DIAS
Smart Adaptive Remote Diagnostic Antitampering Systems

EUROPEAN COMMISSION
HORIZON 2020
LC-MG-1-4-2018
Grant agreement ID: 814951

Deliverable No.	D3.1
Deliverable Title	The market of cheating devices and testing matrix with a prioritization for testing of vehicle tampering technique combinations
Issue Date	27/01/2020
Dissemination level	Public
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Version	V1.0

DIAS Consortium

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 814951.

Document log

Version	Description	Distributed for	Assigned to	Date
V1.0	First final version *(to be submitted to EC)*	-	-	27/01/2020

Verification and approval of final version

Description	Name	Date
Verification of the "Final content of deliverable (v0.3)" by WP leader	Ann Delahaye (TNO)	24/01/2020
Check of the "First final version (v1.0)" before uploading by coordinator	Zissis Samaras (LAT/AUTh)	28/01/2020

Executive summary

Pollutant emissions of road vehicles have reduced significantly thanks to the development and application of effective and often complex emissions control systems. Tampering of these systems leads to elevated emissions levels comparable to uncontrolled levels of vehicles of decades ago. Therefore, a small share of tampering potentially leads to a significant increase of the EU fleet average emissions.

For task 3.1 of DIAS, a market assessment was conducted to determine the market of tampering in terms of size, appearance and involved players, to reveal the motivations for tampering and to identify the different types of tampering offered. The exercise has led to a proposal for a test matrix of vehicle – tampering combinations that poses the largest environmental risk and which should be tested in the next project phase to determine the current vulnerabilities and exploits of vehicles that need to be addressed by the DIAS concept. The following conclusions can be drawn:

- There is a substantial market where tampering is offered for both light- and heavy duty vehicles and non-road mobile machinery. However, not much quantitative information is available which indicates the magnitude of the problem, i.e. the number of vehicles that are tampered in the EU.
- An important source that does indicate tampering in the EU are road side inspections for trucks were significant tampering rates were found for previous generations of heavy duty vehicles for which an advanced emissions control system is required (Euro IV and V). The inspections are however often selective, targeting specific vehicles based on experience and assumptions, most likely resulting in biased data. The magnitude of the problem is largely unknown for Euro VI and the light duty and non-road mobile machinery segments.
- The motive mentioned most for tampering is to avoid costs for repair of malfunctions of the emissions control systems of diesel engines. Other motives mentioned are: costs for consumables, costs for downtime, performance tuning and exhaust sound level.
- Emissions control systems with higher rates of malfunctions and related costs for repair may therefore pose the largest environmental risk: SCR (Selective Catalytic Reduction), DPF (Diesel Particle Filter), EGR (Exhaust Gas Recirculation) for diesel engines but possibly also TWC (Three-Way Catalyst) for older gasoline engines.

Two main types of tampering were found for vehicles of the latest generation, backed up by findings of consortium partner LAT:

1. Emulators
2. ECU (Engine Control Unit) reprogramming (also called ECU flashing, ECU remapping)

This tampering is either offered as a service in workshops or as product with instructions for installation offered on the internet in web shops, online shopping areas, forums and social media. OBD (On-Board Diagnostics) diagnostic trouble codes (DTC) may arise when tampering leads to errors detected by the current OBD. Diagnostic Trouble Code deletion tools are offered to support the tampering, i.e. to by-pass periodic inspection and to avoid power inducement of the engine forcing an owner to repair the malfunction.

Other types of tampering exist which should also be assessed regarding the possible risk:

- Tampering and emulation of temperature sensors so that temperatures outside the window of normal operation are generated to fool and shutdown the emission control system.
- A lambda sensor catalyst that provides a correct air fuel mixture to the sensor, while in fact the mixture is not correct, such that no error is generated.

The market assessment has led to a test matrix in which the vehicle-tampering combinations are defined that most likely pose the largest environmental risk. The test matrix contains light and heavy duty vehicles and non-road mobile machinery with diesel engines, the two main types of tampering devices and services, the OBD DTC delete tool and temperature sensors tampering.

A list was compiled with tampering devices and services found to date. This list will be further expanded when new or other tampering is found in the course of the project. It is recommended to continue the market assessment in order to better define the magnitude of the problem and to scan the market for other or new types of tampering.

Other relevant observations made during the tampering market analysis and assessment are:

- There is an increased intensity of road side inspections with prosecution and sanctioning by several Member States, mainly for heavy duty vehicles.
- There is an increased stringency of requirements for OBD and control of NO_x measures (EU) towards current EU requirements (Euro 6dtemp, VI step-D, stage V).
- There are plans by some EU member states for checking the DPF at periodic inspection.

These measures may already lead to a less attractive ‘environment’ for tampering.

Contents

List of Abbreviations

ACEA	European Automobile Manufacturers Association
AMOC	Ammonia Oxidation Catalyst
BDM	Background Debug Mode
BTX	Benzene, Toluene and Xylene
CI	Combustion Ignition
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CoC	Certificate of Conformity
CoP	Conformity of Production
CRT	Continuously Regenerating Trap
DEF	Diesel Exhaust Fluid (AdBlue/urea solution)
DIAS	Smart Adaptive Remote Diagnostic Antitampering Systems
DOC	Diesel Oxidation Catalyst
DoW	Description of Work
DPF	Diesel Particle Filter
DTC	Diagnostic Trouble Code
DVSA	Driver & Vehicle Standards Agency
EC	Elemental Carbon
EC	European Commission
ECE	Economic Commission for Europe
ECU	Electronic Control Unit
EEV	Enhanced Environmentally Friendly Vehicle
EFTA	European Free Trade Association
EGR	Exhaust Gas Recirculation
EPA	United States Environmental Protection Agency
EU	European Union
EU-28	European Union and all present member states as of October 2019
EU-33	European Union and all present member states as of October 2019 together with Iceland, Liechtenstein, Norway, Switzerland and Turkey
EVAP	Evaporative Emission Control System
GDI	Gasoline Direct Injection
GPF	Gasoline Particle Filter
GWPeq	Global Warming Potential
H_2O	Water
HC	Hydrocarbons
HD(V)	Heavy Duty (Vehicle)
HDDF	Heavy Duty Dual Fuel
I/M test	Vehicle Inspection and Maintenance Test
JTAG	Joint Test Action Group
LA	Light Aldehydes (formaldehyde, acetaldehyde, acrolein)
LD(V)	Light Duty (Vehicle)
LNT	Lean NOx Trap
MI(L)	Malfunction Indicator (Light)
N_2	Nitrogen
NO_x	Nitrogen Oxides

NMHC	Non-Methane Hydrocarbon
NMVOC	Non-Methane Volatile Organic Compounds
NRMM	Non-Road Mobile Machinery
NRSC	Non-Road Stationary Cycle
NRTC	Non-Road Transient Cycle
NTE	Not-To-Exceed testing
O_2	Oxygen
OBD	On-board Diagnostics
OC	Organic Carbon
OCE	Off-Cycle Emission testing
OEM	Original Equipment Manufacturer
OTL	OBD Threshold Limit
PAH	Polycyclic Aromatic Hydrocarbons
PEMS	Portable Emissions Measurement System
PM	Particulate Matter
PN	Particulate Number
PTI	Periodic Technical Inspection
RDE	Real Driving Emissions
RPM	Rotations Per Minute (engine speed)
SCR	Selective Catalytic Reduction
SI	Spark Ignition
SO_x	Sulphur oxides
SO_2	Sulphur dioxide
SO^{4-}	Sulphate
TWC	Three-way catalyst
UNECE	United Nations Economic Commission for Europe
VAG	Volkswagen, Audi Group or Volkswagen Group
WHSC	World Harmonized Stationary Cycle test
WHTC	World Harmonized Transient Cycle test
WLTC	Worldwide harmonized Light vehicles Test Cycle
WLTP	Worldwide harmonized Light vehicles Test Procedure
WNTE	World harmonized Not-To-Exceed cycle

Definitions

Approval authority	The authority of a country or Member State with competence for all aspects of the approval of a type of vehicle, system, component, or separate technical unit or of the individual approval of a vehicle; for the authorisation process, for issuing and, if appropriate, withdrawing approval certificates; for acting as the contact point for the approval authorities of other Member States; for designating the technical services and for ensuring that the manufacturer meets his obligations regarding the conformity of production. As defined in directive 2007/46/EC.
Aftermarket parts	Replacement parts that are not made by the original manufacturer. Aftermarket parts are used to replace damaged parts in vehicles and other equipment. They are typically cheaper than OEM parts but are likely to have similar effect.
Authority	Person or body having the legal power to make and enforce the law. With regards to the legislation on vehicle emissions and emission control systems the following types of authorities are involved: • Development of regulations and norms, like the UNECE. Typically, a global or international organisation. • Enforcement of regulations and norms, like approval authorities as the RDW or DVSA. Usually organised per country or Member State.
Branch organization	Organisation that takes an active role in improving, advising, informing or securing the automotive branch.
Customer	A person who buys goods or services from a shop or business. With regards to emission control systems the distinction can be made between: *Customer:* a person who buys goods or services without the intention of tampering of the emission control systems. This includes the *uninformed customer:* who believes no tampering is involved while in fact it is. *Intentional customer:* a person who buys goods or services with the intention to tamper with the emission control systems of the vehicle.
ECU	Embedded system in automotive electronics that controls one or more of the electrical systems or subsystems in a vehicle.
Emission Control System	System fitted to a vehicle that is designed to reduce any (pollutant) emissions of that vehicle, e.q. EGR, DPF and SCR.
Hacking Event	Event organised within this project which gives hackers the opportunity to tamper with (parts of) the emission control systems of vehicles to show and explain how they approach these systems.
Hacker	Person who uses computers to gain unauthorised access to data. With regards to emission control systems a hacker typically is a computer expert or vehicle technician that is able to, using his technical knowledge, make (unauthorised) changes to (secure) automotive ECU's or sensor communication, with either good or bad intentions.
Heavy Duty	Vehicles that meet the requirements of vehicle categories M2, M3, N2 and N3 as defined in directive 2007/46/EC which involves:

- M2 and M3: Vehicles designed and constructed for the carriage of passengers, comprising more than eight seats in addition to the driver's seat, and having a maximum mass not exceeding 5 tonnes for M2 and exceeding 5 tonnes for M3.
- N2 and N3: Vehicles designed and constructed for the carriage of goods and having a maximum mass exceeding 3,5 tonnes but not exceeding 12 tonnes for N2 and having a maximum mass exceeding 12 tonnes for N3.

Light Duty — Vehicles that meet the requirements of vehicle categories M1 and N1 as defined in directive 2007/46/EC which involves:

- M1: Vehicles designed and constructed for the carriage of passengers and comprising no more than eight seats in addition to the driver's seat.
- N1: Vehicles designed and constructed for the carriage of goods and having a maximum mass not exceeding 3,5 tonnes.

Limp mode — Limp mode is a security function integrated in a vehicle that reduces the power and limits the RPM of the engine to prevent any serious damage in case the electronic control unit detects a vehicle system failure.

Manufacturer — Person or body that makes goods for sale. With regards to vehicle manufacturing and especially emission control systems the distinction can be made between:
Manufacturer: a person or body who is responsible to the approval authority for all aspects of the type-approval or authorisation process and for ensuring conformity of production. It is not essential that the person or body be directly involved in all stages of the construction of the vehicle, system, component or separate technical unit which is the subject of the approval process, as defined in directive 2007/46/EC.
Tampering manufacturer: person or body that constructs a tampering device.

NRMM — Non Road Mobile Machinery. Any self-propelled vehicle which is designed and constructed specifically to perform work, which, because of its construction characteristics, is not suitable for carrying passengers or for transporting goods, as defined in directive 2007/46/EC. Machinery mounted on a motor vehicle chassis shall not be considered as mobile machinery.

Supplier — Person or body that provides something needed such as a product or service. With regards to emission control systems the following distinction can be made for suppliers:
Supplier: Vendors or workshops/repair shops that provides a product or service regarding all stages of the construction of a vehicle, system, component or separate technical unit in a vehicle without involvement in any tampering related device or service.
Tampering supplier: Vendors or workshops/repair shops that provides tampering devices and/or the service to tamper with emission control systems.

Tamperer — Person who for whatever reason deliberately tampers with the emission control systems of any vehicle.

To tamper — Interfere with something in order to cause damage or make unauthorised alterations.

Tampering Device — Also known as cheating device. A systems, component or separate technical unit that, when fitted to a vehicle, actively or passively tampers with an emission control system of a vehicle with the purpose to (partly) deactivate or bypass it. This typically includes

	the removal or deactivation of systems in a vehicle that monitor the status of those emission control systems and give feedback about malfunctions.
Tampering Service	A service provided by a supplier or tamperer to make changes to an emission control system or ECU with the purpose to (partly) deactivate or bypass it. This typically includes the removal or deactivation of systems in a vehicle that monitor the status of those emission control systems and give feedback about malfunctions.
Tuner	Workshop, dealership or any other company that provides hardware for or the service to make changes to the performance of any vehicle. Also known as 'chip' tuner.
Type-approval	The procedure whereby a Member State certifies that a type of vehicle, system, component or separate technical unit satisfies the relevant administrative provisions and technical requirements as defined in directive 2007/46/EC.
(Motor) Vehicle	Any power-driven vehicle which is moved by its own means, having at least four wheels, being completed i.e. type-approved, with a maximum design speed exceeding 25 km/h.

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1 Introduction

1.1 Background

With the EU emissions standards for vehicles becoming increasingly stringent manufacturers have managed to introduce state-of-the-art emission control systems that have brought significant reductions to the actual emission levels. However, there is increasing evidence of illegal manipulation of environmental protection systems by vehicle owners and widespread usage is observed in the market [1, 2]. These manipulations, also known as tampering, can substantially affect the emissions of the tampered vehicles, by bringing them back to uncontrolled or partially controlled conditions and therefore may constitute a significant threat to the efforts to regulate the emissions and improve air quality.

In early 2017, it was discovered that the SCR systems of up to 20 percent of eastern European heavy duty vehicles on German roads are suspect of being manipulated [3]. Again in 2017 reports by Swiss authorities [4] indicate that in Switzerland vehicles have been caught, with hardware manipulations (mostly SCR emulators and simple built-in potentiometers that stop the dosing of the reagent which is needed for the operation of an SCR system to reduce diesel engine NOx emissions). In January 2018 the British government reported that 8% of heavy-duty vehicles were found to have a cheat device [5]. Next to these examples, several news sources [6, 7, 8] can be found that report about environmental protection systems, like the DPF and EGR are being tampered with on a large scale and that this tampering is hardly detected by the authorities. After initial suspect actual tampering is difficult to prove without an extensive inspection of the vehicle.

The European Commission set up the project DIAS: Smart Adaptive Remote Diagnostic Antitampering Systems to tackle the problem of tampering, by exploring possible measures, legal and technical solutions to strengthen the anti-tampering with the exhaust emission control system. This project is funded by the EU Research and Innovation program Horizon 2020. It started in September 2019 and runs for three consecutive years until August 2022.

The primary target of DIAS is to harden vehicle emission control systems against tampering. This means that any changes in emission control system hardware and software that degrade the performance of the system will be prevented or detected. DIAS will develop innovative protection and security measures to increase the level of prevention. In case detected, information about the tampering attempt is available and is used to introduce countermeasures e.g. the activation of the driver inducement systems.

As participant in the consortium assigned to DIAS, TNO has a leading role in assessing the current market involved in tampering of the emission reduction systems in the vehicle. This task is one of the main objectives of DIAS and is included in work package 3 (WP3).

1.2 Objectives

Throughout the project, market analyses, testing and evaluation is required to determine vulnerabilities, to quantify risks and impacts of tampering on system functionality. The objectives for this work are to perform a market assessment of the most effective (critical) cheating devices and their impact on the emissions, OBD and vehicle systems and signals. The cheating devices will be categorised and prioritised for extensive testing in a testing programme to disclose the working principles of the tampering and the vulnerabilities of existing environmental protection systems. The market assessment results in a test matrix and list (Excel) of critical tampering, categorised per working principle and application.

The market analysis and assessment of the operation of representative tampering systems and of their effect on the performance of existing on-board emission monitoring and emission control systems over real-world and laboratory testing is a task of WP3. The market analysis and assessment also directly provide information for the identification and implementation of detection methods and counter-measures to be developed in WP4 and WP5 and for setting up guidelines and recommendations for future legislation for the introduction of future safe monitoring systems in WP6.

1.3 Approach

In achieving these objectives, a methodology for this market analysis and assessment is established. Using this method:

- An inventory of tampering devices and service suppliers is compiled to enable the assessment of the overall dimension of what is being offered on the market to identify:
    - The parties involved; from hackers, companies offering tampering to the customer and their motives. This will result in an overview of the market, supply and demand, roles of parties involved, costs and 'benefits' for the customer.
    - All possible methods and devices of cheating that can impact emissions of a vehicle. This will result in an overview of the devices, services and their characteristics. An Excel file is used to collect the information about the devices with the following information: tampered system, type of tampering, fuel type, emission standard, sub-systems affected, ECU (software) intervention, hardware intervention, anticipated 'benefit', effects on performance (power/torque), effects on fuel consumption and CO2 emissions, costs, brand, location/country, market, source, webpage.
- Tampering devices and services are listed (tampering list) and categorised in terms of basic principles of operation.
- A risk assessment is performed for the potential of tampering separately for light- and heavy duty vehicles, as well as non-road mobile machinery and the corresponding emission control systems.
- The categorised tampering devices and the risk assessment are combined to compile a test matrix. This test matrix is used to evaluate the working principles of the tampering and the functionality of existing vehicle diagnostics in a testing programme, particularly regarding its effectiveness in preventing tampering.

With the project DIAS running for three years the described method is applied as an ongoing process with the market analysis and assessment being more elaborated over time. This initial version of the document therefore does not give a complete reflection of the market involved in tampering of emission control systems but presents the information about this market gathered so far.

