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Summary report on applications and results in EU and China

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Executive Summary

Summary report on applications and results in EU and China

The EU CARES project and China MOST projects have both the objectives to further study and develop contactless emission monitoring technology, and to test them in real urban operations. The report details testing activities conducted by both projects, and includes the development of three remote sensing techniques, namely open-path, roadside point sampling and plume chasing.

Attainment of the Objectives and Explanation of Deviations

Description of work related to deliverables as given in DOW

CARES aimed to bring together leading experts in non-intrusive real-world vehicle emissions measurement from across the EU and China to reduce deployment barriers. In particular, the regular exchange with China would foster the exchange knowledge and experience between researchers, cities and national authorities in the EU and China.

Time deviation from original DoW

According to the 3rd amendment of the project agreement, the timeline of this deliverable was due on 31 January 2023. The 2 months delay were driven by the need to obtain most up to date information from all partners, including for those in China for which the work is still in progress.

Content deviation from original DoW

None.

1. Introduction of EU CARES project and China MOST project

Emissions of internal combustion vehicles are currently not properly monitored during their lifetime. In particular, NO_X and particulate matter (PM) emissions of a small share of poorly maintained or tampered vehicles are responsible for a large share of emissions[1]. Remote emission sensing (RES) is one potential method of screening in-use vehicles bringing along the potential capability of high emitter identification. Different RES concepts exist, such as open-path RES, extractive point sampling (PS), or plume chasing (PS). So far, validation studies are rare which compare these technologies, especially under real world conditions. In the frame of the EU H2020 project CARES (City Air Remote Emission Sensing - https://cares-project.eu/) a detailed validation study was conducted on test tracks and during the city measurement campaigns in Milan, Krakow and Prague, which compare and evaluate the different methods.[2] Since the H2020 call, to which the CARES project proposal was submitted, was entitled “InCo flagship on reduction of transport impact on air quality” (LC-MG-1-1-2018), and it was stressed in the call text that in line with the strategy for EU international cooperation in research and innovation (COM(2012)497), international cooperation was encouraged, in particular with China, contacts were made already in the proposal stage with Chinese researchers in the field. This resulted in a Chinese research project mirroring and running almost in parallel to CARES, briefly entitled the MOST project, since it was funded by the Ministry of Science and Technology in China. Also in the CARES proposal stage, contacts were made with the Hong Kong University of Science & Technology, which have a vast experience of research and applications in the remote emission sensing field, and they became international partners to the CARES project together with The Vehicle Emission Control Center of the Chinese Research Academy of Environmental Sciences (CRAES-VECC) and Tsinghua University.

CRAES-VECC is leading the MOST project. The MOST project aims to study the non-contact emission monitoring technology that does not affect the normal operation of vehicles for efficiently identifying high emitters. The research goals include: establishing a vertical multi-lane open-path RES and developing an inversion model for diesel vehicle emission RES data; building a plume chasing test system with high accuracy and robustness and a correction model applicable to the plume chasing data; developing a prototype of point sampling system for particulate matter measurement; developing multi-source data processing tools and carrying out demonstration and application programs Chinese cities. The research team includes CRAES-VECC, Tsinghua University, Beijing Institute of Technology, University of Science and Technology of China, Anhui Baolong Environmental Protection Technology Co., LTD, and Tsinghua-Solution Information Technology Co., LTD.

[1] Park, S. S., Kozawa, K., Fruin, S., Mara, S., Hsu, Y.K.,Jakober, C., Winer, A., and Herner, J. (2011) Emission Factors for High-Emitting Vehicles Based on On-Road Measurements of Individual Vehicle Exhaust with a Mobile Measurement Platform. Journal of the Air and Waste Management Association, 61:10, 1046-1056. https://doi.org/10.1080/10473289.2011.595981

[2] Farren et al. (2022) Measurement Technology Intercomparison and Evaluation https://cares-project.eu/measurement-tech-compare-d1-1/.

2. Applications in China and EU

2.1. Open-path remote sensing applications in EU

In Fall 2021, overhead open-path remote sensing technology from HEAT was used to measure vehicle exhaust emissions used in two locations in Milan, Italy. Over 35,000 emissions records were collected for NO, NO_2, HC, CO, CH_4, THC, PM relative to CO_2. In Winter 2022, OPUS's cross-road technology RSD5700 was used in Krakow, Poland, to collect over 100,000 measurements. The same technology was used in Fall 2022 in Prague and Brno, Czech Republic and collected over 100,000 records for NO, NO_2, HC, CO, THC, and PM relative to CO_2.

