. It is worth noting that Buses 3, 9, and

10 are of the same China IV bus model registered in 2007-2008 with similar odometer readings, but the emissions performances were completely different.

As Figure 11 shows, Buses 3, 9, and 10 emitted almost the same amount of CO_2 in each trip, but the NO_x emissions factor from Bus 3 was 26 times the levels of Buses 9 and 10. The results clearly indicate that the SCR system of Bus 3 was not working properly during the test, whereas the SCR of Buses 9 and 10 were effectively reducing on-road NO_x emissions. Similarly, Bus 14, a China V bus produced in 2013, performed substantially better than other China V buses. To further study the cause of elevated NO_x emissions, a detailed comparison of situation-specific and instantaneous emissions of Buses 3 and 9 follows.

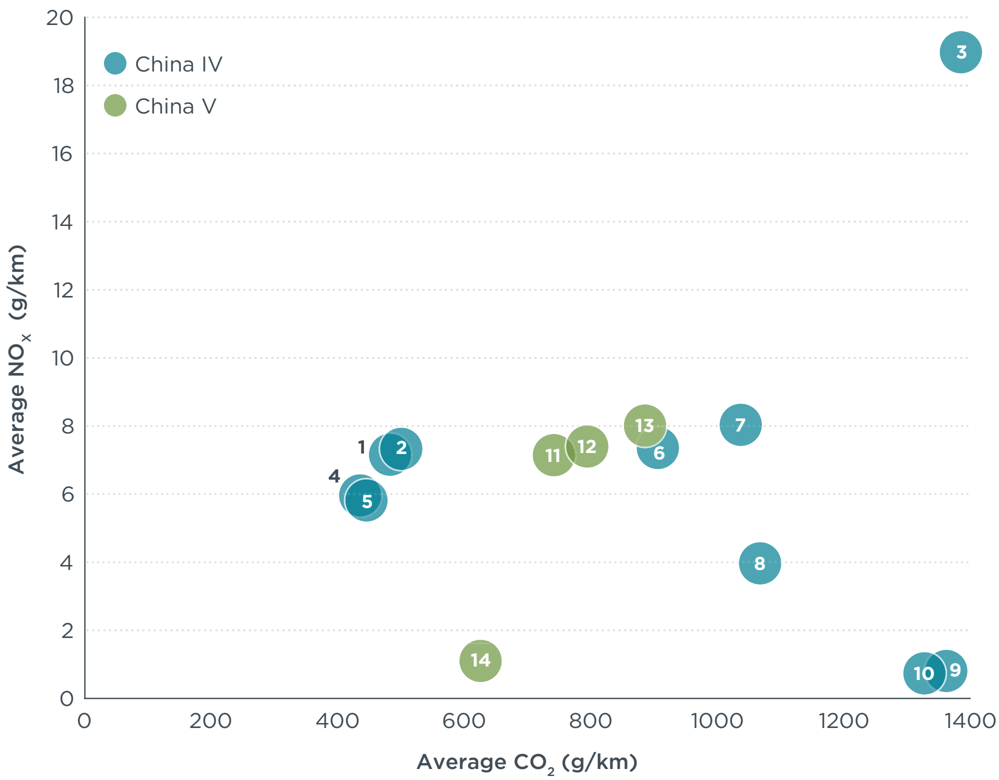

Figure 11. Overview of CO_2 and NO_x emissions factors of diesel buses, by vehicle

4.2.2 Situation-specific emissions and instantaneous emissions analysis

In this section, we chose Truck 53, the best performer among China IV trucks, and Buses 3 and 9, the good and bad performers among the same bus model, as examples and conducted a comparison. Technicians carefully checked the vehicle specifications and aftertreatment devices before the tests. They confirmed that these three HDVs were all equipped with SCR. Table 9 gives a summary of emissions and trip comparisons of Truck 53, Bus 3, and Bus 9. As Table 9 shows, the CO_2 emissions factors of these two trips were almost the same (~1300 g/km), whereas the NO_x emissions factor of Bus 3 was 24 times higher than that of Bus 9. In situation-specific emissions analysis, we classified velocity into four categories, idling (<1.6 km/h), urban (1.6-40 km/h), rural (40-80 km/h), and motorway (>80 km/h). As Figure 12 illustrates, NO_x emissions factors from Bus 3 were substantially higher than those from Bus 9 under all driving situations.

In addition, significantly high NO_x emissions in urban driving can be observed for Bus 3. This indicates that the SCR system of Bus 3 was not effectively working during the test, reflecting failure to refill urea tanks or failure of urea injection. For Truck 53, the NO_x emissions factors under urban and rural driving were at similar levels with Bus 3, and an order of magnitude higher than Bus 9. Therefore, the high NO_x emissions from Truck 53 could be also attributed to the fact that the SCR system was not working effectively on the road. Given that Truck 53 is the best performer of all China IV trucks tested, it is likely that the SCR systems of all China IV trucks tested were not working properly.

