2023 OSAR Conference

On-board monitoring (OBM) of NOx emissions for heavy-duty vehicles in China

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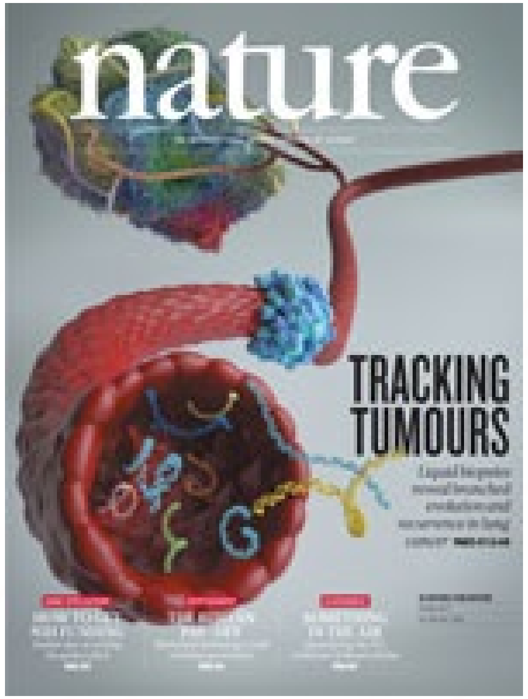
Outline

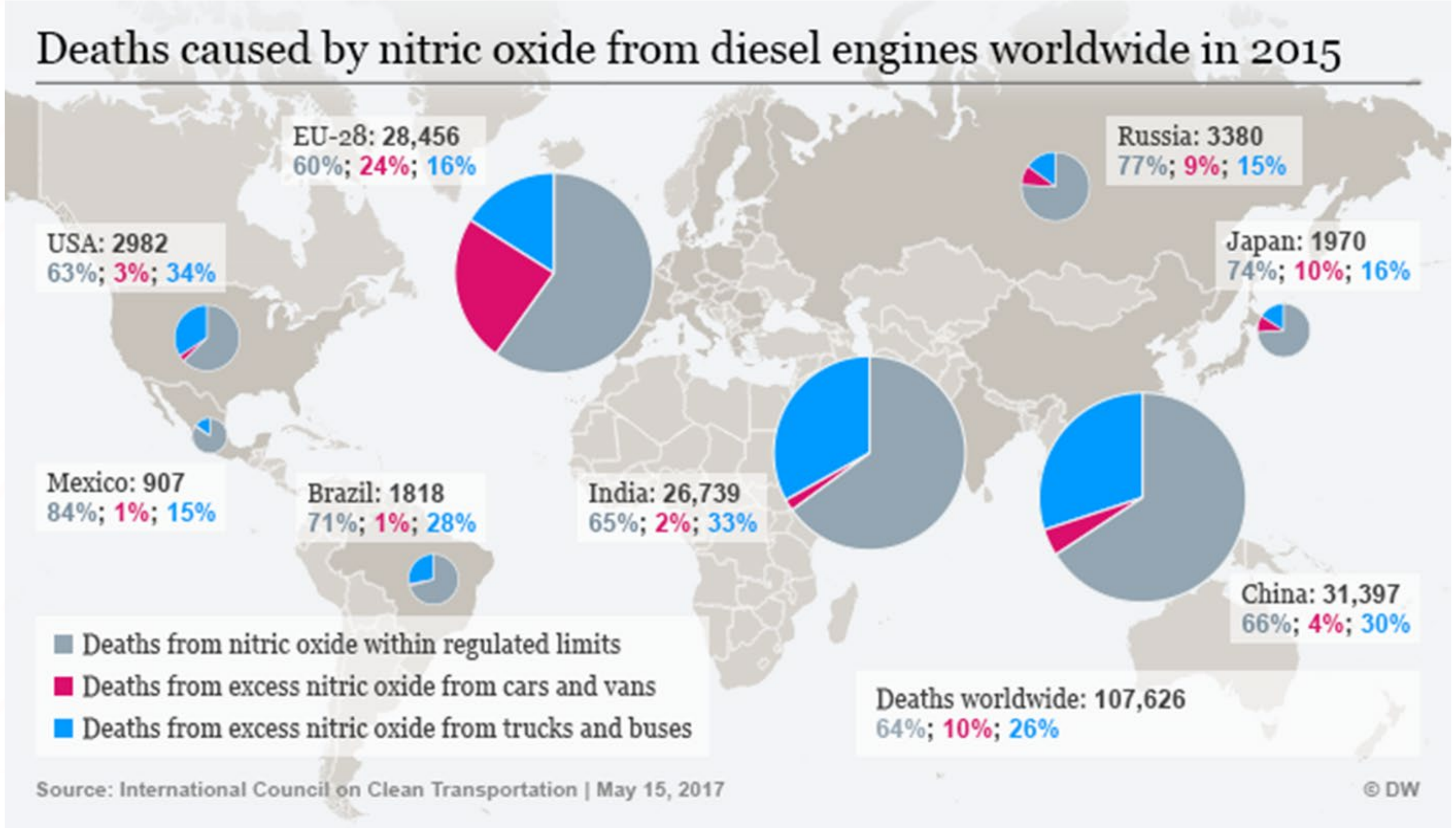
- **Background**
- OBM data quality and accuracy
- Real-world characteristics of NO_X emissions and after-treatment performance
- Summary and future suggestions

Controlling vehicular NO_X emissions is a global challenge

- Vehicular NO_X emissions challenge the world: air pollution, health threats and climate change.
- Mitigating NO_X emissions is an essential task for future cleaner transportation (e.g., *the approved Omnibus NO_X regulation of 0.02 g/bhp-hr in California*).



May 25, 2017 Issue



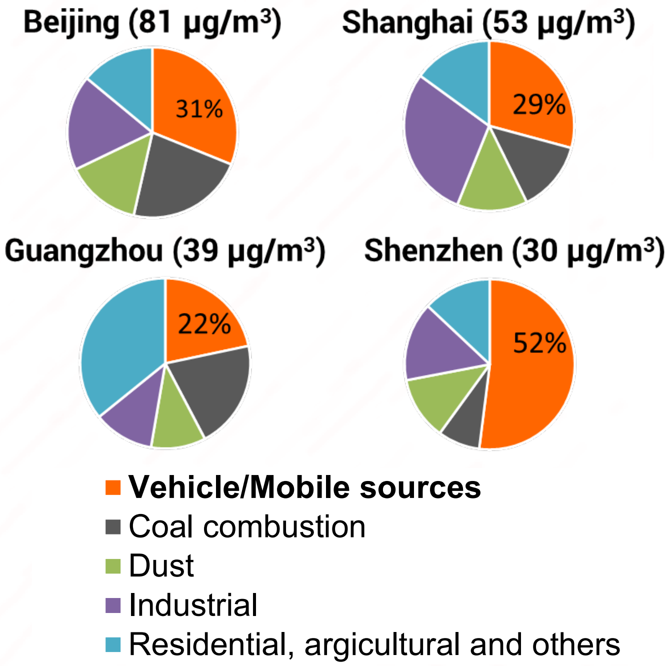
Sources: Anenberg et al., Nature, 2017; ICCT.

In China, controlling NO_X emissions from *heavy-duty diesel vehicles* (HDDVs) is a priority in the clean air actions

- Emission control of heavy-duty vehicles has been a significant part in China's "Three-year Blue-Sky Defense Battle (2018-2020)"
- NO_X emission control for HDDVs is a priority of clean air actions in the 14th Five Year Plan (2021-2025) due to the significant contribution to the formation of both $PM_{2.5}$ and O_3.

Official apportionment of local $PM_{2.5}$ sources for megacities

Note: Cross-boundary transport not included



Important concerns:

- Mobile emission sources contributed 45% of $PM_{2.5}$ among local sources in Beijing
- Higher nitrate fraction, particularly during the wintertime pollution episodes
- Summertime O_3 pollution deteriorated during 2013-2019