Figure 1 From left to right, overhead RES in Milan, cross-road RES in Krakow, cross-road RES in Prague.

2.2. Open-path remote sensing applications in China

In China, a total of 2,590 remote sensing stations have been established, connected to the national platform, and transferring data by the end of 2021[3]. In 2017, China created a national regulation for measuring emissions from diesel vehicles using remote sensing. It is the first national-level remote sensing regulation in the world. The standard applies to all diesel vehicles, including light-duty and heavy-duty vehicles. The regulation is a technical standard for test protocols with recommended limits for local agencies to follow if they currently have or decide to implement a remote sensing program. This standard limits PM emissions through opacity and Ringelmann blackness (see Table 1). For NO, the limit is only used for screening high-emitting vehicles that are then subject to further inspection. A vehicle is considered non-compliant if it exceeds the limit for the same pollutant in two or more consecutive remote-sensing tests within 6 months. In cities that are implementing remote sensing programs, vehicles that are found to be non-compliant with the opacity or Ringelmann blackness limits can be subject to a penalty and will be required to be repaired.[4]

Table 1: Remote-sensing emission limits for diesel vehicles in China

Pollutant	Limits
Opacity*	30%
Ringelmann blackness**	Level I (20%)
NO***	1,500 parts per million (ppm)

Notes:

[3] Ministry of Ecology and Environment. (2022). China mobile source environmental management annual report. https://www.mee.gov.cn/hjzl/sthjzk/ydyhjgl/202212/W020221207387013521948.pdf

[4] Yang, Liuhanzi, Yoann Bernard, and Tim Dallmann. "Technical Considerations for Choosing a Metric for Vehicle Remote-Sensing Regulations." Washington, D.C.: International Council on Clean Transportation, November 19, 2019. https://theicct.org/publication/technical-considerations-for-choosing-a-metric-for-vehicle-remote-sensing-regulations/.

*Opacity is measured by the absorption percentage of green light (wavelength range 550 nanometers – 570 nanometers) going through the exhaust plume.
**Ringelmann blackness is an indicator of smoke density that compares the darkness of smoke with the Ringelmann scale. It has five levels of density. The levels are inferred from a grid of black lines on a white surface that, if viewed from a distance, merge into known shades of grey. Smoke Level 0 is represented by white, and Level 5 is represented by all black. Levels 1 (20%) to 4 (80%) are represented by 10-millimeter (mm) square grids drawn with 1-mm, 2.3-mm, 3.7-mm, and 5.5-mm-wide lines. Vehicle smoke is videotaped to determine its Ringelmann blackness.
***NO limit is only used for screening high-emitting vehicles.

The remote sensing monitoring equipment designed for gasoline and diesel vehicles must deal with the vehicle fuel types separately. Different inversion calculation methods are used for the remote sensing measurement of the absolute concentrations of gaseous emissions of gasoline and diesel vehicles[5]. Due to the much residual air in the combustion process of diesel engines, the absolute concentrations of gaseous exhaust emissions from diesel vehicles must be calculated by the inversion calculation method based on the correction of excess air coefficient[6]. In the MOST project, the research team developed an inversion calculation method for diesel vehicles. To verify the accuracy of the method, the research team tested the exhaust emissions from 15 diesel vehicles from September to November 2020 using remote sensing system and portable emission measurement system (PEMS) synchronously in Chongqing, Chengdu and Yancheng. The instrument layout and test method are shown in Figure 2.

