uCARe

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uCARe consortium

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Executive summary

Emission legislation for motorised vehicles typically focuses on new models, who's effect on air quality only slowly takes form due to the existing fleet's inertia to change. Tampering with, or illegally modifying, emission control devices can substantially distort a fleet's impact as only a few high emitting vehicles with improperly working/removed emission control devices can be held responsible for disproportionally high contributions to poor local air quality.

This report documents an overview of what research has been done to date to estimate the impact of tampering, and to estimate its scale within the European Union. Whereas tampering with diesel particulate filters is mostly applied on light-duty vehicles, deactivating de-NO_x systems like selective catalytic reduction systems generally occurs in the heavy-duty sector. Nonetheless, as SCR technology is deemed to become the reference in light-duty diesel vehicles, it's only a matter of time before consumers try to bypass such systems. The impact of these measures are unambiguous, as a removed particle filter increased particle number emissions by a factor thousand, while heavy-duty de-NO_x bypassing increases NO_x emissions by a factor 4 to 20 for Euro VI technology.

Motives for tampering are diverse. Firstly, there's the perceived monetary gain of saving AdBlue® expenses and the avoided maintenance. Secondly, there's the emission test during periodic technical inspection, which often is incapable of detecting tampering. Lastly, there's the perceived lack of enforcement against it. In a survey held across different EU Member States, we asked for the local measures against tampering. The following recommendations came forward:

- PTI and roadside inspection directives should be urgently updated to reflect real-world issues with emission control devices and should be revised on a regular basis to stay aligned with the state-of-art. Member States seldomly perform stricter tests than what's required as a minimum by the European Commission.
- A registration of every action and/or assessment performed by repairers, roadside- and PTI inspectors concerning emission control systems should be stored on an international database. This allows for each vehicle to have a history in which one can trace illegal manipulations.
- Tampering in the widest sense of the word, including advertising, performing and trading of tampered vehicles and/or parts should be prohibited. This should be done by requiring Member States to lay down penalties for these offences.
- Roadside inspections should include light-duty vehicles, next to heavy-duty commercial vehicles,

The chain of responsibility in the ownership and operation of a vehicle including manufacturers, repairers and vehicle users would be strengthened through the following provisions. Firstly, vehicle manufacturers will be held accountable for the type approval of vehicles and is-use conformity through the stricter requirements in (EU) 2018/858. Secondly, vehicle owners will be stimulated to keep their vehicles in a good state through effective PTI and roadside inspections. Thirdly, repairers will be obliged to use certified anti-pollution replacement parts. Finally, a strict penalty system will discourage all these actors from breaching national laws.

Various technologies are present to detect high-emitters complementary to PTI, i.e. through remote sensing and/or plume chasing. An implementation of the latter two, however, mostly hinges on setting proper detection limits.

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Definitions & Abbreviations

CAL ID	……..	Calibration identification
CAN-bus	……..	Controller area network
cm^3	……..	Cubic centimetre
CO	……..	Carbon monoxide
CO_2	……..	Carbon dioxide
CVN	……..	Calibration verification number
CVUT	……..	Czech Technical University
DOC	……..	Diesel Oxidation Catalyst
DPF	……..	Diesel Particulate Filter
DTC	……..	Data trouble code
e.g.	……..	Example given
EGR	……..	Exhaust Gas Recirculation
etc.	……..	Et cetera
EU-28	……..	Abbreviation of European Union with 28 member states
EATS	……..	Exhaust after-treatment system
EC	……..	European Commission
ECU	……..	Engine control unit
HC	……..	Hydrocarbon
HD	……..	Heavy-duty
GPF	……..	Gasoline particulate filter
i.e.	……..	Id est
JRC	……..	European Commission’s Joint Research Centre
ISC	……..	In-service-conformity
LD	……..	Light-duty
LEZ	……..	Low-emission zone
LNT	……..	Lean NOx trap
NO	……..	Nitrogen monoxide
NO_2	……..	Nitrogen dioxide
NO_x	……..	Nitrogen oxide
OBD	……..	Onboard Diagnostics
OBM		Onboard monitoring
OEM	……..	Original Equipment Manufacturer
PEMS	……..	Portable Emissions Measurement System
PM	……..	Particle Mass
PN	……..	Particle Number
ppm	……..	Parts per million
PTI	……..	Periodic technical inspection
RDE	……..	Real Driving Emissions
RSI	……..	Roadside inspection
SCR	……..	Selective Catalytic Reduction
SEMS	……..	Simplified emission measurement system

1 Introduction

1.1 Background uCARe

With four million people dying annually due to outdoor pollution, improvement of air quality has become one of society's main challenges. In Europe, traffic and transport have a large effect on air quality, specifically passenger cars and commercial vehicles and to a lesser extent non-road mobile machinery. While technical improvements and more stringent legislation have had a significant impact, traffic and transport emissions are still too high and air quality is still poor. Although the use of electric and other zero-emission propulsion technologies may drastically reduce the pollutant exhaust emissions from traffic, the slow introduction of such vehicles as well as the trend of increasing vehicle lifetimes means that vehicles with internal combustion engines are expected to dominate the fleet beyond 2030. This project is the first opportunity to improve emissions of vehicles, not by improving vehicle technology, but by actively involving vehicle users and enabling their contribution to clean driving.

So far, expertise on pollutant emissions has mainly been used to advise European policy makers on limited effectiveness of emission legislation (through real-world emission factors such as HBEFA and COPERT) and how to reduce traffic and transport pollutant emissions. The numerous mitigation methods are rarely extended to include the perspectives of users. uCARe enables a next essential step: providing user targeted emission reduction measures. These measures will be implemented and evaluated in real-life pilot projects.

The overall aim of uCARe is *to reduce the overall pollutant emissions of the existing combustion engine vehicle fleet by providing vehicle users with simple and effective tools to decrease their individual emissions and to support stakeholders with an interest in local air quality in selecting feasible intervention strategies that lead to the desired user behaviour*. The overall aim is accompanied by the following objectives:

1. To identify **user-influenced vehicle emission aspects** (such as driving behaviour and vehicle component choice).
2. To determine the **emission reduction potential** of each vehicle emission aspect with help of the uCARe model developed within a toolbox.
3. To develop a **toolbox**, containing models and emission reduction measures, that enables stakeholders to identify the most appropriate intervention strategies that reflect the specific users and their motivation.
4. **Support policy makers** and other **stakeholders with an interest in air quality,** such as municipalities and branch organizations, **in identifying intervention strategies** that translate the measures into desired behaviour of the user.
5. **To test and evaluate** intervention strategies in a set of pilot projects conducted with various target user groups in at least four European countries. The pilot projects illustrate effectiveness and feasibility of the toolbox and intervention strategies developed on its basis.
6. Perform an **impact assessment** of the intervention strategies effectiveness, in terms of cost, penetration, achieved emission reduction and lasting effects.
7. **Actively feed** European cities and international parties with uCARe learning and results, via awareness raising campaigns, communication tools, interactive web application and other dissemination activities. Open access to the broad public to the toolbox, data and developed tools.
8. Summarise the findings **in blueprints for rolling out** different user-oriented emission reduction programmes, based on successful pilots.

This document is part of WP1. It addresses a very specific user behaviour: tampering of the vehicle.

1.2 Purpose of the document

With this deliverable, we want to raise the attention of policymakers to the impact of tampering on the pollutant behaviour of both light-duty (LD) and heavy-duty (HD) vehicles. Whereas the Euro emission limits have been progressively brought down by more than 90% since 1990 [1], the applied exhaust after-treatment systems (EATS) have become increasingly more sophisticated and more effective. This allows vehicle manufacturers to de-couple the on-going challenge for improving fuel efficiencies and compliance with emission limits, whereas before highly efficient EATS were introduced, fuel efficiency and emissions were often in balance. Nonetheless, ensuring extremely low emissions over the entire application range of a vehicle's engine remains an objective, specifically for diesel-fuelled engines.

Diesel technology is widely represented in the European road transport sector, especially when compared to other major car markets around the world. Reasons for this are divers. For light-duty applications like in passenger cars, the technology historically received substantial allowances to emit more nitrogen oxide (NO_x) emissions than positive injection vehicles (i.e. petrol, LPG, CNG, and so on), both through diverging emission limits in the consecutive Euro classes and through conformity (multiplication) factors during real-world testing for passenger cars using portable emission measurement systems (PEMS). The introduction of the latter by means of the Real-world Driving Emissions (RDE) packages[1] has significantly brought down in-use emissions of NO_x, although only part of the engine's operating range is covered in the current type-approval of new passenger cars. Concerning particulate matter (PM) and particulate number (PN) emissions, the introduction of the diesel particulate filter (DPF) since Euro 5 for LD vehicles has drastically brought down engine-out emissions.

Despite these technological successes, diesel cars remain an important source for persisting local air quality issues. One important reason for this is that EATSs aren't robust enough and hence can be tampered with. Tampering is a relatively undocumented field that deserves specific attention given the threat it induces. One manipulated vehicle can outdo the emission improvement techniques applied on a whole fleet of well-functioning vehicles. For this reason, we will focus on both what tampering practices are common, and what moves vehicle users to do this. Therefore, we summarize the latest findings from literature and discuss a survey that covers this topic across the European Member States.

1.3 Document Structure

This deliverable starts with the different ways of tampering for both light-duty (LD) and heavy-duty (HD) vehicles, including diesel and petrol engines, in Chapter 2. Then, we discuss the different options for detecting high emitters in real traffic. In Chapter 4, a literature study review is presented covering the impact and the scale of tampering throughout the EU. In Chapter 5 we discuss the findings from a survey that was performed across different EU Member States to encompass how/if national legislation tackles illegal manipulations to road vehicles. Finally, in Chapter 6 we look outside of the EU to see if

[1] Regulation 2016/427, Regulation 206/646, Regulation 1154/2017, Regulation 1832/2018

tampering is an issue in the US (California) and China. The conclusions and recommendations following this deliverable are presented in Chapter 7.

1.4 Deviations from the original DoW

1.4.1 Description of work related to deliverable as given in the DoW

"Its [Tampering] impact on pollutant emissions, occurrences and countermeasures"

This deliverable serves as a guidance through what is known to date about tampering with vehicle emission control systems. In addition, it describes the legal situation in the Member States on this topic.

1.4.2 Time deviations from the original DoW

As agreed with the Project Officer, a delay was allowed for the finalisation of this document for the following reasons.

- To streamline the conclusions during the General Assembly in Graz, Austria
- To make use of this GA to reach more respondents to the survey via the project members.

1.4.3 Content deviations from the original DoW

None.

2 Tampering, cases and motives

Contrary to the long-established and robust aftertreatment of petrol exhaust gases, diesel powertrains come with a complex exhaust line and measures to make their combustion gases comply with the emission standards. An example is given in Figure 1, which shows how a multitude of sensors and actuators are installed to control 1) the oxidation of carbon monoxides (CO) and unburnt hydrocarbons (HC) in the diesel oxidation catalyst (DOC); 2) the accumulation and controlled regeneration of particulate matter (PM) and particle numbers (PN) in the diesel particulate filter (DPF), and; 3) the conversion of NO_x to harmless substances like carbon dioxide (CO_2), nitrogen (N_2) and water (H_2O) by an injection of a urea-water solution (commercially known as AdBlue®) prior to the selective reduction catalyst (SCR). Excluded from this example is how exhaust gas recirculation (EGR) into the combustion chamber is implemented in modern diesel engines to bring down combustion temperatures and thus NO_x emissions. This example also does not include a post-combustion regenerating NO_x storage system like a lean-NO_x-trap (LNT). All these components are monitored by onboard diagnostics (OBD) for proper functioning, although currently, no direct measurements of emissions take place using OBD. Instead, it relates inputs from the various sensors to situations for which emissions were measured during the type-approval process of the vehicle, to decide whether the exhaust gas aftertreatment system is working properly.