Multiple technologies to manage vehicle emissions

Type-approval and in-use compliance methods

PEMS
1~2 vehs per day

Dynamometer
1~2 vehs per day

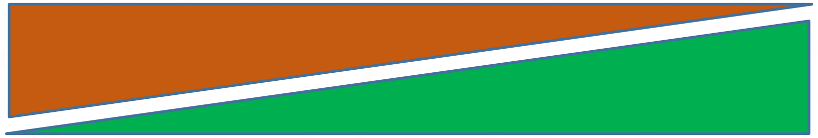
Real-world RSD methods

Plume chasing
50~80 vehs per day
2~5 mins per veh

Remote sensing
1000+ vehs per day
Short snap per veh

Accuracy

High accuracy
Small sample size

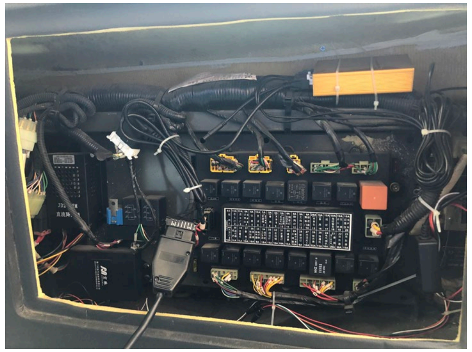


Low accuracy
Large sample size

Fleet coverage

On-board monitoring

Applicable to key fleets
NOx sensor required



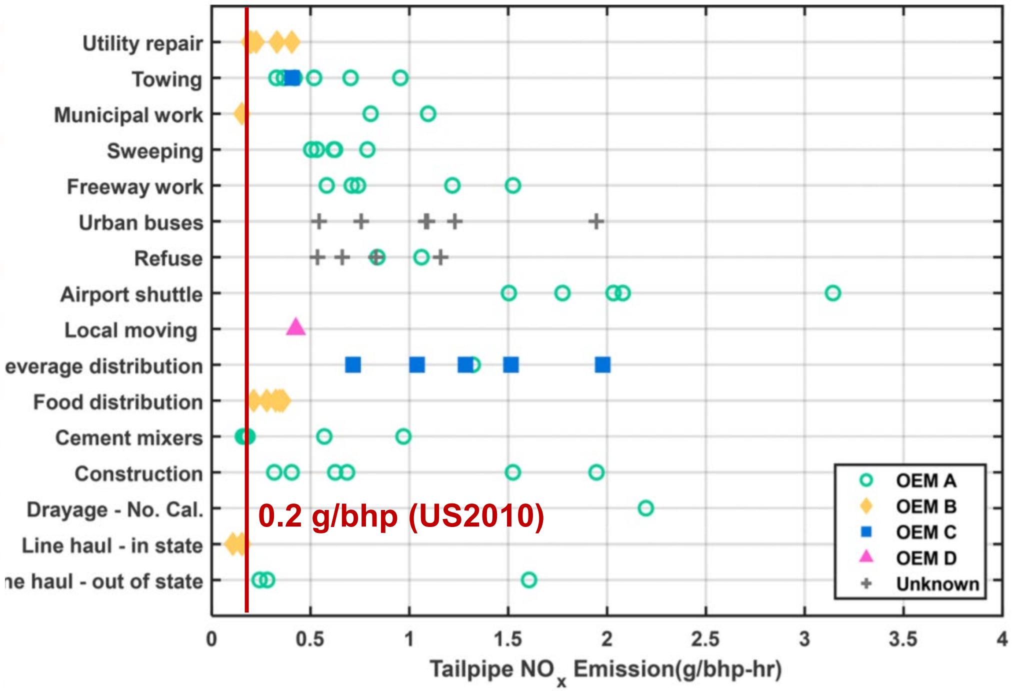
OBM data collection and transmission (periodically or remote real-time)

- **Multiple tasks of emission management**: type approval, in-use compliance, anti-tamper/malfunction, detection of high emitters, emission inventory development (for air quality planning)

Global progress on OBM/OBD regulations

- **California, US**
  - 2022: Evaluate HDDVs CO_2 and NO_X emissions by OBM (the REAL project)
  - 2024: Conduct emission control system inspections and emission compliance by OBM
- **China**
  - China VI standard (remote OBM): required the installation of OBM hardware from China VIa (2021), and the mandatory submission of data from China VIb (2023).
  - Only announced the NO_X OTL (1.2 g/kWh) in the China VI
- **Beijing**
  - Local OBM standard (2017): required the installation of China VI-style OBM from Sep 2018 for new China V and China VI HDDVs.
  - Local legislation on mobile source emission control (2021): to expand the OBM installation to pre-2018 MY HDDVs by 2022 (conducted by OEMs and paid by owners)
- **Europe**
  - Euro VI OBD requirements: event-based inspection against defeat, malfunction or misuse, including the NO_X OTLs

NO_X emissions evaluation of heavy-duty vehicles based on OBD in California



Tan et al., ES&T, 2019

https://ww2.arb.ca.gov/our-work/programs/board-diagnostics-obd-program
https://ww2.arb.ca.gov/rulemaking/2020/hdomnibuslownox

China VI OBM standard: data requirements

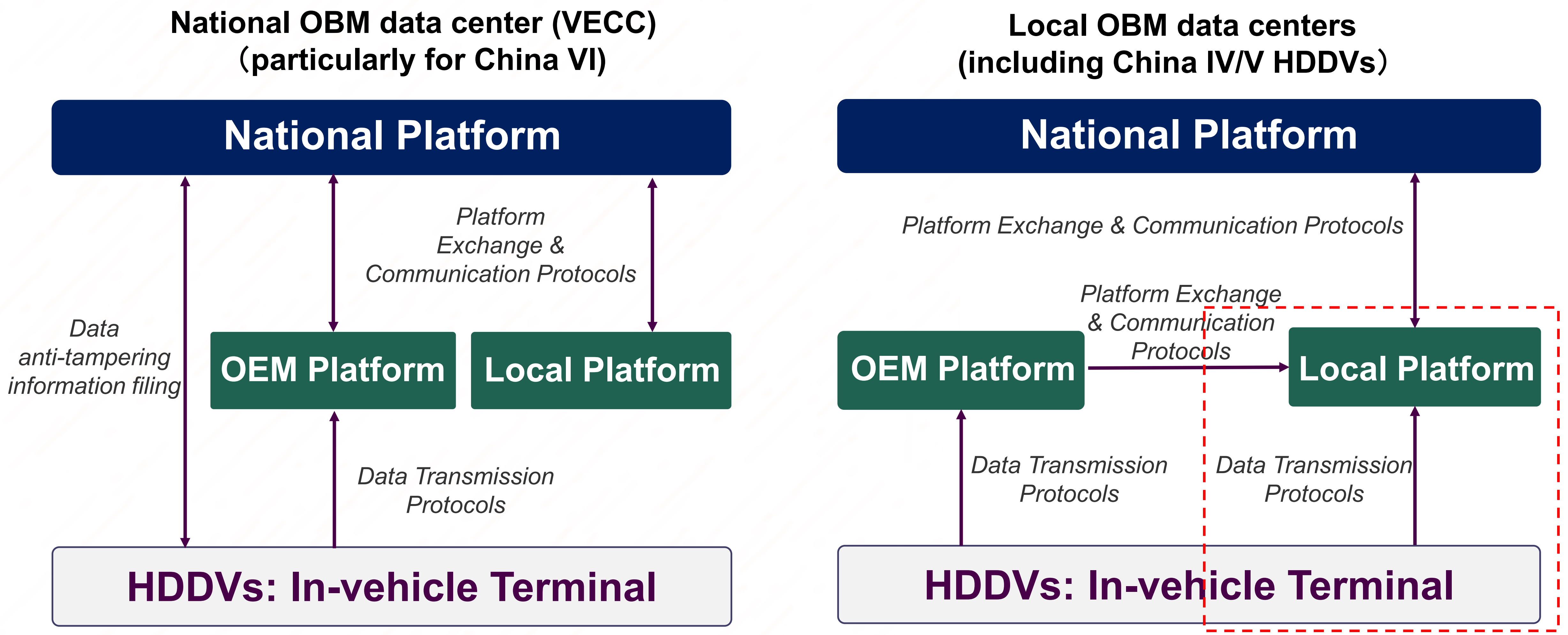
- OBM installation, data indexes (including valid ranges) and collecting frequency are well defined in the China VI standard
- Beijing's local OBM regulation implemented in 2017 is almost consistent with the China VI standard

Data field	Unit
Car_ID	—
VIN	—
Vehicle License Number	—
Time	—
Speed	km·h^{-1}
Air pressure	kPa
Engine output torque	%
Fraction torque	%
Engine speed	rpm
Engine fuel flow	**L·h^{-1}**
NO_X sensor output of upstream SCR	ppm

Data field	Unit
NO_X sensor output of downstream SCR	**ppm**
Urea liquid level	%
Intake airflow by mass airflow (MAF)	**kg·h^{-1}**
SCR inlet temperature	℃
SCR outlet temperature	℃
DPF pressure difference	kPa
Location status	—
Longitude	°
Latitude	°
Engine coolant temperature	℃
Fuel level	%
Odometer	km

Analyzing NO_X emission rates (g/s) at least requires NOx concentration, fuel flow and MAF.

The data transmission flow of China's OBM systems



Beijing requires direct, real-time data submission from local China V/VI HDDVs to the local platform.