1.4 Document structure

Chapter 1 presents the background, purpose, approach and structure of the current document and deviations from the DoW (Description of Work). Chapter 2 describes the methodology used for the market analysis and assessment. In chapter 3 all the results from the market analysis found so far are presented. Chapter 4 includes the prioritisation of tampering devices and services by performing a risk assessment and a preliminary test matrix is presented. An overall conclusion is given in chapter 5. The list of tampering devices can be found in Annex A.

1.5 Deviations from original DoW

1.5.1 Description of work related to deliverable as given in DoW

D3.1: The market of cheating devices and testing matrix with a prioritisation for testing of vehicle tampering technique combinations.

Concise and categorised overview of the cheating devices impacts and current and future risks. A prioritisation matrix to identify the most important tampering techniques for testing.

1.5.2 Time deviations from original DoW

There are no time deviations from the original DoW, with respect to the KO meeting (held on October 23 and 24, 2019).

Due to necessary consortium partners feedback and alignment between D2.1 and D3.1, there is a shift of 1 month with respect to the absolute delivery date of 31.12.2019.

1.5.3 Content deviations from original DoW

There is no deviation from the original DoW. It should be noted that this report discusses the results as obtained in the first months of the project. The market will be continuously monitored for tampering devices until the second hacking event and each new device will be added to the list of tampering devices.

2 Methodology

2.1 Introduction

All of the most effective tampering devices and services and their estimated impact on vehicle emissions, the OBD system and other vehicle systems and signals have to be determined, categorised and prioritised for testing. The method used for this investigation is described in this chapter. It should be noted that, since this investigation is an ongoing process the method described here only reflects on the outcomes of the market analysis and assessment presented in this version.

2.2 Type of research

The market on tampering devices and services of emission control systems can be described both quantitatively and qualitatively. Both approaches were followed to gather enough information to get a complete picture of the market. As can be seen in chapter 3 the qualitive part of the research surpasses the quantitative part because of the size and nature of the market.

2.3 Scope of the work

This research is part of a project organised and funded by the European Commission. The research on the tampering of emission control systems of vehicles is therefore focused on the European (EU-28) market.

An important distinction that has been made in the market is the distinction between LD, HD and NRMM vehicles. The differences in properties and usage of these vehicle types also gives different outcomes of the market analysis.

2.4 Sources

The market analysis and assessment performed is comprehensive because three different vehicle categories are examined on a European wide scale. The goal was and is therefore to retrieve information from a variety of sources that fulfil different roles within the market. A global overview of the different players involved in the market and some examples is listed below:

- (Uninformed or intentional) Customers
    - Private vehicle owners
    - Vehicle fleet owners
- Suppliers
    - OEM dealership
    - Emission control system cleaning companies
    - Car parts (web) shops
    - Tampering suppliers
- Manufacturers
    - Vehicle OEM
    - Aftermarket part manufacturers
    - Tampering device manufacturers
- Vehicle experts
    - (Ethical) vehicle hackers
    - Diagnose experts by experience
- Branch organisations
    - Transport associations
    - Automobile manufacturer’s organisation

- Consumer organisations
    - Road side assistance
    - Consumer representatives
- Authorities
    - Law makers
    - Law enforcers

2.5 Information gathering methods

Information from the sources that are available in the market is obtained by using various instruments. For legal and ethical reasons, TNO approached all involved parties openly and transparently about the investigation being performed with the consequence that some parties do not cooperate with the investigation, for various reasons. A direct approach only, could result in an incomplete investigation of the market. Therefore, both direct and indirect approaches are used.

Table 2.1: Information gathering methods

Direct approach	*Indirect approach*
Email contact/questionnaires	Internet search queries/web pages
(Phone) interviews	Forums
Company visits	Visit dark web
Surveys	
Visit vehicle/tuning fairs and events	
Reports	

2.6 Procedure

The market analysis and assessment are divided in a first and comprehensive analysis at the start of the project. From November 2019 till March 2020 major efforts have and will be put into defining the market. Over the course of the project (March 2020 to Feb 2022) multiple attempts will be made to reassess the market in order to track changes in the market.

The initial market analysis and assessment performed for which the results are presented in this document are gathered by indirect approach of the market. The choice for this approach is based on the available information at the start of the project. In this initial analysis the consulted instruments are roadside inspection reports, news reports, documentaries aired on television or available on video-sharing platforms and internet search queries and web pages.

2.7 Data analysis

The collected information on emission control system tampering is combined separately for the three different vehicle categories to get a well-founded impression of the market and to be able to compare the different vehicle categories with each other. As shown in the following chapter the information found is not always in line or based on opinions and assumptions. Therefore, a reluctant attitude is used for drawing conclusions.

An initial risk assessment is performed by combining all currently known market data, with environmental impact and costs-benefits, and weighing them to assess the potential risk.

2.8 Reliability and validity

2.8.1 Sources

The sources approached and information gathering methods used for an initial market evaluation are not complete for describing the whole market on emission control system tampering devices and services, as previously indicated. Until now only the part of the market known to the authorities and presented in the media is described. Inside information from the parties that tamper themselves or are directly involved in the illegal act of tampering is not gathered until now.

Overall it is assumed that the reliability and validity of the sources consulted up to now is good because of the nature of these sources and the interests they have for conducting thorough research. However, signs were found where news reports tend to create more publicity by making poorly founded assumptions or show to be ignorant by describing the tampering problem incorrectly or incompletely. In this investigation care was taken to filter out these assumptions.

Because of the nature of the sources consulted until now it is not found likely that these sources would have the incentive to provide wrong or incorrect information to have influence on the market.

2.8.2 Privacy-sensitive information

Until now no information was gathered for which privacy-sensitive information needed to be removed in order to encourage sources to speak freely since the sources consulted were mostly indirect sources.

2.8.3 Response percentage

A response percentage of the consulted sources is not relevant to the approach used thus far.

2.9 Follow-up

The next step in the market analysis and assessment is the gathering of information from companies involved in the maintenance and/or tampering of emission control systems, the manufacturing of tampering devices and in parties that have experience with emission control systems or experience problems with their own vehicles or fleets. This will be done by means of direct approaches.

Furthermore, follow-up of the project DIAS involves the testing and examination of tampering devices and services to obtain the general working principle of these devices and services.

3 Market analysis results

3.1 Introduction

Before the findings on emission control system tampering are presented, more general information is given about emission control systems and the European vehicle market. Firstly, the most relevant and common emission control systems are described followed by an explanation of the legislation and enforcement that is currently in place in the EU to ensure emission control systems are applied in vehicles and are maintained correctly. Furthermore, general figures are given about the EU vehicle fleet and its tail pipe emissions.

The results of the market analysis on tampering of emission control systems are presented separately for the vehicle categories LD, HD and NRMM. For the different vehicle categories, different outcomes of the market analysis are found. This relates to the most common emission control problems, the emission control system tampering weaknesses but also the motives for customers and users of the tampering devices and services, which vary for the different vehicle categories.

3.2 Emission legislation and enforcement

An overview is given on the EU legislation and enforcement regarding the emissions of vehicles and the role of authorities in the market of applying, maintaining and tampering of emission control systems of vehicles.

3.2.1 Type-approval

Vehicle manufacturers that want to register and sale vehicles in the EU and/or ECE countries must comply to EC guidelines and/or ECE regulations respectively. These guidelines stipulate the conditions that the production process (Conformity of Production, CoP), the product and the manufacturer itself must meet. In the case these guidelines and regulations are met the vehicle is European type-approved and a Certificate of Conformity (CoC) for the vehicle is obtained. The approval authorities are established or appointed by the EU countries themselves.

3.2.1.1 Vehicle emission limits

EU legislation and standards aim to reduce the emission of carbon dioxide (CO_2), nitrogen oxides (NO_x) and particulate matter (PM) for all three vehicle categories: LD, HD and NRMM. Part of the vehicle type-approval includes that vehicles must meet the emission limits set by the European Commission.

For both LD and HD vehicles the latest emission standards, Euro 6 (2014) and Euro VI (2013) respectively, set limits for the (pollutant) emissions: carbon monoxide (CO), hydrocarbons (HC), NO_x, PM, all expressed in (g/km), and particle number (PN) expressed in (#/km) [9, 10]. Depending on diesel or gasoline engines, the absolute limits vary.

Limits for the same list of (pollutant) emissions are set for NRMM vehicles as well. Instead of Euro classes the emission standards for NRMM are expressed in stages, with Stage V being the most recent EU standard, in place from 2018 [11]. A major difference compared to the emission legislation for LD and HD vehicles is that the limits are set based on engine categories which include engine power outputs and engines specifically designed for a certain vehicle category, like railway locomotives or snowmobiles.

3.2.1.2 Emission testing

Vehicles are tested for emissions over predefined chassis dynamometer test cycles under laboratory conditions. Over the years these test cycles have changed several times to come closer to real-world conditions. Recent and ongoing developments in emission testing introduced so-called on-road emission testing on the road, instead of in a laboratory.

The current emission tests in place as part of the most recent emission standards for LD, HD and NRMM vehicles that need to be performed successfully to obtain EU type-approval are:

Light-duty vehicles:

- Laboratory testing
    - Worldwide harmonized Light vehicles Test Procedure (WLTP) and corresponding Test Cycle (WLTC)
- On-road testing
    - Real Driving Emissions (RDE) testing using a Portable Emissions Monitoring System (PEMS), which is introduced in phases from April 2016.

Heavy-duty vehicles:

- Laboratory testing
    - World Harmonized Stationary Cycle (WHSC) and World Harmonized Transient Cycle (WHTC) testing for diesel engines
    - WHSC testing for positive ignition engines
- Off-cycle emission (OCE) testing
    - Not-To-Exceed (NTE) testing using the WNTE (World harmonized Not-To-Exceed) cycle
    - PEMS testing

NRMM vehicles:

- Laboratory testing
    - Non-Road Stationary Cycle (NRSC) testing
    - Non-Road Transient Cycle (NRTC) testing

3.2.1.3 On-board diagnostics

The on-board diagnostics (OBD) system is designed to monitor the performance of vehicle's emission controls, such as catalytic converter, particulate filter, evaporative emission controls (SCR), engine misfire detection, etc., and to detect emission faults [12]. Such faults are signalled to the vehicle operator by lighting a malfunction indicator light (MIL).

Detailed requirements of the OBD system are specified in several regulations. For the different vehicle types and fuels, gasoline and diesel, generally there are differences between the requirements. The following components or systems are typically monitored by the OBD system:

- Emission aftertreatment devices (catalysts, particulate filters)
- Evaporative system, secondary air system, oxygen sensor (gasoline engines)
- Engine misfire
- Fuel system
- EGR system

Regarding NO_x emission control systems (EGR, SCR) several specific provisions apply to prevent the driver from driving the vehicle with a malfunctioning emission control system [10]. These requirements include:

- Incorrect operation of NOx emission control systems shall be determined through monitoring of the NO_x level by an exhaust sensor.

- If the NO_x level exceeds the OBD threshold limits (OTL), a torque limiter shall reduce the performance of the vehicle.
- For vehicles that require the use of a consumable reagent (e.g., urea) the driver shall be informed of the level of reagent in the vehicle's reagent storage tank through an indication of the vehicle's dashboard. A warning should be triggered when the level of reagent goes below 10% of the tank.
- Engine systems shall include a means of determining that a fluid corresponding to the reagent characteristics declared by the manufacturer is present on the vehicle.
- Engine systems shall include a means for determining reagent consumption and providing off-board access to consumption information.

3.2.2 In-service conformity testing

Next to the emission tests vehicles must undergo for type-approval, also in-service emission testing is required to monitor the effect of ageing of the vehicle on the emission levels. For LD, HD and NRMM vehicles, the in-use testing requirements involve field measurements using PEMS. For LD and HD vehicles the testing is conducted over a mix of urban, rural and motorway conditions, with exact percentages of these conditions depending on vehicle category. Requirements on the age and/or mileage of the vehicle also depend on the vehicle type.

3.2.3 Periodic vehicle emission inspection

Vehicle owners of vehicles registered in EU and ECE countries have the legal obligation to get their vehicles inspected periodically to check the overall condition of the vehicle. The body responsible for performing and regulating these periodic inspections is arranged separately per EU member state. The inspection must be performed according to EU directive 2014/45/EU which lays down the minimum requirements for a regime of roadworthiness testing.

3.2.3.1 General description

Part of the periodic vehicle inspection is aimed at emissions by means of an inspection of the vehicle's exhaust system and certain indicative emission levels. Based on the type and age of the vehicle, specific emission level requirements apply. Regarding both LD and HD vehicles this generally includes the following items [13]:

Vehicles with an internal combustion engine

- Visual inspection to check if the emission control equipment fitted by the manufacturer is absent, modified or obviously defective and if leaks in the exhaust system are present that would affect emissions.

For positive ignition engine (Gasoline) emissions

- Gaseous emission measurement using an exhaust gas analyser or reading of OBD to check if the emission levels exceed the specific levels given by the manufacturer or if not available the CO emissions exceed specified requirements, lambda coefficient and OBD read-out indicating significant malfunction.

For compression ignition engine (Diesel) emissions

- Exhaust gas opacity measurement or reading of OBD to check if opacity exceeds the level recorded on the manufacturer's plate on the vehicle or if not available the opacity exceeds specified requirements.

3.2.3.2 Differences between EU member states

Since the body responsible for performing and regulating the periodic inspections is organised separately per EU member state differences in the interpretation of the legislation and inspection procedure are to be expected. An example of differences between EU member states is the way the emission control systems are inspected.

For vehicles fitted with the OBD2 diagnostics system, it is possible to test the emission control systems of the vehicle by performing a so-called readiness test. Since the 1st of April 2012 in The Netherlands reading the vehicle's OBD system for inspecting the emission levels of the vehicle is mandatory and replaces the emission gas test completely in case no errors are detected during this readiness test [14]. In the United Kingdom however all vehicles need to undergo a physical emission gas test [15]. No readiness test is performed.

3.2.3.3 Shortcomings of the periodic inspection

With the introduction of increasingly stringent emission regulations the application of DPF and GPF systems is needed to meet the emission limits. However among the authorities it is widely known that the current exhaust gas opacity measurement is so outdated that the lack of a filter is not noticed [7, 16, 17]. Efforts by for example the Dutch government to implement an additional visual inspection of the DPF or GPF in the periodic inspection to identify tampering or malfunctions turned out to be unenforceable and not working properly [17].

3.2.4 Roadside inspections

According to EU directives 2014/45/EU and 2014/47/EU, unannounced roadside inspections of motor vehicles and their trailers and commercial vehicles can be carried out in any EU member state, whether the vehicle is registered in the EU. Drivers may also be required to present recent inspection reports and/or proof the vehicle passed the roadworthiness test (periodic inspection).

The authorities within EU member states are free of interpretation on what to include in these roadside inspections and can focus on topics that need to be emphasized with drivers and/or vehicle owners.

3.2.5 Punitive measures

Since the enforcement of the emission legislation of vehicles is organised separately per EU member state also the punitive measures are different. In most countries the amount of the fine or punishment is dependent of the extent to which the law is broken, i.e. the difference between a malfunctioning emission control system or a deliberately tampered system, how often the law has been broken in the past and the country of origin of the driver. The overall trend of the past few years shows that the amount of the fines and severity of the penalties is increasing.

In Denmark fines for the removal of emission control systems of HD vehicles could reach EUR 6.000,- and EUR 3.000,- for haulers and drivers respectively if the offence is repeated. For LD vehicles the fine is EUR 100,- [18].

In The Netherlands tampering of the emission control system of a vehicle could result in a maximum fine of EUR 20.500,- or a prison sentence of maximum 2 year since it is considered an environmental crime [19]. Currently, truck owners that have manipulated aftertreatment systems are fined EUR 7000,- and are obliged to remove the tampering and repair the vehicle until it fulfils requirements of periodic inspection.

A truck intercepted in Spain in 2018 received a fine of EUR 9.000,- [20] as it violated Spanish Law 34/2007 on air quality and environmental protection. Such violation can be punished with an economic sanction of up to EUR 20.000,-.

In Germany new plans have been made in 2019 to increase the fine for emission control system manipulation to EUR 10.000,-. In addition, it is possible for carriers to lose their transport licenses and be banned from entering German territory [21].

England is increasingly acting against manipulation of emission control systems, especially with HD vehicles. Fines for tampering could reach thousands of euros and the DVSA also introduced measures like revoking licenses and inspection complete truck fleets upon the detection of a single tampering device [22].

3.3 Emission control systems

With the introduction of the increasingly stringent emission standards in Europe, manufacturers are challenged to introduce new and more effective emission control systems. The most common and important emission control systems are discussed.

3.3.1 Exhaust Gas Recirculation

3.3.1.1 Working principle

A technique used in gasoline and diesel engines to reduce NO_x that is produced in the combustion engine is exhaust gas recirculation (EGR) [23]. The EGR system directs exhaust gasses into the intake of the engine, reducing the O_2 concentration and increasing the inert CO_2 and H_2O concentrations of the air going into the engine. Because of this change in gas mixture supplied to the engine, the combustion temperature in the engine is lowered, reducing the formation of NO_x in the exhaust mixture. The recirculation of the exhaust gas is regulated by a valve. For some applications the EGR is cooled using an EGR cooler to improve engine efficiency and reduce PM emissions. The EGR can also be used to optimise the NO_2/NO_x ratio to maximise the efficiency of the catalytic reaction of the SCR system, resulting in a higher NO_x reduction.

Over the years multiple variations of an EGR system were introduced in vehicles. The two main options for EGR are the high pressure loop EGR (HPL EGR) and low pressure loop EGR (LPL EGR). Schematics for both variations are seen in Figure 3.1 and Figure 3.2.