Table 9. Emissions and trip summary of Truck 53, Bus 3, and Bus 9

	Truck 53	Bus 3	Bus 9
Emissions standard		China IV	
Registration year	2009	2008	2007
Mileage	40,000 km	116,000 km	100,000 km
Average NO_x EF	6.3 g/km	18.9 g/km	0.8 g/km
Average CO_2 EF	1,074 g/km	1,386 g/km	1,363 g/km
Average speed	45 km/h	15 km/h	22 km/h
Total trip distance	160 km	15 km	39 km

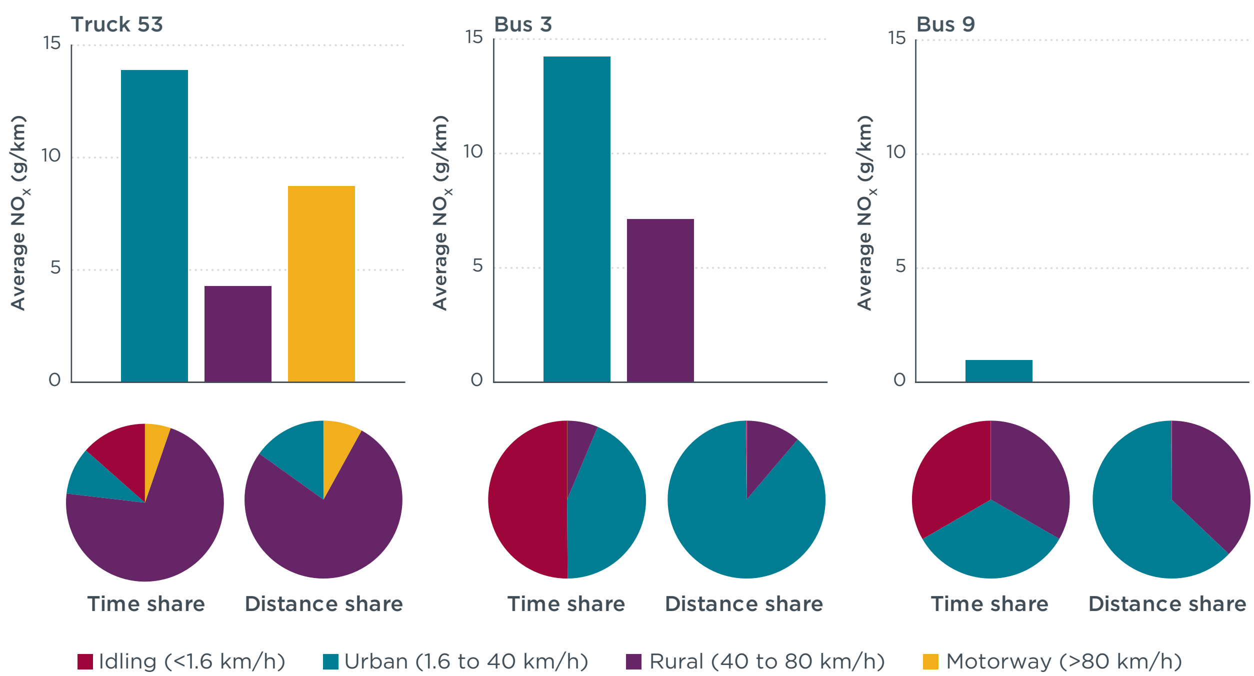

Figure 12. Situation-specific emissions analysis of Truck 53, Bus 3, and Bus 9

5. DISCUSSION

This report provides an in-depth analysis of real-world emissions from gasoline LDVs and diesel HDVs in China. Second-by-second on-road PEMS data from 122 vehicles, including 55 LDVs and 67 HDVs, were collected and analyzed. The results point out a serious noncompliance issue for LDVs and HDVs in China: Real-world emissions are not sufficiently controlled in real driving conditions.

5.1 DISCUSSION OF LDVS

The results indicate that vehicle emissions standards played an important role in reducing emissions in China. NO_x, CO, and THC emissions declined significantly as vehicle technology improved since China 4. The high emitters are mostly China 0 to China 2 cars. According to our results, the average on-road NO_x emissions from China 0 private gasoline cars are 19 times those from modern China 5 gasoline cars, while NO_x emissions from China 1 autos are eight times as high and from China 2 cars, four times as high. In 2016, pre-China 3 vehicles still accounted for 13% of the vehicle population in China (MEP, 2017a), yet they contribute significantly to total emissions. Accelerating the phase-out of these high emitters would bring substantial benefit in reducing vehicle emissions in China. In March 2017, Beijing implemented a vehicle banning policy whereby pre-China 3 light-duty gasoline vehicles are barred from entering the area enclosed by Beijing's fifth ring on weekdays (BJEPB, 2016). Beijing EPB estimated that this measure will reduce vehicle NO_x emissions from LDVs by 15% and volatile organic compounds by 12% in Beijing (People's Daily, 2016).

TWCs can effectively control NO_x emissions from gasoline cars. This exhaust aftertreatment technology has been successfully improved since China 3. In this study taxis are observed to have higher emissions factors than private cars of comparable ages, mainly because intensive operation of taxis may cause TWC deterioration. The average odometer reading of old taxis (China 2 and 3) is 380,000 km, four times the average odometer reading of private cars of comparable ages. As a result, the NO_x emissions factors of these old taxis average five times that of comparably aged private cars. Combining these two factors of very high per kilometer emissions and much more mileage driven per day, taxis make a disproportionate contribution to local emissions.

Figure 13 presents the real-world NO_x and CO emissions factors of 17 China 4 taxis. Those taxis are of the same model from the same manufacturer but had different mileage readings when tested. The figure shows that NO_x and CO emissions spiked at around 300,000 km. This is probably because TWC or other components such as oxygen sensors deteriorate and cause emissions to rise sharply after 300,000 km. The OBD system was designed to identify which components need maintenance. For older taxis that do not have OBD systems, the results suggest that TWCs of taxis should be replaced at least every three years given that the typical number of annual vehicle kilometers traveled for taxis in China is around 100,000 km (Wang et al., 2010). For any taxi with an effective OBD system, it would be helpful to mandate OBD checks every year or two to identify deteriorated components and maintain or replace them.

