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Summary

This deliverable summarizes the procedures and threshold values for high-emitter detection using the cross-road and top-down remote emission sensing instruments as well as plume chasing and point sampling techniques that have been developed over the course of the CARES project.

Their effectiveness in real-world applications has been demonstrated by exemplary roadside inspections. However, more systematic measurements are needed to fine tune these thresholds and adapt to different driving conditions, vehicle categories and requirements for true positive rates. With the foundations presented here such measurements are straightforward – and should be conducted beyond the end of the CARES project.

Attainment of the objectives and explanation of deviations

Description of work related to deliverable as given in the DoW

This deliverable summarizes the procedures and threshold values for high-emitter detection using the cross-road and top-down remote emission sensing instruments as well as plume chasing and point sampling techniques that have been developed over the course of the CARES project. Importantly, experiences from field measurements conducted in September 2022 were integrated here. During the campaign in and around Prague extra road-side inspections could be conducted which had not been originally planned in the CARES project. These inspections have however been crucial to demonstrate the usefulness of the approach in real-world conditions.

Time deviation from original DoW

The original plan was to deliver in month 33. However, the pandemic greatly postponed the experimental work; notably the campaign in Prague was postponed to September 2022. In accordance with the partners, we therefore also postponed this deliverable.

Content deviation from original DoW

Beyond the original planning not only the experiences from the characterization experiments on the test track but also from on-road measurements with additional road-side inspection could be integrated. This proved crucial for testing and refining the initial approach and confirmed the thresholds used.

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Introduction

Frequently cited anecdotal evidence suggests that “a small number of vehicles contributes a disproportionately large amount of pollutants to a fleet’s total emissions” (Zhang et al. 1995; Pokharel et al. 2003; Smit and Bluett 2011; Buhigas, Fleire, and De la Fuente 2021). These so-called ‘high-emitters’ are then suggested as attractive targets for corrective actions: The repair or elimination of a potentially small number of vehicles might result in a substantial reduction of pollutant emissions. The resources for in-use surveillance of the fleet should be directed to these few vehicles instead of periodically checking large numbers of vehicles with correctly working exhaust emission controls. In this understanding such high-emitting vehicles are rare and not representative, and their emissions are typically not included in standard emission inventories used for air quality management.

However, a rigorous definition of a high-emitting vehicle has so far been elusive. Partly that is due to difficulties in finding and investigating such vehicles with the conventional measurement techniques that have been used so far like free acceleration tests or PEMS tests, partly because of a lack of pass/fail criteria in the legislation. Furthermore, all these tests interact with the vehicle operator and/or the vehicle’s control unit, which both would allow switches to sidestep the test. Both issues are intertwined and hamper each other. Therefore, the various forms of remote sensing measurements appear particularly useful for such investigations as they measure without contact while the vehicle is passing by, i.e., in real traffic conditions, and they allow sampling large numbers of vehicles.

Objectives and scope of this report

This report **summarizes the lessons learned over the course of the CARES project for all three RES techniques, cross-road and top-down Remote Sensing, for plume chasing and point sampling techniques**; all have progressed significantly over the course of the CARES project

Current testing regimes for emissions from road vehicles in the European Union

Exhaust emissions standards for road vehicles have been gradually tightened for the past decades (Delphi Inc. 2020; 2018). There are several intertwined regimes in the legislation of the European Union. Thanks to coordination among the UNECE partner states the same regulations have been adopted in most other European countries with individual modifications notably as concerns the introduction dates of the various so-called Euro norms. The most stringent requirements are set in the type-approval process for new vehicles, typically tested on individual vehicles taken from the production line. That these sample vehicles are representative is checked with the Conformity of Production (CoP) tests: Vehicles are checked at or near the factory if they comply with the standard based on typical quality control procedures. Both tests address new vehicles.

Manufacturers also must guarantee the in-use durability of the emission performance. This is regulated with In-Service Conformity (ISC) procedures stipulating the accepted maximal deterioration, provided the vehicles are properly maintained. For passenger cars certified to the Euro 4 emission standard, for instance, the constraints apply for up to 100,000 km or 5 years, while the guarantee period extends to 160,000 km for Euro 5 and Euro 6 certifications (Delphi Inc. 2020). The ISC is considered ‘failed’ if 12 out of 20 tested vehicles fail. In other words, there is no ‘in-service conformity’ for individual vehicles but only a statistical threshold for a vehicle family.

Lastly, the Periodic Technical Inspection (PTI) has still weaker threshold values but applies to vehicles beyond their in-service guarantee period. However, so far PTI tests have not been required for NOx emissions for any types of vehicles.

For heavy-duty vehicles road-side inspection is focused on safety issues and contains only the most rudimentary principles of emission testing. However, the police, is authorised to check for emission tampering, even if this has not been done systematically. Typically, the police have checked for tampering of the SCR system that leads to a substantial increase in NO_x emissions.

The PTI and regular dealership servicing is known not to detect serious malfunctions and tampering of vehicles. In cases that the lambda sensor has drifted, and petrol cars emit more than ten times the NO_x emissions, both the PTI and the servicing did not detect the problem (Hooftman, N. 2019). Generally, detecting high NOx emission in a stationary PTI test is difficult because vehicle may have a different emission control strategy in these conditions than in normal operation.

The decades old smoke opacity and two-speed idle tests, while useful to detect many engine problems, have several shortcomings: The low sensitivity of the smoke opacity method to small particles (most of the particles are of diameters in tens of nm range, more than one order of magnitude smaller than the wavelength of visible light) is not suitable to detect minor damage (leaks, cracks) of diesel particle filters (DPF), and in some cases, not even to detect absence of the DPF. Simple stationary tests do not allow for testing of the engine under a realistic load, required for testing of NOx reduction capability of three-way catalysts on positive ignition engines operated at stoichiometric air-fuel ratio and of NOx reduction catalysts – SCR (selective catalytic reduction) and NOx storage and reduction catalysts – used on diesel engines and other engines running considerably lean of stoichiometric.

As a malfunction leading to high emissions is not always readily detected by the driver, a high-emitter may be operated for a considerable length of time before being detected. Further, in many regions of Europe, some vehicle operators circumvent the periodic inspection by various means[1]. In some cases, the periodic inspections themselves are tampered with by the inspection technicians by various means, with the motivation to obtain a passing result on a vehicle that would fail a properly performed periodic test.

Consequently, periodic inspections have in most European countries so far only had limited effectiveness in controlling actual on-road emission and finding vehicles with improper emission control, either because of low testing rates, ineffective testing protocols, or because the tests performed (e.g., idle or free acceleration) are not representative for on-road driving emissions, or absent standards. Thus, there are only few cases where a legally binding emission standard and testing protocol is useful for identifying high-emitting vehicles in the European Union.

The more promising approaches stem from research applications discussed below. However, those methods have so far either not been mature enough or not been recognised as legally binding test methods. Therefore, the following characterisations of high-emitting vehicles are operational definitions without legal binding; the definition is typically related to a certain measurement method. Whether the high emission rate can be reduced by e.g., better maintenance and/or repair, or more robust design in the first place, is outside the considerations here.

Evidence for high-emitters

It is assumed that all vehicles that have been sold in the European Union have initially, when new, complied with the exhaust emission legislation in force at the time. Excessive emissions above what is expected from the emission testing, for comparable driving and boundary conditions considered 'normal use', are then considered high. There has been compelling evidence for such cases of high-emitting vehicles in Europe:

- Manufacturers have optimised the performance of the exhaust emission controls to the narrower conditions of the type approval testing protocol. In on-road driving average emissions can then be higher because the driving condition is outside the narrower range of conditions tested. This has been notorious for type approval against the New European Driving Cycle, i.e., up to Euro 6b emission standard. With the introduction of an on-road real-driving tests from Euro 6d-TEMP onwards the range of tested operating conditions has been expanded significantly. When emissions are found high at driving conditions outside the prescribed driving range of the homologation test it is a matter of judgement if such a vehicle is to be considered a high-emitter.
- In other cases, manufacturers have equipped their vehicles with defeat devices that reduce an effective emission control outside the test conditions. This has been found for many manufacturers of diesel cars leading to high on-road NOx emissions (EP 2017).
- In other cases, operators or drivers have equipped their vehicles with a defeat device, reducing the effectiveness of the exhaust emission controls. This has been found in heavy-duty vehicles circumventing the urea injection for the SCR catalyst and deactivating the monitoring of the associated OBD system (see for instance Pöhler & Engel 2019, Pöhler 2020).
- Excessively high emissions might result from the removal or deactivation of the diesel particle filter or of the three-way catalyst. This has usually been individual cases related to individual drivers, not to a whole fleet operated.
- Lastly, wear and accidental break of components relevant for the emission control can result in high emissions. For particle emissions the deterioration of particle filters has the greatest impact on increasing emissions from in-use vehicles.

[1] For example, running the vehicle at high speeds or engine demands, either on the road or a rolling road, so all emission controls are extremely "hot", then promptly returned for testing when substrates in particle filters expanded to fill cracks. Such 'advice' on how to prepare for an emissions test is readily available at free internet sites. In addition, modifications of the vehicle might be removed so that the vehicle is returned into a 'road legal' condition solely for the inspection.

- The period technical inspection is designed to detect cases where the three-way catalyst is not working properly, but PTI is not robust enough to detect deteriorated particle filters.