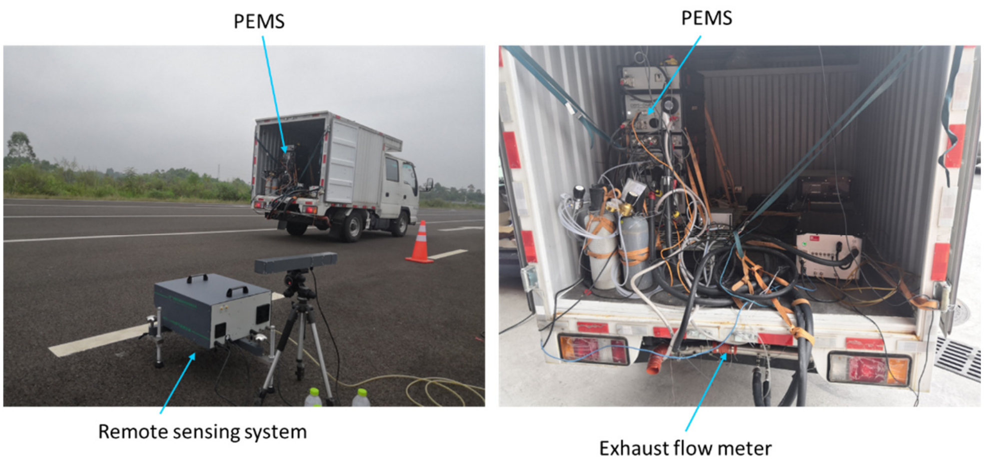

Figure 2 Measurement of diesel vehicle emissions by RSD and PEMS in China.

The experimental results show that the remote sensing results of tailpipe CO_2 emissions calculated by the inversion calculation method are very close to the PEMS tested results, which shows that the inversion calculation method for remote emission CO_2 results for diesel vehicles is correct and reasonable. However, there are discrepancies between the remote sensing NO data and the PEMS NO data. The differences between the RSD and PEMS data may be caused by instrument errors, environmental conditions, and data synchronization deviations. Despite the measurement errors, the errors of the remote sensing NO tailpipe emission concentrations are reduced from several times to a few percent or tens of percent compared with the result calculated based on engine theoretical air-fuel ratio mixture combustion.

In the first half of 2021, nearly 900,000 in-use diesel vehicle emission remote sensing data were collected from 60 remote sensing sites in Beijing to investigate the emission compliance status of in-use diesel vehicles in Beijing. Using the method developed by the research team, the proportion of high-emitting diesel vehicles (with NO emissions higher than 1,500 ppm) is 3.84% based on single

[5] Hao, L.; Yin, H.; Wang, J.; Tian, M.; Wang, X.; Ge, Y.; Bernard, Y.; Sjödin, Å. Research on Analysis Method of Remote Sensing Results of NO Emission from Diesel Vehicles. Atmosphere 2022, 13, 1100. https://doi.org/10.3390/atmos13071100

[6] Hao, L., Yin, H., Wang, J., Wang, X., Ge, Y., Remote sensing of NO emission from light-duty diesel vehicle, Atmospheric Environment (2020), 242,117799 :1-8. doi: https://doi.org/10.1016/j.atmosenv.2020.117799.

measurement[7]. The remote sensing emission limit for screening high-emitting vehicles can also be dynamically updated in real-time with the change of vehicle fleet composition, so as to screen high-emitting vehicles by remote sensing more effectively [8].

In the development of the remote sensing instrument, the research team has carried out optimization work in data matching logic, vehicle trigger algorithm rework, position mapping module and other aspects, improved the stability of the acquisition software, and the data acquisition effect has been improved. Furthermore, the research team has further optimized the design of the circuit board based on Tunable Diode Laser Absorption Spectroscopy (TDLAS) technology, the detection accuracy has been slightly improved, and the device actuator drive control system and software will continue to be improved in the future. The next step is to optimize the remote sensing inversion calculation method and the remote sensing instrument to improve the measurement accuracy.

2.3. Roadside point sampling applications in the EU

In September 2021 in Milan, Italy, a newly developed point sampling (PS) remote emission sensing system was co-located alongside a commercial open-path RES system (EDAR, Hager Environmental & Atmospheric Technologies (HEAT)) during a period of eight days. Emission factors (EF) for several thousands of vehicles were derived using both systems. The PS system features the determination of black carbon (BC), particle number (PN) concentration and NO_X EFs with high-grade equipment, such as a newly developed black carbon tracker, a custom-developed diffusion charger[9]and an iterative cavity-enhanced differential optical absorption spectroscopy ICAD (Airyx GmbH). In addition to the co-location, validation measurements with portable emission measurement systems (PEMS) were conducted to get more insight into the performance of the RES methods. More than 100 test drives were performed with several test vehicles equipped with PEMS.

