# Developing emission factors for inland vessels in China

## An Introduction to Regulation and PEMS Practice

Dr. Xin Wang

National Laboratory of Automotive Performance & Emission Test,

Beijing Institute of Technology (BIT)

# Contents

# Background

- In China, annual $NO_x$ and PM emissions from on-road sector and non-road sector are approximately equal, and inland vessels are the dominate contributor to non-road sector
- The total perseveration of vessels in China is slightly shrinking, but the overall turnover of waterborne business is expanding at high rates, indicating the activity level is increasing

| As of 2015 | Inland vessels | Coasters | OGVs |
|---|---|---|---|
| **Preservation** | **152,500** | **10,721** | **2,689** |
| **Ave. net capacity** | **819** | **6,397** | **29,350** |
| **Ave. engine power** | **215.0** | **1,372.7** | **7,895.9** |

- Before 2018, there is basically no national standard to control toxic emissions from vessels, either new or in-use vessels
- Now, MEE (Ministry of Ecology & Environment, former MEP), MOT and CCS (China classification Society) are taking actions to purify smoky exhaust from vessels

# Introduction to China's standards

- Currently in China, **gaseous and particulate** emissions from **inland**, **coaster**, **river-sea going**, **channel** and **fishing vessels** are regulated; 3 standards specify the requirements for **new** engines
  - GB 15097-2016 Limits and measurement methods for exhaust emissions from marine engines (CHINA I, II), **forcible, effective from Jul, 2018**
  - GB 20891-2014 Limits and measurement methods for exhaust emissions from diesel engines of non-road mobile machinery (CHINA III, IV), **forcible, effective from Oct, 2014**
  - GD 11 Guidelines for testing and certification of $NO_x$ emissions from marine engines, **guidance notes, revised on May, 2017**
- Apart from above standards, some others also set requirements for
  - Fuel: GB 252-2015
  - Equipment and method: GB/T 6072.3-2018; GB/T 6379.2-2014; GB/T 21404-2008

# Classification of vessel engines

- Classification of marine engines is based on both **net power (P)** and **displacement per cylinder (SV)**
  - Category 1: SV<5L but P>=37kW
  - Category 2: 5=<SV<30L
  - Category 3: SV>=30L
  - "Category 0": No category assigned to engines with P<37kW, but **their emissions are regulated**
- Engines belong to different categories shall comply with different national standards
  - Category 1 and 2 shall meet GB 15097-2016
  - Category 3 shall follow GD 11
  - Engines with P<37kW shall meet GB 20891-2014

# Limits for exhaust emissions

- Limit values set for marine engines (SV=<30L) are also **power- and displacement-dependent**

| Cate. | SV (L/cyl) | P (kW) | CO | $HC+NO_x$ | $CH_4$ | PM |
|---|---|---|---|---|---|---|
| 1 | SV<0.9 | P>=37 | 5.0 | 7.5 | 1.5 | 0.40 |
| 1 | 0.9=<SV<1.2 | | 5.0 | 7.2 | 1.5 | 0.30 |
| 1 | 1.2=<SV<5 | | 5.0 | 7.2 | 1.5 | 0.20 |
| 2 | 5=<SV<15 | | 5.0 | 7.8 | 1.5 | 0.27 |
| 2 | 15=<SV<20 | P<3000 | 5.0 | 8.7 | 1.6 | 0.50 |
| 2 | 15=<SV<20 | P>=3000 | 5.0 | 9.8 | 1.8 | 0.50 |
| 2 | 20=<SV<25 | | 5.0 | 9.8 | 1.8 | 0.50 |
| 2 | 25=<SV<30 | | 5.0 | 11.0 | 2.0 | 0.50 |

* $CH_4$ only applies to NG engines (incl. dual- or bi-fuel models)

** Manufacturers could use NMHC to replace HC when certifying a NG model

*** Unit for pollutants is g/kWh

| Cate. | SV (L/cyl) | P (kW) | CO | $HC+NO_x$ | $CH_4$ | PM |
|---|---|---|---|---|---|---|
| 1 | SV<0.9 | P>=37 | 5.0 | 5.8 | 1.0 | 0.3 |
| 1 | 0.9=<SV<1.2 | | 5.0 | 5.8 | 1.0 | 0.14 |
| 1 | 1.2=<SV<5 | | 5.0 | 5.8 | 1.0 | 0.12 |
| 2 | 5=<SV<15 | P<2000 | 5.0 | 6.2 | 1.2 | 0.14 |
| 2 | 5=<SV<15 | 2000=<P<3700 | 5.0 | 7.8 | 1.5 | 0.14 |
| 2 | 5=<SV<15 | P>=3700 | 5.0 | 7.8 | 1.5 | 0.27 |
| 2 | 15=<SV<20 | P<2000 | 5.0 | 7.0 | 1.5 | 0.34 |
| 2 | 15=<SV<20 | 2000=<P<3300 | 5.0 | 8.7 | 1.6 | 0.50 |
| 2 | 15=<SV<20 | P>=3300 | 5.0 | 9.8 | 1.8 | 0.50 |
| 2 | 20=<SV<25 | P<2000 | 5.0 | 9.8 | 1.8 | 0.27 |
| 2 | 20=<SV<25 | P>=2000 | 5.0 | 9.8 | 1.8 | 0.50 |
| 2 | 25=<SV<30 | P<2000 | 5.0 | 11.0 | 2.0 | 0.27 |
| 2 | 25=<SV<30 | P>=2000 | 5.0 | 11.0 | 2.0 | 0.50 |

# Limits for exhaust emissions (continued)

- Compared to CHINA-I, CHINA-II gives more detailed power-bins and sets 30-50% tighter limits
- Engines with P<37kW shall meet GB 20891-2014, in which broader limits are mandated compared to GB 15097-2016

| Stage | P (kW) | CO | HC | $NO_x$ | $HC+NO_x$ | PM |
|---|---|---|---|---|---|---|
| | 0<P<8 | 12.3 | - | - | 18.4 | - |
| I | 8=<P<18 | 8.4 | - | - | 12.9 | - |
| | 18=<P<37 | 8.4 | 2.1 | 10.8 | | 1.0 |
| | 0<P<8 | 8.0 | - | - | 10.5 | 1.0 |
| II | 8=<P<18 | 6.6 | - | - | 9.5 | 0.8 |
| | 18=<P<37 | 5.5 | 1.5 | 8.0 | - | 0.8 |
| III | P<37 | 5.5 | - | - | 7.5 | 0.60 |
| IV | P<37 | 5.5 | - | - | 7.5 | 0.60 |