OBM technological and implementation features

	Data requirement	Hardware	Data transmission	OBD requirements (e.g., OTLs)	In-use conformity limit
China (China VI)	**Accessibility of NO_X emission rates relevant parameters**	OEM	real-time transmission to OEM platforms, and thus to national the platform	China VI	Not announced
Beijing		OEM (post-2018 new HDDVs)	real-time transmission to local authority	China VI, Beijing V	Not announced
		OEM retrofit (pre-MY 2018) [a]	real-time transmission to local authority	Beijing V	Not announced
		Third-party retrofit (pre-MY 2018) [b]	real-time transmission to local authority	Beijing IV/V	Not announced
California		OEM (for MY 2010+ vehicles)	data stored in vehicle and submitted periodically	California Code of Regulations (CCR) §1971.1	Not announced

Notes: a) all Beijing V HDDVs will be retrofitted with OBMs by their OEMs by 2022; b) only experimented in a pilot project in the very early stage, and will be no longer considered in Beijing

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Sampled OBM data

- OBM data of 263 vehicles from Beijing Platform (164, China V to VI) and OEM Platforms (99, all China VI) for emission characterization
  - third-party retrofitted OBM systems for in-use China IV/V HDDVs for data quality comparison
  - OEM Platforms report extra parameters than China VI standard required (e.g., *instantaneous urea injection volume*)

Platform	OBM type	Emission standard	GVW	Number of vehicles
Beijing Platform	Retrofitted OBM	China IV	≤ 4.5 t	11
			> 4.5 t	14
		China V	≤ 4.5 t	6
			> 4.5 t	19
	OEM-OBM	China V	≤ 4.5 t	62
			> 4.5 t	11
		China VI	≤ 4.5 t	2
			> 4.5 t	4
OEM-operated Platforms	OEM-OBM	China VI	≤ 4.5 t	35
			> 4.5 t	59

Inspection procedure of OBM data quality

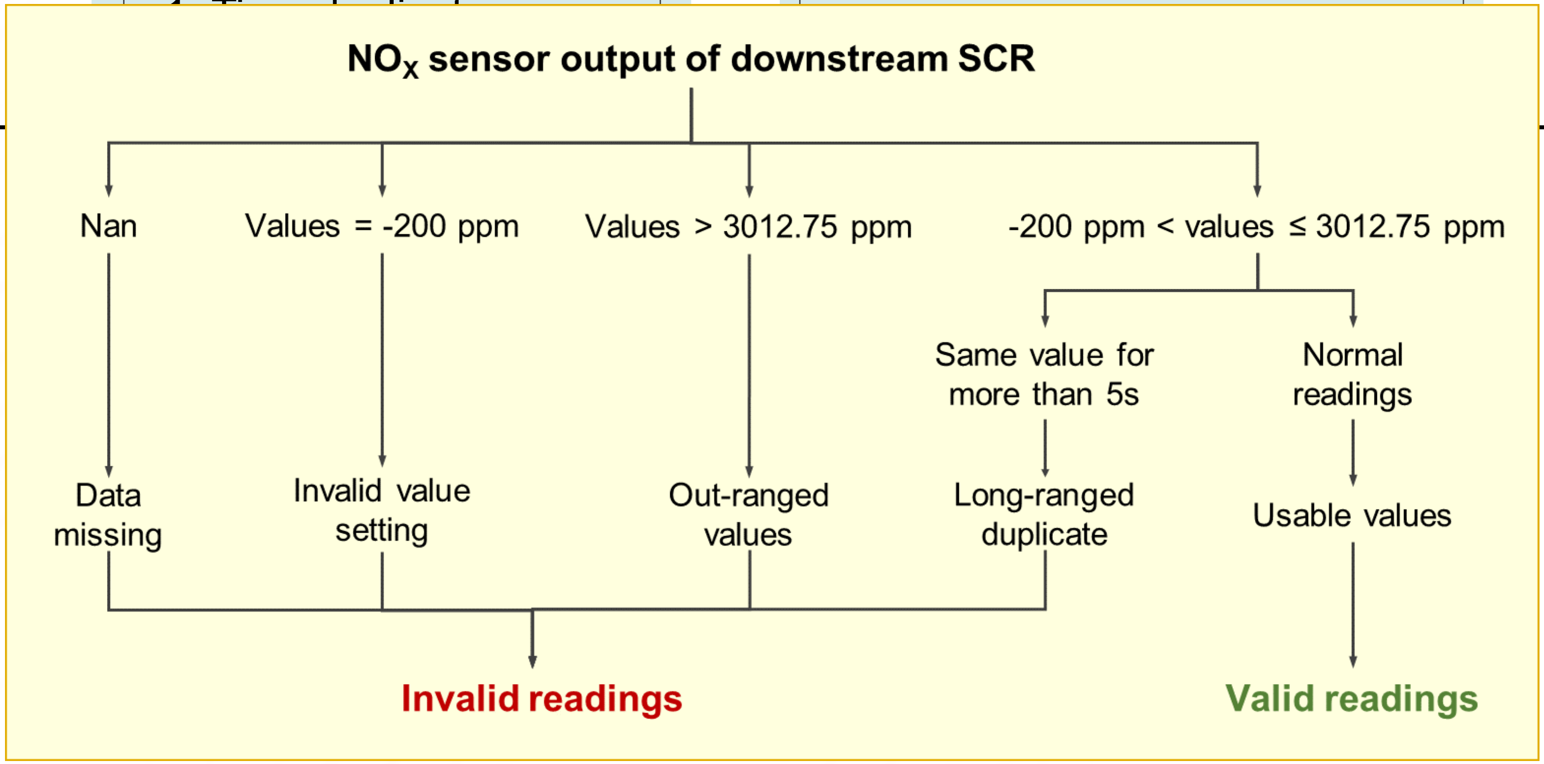
- Check OBM data consistency to ensure presentative unbiased emission result.
  - Timestamp consistency, key parameter invalidation and typical data error are inspected.

Consistency check
(Key index: time)

Key index validity check

1. Data missing
   - ***NOx concentration***

Raw data



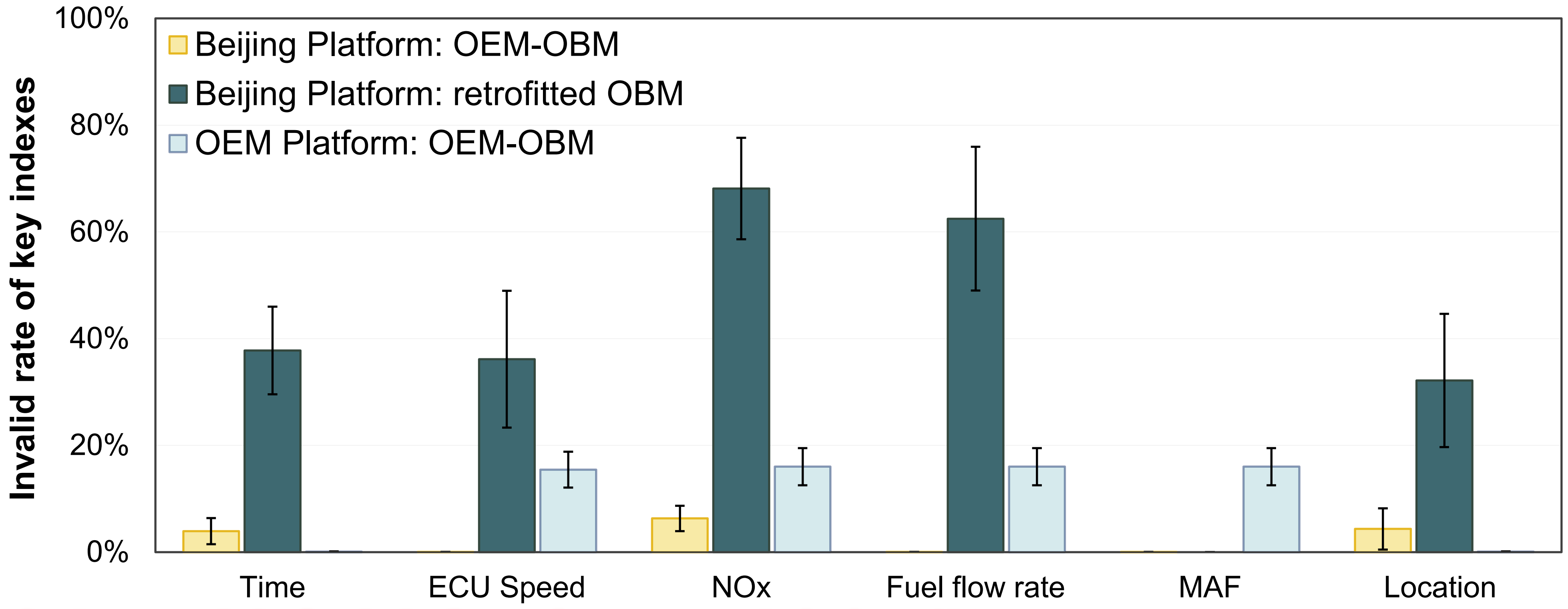
Data quality report

Zhang et al., STOTEN, 2020

OBM data quality inspection results

- Summarize missing data and invalid values of key parameters in OBM data from HDDVs.
  - Beijing Platform: OEM OBM (79) + retrofitted OBM (50)
  - OEM Platform: OEM OBM (99)