Typically, remote observations can only observe the occurrence of high emissions and at best provide clues as to the cause (see next chapter). The ascertainment will additionally require an individual inspection of the vehicle under question. However, authorities could employ remote measurement techniques to screen the fleet and to identify vehicles with suspiciously high emissions for follow-up inspections (Borken-Kleefeld and Dallmann 2018).

Furthermore, records of single emission events may be meaningless; there is consensus that emission measurements need to encompass different driving conditions before there can be any judgement drawn on the general emission behaviour. It is however subject to debate and objective of the CARES project to determine how many records, time or driving conditions are needed for a robust judgement on the general emission performance of a vehicle. There is merit to establish the distribution of (high) emissions in the fleet before setting a threshold value to determine which vehicle has (on average) unacceptably high emissions or not. This will help with a more accurate assessment of both the impact on air pollution and the benefits of high-emitter removal.

Causes and characteristics of high-emitting behaviour

As previously mentioned, remote measurements also provide clues on the cause of high emissions:

- If a similar emission behaviour is observed in a large fraction of vehicles of a certain manufacturer or a certain vehicle model, it is likely that this is an OEM related issue.
- If a suspicious emission behaviour occurs predominantly after a certain age (or mileage) this is a strong indication for a problem related to degradation or durability of the emission control equipment.
- If several vehicles with suspicious emission behaviour can be traced back to a common operator or workshop this might indicate a problem with a fleet.
- If none of the above, then it might be an individual vehicle's issue.

There are different forms of high-emitting behaviour. A vehicle might emit a high rate for one or more pollutants

- permanently, i.e., for a long time and under normal driving conditions, in excess of some reasonable reference value.
- temporarily in excess of some reasonable reference value, e.g., only at certain times or during certain operating conditions (for instance under given ambient temperatures).
- Randomly in excess of some reasonable reference value.

Over the course of the CARES project, we endeavour to come up with a reasonable classification, with a way for measuring any of the high-emitter types to be defined, with a method to derive a reasonable reference value and with a first quantification of their frequency of occurrence and their contribution to total emissions from the fleet in the given testing area.

Towards a definition of high-emitting vehicles

There is so far no universally accepted definition for a high-emitting vehicle. However, there is consensus that

- the observations need to cover some kind of reasonable range of driving conditions for an individual vehicle,
- that observations need to relate to a type approval or in-use standard in force,
- that observations cover environmental conditions as pertaining to both type approval tests as well as outside, and that
- there needs to be some margin of error allowance between observation and the reference value.

There is merit to establish the distribution of (high) emissions in the fleet before setting a threshold value to determine which vehicle has (on average) unacceptably high emissions or not. This will help with a more accurate assessment of both the impact on air pollution and the benefits of high-emitter removal.

Thus, a working definition to be tested over the course of the CARES project could be:

> **A high-emitter is a vehicle whose emissions exceed for at least one pollutant a reasonable reference value under normal driving conditions.**

For this definition several elements need to be specified:

- What is a 'normal' driving condition?
- What is the minimum number of (instantaneous) records within normal driving conditions that are needed for a robust assessment?

- What is the reference value to compare with?

These points will be elaborated for plume chasing and point sampling techniques below.

Earlier, a simple statistical approach has been used (Zhang et al. 1995; Pokharel et al. 2003; Smit and Bluett 2011; Buhigas, Fleire, and De la Fuente 2021): The highest records of a rank ordered distribution of (instantaneous) emissions are considered as representing high-emitters. This implicitly equates “instantaneous high emission record” with “average emissions high”. This approach might work for the worst vehicles, that permanently eject excessive amounts of pollutants. However, instantaneous emission peaks are the norm over the course of driving (as e.g., observed in any continuous measurement like chassis dynamometer or PEMS measurements), not the exception. Therefore, single instantaneous records are insufficient to determine an average emission behaviour of a vehicle. In addition, such an approach needs a reference to some emission standard. But promising and robust approaches have been developed over the course of the CARES project that are summarized in the following.

Lessons learnt from chassis dynamometer, PEMS and SEMS measurements

As described in detail earlier, predetermined driving cycles in engine tests and chassis dynamometer tests do not necessarily reflect real driving conditions, resulting in emission control systems being optimised for the cycle and not for real driving (EP 2017). To overcome this limitation portable emission measurement systems have been used to measure emissions in on-road trips. Thus, there is a wealth of data from these ‘on-board laboratories’ that by now have been well accepted. However, because of the costs and time requirements of PEMS there is an unknown sampling bias with this measurement technique: Typically, new, or well-maintained vehicles with known history of commercial ownership have been measured, and emission after-treatment defects are fixed before the tests. Moreover, sample numbers and scope are usually too limited to ever be sure that the whole fleet is well represented, let alone of an occasional high-emitter would be representative. Consequently, little is known about the emission performance of dysfunctional vehicles (Notter et al., 2019).

Hence, in general, data from chassis dynamometer and PEMS tests provide a database for emission performance with functioning exhaust controls. This might also be useful for comparison and context of (instantaneous) records from RES measurements. Laboratory, PEMS and SEMS[2] measurement data can help to establish typical emission probability distributions and underlying dependencies on, e.g., velocities, dynamics, ambient temperatures, and vehicle maintenance. The instantaneous or short-time results, from remote sensing can be put in the context of the typical, characteristic emission behaviour. During normal operation, especially in high dynamics, a few spikes of emissions may occur. This is not necessary a failure of the system, leading to high overall emissions. This suggests that instantaneous emission records either need to be controlled for the vehicle dynamics or that there are multiple records needed for the same vehicle but under different driving conditions. High emissions might indeed also occur as part of a regular regeneration of the diesel particle filter, which can occur over the course of a couple of minutes. Therefore, single instantaneous records from pass-by measurements are not sufficient to give certainty to a high-emitter assessment. What is clearly needed are repeated measurements of the same vehicle under different driving conditions. Then, the probability of always measuring high emission rates is low and therefore the inverse is true: If those repeated snapshot measurements are all (or on average) high, there is a highly likelihood that the vehicle has indeed elevated emissions on many driving situations and hence on average. The advantage of SEMS is the long-term monitoring, showing all kind of dependencies and trends over the course of several months to several years. Specific effects where pollutant and CO_2 emissions, and fuel consumption, have different trends, causing variation in the ratios reported in remote sensing may help to put context on findings of high emissions. Two aspects require special attention. First, the regeneration events of DPF and LNT, which lead to short periods of high emissions. Second, the idle emissions of vehicles, which may have high ratios but limited associated absolute emissions, since engines are typically optimized to have low fuel consumption during idling.

There are instantaneous records from PEMS and SEMS measurements available to project partners. One workstream is to investigate these data further to help deriving suitable reference thresholds for high-emitting behaviour and their typical variability. This has by now lead to a research paper by (Qiu and Borken-Kleefeld

[2] SEMS stands for Smart Emissions Measurement System, a compact and cheap sensor mounted on individual vehicles for a continuous measurement notably of the NOx emission rate.

2022) developing a method merging instantaneous RS with modal PEMS data. Another workstream could investigate under what conditions RES measurements can replace more elaborate PEMS measurements.

Lessons learnt from cross-road and top-down RES measurements

High-emitter identification has a legal place in inspection and maintenance programs for light duty vehicles in the USA and in Hong Kong (McClintock 2007; 2009; Huang et al. 2018). There are also efforts to cover heavy duty vehicles but, except for China, no legally binding thresholds or procedures have been stipulated. In Europe, RES has received a legal place only with the Euro 6 legislation, but without specifics about a protocol or threshold values for high-emitter detection. Therefore, we review approaches from research teams.

Identification of individual high-emitting vehicles – light-duty

The approach proposed by the US Environmental Protection Agency focuses on spark-ignition light duty vehicles (US EPA 1996). Such a vehicle is considered a high-emitter (also called gross emitter) if the CO reading in a cross-road RES measurement is above a certain cut-off concentration. This concentration value depends on the vehicle's certification standard or model year, respectively. The cut-off thresholds are related to in-use emission testing standards as a "not to exceed" reference value. If a vehicle's CO emission rate is found higher than the cut-off threshold the owner is requested to bring the car to a garage for a confirmatory I/M test. If that test is failed the vehicles needs to be repaired. This basic design has been implemented with variations in various US States with air quality problems. As a refinement, some US States require at least two RES records taken within a certain period and both above the cut-off threshold as necessary condition before issuing a notice for confirmatory inspection to the vehicle owner. In addition, this assessment may account for historic experience with inspection results: If a vehicle measured by RES belongs to a model category that has been found to display emission control failures more frequently than others a lower threshold criterion is applied, i.e., it is considered more likely also to be a high-emitter (Borken-Kleefeld 2013).

Hong Kong has also been using RES for monitoring on-road emissions and identifying potential high-emitters among its LDV fleet. It addresses notably gasoline and LPG powered cars and taxis. The monitoring system works with two RES instruments placed within a short distance apart from each other on the same road. If both readings are above a certain threshold value, the owner receives a letter requesting that the vehicle to be tested in a certified garage. Thanks to the dual set-up the program claims a low failure rate (Borken-Kleefeld and Dallmann 2018).