# Limits for exhaust emissions (continued)

- For large engines (Category 3, SV>30L), only $NO_x$ emissions are regulated, and the limits are either fixed values or functions of **rated engine speed (n)**

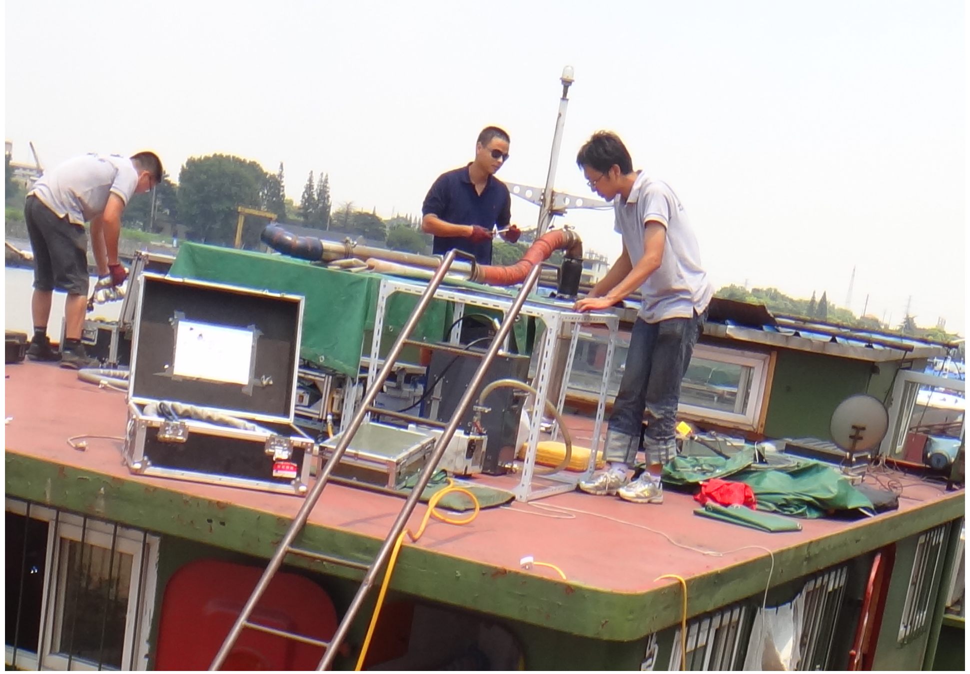
| Date of manufacture | Emission standard | $NO_x$ | | |
|---|---|---|---|---|
| | | $n<130$ | $130=<n<2000$ | $n>=2000$ |
| 1 Jan, 2000 to 1 Jan, 2011 | Tier I | 17.0 | $45 \cdot n^{(-0.2)}$ | 9.8 |
| 1 Jan, 2011 or later | Tier II | 14.4 | $44 \cdot n^{(-0.23)}$ | 7.7 |
| 1 Jan, 2016 or later | Tier III | 3.4 | $9 \cdot n^{(-0.2)}$ | 2.0 |

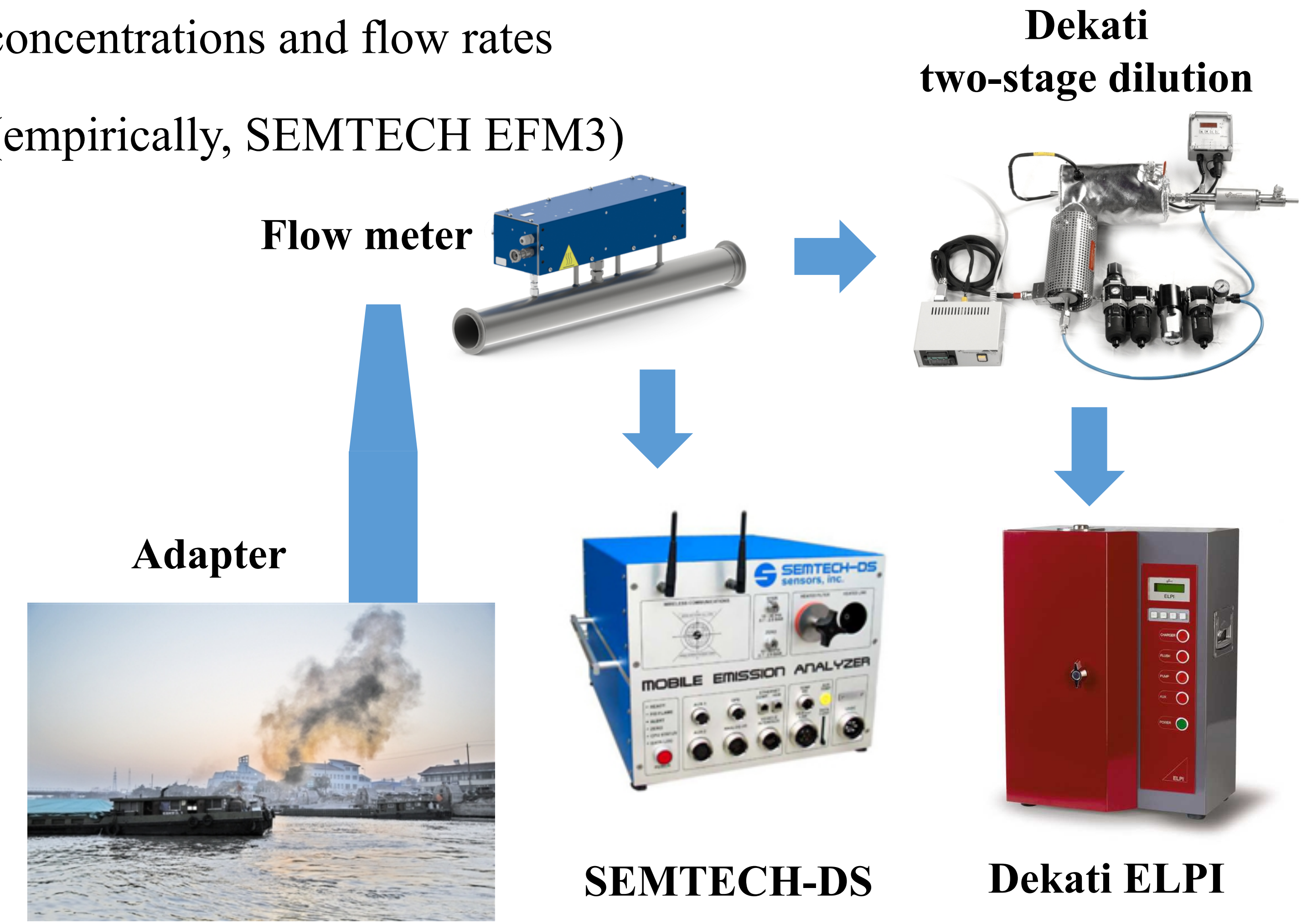
# PEMS research conducted by BIT

- Since 2010, the BIT-LAE team has tested 13 freight vessels on the Grand Canal, 6 passenger vessels on the Pearl River, 3 liners on the Yangtze River, 8 fishing ships and 1 coaster on the Bohai Sea