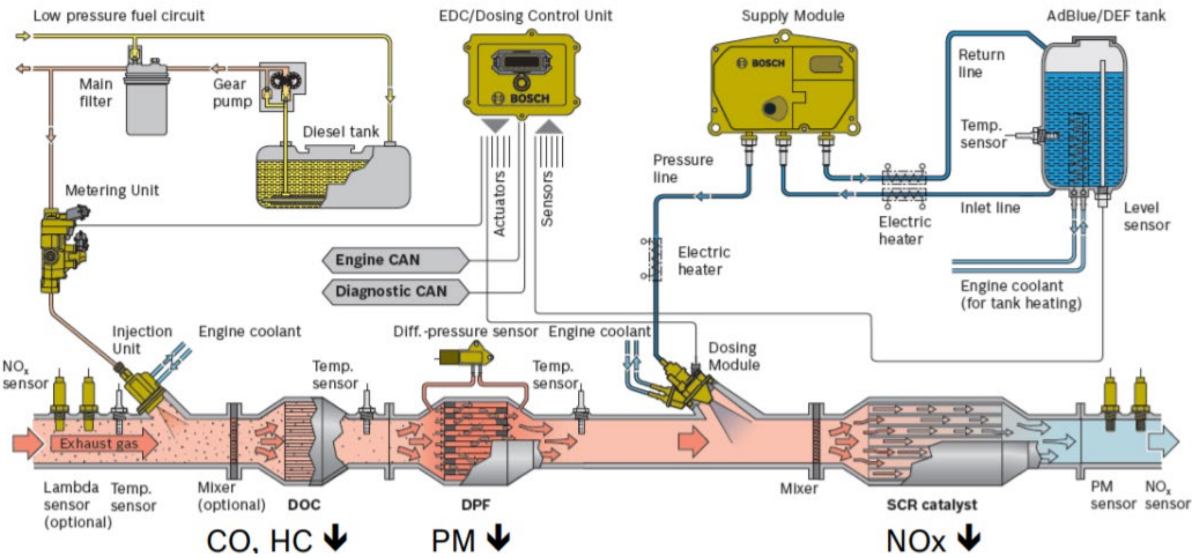

Figure 1 - An example of a diesel vehicle's exhaust line (source: Bosch)

Table 1 and Table 2 present an overview of the Euro emission standards for PM and NO_x for both diesel passenger cars and trucks, combined with the exhaust aftertreatment systems that were introduced to reach these respective targets. Whereas these technologies are proven to be effective in reducing the exhaust pollutants for diesel engines during type-approval, issues persist for being as effective in *every* real-world driving situation. On top of that, they are susceptible to being tampered with by vehicle owners. The fact that engines are calibrated for high efficiencies, and thus potentially high engine-out pollutant emissions, emphasizes the impact that tampering can have on both an individual vehicle level and a fleet level. The contribution of high-emitters to total fleet emissions is discussed further on in Chapter 3.

For heavy-duty vehicles (HD) and light-duty vehicles (LD), differences can be noticed in terms of which form of tampering currently takes place. In the paragraphs below we provide a list of the most frequently occurring tampering methods and what drives consumers/vehicle owners to do so.

Table 1 - PM and NO_x emission limits and applied exhaust after-treatment systems for light-duty diesel vehicles in Europe [1]

	Since	NO_x (mg/km)	PM (mg/km)	PN (#/km)	Exhaust After-Treatment System applied
Euro 1	1992	970	140	-	-
Euro 2	1996	700	80	-	-
Euro 3	2000	500	50	-	DOC
Euro 4	2005	250	25	-	EGR+DOC
Euro 5a	2009	180	5	-	Cooled EGR+DOC+DPF
Euro 5b	2011	180	4.5	$6x10^{11}$	Cooled EGR+DOC+DPF
Euro 6	2014	80	4.5	$6x10^{11}$	Cooled EGR+DOC+DPF+LNT/SCR

Table 2 - PM and NO_x emission limits and applied exhaust after-treatment systems for heavy-duty diesel vehicles in Europe [1]

	Since	NO_x (g/kWh)	PM (g/kWh)	PN (#/kWh)	Exhaust After-Treatment System applied
Euro I	1992	8.0	0.35	-	-
Euro II	1996	7.0	0.15	-	-
Euro III	2000	5.0	0.10	-	
Euro IV	2005	3.5	0.02	-	Cooled EGR/SCR
Euro V	2008	2.0	0.02	-	Cooled EGR+DOC+SCR
Euro VI	2014	0.46	0.01	$6x10^{11}$	Cooled EGR+DOC+DPF+SCR

2.1 Exhaust gas recirculation tampering

The exhaust gas recirculation (EGR) system and its intercooler tend to clog with carbonaceous soot due to upstream issues such as worn or broken piston rings or leaking turbo seals, allowing oil into the EGR intake. Other causes can be rich running engines and/or faulty injectors or improperly working lambda sensors. As a result, the EGR valve may no longer open or close properly, causing the engine to run poorly in idle speed, to run at reduced power, and so on. Proper maintenance would include cleaning the EGR housing (or to replace it in the worst case) and diagnosing what causes it to clog. As this can easily turn out to be a costly operation, consumers can be tempted to disable the entire system and save on (recurring) maintenance costs.

Disabling the EGR can easily be done by means of deleting its functionality from the engine control unit (ECU) via a remapping (reflash). Another option is to mechanically block the EGR gas tube or by sealing the hose to the vacuum actuator, although this form of tampering is more susceptible to being noticed during a periodic technical inspection (PTI).

2.2 Diesel particulate filter tampering

DPF systems tend to clog when a diesel vehicle is only used for short-distance trips, preventing the exhaust gas temperatures to rise for a longer period to allow a regeneration of the filter, e.g. when driving on a motorway. As HD vehicles typically cover many kilometres at motorways speeds, this DPF problem is virtually only reported for passenger cars. Next to the failure to reach higher exhaust temperature, higher engine-out soot emissions can be caused by, for example, underlying problems such as a poorly maintained fuel system or chip-tuning for higher engine performance. A gradually clogging filter will increase the back-pressure of the exhaust gases when leaving the combustion chamber, thereby leading to fuel consumption increases. If no regeneration event can take place, the entire filter fills up and eventually prevents the engine from starting. Solutions are to clean the filter substrate and to repair the problem that is causing higher engine-out emissions. In the worst case, the filter needs to be replaced, coming with a cost that can easily exceed €1,000-€2,000.

Due to the high replacement costs, complete removal of the filter becomes an attractive solution if it can go unnoticed by enforcement measures, for instance during periodic technical inspection (PTI). This is currently the case as the applied PTI smoke opacity test shows no correlation with the actual emissions of PM/PN [2]. Besides the physical removal of either the filtration element or the whole canister, the engine’s control unit will need to be misled as the differential pressure sensor needs to provide a signal to the engine control unit (ECU). Like the EGR case, the ECU needs to be ‘re-flashed’ to delete the pressure sensor from the onboard diagnostics (OBD) ‘scanning field’ or to simulate its functionality.

2.3 Selective catalytic reduction tampering

SCR systems require an AdBlue® injection to allow for a NO_x reduction. Typically, AdBlue® consumption is equivalent to 3-5% of the fuel consumption of a vehicle and the cost of AdBlue® is approximately half that of diesel[3]. Thus, next to a complex system that is susceptible to costly repairs due to wear and defects, operational costs can sum up to €1,000-€2,000 per truck per year. Therefore, the incentive for truck owners/fleet operators to disable the SCR becomes viable. ‘Removals’ take place in two ways:

- Physically using an emulator that is placed between the SCR’s sensor(s) and the engine’s ECU to mimic its functionality

- Software-wise by re-flashing the ECU

Emulators can simulate both the reagent level, a proper functioning NO_x sensor and provide feedback to the ECU as if everything is working correctly but can also signal to the ECU that no AdBlue® injection is needed by reporting false reagent tank temperatures. These devices can come tuned for virtually every truck brand to show the correct vehicle identification codes in the data it communicates over the CAN-bus to the ECU to prevent being detected as an aftermarket (non-OEM) part. Finally, both ways of tampering can be complemented by the removal of the SCR+DPF combination, although this isn't necessarily needed.

2.4 Petrol car tampering

The focus concerning pollutant emissions is generally set on diesel cars. However, one should not forget that petrol cars can be manipulated as well, although such measures are far less common in daily practice. Given that car manufacturers must guarantee a good condition of the emission-related devices throughout the 'useful' lifetime of 160,000 km, three-way catalysts can deteriorate to an unacceptable extent afterwards. If such defective vehicles are detected during a periodic technical inspection (PTI), repairs are required. A German study on the performance of aftermarket (non-OEM) three-way catalysts revealed that many of them are nearly uncoated and thus ineffective in converting pollutants. As a result, repaired petrol cars may emit NO_x emissions many times higher than allowed. A TüV Nord investigation, in fact, pointed out that 3 out of 4 EU Certified aftermarket catalysts did not work correctly. Moreover, 3.5 million of these devices are estimated to be installed in Germany alone, with about 1% of them currently detected during PTI [4]. This indicates both the need for a robust testing of aftermarket devices and an adequate methodology to detect high emitters.

3 Identifying high emitters

Both design, maintenance, usage and fuel quality play a role in high emissions from (older) vehicles. Illegal tampering comes on top of that and may affect even the most recent vehicle types. The extent to which tampering occurs across the EU, however, is largely unknown [5]. Therefore, the need for robust methods to identify high emitters is currently a topic of debate and research. Identification is important as more and more cities are implementing their own measures to improve local air quality issues by implementing low-emission zones (LEZ). The access to these LEZs is often based on the first registration date and/or Euro-class of the vehicles. This approach is problematic as abundant scientific evidence points out that barely any reduction in NO_x emissions is reported between Euro 1 and Euro 5 for passenger cars. Moreover, the most significant real-world Euro 6 reductions are yet to be realised, with the latest models certified for Euro 6d limits only being sold from January 2020 onwards. With emission reductions taking place for the newest vehicles, we shouldn’t forget about the existing fleet that carries a certain inertia against sudden air quality improvements as, on average, European passenger cars stay in use for 15 years. This is precisely where project uCARe shows its relevance.

Five main ways of detecting high-emitters are discussed in this chapter, i.e. PEMS/SEMS, remote sensing, plume-chasing, periodic technical inspection and roadside inspections. In addition, one extra option of company auditing (in case of HDV fleet operators) is discussed.

3.1 Portable emissions measurement systems

Real-world driving emissions can be measured by re-testing vehicles with portable emission measurement systems (PEMS). This will become mandatory for EU Member States with the introduction of in-use conformity testing and market surveillance under (EU) 2018/858 and is the reference methodology for comparing results with type-approval data. Due to both cost and time restraints, as well as the technical expertise that is needed to perform the tests, only a limited number of vehicle models will be tested annually per Member State. Therefore, simplified emission measurement systems (SEMS) can be a more suitable option as they can be applied to a larger number of vehicles for the same price. Nonetheless, an extended sampling period is advised before statements can be made on the pollutant behaviour of a specific model. Whereas SEMS offers acceptable accuracy levels for testing, it remains too time-consuming and too expensive per vehicle for fleet wide detection of tampering. It can however be very useful for gaining insights into the real-world behaviour of tampered vehicles. For detecting high emitters in entire fleets, other, more suitable, options should be explored.