OPUS RSE has pushed the identification of high-emitting vehicles in Europe. At first, the top 5% of a rank ordered distribution of RS emission rates in a fleet were classified as high-emitters (Pujadas, Domínguez-Sáez, and De la Fuente 2017). However, there has not been any confirmatory checking of vehicles classified as high-emitters based on – at best – a single instantaneous emission rate. Consequently, a more sophisticated approach has been proposed, requiring several exceedingly high emission records per vehicle: A passenger cars/light commercial vehicles is considered a high-emitter, if one emission record is higher than the 98th percentile and another emission record is above the 80th percentile of the distribution of emission rates of the fleet (for any pollutant measured). Alternatively, if more than 70% of a vehicle's emission records are above the 80th percentile value of the fleet measured, this vehicle is considered a potential high-emitter (Buhigas, Fleire, and De la Fuente 2021). This approach is currently under scrutiny, notably with authorities in Spain.
However, the method as proposed has several obvious short-comings: There is no reference to the emission standard to which the vehicle is certified, and it does not seem to disaggregate the measured records by age or emission standard. In consequence, the highest emission records will most often stem from the oldest cars. These are however not necessarily illegal high-emitters but just old vehicles, certified to more lenient emission standards and possibly deteriorated over the course of time. Yet indeed, if modern vehicles are found with as high emissions as old (pre-Euro 5) cars, then there is a high likelihood that those are malfunctioning.

In all cases, RES is used as a screening tool for identifying vehicles with suspiciously high emissions. The assessment of pass or fail is then delegated to an appropriate garage and stationary testing. Cut-off values for high-emitter detection are derived from legislated in-use (or type approval) tests typically with a large safety margin to avoid false positives. In other words, these simple approaches tend to identify only the dirtiest of the high-emitting vehicles (we might call them "super high-emitters") but are not sensitive enough for other faulty vehicles, as e.g., argued by (Huang et al. 2020). The authors further argue that the cut-off threshold should be derived from on-road tests, i.e., from field observations. In any case, all RES approaches have focused on regulated gaseous pollutants (CO, HC and NOx). Particle number or particle mass concentrations would need different means for a robust assessment, as for instance fast roadside air quality sensors.

Qiu and Borken-Kleefeld (2022) have developed an approach starting from reference data measured in laboratories and during PEMS tests. These tests represent a spectrum of instantaneous as well as average emissions that are taken as reference for typical instantaneous emissions from vehicles whose emissions controls work well or not

(=high-emitters). They demonstrate that with just a few repeat measurements (three to five) it is possible to identify high-emitting vehicles with 80 to 90% accuracy. It is also demonstrated that the simple approach to consider e.g., the highest 5% of instantaneous records as indicating permanent high-emitters is justified – as those values are so high, that this can be emitted only from malfunctioning vehicles. However, with this approach, only a small though relevant number of vehicles with improper emission behaviour would be detected while the approach using reference data demonstrates a capture rate of 80% and more, depending on the threshold value used. More work is under-way to text and extend the scheme to the latest emission categories – and to put it to a ground test. The scheme relies on external instantaneous emission data for reference. However, for the time being, this is the most sophisticated and sound identification scheme of high-emitters using the traditional cross-road or top-down open-path instruments.

Estimating a fleet's share of high-emitting vehicles – light-duty

For air quality assessments it is important to know the share of vehicles with excessive emissions. Current traffic emission models are based on properly functioning vehicles as measured in chassis dynamometer or PEMS tests. The contribution from high-emitters to emission totals needs to be determined separately. Several approaches have been put forward using on-road RS measurements:

(Smit and Bluett 2011) compared distributions of instantaneous emissions rates measured by RS instruments on petrol cars in Australia with distributions from 400 chassis dynamometer tests. The authors propose to interpret deviations in the distribution of RS emission rates to chassis test distribution as the contribution from high-emitting vehicles. They derive correction factors per engine load (VSP bin) for each of the emission certification standards to be applied in road emission models. There can be doubts whether the deviations between distributions of (modal) emission rates measured on chassis dynamometers in the laboratory and instantaneous records from on-road vehicle remote sensing are fully or predominantly due to high-emitters. However, the idea to link RS records with data from longer tests (or trips) is promising.

Qiu & Borken-Kleefeld (2022) do combine instantaneous data from external reference measurements with the instantaneous emissions measured from with RS instrument at the roads. Their scheme is also capable to determine the fleet share of high-emitters and hence the extra emission from these vehicles to fleet emissions. This appears as a very promising approach.

However, none of the above approaches has been tested on individual vehicles or a fleet with known emission problems. Therefore, the validity of either approach still needs to be established.

Identification of individual high-emitting vehicles – heavy-duty

The identification of high-emitting heavy-duty vehicles has arguably been more successful. This is likely related to a different legal situation in the European Union where enforcement agencies have a mandate and flexibility in their approach to check vehicles suspected malfunctioning (or tampered) emission controls. Moreover, the emission standards for heavy-duty vehicles are set units of gram pollutant per unit of engine work, which is directly related to the fuel consumption and thus to the output from remote sensing.

RES instruments have been deployed to screen trucks for suspiciously high NOx emissions. If vehicles have high emission rates and if they appear young, then traffic police pulled over the vehicle and checked for tampering. Unlike in other campaigns the vehicle's number plate was not recorded and no recourse was made to the vehicle registry. This screening for the highest emission rates strongly increased the chances for finding high-emitting vehicles (Ellermann et al. 2018; Hooftman, Ligterink, and Bhoraskar 2020). With cleaner vehicles entering the market, already a small fraction of tampering has substantial impact on the overall emissions. This was confirmed in a RS measurement campaign in Flanders with confirmatory roadside inspections by the police: about 10% and 5% of measured Euro V and Euro VI trucks, respectively, were found to be high-emitters increasing NOx emissions of an otherwise clean fleet by an estimated 24% and 67%, respectively.

A threshold value of 25 g NOx/kg fuel and 3 g NOx/kg fuel was used as indicative threshold for high-emitter identification of Euro V and Euro VI trucks (Ellermann et al. 2018). Hooftman, Ligterink, and Bhoraskar (2020) discuss several possible approaches: For one they propose a threshold of 3 to 5 times exceedance of the emission limit value if only a single passage (and RES record) is used, notably on a motorway. Thus, quite a large range exists for high-emitter thresholds for NOx from trucks (Table 1).

Table 1: High-emitter thresholds for single passage/record RS measurements of trucks on highways. [1] Ellermann et al. 2018; [2]: Hooftman, Ligterink, and Bhoraskar 2020

Threshold valued for single passage	Euro V	Euro VI
Limit values (test cycle/RDE)*	~10 g/kg	~3.3 g/kg
Screening [1]	25	3
Screening threshold: 3-5 times emission limit value [2:p.5]	~30 – 50 g/kg	10-17 g/kg
High-emitter threshold from actual sampling [2:p.78]	NA	7 g/kg

*: assumed fuel consumption rate of 212 g/kWh.

A drawback of this approach is the lack of live vehicle information notably on its age and emission certification level at the time of measurement. When given, then a threshold differentiated by emission standard is particularly useful. If absent, then the approach must be focussed on finding the highest absolute emitters and this can then include older Euro-IV trucks that would have higher allowed emission rates. The thresholds summarized above appear high with reference to the limit values reflecting both a significant margin to avoid false positives but also reflect the high variance for instantaneous records. Therefore, the values are indicative only and are likely to be lowered with more experience and sophistication.

Recommended next steps

The current situation is characterised by a plurality of high-emitter thresholds mostly developed by practitioners from the ground but a lack of cross-checking with roadside inspections. However, all campaigns so far have clearly demonstrated that the RES identification of vehicles with highly suspicious emission behaviour, light- and heavy-duty alike, greatly increases the chances for finding malfunctioning or tampered vehicles.

Therefore, it is strongly recommended to design and carry out RES campaigns

- with multiple RES instruments in a row to ensure several measurements of each vehicle,
- with live classification of technical data (notably the emission certification standard of the vehicle),
- at locations not prone to cold-start conditions,
- with vehicle inspections following a "suspicious" or "high" classification from the RES records.

Such a carefully designed campaign can then adjust the threshold level(s) and the necessary number of valid RES records as a function of vehicle category, its certification emission standards on the one hand and of the required (or accepted) true positive (or false positive) rate and the available inspection capacities.

Lessons from plume chasing

Plume Chasing principle

For plume chasing (PC) measurements an instrumented vehicle follows the vehicle under investigation in order to sample gas right in the wake of its exhaust plume. The instruments in the chasing car (sometimes also called a sniffer car) measure gases from the plume over several seconds to minutes (Chui et al. (2015); see Fig. 1).