A good agreement was found for the average NO_X emissions of the overall measured fleet between PS and HEAT with mean values of 4.63 and 4.44 g/kg fuel (median: 1.11 and 1.04 g/kg fuel), respectively (Figure 3). In the case of PM emissions, BC EFs from PS and PM EFs from HEAT were compared. Similar average values (115.46 and 85.77 mg/kg fuel) were determined. In contrast, median values (16.25 and 0.46 mg/kg fuel) show a high deviation between the two systems with a factor of 35. A more detailed view of individual measurements was performed with PEMS test drives. In the case of NO_X, mean and median EFs determined by PS and HEAT agree well with the PEMS result. Looking at the comparison with PEMS, the PS system delivers a better precision for individual measurements compared to the HEAT system (Figure 3). For PN, a high correlation (R^2 = 0.8, excluding outliers) between PEMS and PS EFs was found (with median values of 0.09 and 0.10 10^{15} particles/kg fuel). The outcome of the investigations provides more insight into the capabilities of the different systems for real-world emission screening and the potential identification of high emitters.

[7] Ren, X.; Jiang, N.; Li, Y.; Lu, W.; Zhao, Z.; Hao, L. Application of Remote Sensing Methodology for Vehicle Emission Inspection. Atmosphere 2022, 13, 1862. https:// doi.org/10.3390/atmos13111862

[8] Lijun Hao，Hang Yin, Junfang Wang, Xiaohu Wang, Yunshan Ge. Potential of big data approach for remote sensing of vehicle exhaust emissions. Scientific Reports 11, 5472 (2021)：1-10. https://doi.org/10.1038/s41598-021-84890-7

[9] Schriefl, M.A., Nishida, R.T., Knoll, M., Boies, A.M., Bergmann, A. *Characterization of particle number counters based on pulsed-mode diffusion charging.* Aerosol Science and Technology. 2020

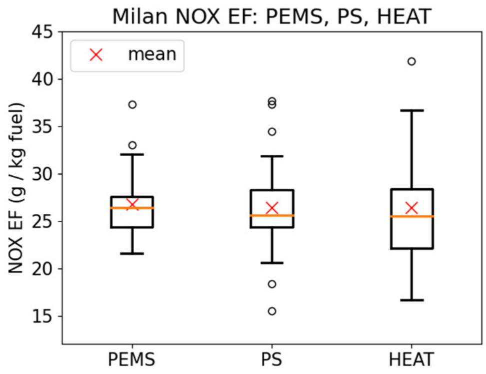

Figure 3 Boxplot of determined NO_X EFs of the PEMS equipped test vehicles and the two RES systems (PS, HEAT).

2.4. Roadside micro-station applications in China

The MOST research team conducted roadside measurements in Chongqing and Yancheng in 2020, and in Beijing in 2021 and 2022. In total, 20 vehicles were tested using PEMS, remote sensing, plume chasing, and a roadside micro-station (Figure 4).

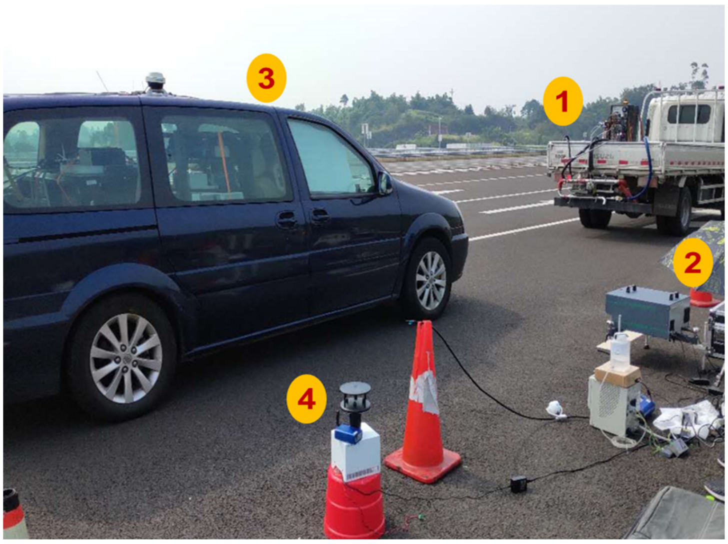

Figure 4 Roadside micro station measurements (marked as 4) in Yancheng, 2020 (1: PEMS, 2: Remote sensing, 3:Plume chasing, 4:Roadside micro station)