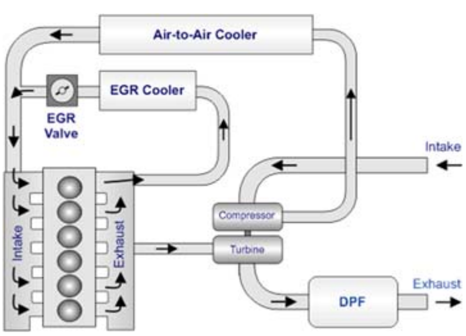


Figure 3.1: High pressure loop EGR [23]

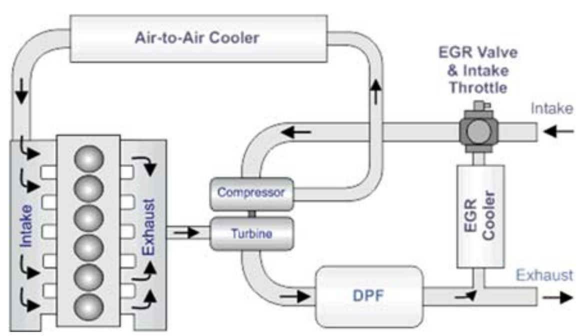


Figure 3.2: Low pressure loop EGR [23]

3.3.1.2 Appearance

EGR technology for light duty vehicles was introduced in the 1990s, but only since the introduction of the Euro 3 and 4 emission standards EGR systems had to meet higher requirements. From the 2000s the EGR systems increasingly got more sophisticated with the application of electronically controlled cooled EGR systems [23].

Upon the introduction in 1977 and during the 1980s and 1990s the use of EGR for heavy duty application remained limited since EGR was not needed to meet the emission standards. Upon the introduction of the Euro IV emission standard in 2005 some heavy duty truck manufacturers (Scania and MAN) introduced EGR, but the majority relied solely on SCR technology. For the current Euro VI standard most manufacturers use a combination of EGR and SCR technology, however some manufacturers (Iveco and Scania) develop engines with SCR technology only [23].

Not until the introduction of the Stage IIIB emission standard in Europe, the EGR technology was used for non-road engines. For engines meeting the Stage IV and V emission standards a variety of after treatment set-ups is seen were EGR is applied solely or in combination with SCR technology. Also, engines with only SCR systems are found [23].

3.3.1.3 Common problems

The most common problem of EGR systems is EGR valve failure due to them becoming blocked or clogged up due to carbonaceous deposits (see Figure 3.3), corrosion or when the valve starts leaking due to normal wear. This results in: lack of power (limp mode), rough engine idling, MIL, poor fuel economy and excessive soot and NO_x emissions [24].

Figure 3.3: Example of a clogged EGR due to deposits, source Axle Addict

The lifetime of the EGR system depends strongly on the usage and the maintenance of the vehicle. EGR problems typically occur in case of:

- Short journeys, preventing the engine and exhaust system from reaching optimal operating temperatures.
- An incorrect air/fuel ratio due to faulty fuel injectors or incorrect engine mapping.
- Incorrect engine oil with a wrong composition, e.q. high ash and Sulphur.
- Turbo failures.

3.3.2 Selective Catalytic Reduction

3.3.2.1 Working principle

Selective Catalytic Reduction (SCR) is a technique in which NO_x in the exhaust gas mixture is converted into N_2 and H_2O with the aid of a catalyst [25] and a reagent. The reagent is a gaseous reductant, typically an aqueous solution of urea. The catalytic reduction takes place in the SCR catalyst of the vehicle that is part of the exhaust system. Urea based SCR systems are the most common SCR systems for vehicles. The liquid urea, that has the commercial name AdBlue, is injected in the exhaust upstream of the SCR catalyst and decomposes (thermolysis and hydrolyses) to form ammonia and CO_2. The ammonia is used in the SCR catalyst to react with NO_x to harmless nitrogen and water. Figure 3.4 shows an overview of the SCR system with all its components. From this figure it is clear that the SCR system is complex with numerous individual parts that could fail over time.

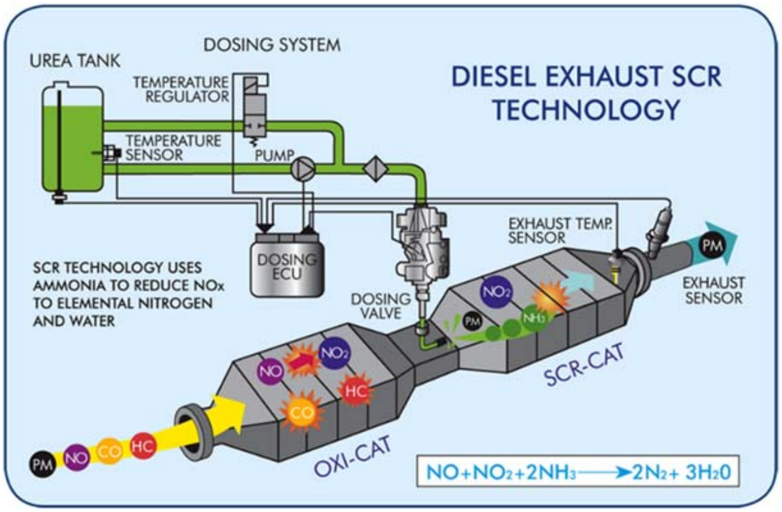


Figure 3.4: SCR system and components; source Research Gate

3.3.2.2 Appearance

In Europe SCR technology was not used in light duty vehicles until the introduction of the Euro 5 emission standard in 2009. From 2014 a much wider application of the technology was seen for the latest Euro 6 standard [25].

From the mid-2000s, SCR technology was introduced for heavy duty engines. Some manufacturers have adopted this technology as the technology of choice since the introduction of the Euro V emission standard (2008). The SCR technology can be found in all heavy duty vehicles with diesel engines or heavy duty dual fuel engines to meet the Euro VI standard from 2013 [25].

The introduction of SCR technology for non-road vehicles was like that of heavy duty vehicles. Wide application occurred from Stage IIIB emission standards [25].

3.3.2.3 Common problems

The most important challenge with SCR systems is the complex chemical reaction that takes place by injection of urea in the exhaust. If this reaction does not take place properly, the conversion of NO_X to N_2 does not occur completely [26]. An incomplete urea evaporation can lead to ammonia deposits, potentially leading to a reduced NO_X reduction, blockage of the urea injector and an increased backpressure in the exhaust which reduces drivability of the vehicle. Furthermore, ammonia is highly corrosive reducing the lifetime of the system.

A malfunctioning EGR system or ageing oxidation catalyst can also be the cause of above SCR problems by having a negative effect on the NO_2/NO ratio in the exhaust system. An optimal ration between NO_2 and NO is needed for a high NO_x reduction efficiency at low exhaust gas temperatures such as occur during low load low speed operation in cities.

Aging of the SCR system is a separate problem itself. After long-term use, the NO_x reduction activity decreases due to catalyst degradation, making emission limits much more critical [27]. As example, at the beginning of 2019 Volvo announced setting aside 780 million dollars to address SCR degradation problems [28].

3.3.3 Diesel and Gasoline Particulate Filter

3.3.3.1 Working principle

The Diesel and Gasoline Particulate Filter technology, (DPF and GPF respectively) is a technology that filters the exhaust gasses to physically capture particulate emissions, including PM and PN, with a high efficiency (>90%) [29, 30].

The application of DPF to reduce PM and PN emissions is very common on diesel engines of LD, HD and NRMM vehicles. As of Euro 5 for LD and Euro VI for HD and stage V for NRMM all new diesel engines have a DPF. To remain fully functional a DPF needs to regenerate regularly to oxidise the trapped soot because otherwise the filter would clog and result in an increased back pressure in the exhaust and power loss and adverse effects on FC and CO_2 emissions as a result. Figure 3.5 shows an overview of the DPF system with components.

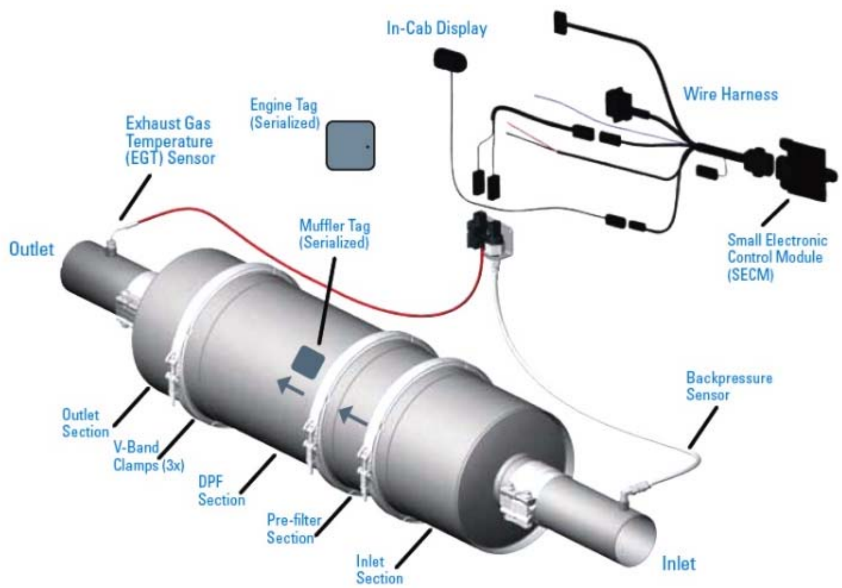


Figure 3.5: DPF system and components; source Fleet Crew Solutions

3.3.3.2 Appearance

From the early 2000s DPF systems were found in light duty vehicles. German car manufacturers introduced DPFs in 2004 in preparation for the Euro 4 standard. From the Euro 5b the PN emission limits forced the application of DPF technology on all vehicles [29].

The introduction of GPF systems for light duty vehicles was not until early 2014. As a result of the PN real driving emission (RDE) testing requirements, that were introduced with the Euro 6d-TEMP emission standard, the number of GPF applications increased rapidly since 2017. From mid-2018 the technology reached a market penetration of at least 10% of gasoline vehicles [30].

Although the first DPF was introduced in 2001, the use of DPF technology on heavy duty engines was only found as of introduction of the Euro IV standard for vehicles that mainly relied on EGR to reduce NO_x (MAN and Scania) and vehicles complying with the EEV standard (Enhanced Environmentally Friendly Vehicle) which mainly consist of a lower PM limit as compared to the respective Euro IV and V limits for PM. With the introduction of the Euro VI standard all heavy duty engines have been factory equipped with a DPF to meet the PM and PN emission limit [29].

Similarly, to the introduction of SCR technology the DPF technology for non-road engines was introduced in accordance with the introduction for heavy duty engines. From the EU stage V emission standard all engines have been equipped with DPF systems [29].

3.3.3.3 Common problems

A DPF can be regenerated many times to burn off soot accumulation but mainly ash cannot be regenerated which means that ash deposition in the filter leads to a gradual blockage of the filter wall over time. Main sources of ash are lubrication oil additives, fuel, engine wear and exhaust corrosion [31]. Most ash cleaning is performed at prescribed service intervals or when a high filter pressure drop triggers a fault. This involves cleaning at the dealer, service centre or by installation of a factory revised DPF.

The most common problem with particulate filters is that for several reasons the filling up of the filter happens faster or more frequent than the regeneration of the filter, resulting in a MIL on the dashboard of the vehicle, loss of power, reduced fuel economy, poor throttle response, harder or failure to start, limp mode or bad smells from the exhaust [32].
The reasons for the accelerated clogging up of the particulate filter are [33]:

- Short journeys, where engine and exhaust system do not optimal operating temperatures.
- Excessive soot emission from the engine due to a (partly) jammed open EGR.
- An incorrect air/fuel ratio due to faulty fuel injectors or incorrect engine mapping.
- Incorrect engine oil with a wrong composition, e.q. high ash and sulphur.
- Turbo failures.
- High vehicle mileage (typically a particulate filter lasts 150 to 200.000 kilometres).

Cracking, clogging (Figure 3.6) or melting (Figure 3.7) of the ceramic filter may lead to changes in the pressure drop which when it extends above or below a certain threshold is detected and will set an OBD fault code, MIL and could lead to limp mode. This type of filter problems usually requires replacement of the filter element.

Figure 3.6: Example of clogged particulate filter, source Auto Expert

Figure 3.7: Example of molten filter, source Big Machine Parts

3.3.4 Three-Way Catalyst

3.3.4.1 Working principle

A three-way catalyst (TWC) is a type of catalytic converter for the application of stoichiometric gasoline engines [12]. With this technology it is possible to simultaneously control NO_x, HC and CO emission by oxidation into N_2, water and CO_2. It is capable of very high (>99%) conversion efficiencies in the case the air-to-fuel ratio in the combustion process is accurately controlled by measuring the O_2 concentration in the exhaust using a lambda sensor.

3.3.4.2 Appearance

Upon the introduction of more stringent emission standards from the 90s the TWC is widely used in all gasoline vehicles and is considered the most important gasoline engine emission control technology.

3.3.4.3 Common problems

Typically, the problems that can occur with TWC systems are component failures or decreased efficiency in case the catalytic converter is clogged or partially blocked. Although the TWC is typically designed to last the lifetime of the vehicle problems occur in case of:

- Short journeys, preventing the engine and exhaust system from reaching optimal operating temperatures.
- An incorrect air/fuel ratio due to faulty fuel injectors or incorrect engine mapping.
- Incorrect engine oil with a wrong composition, e.q. high ash and sulphur.

Figure 3.8: Example of cracked catalyst, source Viper Motorsports

3.3.5 Diesel Oxidation Catalyst

3.3.5.1 Working principle

A diesel oxidation catalyst (DOC) is a type of catalytic converter especially designed for diesel engines. It is an after treatment component that was initially designed to convert CO and HC into CO_2 and water. Currently also DOC formulations are on the market that provide some degree of PM emission control through the oxidation of the organic fraction of diesel particulates.

3.3.5.2 Appearance

The DOC could be found in LD diesel vehicles from the late 90s, with the introduction of the Euro 2 emission requirements [34]. In the early days the DOC typically was a standalone system. Currently the DOC is mainly used to change the exhaust gas composition (oxidize NO and HC) to improve the efficiency of other after treatment systems like the DPF and SCR.

Standalone DOC systems were introduced in HD vehicles on a limited scale at the Euro IV/V stage [48]. With the widespread use of DPF and SCR aftertreatment systems the DOC is used for NO_2 generation for a higher SCR efficiency and to facilitate DPF regeneration at lower temperatures than otherwise would be possible with the oxygen that is present in diesel exhaust gas. This is also the case for stage IV and stage V non-road diesel engines.

3.3.5.3 Common problems

Overall DOC’s are simple, inexpensive and require low maintenance compared to other emission control systems. Potential problems are similar to problems occurring for the TWC systems. DOC can age over time, becoming less active. This generally means that less NO will be oxidized to NO_2 which will affect the operation of other systems of the aftertreatment such as DPF regeneration and SCR efficiency.

3.3.6 NO_x Adsorber

3.3.6.1 Working principle

A NO_x Adsorber (also known as NO_x trap or Lean NO_x trap (LNT)) is a type of adsorber-catalyst in which the adsorber is incorporated in the catalyst wash coat, chemically binding NO_x during lean engine operation (typically diesel engines [35]). After the adsorber capacity is saturated, the system is regenerated during a period of rich engine operation, and released NO_x is catalytically reduced to nitrogen.

3.3.6.2 Appearance

NO_x adsorber-catalyst systems have been developed to control NO_x emissions from partial lean burn gasoline engines and from diesel engines. Due to their declining NO_x reduction performance at higher exhaust temperatures, NO_x adsorbers are only very limitedly applied on heavy-duty truck engines. Considering the trends in light-duty emission regulations, the use of active NO_x adsorbers as the primary stand-alone aftertreatment technology for NO_x control can be also expected to decline in future light-duty vehicles [35]. To meet the latest emission requirements a combination of emission control system is deemed necessary.

3.3.6.3 Common problems

Due to the limited application in vehicles specific system related problems with the NO_x adsorber other than similar problems with catalytic converters are not known.

3.3.7 Evaporative Emission Control System

3.3.7.1 Working principle

The Evaporative Emission Control System (EVAP) prevents gasoline vapours, containing hydrocarbons (HC) from the fuel tank or fuel system from escaping into the atmosphere [36]. This is done by capturing the hydrocarbon rich fuel vapor via a vent line in a so-called carbon canister. Typically, in the vent lines an under pressure is created when the engine is turned off, so the fuel vapor is sucked through the cannister. When the engine is turned on again the canister is emptied, and the HC's are burned off in the engine.

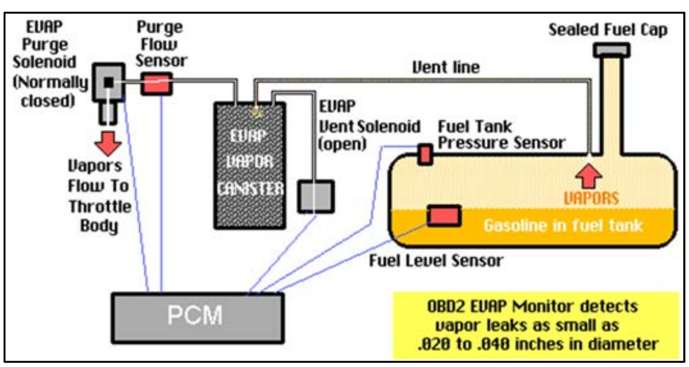


Figure 3.9: EVAP system in gasoline vehicles, source AA1car.com

3.3.7.2 Appearance

The EVAP system is mandatory for all gasoline vehicles from the introduction of OBDII in the mid-90s. Because for diesel the problem of evaporative emissions does not occur, this system is only applied for gasoline engines.