# Testing equipment arrangement (full flow)

- All the exhaust stream flow through the flow meter
- Mass of the pollutants is calculated from concentrations and flow rates
- Suitable for engines smaller than 350kW (empirically, SEMTECH EFM3)
- Air tightness of the adapter is important





# Testing equipment arrangement (partial flow)

- Only concentrations are measured in tailpipe, a fuel meter is inserted into the delivery system
- Mass of the pollutants is calculated from fuel-derived exhaust flow rates and concentrations
- Wrong direction of the sampling probe could result in high inaccuracy
- Fire risk & fuel quality matters

**Fuel flow meter**

**Dekati two-stage dilution**


**SEMTECH-DS**

**Dekati ELPI**

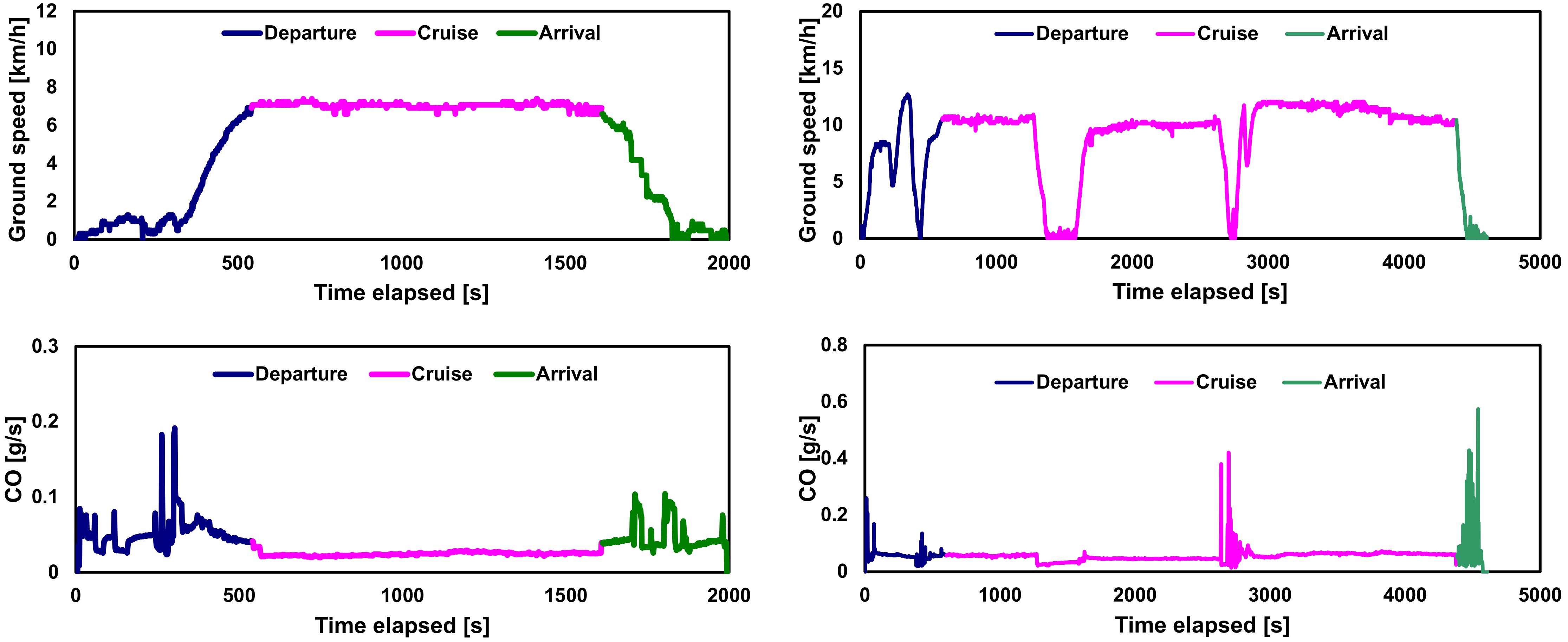
# Testing equipment arrangement (partial flow)

- Catching fire during testing may ruin everything, safety is always the priority

- Filters must be replaced timely to tackle with poor fuel quality (such as residual fuel)

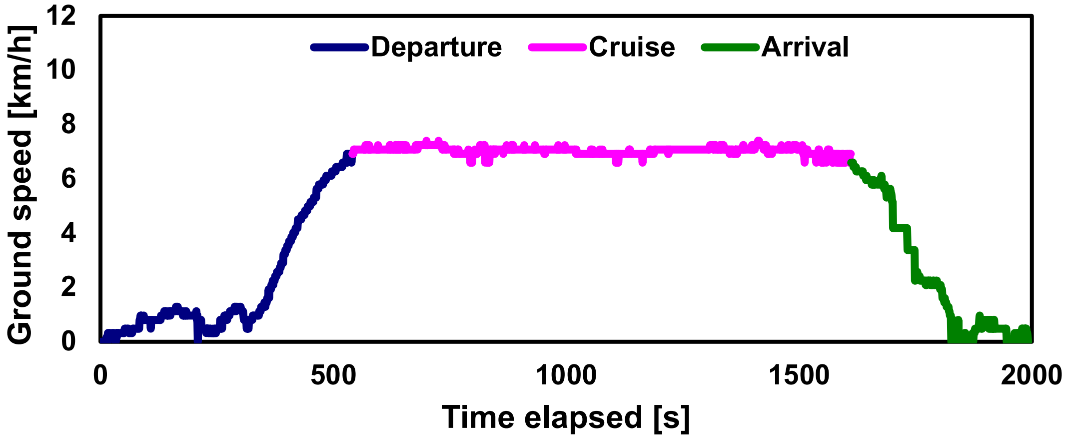
# Increased CO associated with transient conditions