In 2016, the Beijing government initiated a substantial effort to control high emissions from taxis by implementing a TWC replacement program for old taxis. By April 2017, the TWCs from 50,000 old taxis in Beijing were replaced, with all costs covered by the government (BJEPB, 2017). In this study, three taxis with newly replaced TWCs and three taxis with no TWCs were recruited and tested in Beijing. The on-road NO_x, CO, and THC emissions of taxis with new TWCs were all below the China 4 laboratory limits, except one taxi with a CO CF of 1.6. The NO_x CF of taxis with removed TWCs was 72 times that of taxis with new TWCs. The CO CF was 10 times as high, and the THC CF, 39 times.

The results further demonstrate that the TWC replacement policy will bring substantial benefits in urban air quality in Beijing. For other local cities facing severe air pollution, we strongly encourage local governments to consider urgent actions such as TWC replacement programs for old taxis. Also, much more intensive and frequent I/M programs and random inspections with high penalties for catalyst removal are also necessary.

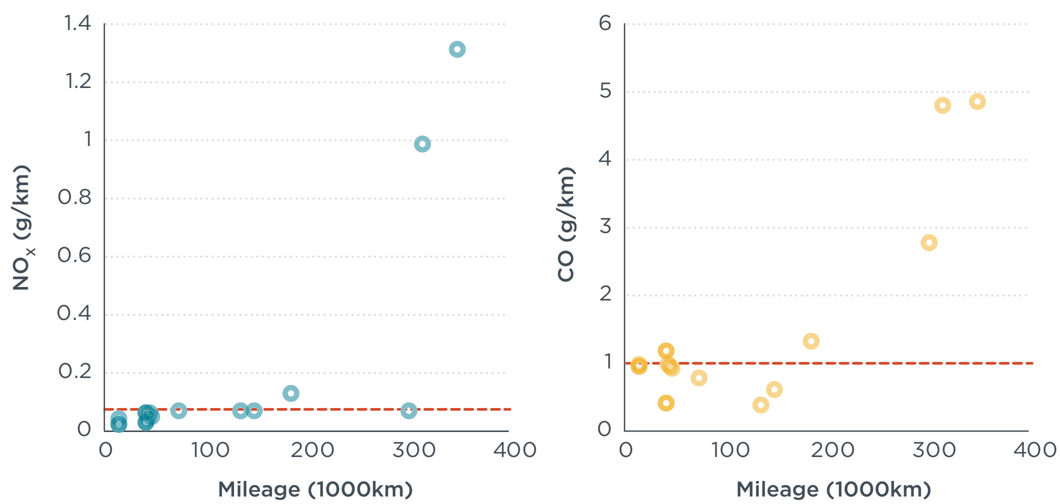

Figure 13. Real-world NO_x and CO emissions factors of China 4 taxis of same model with different mileage readings

In addition to the high emissions from old cars, NO_x from modern China 4 and 5 gasoline autos are still unsatisfactory. Some modern vehicles that have passed the type-approval test emitted seven to 35 times the NO_x limits in real-world driving. This does not mean that technologies are not available to meet the increasingly stringent standards. Instead, we found that some China 5 models had extremely low NO_x emissions in a valid RDE test—as low as a third of the China 6b NO_x limit. It further proves that advanced technologies are already available and applicable in the current market for the next phase of emissions standards. The most critical problems now are how to ensure that manufacturers deploy these technologies, calibrate them, and make sure they work properly and that maintenance issues are detected early and addressed quickly throughout useful vehicle life.

The China 6 emissions standard finalized in 2016 will be a great step in the right direction for reducing real-world emissions. China 6 is the first emissions regulation in China to introduce RDE test requirements for both type test and in-service test. Moreover, China 6 introduced the most comprehensive compliance program in China, including a number of manufacturer-run and agency-run emissions tests from prototype throughout useful vehicle life. Under the new testing framework, manufacturers will have to demonstrate that vehicle emissions stay low not only in the lab but also in real driving conditions.

The China 6 RDE regulation will take effect for all new vehicles beginning July 1, 2023. However, no CO limit has been set in the current China 6 RDE regulation. The experimental results of this study indicate that CO from gasoline cars can be significantly high in real-world driving. Even though CO is not a major pollutant for urban air quality, it is toxic and affects human health. In addition, THC and CO are often emitted together (see Figure 14, the correlation between CO and THC emissions for gasoline cars). Given that on-road THC is difficult to measure with LDV PEMS testing, limiting on-road CO emissions would also indirectly limit THC emissions from gasoline cars and further reduce the semi-volatiles that contribute to secondary PM in the atmosphere.

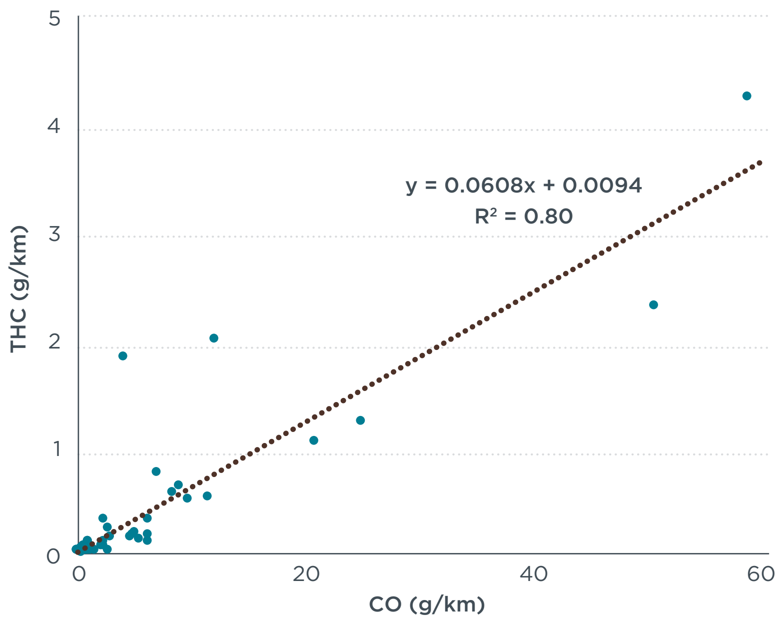

Figure 14. CO and THC emissions factors of all gasoline cars tested in this study