The MOST research team developed a compact, cost-effective sensor platform that can successfully measure CO_2, PN, and NO concentrations[10]. By considering both NO and PN emission factors, diesel trucks with failed or outdated after-treatment systems were successfully identified as potential high emitters. The NO emission factors obtained by the sensor platform were consistent with that measured by a benchmark PEMS. These results demonstrate the feasibility of a sensor-based system for high-emitter identification. The proposed sensor platform has greater potential for establishing low-cost

[10] Shen, Y.; Q. Zhang; D. Wang; M. Tian; Q. Yu; J. Wang; H. Yin; S. Zhang; J. Hao; J. Jiang*, Evaluation of a cost-effective roadside sensor platform for identifying high emitters, Science of The Total Environment, 2022, 816: 151609

roadside measurement networks for supporting regulatory protocols for screening high-emitters on public roads. Although this technology is suitable for identifying high-emitters when a single vehicle passes by, the key challenge remains on how to identify high-emitters from multiple drive lanes or multiple vehicles. Hence, the application of this method needs to be examined and potentially improved in these scenarios.

The research team at Hong Kong University of Science and Technology led by Prof. Ning Zhi developed a high-density roadside sensor network focusing on a) single-vehicle Emission Factors (EF) determination and b) fleet emission source apportionment (Figure 5).

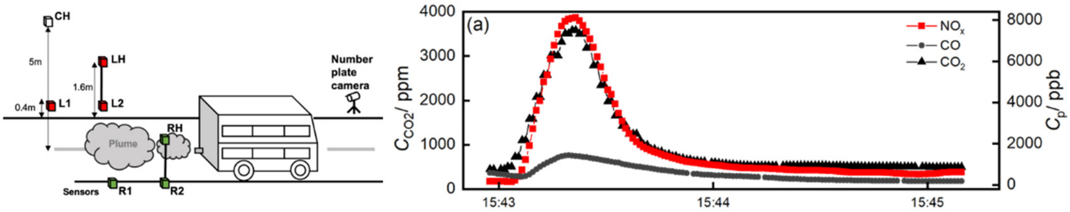

Figure 5 Left: Schematic of the sensor network setup. Right: an example of a typical plume

During the project period, four campaigns were conducted from Dec. 2020 to Jan. 2023 in Hong Kong along the roadside of Causeway Bay, Hung Hom, Kwai Chung, and Sai Kung to evaluate the effectiveness of the deployment of a multi-sensor network. Test sites includes street canyons, rural areas, trunk roads in the downtown area, and suburban (Figure 6). Pollutants such as NOx, CO, and CO_2 were monitored in the campaigns. More than 20 hours of data were collected at each site between 9 am and 9 pm, covering vehicle fleets of 1,000 to 10,000 per day. The research team has developed novel algorithms for plume data[11]. The real-world NOx and CO emissions factors of individual vehicles and fleets were estimated at each site.

Figure 6 Four monitoring sites in Hong Kong.

There were several key findings from the analysis[12]:

- Kerbside NOx and CO concentrations are skewed, with high concentrations representing plume segments from a larger number of vehicles. The roadside concentration of NOx related to bus frequency, and Euro 4 or lower-emission standard vehicles for CO in a street canyon in Causeway Bay.

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[11] Brimblecombe, P., Chu, M. Y., Liu, C. H., & Ning, Z. (2021). NO_X and CO fluctuations in a busy street canyon. *Environments*, 8(12), 137.
Chu, M., Brimblecombe, P., Wei, P., Liu, C. H., Du, X., Sun, Y., & Ning, Z. (2022). Kerbside NO_X and CO concentrations and emission factors of vehicles on a busy road. *Atmospheric Environment*, 271, 118878.
Wei, P., Brimblecombe, P., Yang, F., Anand, A., Xing, Y., Sun, L., & Ning, Z. (2021). Determination of local traffic emission and non-local background source contribution to on-road air pollution using fixed-route mobile air sensor network. *Environmental Pollution*, *290*, 118055.

[12] Chu, M., Brimblecombe, P., Wei, P., Liu, C. H., Du, X., Sun, Y., & Ning, Z. (2022). Kerbside NO_X and CO concentrations and emission factors of vehicles on a busy road. *Atmospheric Environment*, 271, 118878.