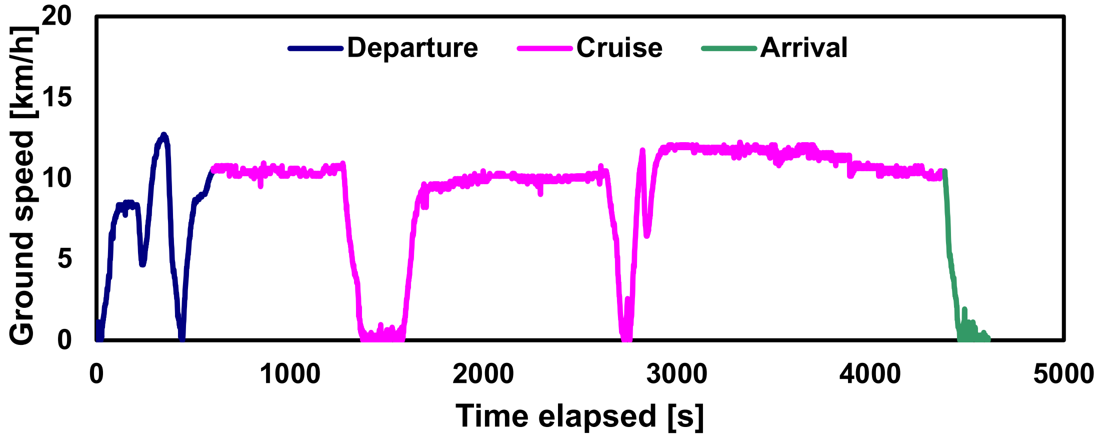
- CO emission was especially sensitive to some deceleration conditions (arrivals)
- Frequent “F-to-R” or “R-to-F” operations resulted in markedly increased CO concentrations

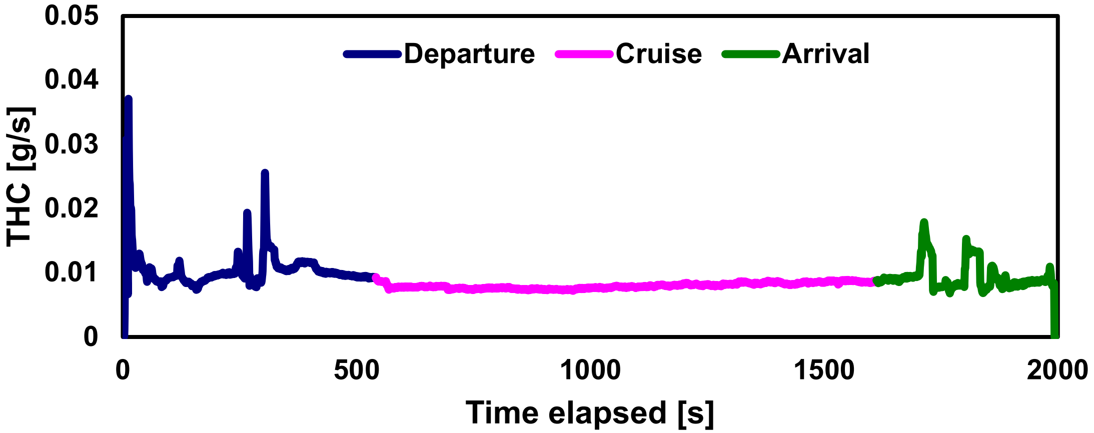


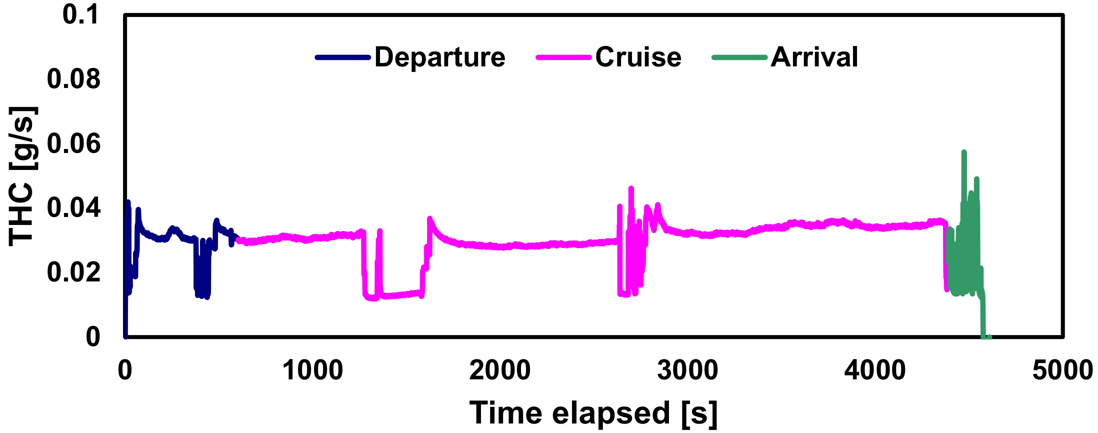
# Increased THC during maneuverings

- THC peaks were found during departures and arrivals, poor air-fuel mixing rendered high emissions
- THC emissions during cruise were somewhat engine-tech-dependent, and varied a lot from ship to ship