In this study, particle emissions were not measured because of the limitations of the PEMS equipment. For the most recent tests of China 5 gasoline cars, we measured PN emissions in RDE tests. The results indicate that PN emissions from gasoline direct injection vehicles were four to eight times the China 5 limit for diesel cars,[3] so PN emissions from gasoline cars should also be paid special attention.

Emissions data from the cold start period were not collected in the PEMS trips in this study. It is widely accepted that NO_X, CO, and THC emissions are mostly generated in the first 300 seconds of cold starts, when the temperature of the catalyst is not high enough. A previous PEMS study on three China 4 taxis illustrated that THC emissions during the first 300 seconds of cold starts were 10 times those in a hot start, and CO emissions, six times (Wang et al., 2010). In northern China where residents experience terrible winter smog events, the issue of catalyst light-off can be critical. Therefore, further research should be done to investigate the impacts of cold starts on real-world emissions.

3 There is no PN limit for GDI vehicles in the China 5 standard.

Finally, evaporative hydrocarbon emissions are not covered in this report. Studies have shown that evaporative hydrocarbon is one of the major pollutants from gasoline cars and plays an important role in degrading urban air quality (Liu et al., 2015). Therefore, further study of evaporative hydrocarbon emissions factors is much needed to evaluate real-world THC emission levels in China.

5.2 DISCUSSION OF HDVS

For HDVs, we focused only on NO_x because CO and THC emissions are not major concerns for diesel vehicles (Bonnel et al., 2011). In 2016, diesel vehicles accounted for only 10.2% of the total vehicle population in China, but they emitted 68.7% of total vehicular NO_x (MEP, 2017a). What we observed from this study added to the growing evidence that NO_x emissions from the heavy-duty sector are not properly controlled under the current testing framework in China. Even though NO_x limits decreased by 56% on paper from China I to China IV standards, real-world NO_x emissions from modern China IV trucks do not follow the reduction pattern set by the standards. In this study, the average China IV truck's emissions factor is 12.8 g NO_x/kg CO_2, 30% higher than the European result of 9.7 g NO_x/kg CO_2 (Muncrief, 2015).[4] However, the high average NO_x emissions from China IV HDVs do not mean that all vehicles would fail the PEMS test. In fact, a few of the best-performing buses had extremely low NO_x emissions under real-world driving conditions. What surprised us most was that the worst performers and best performers were of the same model produced by the same manufacturer. Therefore, it is likely that the SCR system, the NO_x aftertreatment device equipped on HDVs since China IV, was not working properly to reduce NO_x emissions on some of the vehicles tested.

Previous studies (Lowell & Kamakaté, 2012) have shown that heavy-duty trucks and buses that are certified to Euro IV and V emissions standards and equipped with SCR systems have significantly higher NO_x emissions during real-world driving, especially during urban driving. As China exactly followed the EU regulatory template in vehicle emissions standards, similar results were found in China on China IV/V heavy-duty trucks and buses. This is mainly because the NO_x conversion efficiency of SCR systems is poor when exhaust temperature is low during urban driving. The root cause, however, is that the current type approval and in-use compliance framework is insufficient to ensure that aftertreatment technologies work effectively throughout a vehicle's useful life. The current type-approval framework requires only that manufacturers demonstrate emissions compliance with a few predefined test cycles, such as the European Stationary Cycle and the ETC, which are not fully representative of the range of real-world engine conditions. In addition to the noncompliance issue on newly produced vehicles, some consumers take measures to stop SCR from working in real-world driving to reduce the costs of urea. A so-called "urea controller" which can reduce or stop urea injection, was sold by online shops in China before 2017 (The Economic Observer, 2017).[5] The in-use noncompliance issue seriously threatens China's efforts to achieve its goals on NO_x emissions reductions and improve urban air quality.

Recently, the government has made substantial efforts on vehicle emissions compliance and enforcement. China's new Air Pollution Prevention and Control Law, which took effect January 1, 2016, gave MEP clear authority to enforce the emissions standards and

4 Estimated by assuming an average engine efficiency of 40%.

5 MEP is looking into this issue and has taken some steps. Such controllers are banned from sales online.

penalize noncompliance. Moreover, the new air law shifts the focus from pre-production to in-use emissions controls. New provisions were created to address various aspects of in-use emissions control. These include recall authority, a requirement for releasing repair technology information on emissions control components, consumer obligations to repair or scrap high-emissions vehicles, and prohibitions on in-use tampering with emissions control systems and defeat devices. Before the new air law, drivers were not penalized for removing TWCs because of the lack of clear legal authority prohibiting tampering. The new air law also cleared up certain grey areas of authority with regard to implementation of emissions standards. For example, the old law barred the production and sale of vehicles and engines not in compliance with emissions standards but did not specify which agency had the authority to implement the provision. The new air law authorizes MEP and EPB to play leading roles in conducting conformity tests. The clearly defined roles of various agencies will increase the practicability of vehicle emissions standards and policy implementation.