- The average EFs for each minute of traffic were determined from the pollutant concentration ratio with ΔCO_2. The 1-minute mean EF_{NOx} 7.55 g kg^{-1} and EF_{CO} 12.6 g kg^{-1} are typical for the fleet dominated by buses, but highly skewed (Weibull shape parameter ~0.44).
- Individual vehicle EFs were determined from peaks in NOx, CO and CO_2 and number plates. Leading and trailing parts of the plume segments gave similar EFs (R^2>0.95), suggesting this method was reasonably robust across the vehicle passage. Nevertheless, these EFs were also skewed, but the shape parameter was ~0.44. EF_{NOX} for vehicle classes was buses>freight vehicles>private cars>vans>taxis and diesel>petrol>LPG.
- Differences were more challenging to assess with CO, but LPG vehicles had the highest CO EFs.

The technique could be extended to other pollutants such as BC or toxic organic substances. The current and future campaign includes more pollutants including PM, VOC, and N_2O. The research team plans to conduct future studies to cover a larger number of vehicles and more locations to allow for achieving a more robust analysis, and the site-specific measurement will offer a chance to investigate the impact of roadway conditions on real-world vehicle emissions.

2.5. Plume chasing applications in EU

Plume Chasing (PC) is a remote emission sensing technique that uses a measurement vehicle equipped with different instruments to chase the emission plume of investigated vehicles. The PC method allows to sample a given vehicle for minutes and is therefore well suitable for high emitter identification[13].

Currently, it has been mainly applied for the detection of high NOx emitters in Europe. The PC technology and the deployment potential of PC has been substantially further developed in the framework of the CARES project. The instrument software has been enhanced so that the police or roadside vehicle inspection staff can easily operate the system. The project included test studies to optimize and validate the PC method in terms of hardware and data analysis algorithms. As one part of this study particle instruments are compared for their usage in PC and the potential of high emitter identification. This enhanced plume chasing technique has been developed as part of the first work package of the CARES project.

During a two weeks measurement campaign in the Czech Republic (12.09.-24.09.22) 1,835 vehicles were measured with PC and several particle instruments were evaluated for their applicability in PC. Several particle metrics exist, where especially particle number concentration (PN) and black carbon (BC) are of particular interest. PN is from increasing interest nowadays due to the introduced emission limits from Euro5b and newer standards for light-duty vehicles and Euro VI for heavy-duty vehicles.

[13] Pöhler, D. (2021) Heavy Duty Vehicle (HDV) NOx emission measurement with mobile remote sensing (Plume Chasing) and subsequent inspection of high emitters, Final Report.

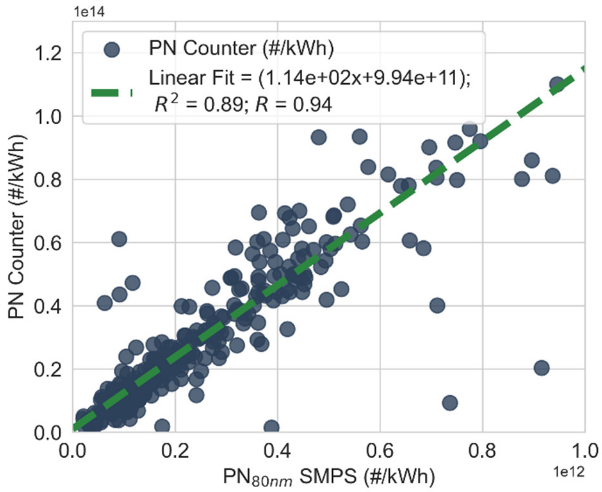

Figure 7 Particle number measured by AVL DiTest Counter versus SMPS (80nm) for 327 HDVs.

In the CARES campaign in the Czech Republic, two diffusion chargers (particle counter, TEN AEM; counter, AVL DiTest) for measuring PN and one instrument (Black Carbon Tracker (BCT), TUG) for measuring BC were compared. The researchers used as reference instrument an SMPS (Electrostatic Classifier 3082 and TSI 3775 CPC) measuring 80 nm particles which showed very good performance in detecting a DPF-tampered vehicle in a validation study of the CARES project[14]. All instruments were installed in a measurement vehicle from TNO (Utrecht, Netherlands).