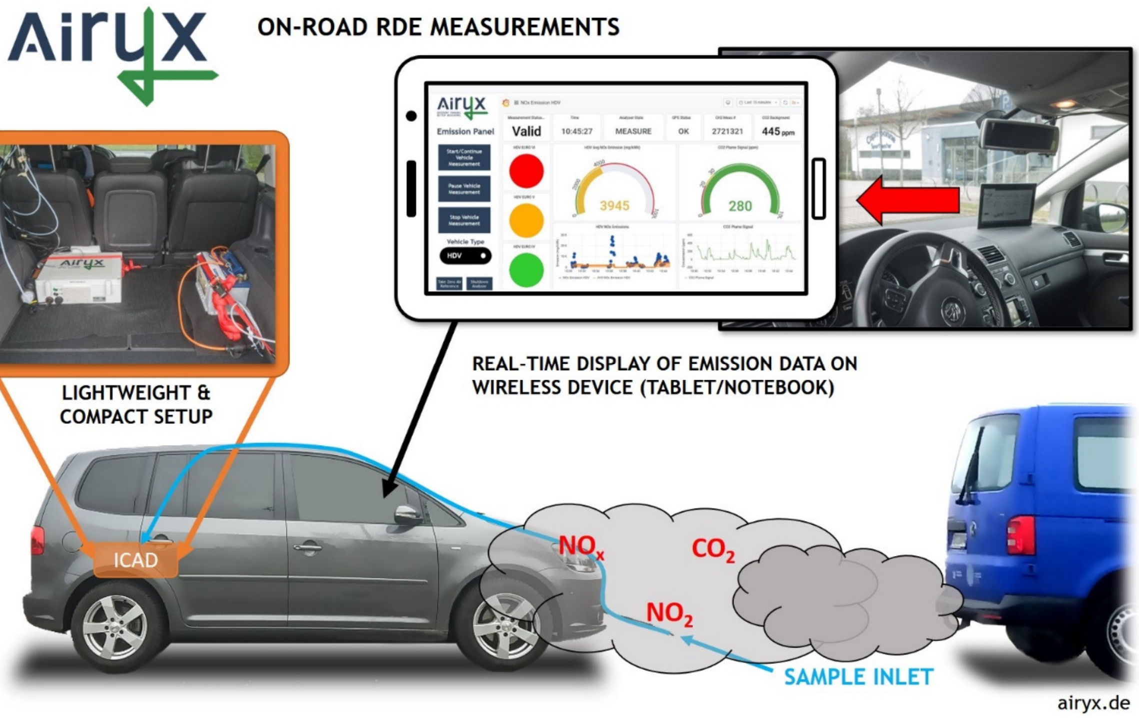


Fig. 1: Principle and setup of the Airyx plume chasing emission measurement. The implemented software directly derives the emission factor of the chased vehicle and performs a real time classification for the NOx emission (green = low, orange = suspicious, red = high).

Due to dilution, the measured pollutant concentrations do not provide a direct emission factor; therefore, the measurement of a reference gas is required that is co-emitted, this being CO_2. The CO_2 emission is well correlated with the fuel consumption. The ratio of the trace gas or particle over the measured CO2 can be interpreted as emission factor, after removing the background concentrations, exactly as for the established Remote Emission Sensing (RES) technique (Bishop and Stedman, 1996). In the case of plume chasing, the background levels, i.e., the concentrations without the immediate plume, are set as the minimum concentrations before reaching the vehicle plume and are continuously adapted to the minimum concentration observed during a chasing measurement. Second, only data points with a sufficient emission signal are considered, defined typically by a CO_2 level of at least 30 ppm above the background. Measurements below this threshold are ignored for the analysis, as they have the potential to be strongly influenced by other sources. Afterwards the ratio of the pollutant to CO_2, e.g., NO_x to CO_2, is derived. This ratio is constant in the plume, directly at the exhaust pipe or 50m behind the vehicle, as all gases have the same dilution. With data or assumptions on the engine efficiency (e.g., 40%) or fuel consumption per km, NO_x emission factors of mg/kWh or mg /km can be calculated from this ratio.

While plume chasing measurements were, in former times, based on research vehicles fully equipped with complex instrumentation (e.g., Chui et al. 2015), new ICAD NO_x technology with CO_2 IR sensor extension made it possible to set up simpler systems suitable for every vehicle without special requirements (as in Fig. 1). The instrument requires only ~30W at 12V or 220V, and no need for gas calibration. Within the CARES project the hardware and the setup on the vehicle was optimized and an automatic real time software was developed with a simple user interface to allow easy emission measurements also by non-experts. The display directly provides the user with the NO_x emission value, giving a classification for low, suspicious and high emitters. In addition, the signal strength of the plume is shown as well indicating whether sufficient data has been gathered in order to give a preliminary or a final emission value. The accuracy of the derived emission value was analyzed in several validation studies where emission factors from plume chasing are compared to PEMS values confirming a high correlation, see Farren et al. (2022a, b) or Janssen and Hagberg (2020).

Instantaneous emissions fluctuate significantly; to assess whether an individual vehicle is indeed a high-emitting vehicle in permanence it is very useful that plume chasing measurements integrate the emissions over the course of several seconds or minutes as long as the vehicle is followed. Thus, this average can also capture different driving conditions. The downside of higher accuracy is that much fewer vehicles can be measured, that a chasing vehicle is required, and that traffic should not be too dense to exclude interfering plumes.

Identification of high NOx emitting heavy-duty trucks (on highways)

PC measurements have so far been focused on emissions from heavy-duty trucks on highways for a number of reasons:

- Trucks have a large exhaust plume that can be traced also under diluted conditions. This is needed for a reliable measurement.
- Trucks drive on highways at quasi constant speed so that they can be followed safely and more easily than e.g., passenger cars.
- only half a dozen manufacturers cater for the vast majority of trucks; therefore, the technical specifics and likely Euro classification can be relatively easily estimated by visual inspection during following and overtaking; thus, no number plate reading is necessary to obtain basic technical details, contrary to light duty vehicles.
- the exhaust emission equipment of trucks should be at optimal operating temperature on highways thus reducing insignificant readings due to cold started vehicles.
- generally, authorities have an interest and mandate for roadside inspections of trucks.

The measurements address NOx emissions. Experience shows that high NOx emissions from trucks often result from missing software updates and missing repair (defects) as well as from manipulations of the SCR and / or EGR system; the intention is likely to reduce operation costs. The following summarizes recommendations for identifying high NOx-emitting trucks with plume chasing.

Recommended measurement conditions

NOx emission reduction systems with SCR and / or EGR are not working continuously at the same reduction rate. For example, SCR is not working below a certain operating temperature; then no exhaust fluid (AdBlue) is injecting either. Therefore, measurements should ideally take place under driving conditions (or at certain road sections) when the attainment of the operating temperature can be safely assumed. Optimal conditions are:

- Measure on highways or rural roads where vehicles are sufficiently warmed up.
- Slight uphill can be an advantage to get a good plume signal.
- Avoid roads where the vehicles idle or where the SCR may cool down, e.g., on long downhill sections.
- Avoid measurements on vehicles that have just began driving e.g., entering the highway from a parking space.
- Avoid strong accelerations or engine loads which are outside normal certification conditions, e.g., steep uphill.

There are some additional recommendations for a successful plume chasing application that are required to reduce interferences from other vehicle emission plumes:

- Drive in close but still safe distance behind the truck; the signal is stronger in closer distance.
- Avoid very dense traffic; close distance between vehicles; low driving speed below 30km/h; tunnels / street canyons

Interferences from other plumes can however not always be avoided. If high emissions are recorded the following procedure is recommended to avoid a false classification:

- overtake the vehicle with seemingly high emissions and measure the emissions at its front, i.e., from preceding vehicles.
- if the emissions are now even higher, then the first measurement was likely interfered by plumes from preceding vehicles.

This procedure is very simple, as all measured vehicles are overtaken anyway at the end of the measurements, and thus a check of the possible interfering vehicle can simply be performed.

Finally, a limitation for weather conditions should be considered:

- Avoid very strong winds (>10 m/s) as emission plumes are too much diluted

The setup and instrumentation of the plume chasing vehicle is described in the recommendations of the manufacturer (Airyx GmbH) and are not discussed in this report.

Recommended procedure for spot checks

In most countries HDT inspections are performed at predetermined locations, either dedicated inspection sites or at temporarily set inspection sites like parking lots. A fixed location however greatly reduces the efficiency of plume chasing if only vehicles will be inspected that have been identified sufficiently ahead of the site. This clearly reduces the probability and compromises the advantage of the mobile instrumentation with which vehicles can be measured wherever they are driven. The recommended inspection strategy therefor is:

- The inspecting officer(s) drive together with the plume chasing car.
- Whenever high emissions are determined by PC the suspect vehicle is pulled over by the officers as soon as possible, e.g., at the next parking lot.
- The inspectors investigate the vehicle e.g., with advanced OBD tools to validate a manipulation or defect and or to exclude a cold SCR. This does require neither heavy equipment nor space for disassembly.

Threshold values for low, suspicious and high-emitting trucks

Trucks are classified – here – by comparing their NOx emissions during plume chasing with a threshold value, differentiated for each emission class. The type approval limit values cannot be used directly as they apply to new vehicles on a standardized test cycle. Furthermore, on-road tests need to account for inaccuracies due to interferences from other vehicles. Therefore, it is recommended to use the Euro emission standard value plus some suitable margin as threshold value.

Euro VI heavy-duty trucks with intentionally manipulated SCR systems can emit 5 to 20 times more NOx than trucks with regularly working aftertreatment, i.e., emissions below 690 mg/kWh (Farren et al. 2022a, b and Janssen and Hagberg, 2020). However, this is an extreme case and defective emission controls often also result in intermediate emissions as not always the complete emission reduction system fails (e.g., EGR still work). Therefore, the threshold should neither be too high as this would risk missing defective vehicles (false negative) nor be too low to avoid wrong identification of actually clean vehicles (false positives). Moreover, the average emission over the course of a plume chasing measurement depends on the integration time. The longer the measurement time, the more robust the measurement becomes i.e., less variability with increasing measurement time. When the after-treatment system is properly working then the plume-chase averaged NOx emission converges after several minutes to the official limit of 690 mg/kWh for Euro VI trucks (Fig. 2, left panel). However, for practical reasons shorter measurement times are desirable, which means to put up with higher variability. When averaged over a few seconds only, the emissions of Euro VI trucks with fully functional aftertreatment can be close to zero or up to 3000 mg/kWh. However, within 60 seconds this spread has decreased considerably for proper functioning after-treatment systems, i.e., allowing a robust classification, while offering a quick assessment. A similar behavior has been found for the emissions from Euro V trucks on highways. We therefore propose the threshold values in Table 2 for suspicious and high-emitters after 60 s measurement time. Note that experience here has led to reducing the required measurement time compared to our earlier work (Pöhler 2020).