3.2 Remote sensing

This technique has been applied for many decades following the developments by the University of Denver (US) in the late 1980s [6]. Recently it is gaining a lot of attention due to its ability to scan large fleets without intervening in traffic, which is of particular interest in light of the market surveillance to be applied by each Member State from September 2020 onwards. To date, however, remote sensing has primarily been used for research purposes, although the various performed studies point out the effectiveness of the technology for gaining insights into fleet emissions in realistic situations. Research findings from studies throughout Europe are currently being grouped in the CONOX project [7] to enhance collaborations between institutes and to get a better understanding of how results should be interpreted. Moreover, such pooling of results allows for detailed monitoring of trends throughout the years and for gaining insights on different levels of details. Thus, we can observe impacts ranging from a fleet-level to the level of specific models, characterised by different fuel types, Euro class, and so on. These impacts can be observed for a wide range of driving conditions and ambient conditions. These latter two are of specific interest for fine-tuning local/regional air quality models to fit as closely as possible to reality.

Currently, a specific challenge is finding a good correlation between remote sensing measurements and results from PEMS-based type-approval. During PEMS-based type-approval, a significant part (but not all) of the engine's operating range is scanned for pollutant behaviour. If the same vehicle passes the lens of a remote sensing device, a snapshot is taken that represents only one point in this engine operating range. Whereas preliminary results from such comparative studies indicated good correlations between instantaneous emissions of NO_x as a function of the vehicle's specific power, the European Commission's Joint Research Centre (JRC) recently confirmed a good agreement of the observed pollutants to CO_2 ratios between remote sensing and PEMS-based measurements [8]. Nonetheless, it is more realistic to think of remote sensing as a *complementary* means to PEMS in terms of market surveillance, i.e. more as a non-intrusive way to cover entire fleets and to highlight suspicious vehicle models. For the evaluation of an individual vehicle, relying on one snapshot of its exhaust plume is not enough to improve enforcement. However, if the same vehicle is tested multiple times on the same trajectory or has passed the lens of a mobile unit several (preferably up to 20+) times, a more robust evaluation can take place and the chance for false positives in terms of detecting suspicious vehicles decreases [9]. Additionally, transient emissions can be many times higher than the emission limit, which creates the need for multiple remote measurements. Type-approval testing considers the *average emissions over the driven test route*, and so these transients are levelled out and thus accepted.

Referring to an existing fleet's inertia to real-world improvements of pollutant emissions, as discussed before, a similar inertia is transposed in legislation for in-service compliance testing. Thus, it will only relate to Euro 6d vehicles which are sold from 2020 onwards, leaving out what's already driving our roads. This once more emphasises the relevance of the uCARe project as it focuses on the existing fleet with simple measures for vehicle users to reduce their environmental impact locally. In addition, remote sensing proves its worth as it provides the necessary insights on the impact of the vehicles that are currently in use and will continue to be sold on the EU car market for the next two decades.

Another challenge with remote sensing is to set measurement limits that are strict enough to detect tampered vehicles and/or high-emitters due to wear, ageing and defects, while not being too strict to prevent false positives. In this light, several pilot studies have been launched in the last two years where local police forces together with remote sensing specialists have attempted to come up with an efficient way of selecting suspicious vehicles rather than focussing on risk profiles of HD haulage companies. The latter methodology is currently applied for roadside inspections following Directive (EC) 2014/47. To date, however, most attention goes to tele-detection of trucks as SCR tampering is far more pronounced for this sector than it is for light-duty. In fact, with SCRs being applied mainly on the most recent diesel cars, virtually no evidence exists of its manipulation by consumers. For light-duty, DPF tampering is more pronounced, as well as EGR manipulation. Suspiciously high emissions will nonetheless come to light in the uCARe project for those vehicles that are monitored for onboard sensor data through the OBD-port for post-driving feedback.

DPF tampering remains difficult to assess using remote sensing, as a robust methodology to determine PM/PN emissions outside of assessing the exhaust gas opacity has not yet been developed. Moreover, vehicles fitted with DPFs emit particles in the nanometre (one-billionth of a metre) range, for which most stationary measuring technology cannot measure, especially considering the distance between remote sensing devices and passing vehicles. Additionally, dependent on the location of the remote camera, snapshots might record a regeneration event of the particle filter., This stresses the need for multiple measurements per vehicle to make well founded conclusions. To counter this issue, research by the Czech Technical University (CVUT) is focussing on laboratory-grade, fast-response instrumentation to sample roadside PM concentrations expressed per kg of fuel burned. Moreover, they are investigating the correlation of the results from these highly sensitive instruments with the results from ionization chamber technology used in household smoke detectors which are capable of measuring particles in the 30-150 nanometre size range. Preliminary results show reliable readings for particle concentrations above 100,000 particles per cubic centimetre (cm^3), this instrumentation is thereby capable of detecting defective filtration systems due to cracks or leaks [10].

3.3 Plume-chasing

Plume chasing or sniffer cars are an alternative method to determine the real-world emissions of vehicles. This is done with a vehicle equipped with frontwards facing measurement devices that follows heavy-duty vehicles on highways. As discussed before, highways are selected due to the decreased chance of transient engine emission peaks. Additionally, highway operation leads to hot, loaded engines at higher speeds, which are preferential for evaluation as this is the zone in the engine operating range where SCR systems are active by injecting AdBlue® to reduce NO_x emissions. As is the case for remote sensing, no direct measurement of pollutants takes place but rather the concentrations relative to CO_2 are recorded, serving as a proxy for fuel consumption. Background concentrations from outside of the exhaust plume are detracted from the sample. For calculating pollutant concentrations, certain assumptions need to be made, like the engine's efficiency and the carbon content of the fuel [11].

Plume-chasing allows for more detailed insights into the real emissions of a targeted vehicle as targeted vehicles can be followed for several minutes if needed. In this view, it differs from the snapshot-nature of remote sensing. The main difference however is in the number of vehicles that can be processed per day. Plume-chasers can still cover hundreds of vehicles per day, but this is in general substantially fewer than in remote sensing. Hence, a balance between quantity of vehicles and quality of measurements applies.

3.4 Periodic technical inspection

Periodic technical inspections (PTI) have a strong potential for enforcement against both poor maintenance and tampering as every light and heavy-duty road vehicle should be inspected at least every two years. To date, this potential has barely been utilised as the minimum requirements for a PTI emission test following Directive (EC) 2014/45 do not match the pace of the technological innovations that have taken place in the automotive industry over the last decades. As such, the evaluation of diesel exhaust gases refers to mechanical engines developed thirty years ago by assessing their opacity. Since the introduction of high-pressure injection, soot particles have significantly decreased in size, while visible particles (in the size range of 10 micrometres) have been entirely removed by the introduction of diesel particulate filters. Even with defective filters or completely removed ones, the applied opacity thresholds are only rarely reached due to the very poor (to non-existent) correlation between opacity and PM/PN emissions [2]. Most likely, the rare cases where the thresholds are reached refer to vehicles for which the DPF was removed due to underlying symptoms caused by oil consumption (see paragraph 2.2 Diesel particulate filter tampering), resulting in measurable engine-out opacity levels. As it has been reported in the Czech Republic, DPF systems can even be 'rented' solely to pass PTI with such vehicles, to be removed again afterwards [12].

In addition to the fact that current measures do not allow for DPF presence or functioning, no other emission reduction systems (EGR, DOC, LNT, SCR) are tested during PTI. Both outdated measurement methods, as well as inaccurate instruments and the fact that inspectors are restricted to visual inspections without removing any parts, can be pointed to as root causes for today's PTI ineffectiveness. Given the potential effects that come with the high efficiencies of EATSs when illegal manipulations take place, we can conclude that the PTI emission test for modern diesel vehicles is currently nothing more than 'pro forma'.

Here, the continuing lack by the European Commission and the Member States to push for a thorough update for testing diesel EATSs, considering the ineffectiveness of current measures has been clear for many years, can be seen as an act of irresponsibility in terms of closing the loop on keeping track of a vehicle's emissions throughout its lifetime. This further emphasises the need for additional attention to the existing vehicle fleet by the European Commission and member states, as opposed to solely focussing on the introduction of legislation for new vehicles.

So what options are there for innovating the PTI emission test? Further decreasing the opacity limit isn't one of them as the accuracy limits for current PTI opacimeters is around 0.3 m^{-1} and thus not suitable for (extremely) low smoke levels [1]. NO_x testing requires engines to be loaded to show representative emissions, and thus requires dynamometers in PTI test centres. Several studies have been published by CITA, the international motor vehicle inspection committee, on potential short tests on dynamometers, however, none of these have been recommended yet for PTI application [13]–[15]. Acknowledging the high NO_x emissions of the majority of the pre-Euro 6d-TEMP diesel cars driving on European roads originates from a weak type-approval process, according to Directive (EC) 2007/46, the question then arises whether NO_x testing for these vehicles during a PTI test makes sense if virtually all of them exceed the Euro emission limits by several factors. For the latest generation of diesel vehicles, fitted with SCR systems and therefore capable of reaching very low NO_x emissions, a test should be developed that at least represents a thorough check of the functionality of its sub-systems by for example:

- disconnecting NO_x sensor(s) and monitoring OBD changes for consistent actuator operation;
- disconnecting urea injection wiring and tank level detectors and monitoring OBD changes;
- cross-checking the running ECU programme with the original one to detect re-flashing; etc.

Including the measures listed above requires amendments to the current PTI directive that encompass including the latest EATS technologies in the inspector's checklist and allowing the inspector to remove parts for inspection. Another option could be to complement PTI with remote sensing so the highest-emitters would be referred to an elaborated emission test where specific attention is given to defects, manipulations and illegal removals by both physical inspections and scanning the vehicle's communication over the CAN-bus for irregularities based on the best available practices. Such tests can either be performed by specialised test centres accredited by the national type-approval authority or by specialised PTI centres. As such, a mandatory emission test for *every* vehicle could become obsolete. The share of the PTI bill relating to the emission test could subsequently be shifted to funding remote sensing on a national level. However, as there is no robust way known yet for detecting PM/PN emissions via remote sensing, other options need to be explored. Using particle number testers to evaluate DPF functionality is a viable way that is close to being implemented in the Dutch PTI, to be followed swiftly by others like the

Belgian, Swiss and German ones once threshold limits have been agreed upon and transposed in national law.

PN testers are capable of detecting filtration efficiency losses as low as 1-10%, making it the only method that is sensitive enough to assess nanometre-size emissions and thus allowing for the smallest irregularities to be traced to issue repairs as soon as possible. This is very relevant as the most sensitive size range for the human respiratory system is the most intensive emission range of engines and the size range most poorly filtered [1]. Moreover, only small defects in the filter can already increase the emissions by orders of magnitude [16]. Also, the near absolute filtration efficiency of DPF systems indicates the impact of defects, as just one defective DPF can double the overall PM/PN emissions of an entire fleet, while a removed one can increase this impact by an order of magnitude [12].

Prior to implementing the PN test in PTI, both a test methodology and a suitable pass/fail threshold need to be agreed upon. Contrary to type-approval procedures, PTI tests should be simple and quick to perform and should be applicable in roadside inspections as well. Moreover, PTI may not be more stringent than type-approval. Research by Kadijk et al. pointed to acceptable correlations between PN emissions during low idling and NEDC testing, indicating the option of an easy test that is very similar than the current CO test for idling petrol cars [17]. Concerning the test limit, several studies have pointed out how diesel cars in proper condition typically emit between 5,000 and 10,000 particles/cm³, whereas high emitters can emit over 100,000 particles/cm³ and up to 1,000,000 particles/cm³. Therefore, a test limit should be defined within the range of the latter two. Switzerland has had PN limit for construction engines of 250,000 particles/cm³ in force since the year 2000. This target limit has been deemed high enough to allow Euro 5b and 6 vehicles with a well-functioning DPF to pass the PTI test independent of (potentially large) influences from engine temperatures, filter loading and the state of the EGR system [16]. For Euro 5a, 4 and 3 equipped with a DPF, TNO proposes a threshold between 1,000,000 and 1,500,000 [17].