Overall time fractions of missing data or invalid values for key parameters

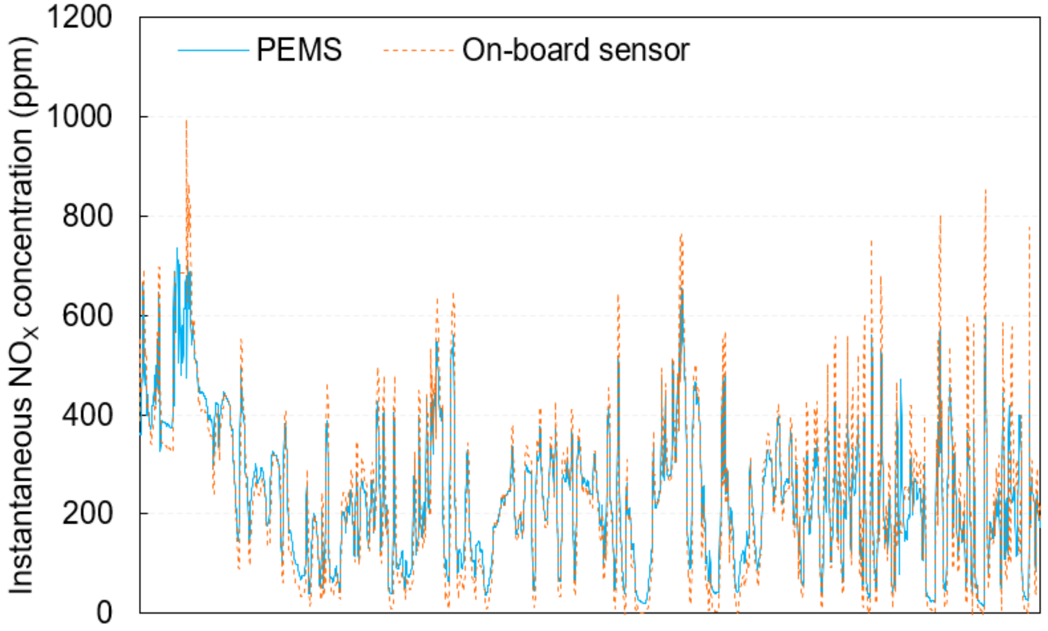


Zhang, Zhao et al., STOTEN, 2020

Sensor accuracy evaluation: PEMS-OBM tests

- PEMS-OBM synchronized tests: evaluate the accuracy of on-board sensors.
- 3 OEM OBM HDDVs and 5 retrofitted OBM HDDVs were tested and analyzed.

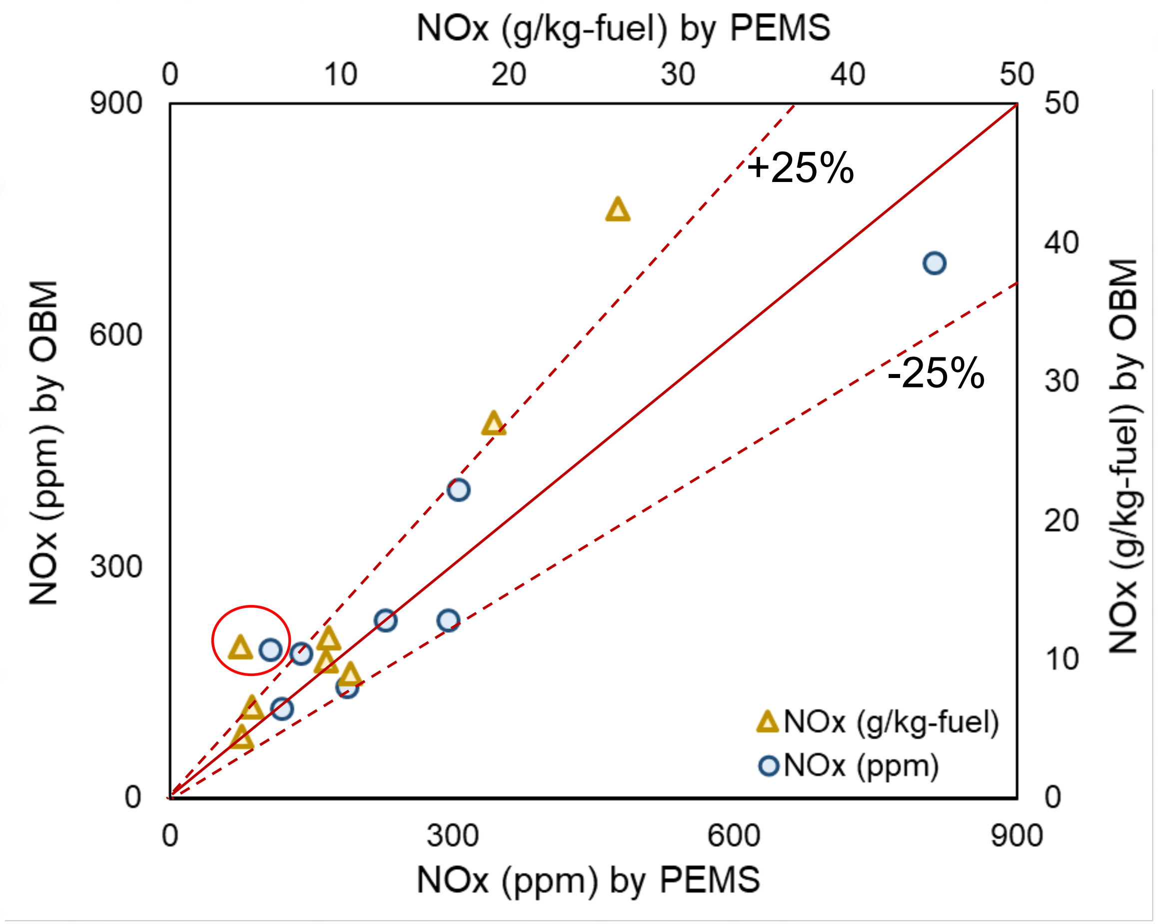
Comparative results for Vehicle 4 (1 h example):
R=0.94, Mean relative error=+8.9% (OBM vs. PEMS)