Table 2: Recommended thresholds and measurement time for HGVs based on data from Pöhler (2020).

Threshold values	Euro V [mg/kWh]	Euro VI [mg/kWh]	Measurement duration
(RDE) emission limit	≤ 2.000	≤ 1.5 * limit = 690	
Low emitter	≤ 2.500	≤ 1.200	≥ 15 sec
Suspicious emitter	> 2.500	> 1.200	≥ 60 sec
High emitter	> 3.500	> 2.200	≥ 60 sec

Inversely, emissions from heavy-duty trucks with improper exhaust cleaning remain above the respective “suspicious” or “high-emitter” thresholds; high-emitters might display low emissions no longer than a few seconds (Fig. 2, right panel). In other words, high-emitters reveal themselves quickly. If a vehicle continues to have emissions below the “suspicious” threshold for tens of seconds, it is mostly like not a suspicious but a clean vehicle. Therefore, inspection times need initially only be as short as 15 seconds to exclude a suspicious or high emitter; this significantly increases the efficiency and allows for more time to focus on defective and manipulated vehicles. (For validation see section ‘Confirmation from roadside vehicle inspections’).

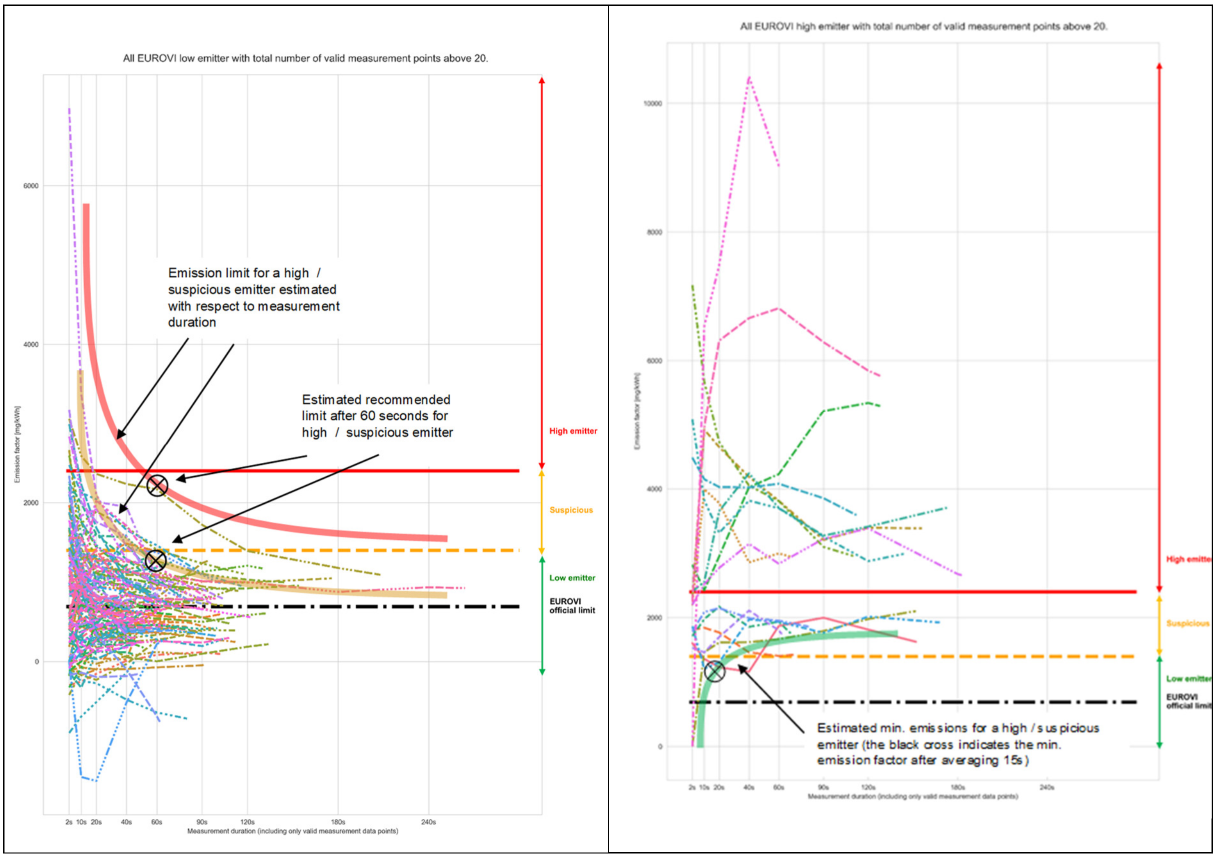


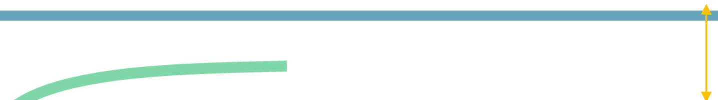
Fig. 2: Average NO_x emission value for Euro VI HDV classified as low emitters (left) or suspicious or high (right) in dependence of the averaging time (x-axis). Each line represents one individual measured HDV. An envelope of the estimated maximum (left) and minimum (right) emissions for a suspicious or high emitter are drawn and the cross indicate the recommended limit after a measurement period of 60 seconds (left)/ 15 (right) seconds. Time corresponds here to time with emission plume signal, not to general time. Figure from Pöhler 2020.

Uncertainties and Unknowns

Several factors affect the accuracy of the emission measurement: These include instrument uncertainties, influences from other emission sources, what background concentration is assumed, the averaging period. The instrument uncertainty is as low as 2% for the latest generation instrument, i.e., the ICAD-NOx-200DE. The other factors can be reduced when following the measurement procedures outlined above and optimised evaluation algorithms developed within CARES studies reduce uncertainties for the emission calculation. The threshold values recommended in Table 2 account for these uncertainties for plume chasing under the defined measurement conditions.

Remote measurements like plume chasing can only observe emissions but exact reasons for (high) emissions can generally only be determined during a vehicle inspection. Several cases are typical where high-emissions are not the result of wear, breakdown or manipulation:

- The after-treatment system and notably the SCR can be below operating temperature (i.e., "cold"). If the system is working properly then NOx emissions will decrease with increasing mileage – and that can also be measured with plume chasing (Fig. 3). The assessment whether this vehicle is a high-emitter should then only begin once emissions have stabilised, i.e., measurement times longer than 60 seconds are recommended.



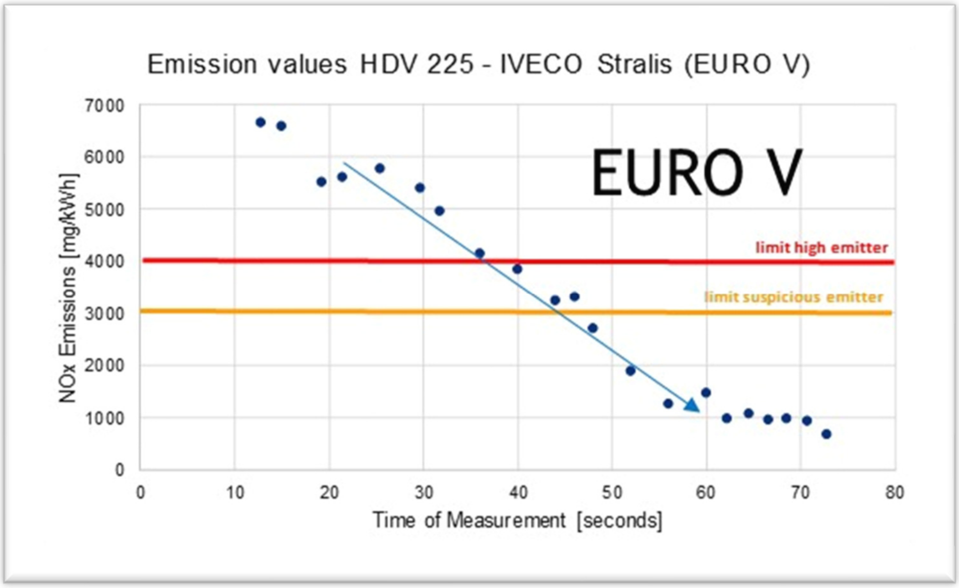


Fig. 3: Decreasing NOx emissions with increasing driving time as observed during a plume chasing measurement, interpreted as SCR warm-up of a Euro V truck.