For petrol cars, the current PTI emissions tests don't go far either as only the concentration of CO and 4-gas analysis (CO_2, CO, HC and O_2) by means of the Lambda value are checked during idling. Although this test is very simplistic and assesses only a minor area of a petrol engine's operating range, it is robust enough to assess the functionality of (original) three-way catalysts. Nonetheless, aged or improperly coated three-way catalysts can have high NO_x emissions, while modern – directly injected – petrol engines can have significant PN emissions. For this reason, they are subjected to the same PN type-approval limits and require gasoline particle filters (GPF). GPFs are less efficient (about 80%) than their diesel counterparts, as raw emissions are lower than those from diesel engines. Therefore, including NO_x and PN in the PTI test would be valuable.

3.5 Roadside inspection

Roadside inspections (RSI) are a fifth means to detect vehicle tampering. Directive (EC) 2014/47 sets a minimum requirement for testing commercial vehicle categories N2, M2, N3, M3, trailers categories O2 and O3 as well as tractors category T5 that are mainly used on public roads with a maximum speed exceeding 40 km/h. Moreover, the Directive advises basing the selection of the vehicles to be inspected on the risk profile of the haulage company, for which a risk classification system is presented. This approach has a drawback as it results in an inefficient detection rate for tampered vehicles. When enforcement officers assist a commercial HDV to the side of the road for inspection, they are referred to the PTI emissions test methodology and limits, although they can also scan the vehicle for illegal manipulations. Finding emulators, however, is challenging as hardware emulators are progressively reducing in size meaning can be hidden in the wiring harness of an engine, and plug-and-play emulators can be quickly removed/deactivated by the driver. For software tampering, the chances of finding evidence are further limited and often require assistance by a representative of the vehicle manufacturer to scan for re-flashes of the engine control unit's (ECU) running programme with original equipment manufacturer (OEM) software. If needed, vehicles can be prompted to be thoroughly checked in the nearest technical inspection centre.

A special clause adopted in the (EC) 2014/47 indicates the possibility for using remote sensing equipment to detect suspicious vehicles that are to be tracked down for further inspection. Only a few Member States have applied this option in pilot projects to date, for which results will be discussed in chapter 5.

In Spain, remote sensing will be implemented for scanning commercial vehicles circulating on national territory, while a Royal Decree has been drafted to include passenger cars and light-commercial in roadside inspection as well, providing traffic authorities with remote sensing as a primary selection tool. The draft includes established emission limits for NO, CO, HC and PM, although it hasn't yet passed Congress.

Currently, only a limited number of EU Member States include every vehicle category in RSI (to be discussed in chapter 5) while local enforcement lacks both the high-level knowledge on tampering techniques as well as a robust emission measurement methodology and suitable measurement equipment. Therefore, a primary selection of suspicious vehicles using remote sensing/sniffer cars can be a first important step to increase the catch rate for illegal manipulators. In combination with roadside inspections, random emulator searches during PTI can be implemented.

3.6 Other measures

AdBlue® fraud in the commercial vehicle sector can be detected by performing audits on a company's administration concerning fuel expenses. If assumptions are made on an average AdBlue® consumption per kilometre driven, the expected expenses for it can be checked with the company's administration [3]. Finally, random checks for potential fraud at the premises of transport companies can serve as a strong deterrent.

3.7 Summary

High-emitters due to ageing, wear, manipulation and tampering need to be detected and enforced as efficiently as possible. In this chapter, six measures have been discussed for their potential in keeping track of the evolution of the existing fleet's emissions after type-approval. This is highly relevant as legislation is changing for the new generations of vehicles through a new type-approval framework, in-service testing and market surveillance following Reg. (EU) 858/2018. However, the existing fleet remains largely out of scope as these vehicles were type approved under a different legal framework. Therefore, the existing measures for PTI and roadside inspections need an update to account for the state-of-art of current technology, while enforcement organisations need adequate methodologies and test limits. In summary, strong enforcement should include:

- Efficient fleet scanning tools such as remote sensing and chaser/sniffer cars;
- Roadside inspections for every vehicle category with dedicated guidelines for detecting fraud
- Periodic technical inspections that include meaningful tests for checking the efficiency of current emission control devices like DPFs and SCRs
- Auditing transport companies for AdBlue® expenses, combined with ad-hoc/random checks for tampering

4 Impact and scale of tampering

Whereas the actual scale of tampering across the European Union remains largely unknown to date, several pilot studies that have been performed over the last years allowing us to grasp to what extent the phenomenon impacts vehicular emissions. What is known, is that SCR tampering is mainly an issue for the HD market (for now), while DPF and EGR tampering, as well as chip-tuning typically occurs on passenger cars. Nonetheless, enforcement measures countering SCR fraud in passenger cars are needed urgently as the technology comes with virtually every new diesel model due to stricter real-world driving (RDE) emission limits for NO_x. In the following two sub-chapters, we will highlight the findings from both DPF and SCR manipulation studies.

4.1 DPF defects and manipulations

Diesel particulate filters are extremely efficient in trapping both particulate mass (PM) and number (PN) emissions. Despite their effectiveness, a small leakage in the filtration element, for instance, due to a crack, can result in an increase of PN emissions by several orders of magnitude. In case of complete removal of the filter, one such vehicle can emit as much as hundreds of properly filtered vehicles. In terms of particle concentration, Burtscher et al. estimate that roughly 10% of the highest emitters cause about 85% of the fleet emissions [16]. This is shown in Figure 2.

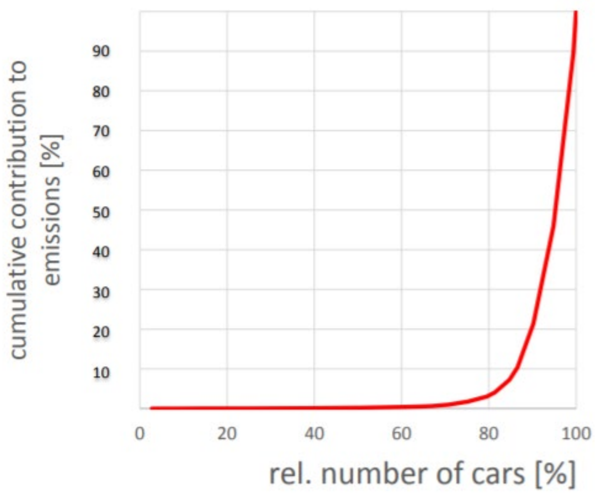

Figure 2 - The cumulative contribution to particle concentrations emitted on a fleet-level [16]

Vojtisek et al. performed a pilot study in Prague to assess the extent to which high emitters contribute to the total PM emissions [12]. Moreover, they wanted to show the impact of roadside inspections, which only rarely take place. They reported that DPFs are often removed due to excessive engine-out PM emissions as a result of poor engine maintenance and/or chip-tuning for increased performance. As it's a cheaper option to remove the DPF rather than to 'dig' deeper and diagnose what causes the higher PM emissions, the decision is often made quickly if consumers perceive that no enforcement exists against such manipulations. As reported by Vojtisek et al., Czech consumers can simply 'rent' a DPF installation prior to PTI, to have it removed again afterwards. In this way, tampering also gets a behavioural aspect as consumers perceive the cost 'benefit' of the avoided maintenance far more important than the environmental consequences of their actions.

Where eco-driving touches upon fuel consumption and thus on the operational costs of driving a vehicle, driving 'environmentally friendly' in terms of local air quality is something large parts of the driving population don't place a high value on. Here, continuous education will prove to be key. In the specific Czech case for removing DPFs the consequences are substantial, as they are estimated as follows:

- 1% of a fleet with a broken DPF doubles the emissions of the whole fleet, while;
- 1% with a removed DPF due to excess engine-out PM (x10) emissions increase fleet emissions by a factor 10.

The Prague roadside measurement campaign resulted in nearly 2.000 unique license plates recorded, of which 64% were diesel-fuelled of which half were DPF-equipped. In total, usable samples were taken from nearly 500 vehicles, of which 150 had a DPF. 5,4% of these were found to have a defective filtration system, which is in line with 5-7% TNO estimated for the Dutch fleet in 2014 [19]. For those vehicles with working DPFs, practically no PM measurements were registered, indicating that virtually all measured particulates originated from the 5,4% with defective DPFs and older pre-DPF diesel vehicles. Figure 3 shows how such a small percentage of high emitters can be held responsible for about 50% of the total PM emissions. What can be concluded from this pilot study is that the polluting behaviour of diesel vehicles with broken/missing DPFs is not the same as that of a pre-DPF diesel vehicle. The reasoning hereto is that those malfunctioning vehicles have maintenance issues upstream of the DPF, causing higher engine-out PM/PN emissions. Extrapolating the findings from the 500 useable samples to the entire measured fleet during the Prague pilot, about 9% of the DPF-equipped diesels were found to be faulty.

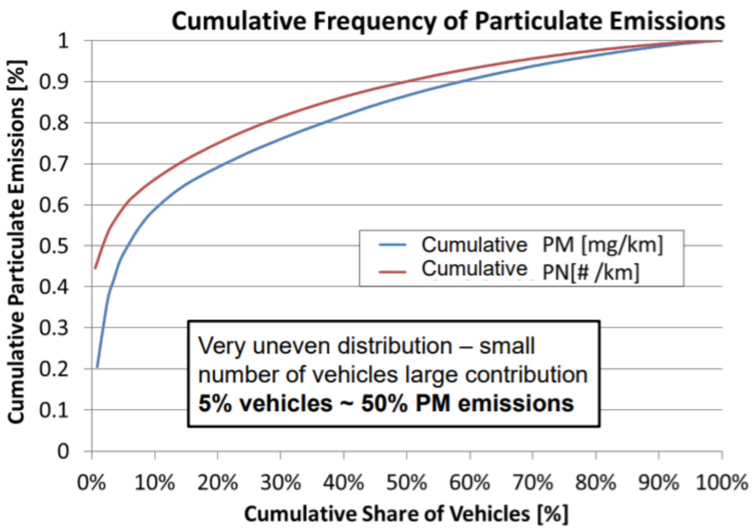

Figure 3 - 12% of PM and 55% of PN originates from roughly 5% of the fleet fitted with a defective/missing DPF [10]

Mayer et al. reported that diesel filtration systems manage to bring down engine-out PN emissions from about 5E+06/cm³ to 5E+03/cm³ or by three orders of magnitude, which is lower than ambient concentrations [20]. This is confirmed by idle PN tests by Kadijk et al. that show properly filtered diesels typically emit less than 5E+03/cm³, while about 10% of the sampled fleet emitted more than 2.5E+05/cm³ [21]. Swiss DPF failure statistics for 2017 indicate that damaged or manipulated DPF/GPF systems emit 100-1,000 times more particles than maintained variants. Correcting DPF failures which in vehicles with emissions over 1E+05/cm³ would improve fleet average emissions by a factor >10. Moreover, high emitters with removed DPF systems, emitting more than 1E+06/cm³ are estimated to contribute more than 90% of a fleet's PN emissions [22]. Finally, TNO simulated a DPF leakage by bypassing the DPF using an adjustable valve connecting two stainless steel hoses to the exhaust line before and after the filtration system. Results in Figure 5 indicate the effectiveness of a DPF when the engine is warmed up (1.31E+07 particles/km), and less efficient filtering during warm-up after cold start, although this effect is dwarfed by the various simulated leakages. Figure 5 shows the impact of simulated 'removed' DPF, corresponding to DPF bypass position 4 in Figure 5.