MEP released a draft proposal of the China VI emissions standard for HDVs in October 2016. The China VI proposal shifts from European Stationary Cycle and ETC to the more representative cycles, the World Harmonized Stationary Cycle and WHTC, and introduces additional off-cycle emissions tests, the World Harmonized Not-To-Exceed test and full-vehicle PEMS test. For the first time in China, newly produced China VI vehicles will have to show compliance with emissions limits not only on an engine dynamometer but also on the road using a PEMS. Moreover, the on-road PEMS test applies to both type test and in-service compliance test, meaning manufacturers must ensure that emissions levels stay below limits throughout the useful life of the vehicles.

In addition, the China VI proposal introduced enhanced OBD requirements such as anti-tampering and remote emissions management. With the enhanced OBD provisions, when low urea level, low urea consumption, bad urea quality, or other malfunctions are detected and not fixed in a timely way, the torque/speed limiter will be activated, forcing the vehicle to drive only at a low speed. For the first time in vehicle regulation around the world, vehicles must be equipped with on-board terminals for remote emissions management. With the help of these stringent provisions on OBD and NO_x control systems, it could be ensured that SCR systems work effectively to reduce real-world NO_x emissions from HDVs. A recent ICCT study also shows that real-world NO_x emissions from Euro VI diesel HDVs stay at an extremely low level, even lower than NO_x from Euro 6 LDVs (Muncrief, 2016). This further indicates that proper real-world NO_x control is technically possible. We believe that the China VI proposal is a significant improvement over the existing standards and with proper implementation will bring significant reductions in emissions and health benefits in decades to come. We recommend that provinces and cities facing severe air pollution implement China VI standard as early as possible.

However, the China VI standard is not likely to be put into effect nationwide until 2020. Before then, urgent remedial actions are needed to reduce excess NO_x emissions from the existing HDV fleet. In 2013, Beijing EPB released two local standards specifically designed to prevent excess NO_x emissions from China IV and China V HDVs (BJEPB, 2013a, 2013b). The first standard requires China IV and V engines to be tested over the WHTC in addition to the current European Transient Cycle. The second standard established in-use complete vehicle PEMS testing requirements for China IV and V HDVs. The Beijing EPB estimates that implementation of these standards will reduce

NO_x emissions from China IV/V diesel vehicles by as much as 60% during urban driving (BJEPB, 2015).

At the national level, China MEP issued a supplemental standard in 2014 that requires China IV and V heavy-duty engines for use in urban vehicles to be tested over the WHTC (MEP, 2014). For in-use buses, Beijing EPB implemented a modification program for 8,800 China IV/V diesel buses in 2015 (BJEPB, 2015). It was estimated that the modification program in Beijing will reduce NO_x emissions by 2,800 tonnes per year. Beijing's urban bus modification program would be a good example for other mega-cities facing severe air pollution to follow. MEP released China's first national PEMS testing standard for HDVs in September 2017 (MEP, 2017b). The standard, a supplement to all requirements under the existing China V standard, requires additional on-road PEMS testing for new and in-use China V HDVs. The supplemental PEMS testing standard for China V HDVs is a step forward that will further control excess NO_x emissions from HDVs in China.

For in-use vehicles, remote sensing is an effective way for authorities to identify high emitters on the road. Compared with laboratory testing and PEMS testing, the advantage of remote sensing is that emissions data from a large sample of vehicles can be collected in a short period. In July 2017, MEP released its first national regulation on remote sensing (MEP, 2017c). This regulation applies to light-duty and heavy-duty diesel vehicles, with a goal of eliminating 5% of noncompliant and high-emitting vehicles. Also, the standard introduces measurement methods for remote sensing and sets emissions limits for opacity, Ringelmann blackness, and nitric oxide (NO)[6] for diesel vehicles. A vehicle is determined to be noncompliant if it is caught exceeding remote sensing emissions limits for the same pollutant in two or more consecutive remote sensing tests in six months.

It should be noted that particle emissions are major pollutants from the HDV fleet. In 2016, PM emissions from diesel vehicles accounted for more than 99% of total vehicular PM emissions (MEP, 2017a). In this study, particle emissions were not collected for all trips because of the limitations of PEMS equipment. Particle emissions for five trucks equipped with mechanical fuel injection (MI) engines and another five trucks equipped with electronically-controlled fuel injection (EI) engines were measured by electrical low pressure impactor. The average PM emissions factor for MI engines was 674 ± 239 mg/km and for EI engines, 63 ± 48 mg/km. MI is a typical engine technology for pre-China III HDVs, and EI is widely employed in China III and IV HDVs. Compared with MI engines, the 91% reduction in PM emissions of EI engines was quite close to the reduction set in the standard (Zheng et al., 2016). More measurements of real-world PM and PN emissions from HDVs should be conducted to gain a better understanding of real-world particle emissions in China.

6 NO is used only for screening high-emitting vehicles. High-emitting vehicles typically are vehicles that are forbidden from entering a city or a low-emissions zone set by the local government.

6. CONCLUSIONS AND RECOMMENDATIONS

This report presents an in-depth analysis of real-world emissions from 55 LDVs and 67 HDVs in China. On-road PEMS testing results from LDVs and HDVs add to the empirical evidence that NO_x emissions are not properly controlled under the current testing framework. For gasoline LDVs, real-world NO_x performance varies widely for different vehicle models. The average NO_x emissions for China 4 taxis with TWCs removed were 72 times those of taxis with new TWCs, and for taxis with high-mileage TWCs, NO_x emissions were 13 times as high. Among diesel HDVs, on-road NO_x emissions performance didn't improve as much as it should have as emission standards became more stringent. It has been widely known that advanced emissions control technologies already exist in the market, so the most important problem now is ensuring that those technologies are deployed on vehicles and work effectively not only in laboratory but also in real driving conditions.