- The engine and notably the after-treatment system does not warm up, e.g., because the load is too low for a large engine. Such cases have mostly been observed for Euro V trucks with empty trailer. Empty trailers can be identified by a lifted axle; the respective vehicle could then be excluded from the measurement.
- SCR systems may cool down after idle periods, e.g., during downhill driving. Such road segments should therefore better be avoided for plume chasing measurements or be excluded from the emission assessment.
- Some truck models have issues with their SCR system for which the manufacturer has provided a software update. But there are no regulations detailing the responsibilities for updating the truck software. For such cases European regulation would be helpful to ensure that all vehicles receive emission relevant updates. A reference list of vehicles with such software updates would be useful for inspectors applying plume chasing measurements to be aware that high emissions may be in these cases due to the missing update and not due to manipulations or defects.

Confirmation from roadside vehicle inspections

The suitability of plume chasing measurements to identify high emitting trucks has been demonstrated in several exercises with police or traffic authorities who stopped and inspected the suspicious vehicle. Major inspection campaigns have been conducted in Denmark (Pöhler 2020) and now in the Czech Republic (2022, this CARES project) as well as in Austria and Belgium (to be published).

Plume chasing with roadside inspections in Denmark

Plume chasing measurements were conducted in cooperation with the police and road safety agency in Denmark in 2020. NOx emissions of 478 heavy-duty trucks were sampled with plume chasing, of which 6.3% were classified as suspicious and 3.4% as high-emitting trucks, i.e., in that campaign with average NOx emissions above 1400 mg/kWh and 2400 mg/kWh for Euro VI trucks. 24 of the identified suspicious or high emitting trucks were pulled over by the authorities and manually inspected with ODB read-out devices. Six trucks, classified as low-emitters, but with NOx emissions at the margin of the 1400mg/kWh threshold were also pulled over and inspected. An apparent reason could be identified for all trucks classified as suspicious or high-emitters in plume chasing measurements, i.e., 0% false positives (Fig. 4).

73% for Euro VI and 44% for Euro V showed a defect which was indicated with the mil lamp or in the OBD diagnostics (e.g., deleted error message in the dashboard). 27% for Euro VI and 20% for Euro V showed a manipulation. However, manipulations can sometimes not be easily separated from defects what may cause manipulations to be classified as defects. For Euro V also some HDV showed cold SCR even when they were driving for 50km. These were vehicles which did not warm up sufficiently due to low load with an empty trailer.

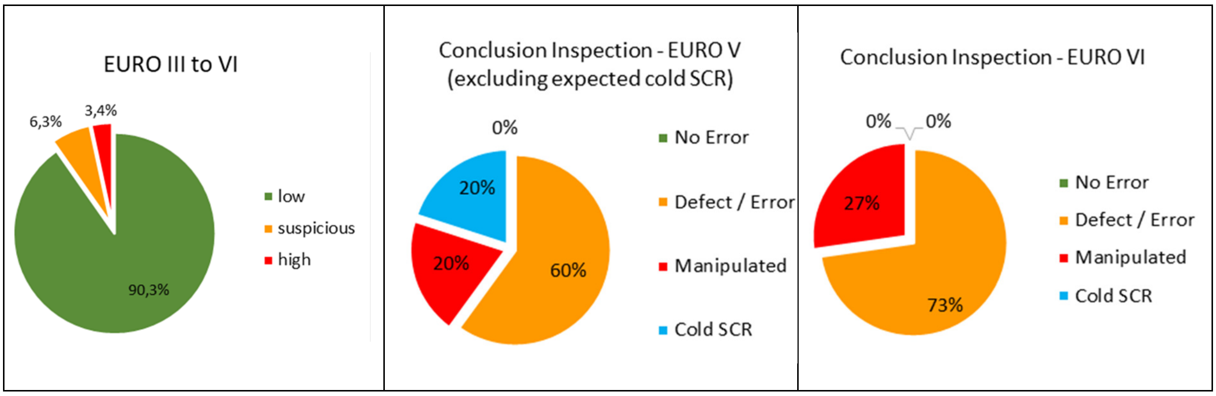


Fig. 4: Left – Emission classification of all trucks measured by plume chasing. Centre and Right – Results of the roadside OBD inspections for Euro V and VI trucks preselected by plume chasing.

The inspections even with advanced OBD tools were time consuming and needed well-trained inspectors. Finding the exact manipulation can take hours. Therefore, it is so important that vehicles can reliably be preselected by plume chasing in order to maximize chances for identifying an actual high-emitters, and not to encumber drivers whose vehicles have properly controlled emissions.

Plume chasing with roadside inspections in the Czech Republic [CARES 2022]

Plume chase measurements of trucks on a highway were conducted in the Czech Republic as part of the CARES campaign centred in and around Prague. Police pulled over a number of trucks classified as suspicious or high emitter and trained officers (actually from the Danish campaign cited above) inspected the vehicle with OBD analysis tools. 990 trucks were measured during the five-day campaign. 36% were classified as suspicious or high emitter, much more than in Denmark, using threshold values from Table 2.

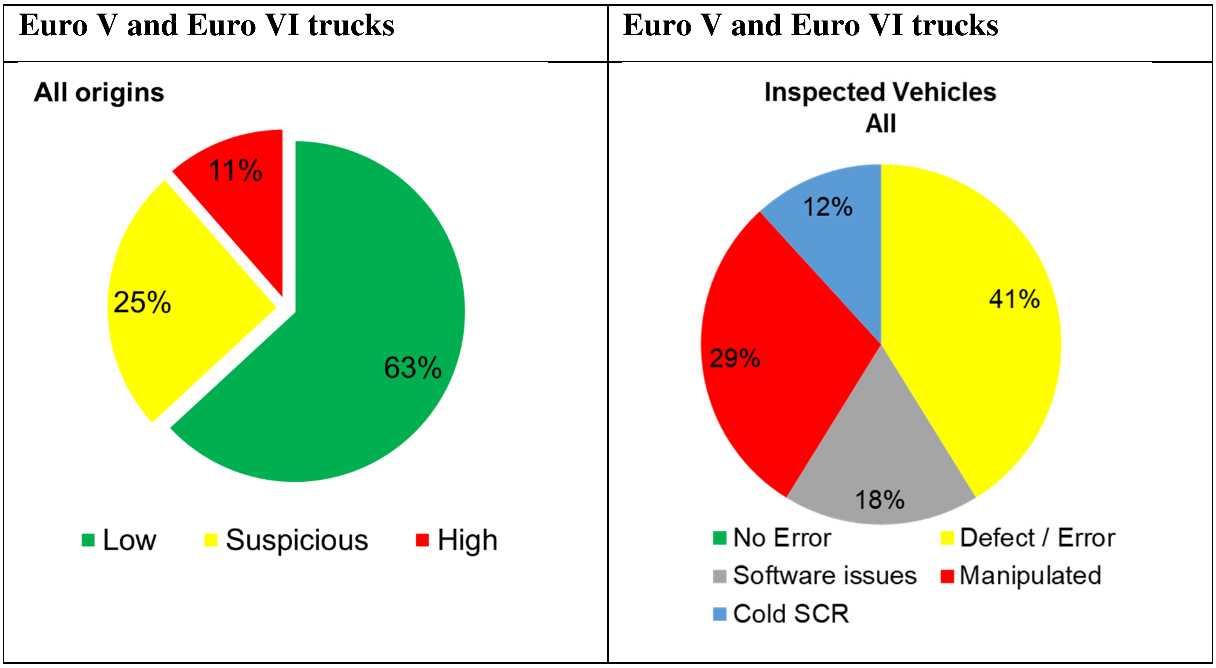


Fig. 5: NOx emission classification of 990 trucks measured by plume chasing and of 17 pre-selected trucks at spot checks in the Czech Republic.

Due to logistical reasons and time constraints only 17 of the pre-identified suspicious and high emitters were actually inspected next to the highway. For all vehicles a reason for high emissions was found (Fig. 5) again meaning 0% false positive. 5 were manipulated (53% Euro V, 20% Euro VI), 7 showed a defect (43% Euro V, 40% Euro VI), 2 had a cold SCR (14% Euro V, 10% Euro VI) due to warm up problems of the engine and SCR; 3 had missed a mandatory emission control software update (only Euro VI with 30%), resulting in increased NOx emissions. This exercise, even limited in numbers, serves to validate the recommended threshold values and inspection procedure for plume chasing measurements.

False classifications (false positives) have been avoided and authority inspections are significantly improved to focus on the problematic vehicles. With the low thresholds defective or manipulated vehicles are unlikely to be classified as low emitters (false negatives). Only those trucks are pulled over that have a serious emission problem.

Recommended next steps

- More plume chasing measurements in combination with detailed, professional inspections are needed to validate the suspicious and high emitter vehicles and better estimate thresholds for emissions and measurement time duration.
- Trends in "normal" degradation vs. defects and manipulations should be addressed. Euro V and VI heavy-duty trucks get older and thus more likely normal degradation may cause a suspicious emission value which is not covered by a defect shown with the mil lamp or OBD system. This may need to be considered in revised thresholds.
- For efficient inspections it is needed to have as short a measurement time for reaching a decision as reliably possible. Among others, quicker response times from the instrument would help. Therefore, technical and software developments are needed.
- EU countries should implement rules that high emitters are inspected, that they are barred from running until repaired and that high penalties are handed out. Inspection authorities need new tools, including plume chasing and OBD diagnostics, to efficiently identify and inspect the relevant vehicles. Well trained specialised inspectors are needed to work this complex topic.
- Authorities need to adapt the inspection procedure from fixed inspection locations to mobile inspection vehicles equipped with plume chasing sensors authorised to stopping suspicious vehicles at next the opportunity.
- A list of vehicles with potential manufacturers software issues need to be created to identify during inspections if the high emissions may be caused by a missing manufacturer software update.