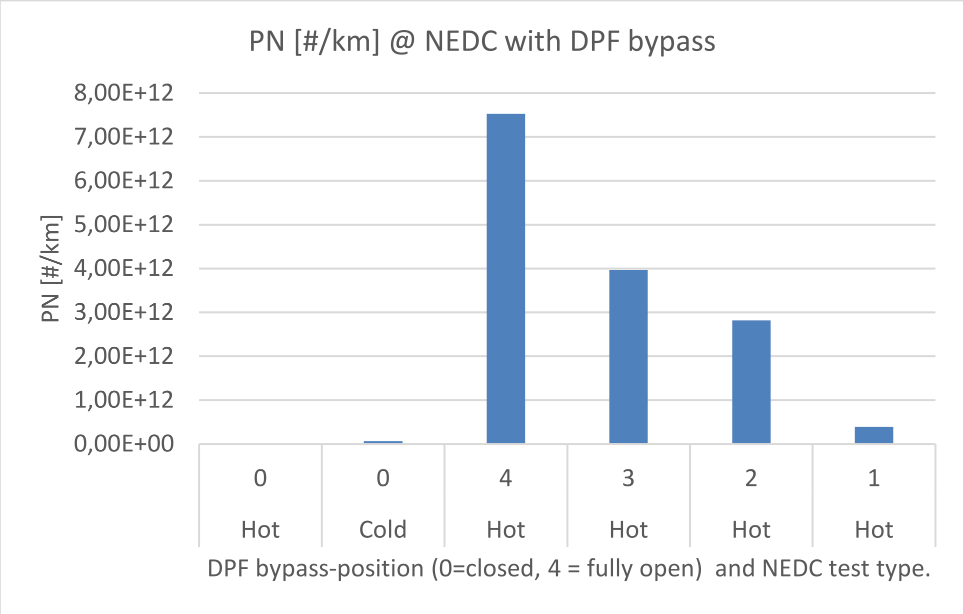

Figure 4 - Overview of the influence of both a cold start and a variable DPF leakage simulated by an adjustable bypass (TNO), properly filtered diesels typically emit less than 5E+03/cm³.

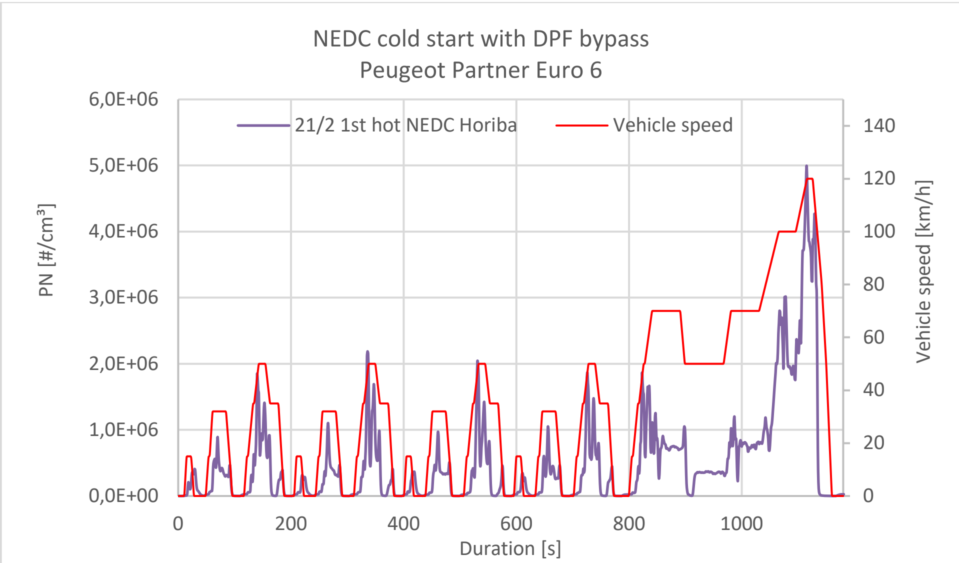

Figure 5 - Detailed PN emissions over the NEDC with a complete DPF bypass (cf. position 4 in figure 4) (TNO)

4.2 SCR defects and manipulations

4.2.1 Potential impact of tampering with SCR systems

To investigate the potential impact of tampering with SCR systems, we can look at the difference between engine-out and after-catalyst NO_x emissions. Figure 6 shows the difference as a function of vehicle speed and CO_2 emission (Figure 6, left), as well as the amount of time spent in each area of the vehicle speed – CO_2 map (Figure 6, right). The bin, which is occupied for the longest amount of time, in this case 3 minutes, has an average difference of 1.5 g/s between engine-out and after-catalyst NO_x emissions. If the engine-out emissions were emitted directly, these 3 minutes would lead to an extra NO_x emission of 270 g. Considering current NO_x emission limits are on the scale of less than 1 g/km, direct emission of engine-out NO_x would have an enormous impact.

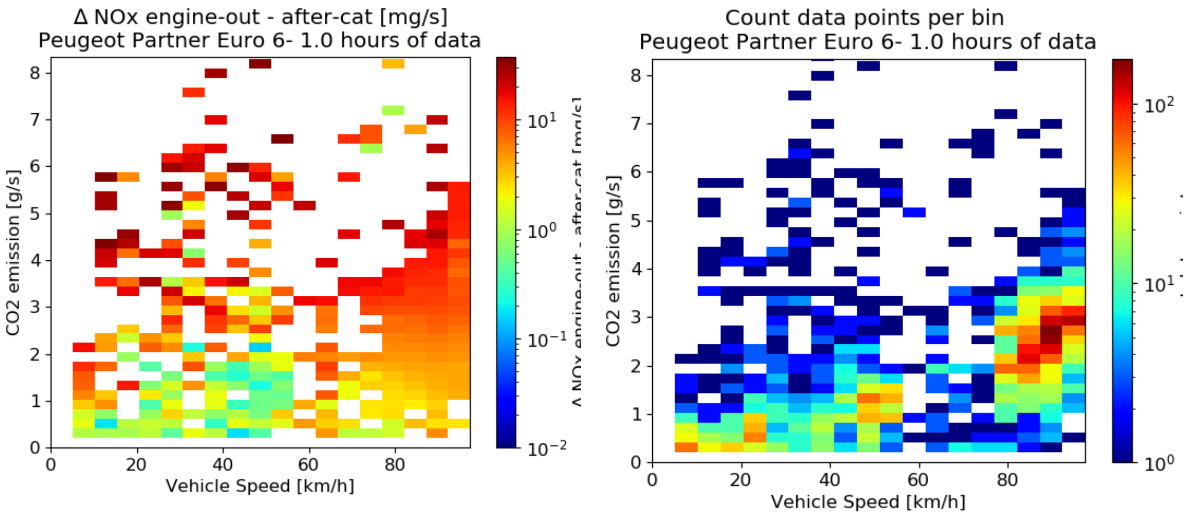

Figure 6 - (Left) Difference between engine-out and after-catalyst (after-cat) NO_x emissions as an emission map. NO_x emissions are shown as a function of CO_2 emission and vehicle speed. (Right) The number of seconds (count data points) spent in each region of the map.

4.2.2 Manipulations in the heavy-duty sector

Manipulations of SCR systems in HD vehicles came to light in 2016, shortly after the revelations of VW's emission fraud with LD vehicles in September 2015. Research by the Heidelberg University pointed out to an estimated 20% of the trucks on German roads that had their SCR systems turned off, with Eastern Europe allegedly being the main source of vehicles with these illegal manipulations. In following years, several roadside and on-road tests were performed to confirm these findings. An overview of the main results is presented in this sub-chapter.

Vermeulen et al. estimated in 2017 that deactivation of the SCR would bring NO_x emissions back to Euro III to Euro I type-approval levels, depending on other emission-reducing technologies applied in the truck and whether these are manipulated as well. Thus, a potential increase for Euro V trucks ranges from a factor 2–4, while for a Euro VI truck this increase could add up to a factor 12 on average, up to a factor 20 if for instance the EGR would be manipulated as well. For the older Euro V technology, SCR systems were less efficient, indicating the lower potential increase of emissions [3]. Concerning the impact of various manipulations on a Euro VI truck, Huang et al. performed a chassis dynamometer test campaign during which both intake system, injection and EATS issues were simulated. Figure 7 indicates the resulting impacts on nitrogen monoxide (NO) emissions, which shows the significant emission alterations for the simulated manipulations to the EATSs. Manipulations to the injection system resulted in NO emission increases by a factor 7 – 13, while manipulations to the emission control devices increased the emission of this pollutant with a factor 8–16. Concerning the emission of carbon monoxide (CO) and unburned hydrocarbons (HC), mostly insignificant changes are reported, except for when EGR valves would be fixed in the fully opened position (CO x12 and HC x3) [23].

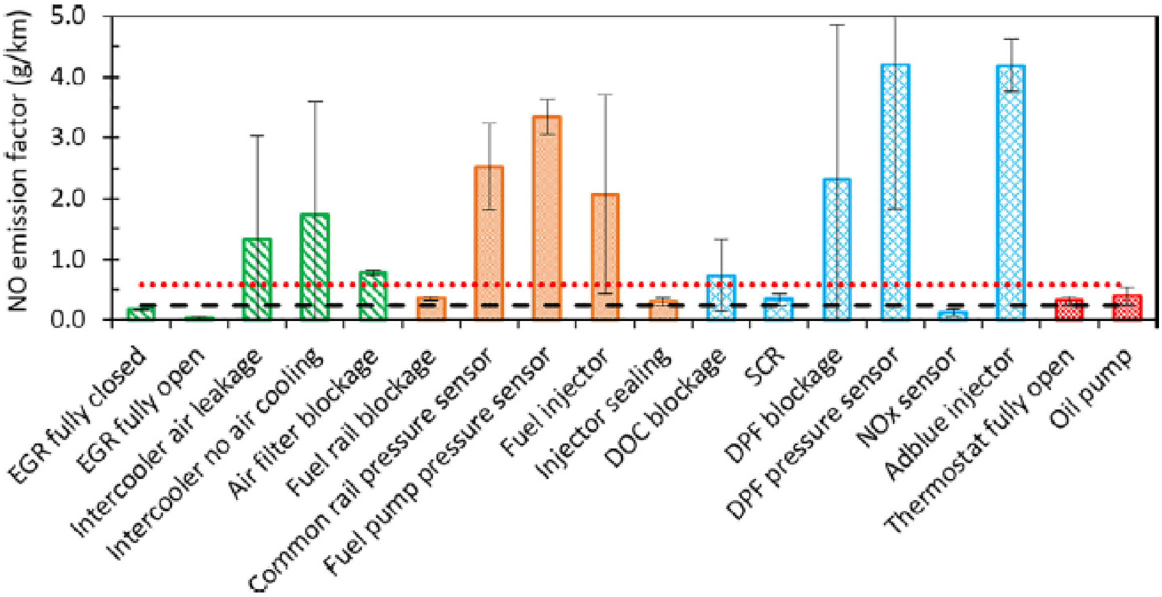

Figure 7 - Overview of the impact of manipulations on the emission of NO, with the dashed line indicating the baseline emission of the Euro VI truck and the red dotted line the applicable emission limit for NO_x [23]

Buhigas et al. performed a 2018 remote sensing campaign to detect truck manipulations in Spain, in co-operation with the Guardia Civil. Of over 1,800 trucks tested, 22 were found to exceed the Euro I limit of 8 gNO_x/kWh, while an astonishing 47% of the monitored Euro V trucks were found to be manipulated. As a detection limit for suspicious emissions, 1,000 parts per million (ppm) nitrogen monoxide was set, corresponding to approx. 5 gNO_x/kWh or the Euro III limits. Evidence to indicate tampering on the spot, however, proved to be extremely hard, except for some manipulated fuses. Also, they found a high variation between trucks from different makes and concluded that it was very difficult to set a suitable detection limit for a single remote sensing 'snapshot' [24].