3.3.7.3 Common problems

The EVAP system is a system with many components including valves, hoses and sensors, see Figure 3.9. Although this system typically requires low maintenance, for ageing vehicles gas leaks are more prone to occur, resulting in MIL's on the dashboard. Finding and fixing those gas leaks can be a challenge resulting in a potentially costly repair.

3.4 Market shares of vehicles across Europe

3.4.1 Light duty vehicles

According to figures from the ACEA [37] from 2014 to 2018 the EU passenger car fleet grew by 8% from 248 million vehicles to a total number of 268 million cars. The average age of passenger cars in the EU is 10.8 years old. Estonia, Lithuania and Romania have the oldest fleets, with vehicles older than 16 years. The newest cars can be found in Luxembourg (6.4 years) and the United Kingdom (8.0 years). The market share for petrol and diesel passenger cars in the EU is 54% and 41.9% respectively.

The total transport volume of passenger cars in the EU-28 in 2016 was 4 827 billion passenger-kilometres [38].

Next to that about 33.2 million vans are in circulation throughout the European Union, with the largest fleet in France (6.2 million vehicles), followed by Spain (4.6 million), the United Kingdom (4.4 million vans) and Italy (4.2 million). The average age of light commercial vehicles in the EU is 10.9 years with diesel-powered vehicles have a market share of more than 91% of the total fleet.

3.4.2 Heavy duty vehicles

In 2018 there were 6.6 million trucks on the EU roads with an average age of 12.4 years according to figures from the ACEA [37]. With 1.1 million trucks, Poland has the largest market share, followed by Germany (947.000) and Italy (904.000). 98.3% of all trucks in the EU run on diesel.

The total transport volume of buses and coaches in the EU-28 in 2016 was 527 billion passenger-kilometres. And the total freight transport volume on the road (both LD and HD vehicles) in the EU-28 in 2016 was 1 786 billion tonne-kilometres [38].

The market share for truck manufacturers in EU and EFTA countries in 2016 was as follows:

Table 3.1: Truck manufacturer market share in EU and EFTA countries in 2016 [39]

Manufacturer	*Daimler*	*MAN*	*Volvo*	*Scania*	*DAF*	*Iveco*	*Renault*	*Other*	*Total*
Market share	21%	15%	14%	13%	13%	12%	7%	5%	100%

Around 770,000 buses are in operation throughout the European Union, 30% of which are found in two countries alone: Poland and Italy. The average age of EU buses is 11.4 years now. 95.4% of the busses in the EU run on diesel.

3.4.3 Non-road mobile machinery

The vehicle registration for non-road mobile machinery is not that well organised as for light and heavy duty vehicles, which must be registered. Actual figures on the amount of NRMM and market shares between tractors, loaders, etc. are not available.

3.5 Emission footprint of road vehicles

Figures on the emission contribution of road transport are presented in this paragraph. It should be noted that the market shares of the vehicle categories and corresponding tail pipe emissions are very limitedly available or are based on relatively old information.

3.5.1 Road transport

Emission footprint figures of the different vehicle categories are not available for the EU. The following figures are available at the European Environment Agency (EEA) and show the emission footprint of the entire transport sector compared to the total pollutant emissions in the EU-28 in 2016.

Table 3.2: Pollutant emission in the EU-28 in 2016

Pollutant emission	*CO in Gg (1.000 tonnes)*	*NH3 in Gg (1.000 tonnes)*	*NOx in Gg (1.000 tonnes)*	*PM2.5 in Gg (1.000 tonnes)*	*PM10 in Gg (1.000 tonnes)*	*SOx in Gg (1.000 tonnes)*
Total	19.415,6	3.937,5	7.441,9	1.300,5	2.012,0	2.244,7
Road transport	3.841,0	53,2	2.930,6	148,0	217,7	5,5
%-fraction	19,78%	1,35%	39,38%	11,38%	10,82%	0,25%

3.5.2 Non road mobile machinery

According to a 2017 report from the Scandinavian GPP Alliance [40] in the EU the NRMM sector is responsible for around 15% of the total NOx emissions and 5% of total PM emissions. The report also states that for 2020 it is expected that the NOx share increases up to nearly 20%, while the PM share is expected to decrease.

3.6 Tampering of light duty vehicles

An overview is given of the tampering devices and services for LD vehicles offered online and found in related news reports and roadside inspection reports on tampering of LD vehicles. A list of common tampering devices can be found in Annex A.

“In 2018 in passenger cars the most tampered emission control systems are the EGR and DPF systems.” according to a documentary aired on the German channel Bayerischer Rundfunk [41]. Disabling the EGR or DPF system in the event of malfunction is less expensive than repairs and this is widely offered by workshops. In combination with the lack of control on tampering and a low chance of getting caught this is the frequently chosen solution for emission control problems.

Based on figures of the ‘Verband der TÜV’ between 5 to 10 percent of all passenger cars in Germany have defective or manipulated emission control systems. This means that out of a total of 45 million vehicles on the German roads, up to 4,5 million passenger vehicles could be involved, causing up to 80 percent of the NO_x emissions [41].

Nevertheless, periodic inspections only aim on the emission of carbon monoxide and the exhaust gas turbidity for gasoline and diesel engines respectively. Nitric oxide or particulate matter are not controlled at all.

3.6.1 Diesel and Gasoline Particulate Filter

From 2015 numerous investigations and news reports can be found on tampering of DPF systems in LD vehicles. Since GPF systems were only sparsely applied to gasoline vehicles until 2018 only very limited information could be found online.

An investigation by TNO performed in 2015 [42] showed that approximately 6% of the tested vehicles had elevated smoke emissions, indicating the DPF of these vehicles were either damaged or removed.

That same year an investigation commissioned by the Dutch Ministry of Infrastructure and Environment showed that in The Netherlands about one hundred thousand passengers vehicles drive without a DPF [43]. Although vehicles without such filter are not allowed on the road, the chance of getting caught is nil.

In the spring of 2018, the Dutch news channel EenVandaag reported large scale fraud of the largest car rental company in the Netherlands, Bo-rent, which removed diesel particulate filters from their Mercedes-Benz Sprinter vans to save on maintenance costs [44]. For a test, EenVandaag rented nine delivery vans at six different locations. After inspection by Dutch DPF specialist Topcats it turned out that for seven out of the nine vans the DPF was removed. An anonymous source confirmed this reading; “The filters are preventively removed from new vehicles, because Bo-rent had many problems with it. They wanted to get rid of the hassle, it saved them a lot of money.”

In direct response to the Bo-rent scandal in The Netherlands the government found it necessary to include an additional check in the roadworthiness test. Since May 2018 a visual inspection is performed during the periodic inspections to check for the presence of the DPF [45]. Nevertheless, this measure turned out to be ineffective because with a simple visual inspection from underneath the vehicle the presence of the filter in the DPF system can hardly be checked. Figures from the RDW and TNO confirmed this conclusion. In the first year after the introduction of this inspection only 397 vehicles were found to have a removed DPF. Based on interviews with car workshops and desk research TNO concluded that an estimated minimum of 20,000 vehicles (1.2%) drive without such filter [46].

In other EU countries investigations on the removal of DPF’s were performed as well. The Driver and Vehicle Standards Agency in Great Britain has penalised 1,800 drivers since 2014 driving with the DPF removed from their vehicles [47].

Belgium Mobility Club VAB estimated that in Belgium tens of thousands and possibly even more than a hundred thousand Diesel passenger cars drive without a DPF [48]. For the whole of Europe this estimate would be a million vehicles.

To address this problem for several years both Belgium and The Netherlands have been trying to find a solution for the detection of a missing DPF or GPF. It is expected that from 2020 a new test is implemented in the regular periodic inspection making this detection possible [48, 49].

Besides the physical checks on the soot emissions of LD vehicles, recent research by TNO [46] focused on gaining insights in the Dutch market around DPF’s by taking interviews with workshops that service diesel vehicles and by performing a desk research. This research showed that the main reason for removing the DPF are the high replacement (on average €1.200,-) or cleaning costs. But also, reasons as recurring problems with DPF and DPF removal as permanent solution to prevent recurring problems are given. Furthermore, the tampering service of removing the DPF is easy and accessible for customers in the whole of The Netherlands. Despite it being forbidden by law the study showed that companies still offer the service of removing the DPF and adapting the OBD software for EUR 300,- to 650,- [46].

For this market analysis TNO searched the internet for DPF removal devices and services. Search queries with keywords like; ‘DPF removal’, ‘delete DPF’ or ‘remove DPF’ on different search engines and at large web shops showed that especially these kinds of tampering services are offered on a large scale. Figure 3.10, Figure 3.11 and Figure 3.12 show three examples of websites of companies in the EU that offer the service of DPF/GPF removal for light duty vehicles. In Figure 3.10 the service is offered for ‘only £249,99’ and preferably in combination with a performance remapping to get more out of the DPF removal itself.

Figure 3.11 suggests "the DPF removal to be an extremely popular alternative for cash strapped customers" and is offered for all makes and models. Figure 3.12 shows an example of a company providing the service of GPF removal as it indicates that with the changing EU legislation new gasoline vehicles can be equipped with a GPF system as well.

Figure 3.10: Example DPF removal website screenshot, source midlanddpfremoval.com

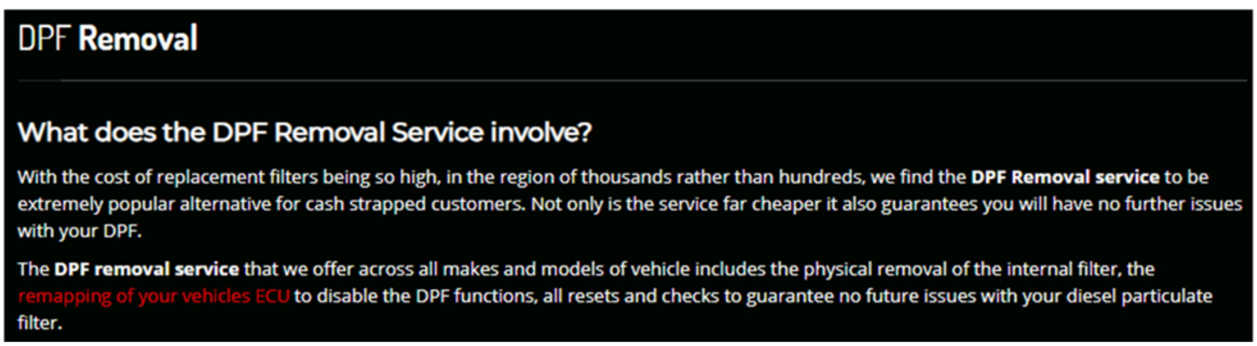


Figure 3.11: Example DPF removal website screenshot, source mfkautocare.ie

Figure 3.12: Example GPF removal website screenshot, source tuningbot.com

3.6.2 Exhaust Gas Recirculation

EGR technology has been implemented in LD vehicles for a long time compared to other emission control system technologies. However limited reports or news items can be found about the tampering of EGR systems for LD vehicles.

During an international specialist conference on sensors for exhaust cleaning and CO2 reduction in 2016 a representative of Brace Automotive reported that in the EU a very common modification for older diesel engines is blocking off the EGR system [50]. Many earlier EOBD systems do not detect EGR blockages, and according to some estimates, as many as 50% of older diesels in the EU may have their EGR blocked. Simple 'Do-It-Yourself' EGR removal kits for older gasoline and diesel vehicle models can be bought easily on the internet.

The search query 'EGR removal kit' on Google alone results in over 6 million hits, in which kits are offered in the range of EUR 5,- to 100,- for almost all makes and models where no software changes to the vehicle are required, typically vehicles introduced between the mid-90s and early 00s. Examples are given in Figure 3.13 and Figure 3.14.

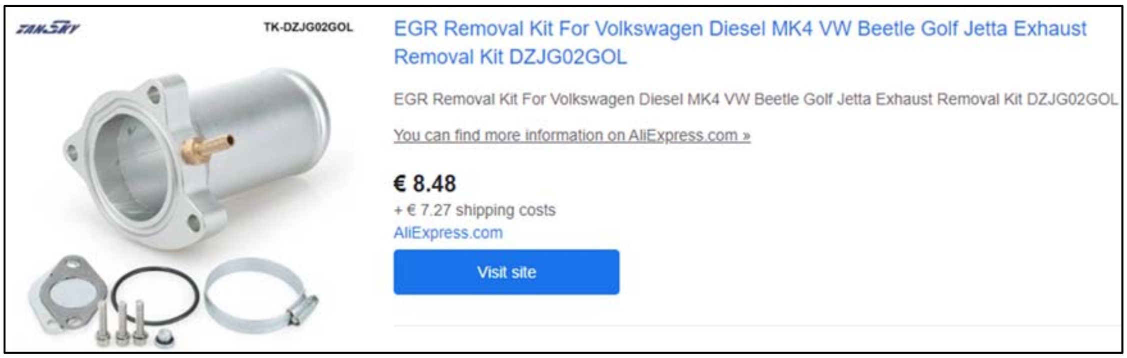
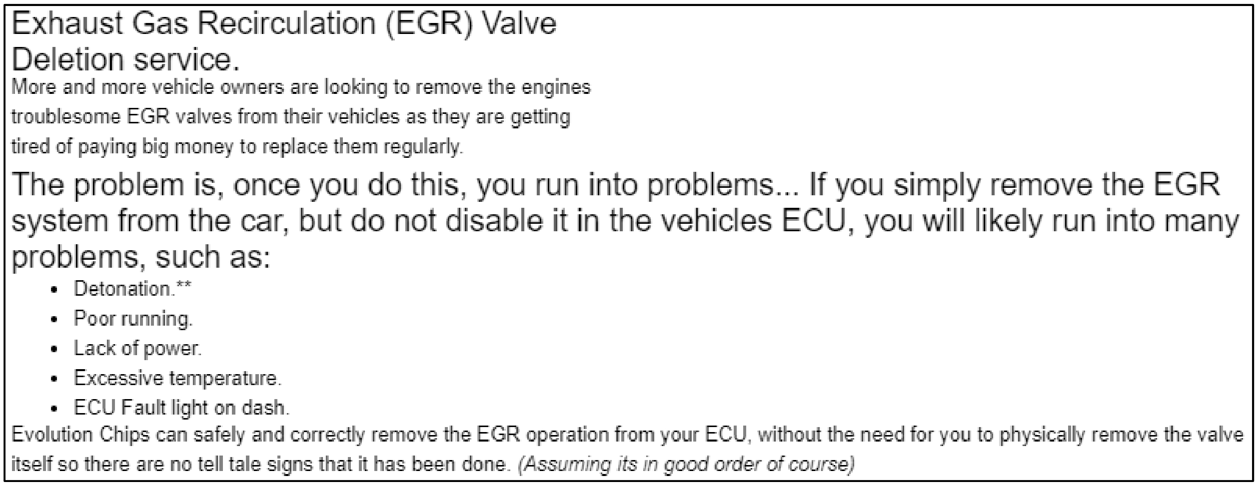


Figure 3.13: Example result on Google Shopping for search query: 'EGR removal kit'

Figure 3.14: Example results on AliExpress for search query: 'EGR delete kit'

For newer LD vehicles, typically from 2004, successful EGR tampering also needs an adjustment to the software of the vehicle. Simply blocking the EGR line or removing the valve results in a MIL and error code that is likely to be detected during periodic inspections. In Europe hundreds of companies provide the service of removing the EGR system and making changes to the vehicle's software. Prizes range from EUR 175,- to 300,-. An example is given in Figure 3.15, which shows a company providing the EGR removal service by removing the ECU code so the valve does not have to be physically removed and thereby "there are no tell-tale signs that it has been done".


Exhaust Gas Recirculation (EGR) Valve
Deletion service.
More and more vehicle owners are looking to remove the engines troublesome EGR valves from their vehicles as they are getting tired of paying big money to replace them regularly.

The problem is, once you do this, you run into problems... If you simply remove the EGR system from the car, but do not disable it in the vehicles ECU, you will likely run into many problems, such as:

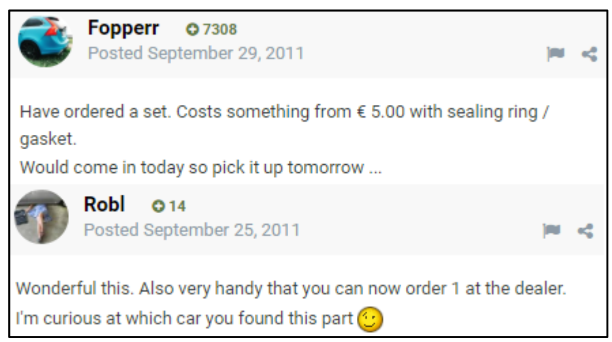
- Detonation.**
- Poor running.
- Lack of power.
- Excessive temperature.
- ECU Fault light on dash.

Evolution Chips can safely and correctly remove the EGR operation from your ECU, without the need for you to physically remove the valve itself so there are no tell tale signs that it has been done. *(Assuming its in good order of course)*

Figure 3.15: Example EGR removal website screenshot, source evolutionchips.co.uk

Besides tampering manufacturers offering EGR removal products at online shopping websites on a large scale, car manufacturers themselves sometimes offer parts to disable this system, as was shown in a 2018 documentary of the German news channel Bayerischer Rundfunk [41]. Here it is shown that Volkswagen offers EGR cover plates for application in industrial diesel engines, see Figure 3.16. In Figure 3.17 a screenshot of a forum discussion is shown with vehicle owner's reactions to this specific VAG part. However, it is imaginable that anyone with some technical knowledge could also apply these parts to vehicles registered for road use. In this example the hardware only costed a couple of euros.

Figure 3.16: Genuine VAG EGR blanking plate for 1.9 and 2.0L 4-cyl diesel engine, source forums.vwvortex.com


Fopperr 7308
Posted September 29, 2011

Have ordered a set. Costs something from € 5.00 with sealing ring / gasket.
Would come in today so pick it up tomorrow ...