Lessons from point sampling measurements

Point sampling (PS) was introduced years ago (Hansen and Rosen, 1990; Janhäll and Hallquist, 2005; Hak et al., 2009; Ban-Weiss et al., 2009) and has since been used in several research studies mainly for the quantification of heavy-duty vehicles (Hallquist et al., 2013; Watne et al., 2018; Liu et al., 2019; Zhou et al., 2020). The main focus of point sampling was predominantly set to overcome the limits of cross-road RES especially in case of particulate matter (PM) detection. In case of PM emissions, cross-road RES is only capable of identifying the highest emitters. With increasingly stringent limits in emission standards cross-road RES is not capable of accurately detecting PM emissions. Growing interest in particle number (PN) emissions and smaller particle sizes in the last years due to health concerns led to novel approaches for in-use vehicle screening (Bainschab et al., 2020). This is where point sampling comes in, a potential method capable of high particle emitter identification and PN emission screening of in-use vehicles.

Overview of the point sampling method

Point sampling is an extractive method where the diluted exhaust plume of the passing vehicles is sampled and analysed. Fig. 6 shows a typical point sampling setup. Vehicles pass by the point sampling spot where the passing time and characteristics like speed and acceleration are recorded (e.g. with light barriers). Commonly, the diluted plume is sampled with a tube which is placed either directly on the road or next to the road. The sampled exhaust is then analysed with instruments which are able to resolve the transient exhaust events and are sensitive enough of quantifying the strongly diluted plume contents. Similar to cross-road RES, the ratios of the pollutant of interest (e.g., PN, black carbon (BC)) to the sampled CO_2 concentration are the basis for the calculation of fuel-based emission factors (Ban-Weiss et al., 2009; Hak et al., 2009). Vehicle technical information is gathered from governmental authorities wherefore the license plates of the passing vehicles are recorded using an automated number plate recognition (ANPR) system. In the frame of the CARES project the point sampling method has been developed to be used for wide vehicle screening and for the measurement of passenger cars. The method is further developed for automated operation and post-processing of a high number of vehicle records.

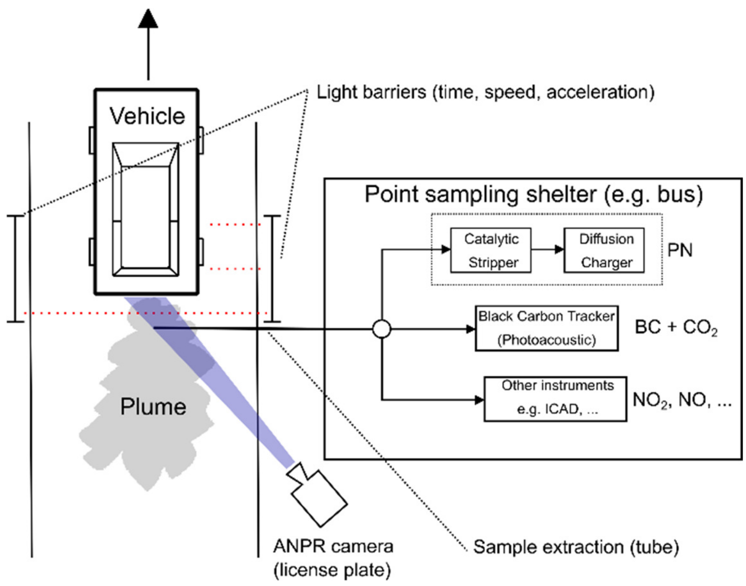


Fig. 6: Point sampling set-up used during CARES measurement campaigns.

Characterization experiments

Characterization experiments were conducted on a test track in Lelystad, the Netherlands, in June 2021 in the frame of the CARES project (see Deliverables D1.1 and D1.2, Farren et al. 2022a, b). The purpose of the characterization experiments was to evaluate and compare the different RES methodologies (cross-road, plume chasing and point sampling) in a controlled environment. In addition, a newly developed black carbon tracker (BCT) for measuring black carbon (BC) and CO_2 was tested alongside a custom developed diffusion charger (DC) (Schriefl et al., 2020) for measuring PN. Several test vehicles were used in various measurement programs including a Caddy with a DPF by-pass to simulate a tampered vehicle. Blind tests were performed where the tampering state of the test vehicle was not known a priori. If the DPF-bypass was switched on, the Caddy was emitting a lot. If the DPF-bypass was switched off, the Caddy was operating normally. Several passes were performed with both configurations. A boxplot of the captured BC (left) and PN (right) emission factors (EFs) is shown in Fig. 7. For both BC and PN, if the DPF by-pass was switched on (high emitter configuration) non-zero emission factors were captured. The measured EFs ranged from 3 to 102 mg/kg fuel for BC and 0.4 to 48 x 10^{13} particles/kg fuel for PN. If the DPF by-pass was switched off (normal operation) only background concentrations were measured. These results showed that a high emitter identification is feasible with the point sampling method. It must be mentioned that the overall emissions of the Caddy are actually rather low and significantly higher emissions are expected from tampered vehicles (Boveroux et al, 2019; Bainschab et al., 2020). A detailed description of the results can be found in the two deliverables from the characterisation experiments ("D1.1 Measurement technology intercomparison and evaluation" and "D1.2 Monitoring of vehicle tampering", Farren et al., 2022a, b).

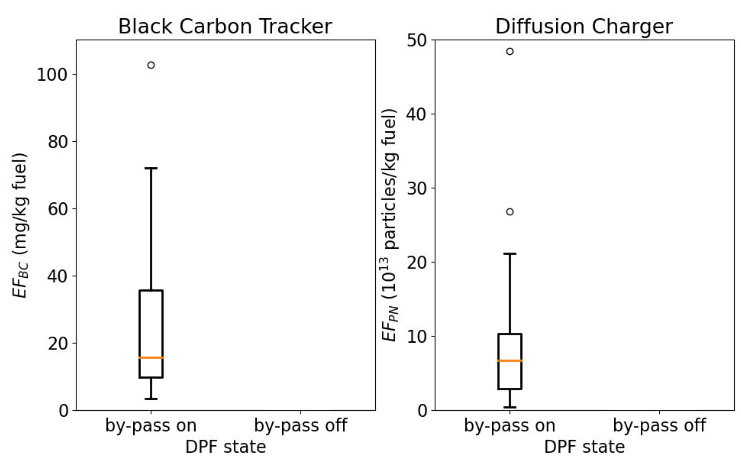


Fig. 7: Boxplots of captured EFs of a test vehicle (DPF by-pass on/off) measured with a BC analyzer (left) and a PN analyzer (right).

Identification of vehicles with high particle emissions

Point sampling and plume chasing measurements were conducted for one day in parallel with police inspectors during the CARES measurement campaign Prague/Brno in September 2022. Vehicles flagged as suspiciously high particle emitters were subsequently inspected by police and technical experts from CVUT Prague. The objective was to test the ability of detecting high particle emitters with point sampling or plume chasing in real-world traffic. Therefore, police inspections including tailpipe measurements were conducted around 1 km downstream the point sampling measurement spot in Brno, Seifertova. Results for 17 inspected vehicles, of which 2 petrol powered, are shown in Table 3. Fuel-specific BC and PN emission factors were measured with the new point sampling device; the particle number concentrations (per cm^3) are from the road-site inspections at the tailpipe. If number concentrations at the tailpipe are higher than 2.5 x 10^5 cm^{-3} (Bainschab et al., 2020) the vehicle is considered a high emitter.

Table 3: Summary of high emitter identification with point sampling and following road-side inspections during one day of the CARES measurement campaign in Brno in September 2020. Colored index shows the vehicle classification. Red: Proven high emitter, Yellow: Suspicious vehicle, Green: Proven low emitter. In bold: Light commercial vehicle.

Vehicle	Reg. Year	Fuel type	PS BC (g/kg)	PS PN (10^{15}/kg)	Inspection PN (10^6/cm³)	Inspection comment
Ford Transit	2008	Diesel	-	-	3	Missing ANPR detection
MAN TGL 12.250	2011	Diesel	-	-	90	Missing license plate information
Fiat Doblo	2014	Diesel	0,43	7,7	9	Expired technical inspection
Ford Transit	NA	Diesel	0,65	6,2	30	
Ford Galaxy	2012	Diesel	2,99	3,6	-	393k mileage, DPF not working according to inspection, no PN inspection
Skoda Octavia	NA	Diesel	-	-	3	Missing ANPR detection
Peugeot 407	2008	Diesel	1,8	3,9	2	
Skoda Superb	NA	Diesel	-	-	2,3	Vehicles too close for proper plume separation
Iveco Daily	2011	Diesel	-	-	5	Missing ANPR detection
VW Transporter	2009	Diesel	1,38	10,9	13,5	
Audi A3	NA	Diesel	-	-	14	Missing ANPR detection
Mercedes Benz	2001	Diesel	19,51	38,6	-	Visible smoke during acceleration, no PN inspection
Dacia Logan	2015	Petrol	0,37	0,49	-	No PN inspection
Skoda Octavia	2007	Diesel	0,17	1,2	-	No PN inspection
Ford S-Max	2006	Diesel	2,78	6,32	-	No PN inspection
Hyundai i30	NA	Petrol	-	-	0,045	No high emitter, vehicles too close for proper plume separation

The vehicles that were pulled over were between seven and twenty-one years old, i.e., certified to Euro 5 or prior. Six out of seventeen suspicious vehicles are light-commercial vehicles, confirming observations from other campaigns that the emission performance of this vehicle category is generally less well maintained. 13 of the 15 suspicious diesel vehicles were confirmed as high emitters by the road-side tailpipe measurements. For two of those no tailpipe PN measurement was needed as already the visual inspection was sufficient (see comments); this is also confirmed by high to very high point sampling records. Some point sampling records are missing either due to missing ANPR recording, missing license plate information or difficulties in plume separation from the automated point sampling postprocessing. Calculated fuel-based emission factors from the point sampling measurements for the identified diesel high-emitters ranged from 0,4 to 19,5 g BC/kg fuel and 3,65 to 38,6 x 10^{15} PN/kg fuel.