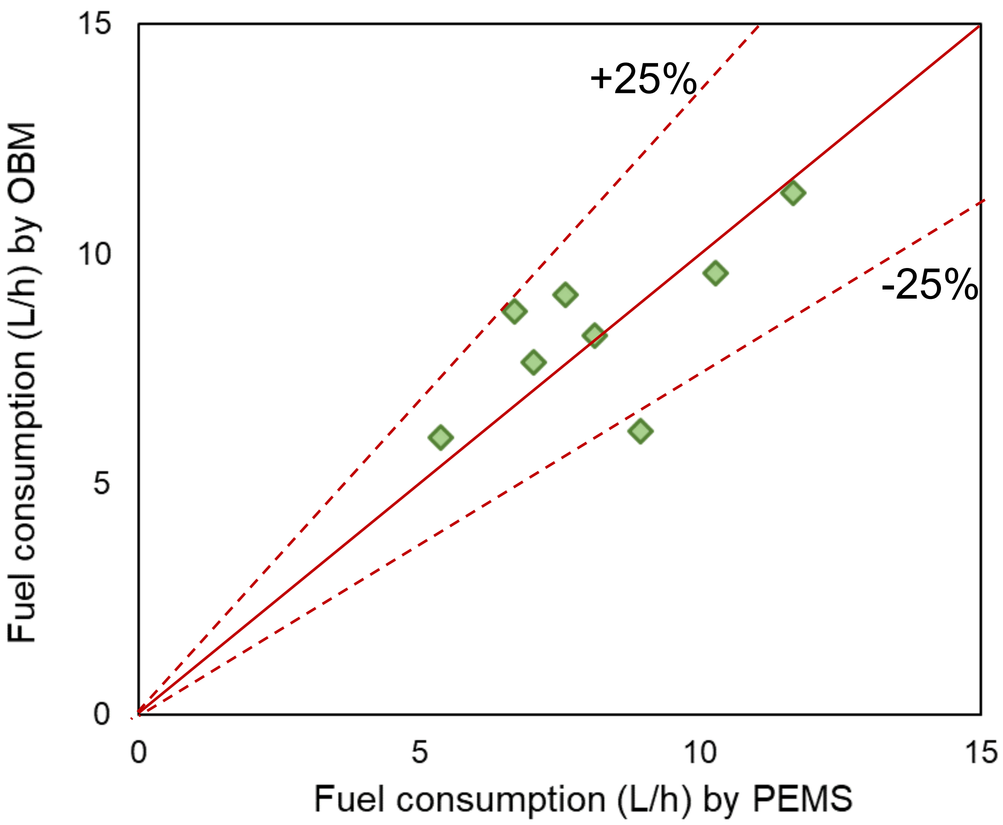
Zhang, Zhao et al., STOTEN, 2020

On-road validation of NOx and fuel consumption data

NO_X measurement comparison between OBM and PEMS of 8 tested vehicles

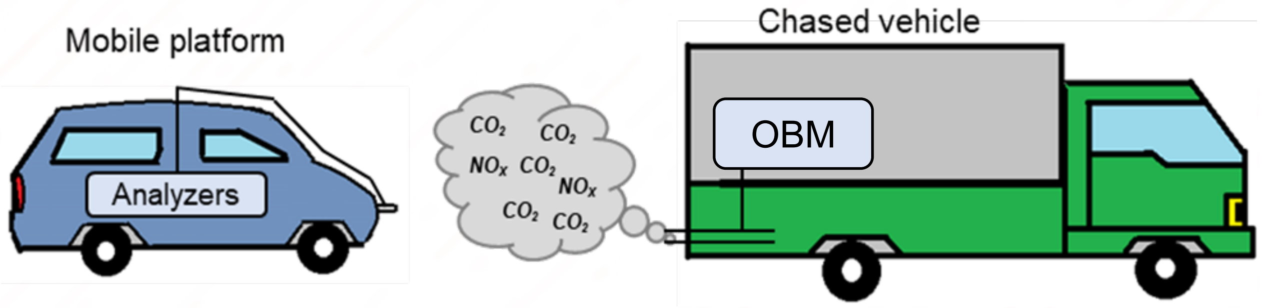


Fuel consumption comparison between OBM and PEMS of 8 tested vehicles

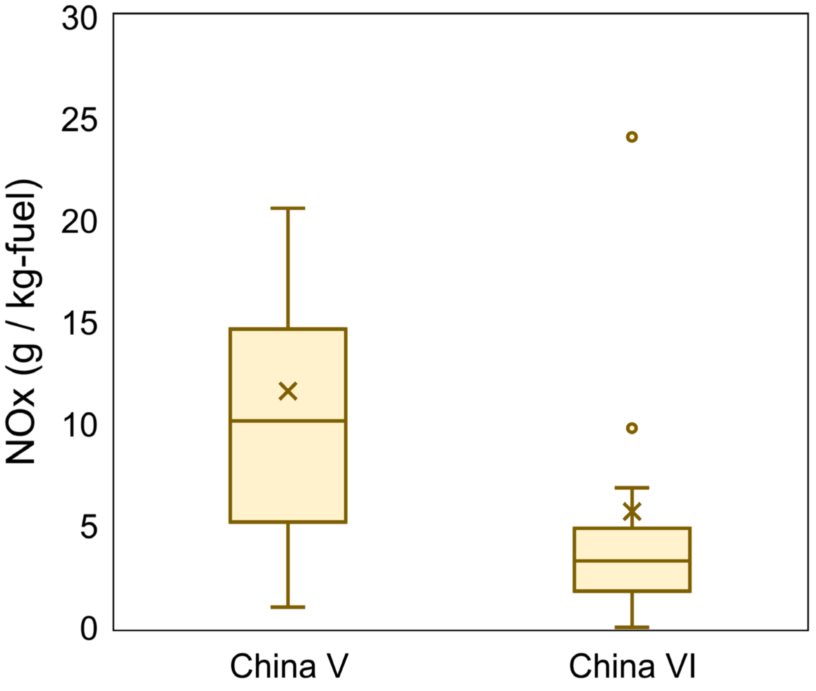


Zhang, Zhao et al., STOTEN, 2020

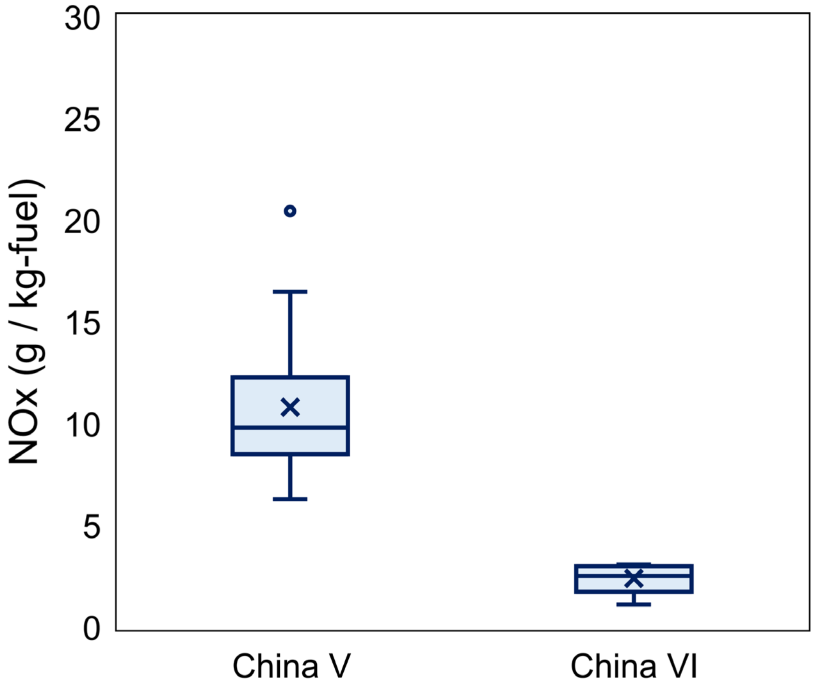
On-road validation by plume chasing: fleet-average NO_X emissions in Beijing



Fleet-averaged NO_X emissions measured by Chasing



Fleet-averaged NO_X emissions measured by OBM



- Compare fleet-averaged NOx emissions in Beijing
  - Plume-chasing : China V (30), China VI (23)
  - OEM-OBM: China V (71), China VI (5)
  - Here, China V indicates the OEM OBM-equipped HDDVs in Beijing

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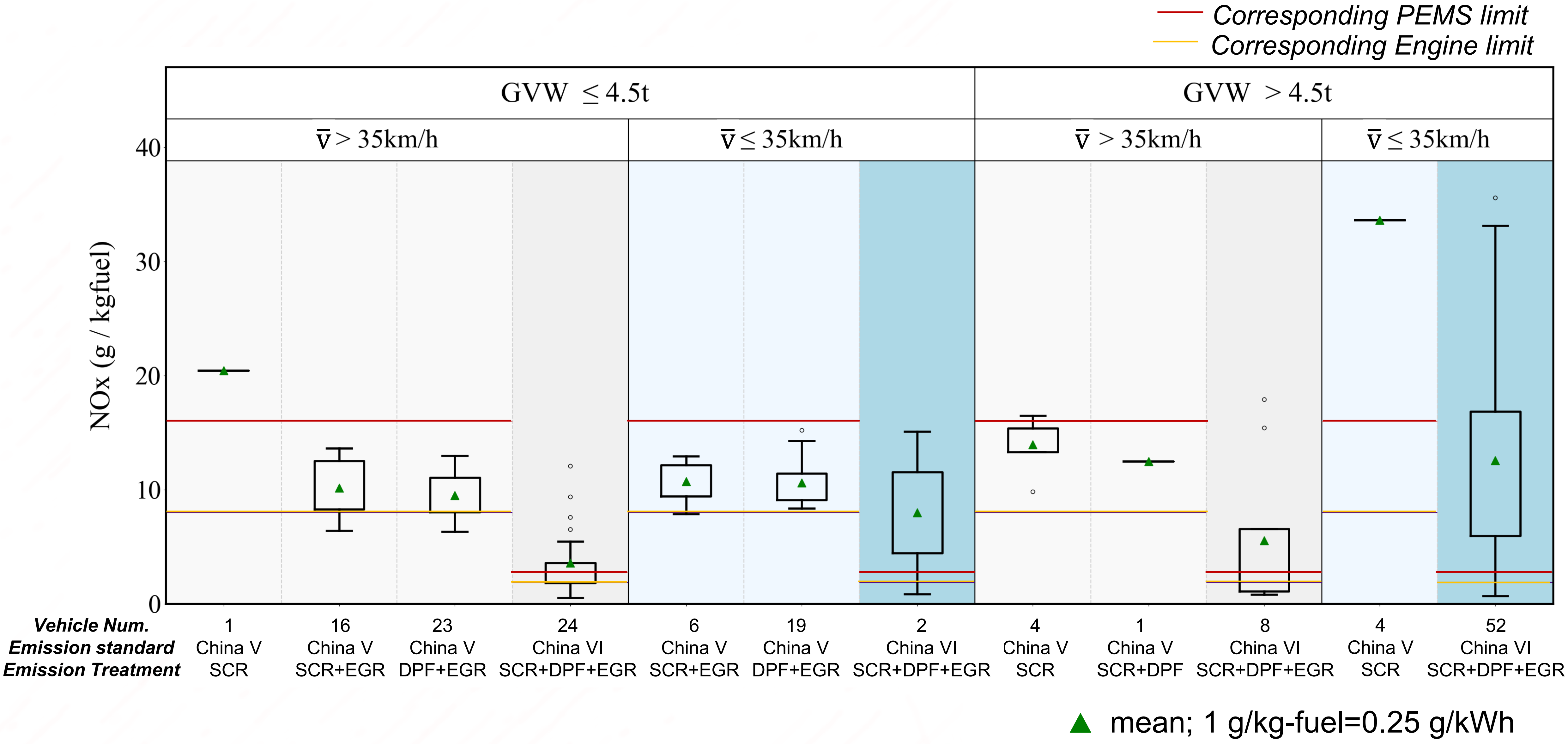
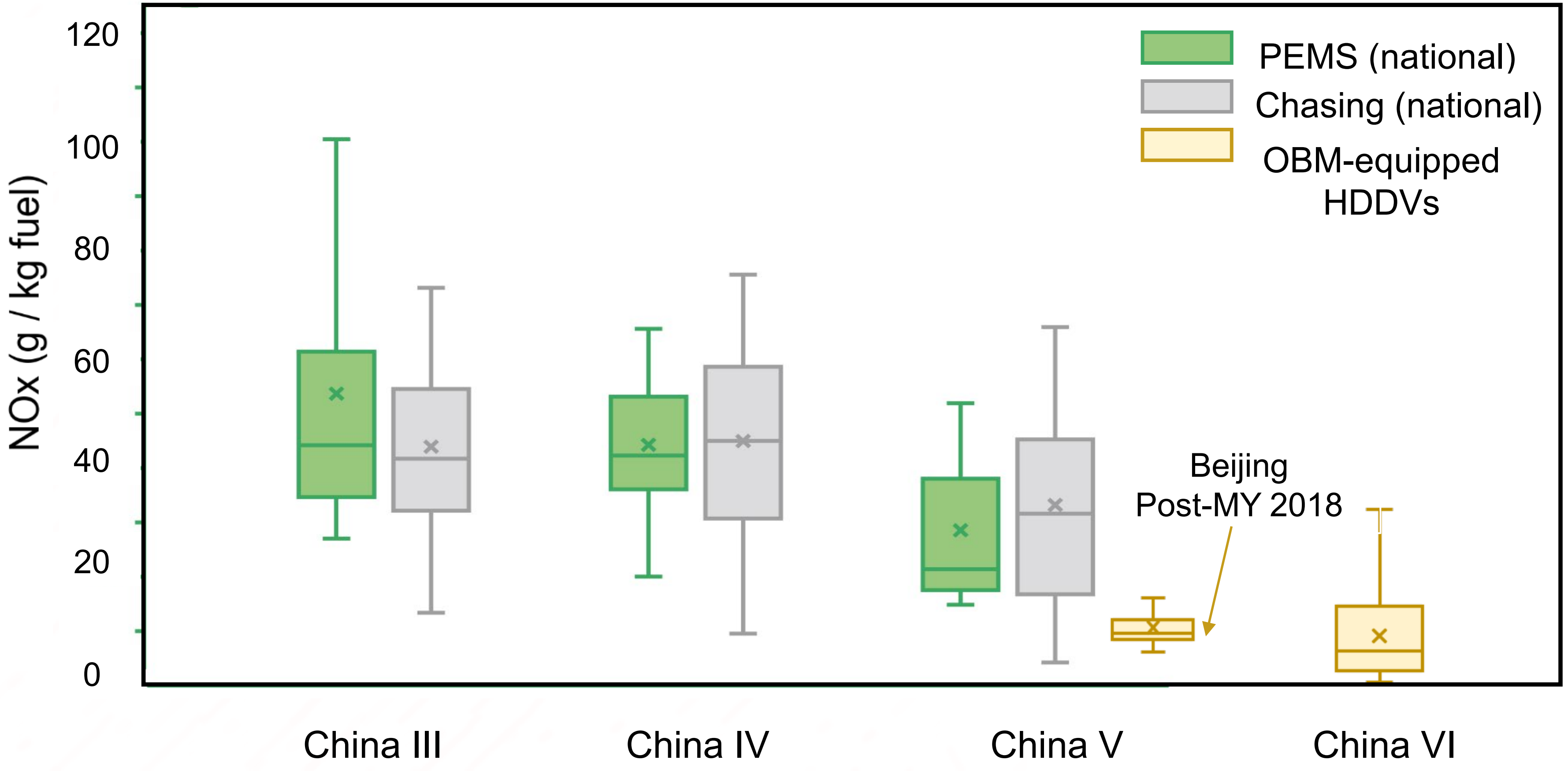
Real-world NO_X emissions by emission standard and control technology type