Robl 14
Posted September 25, 2011

Wonderful this. Also very handy that you can now order 1 at the dealer.
I'm curious at which car you found this part

Figure 3.17: Forum discussion about VAG EGR blanking plate, source forum.vwpassat.nl

Although tampering with the EGR system is illegal in Europe, normally only the fault codes of the vehicle are checked during periodic inspections. The physical removal of the EGR valve and deletion of the software part resulting in errors therefore is almost never discovered. On automotive forums vehicle owners confirm this story with examples found of people driving their cars for years, and never being caught during their annual periodic inspection, see Figure 3.18.

Probenator
Re: EGR write 1.6 TDI CR
08-03-2019 22:24

> *Quote*
> ***Pietzoveel***
> *A **soot measurement** is still being done at the MOT.*

No, cars with a construction year after 01-01-2006 will only be hung on the OBD. If there are no error messages and the equipment completes the Readiness test, that part is approved. If the EGR software is written, it does not give an error message, so approve at that point. A closed EGR with an error message (so without written software) is rejected.

Respond   Respond with quote

Figure 3.18: Discussion on a Dutch forum about the EGR removal not being detected during periodic inspection (reference is made to Dutch legislation), source autoweek.nl

3.6.3 Selective Catalytic Reduction

SCR technology for light duty vehicles has made its appearance relatively recently (2014) compared to EGR and DPF technology (2000s). In contrast to the wide spread focus on SCR manipulation for HD vehicles, as will be explained in Paragraph 3.7, for LD vehicles no information can be found on road side inspection results or news channels reporting on the tampering of the SCR system in passenger vehicles.

Nevertheless, signs of tampering services being provided by certain workshops or garages are present. By search queries on Google like "AdBlue removal passenger car" thousands of results are returned showing dozens of companies providing tampering services or devices to shut down the SCR system of a vehicle. In The Netherlands alone over 30 companies can be found on the internet that advertise with the removal of certain systems, guaranteeing a permanent solution and giving a life time warranty [51]. Prices range from EUR 300,- to 800,- . Figure 3.19 shows an example of a company providing the SCR removal service. Depending on the installation of the module, which can be done by the vehicle owner itself, the software programming can be done at the customers location in several hours (considering an hour rate of about EUR 60,- to 80,-).

Price and installation

We can program software for you at our store, at one of our dealers, or at your location. Switching off AdBlue via software is from € 300. For an exact price you should contact us because there is a lot of difference per type and brand of car.

You can order the modules and easily assemble them yourself or you can choose to have them assembled by one of our engineers. The price of this module is from € 799 excl. VAT and excl. Assembly costs.

Cars and commercial vehicles

For the cars below, we can disable the ad-blue via Software;

- Audi (all models)
- BMW (X5, X6)
- Mazda (CX-7 / CX-9)
- Mercedes (ML, GL, Sprinter)
- Volkswagen (All models)

If your model is not listed, please contact us. Perhaps we now have a suitable solution for your car that has not yet been posted on the website.

Figure 3.19: Example of SCR removal service for LD vehicles offered online, source chipperformance.nl

3.7 Tampering of heavy duty vehicles

An overview is given of the tampering devices and services for heavy-duty vehicles offered online and found in related news reports and roadside inspection reports on tampering of heavy-duty vehicles. A list of common tampering devices can be found in Annex A.

3.7.1 Selective Catalytic Reduction

In 2018 in trucks the most tampered emission control system was the SCR system [41]. Reports of tampering of these systems are available in abundance because roadside inspections organised in Europe focus on this type of tampering for HD vehicles. Several documentaries aired on German and Dutch television showed the extend of the SCR tampering problem amongst HD vehicles.

At the beginning of 2017 a German ZDF documentary broadcasted on TV showed SCR tampering. Inspections of trucks on German motorways on behalf of ZDF and the professional association for companies in the transport industry, Camion Pro, suspected mainly Eastern European transportation companies tamper with the SCR systems of trucks [52]. According to Camion Pro annual profits per truck seldomly exceed EUR 6.000,- and by avoiding AdBlue costs typically about EUR 1.500,- per truck (100.000 km annually) can be saved on a yearly basis. Due to a lack of control the risk of being caught with a defeat device is limited and when caught the fines for tampering are low, not outweighing the profits gained. ZDF and Camion Pro furthermore showed that so called 'AdBlue Killers', that shut down the SCR system, can be easily bought in East European countries, both in workshops or on the internet.
In the documentary the following calculation is made; "In 2017 trucks drove about 30 billion kilometres on German road of which 8 billion by Eastern European trucks. Assuming that 20% of the Eastern European trucks is tampered with, according to Professor Thomas Koch from the Institut für Technologie, it is estimated that an additional 14,000 tonnes NO_x per year is emitted. In comparison in the USA the VW diesel gate contributed to approximately 7,000 tonnes NO_x per year."
The assumption that 20% of the Eastern European trucks is tampered with is debatable since the documentary does not clearly indicate on which figures this is based. Furthermore, it remains unclear if the vehicles are actually tampered with or have unremedied malfunctions of the emission control systems. This is also concluded from the following research.

A study by Heidelberg University [53], commissioned by T&E's German member Deutsche Umwelthilfe (Environmental Action Germany, DUH), measured the NO_x emissions of 141 trucks (one Euro III, 40 Euro V and 100 Euro VI trucks) during driving on the road by chasing the trucks and measuring the NO_x concentration in the exhaust plumes of the vehicles. Based on predefined NO_x thresholds that were set by the investigators, namely 3000 mg/kWh and 1400 mg/kWh for Euro V and VI respectively, trucks were classified as OK (under the threshold) or NOT OK (over the threshold), with the latter indicating either defects or manipulation of the emission control system of the truck.
Of the 141 vehicles measured on German roads, 52 (37%) were registered in Germany, with the other 89 (63%) coming from other EU states and some non-EU states namely; Russia, Belarus, Serbia and Turkey. The emission results showed that the NO_x emission of 12 (30%) of the Euro V and 16 (16%) of the Euro VI trucks exceeded the predefined thresholds. In total 20% of all measured trucks.
The DUH is convinced the exceeding of the predefined NO_x thresholds is a deliberate attempt by haulers to keep costs down. However, no conclusions can be drawn if the trucks had emission control system malfunctions, were tampered with because of emission control system malfunctions and avoid repair costs or were tampered with to prevent maintenance and repair costs in the first place.

Danish investigations commissioned by the Transport Ministry of Denmark showed that trucks equipped with tampering devices have up to 45 times higher NO_x emissions than trucks with a well-functioning emission control system [54]. The illegal truck manipulation is typically done to save money for the operation and maintenance of the truck's NO_x control system.

Between August and November 2017, the British Driver and Vehicle Standards Agency (DVSA) started to include checks for emission cheat devices in roadside checks of trucks at five locations across Great Britain [5, 55]. According to the DVSA the main incentives for vehicle operators to tamper with emission control systems is to reduce the cost of operating the vehicle, whilst still appearing to meet the engine emissions standards, and to prevent malfunctions of the emissions control systems preventing the engine from starting or putting the engine into 'limp mode'.
The DVSA made a list of "Quick Indicators" by which SCR issues or tampering can more easily be detected. This list includes:

- Reagent tank gauge showing exactly 25%, 50%, 75% or 100%.
- Fuse removed/blown from SCR system, as replacing the fuse can sometimes override the emulator fitted.
- Reagent tank level does not correspond with gauge.
- Switch, for purpose of switching off the SCR, ECU wiring loom spliced.
- Reagent tank empty without dashboard MIL.
- Electronic device fitted in OBD port, may be an emulator.
- Electronic device fitted with wires spliced into the wiring for SCR ECU modulator.

By the end of November 2017, DVSA examiners had searched 3,735 trucks at these locations and found 293 lorries with a cheat device fitted (7.8%). By the end April 2018 The British DVSA said that a total of 388 vehicles were found with cheating devices from checks on more than 10,000 trucks in total (3.8%) [56]. UK-registered vehicles were bigger offenders than foreign-registered vehicles. There were 4,339 checks on UK-registered vehicles, during which 261 cheat devices were found (6.0%), as against 5,898 checks on foreign-registered vehicles, with 127 cheat devices found (2.1%). There was no pattern in manufacturers or age of vehicles. The DVSA said that it was mostly Euro IV and V vehicles that had the emulator devices although there were some Euro VI.

An investigation by Dutch Television channel SBS6 [57] showed that devices that shutdown the AdBlue systems in trucks can easily be bought in The Netherlands. At eight randomly selected truck parts and maintenance specialists the investigator was told about the possibilities to bypass the AdBlue system. These services were offered for prices fluctuating between EUR 500,- and 1.000,-. One of the companies said it had been doing this work for almost ten years.

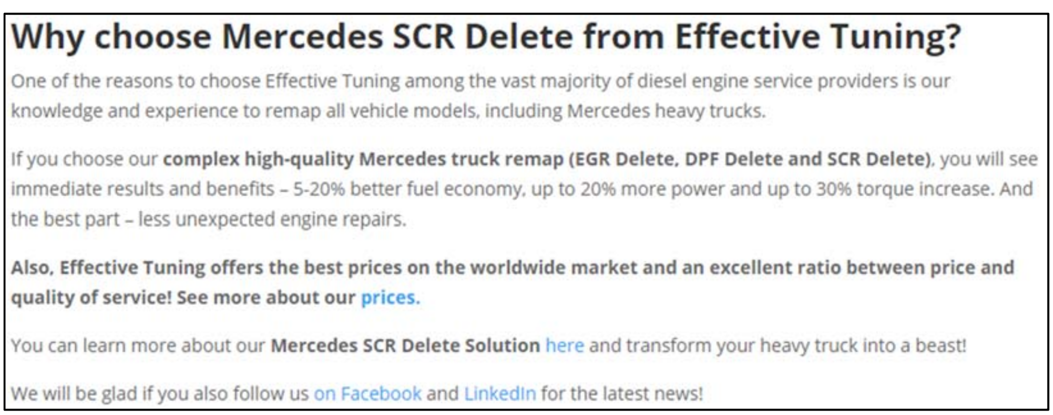


Figure 3.20: Example SCR removal website screenshot, source effective-tuning.com

Similar to the tampering devices and services offered for LD vehicles, also for HD vehicles countless websites promote or offer devices and services to shut down the SCR system in a truck or bus. Figure 3.20 shows an example company website where SCR tampering in combination with EGR and DPF removal is promoted to improve fuel economy and power and torque output of the engine, while less repair costs can be expected.

Another company provides the option to install a switch in the truck which can be used to switch on and off the AdBlue dosing so the driver can “arrange AdBlue consumption itself” (see Figure 3.21). This company also lists makes and models of trucks that can be tampered with. It is important to note that for some of the Euro VI trucks in the screenshot the removal of the DPF system is required if the SCR system needs to be tampered with.
TNO also received similar information from the Dutch Police that for some trucks the SCR and DPF system is controlled by a single ECU. Upon shutdown of the SCR system also the DPF system needs to be removed since this system would otherwise not be able to regenerate the filter and get clogged quickly, causing even more problems.

Arrange AdBlue consumption yourself

You can replace the original AdBlue computer with the fuse or relay. As a result, the truck will immediately return to normal AdBlue use. If you remove it again, the AdBlue off module will take over everything again. Switching is therefore always possible within a minute. If desired, we can build a switch between them so that it is even easier to operate.

Trucks

ADBLUE OFF / DELETE EMULATOR TRUCKS

Scania

Scania Euro 5 with EMSS6 ECU:

• We reduce SCR UREA consumption by up to 80% via Software (Tuning Files - Chip Performance)
• SCR UREA Delete Emulator (you can remove SCR unit + NOX sensors)
• SCR UREA Delete Emulator Next Generation (you can remove SCR unit + NOX sensors + emulation SCR ECU + VIN number - Only on order)

Scania Euro 6 with EMSS8 ECU:

• DPF Delete + SCR UREA Delete Emulator (you can remove DPF + SCR Urea Unit, or remove the fuse. + Simulation of all ECM + VIN number)

Volvo

Volvo Euro 5 with TRW 2 ECMs:

• SCR UREA Delete Emulator (you can remove SCR unit + NOX sensors)
• SCR UREA Delete Emulator Next Generation (you can SCR unit + NOX sensors + emulation SCR ECU + Chassis number simulation)

Volvo Euro 6:

• DPF removal + SCR UREA Delete Emulator (DPF must be removed + SCR Urea Unit can be removed, or remove the fuse. + Simulation of all ECM + VIN number)

DAF

DAF Euro 5 with Delphi DCMI ECU:

• SCR UREA consumption with 100% reduction via Software (Tuning Files - Chip Performance) tested on model XF105 etc.
• SCR UREA Delete Emulator (you can remove SCR-unit + NOX sensors)
• SCR UREA Delete Emulator Next Generation (you can remove SCR unit + NOX sensors + emulation SCR ECU + Chassis number)

DAF Euro 6 with Delphi etc3 ECU:

• DPF removal + SCR UREA Delete Emulator (DPF must be removed + SCR Urea Unit can be removed, or remove the fuse. + Simulation of all ECM + VIN number)

Figure 3.21: SCR tampering offered for trucks (website screenshot), source chipperformance.nl

Also found at road side inspections is SCR tampering by means of replacing a temperature sensor by a resistor such that a temperature is emulated at which no AdBlue dosage must take place. For instance, below – 11°C AdBlue freezes and therefore dosage is stopped. Emulating an AdBlue temperature below – 11°C stops AdBlue dosage. Another case is known were the ambient temperature sensor can be replaced by a resistor to emulate a value of the ambient temperature above 40°C. According to formal requirements for HD vehicles emissions control does not need to be active because this temperature is outside of the boundary for off cycle emissions.

3.7.2 Diesel Particulate Filter

Instead of the widespread focus on the detection of SCR tampering of heavy-duty trucks by the different authorities in Europe, this focus is a lot less for DPF tampering. Also, news channels on the internet have not reported about tampering of DPF systems for trucks on a similar scale as for SCR tampering. Nevertheless, plenty of signs can be found, simply by searching the internet for companies providing these services, that DPF tampering is also taking place for heavy-duty vehicles.

The overall picture that is shown on websites [58, 59, 60] providing DPF tampering services is that DPF removal increases fuel efficiency, improves the engine performance, increases the service life of the engine and reduces vehicle repair costs. Replacing the entire DPF system of a truck costs many thousands of euros, typically between EUR 5.000,- and EUR 20.000,- [61], with DPF filters alone coming in at around EUR 2.500,- to EUR 4.500,-. In case the filter is not damaged but clogged only it can also be cleaned for 10 to 20% of the price of a new filter. The costs for removing the DPF system are however much lower with an example found on the internet of EUR 1.500,- (see Figure 3.22).

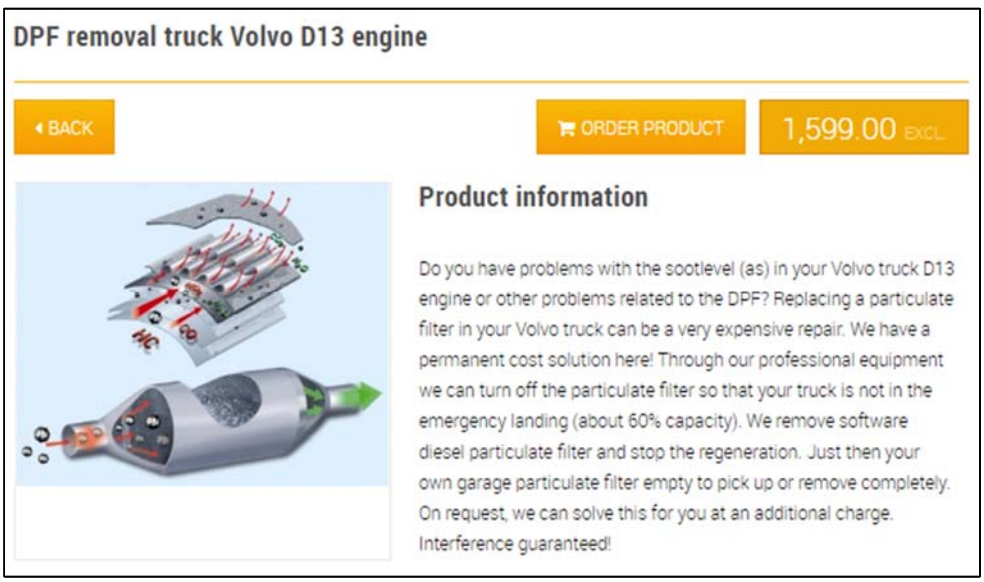
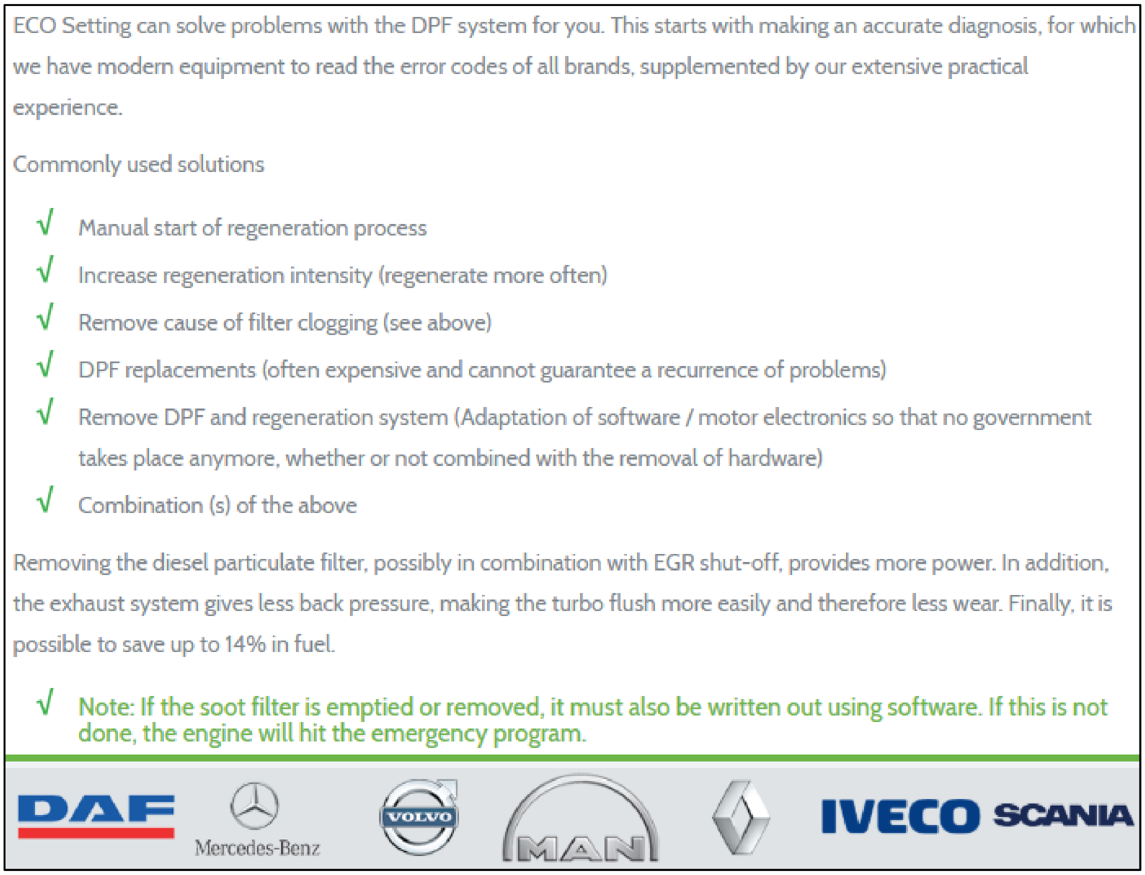


Figure 3.22: Example of DPF removal for a Volvo D13 truck engine, source truckgadgets.nl

In Figure 3.23 a screenshot is seen from the website of a company providing DPF tampering for all major truck manufacturers in the EU. Note that the physically removing of the filter is not enough to shut down the system, also the software needs to be adjusted. Next to this the company recommends tampering of the DPF in combination with shutdown of the EGR to improve the power output of the engine.