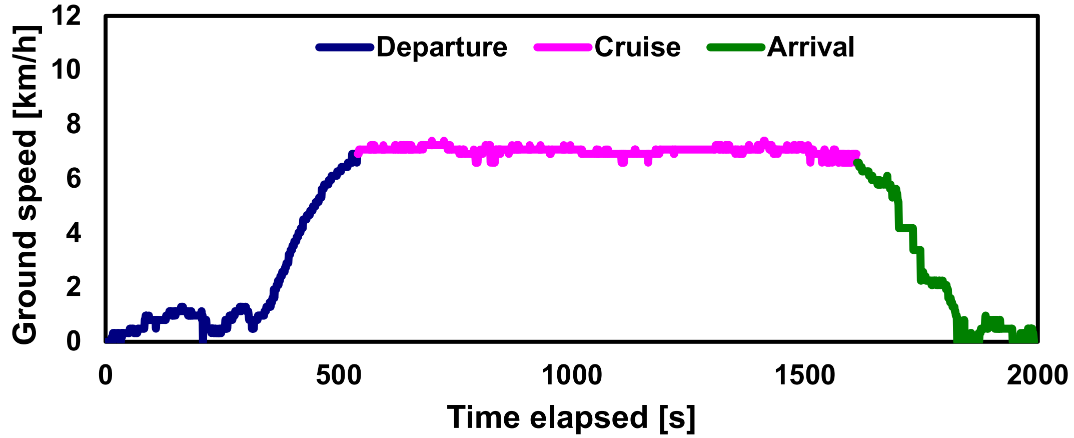



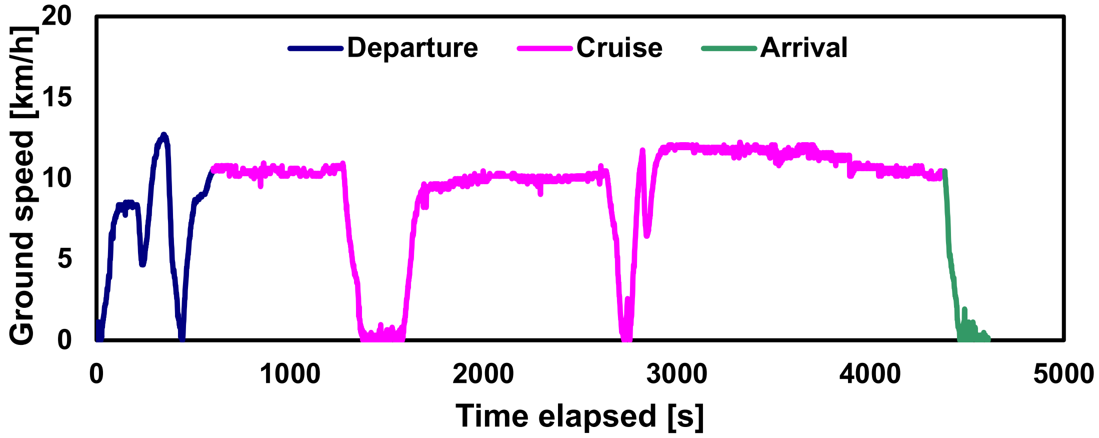



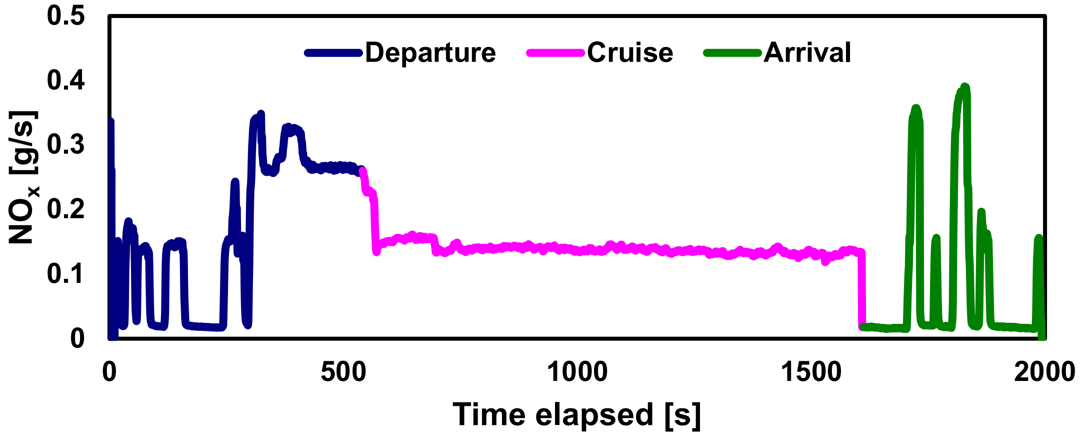



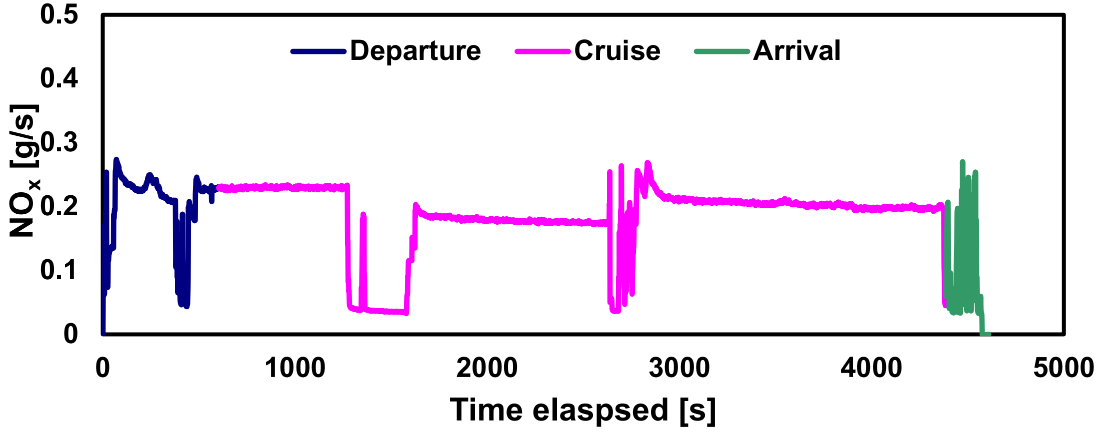
# High-level $NO_x$ emissions across trips

- On average, $NO_x$ emissions during cruise could approximately equal those within maneuverings
- Inland vessel engines had no control on $NO_x$, raw emission rates of $NO_x$ are even higher than CO