OBM-instrumented HDDVs have substantially lower NO_X emissions than previous models

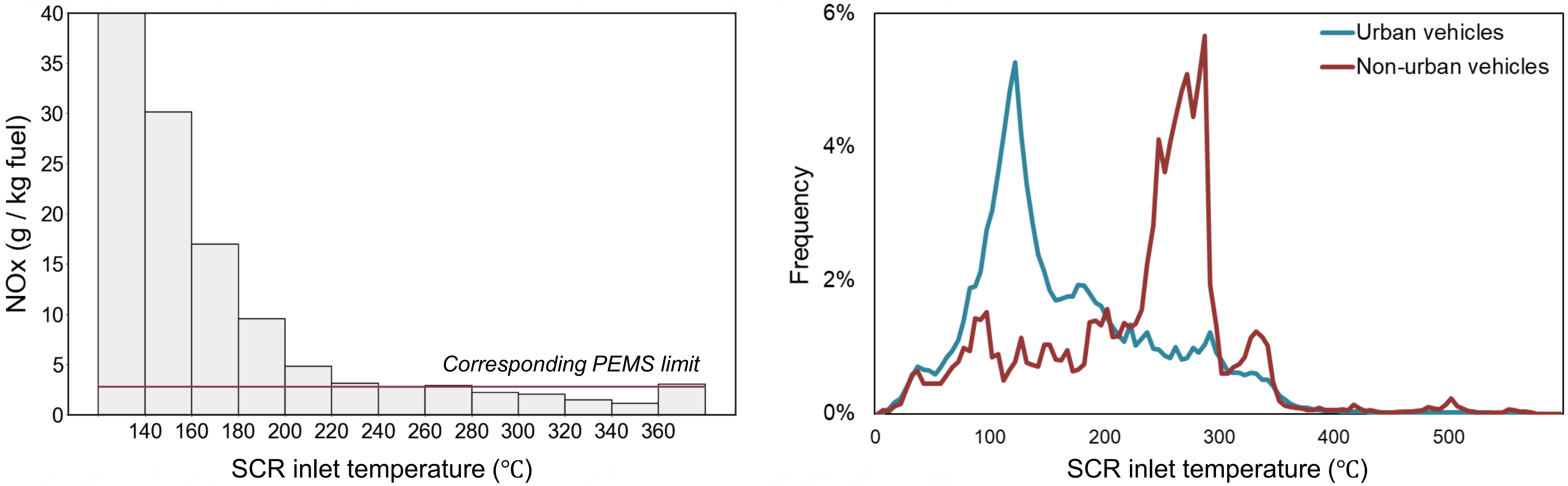
- One of the most important progresses in mitigating on-road NO_X emissions in China.
- In a good relation with the rapid reduction in ambient NO_2 concentrations in Beijing
  - Average NO_2 concentrations: 46 μg/m^3 in 2017, 37 μg/m^3 in 2019 and 29 μg/m^3 in 2019



SCR temperatures significantly affected NO_X emissions, and varied by driving conditions

- SCR temperature is the key parameter that determines control efficiency of NO_X emissions.
  - Need to be higher than 240 ℃ to warrantee a complete incompliance with the corresponding China VI PEMS standard limit (0.69 g/kWh; ~2.8 g/kg-fuel).
  - Different SCR temperature distributions between urban and non-urban vehicles

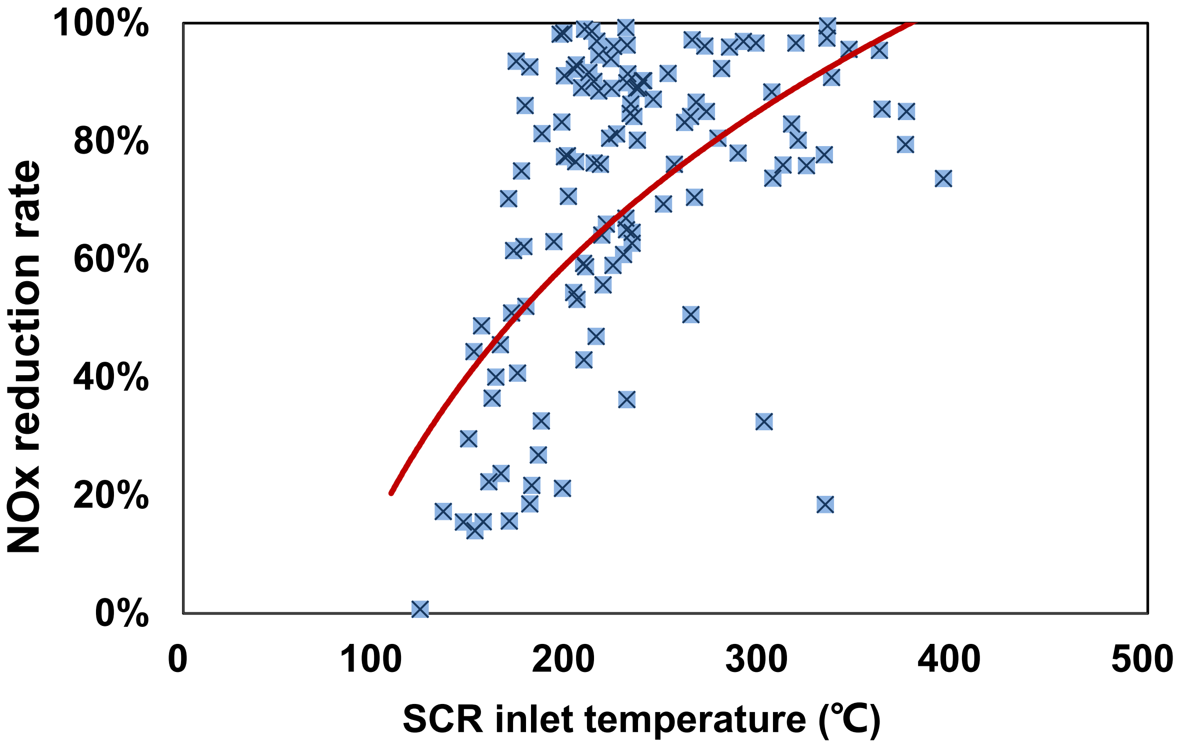
NO_X emissions in SCR temperature bins and SCR inlet temperature distribution
(60 China VI HDDVs, SCR+DPF+EGR, GVW>4.5t)