ECO Setting can solve problems with the DPF system for you. This starts with making an accurate diagnosis, for which we have modern equipment to read the error codes of all brands, supplemented by our extensive practical experience.

Commonly used solutions

- √ Manual start of regeneration process
- √ Increase regeneration intensity (regenerate more often)
- √ Remove cause of filter clogging (see above)
- √ DPF replacements (often expensive and cannot guarantee a recurrence of problems)
- √ Remove DPF and regeneration system (Adaptation of software / motor electronics so that no government takes place anymore, whether or not combined with the removal of hardware)
- √ Combination (s) of the above

Removing the diesel particulate filter, possibly in combination with EGR shut-off, provides more power. In addition, the exhaust system gives less back pressure, making the turbo flush more easily and therefore less wear. Finally, it is possible to save up to 14% in fuel.

- √ Note: If the soot filter is emptied or removed, it must also be written out using software. If this is not done, the engine will hit the emergency program.

Figure 3.23: DPF removal offered online (website screenshot), source ecosetting.com

3.8 Tampering of non-road mobile machinery

Information from inspection or news reports regarding the emission control system tampering of non-road mobile machinery is scarce. Widespread attention regarding this topic for this type of vehicles is simply not present compared to all the media attention about the tampering of heavy duty trucks. However, it is highly likely that especially NRMM used for agriculture and construction work are being tampered with on a similar scale as are LD and HD vehicles. Several companies selected during the investigation by Dutch television channel SBS6 [57] also indicated to tamper with this kind of machinery or at least provide devices to shut down emission control systems of such vehicles.

On the internet numerous companies can be found, all over Europe, that provide services for the replacement, cleaning, reinstatement but also removal of emission control systems like the EGR, SCR and DPF systems. In the case of removal, companies indicate that for example “DPR removal is legal in certain countries and when used for off-road or motorsport” [62].

TNO found a Dutch company that offers EGR, SCR and DPF tampering devices and services on their website for major NRMM manufacturers like; New Holland, Fendt, Deutz-Fahr, John Deere and Doosan, see Figure 3.24 to Figure 3.28. AdBlue manipulation is offered for prices between EUR 625,- and 800,- and EGR manipulation for EUR 600,-.

NEW HOLLAND

Switching off AdBlue is possible on all types with an IVECO engine. At New Holland this is possible in 3 ways.

1. Switch off AdBlue injection (AdBlue OFF)
2. Completely disable AdBlue via software whereby the pump and attachments can be completely removed.
3. Switching off AdBlue using a Module (not Chinese!) You can also remove everything that has to do with AdBlue.

Switching off AdBlue is possible from € 625 excluding VAT.

Figure 3.24: New Holland SCR tampering offered online, source chipperformance.nl

FENDT

Switching off AdBlue is possible with Fendt tractors. This is only possible through the software and is not possible with an external module.

- We can deactivate the adblue injection and adjust the entire system so that you can disassemble the pump nox sensors and tank.

We can adjust the AdBlue at your location or at 1 of our dealers .

Price from € 799 excluding VAT.

Figure 3.25: Fendt SCR tampering offered online, source chipperformance.nl

JOHN DEERE

Switching off and / or removing EGR at John Deere is only possible via software. We can offer this option in 2 variants;

1. Close EGR. Hereby the valve is only closed but must not be broken!
2. Completely disable EGR via software. The valve can be completely dismantled including the cooler.

This is possible for the John Deere xx30 Series with L14 ECU, and the John Deere R and M series with the L21 and L33 computers

Price from € 600 ex VAT

Figure 3.26: John Deere EGR tampering offered online, source chipperformance.nl

DEUTZ-FAHR

Switching EGR off is possible on Deutz tractors with the following computer;

- Bosch EDC17CV52
- Bosch EDC17CV41

We can disable the EGR valve at your location or at 1 of our dealers .

Price from € 600 ex VAT.

Figure 3.27: Deutz-Fahr EGR tampering offered online, source chipperformance.nl

SOOT FILTER CAN BE ADJUSTED FOR THE FOLLOWING MACHINES, AMONG OTHERS;

- **John deere** R & M series with Phoenix L21 ECU (Tier 4A)
- John Deere R Series with L33 ECU is in test phase
- **New Holland** T5 with Bosch EDC17C49 ECU
- **Doosan** equipped with soot filter / Dpf with EDC17CV41 ECU

Figure 3.28: DPF removal for NRMM offered online, source chipperformance.nl

Next to these obvious signs of tampering for NRMM taking place, TNO was told by an agricultural mechanic with experience in ECU programming that for agricultural vehicles the OEM provides software to dealerships and workshops that allows to reprogram the engine and aftertreatment ECU's. This because agricultural machines are commonly customised and composed of specific parts to suit the working environment and tasks of the machine best. Therefore, an open architecture is required, also acting as a backdoor for tampering of the emission control systems.

Vehicles like, train and inland vessel, which are also classified to the NRMM vehicle category are not considered in the report up to now due to the lack of information on tampering of the emission control systems of these kinds of vehicles.

3.9 Shift from tampering devices to ECU reprogramming

Based on the information found on tampering, as described in the previous paragraphs, it is clear that tampering takes place for all three vehicle categories, LD, HD and NRMM. However, the extent to what tampering takes place is still hard to capture. From the information found on websites it does become clear that due to the increasingly complex emission control systems the way of tampering is also changing.

Researchers at the department of mechanical engineering at the Thessaloniki Aristotle University, which is a consortium partner of TNO in this project, visited a workshop that has been altering aftertreatment systems for many years. Based on the information obtained during this visit and the information found by TNO the market on tampering of emission control systems can be described as follows.

Earlier tampering methods were focused on all kinds of emulators or tampering devices (mostly from China) that suppress the functions of emission control systems and the OBD system communication. The problem with this is that in general this turns out to be problematic since no or less diagnostic messages will be returned for the entire vehicle. Furthermore, the authorities have gained sufficient experience with such devices that they can be easily identified.
According to the visited workshop the most common practice for tampering of EGR, DPF, SCR and also TWC is so called 'ECU flashing' (ECU reprogramming), since this proves to be a reliable way of shutting down the emission control systems. ECU flashing requires both software and hardware changes to be made. Using software packages like WinOLS the original binary ECU image can be viewed and altered. Depending on the type of ECU and available hardware the ECU is flashed through either the Background Debug Mode (BDM) or Joint Test Action Group (JTAG) interface, via the OBD port or via the ECU flash memory pinout. Next to the binary file also the description file (A2L) is required that defines the implementation of the ECU.

One of the most important aspect of the tampering of emission control systems nowadays is the tampering community itself. This community is organised online through forums that are hierarchically structured where, based on the user's accessibility, ready-to-use modified binary files, or even description files can be exchanged or bought. Hierarchy is mainly defined based on the amount of provided content by the tamperer; if a tamperer contributes a significant amount of content to the forum community, then he gradually rises in hierarchy and gains access in more content.

ECU's that are mostly targeted by the tampering community are those by Bosch, since they are found in a large share of vehicles. Other ECU types like Continental or Denso are, according to the visited workshop "more difficult to tamper". According to the visited workshop, future systems are expected to be so tightly secured, that the tampering effort will not be so cost-efficient as it was some years ago. This is combined to the fact that when a new model comes to the market, the tamperer already needs "some years" to find a reliable way to tamper a targeted system.

4 Prioritization of tampering devices and services

4.1 Introduction

In this chapter tampering devices and services are prioritised for testing within WP3. The prioritisation is done based on a risk assessment. The risk assessment will make clear what kind of tampering on which vehicle categories poses the largest environmental risks and thus which tampering needs to be fully evaluated and tested to determine how the tampering works, the vulnerability of current OBD and the impact on emissions.

4.2 Risk assessment

4.2.1 Risks

EU emissions regulation has resulted in significant reductions of emissions of pollutants from the tail pipe. Latest generations of vehicles are substantially cleaner than older generations. This is achieved by manufacturers thanks to the application of effective emissions control systems. This in turn has resulted in a significant reduction of air pollution, as reported by the European Environment Agency [63]:

- Emissions from all transport types have declined between 1990 and 2017, despite the general increase in activity within the sector.
- Across the EU-33 between 1990 and 2017, emissions of NO_x from transport decreased by 40 %, those of SO_x decreased by 66 %, and those of both CO and NMVOCs decreased by 87 %.
- Between 2000 and 2017, emissions of particulate matter with a diameter of 2.5 µm or less (PM2.5) decreased by 44 %.

According to the European Environment Agency [63]: “The scale of policy actions undertaken in Europe to specifically address transport-related air pollution has increased over recent years, reflecting the important contribution that transport still makes to reducing air quality. Local and regional air quality management plans, including initiatives such as low emission zones in cities and congestion charges, are now undertaken in many areas where the level of air pollution from transport is high. Different European legal mechanisms are used to address air quality (including that influenced by traffic-related sources). These include the setting of limit or target values for ambient concentrations of pollutants, limits on total emissions (e.g. national totals) and regulating emissions from the traffic sector either by setting emissions standards (such as Euro emissions standards 1-6) or by setting requirements for fuel quality.”

Figures from TNO support the conclusions by the EEA, see Figure 4.1 and Figure 4.2:

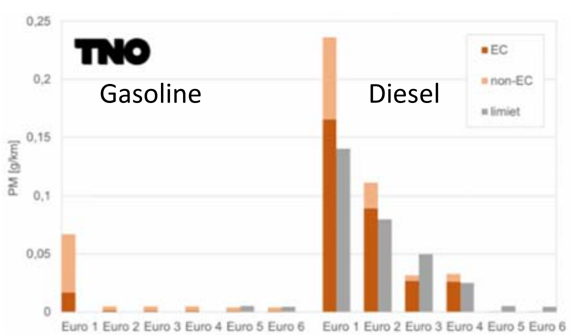


Figure 4.1: PM emissions for urban driving per Euro class (passenger cars)

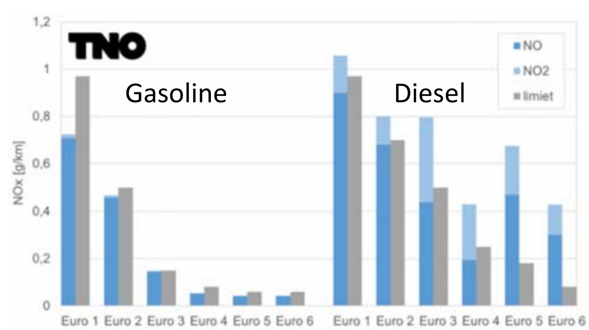


Figure 4.2: NOx emissions for urban driving per Euro class (passenger cars)

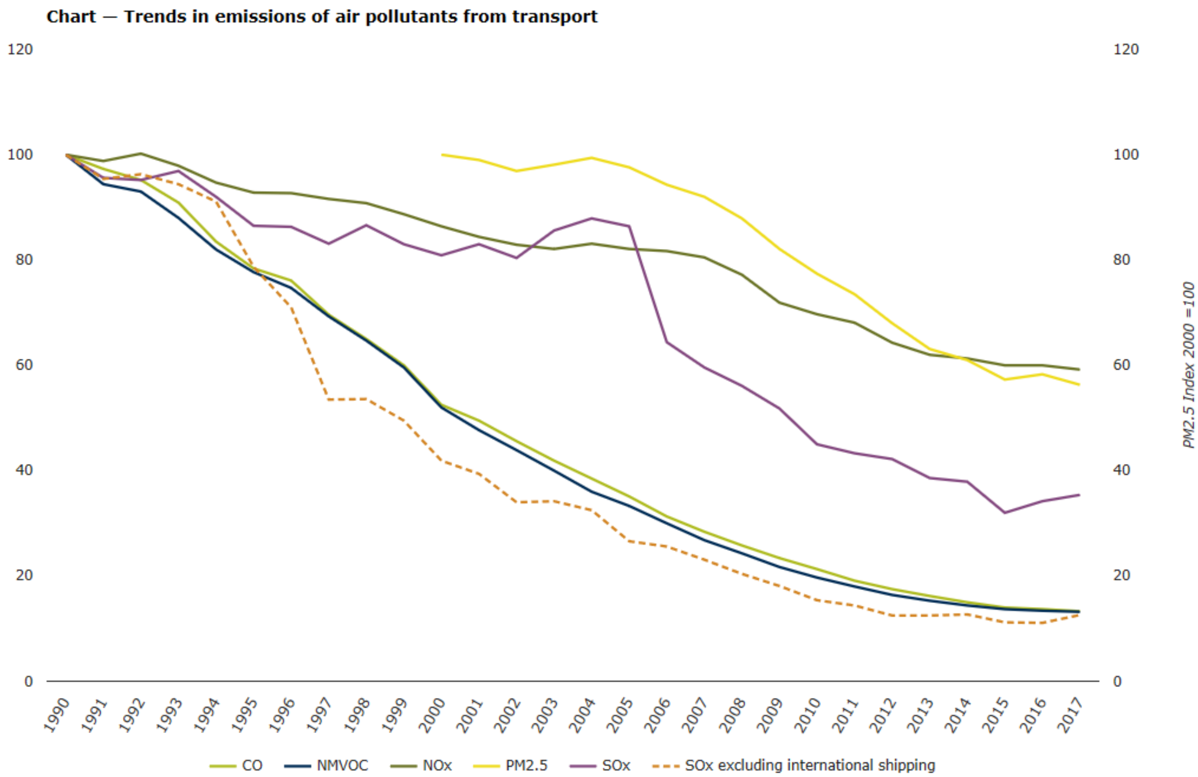


Figure 4.3: National emissions reported to the Convention on Long-range Transboundary Air Pollution (LRTAP Convention) provided by European Environment Agency (EEA)

Tampering of an emissions control system generally results in a deactivation of the system and most of the times a drastic increase of the tail pipe emissions. Therefore, a small share of tampered vehicles could significantly increase the total fleet emissions. When increases of tail pipe emissions levels are considered, what would be the main environmental risks? Three different effects can be distinguished:

1. *Human health effects*: by means of dispersion of pollutants in the ambient air which is mainly problematic in densely populated areas and along busy roads. In several cities and regions in the EU, the EU limits for ambient air concentrations of criteria pollutants (indicators for air pollution) NO_2 and PM_{10} are exceeded. Combustion engines without emissions control emit ultrafine particles and it is mainly these small particles (PM_{10}, PM_5 and $PM_{0.1}$) that pose the largest risks for human health.
2. *Ecological effects*: Eutrophication, acidification, and ground level ozone formation: pollutants such as NO_x and NH_3.
3. *Climate effects*: global warming and stratospheric ozone depletion. CO_2, CH_4, N_2O.

The total impact of tampering on the emissions level of the total fleet depends on:

- *The fraction of the fleet and number of vehicles* tampered with each type of tampering. How much of the vehicles registered and driving in the EU have tampering? Which vehicles, fuel types and emission control systems are affected? Drivers and barriers:
  - o What are the motives to tamper from the perspective of the vehicle owner? Avoidance of costs of maintenance, repair, down time, consumables?
  - o How easy is it to purchase (availability, costs), install (how easy and intrusive is the install, is it reversible?), how easy is it to by-pass vehicle control functions and de-activate emissions

control systems, what is needed to maintain the tampering (active resetting required or for by-passing periodic and road side inspections).
  - What are the risks of the tampering for the user in terms of damage to the vehicle, what is the risk of detection (road side inspection, periodic inspection, others...), prosecution, sanctions and are there any incentives for proper use of a vehicle?
  - The various arguments need to be considered for the future as well, because these are the main drivers and barriers for the vehicle owner to decide whether to tamper.
- *The effect of each type of tampering on the emissions level* of the pollutants and which pollutants are affected.
- *The total mileage of the vehicle driving with the tampering* during its lifetime. Tampering may in certain cases only happen after occurrence of malfunctions and thus may not be happening for the whole lifetime of a vehicle. E.g. a DPF would only be removed when after a certain high mileage, the DPF gets clogged or breaks and the OBD gives a DTC and MIL. A case of immediate removal of all DPFs of a fleet of new vehicles is also known however.