6.1 CONCLUSIONS AND RECOMMENDATIONS FOR LDVS

The China 6 LDV emissions standard, which will take effect July 1, 2020, is a significant step toward solving the noncompliance issue. We applaud the adoption of RDE testing and requirements in China 6, although there are still some limitations in the current RDE regulation.

Firstly, cold starts are excluded from the data evaluation process. It is widely accepted that most NO_x, CO, and THC emissions are generated in the first 300 seconds of cold starts, when the temperature of the catalyst is not high enough. Cold-start operations were included in the data evaluation process in the EU RDE regulation Package 3 passed in December 2016. The inclusion of cold starts will be essential for ensuring the use of improved emissions control technologies, which already exist in the market. We recommend further study of the impacts of cold starts on emissions in future RDE testing projects, and full inclusion of cold starts in the final China 6 RDE regulation, as is currently done in the European RDE regulation.

Secondly, the current China 6 RDE regulation doesn't set a CO limit. The experimental results in this study suggest that CO from gasoline cars could be substantial in real-world driving. THC and CO are often emitted together. Therefore, limiting on-road CO emissions would also indirectly limit THC emissions from gasoline cars and further reduce the semi-volatiles that contribute to secondary particulate matter in the atmosphere. CO limits were not introduced in the EU RDE regulation mainly because CO emissions are mostly generated from gasoline cars, and diesel cars account for more than 50% of the European passenger vehicle market (ICCT, 2017).[7] Considering that more than 99% of passenger cars in China are powered by gasoline, we recommend further exploration of real-world CO emissions of gasoline cars in China and introduction of a CO limit in the final China 6 RDE regulation.

Thirdly, our test results demonstrate that TWCs play an important role in emissions control for gasoline cars. Taxis are observed to have higher emissions factors than private cars of comparable ages, mainly because intensive operation of taxis may cause TWC deterioration. Therefore, we strongly recommend that local governments consider urgent actions such as TWC replacement programs for old taxis as well as much more

7 From communication with European Commission Joint Research Center.

intensive and frequent I/M programs and random inspections with high penalties for catalyst removal.

In the China 6 final rule, it clearly indicates that the CFs of NO_x and PN are set as temporary limits and will be re-evaluated and determined by July 2022. In theory, there are still opportunities to fix the limitations in the China 6 regulation by 2022. Currently, the research on RDE testing procedure and emissions results remains very limited in China. To increase the stringency of the China 6 RDE regulation and address severe urban air pollution in China, we encourage authorities and research organizations to conduct further RDE testing campaigns, and we recommend that authorities adjust RDE requirements based on the actual situation in China.

6.2 CONCLUSIONS AND RECOMMENDATIONS FOR HDVS

Test results for three buses demonstrate that on-road NO_x emissions can be well controlled if SCR systems work effectively in real-world driving. However, most of the trucks and buses tested had very high NO_x emissions, illustrating widespread problems with implementing standards. Specifically, no significant improvement in real-world NO_x emissions can be observed for China IV trucks. The proposed China VI HDV standard, which is likely to be implemented starting January 1, 2020, introduces new off-cycle engine tests and full-vehicle PEMS tests, comprehensive in-use compliance programs, and stringent OBD provisions and remote emissions management systems. We believe the China VI HDV standard will bring significant emissions reductions and health benefits to China with proper implementation.

Similarly to LDVs, cold starts are not included in the PEMS tests in the China VI proposal. The latest Euro VI amendatory regulation includes a requirement for monitoring emissions performance in a warm-up period in the PEMS tests (European Commission, 2016c). We recommend further study of the impacts of cold starts and addition of a monitoring phase for cold starts in the China VI regulation.

High-emitting HDVs make a major contribution to air pollution in urban areas. Before the new HDV standard is implemented in 2020, urgent remedial actions are essential to address the high NO_x emissions problem from the in-use HDV fleet. We strongly recommend the management measures carried out by Beijing EPB. We encourage other local governments to learn from Beijing's experience and take urgent actions such as modification or retrofit programs for urban buses and trucks. In addition, developing technical regulations of retrofitting in-use diesel vehicles would contribute to effective implementation of retrofit programs.

The new air law, which took effect January 1, 2016, cleared up certain grey areas of authority and gave MEP and EPBs authority to enforce the emissions standards and penalize noncompliance. A robust in-use surveillance program heavily relies on implementation and enforcement at the local level. We recommend local EPBs put a strong focus on in-use surveillance programs, conduct regular in-use testing and issue penalties for non-compliance.