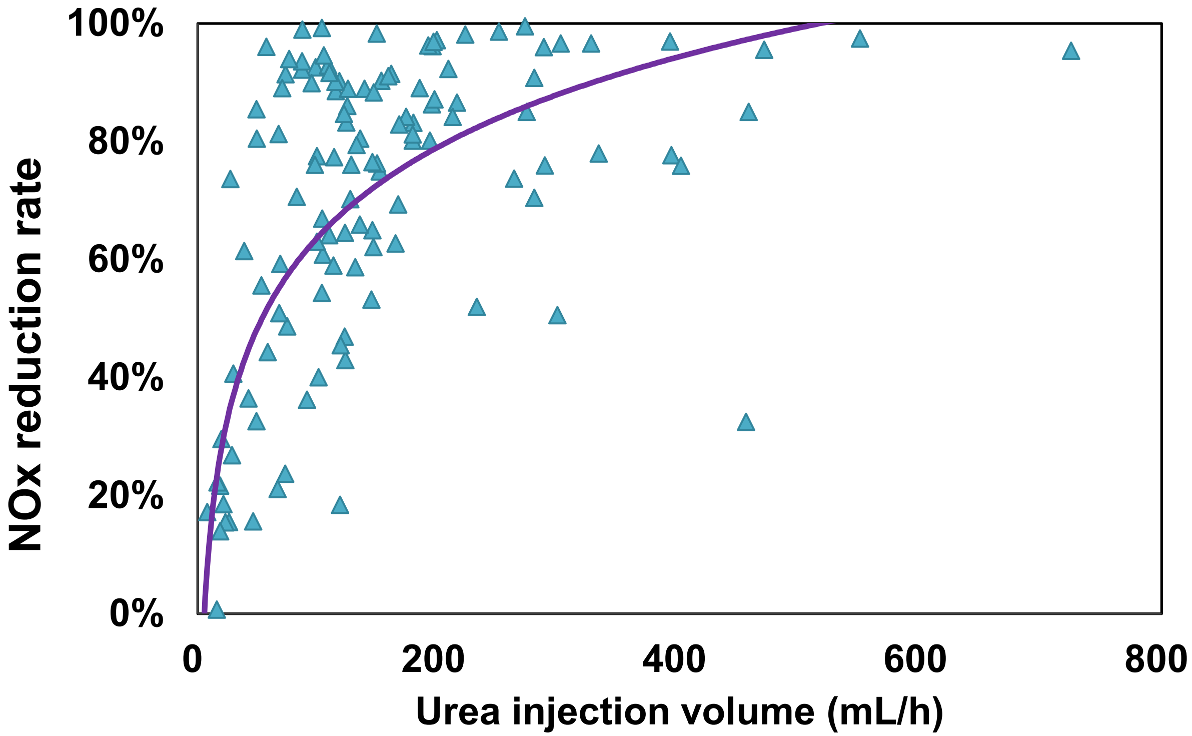


An in-depth watch of real-world SCR efficiency

- Real-world SCR efficiency derived according to SCR-upstream/downstream NO_X concentrations.
  - When SCR temperatures were around 200 ℃, the average NO_X reduction rate was about 60%
  - An average efficiency of 90% needs SCR temperatures to be up to 300 ℃

The influence of SCR inlet temperature and urea inject volume on NO_X reduction rate
(31 HDDVs with instantaneous pre-SCR NOx and urea consumption data)



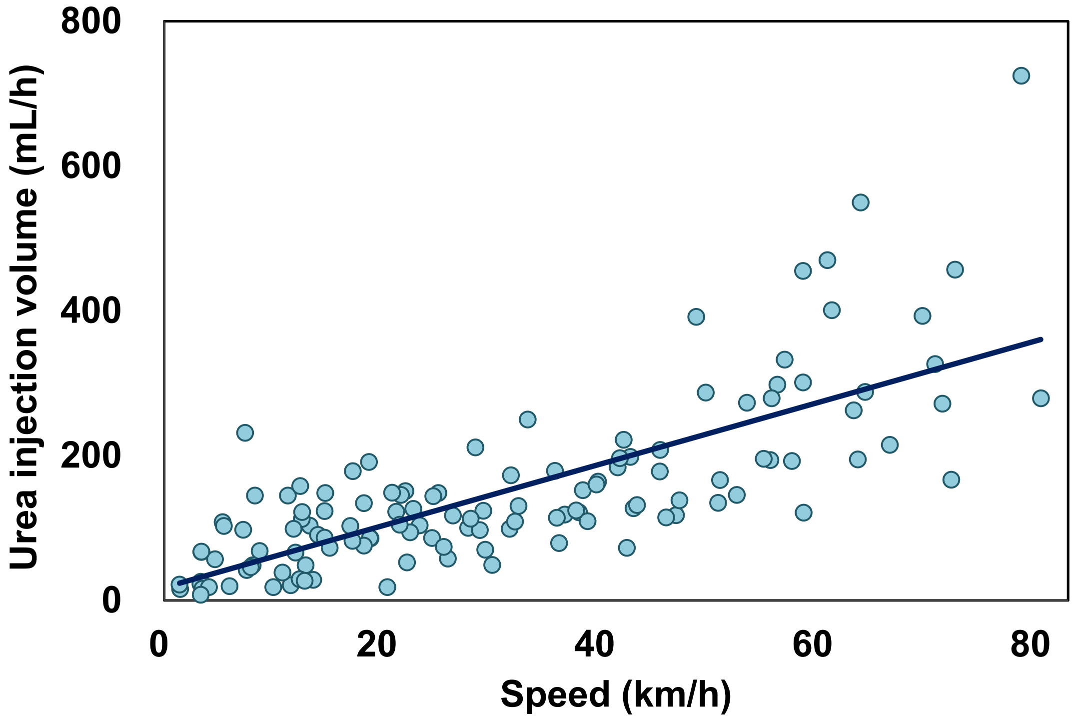


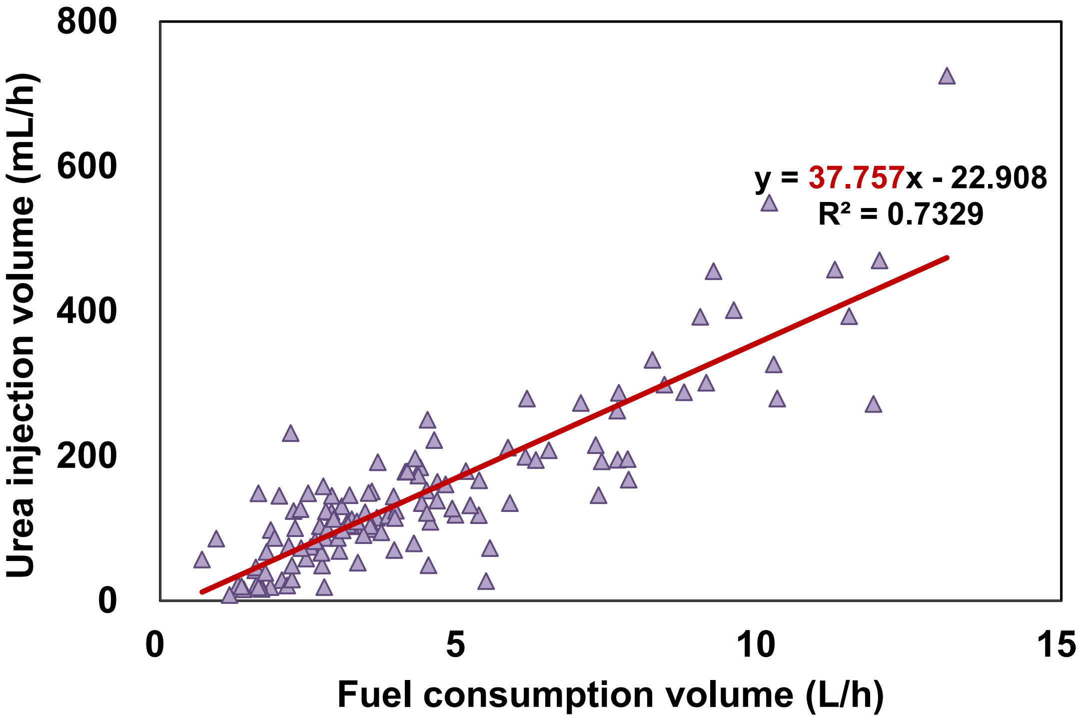
Note: each data point represent a trip segment of 180s

Urea liquid consumption

- The OEM platform provides instantaneous urea injection rates, while the urea liquid level data required by the China VI standard is neither temporally sensitive nor accurate.
- Linear relationship between urea injection volume vs. driving speed / fuel consumption.
  - Urea liquid (32.5% urea) injection volumes are around 3.8% of concurrent fuel consumption.