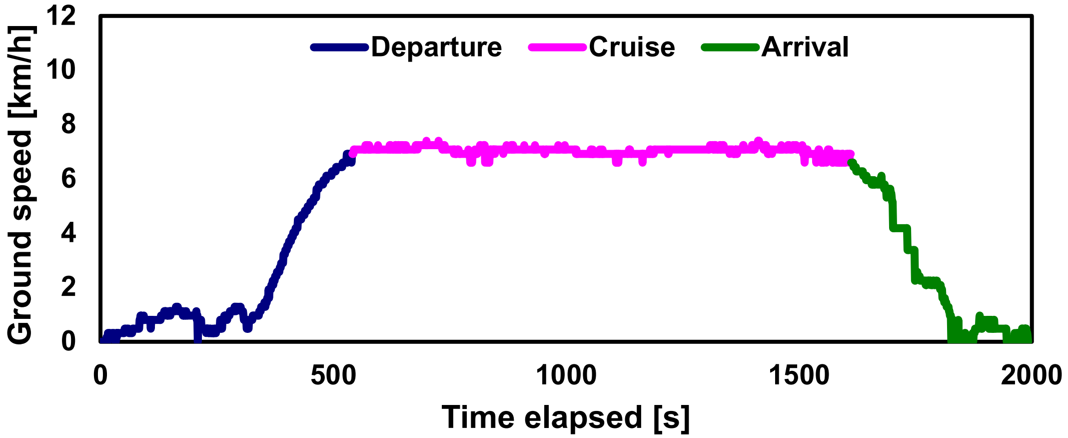



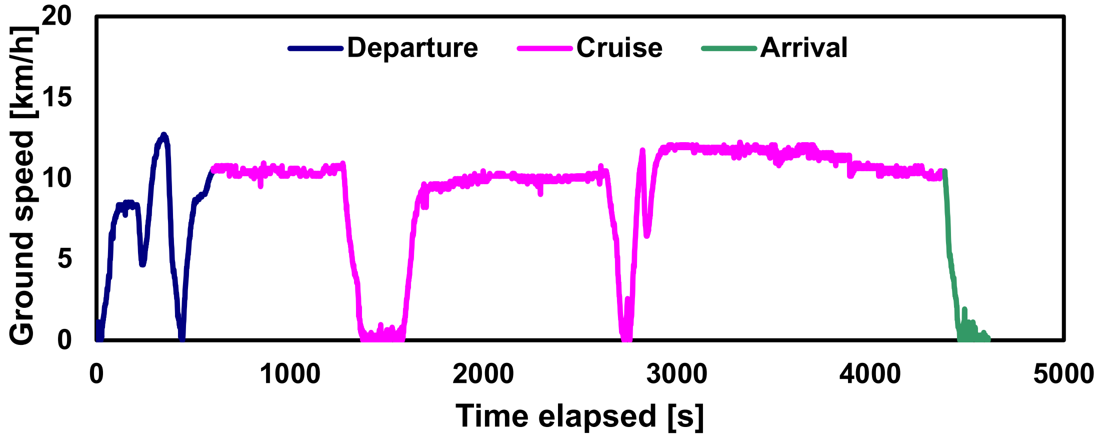



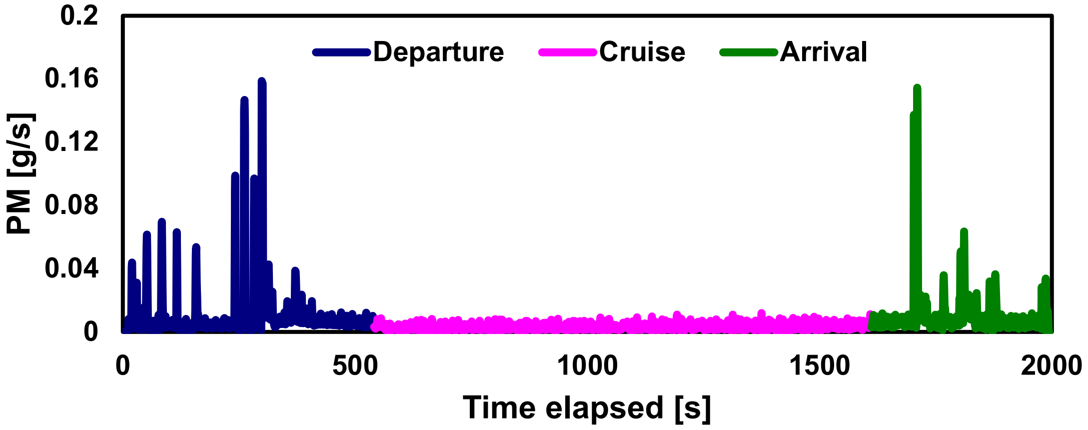



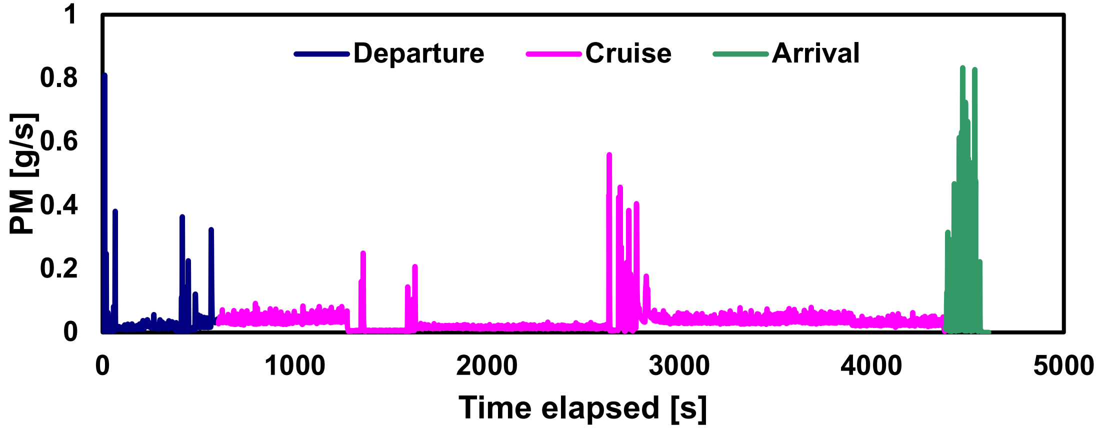
# High-level PM during maneuverings

- Increased PM emissions were noticed within maneuverings
- PM emissions were very sensitive to gear changing operations