All three vehicles classified as "suspicious" based on the point sampling measurement, two diesel and one petrol car, emitted substantially higher amounts than the supposedly "high emitting" Caddy used during the characterization measurements. Their emissions ranged from 0.17 to 2.78 g / kg fuel for BC and 0.49 to 6.32 10^{15} / kg fuel for PN. However, no PN tailpipe measurements could be performed for these three vehicles for logistical reasons.

The road-side inspections determined that one petrol vehicle was a low emitter; its tailpipe measurement of 4.5 x 10^4 cm^{-3} is clearly below the defined threshold. This vehicle was most likely wrongly identified as suspicious vehicle due to communication difficulties between the point sampling operator and the road-side inspectors. The classification is summarized in Figure 3. From the 17 inspected vehicles were 13 classified as proofed high emitter (76.5 %), 3 as suspicious vehicles (17.5 %) and one as low emitter (6 %).

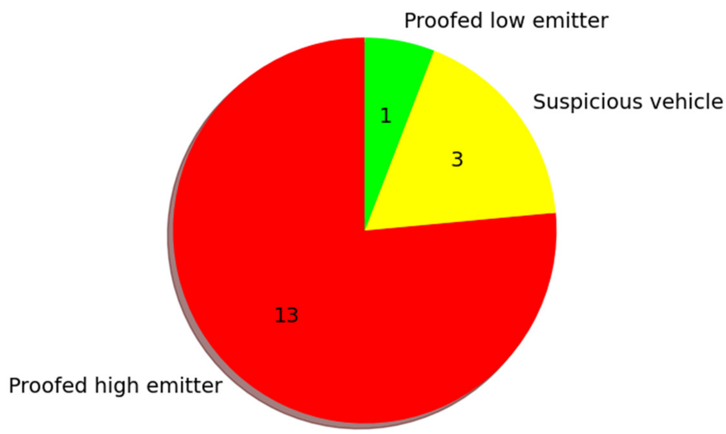


Figure 1: Classified vehicles according to vehicle inspections in Brno.

Towards the application of point sampling in high emitter identification

Results presented above demonstrate the ability of the point sampling measurement technique to reliably identify vehicles with high particle emissions. The detection is robust as high emitter identification for particles is not as dependent on the driving condition or load as for gaseous compounds: Vehicles with exhaust after-treatment systems that are not at operating temperature ("cold") have for instance significantly elevated NO_x emissions and can therefore be falsely classified as (permanent) high emitters. Diesel cars certified to Euro 5 emission standard or later are typically equipped with particle filters; total PN emissions from diesel cars with "cold" particle filters are no more than 35 percent higher compared to emissions from vehicles with warm particle filters (Lodi et al., 2021). By contrast, if the diesel particle filter does not function properly, PN emissions from the vehicle increase by 2-3 orders of magnitude (Bainschab et al., 2020). This can very robustly be identified by point sampling.

A false high-emitter classification could result from DPF regeneration events as they result in elevated PN emissions. However, for properly functioning vehicles such events should occur less than 10% of their time. In addition, vehicles preselected as suspicious by point sampling measurements are generally sent for confirmatory inspections where the proper functioning could easily be established. Such false classifications could however also be avoided by an adapted measurement strategy: A vehicle is classified as a high-emitter only if two point sampling records for the vehicle (within a certain period) are above the threshold. However, this would decrease the overall lower productivity of the system or would require more (and inter-connected) sensors to be deployed.

The key issue is the definition of (high-emitter) thresholds. In case of remote emission sensing, there is a lack literature on thresholds for high particle emissions. One possibility is to use the Euro emission standard value as reference. Particle mass limits are set for diesel vehicles and onwards from Euro 5a for petrol vehicles. PN limits are defined for diesel and petrol vehicles for Euro 5b and for Euro 6b onwards, respectively. The PN limit is set at 6×10^{11} #/km. This needs to be converted to the customary fuel-based unit of remote emission measurements assuming a certain fuel consumption. Bernard et al. (2018) proposed using the real-world adjusted average CO_2 emission determined during type approval; Davison et al. (2020) propose a more sophisticated approach based on the vehicle specific power (VSP) measured for the vehicle. This leads to our working hypothesis for point sampling measurements:

The distance-based PN emission limit of 6×10^{11} #/km translates to a **fuel-based limit of 1,89 to 1,26 x 10^{13} # per kg fuel** assuming an average CO_2 emission of 100 to 150 g/km. A safety margin should be added to establish a threshold value for PN high-emissions.

Detailed investigations are required to determine if an absolute threshold value is reasonable – and how low this threshold can be while leading to a robust classification. Future emission regulations must be considered, and RES should be better integrated into regulations to evolve its capability.

Conclusions: Supporting PTI and enforcement

Key objectives of the CARES project are to develop measurement tools, strategies, and analytical procedures to identify high-emitting vehicles. The typical use cases would be first to complement periodic technical inspections by identifying vehicle models that have much higher emissions than in-use standards or than comparable vehicles in their respective class. Second, schemes to identify individual high-emitting vehicles are most useful to support enforcement actions in real-world traffic. The inter-play of the various techniques allows their deployment where it is most useful per vehicle category and per pollutant. If these two objectives are clear, then it follows which traffic situation and set-up to employ. For instance, for targeting particulates from either light or heavy-duty vehicles it would be recommended to use a point sampler in urban, but not dense traffic.

Vice versa, if the measurement location is fixed then the suitable instrument and suite of pollutants are given; for instance, if the measurements are to be conducted on highways, then the plume chasing instrument with focus on NOx emissions or the top-down RES instrument with all gaseous pollutants and some PM capabilities would be he instruments of choice. (Table 4). The effectiveness of the identification procedures has been demonstrated; however, being novel techniques, we strongly recommend more measurements to adjust these thresholds to the various driving conditions and vehicle categories – and new emission standards. This should urgently include roadside inspections where authorities can validate and benefit from these new possibilities for in-service testing and enforcement.

Table 4. Recommended use cases for the different remote emission measurement techniques investigated in CARES.

	NOx / HC / CO	PM / BC / PN
Light-duty vehicles	**Cross-road/top-down RES** Best: single lanes with moderate load/acceleration, avoiding stop-and-go and minimizing (known) cold-start influence. Several instruments to be placed in a row for robust identification of individual vehicles	**Point sampling** Demonstrated in urban, not too dense traffic. **Cross-road/top-down RES** For classification "with or without particle filter"
Heavy duty vehicles	**Plume-chasing (with focus on NOx)** On highways **Top-down RES** On urban as well as extra-urban roads; best to have several instruments in a row. **Cross-road RES** Needs careful choice of location and adjustment (of the height) of the instruments.	**Point sampling** Likely also working in urban, not too dense traffic **Cross-road/top-down RES** For classification "with or without particle filter"

For a successful identification of high-emitting vehicles, a certain set-up and procedure should be followed:

For cross-road and top-down remote emission sensing

- Place multiple RES instruments in a row to ensure several measurements per vehicle,
- Choose locations with moderate acceleration or slope, and best not prone to cold-start conditions,

For a live high-emitter identification it would be necessary to have the technical data, in particular the emission certification standard of the vehicle, live. Otherwise, the procedure is only robust for the old and worst emitting vehicles.

For plume chasing

- the vehicle should be followed for one minute or more, which is usually the case for trucks on highways.
- the inspector should be on-board of the chasing vehicle so that the vehicle can be stopped and inspected as soon as possible; fixed inspection sites strongly reduce the success rate.
- expertise and tools should be at hand to access the engine control unit and read out the emission relevant parameters. This has proven sufficient to establish whether tampering, malfunction, software, or cold start are the root cause for high emissions.

For point sampling

- needs single lanes and not too dense traffic to allow for a clear separation of exhaust plumes.
- should be placed down-wind of the road or at least down the dominant wind direction.
- needs an automated, live classification and transmission of the information to the inspector.

End note

The current situation is characterised by a plurality of high-emitter thresholds mostly developed by practitioners from the ground but a lack of cross-checking with roadside inspections. However, all campaigns so far have clearly demonstrated that the RES identification of vehicles with highly suspicious emission behaviour, light- and heavy-duty alike, greatly increases the chances for finding malfunctioning or tampered vehicles. It is important now to conduct roadside inspections so that the threshold level(s) and the necessary number or duration of measurements can be refined for the different vehicle categories and their certification emission standards on the one hand and of the required true positive (or accepted false positive) rate and the available inspection capacities.

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