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APPENDIX

Table A1. Trip information and raw emissions factors for LDVs

PC No.	Emissions standard	Trip duration (hr)	Type	Trip distance (km)	Average trip velocity (km/h)	Average CO_2 (g/km)	Average CO (g/km)	Average NO_x (g/km)	Average THC (g/km)
1	China 0	0:58	PC	36.0	37.2	322.5	4.17	2.51	1.82
2	China 0	1:3	PC	28.6	27.5	396.7	58.27	1.84	4.23
3	China 0	1:2	PC	31.1	30.4	212.2	20.71	0.32	1.03
4	China 1	0:28	PC	13.4	28.6	338.5	2.45	1.23	0.30
5	China 1	1:17	PC	28.2	21.9	352.2	11.43	0.58	0.51
6	China 1	1:17	PC	36.6	28.4	219.4	24.73	0.32	1.21
7	China 2	1:5	Taxi	31.4	29.2	237.6	12.09	3.01	1.98
8	China 2	1:11	Taxi	31.1	26.2	199.1	6.94	1.74	0.74
9	China 2	1:2	Taxi	31.1	30.3	206.2	50.22	1.35	2.28
10	China 2	0:53	Taxi	31.1	35.2	206.2	9.83	1.09	0.48
11	China 2	1:7	PC	36.0	32.4	248.7	5.49	0.75	0.12
12	China 2	0:55	Taxi	30.5	33.1	214.3	5.19	0.53	0.18
13	China 2	1:7	PC	36.5	32.9	246.3	2.36	0.46	0.10
14	China 2	1:10	Taxi	31.0	26.4	232.7	2.50	0.28	0.05
15	China 2	0:55	PC	36.9	40.4	263.1	2.80	0.26	0.21
16	China 2	1:0	Taxi	31.0	31.0	218.0	6.32	0.25	0.09
17	China 2	1:27	PC	36.6	25.4	326.5	6.36	0.16	0.29
18	China 2	1:6	PC	27.6	25.2	417.5	6.19	0.03	0.17
19	China 3	1:16	Taxi	30.1	23.7	325.7	3.05	0.67	0.14
20	China 3	0:58	PC	35.8	37.3	171.0	0.65	0.12	0.05
21	China 4	2:19	Taxi	70.3	30.3	231.5	9.54	2.81	N.A.
22	China 4	1:30	Taxi	50.4	33.7	182.0	9.00	2.51	0.62
23	China 4	1:41	Taxi	53.2	31.5	197.2	8.30	1.62	0.55
24	China 4	1:37	Taxi	52.6	32.7	122.3	4.86	1.31	0.16
25	China 4	1:22	Taxi	52.3	38.1	165.3	4.80	0.99	0.13
26	China 4	1:15	Taxi	52.8	42.2	187.8	1.12	0.22	0.02
27	China 4	1:19	Taxi	53.8	40.6	213.3	1.34	0.13	0.01
28	China 4	1:41	PC	52.5	31.3	237.6	2.24	0.10	0.05
29	China 4	1:10	Taxi	52.8	45.0	200.8	0.78	0.07	0.01
30	China 4	1:42	Taxi	54.9	32.2	187.4	2.77	0.07	0.02
31	China 4	1:18	Taxi	52.8	40.9	190.2	0.61	0.07	0.02
32	China 4	1:18	Taxi	53.1	40.6	188.5	0.40	0.07	0.02
33	China 4	1:14	Taxi	45.6	36.9	238.5	1.19	0.07	0.06
34	China 4	1:14	Taxi	45.6	36.9	238.4	1.19	0.07	0.06
35	China 4	1:4	Taxi	49.0	45.9	197.0	0.95	0.07	0.01
36	China 4	1:15	Taxi	52.8	42.4	192.5	0.95	0.05	0.01
37	China 4	1:31	Taxi	52.2	34.5	204.2	1.60	0.05	0.01
38	China 4	1:17	PC	52.9	41.1	205.1	0.34	0.04	0.01

PC No.	Emissions standard	Trip duration (hr)	Type	Trip distance (km)	Average trip velocity (km/h)	Average CO_2 (g/km)	Average CO (g/km)	Average NO_x (g/km)	Average THC (g/km)
39	China 4	1:1	Taxi	41.3	40.6	194.7	0.99	0.04	0.09
40	China 4	1:1	Taxi	41.3	40.6	194.7	0.99	0.04	0.09
41	China 4	1:20	Taxi	52.8	39.7	189.1	0.43	0.03	0.01
42	China 4	1:20	Taxi	52.8	39.7	189.1	0.43	0.03	0.01
43	China 4	1:18	Taxi	48.2	36.9	195.9	0.98	0.03	0.01
44	China 4	1:19	Taxi	43.7	33.4	219.2	0.97	0.02	0.10
45	China 4	1:19	Taxi	43.7	33.4	219.1	0.97	0.02	0.10
46	China 4	2:9	Taxi	55.1	25.6	202.5	0.52	0.02	0.03
47	China 4	1:16	Taxi	47.8	37.5	178.0	0.12	0.01	0.01
48	China 4	1:46	Taxi	53.8	30.4	167.3	0.57	0.01	0.02
49	China 5	1:3	PC	44.0	42.2	172.5	0.19	0.45	0.02
50	China 5	1:40	PC	82.5	49.6	250.3	3.05	0.10	N.A.
51	China 5	1:38	PC	82.1	50.3	225.8	0.44	0.10	N.A.
52	China 5	1:12	PC	48.3	40.3	201.2	0.95	0.06	0.02
53	China 5	1:26	PC	52.3	36.4	214.4	0.52	0.04	0.00
54	China 5	1:39	PC	82.9	50.2	157.4	0.03	0.03	N.A.
55	China 5	1:23	Taxi	50.2	36.5	177.8	0.17	0.02	0.01
56	China 5	1:34	PC	52.7	33.8	142.4	0.44	0.02	0.03
57	China 5	1:35	PC	82.6	52.2	337.7	6.40	0.02	N.A.
58	China 5	1:34	PC	82.4	52.4	328.9	4.96	0.01	N.A.
59	China 5	1:37	PC	82.9	51.2	245.6	1.47	0.01	N.A.