4.2.2 The fraction of the fleet and number of vehicles tampered

Ideally, the risk assessment would be based on quantitative information about the share and amount of tampering. Such information is rather scarce unfortunately. Road side inspections where tampering was found mostly targeted trucks and the inspection may even have targeted certain categories of trucks which means that the sample would be selective. Tampering rates of 1 to about 9% were found. Besides the offerings of tampering on the market, there are not many other sources that provide the information to estimate the magnitude of the problem and the environmental impact.

Nevertheless, when the market was initially assessed in terms of demand and supply it became clear that the tampering market mainly addresses the demand from vehicle owners to primarily avoid costs for repair of the emission control systems, followed by avoiding costs for maintenance, consumables and downtime related to malfunctions (reliability). This means that there is a potential larger risk for tampering of vehicles with environmental protection systems that wear over the lifetime or break down and thus parts need to be serviced or replaced, especially for the types of emission control systems which are more likely to break down. The same accounts for emission control systems that require regular maintenance or consumables, e.g. the regular AdBlue refills that are needed to keep the SCR working. Clear indications were found of the widespread use of ‘AdBlue killers’ as brought up by the media and as detected at various road side inspection campaigns in several EU member states. Results from road side inspections indicate that when tampering was removed for a large share of vehicles still malfunctions of the emission control systems were present which in turn indicated the emission control system may have already been broken down in the past hereby providing the motivation to tamper it. Other motivations found and which involve modification or removal of emission control systems are ‘performance tuning’ and even increase of the exhaust sound level or tone may be an argument to remove parts of the exhaust such as filters or catalytic elements. Table 4.1 gives an overview of the emission control systems affected by specific tampering and summarises the main motivations to tamper the respective system.

Table 4.1: Overview of emission control systems affected by tampering and the main motivations to tamper.

Emission Control System	*Targeted system for tampering*	*Main motivations*
DPF (+DOC)	Removal of filter element	Avoid costs for replacement of filter element Avoid costs for maintenance, filter cleaning Decrease costs for fuel Avoid costs for possible down time due to malfunction
SCR (+AMOC)	Stop reagent dosing Removal of catalyst	Avoid costs for maintenance and repair/replacement of catalyst and SCR system components (NO_x sensor, pump, dosing unit) Avoid costs for reagent Avoid costs for possible down time due to malfunction
EGR	Valve fixed in closed position or blockage of piping	Avoid costs for repair/replacement Performance tuning Avoid costs for possible down time due to malfunction
TWC removal	Removal of catalyst	Other possible motivation: avoid costs for repair/replacement of catalyst and system components (lambda sensor) Probably a niche mostly for performance tuning
OBD	Deletion of trouble codes and MI off	Avoid malfunction indication and 'emissions related diagnostic trouble codes' to: · By pass periodic inspection · Avoid costs for repair/replacement · Enable tampering of other systems by deleting the trouble codes arising from the tampering of these systems This may affect all emission control systems
New emission control systems for which so far, no tampering is reported		
GPF removal	Possible future problem: Removal of filter element	No tampering device or service found.
LNT removal	Possible future problem: Removal of catalytic element	No tampering device or service found.
Other types of emission control systems possibly affected		
Fuel Canister	Removal of canister	

4.2.3 The effect of each type of tampering on the emissions of the pollutants affected

Table 4.2 gives an overview of emission control systems applied for current (latest) vehicles, per engine type, per category, showing which pollutants are affected primarily. Since each emission control system was designed to reduce specific pollutants, tampering of the system has a primary effect on those specific emissions. Additionally, the secondary effect indicates which pollutants are affected because deactivation or removal of the emission control system would bring an additional increase or in some cases a decrease of secondary emissions.

Table 4.2: Overview of emission control systems present on current (latest) vehicles, for what engines and in what vehicle category the emission control systems are used and the pollutants that are affected. CI: Compression Ignition (diesel), SI: Spark Ignition (gasoline/gas), GDI: Gasoline Direct Injection, HDDF: heavy duty dual fuel engine running on diesel and gas. NMHC, Non-Methane Hydro-carbons, PAH, Polycyclic Aromatic Hydrocarbons, THC, Total Hydrocarbons

Emission Control System	*Combustion engine types using the emission control systems*	*Category where engine and emission control system is used: LD, HD, NRMM*	*Pollutants primary effect: increase of emissions*	*Pollutants secondary effect: both increase or decrease possible, indicated by < and >*
DPF (+DOC) Removal	CI, HDDF	LD, HD, NRMM	PM, PN	PAH>, NMHC>, CH_4> (HDDF), CO_2<
SCR (+AMOC) removal of catalyst or stop reagent dosing	CI, HDDF	LD, HD, NRMM	NO_2, NO (NO_x)	CO_2<, NH_3<
EGR deactivation	CI, SI, HDDF	LD, HD, NRMM	NO_2, NO (NOx)	PM<, PN<
TWC removal	SI	LD, HD	NO_2, NO (NO_x), NMHC, CO, PAH, CH_4 (GHG)	
New emission control systems				
LNT removal	GDI, CI	LD	NO_2, NO (NO_x)	
GPF removal	GDI	LD	PM, PN	THC>
Other types of emission control systems possibly affected				
Carbon Canister	SI, GDI	LD	THC	

4.3 Categorisation of tampering

To categorise the tampering, following items are to be considered:

- Fuel/combustion type, e.g. gasoline and diesel
- Emissions standard, legislative category, e.g. Euro 6/VI and consecutive indication for sub-standards (e.g. Euro 6dtemp for LD and step D for HD)
- Emission control system affected
- Main working principles (hardware and software intervention).

The detailed working principles will be determined in the test programme that is part of WP3.

For Euro VI heavy duty diesel vehicles several emulators are offered that work in the same way and require the same or very comparable interventions to tamper the Euro VI SCR emissions control system to stop the dosage of reagent. These devices can be grouped in one family. Depending on how the list of devices evolves in terms of new tampering techniques found, categorization may still change.

The market assessment (Chapter 3) revealed several types of tampering. The type of tampering that is needed to disable or remove the respective emission control system depends on the system targeted and on the exact requirements for the OBD and control of NO_x measures that are applicable for each emissions step in the EU emissions legislation for LD and HD vehicles and NRMM and the control functions that are implemented in the ECU's. The OBD system requirements and control of NO_x measures (HD vehicles) in the EU emissions regulation namely require functionality checks of components that are relevant for correct operation of the emission control system. A check done against a certain value that exceeds a threshold should set a diagnostic trouble code which is stored in the ECU and which can be the reason to activate a MIL. For tampering, these checks need to be by-passed and thus require additional functionalities from the tampering. This can be either achieved by emulating the signals that are broadcasted by components such as sensors that are used to check the correct operation of these components. Another way is to regularly delete the DTC's such that a MIL will not appear on the dashboard and the DTC's are not stored in the memory of the OBD system. Different manufacturers or suppliers may implement different functions and security checks, which means that the tampering needs to be adapted to specific ECU's, brands and suppliers.

Earlier generations of OBD (called OBD I for LD vehicles) allowed easy tampering. An example is plugging the EGR piping because this was not mandatory checked by the OBD system. For latest generations the OBD system needs to check the EGR flowrate and at a wrong rate will set a DTC, a MIL and eventually will activate a power inducement. This needs to be avoided by the tampering. For HD vehicles, the police of various Member States collect information from tampering found at road side inspections [64]. Information indicates different architectures for engine and emission control systems which would require different tampering techniques. HD vehicle types are identified with integrated ECU and ACM (Aftertreatment Control Module) and types are identified with separate units.

From the market assessment it became clear that the main emission control systems affected are probably the ones present on vehicles with diesel engines, although for LDV there is not much quantitative information that can back this up. SCR, DPF and EGR systems are known to come with costs and in some cases high costs for repair of malfunctions. Emissions abatement of diesel vehicles mainly relies on the correct operation of these emission control systems and therefore, with a market share of 42% (paragraph 3.4) and pollutants that still exceed ambient concentration limits of air quality standards for PM and NO_2 in many cities and regions in the EU, tampering of diesel vehicles, LD, HD and NRMM poses a large risk for the environment.

Another emission control system known to break down is the TWC as used for gasoline and gas fuelled vehicles. The systems lambda sensors may degrade over time or break down and the catalyst itself may degrade leading to OBD system DTC's. From the assessment of the market it became clear that a lot of various devices are offered to tamper with the EPS from LD, HD vehicles and NRMM, see paragraphs 3.6, 3.7 and 3.8. However, since tampering more and more involves remapping or reprogramming of the ECU, tampering is often offered as a service because of the tampering activities that are quite specialistic. Web shops clearly have shown that such services are offered by garages, often tuning workshops, but it is not known if and how much and what types of workshops offer such ECU tampering that do not advertise on a website/Facebook/eBay/Ali-express but may offer the tampering as soon as a customer shows up with a vehicle with a malfunction of the EPS.

Two main types of tampering can be distinguished for vehicles of the latest generation, backed up by findings of consortium partner LAT:

1. Emulators, see Figure 4.4
2. ECU reprogramming (also called ECU flashing, ECU remapping), see Figure 4.5

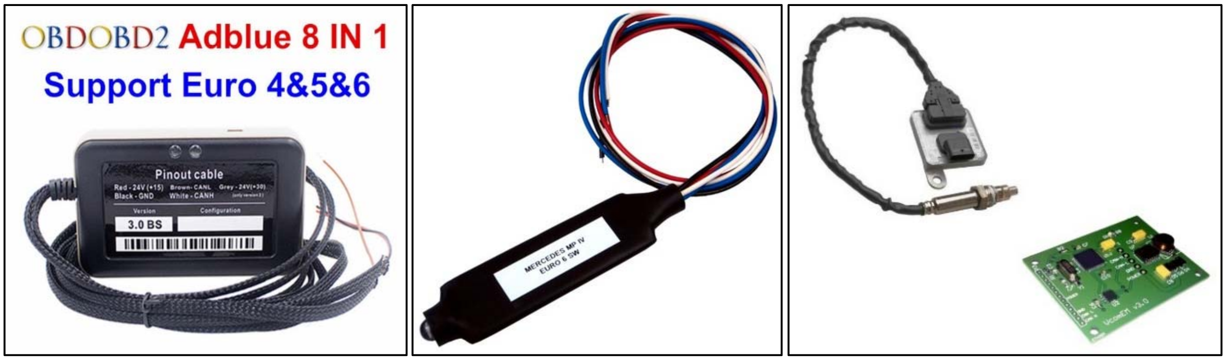


Figure 4.4: Examples of emulators and their appearance

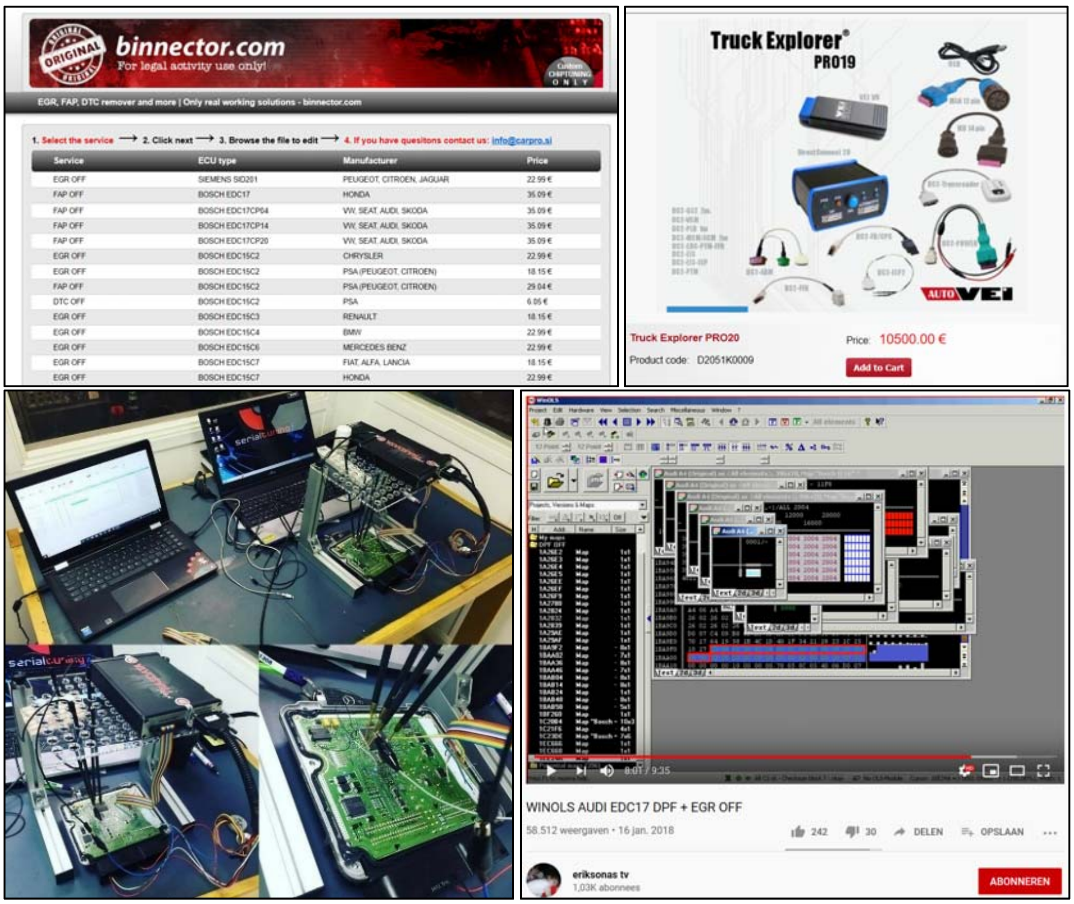


Figure 4.5: ECU reprogramming / flashing examples and their appearances

OBD diagnostic trouble codes may arise when tampering leads to errors detected by the current OBD. DTC deletion tools are offered to support the tampering, i.e. to by-pass periodic inspection and to avoid power inducement of the engine forcing an owner to repair the malfunction. It is advised to add this tool that facilitates tampering to the test matrix, see Figure 4.7.

Other types of tampering exist which should also be assessed with regard to the possible risk, Figure 4.6:

- Tampering and emulation of temperature sensors so temperatures outside the window of normal operation are generated to fool and shutdown the emission control system.

- A lambda sensor extension or catalyst that provides a correct air fuel mixture to the sensor, while in fact the mixture is not correct, such that no error is generated, and the Three-Way Catalyst can be removed.

Figure 4.6: Examples of sensor tampering / emulation and their appearances

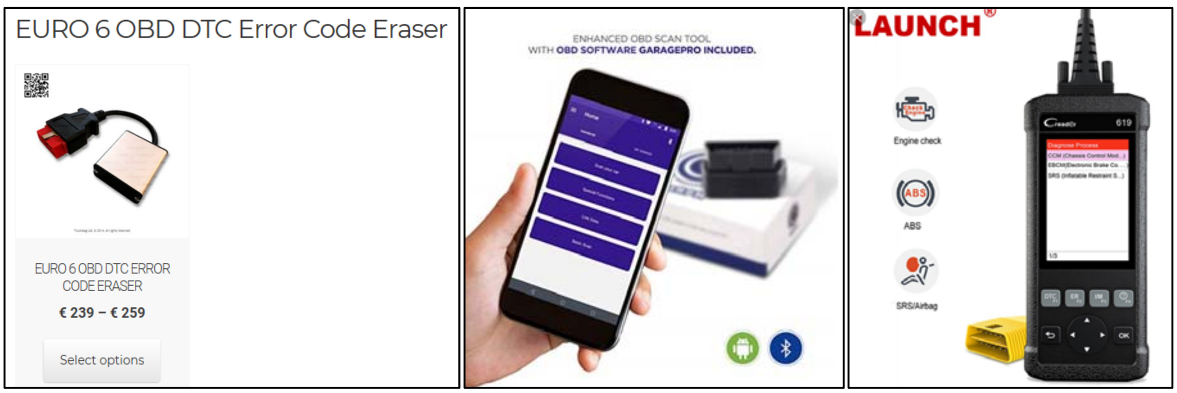


Figure 4.7: Examples of OBD DTC erasing tools and appearances

Table 4.3 gives an overview of the types of tampering per emissions control system and tampering target and lists devices and services found to date in the market assessment from the tampering list (A, Annex: List of tampering providers and devices).

Table 4.3: overview of tampering devices and services per emission control system applicable for the latest emission regulation step (Euro 6/VI) and emission control systems that may appear on the market more frequently in the near future.