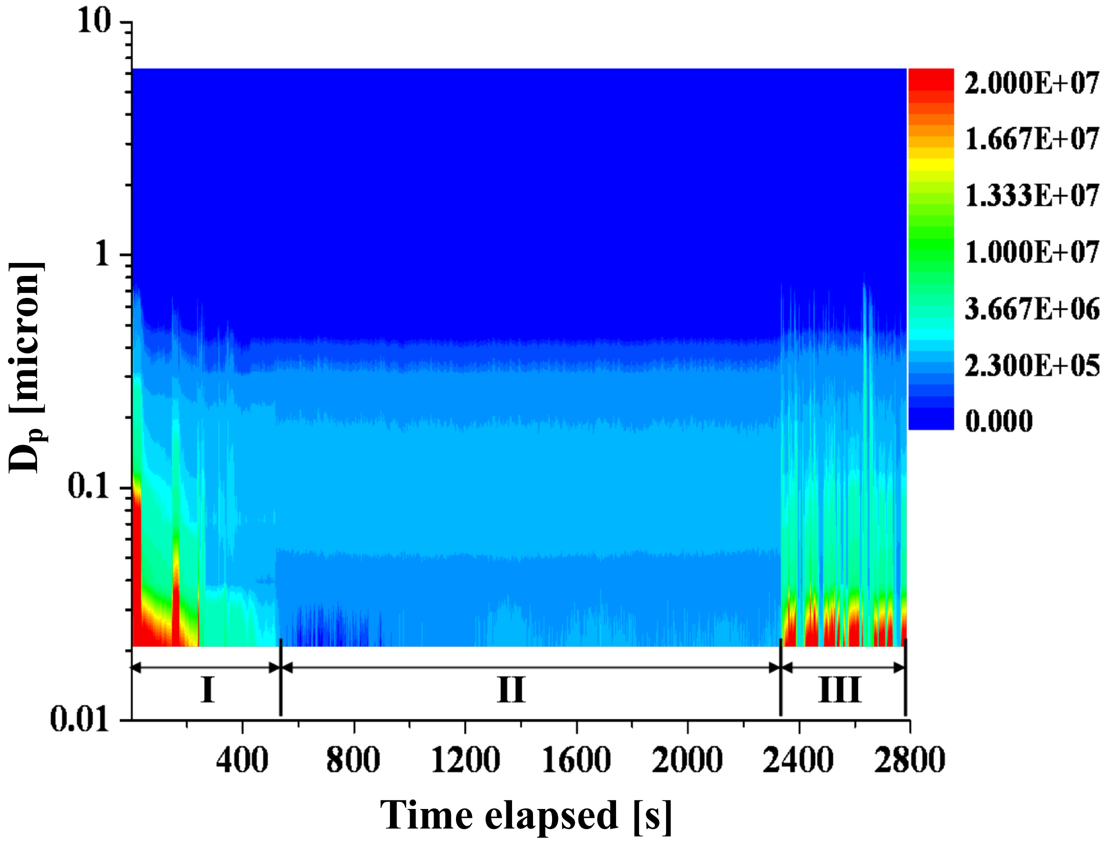



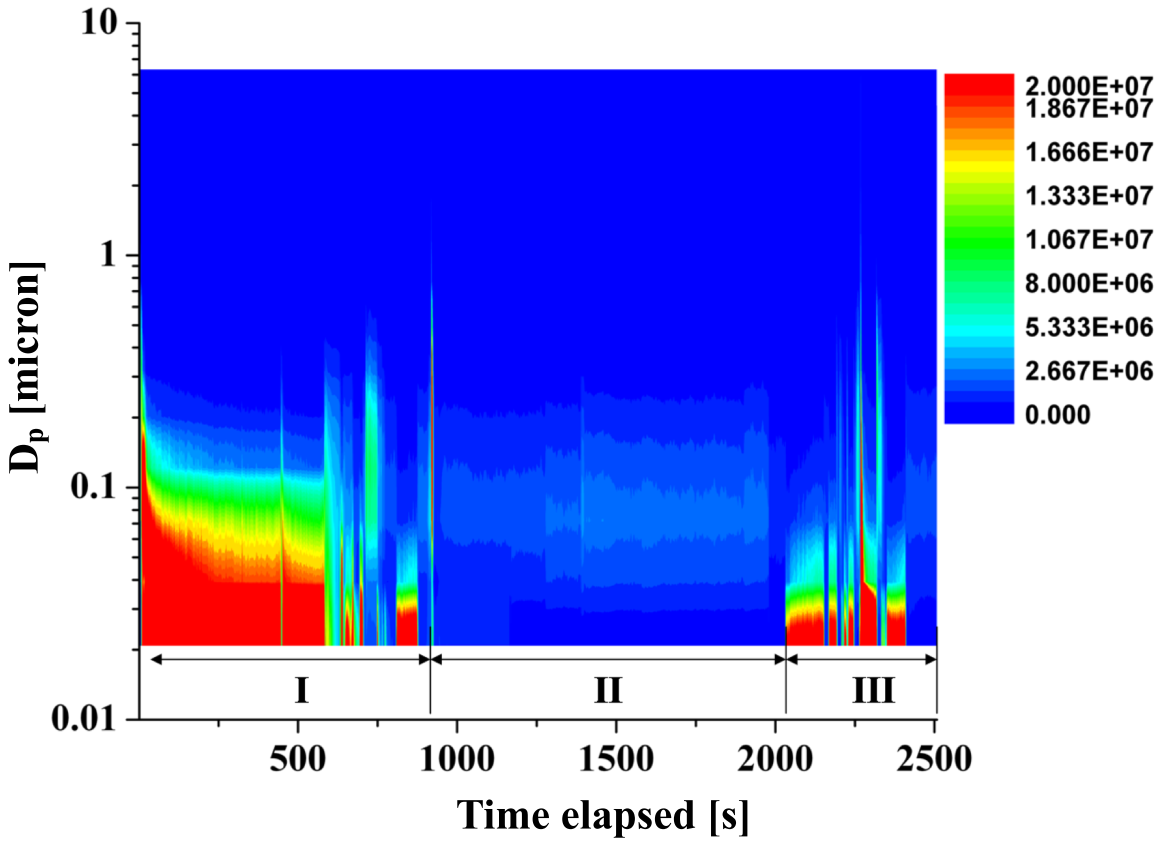



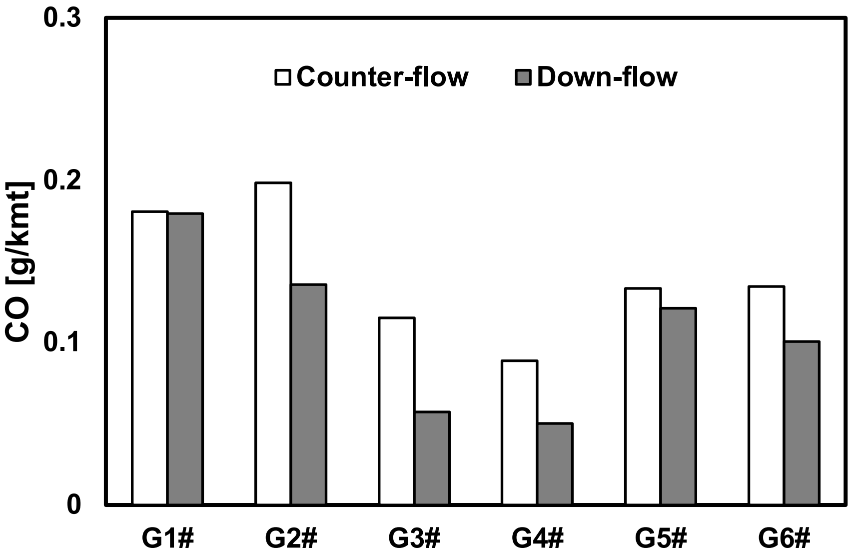
# Stronger ultrafine particle exposure near ports