Ellermann et al. performed a similar measurement campaign in Denmark a year earlier to confirm a previous roadside inspection campaign (without remote sensing) by the Danish police that reported an estimated 25% of the inspected trucks had their De-NO_x systems switched off. Results from nearly 900 sampled trucks indicate 9 had emissions over the set limit of initially 400 ppm, which was later adjusted to 600 ppm, and were subsequently inspected by the police. Two foreign Euro V trucks had been tampered with, while 4 others had malfunctioning SCR systems. A substantial difference was found between Danish and foreign vehicles, while remote sensing thresholds for indicating illegal manipulations were found to be 25 gNO_2/kg and 3 gNO_2/kg for Euro V and VI trucks respectively. Following this pilot study, the earlier claim by the Danish police stating a quarter of the trucks would be manipulated with was found to be an overestimation [25].

In a 2018 Swedish study performed by IVL, Jerksjö et al. carried out on-road tests with two deliberately manipulated Euro VI trucks using AdBlue® emulators (or 'killers'), which were also fitted with PEMS to assess the correlation with the remote sensing read-outs. These trucks also passed the lens of the remote sensing device several times to make sure transient emission peaks were levelled out. PEMS test results showed very high emissions when the manipulations were active, i.e. 10 – 100 times higher than the Euro VI RDE limit (including a conformity factor of 1.5). Remote sensing read-outs also showed a large difference between the two, even when the emulators weren't applied. The RS results show that one truck emitted 1 gNO_x/kg while the other emitted nearly 12 gNO_x/kg. Once manipulated and tested several times, emissions increased to 33 gNO_x/kg and 25 gNO_x/kg, respectively, resulting in exceedances by a factor 2 – 33. Next to these two specific trucks, more than 800 other Euro VI variants passed the remote sensing device. In total, 1 – 2% of the sampled trucks showed intolerably high emissions, although there was no further inspection taking place of these vehicles [9].

Buhigas et al. combined the results from the Spanish, Danish and Swedish pilots to a total of more than 2,200 trucks tested. After the classification by manufacturer and Euro standard in the post-processing of the results, significant variations were found between trucks from different brands. Figure 8 indicates these differences per Euro standards for the seven major manufacturers in Europe. These results do not necessarily indicate that truck A from manufacturer X emits more than another but shows that specific models may be more prone to tampering than others, for instance the Euro V Scania or MAN Euro VI models. Even though some manufacturers show higher NO_x emissions than others, a clear overall reduction can be reported from Euro V to Euro VI, a trend we also report for passenger cars.

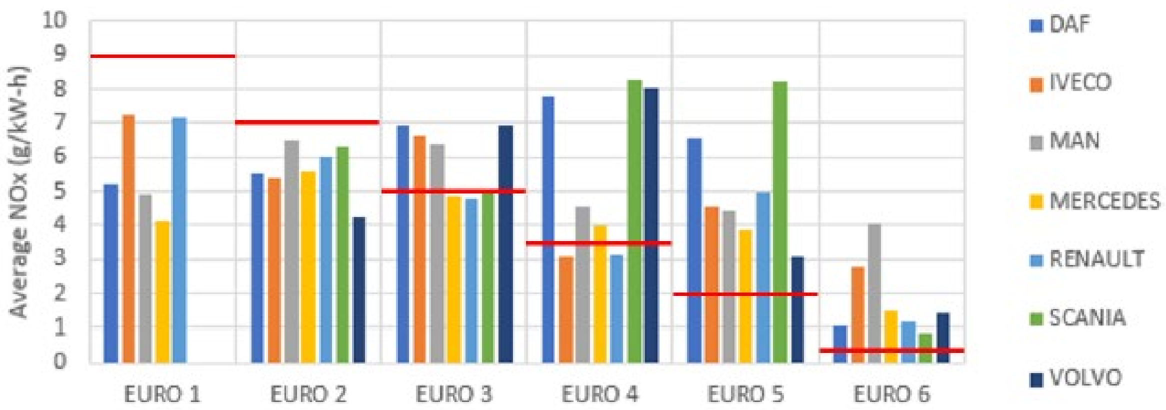

Figure 8 - NO_x emissions per manufacturer per Euro standard, with the type-approval limits indicated in red [24]

Finally, Pöhler et al. performed a 2019 plume-chasing study in Germany during which 141 trucks were chased. Roughly half were German, the other half Polish. As discussed in paragraph 3.3 Plume-chasing, samples were taken on highways to make sure stable NO_x conversions were measured. Figure 9 shows the main difference between remote sensing, plume chasing and regulatory PEMS testing. Whereas the latter results in an average emission over a complete test cycle, remote sensing represents only an instantaneous snapshot of a vehicle's emissions. Given the variance in emissions during a normal drive, sampling for plume-chasing has the advantage of covering several minutes, allowing for more balanced results. Hereby, wrongfully accusing vehicles due to a sudden emission peak when it passes the lens of a remote sensing device is overcome [11].

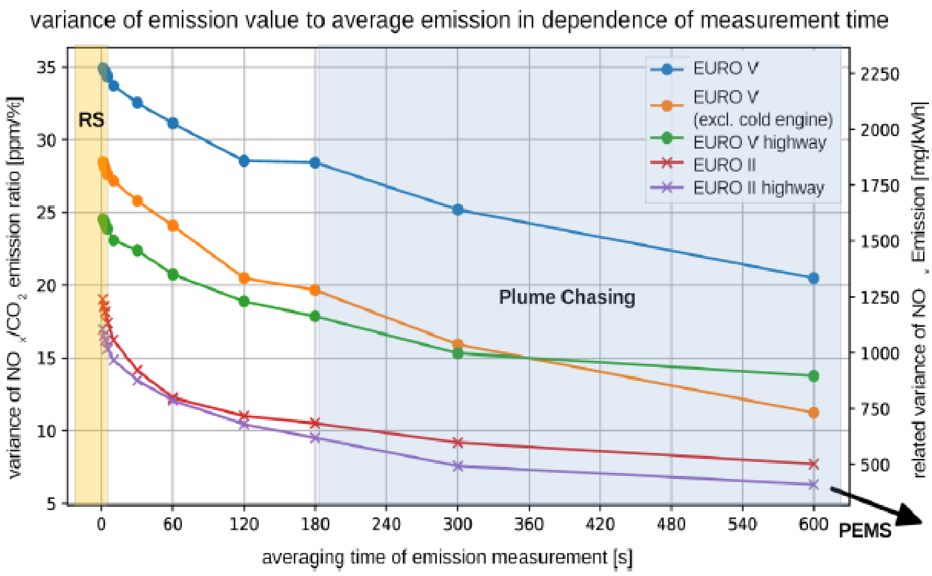

Figure 9 - Variance of emissions to averages as a function of measurement time [11]

Results show that 30% of the Euro V trucks had NO_x emissions well over the 3 g/kWh threshold, most likely due to their age (i.e. wear) and the avoidance of repairs. For Euro VI trucks, approx. 16% a 1,4 g/kWh threshold, confirming earlier performed plume-chasing results in 2016 and 2018. Figure 10 shows the results for both Euro V and VI tested trucks according to emission bins. Overall, 20% of the test fleet was found to be suspicious, which could point out to defective or manipulated De-NO_x systems. Mainly the foreign trucks were found to have unacceptable NO_x emissions levels [11].

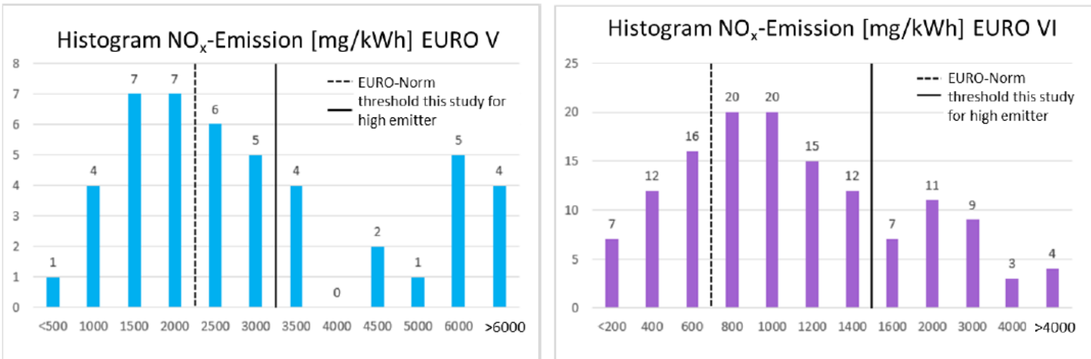

Figure 10 - Results for plume-chasing Euro V and VI trucks, sorted per emission bin and compared to the type-approval limit and the ad-hoc thresholds set during the measurement campaign [11]

4.3 Summary

High emitters have a disproportional impact on a total fleet's emissions. In terms of passenger car DPF manipulations and defects, approx. 10% of the fleet is deemed responsible for 90% of the total emissions, while 5% represents over 50% of the same total. The reason for this is the near-absolute efficiency of current diesel filtration systems. For this reason, only a small percentage of a fleet contributes virtually all the PM/PN emissions. In many countries, consumers perceive that no enforcement exists against DPF removals as PTI tests cannot distinguish between tampered and normally functioning vehicles. Therefore, the benefits of tampering are perceived to be (much) bigger than its adverse impact on local air quality. This statement stresses the need for ongoing, continuous education as this has proven its worth for eco-driving.

Based on literature, 5 to 10% of the passenger car fleet in Europe is deemed to have either defective or missing DPF systems. Additionally, the existing DPF technology allows for a reduction of PN by three orders of magnitude, meaning that exhaust gases contain fewer particles than ambient air. Considering this, a fully functioning filtered passenger car fleet could help in improving local levels of particulate matter.

Concerning SCR fraud in heavy-duty vehicles, NO_x emission exceedances are found to range from a factor 2-4 for Euro V trucks and up to a factor 20 for Euro VI. These factors cover both on-road and test-bench research and indicate the significant threat for local air quality levels. Proving tampering during roadside inspections is extremely hard if perpetrators have gone beyond simple hardware manipulations (e.g. manipulating fuses or using EOBD plug-in emulators). Remote sensing is currently being used in many pilot studies due to its potential to scan large fleets and detect suspicious vehicles once a suitable threshold value has been determined. Given that different thresholds have been applied throughout the different studies, a consensus for a Pan-European way of detecting high-emitters should be found. Applying emulators or 'AdBlue® killers' could influence NO_x emissions by a factor 10-100, according to PEMS testing. Additionally, significant changes are reported between the major HD manufacturers, indicating that certain models are more prone to tampering than others, for instance, to avoid repair costs.

Whereas the extent to which tampering is applied across the EU's Member States is largely unknown, the pilot studies covered here indicate a large spread in assumptions, ranging from 1–2% in Sweden to about 20% in Germany and Denmark, and 47% in Spain. On average, Euro V (30%) vehicles are found to be more susceptible to manipulations than Euro VI (16%) variants, following the insights from plume-chasing. This may indicate that more recent trucks are tougher to manipulate. Technology-wise, both remote sensing and plume-chasing prove to be very suitable for detecting emission violators.

Overall, the high shares of suspicious vehicles found both by Buhigas et al. and Pöhler et al. may point out that manipulated trucks often originate from both Southern and Eastern Europe, although more research is needed for confirmation.