The relationship between speed / fuel consumption and urea injection volume

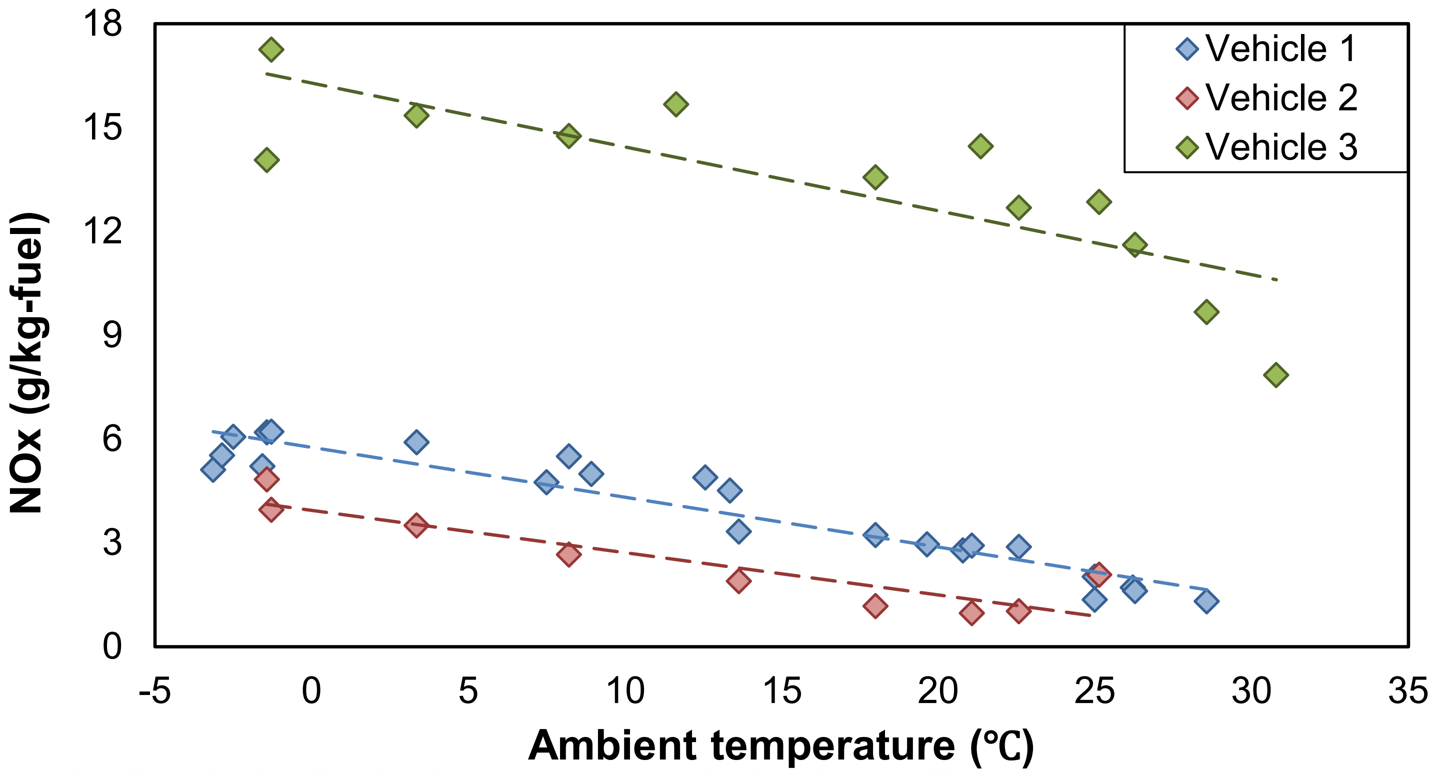




The impact from ambient temperature

- Strong temperature dependence of real-world NO_X emissions for China V and VI HDDVs (3 samples with at least six month OBM records)
  - On average, NO_X emissions will decrease 0.12~0.14 g/kg-fuel when ambient temperature increases 1 ℃

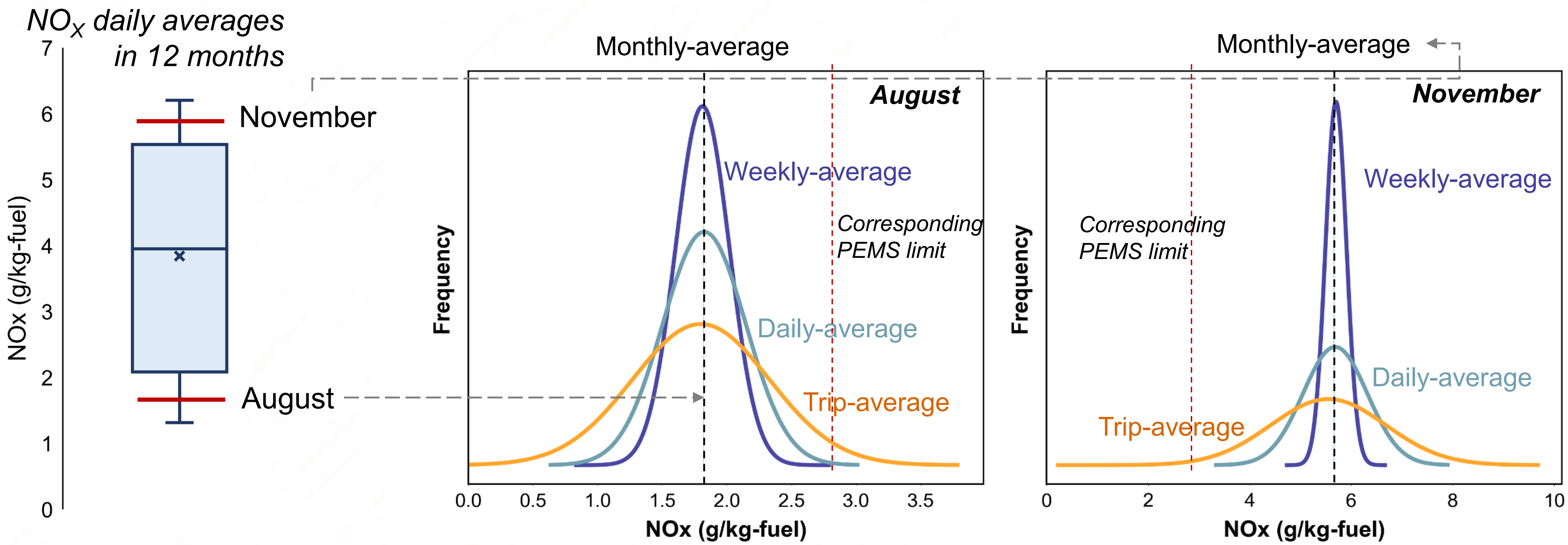
Influence of ambient temperature on NO_X emissions of 3 HDDVs



How to utilize OBM for in-use compliance and detection of high emitters: to manage the inter-trip/day/season variability

- ***A Principle Question***: **should the OBM be used as a real-time identification (i.e., a snapshot) of high emitters like other RSD tools, or utilized to develop a PEMS-like in-use conformity protocol covering an appropriately longer period?**

The distributions of OBM-informed NO_X emissions for one HDDV with one-year monitoring data



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Take-away remarks

- **OBM regulations**: China has been the pioneer in implementing remote OBM for China VI HDDVs. Beijing has further required the installation of remote OBM for local in-use China V HDDVs. However, the detailed in-use compliance protocol has not been developed yet.
- **Data quality:** OBM systems equipped by HDDV OEMs can provide much better data quality than the retrofitted OBMs by third-party companies (an important lesson for future OBM programs for in-use pre-China VI HDDVs).
- **Accuracy:** a majority of tested HDDVs showed good agreement between OBM vs. other on-road tests (e.g., PEMS, chasing).
- **Emission characteristics**: China VI HDDVs (and China V HDDVs in Beijing following the local OBM regulation) had significant lower NO_X emissions compared with previous models. However, low speed conditions and low temperatures would increase their NO_X emissions.
- **SCR efficiency**: strongly affected by SCR temperature (fundamentally by driving conditions and ambient temperatures).
- **In-use compliance**: we suggest monitor at least the daily-based emissions, and adequately account the inter-season variability and the usage features (e.g., routine driving conditions). This is also relevant to **the identification method of high emitters**.

Future research questions

- **To assure and manage the reliability of NO_X sensor in a long lifespan**: the number of vehicle samples evaluated by concurrent PEMS tests is rather small (also limited in California), and many of these vehicle samples had short usage durations.
- **To develop reliable protocols for in-use compliance and high emitter identification:** these protocols should be judged based on an appropriate time window to account the emission variability, and also account the reliability of NO_X sensors
- **To utilize OBM data for smart management of air quality and GHG mitigation:** OBM systems can not only report NO_X concentrations but also real-time trajectory and fuel consumption. They will serve as important intelligent transportation system (ITS) data to improve policy decision of air quality management and GHG emission mitigation through atmospheric simulations or data-driven approaches.

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Thank you

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