Table A2. Trip information and raw emissions factors for trucks

Truck No.	Emissions standard	Trip duration (hr)	Trip distance (km)	Average trip velocity (km/h)	Average CO_2 (g/km)	Average NO_x (g/km)	g NO_x / kg CO_2
1	China I	2:18	80.4	34.9	535.4	10.1	18.8
2	China I	2:52	102.5	35.9	500.5	6.6	13.2
3	China I	0:35	22.5	38.2	647.7	6.1	9.4
4	China II	3:1	83.8	27.7	501.3	16.0	32.0
5	China II	1:38	40.8	25.0	332.0	8.6	25.8
6	China II	2:30	80.5	32.3	523.7	10.8	20.7
7	China II	2:11	80.3	36.8	497.8	8.7	17.4
8	China II	0:48	27.0	33.5	456.1	6.9	15.2
9	China II	3:2	117.1	38.6	415.1	5.8	14.0
10	China II	1:55	53.5	27.9	570.8	7.8	13.7
11	China II	2:57	111.8	37.8	491.1	6.6	13.5
12	China II	3:52	112.0	28.9	505.9	6.4	12.7
13	China II	3:20	85.8	25.7	361.2	4.1	11.5
14	China II	3:8	70.7	22.6	637.6	7.1	11.1
15	China II	3:59	109.1	27.4	363.9	4.0	11.1
16	China II	2:43	37.7	13.8	1163.0	11.6	10.0
17	China II	0:47	28.6	36.8	616.7	5.1	8.3
18	China II	2:47	33.0	11.9	928.7	5.7	6.1
19	China III	0:51	14.4	16.8	569.2	12.9	22.6
20	China III	3:25	71.9	21.0	683.5	15.2	22.2
21	China III	1:15	39.2	31.5	611.1	13.4	22.0
22	China III	2:43	44.6	16.4	594.5	12.8	21.6
23	China III	2:43	44.6	16.4	594.5	12.8	21.6
24	China III	0:37	14.3	23.0	503.2	10.6	21.1
25	China III	2:27	71.3	29.0	625.8	13.1	20.9
26	China III	0:42	14.3	20.4	435.8	8.9	20.4
27	China III	2:41	70.8	26.4	584.7	11.1	19.0
28	China III	2:47	99.1	35.7	614.9	11.3	18.4
29	China III	2:30	67.5	26.9	344.2	5.7	16.7
30	China III	0:43	24.7	34.3	434.5	6.9	15.9
31	China III	3:51	85.5	22.3	381.6	6.0	15.8
32	China III	3:3	66.1	21.7	664.9	10.2	15.3
33	China III	0:48	27.0	33.5	456.1	6.9	15.2
34	China III	0:51	14.2	16.6	626.9	8.9	14.2
35	China III	0:42	14.3	20.5	556.0	7.8	14.1
36	China III	2:21	70.4	29.9	537.3	6.7	12.6
37	China III	2:37	75.3	28.8	528.4	6.3	11.9
38	China III	1:33	51.0	32.7	716.9	8.1	11.3
39	China III	2:30	78.0	31.1	476.1	5.3	11.0
40	China III	2:37	75.9	29.0	559.0	6.1	11.0
41	China III	1:18	52.0	40.0	1038.4	9.0	8.7

Truck No.	Emissions standard	Trip duration (hr)	Trip distance (km)	Average trip velocity (km/h)	Average CO_2 (g/km)	Average NO_x (g/km)	g NO_x / kg CO_2
42	China III	1:44	78.6	45.4	638.8	5.4	8.5
43	China III	0:38	24.8	38.6	349.8	2.7	7.8
44	China IV	0:47	16.6	21.1	622.5	11.7	18.8
45	China IV	0:47	14.2	18.3	778.0	13.1	16.8
46	China IV	2:18	71.6	31.0	540.6	8.2	15.1
47	China IV	2:46	84.8	30.6	739.9	10.9	14.7
48	China IV	0:37	14.2	22.9	605.4	8.0	13.3
49	China IV	2:9	89.9	41.8	413.3	5.3	12.8
50	China IV	0:39	14.5	22.4	686.8	8.4	12.2
51	China IV	1:23	36.6	26.4	653.9	7.7	11.7
52	China IV	2:46	127.1	46.1	1223.7	8.7	7.1
53	China IV	3:33	160.0	45.1	1073.9	6.3	5.9

Table A3. Trip information and raw emissions factors for buses

Bus No.	Emissions standard	Trip duration (hr)	Trip distance (km)	Average trip velocity (km/h)	Average CO_2 (g/km)	Average NO_x (g/km)	g NO_x / kg CO_2
1	China IV	1:33	46.7	30.1	484.2	7.1	14.7
2	China IV	1:20	35.9	26.9	501.9	7.3	14.5
3	China IV	0:60	15.2	15.3	1386.9	18.9	13.7
4	China IV	0:56	39.1	42.2	437.0	5.9	13.6
5	China IV	0:55	36.4	39.6	446.8	5.8	13.0
6	China IV	1:8	19.5	17.3	907.7	7.3	8.1
7	China IV	1:11	19.5	16.3	1038.8	8.0	7.7
8	China IV	0:46	16.4	21.3	1069.5	3.9	3.7
9	China IV	1:46	39.6	22.5	1363.9	0.8	0.6
10	China IV	2:5	39.5	19.0	1329.4	0.7	0.5
11	China V	1:21	23.6	17.5	743.3	7.1	9.6
12	China V	1:44	35.9	20.7	796.1	7.4	9.3
13	China V	1:47	35.6	20.0	887.4	8.0	9.0
14	China V	0:23	6.3	16.4	627.4	1.1	1.7