5 Legislation and enforcement

European Regulation (EC) 595/2009 on type-approval of heavy-duty vehicles is very clear when it comes to tampering. It defines it as the 'inactivation, adjustment or modification of the vehicle emissions control or propulsion system, including any software or other logical control elements of those systems, that has the effect, whether intended or not, of worsening the emissions performance of the vehicle'. The following articles directly/indirectly mention the act of tampering as well:

- Article 5 on requirements and tests requires specific provisions to ensure the correct operation of NO_x control measures; such provisions shall ensure that vehicles cannot be operated if the NO_x control measures are inoperative due, for example, to lack of any required reagent, incorrect exhaust gas recirculation (EGR) flow or deactivation of EGR.
- Article 7 on obligations concerning systems using a consumable reagent states that 'Manufacturers, repairers *and operators* of the vehicles shall not tamper with systems which use a consumable reagent', indicating the SCR systems and their AdBlue® dosing, without which operators shall ensure not to drive.
- Article 11 on penalties, which are to be defined by the Member States, includes tampering with NO_x emission control system by the earlier mentioned three actors.

The more straightforward this HD Regulation is, the bigger the gap in its counterpart for LD seems. In Regulation (EU) 2017/1151 supplementing Regulation (EC) 715/2007 on type-approval (…) with respect to emissions from light passenger cars and commercial vehicles (Euro 5 and Euro 6), tampering is mentioned, albeit that it refers to:

- *provisions* to be *taken* (by manufacturers) *to prevent tampering with and modifications of the emission control computer*, (…) *including the facility for updating using a manufacturer-approved programme or calibration*
- *Any vehicle with an emission control computer shall include features to deter modification, except as authorised by the manufacturer. The manufacturer shall authorise modifications if these modifications are necessary for the diagnosis, servicing, inspection, retrofitting or repair of the vehicle. Any reprogrammable computer codes or operating parameters shall be resistant to tampering and afford a level of protection at least as good as the provisions in ISO 15031-7 (March 15, 2001). Any removable calibration memory chips shall be potted, encased in a sealed container or protected by electronic algorithms and shall not be changeable without the use of specialized tools and procedures.*

Furthermore, Article 13 on penalties in Regulation (EC) 715/2007 doesn't mention any measure taken by the vehicle operator as it addresses only the manufacturer. Links to Annex 11 to UN/ECE Regulation No 83 throughout Regulation (EU) 2017/1151 refer to the requirements for the onboard diagnosis system (OBD) to monitor the total failure or removal of a DPF, a NO_x after treatment system and a diesel oxidation catalyst fitted to compression ignition (diesel) engines. Hence, the OBD system is the only watchdog against tampering, while any form of prohibition or sanctioning is left out of the Regulation(s).

This overview of how LD vehicles are currently regulated indicates the need for an update to bring Regulation (EC) 715/2007 back in line with current practices of removing DPFs and the (potential) removal/deactivation of De-NO_x systems like SCRs. The following points are recommended to be included in the amendment:

- Corresponding to Article 3 in Regulation (EC) 595/2009, 'tampering' should be included in the definitions

- Corresponding to Article 7 in Regulation (EC) 595/2009, obligations should be added concerning both systems using consumable reagent and particulate filtration systems, which are not to be tampered with by manufacturers, repairers and operators of the vehicles
- Corresponding to Article 11 in Regulation (EC) 595/2009, penalties should be laid down by Member States that are applicable to the types of infringements by manufacturers, repairers and operators of the vehicles which include tampering with systems which control NO_x and PM/PN emissions.
- Following the restrictions for replacement pollution control devices as in Article 4 of Regulation (EC) 715/2007, a similar demonstration of accordance to type-approved parts should be demanded for third-party after-market parts.

In a survey covering 18 European Member States, we interviewed people working for (granting) type-approval authorities, ministries of transport and technical people that are involved in either PTI and/or roadside inspections. By means of the questions presented in the Annex A of this report, we tried to encompass how tampering is addressed in each Member State and to what extent enforcement is implemented. Where 6 out of 19 countries filled in the questionnaire, data for the 13 others were either obtained via interpersonal communication and/or desktop research. Results (see Table 3 in the Annex A to this report) indicate that only a few Member States have included tampering in its broad sense in their national legislation. The following observations are made:

- Firstly, only few actually mention the need for the presence and proper functioning of a DPF (e.g. in the Netherlands, UK, Austria, France, Germany and Luxembourg).
- Secondly, only 5 Member States mention engine/chip-tuning, stating any change of engine power or similar is forbidden, unless the modification is certified by an accredited test centre.
- Thirdly, when asked for the implementation of PTI Directive (EU) 2014/45 and whether the minimum requirements for emission testing were exceeded with other and/or stricter tests, practically every Member State sticks to the minimum. Idle PN testing is close to be introduced in the Netherlands and Belgium, serving as precedents for EU-wide adoption if the PTI Directive (and UN/ECE Reg. No 83) would be amended. Also, we have to report that slight changes are applied during PTI, e.g. a lowered opacity limit (0.25 m^{-1}) for Euro 6 diesel in the Czech Republic, an additional OBD read-out in Latvia and Germany and additional idle testing of HC for Austrian petrol cars. In Poland, the PTI Directive only recently got ratified by the government, while a general lack of PTI centre auditing/oversight is reported. Moreover, opacity limits have only recently been adjusted for post-Euro 4 diesel vehicles, indicating to what extent emission legislation can lag throughout the EU.
- Fourthly, roadside inspection emission tests generally refer to the PTI test, although some Member States already go further to counter tampering. In Spain, remote sensing is proposed as a detection tool, while Denmark, the UK, Belgium, France and Estonia issue fines in case of detecting illegal manipulations to emission control devices. Whereas Belgian enforcement stipulates a €2,500 fine for tampering with HD SCRs, France issues up to €7,500 per tampering case regardless of the vehicle category. Denmark fines €140–€2,000 in case of HD tampering, with a €15,000 penalty per repeating offenders. These fines require that evidence for the alleged tampering is found, which is not simple if the PTI emissions test is the legal basis for this.
- Fifthly, we report that in only 3 countries passenger cars are included in roadside inspections. These are Latvia, Hungary and Austria, whereas a draft Royal Decree issued in Spain proposes to include LD vehicles and remote sensing thresholds for

the regulated pollutants. In Belgium, light-commercial vehicles (LCV) are included in both the Brussels and the Wallonia regions, but not in the Flanders region.

- Finally, when asked for the legal basis for the advertising and performing of tampering, as well as who can be held responsible for it. From the received feedback, only Latvia and Estonia reported to be discussing the prohibition of advertising tampering, while performing it is illegal in every Member State except Estonia (although here it is under discussion as well). Only in Romania and in Austria, both the consumer and the repairer can be held liable for tampering. A fact-check on the internet to see whether the prohibition of advertisement for tampering is effective allows us to conclude that due to a general lack of enforcement, such services are provided in most of the Member States. Most likely, the specific link with tampering hasn’t been made in the various national legislations but only discussed generally.

6 Tampering outside of Europe

Whether the element of tampering causes a similar threat to air quality levels in other major car markets outside of the European Union depends mostly on how fleets are composed and how legislation and enforcement address the issue. In this chapter, we will discuss the specific cases for California and China, which both have a long history of poor air quality episodes that have led to progressive regulations in the automotive sector. Consequently, strict emission limits for passenger cars have been implemented (California) or are being phased-in (China), resulting in negligible diesel car sales. Additionally, their heavy-duty sectors rely virtually entirely on diesel technology. In the following paragraphs, we will first highlight the most prominent deficiencies in the European onboard diagnostic (OBD) system compared to the Californian variant. Subsequently, we'll have a look how China is harnessing itself against HD tampering through onboard monitoring (OBM).

6.1 Shortcomings of the European onboard diagnostics system

One important means to monitor the performance of emission control devices with which every light- and heavy-duty vehicle in both regions and the EU is equipped, is the onboard diagnostics system (OBD). This technology is designed to perform a diagnostic monitoring of components that are part of a vehicle's emission control system and to detect situations that could lead to high emissions. Thus, it serves as an interface between the vehicle and its driver to report issues and urge repair, while at the same time it allows the repairer to diagnose engine and after-treatment related problems. Moreover, OBD serves as a key indicator for a vehicle's maintenance level during PTI and throughout the vehicle's lifetime.

Whereas California introduced the OBD system in the 1990s, Europe and Korea followed roughly 10 years later with its EOBD and KOBD, respectively, based on the Californian variant. In 2016, China followed and adopted most of the Californian OBD II protocol as well. In general, OBD systems have two kinds of monitoring requirements, being 1) emission threshold monitoring, and 2) general monitoring of the system functionality. Overall, a much wider scope and greater stringency is reported for the CA OBDII and KOBD compared to EOBD. Exemplary are the inclusion of cold start monitoring in CA OBDII and the fact that EOBD leaves most of the responsibility for exhaust aftertreatment systems (EATS) monitoring exclusively to the manufacturer. In addition, EOBD applies less stringent emission thresholds in general, when compared to the Californian system, but also when comparing the requirements for diesel vehicles with those for petrol variants. The EOBD categorises many of the requirements for the EATS under 'other emission control systems', whereas CA OBDII provides clear, non-suggestive definitions of them. As a result,.

Besides the lack of monitoring requirements, the EOBD system isn't robust enough when it comes to tampering. Crucial threats to the current system are that data trouble codes (DTC) can be cleared using low-cost communication tools, while new software can be loaded into the engine control unit (ECU) to increase power and to disable EATS functionalities to alter the system in such a way that it avoids DTCs. Several measures are taken to prevent such practices, including permanent DTCs, readiness codes, and the combination of calibration ID and calibration verification numbers. DTCs are generated when a malfunction occurs in one of systems that are monitored by OBD. In this case, the driver will be warned when something is wrong via a dashboard malfunction indication. Both the CA OBDII and KOBD have clear requirements for storing DTCs *permanently*, offering a better protection against clearances and thus providing a much better technical support for PTI purposes based on OBD. The EOBD system, however, lacks this fundamental possibility. One way to work around this flaw in current EOBD legislation is by remote exchange of emission data and/or DTCs or monitoring them onboard, which will be discussed for the Chinese case in the following sub-chapter.

Complementary to the permanent DTCs, readiness bits indicate the status of the ten most important monitored systems. These bits will indicate when a certain monitor hasn't yet finished a complete diagnostics cycle which can result in a failed PTI in California, in case a permanent DTC indicates an underlying problem. If no such DTC was stored, the incomplete cycle might refer to a recent repair during which the battery was disconnected. This back-up isn't available in case for EOBD, although it wouldn't make sense for vehicle owners to erase the readiness bits as this could also lead to a failed PTI (depending on if EOBD is applied complementarily to the emission test). Instead, the vehicle owner could simply have all non-permanently stored DTC erased.

A last measure that the CA OBDII and KOBD have against tampering is to download the running calibration ID (CAL ID) number from the inspected vehicle and to compare this to a national database containing the possible combinations with the calibration verification number (CVN). This allows for the detection of non-original ECU software and thus tampering if it doesn't come with an approval certificate issued by an accredited lab. This approach, however, requires all vehicle manufacturers to provide the regulators with every available CAL ID/CVN combination, for them to keep the database continuously up to date. One pitfall of this approach is that the correct CAL ID can be re-flashed into the ECU solely to pass PTI, to be reset afterwards. Also here, opportunities arise for remote transmission of a vehicle's CAL ID. The European OBD programme[2] requires CAL IDs to be made available via the EOBD data link connector but doesn't mention any requirements on CVN.

6.2 The potential for onboard monitoring/remote OBD

The ultimate goal for regulators would be to have all relevant emission data per vehicle available *online* and in *real-time*. Through this substantial improvement to local air quality levels could be realised due to a near 100% catch rate, whereas high emitters today remain largely off the radar.