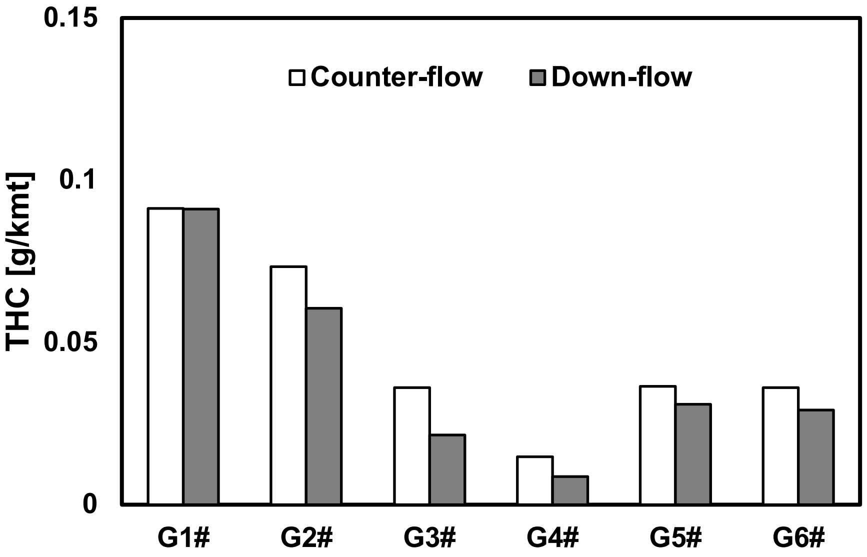
- High concentrations of ultrafine particles ($D_p$<100nm) were emitted during maneuverings, which created higher exposure risk for the citizens live or work near ports
- Compared to arrivals, ultrafine particle emissions were even stronger within departures

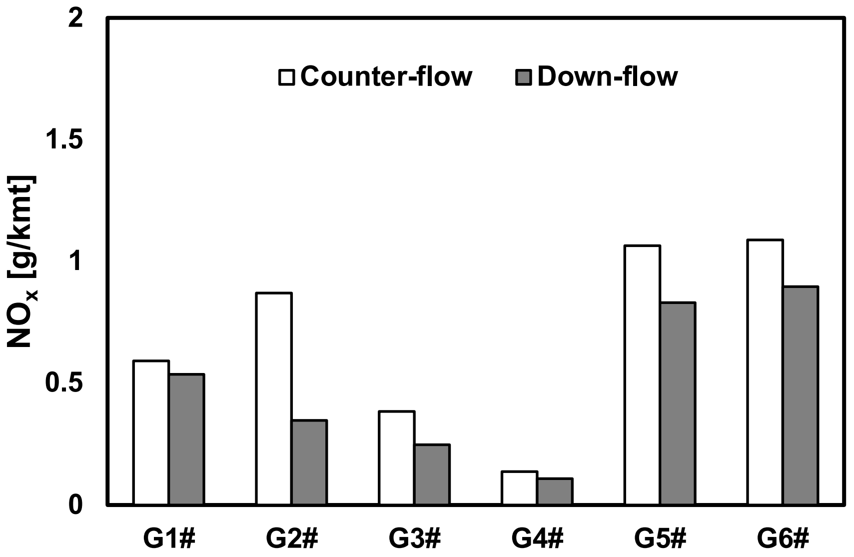


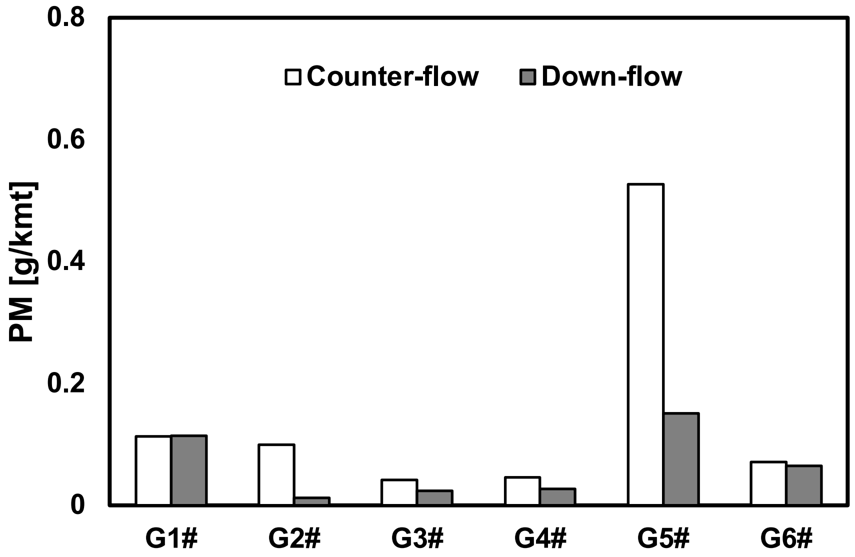



# Influence of flow direction




- Different flow directions can cause significantly different emission factors, even for the same vessel
- Influences of flow direction must be accounted when performing AIS-based modeling

# Inland vessels vs. in-use trucks

- China-III diesel trucks are being phased out by many metropolitans in China, the table below compared fuel-based emission factors of inland vessels to those of diesel trucks
- PM emissions emitted by an inland vessel equal **18.4 to 46.6 diesel trucks**

| | Operating condition | CO | THC | $NO_x$ | PM |
|---|---|---|---|---|---|
| Inland vessel | Departure | 23.97 | 5.37 | 80.26 | 11.31 |
| | Cruise | 23.99 | 5.68 | 89.25 | 9.59 |
| | Arrival | 46.60 | 8.73 | 74.00 | 24.21 |
| China-III diesel truck | | 10.00 | 2.10 | 51.00 | 0.52 |

# Conclusions and suggestions

- Vessels activities created high-level CO, THC, $NO_x$, and PM emissions, and could increase the forming potential of secondary ozone and ultrafine particle exposure level in near-port zones
- Counter-flow cruise could result in ~2X the emissions measured in down-flow direction, future emission inventories or AIS-aided modelling shall be aware of this impact
- From the perspective of PM reduction, inland vessels showed no advantage over modern HD trucks at all, cutting inland vessels PM emissions is essential and emergent
- Improved maneuvering organization at ports may help lower emissions during departures and arrivals, in particular arrivals
- Any possibility to make inland vessels partially electrified (considering serial hybrid)? Inland vessels usually use battery matrix instead of an auxiliary engine. Since vessels are not only workplaces but also homes for the owners, NG seems dangerous and occupies too much room

# Acknowledgement


- **Dr. Mingliang Fu**, Tsinghua University
- **Dr. Linxiao Yu**, Cummins
- **Dr. Jiadong Guo**, China National Heavy Duty Truck Group
- **Dr. Zihang Peng**, Delphi
- **Dr. Zhihua Liu**, Cummins
- **Mr. Zhenxian Xu**, Guangzhou Automobile Company
- **Mr. Chenlei Yu**, AVL List
- **Mr. Hongkun Liu**, China General Nuclear Power Corporation
- **Mr. Luqiang Li**, Shanghai Automobile Industry Company
- **Mr. Yao Zhang**, CRRC

# Thanks for your attention!

Dr. Xin Wang

National Laboratory of Automotive Performance & Emission Test, Beijing Institute of Technology

xin.wang@bit.edu.cn; wangxin0901@hotmail.com

86 (10) 6891 2035