The AVL DiTest counter showed a very good correlation (R^2=0.94) with the SMPS (see Figure 7). A good agreement could also be found for the BCT (R^2=0.71). The performance of the TEN AEM particle counter could be improved to a previous campaign. Nevertheless, it still has a significantly higher, likely false positive, identification of high particle emitters compared to the SMPS. This evaluation shows the applicability of the individual instruments for their usage in PC and shows the great potential of high particle emitter identification with the PC method.

2.6. Plume chasing applications in China

The MOST research team carried out plume chasing and PEMS concurrent tests for seven China V/VI diesel and natural gas trucks (564 plume-specific tests) in Chongqing and Yancheng in 2021 (see Figure 8). A large-size plume chasing campaign (one thousand vehicles) was carried out in Chengdu from September to October 2021.

[14] Farren, N. et al (2022) *D1.1 – Measurement technology intercomparison and evaluation*, Public Report, CARES Project.

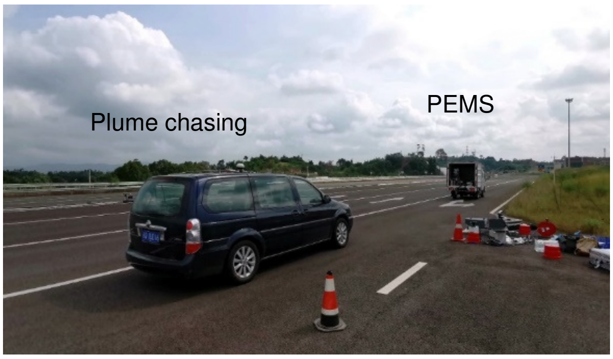

Figure 8 The picture of concurrent plume chasing and the PEMS test

Based on comparative plume chasing and PEMS tests on a restricted driving track, a relationship that links the accuracy of NOx emission factors (EFs) calculated from chasing measurements to meteorological variables was quantitatively evaluated[15]. An “effective ratio” concept is a function of meteorological variables in the vehicle wake based on the momentum wake theory. The results showed that the relative errors of chasing EFs were positively correlated to the effective ratios. The effective ratio could be a good parameter to identify erroneous chasing measurements and improve the accuracy of chasing EF.

A comparative plume chasing and PEMS test by defeating the control devices were designed on a test track to determine the suitable thresholds for high-emitters identification using the plume chasing tests. Significant differences were identified by plume chasing between normal and failure vehicles. Then reasonable NOx thresholds of high-emitters due to the inactivation of after-treatment devices were proposed based on the diagnostic method (10.4 g/kWh for China V and 2.67 g/kWh for China VI trucks) and the corresponding high-emitters recognition efficiency exceeds 97%. These determined thresholds used for identifying NO_X high-emitting trucks will be further verified in large-scale real-world tests.

Large-size plume chasing campaigns were launched in Chengdu, China, and one thousand tests of NO_X and BC emissions for trucks were collected. The results indicate that fleet-average NO_X and BC EFs have both substantially improved in line with the strengthening of the emissions limits (e.g., from China III to China VI). Of note, the tightening of supervision since 2018 has achieved significant benefits in improving China V NO_X EFs levels. HDTs manufactured in 2018 and 2019 could reduce NO_X EFs by 11% and 30%, respectively, compared with the earlier China V HDTs. Furthermore, the NO_X EFs of advanced China VI trucks are reduced by 68% compared with that of China V truck fleets.

The identified thresholds of high-emitting trucks obtained in the test track using plume chasing tests are critical for the rapid identification and supervision of high-emitters. However, the reliability of high-emitters identification thresholds applied for on-road trucks needs to be further verified. The research team plans to conduct a demonstration program of in-use high-emitter monitoring in Tangshan, China. Then the real-world thresholds for after-treatment failure vehicle identification will be determined.

[15] Xiang S., Zhang S., Yu Y. T., et al. Evaluation of the Relationship between Meteorological Variables and NOx Emission Factors Based on Plume-Chasing Measurements. ACS ES&T Engineering, 2023.

3 Conclusions and next steps

The city demonstration in Europe was the occasion to test the various contactless techniques and methods to measure vehicle emissions in real urban situations. However, due to the pandemic, the city demonstration campaign in China is expected to take place in Summer 2023. The comparison between the EU and China projects shows similarities in methods, all using a mix of light-based remote sensing systems, road-side point sampling, and plume chasing. Future collaboration between China and EU could focus on an intercomparison of instrument performance and an evaluation of the costs to deploy these solutions.