- Both in California and specific regions in China, pilot studies are up and running to assess the potential and work ahead for streamlining onboard monitoring (OBM). In a first stage, this principle can be applied to detect high emitters during operation. Practically, this consists of a transmission of real-time NO_x data from the controller area network (CAN-bus) of heavy-duty vehicles. In an evaluation of one such pilot in Beijing, Cheng et al. tested a China IV diesel truck fitted with both OBM hardware and PEMS. A 15-day test trial showed actual NO_x emissions ranging from 3.29 g/km to 6.65 g/km, relative to a threshold of 3.5 g/kWh. Simulation of a tampering with the SCR by removing the AdBlue® resulted in an increase from 22 gNO_x/kg fuel to 48 gNO_x/kg fuel, equal to increased up to 15 gNO_x/kWh. A good correlation with PEMS suggests OBM can accurately capture dynamic fluctuations in instantaneous NOx concentrations. The worst correlation was found at low NOx concentrations (20–100 ppm OBM vs 1–6 ppm PEMS), indicating that for PEMS a 99% NOx conversion is accomplished [27].

[2] Regulation 1151/2017

These results prove OBM can effectively and accurately identify high-emitters for in-use diesels. As the so-called 'OBD-III', including wireless communication, will increase the upfront vehicle cost, the technology is recommended for installation on vehicles with high emission factors and high mileages, like city buses and long-haulage trucks. In 2018, Beijing set up local municipal-level standards for China IV and V vehicles, i.e. 8.4 g/kWh and 5 g/kWh, representing exceedance factors to the type-approval values of 2.8 and 2.5, respectively. New China V HDVs registered in Beijing should all comply with this standard and transmit data to the Beijing Ecological Environment Bureau, although it is more likely that the first data collection will be taken care of by the manufacturer. So far, more than 15,000 HD vehicles have participated in this program by adding special OBM loggers. In the second phase, China VIb, data transmission will become mandatory covering the HD vehicle's entire lifespan. A tampering detection limit for China VI HDV of 1.2 g/kWh, relative to a 0.4 g/kWh type-approval limit, is to be phased-in from 2020 onwards. For China IV and V, agreements are needed between governments and the industry on OBM data collection covering NOx concentration, urea levels/injection, air flow and other useful channels. In a next step, DPF functionality will be assessed by OBM using the differential pressure sensor(s), as there are no robust PM sensors commercially available yet on the global market. OBM is not deemed relevant for application in Chinese LD vehicles, as the diesel share is marginal.

Following the pioneering work performed in China, California amended the OBD regulation in November 2018 with an OBS programme called 'Real Emissions Assessment Logging' (REAL) for NO_x and CO_2 in medium- and heavy-duty diesel vehicles, for which data will be collected from model year 2022 in California onwards. In this approach, engine manufacturers will perform emissions calculations, after which governmental services evaluate and validate with PEMS [28].

7 Conclusions and recommendations

Throughout this report, we have focussed on specific cases of tampering revealed for passenger cars and heavy-duty vehicles on European roads. Given the high efficiencies of recent exhaust after-treatment systems (EATS), the potential threat tampering induces is large. As such, a removed particulate filter can result in an increase of PM/PN by three orders of magnitude. One such vehicle can, therefore, level out the near-total reduction of the pollutant by a well-performing fleet of vehicles. Concerning De-NO_x systems such as SCRs, the impact of tampering can be as high as a factor 100 according to a PEMS test campaign on HD trucks. Most results obtained so far, however, can be found in the range of a factor 4-20 for the most recent technology (Euro VI).

Next to a gathering of all relevant data from literature on tampering, a survey was performed across different EU Member States to check how national legislation allows for enforcement against tampering practices. Based on the output from this survey, we can draw important recommendations:

- PTI and roadside inspection directives should be urgently updated to reflect real-world issues with emission control devices and should be revised on a regular basis to stay aligned with the state-of-art. This should include all possible checks of components that are prone to mechanical tampering, while specific attention should go to (illegal) changes in the vehicle's software.
- Like the Car Pass system applied in Belgium to counter mileage fraud, a registration of every action and/or assessment performed by repairers, roadside- and PTI inspectors concerning EATSs should be stored on an international database. This allows for each vehicle to have a history in which one can trace illegal manipulations.
- Tampering in the widest sense of the word, including advertising, performing and trading of tampered vehicles and/or parts should be prohibited. This should be done by requiring Member States to lay down penalties for these offences. Such penalties should include:
    - The withdrawal of transport licenses for haulage companies
- Roadside inspections should include light-duty vehicles, next to heavy-duty commercial vehicles,
- Detection limits for remote sensing should be established based on ongoing research.

Only through strong legislation, issued through European Regulations, and the implementation of effective enforcement against tampering, will consumers and companies no longer be tempted to illegally modify their vehicles. Education is an important aspect as well, given the perception that operational costs like AdBlue® refilling and system maintenance largely exceed the cost of tampering. What often goes unnoticed here, is the substantial increase in external costs due to the excessive emissions following the illegal manipulations to the emission control devices. In case of air pollutants, however, a lot of work is ahead of us to explain the impact of passenger cars and how they are used in daily traffic.

Various technologies are present to detect high-emitters complementary to PTI, i.e. through remote sensing and/or plume chasing. Whereas an implementation of the latter two mostly hinges on setting proper detection limits, we should also think of the next generation of vehicles that can be inter-connected with each other, and with a cloud-based system that communicates emission-related data in real-time. In this matter, both China and California lead by example, indicating that the wheel doesn't need to be reinvented.

High emitters can represent vast amounts of a fleet's total emissions, the technology to filter them out of traffic is here. The final gap to close is in the hand of legislators.

Finally, the chain of responsibility in the ownership and operation of a vehicle including manufacturers, repairers and vehicle users would be strengthened through these provisions. Firstly, vehicle manufacturers will be held accountable for the type approval of vehicles and is-use conformity through the stricter requirements in (EU) 2018/858. Secondly, vehicle owners will be stimulated to keep their vehicles in a good state through effective PTI and roadside inspections. Thirdly, repairers will be obliged to use certified anti-pollution replacement parts. Finally, a strict penalty system will discourage all these actors from breaching national laws.

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Annex A

Questionnaire sent out to the different EU Member States

1. Could you refer the specific law in your country that covers EU Regulation (EC) nr. 715/2007 on type-approval of motor vehicles?
    a. Is there a specific mentioning for the presence and/or proper functioning of emission protection systems (DPF, EGR and/or SCR)?
    b. Is engine/chip tuning covered?
2. Could you refer to the specific penal law in your country that covers EU Directive 2008/99/EC on the protection of the environment through criminal law?
    a. Which sanctions are issued in case of breaching the law?
    b. Are there any precedential cases of jurisdiction against emission tampering? This can be both on consumer or fleet level.
3. Could you refer to the specific law in your country that covers EU Directive 2014/45/EC on periodic roadworthiness tests for motor vehicles?
    a. Do the emission tests during periodic inspection in your country outperform the minimum requirements stipulated in this Directive (visual inspection, specific visual inspection for checking the presence of a DPF (or other emission protection systems), opacity testing for diesels, idle CO and lambda testing for spark-ignited vehicles)?
4. Could you refer to the specific law in your country that covers EU Directive 2014/47/EC on the technical roadside inspection of the roadworthiness of commercial vehicles?
    a. Do the emission tests during these roadside inspections in your country outperform the minimum requirements stipulated in this Directive? These are the same as in Directive 2014/45/EU as elaborated in the point 4.a.i.
    b. Is an amendment made to this national transposition of the respective Directive to include passenger cars and light-commercial vehicles to the scope?
5. Are there other measures being taken in your country to improve enforcement on emission tampering?
    a. Is advertising for measures like removing catalysts by professionals legal?
    b. Are the actions provided by professionals to eliminate emission protection systems in road vehicles legal?
    c. What about liability in case of such actions? Is the consumer to be held responsible or the garage technician, or both?

Table 3 - Summary of the responses to the questionnaire

Member State	National transpostion of (EC) 715/2007	Coverage of DPF/EGR/ SCR/others?	Coverage of chip-tuning?	PTI emission test	Roadside emission test	Precendents	Roadside inspection for M1&N1?	Under discussion?	Other measures to enforce against tampering?	Advertising tampering	Performing tampering	Liability
Latvia	Regulation of the Cabinet of Ministers No 1494 of December 22, 2009 on Certification of road	No	No	Minimum + EOBD read-out	Minimum (PTI)	-	Yes	No	No	Under discussion	Illegal	-
Germany	Straßenverkehrs-Zulassungs-Ordnung (StVZO)	Yes	Yes*,**	Minimum + EOBD read-out	Minimum (PTI)	-	No	No	No	Illegal	Illegal	Consumer
Hungary	5/1990. (IV. 12) Ministerial decree on roadworthiness tests for road vehicles	No	No	Minimum	Minimum (PTI)	No	Yes	No	No	Illegal	Illegal	Consumer 15 -450€ fine
Luxembourg		Yes	Yes	Minimum	Minimum (PTI)	-	No	No	No	Illegal	Illegal	Consumer
Austria	Kraftfahrgesetz 1967	Yes	Yes	Minimum + HC idle test for petrol cars		Yes	Yes	-	AdBlue emulator detection via EOBD and other measures	Illegal	Illegal	Consumer + garage

Ireland	S.I. No. 280/2017 - European Communities (Road Vehicles: Type Approval) (Amendment)	No	No	Minimum	Minimum (PTI)	-	No	No	No	Illegal	Illegal	Consumer
Spain		Draft decree		Minimum	Pilots with remote sensing + link with 2008/99/EC		Not yet	Draft decree remote sensing for every vehicle				
Switzerland	VTS (Verordnung über die technischen Anforderungen an Strassenfahrzeuge)	Yes	Yes*	Slight deviations to 2014/45/EU		-						
Denmark	Danish Road Traffic Act	Yes***			Minimum (PTI) + Fines against tampering from €140 €2.000 (€15.000 if repeated)	Yes	No					
Poland	Road Traffic Act	No	No	2014/45/EU only recently transposed	2014/47/EC only recently transposed	No	No			Not mentioned/ legal	Not mentioned/ legal	-
Czech Republic		Yes		Minimum + 0,25 m-1 opacity limit	Minimum (PTI)		No			-	Illegal	Consumer

France		Yes	Yes*	Minimum + NOx and opacity for petrol, 5-gas for diesel from 2022	Minimum (PTI)	€7.500 fine for tampering/ modifications	No			Illegal	Illegal	
Netherlands	Ministriële Regeling Voertuigen	Yes	No	Minimum	Minimum (PTI)		No			Illegal	Illegal	
UK	Road Vehicles Regulations	Yes	No	Minimum	Minimum (PTI)	£1.000 fine for cars, £2.500 for vans, lorries and buses	No			Illegal	Illegal	Consumer
Italy	Codice della Strada	No	Yes	Minimum	Minimum (PTI)	No						
Estonia	Technical requirements and equipment requirements for motor vehicles and their trailers	Draft decree	No		Minimum (PTI)	Fines up to €200 for unallowed modifications				Under discussion	Under discussion	Under discussion, now only consumer
Belgium	KB March 15 1968	No	Yes*	Minimum	Minimum (PTI)	No, €2.500 fine per manipulation, from €300 per defect	No (N1 in Brussels & Wallonia)			Illegal	Illegal	Consumer
Romania	Government Ordinance 78/2000	No	No	Minimum	Minimum (PTI)	No	no		No	Illegal	Illegal	Both

*any change of engine power or similar is forbidden, unless certified, **Risk of losing driver's license, prosecution by Fin. Dept. Due to tax evasion, ***Driver awareness on legal condition of anti-pollution equipment