Emission control system	*Targeted system for tampering*	*Types of tampering found*	*Tampering devices and services from the draft list per type*
DPF (+DOC)	Removal of filter element	Physical removal of filter element by: - ECU reprogramming - Emulator Can be done in combination with SCR removal.	 36, 37 24, 26, 35, 36

SCR (+AMOC)	Stop reagent dosing Removal of catalyst +(1)	Stop the dosing of AdBlue by: - Emulator stopping the active control of the dosage unit and emulate the CAN signals that are to be controlled for a correct operation of the SCR, such as NOx sensor signal and emulate a signal for the dosing pump. - ECU reprogramming can be done to deactivate SCR control functions such as AdBlue dosing but also to allow catalyst removal. - Changing temperature sensor resistance to emulate a low reagent temperature or high ambient Remove the catalyst. Can be done in combination with DPF removal.	10, 11, 12, 13, 14, 15, 16, 17, 24, 27, 28, 29, 30, 31, 32, 33, 34, 36 36, 37, 38 16, 18, 24, 26, 35, 36
EGR	Valve fixed in closed position or blockage of piping	Plug EGR piping (OBD I) ECU reprogramming	7, 8, 9, 35, 36, 37, 38
TWC removal	Remove TWC	Lambda sensor extension	Various plugs
OBD	Deletion of trouble codes and MI off	Deletion/suppression of diagnostic trouble codes and MI off: · Deactivates the control functions by means of an OBD tool or reprogramming the ECU. As part of the other ECU reprogramming services or tools. · Relates to functioning of all exhaust EPS: EGR, SCR, DPF, TWC · As part of an emulator box, emulating of signals hereby by-passing the setting of DTC's · As part of an emulator box, with a function that regularly erases DTC's · Reprogramming the ECU deactivating the control functions. As part of the other ECU reprogramming services or tools.	18, 23, 26, 34, 35, 36, 37
New emission control system for which so far, no tampering is reported			
GPF removal	Possible future problem: Removal of filter element	No tampering device or service found.	-
LNT removal	Possible future problem: Removal of catalytic element	No tampering device or service found.	-

4.3.1 Definition of the test matrix

The combinations of current and near future vehicle/fuel types and tampering that pose the largest risks, currently and in the near future, need to be tested and evaluated to understand the impact of the tampering of the emission control system and its vulnerabilities on the tail pipe emissions level. The market assessment and the risk assessment are thus used to select the vehicles and tampering combinations that need to be tested. The test matrix contains the main types of tampering found and are to be applied across the three vehicle categories subject to this investigation and targeted by tamperers. For the vehicles and tampering targeted a few variants exists to tamper, meaning that these variants will be tested.

Table 4.4: Draft test matrix. Proposed combinations of vehicles, tampering target and type of tampering to be tested. Some vehicle/tampering combinations may prove to work similarly and may thus be

combined and applied to a single test vehicle. The actual devices to be tested need to be selected from the device list where a prerequisite is that the device should work on the vehicle selected.

Test vehicle	*Tampering target*	*Tampering type to be subjected to test*
LD diesel 1, 2	DPF removal	ECU service, download ECU service
LD diesel 1, 2	Stop AdBlue dosage	Emulator
LD diesel 1, 2	Stop AdBlue dosage	ECU service, download ECU service
LD diesel 1, 2	EGR	Emulator/ECU?
LD diesel 1, 2	OBD DTC deletion	OBD DTC deletion
HD diesel 1 (demo truck), 2	Stop AdBlue dosage	Emulator 3 types
HD diesel 1 (demo truck), 2	Stop AdBlue dosage	Temperature sensor
HD diesel 1 (demo truck), 2	SCR and DPF removal	Emulator, ECU service
HD diesel 1 (demo truck), 2	OBD DTC deletion	OBD DTC deletion
NRMM 1	SCR and DPF removal	Emulator or ECU service
NRMM 1, 2	Stop AdBlue dosage	Emulator
NRMM 1, 2	Stop AdBlue dosage	ECU service
NRMM 1, 2	OBD DTC deletion	OBD DTC deletion

5 Discussion

The past few decades the (pollutant) vehicle exhaust emission limits in Europe, imposed by the European Commission, have become more and more stringent. To ensure that new vehicles (light duty (LD), heavy duty (HD) and Non-Road Mobile Machinery (NRMM)) meet these type approval requirements, vehicle manufacturers are forced to equip their vehicles with all kinds of emission control systems to reduce the exhaust emissions.

The most common emission control systems found in vehicles are the;

- Exhaust Gas Recirculation (EGR) system;
- Selective Catalytic Reduction (SCR) system;
- Diesel and Gasoline Particulate Filter (DPF/GPF);
- Three-Way Catalyst (TWC);
- Diesel Oxidation Catalyst (DOC);
- NOx Adsorber;
- And Evaporative Emission Control System (EVAP)

Next to these systems since 2001 for gasoline vehicles and 2004 for diesel vehicles an OnBoard Diagnostics (OBD) system is mandatory in newly registered vehicles. This system monitors and checks amongst other systems the emission control systems in the vehicle, logs Diagnostic Trouble Codes (DTC's) and displays Malfunction Indications (MIL) on the dashboard to notify the driver of any problems with the emission control systems of the vehicle. In Europe vehicle owners are obliged to have their vehicle subjected to periodic inspections during which certified mechanics inspect and check the emission control systems and the OBD system DTC's.

Despite the established regulations and arranged measures to enforce the proper application and maintenance of emission control systems in vehicles the past few years it was found that tampering of these kinds of systems takes place on a large scale. Earlier stages (around end-'90s, early '00s) of tampering mostly involved the removal or disabling of the emission control systems for vehicles without the 'smart' OBD system and mainly involved removal or blocking of the EGR system for both gasoline and diesel vehicles. Next to that from the end '00s, early '10s so-called emulators were developed by vehicle experts with the goal to deliberately shutdown or tamper the emission control systems of the vehicles. These emulators got more and more sophisticated over the years and are now an easy tool to reliably shutdown the latest emission control systems (Euro V and VI), without causing MIL's or DTC's being stored in the OBD system of the vehicle. In particular the tampering of SCR systems of diesel HD vehicles got major attention in the media.

In response to this growing media attention on the tailpipe emissions of vehicles, the authorities in various EU member states are more and more focussing on tampering of emission control systems in vehicles, mainly on SCR tampering of diesel HD vehicles, but also DPF tampering of diesel LD vehicles (Belgium, Germany, Denmark, Switzerland, The Netherlands, Poland). With the gaining experience on how SCR tampering emulators work, the authorities become more and more skilled in identifying this kind of tampering. However, the authorities are only scratching the surface due to the limited roadside inspection being performed, resulting in the chance of getting caught with such devices being very low.

Motives for vehicle or fleet owners to tamper with the emission control systems are mainly cost related. In particular the relatively low costs of tampering devices and services in comparison to the high maintenance and repair costs of the emission control systems (2 to 5 times higher for SCR and DPF). But for SCR systems also savings of AdBlue costs is a reason, often mentioned. In combination with the fact that tampering devices are widely offered online and at specialised companies and workshops all over Europe, the devices can be installed easily and the chance of getting caught being very low, the choice of using tampering devices can be logically reasoned. Next to that there are also signs of tampering taking place for performance tuning. The market share for this group is yet unknown but expected to be small.

In recent years, a shift in tampering solutions offered on the market seems to take place. Instead of hardware solutions in the form of tampering devices (emulators), tampering is more and more offered as a service, involving the reprogramming of the ECU of the vehicle. Companies specialised in ECU reprogramming can often remove the functionalities of the EGR, SCR and DPF system from the vehicle's ECU by shutting down the complete after treatment, without any indication found on the dashboard or in the OBD system.

The effects of tampering of the emission control systems on the exhaust emissions of a vehicle are large. Especially the NO_x and PM emissions increase catastrophically upon tampering of respectively the SCR and DPF system. However, the impact of the market involved in tampering on the environment is hard to capture since no clear figures are known of the amount of tampering taking place. This is mostly because of the limited monitoring of the vehicle's emissions during periodic and roadside inspections and the fact that it often remains unclear if the vehicle's emission control system is malfunctioning or tampered with. According to investigations performed by various authorities in Europe, it is estimated that between 5 and 20% of the vehicles on the road drive around with malfunctioning or tampered emission control systems.

Currently the largest risk is found with LD, HD and NRMM diesel vehicles, since signs of tampering taking place for these types of vehicles are evident, while for gasoline or gas powered vehicles this is not so much the case. Especially the SCR system is a complex emission control system that is prone to causing problems in the long term without proper and in particular costly maintenance. Nevertheless, the latest developments in the emission legislation and applied emission control systems in gasoline vehicles (EGR, GPF) could pose a risk for the near future.

6 Conclusions

Pollutant emissions of road vehicles have reduced significantly thanks to the development and application of advanced and sometimes complex effective emissions control systems. Tampering of these systems would lead to elevated emissions levels comparable to uncontrolled levels of vehicles of decades ago. Therefore, a small share of tampering can potentially lead to a significant increase of the EU fleet average emissions.

For task 3.1 of DIAS a market assessment was conducted to determine the market of tampering in terms of size, appearance and involved players, to reveal the motivations for tampering and to identify the different types of tampering offered. The exercise has led to a proposal for a test matrix of vehicle – tampering combinations that pose the largest environmental risk and which should be tested to determine the current vulnerabilities and exploits of vehicles that need to be addressed by the DIAS concept. The following conclusions can be drawn:

- There is a substantial market where tampering is offered for both light and heavy duty vehicles and non-road mobile machinery. However, not much quantitative information is available that indicates the magnitude of the problem, i.e. the number of vehicles that are tampered in the EU.
- An important source that does indicate significant tampering happens in the EU are road side inspections for trucks were significant tampering rates were found for previous generations of heavy duty vehicles for which an advanced emissions control system is required (Euro IV and V). The inspections are however often selective, targeting specific vehicles based on experience and assumptions, most likely resulting in biased data. The magnitude of the problem is largely unknown for Euro VI and the light duty and non-road mobile machinery segments as a whole.
- The motive mentioned most for tampering is to avoid costs for repair of malfunctions of the emissions control systems of diesel engines. Other motives mentioned are: costs for consumables, costs for downtime, performance tuning and exhaust sound level.
- Emissions control systems with higher rates of malfunctions and related costs for repair may therefore pose the largest environmental risk: SCR, DPF, EGR but possibly also TWC for older gasoline engines.

Two main types of tampering were found for vehicles of the latest generation, backed up by findings of consortium partner LAT:

1. Emulators
2. ECU reprogramming (also called ECU flashing, ECU remapping)

This tampering is either offered as a service in workshops or as product with instructions for installation offered on the internet in web shops, online shopping areas, forums and social media. OBD diagnostic trouble codes may arise when tampering leads to errors detected by the current OBD. DTC deletion tools are offered to support the tampering, i.e. to by-pass periodic inspection and to avoid power inducement of the engine forcing an owner to repair the malfunction.

Other types of tampering exist which should also be assessed with regard to the possible risk:

- Tampering and emulation of temperature sensors so temperatures outside the window of normal operation are generated to fool and shutdown the emission control system.
- A lambda sensor catalyst that provides a correct air fuel mixture to the sensor, while in fact the mixture is not correct, such that no error is generated.

The market assessment has led to a test matrix in which the vehicle-tampering combinations are defined that most likely pose the largest environmental risk. The test matrix contains light and heavy duty vehicles and non-road mobile machinery with diesel engines, the two main types of tampering devices and services, the OBD DTC delete tool and temperature sensors tampering.

Other relevant observations made during the tampering market analysis and assessment are:

- There is an increased intensity of road side inspections with prosecution and sanctioning by several Member States, mainly for heavy duty vehicles.
- There is an increased stringency of requirements for OBD and control of NO_x measures (EU) towards current EU requirements (Euro 6dtemp, VI step-D, stage V).
- There are plans by some EU member states for checking of DPF at periodic inspection.

These measures may already lead to a less attractive ‘environment’ for tampering.

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A. Annex: List of tampering providers and devices

Table A.1: List of tampering providers and devices

	Company	*Vehicle type*	*Vehicle brands*	*Type*	*Hard- / software*	*ECU type*	*Euro class*	*DPF*	*EGR*	*SCR*	*DTC*	*Price €*	*Distribution*	*Place*	*Country*	*Remarks*	*Website (active link)*
1	Digicar	LD	all	service	H + S	all	all	X	X	X	X	400	NL	Doetichem	The Netherlands		https://www.digicar.nl/
2	Volvotune	LD	Volvo	service	H + S	?	?	X	X			-	NL	Elst	The Netherlands		http://www.volvotune.nl/
3	OBD-Chiptuning	LD	all	service	H + S	all	all	X	X			-	NL	Almelo	The Netherlands		https://www.obd-chiptuning.nl/
4	Orange Chiptuning	LD	all	service	H + S	all	?	X	X	X	X	-	NL	Waalwijk	The Netherlands		https://www.orangechiptuning.nl/
5	Chip Performance	LD + HD	all	service	H + S	all	all	X	X	X	X	-	NL	Maasland	The Netherlands	Agricultural vehicles also; complete lists of ECU's	https://www.chipperformance.nl/
6	Unlimited Tuning	LD + HD	all	service	H + S	all	all	X	X	X	X	-	NL	Amersfoort	The Netherlands		https://www.unlimitedtuning.nl/
7	Tafmet	LD		part	H				X			70	ONLINE	Opole	Poland		https://tafmet.pl/
8	CES24	LD		part	H				X			50	ONLINE	London	United Kingdom	EGR valve emulator	https://ces24.com/
9	Abbes-Performance	LD		part	H				X			30	ONLINE	Prague	Czech Republic	EGR valve emulator BOX Mercedes C / E / S...	http://abbes-performance.com/
10	SDS	HD		part	H					X		520	ONLINE	Zaporozhye	Ukraine	Cutoff of urea – AdBlue and NOx Original Emulator	https://sdsauto.com/
11	SDS	HD		part	H					X		60	ONLINE	Zaporozhye	Ukraine	AdBlue Emulator (SCR)	https://sdsauto.com/
12	TruckECU	HD		part	H					X		51	ONLINE			AdBlue removal	https://nl.aliexpress.com/
13	TruckECU	HD		part	H					X		14	ONLINE	Guangdong	China	AdBlue removal	https://nl.aliexpress.com/
14	DHCarTool	HD		part	H					X		13	ONLINE	Guangdong	China	AdBlue removal	https://nl.aliexpress.com/
15	CAN-BUS emulator	HD + NRMM	Volvo, Scania, DAF, Renault, Mercedes, Iveco, MAN, Ford, Deutz, New Holland	part	H					X		100	ONLINE	Adana	Turkey	Euro 6 AdBlue (SCR) Emulator	https://www.canbusemulator.com/
16	Trucktool	HD		part	H			X		X		600	ONLINE		Poland	AdBlue removal	https://trucktool.pl/
17	Cardiag	HD		part	H					X		200	ONLINE	Hongkong	China	SCR Emulator EURO 6	https://www.cardiag.com/
18	Trucktool	NRMM		part	H			X		X	X	615	ONLINE		Poland	AdBlue removal	https://trucktool.pl/
19	autodtc	LD		service	S	all	all	X	X	X	X	99	ONLINE			Software to remove DPF/SCR & EGR	https://autodtc.net/
20	Flashtec	LD		service	H + S	all	all	X	X	X	X	100	ONLINE		Switzerland	BOSCH ERASE CALIBRATION	http://srv162.flashtec.ch/
21	RICA	LD		service	S	all	all	X	X			500	NL	Wateringen	The Netherlands	Software to remove DPF/SCR & EGR	https://rica.nl/index.php
22	auto-remap	LD + HD	all	service	S	all	all	X	X	X	X	-	ONLINE	Vilnius	Lithuania	Remap ECU	https://auto-remap.com/
23	SCAN TRUCK.com	HD + NRMM	Volvo, Iveco, Mercedes, DAF, Cummins and Ford	part	H + S	all	all				X	-	ONLINE		Brazil		https://www.scantruck.com.br/
24	CANlogic	HD	Volvo, Mercedes, Iveco, Scania, MAN, DAF, Renault	part	H			X	X	X	X	-	ONLINE	LONDON	UK	SCR emulator	https://www.canlogic.eu/
25	AG-tuning	NRMM		parts	H	all	all	X		X		-	ONLINE		Belgium	AdBlue removal	https://www.agricultural-tuning.com/
26	FAP REMOVE	-		parts	H + S			X	X	X	X	-	ONLINE		Bulgaria	DPF/EGR and SRC removal, reflash ECU	http://fapremove.com/
27	obDfr	HD		parts	H					X		-	ONLINE		China	NOx Emulator V4/V5	http://www.obdfr.com/
28	Vgate	HD	8 in 1	parts	H					X		-	ONLINE		China	V3.0 Truck Diagnostic Cable , Truck AdBlue Emulator 8 in 1 Diagnostic with NOx	http://vehiclediagnosticscanner.sell.wpc-board.com/
29	Auto Tool.fr	HD	8 in 1	parts	H					X		-	ONLINE		China	Ad-blue Emulator OBD2, AdBlue- NOx Emulator, AdBlue Emulator 8 in 1	http://www.autotool.fr/
30	OBD2 & EOBDTool.co.uk	HD	7 in 1	parts	H					X		-	ONLINE		China	Ad-blue Emulator OBD2	http://www.uobdii.com/
31	ODB2Express.co.uk	HD		parts	H					X		-	ONLINE		China	Ad-blue Emulator OBD2 dongle	http://www.obd2soft.com/

32	OBD2soft.com	HD		parts	H					X		-	ONLINE		China	Ad-blue Emulator OBD2, AdBlue- NOx Emulator, AdBlue Emulator 8 in 1	http://www.obd2soft.com/
33	OBDiag I	HD		parts	H					X		-	ONLINE		Ireland	AdBlue v3 NOX emulator for all kinds of trucks	http://www.obdiag.ie/trucks-c-1.html
34	Universaltuning.it	HD		parts	H					X	X	-	ONLINE		Italia	ADBLUE / NOX EMULATOR	https://www.universaltuning.it/
35	WODOO	HD + NRMM		parts	H			X	X	X	X	-	SERVICE		Latvia	TRUCK ADBLUE/SRC & DPF EMULATOR	http://www.wodoo.lv/gb
36	Truck explorer	HD	MB, MAN, Iveco	toolkit	H + S		all	X	X	X	X	2800 - 9000	ONLINE	Vilnius	Lithuania	Workshop toolkits and licenses	http://autovei.com/
37	WinOLS Open source	LD/HD	Most	software	H + S	all	all	X	X	X	X	-	ONLINE		Germany	Exchange of A2L files via closed forums. Enables ECU tampering.	Various websites
38	Binnector	LD	Most	software	S			x	x			30	ONLINE (download)			Online tool	www.binnector.com