Adapting driver behaviour for lower emissions

MODALES D4.2: Recommendations for anti-tampering and an improved mandatory vehicle inspection

WORK PACKAGE	WP4: Effectiveness of inspections and depollution systems
TASK	T4.2: Periodic inspection and other anti-tampering solutions
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Legal disclaimer

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List of abbreviations and acronyms

Abbreviation	Meaning
AFR	Air Fuel Ratio
API	Application Programming Interface
CAA	Clean Air Act
CAN	Controller Area Network
CARB	California's Air Resources Board
CINEA	European Climate, Infrastructure and Environment Executive Agency
CO	Carbon monoxide
CO2	Carbon dioxide
COVID-19	Coronavirus Disease 2019
CSS	Cascading Style Sheets
CVS	Constant Volume Sampling
DEF	Diesel Exhaust Fluid
DOC	Diesel Oxidation Catalytic Converter
DOORS	DBE Office Online Reporting System
DPF	Diesel Particulate Filter
DTC	Diagnostic Trouble Codes
DoA	Description of Action
EATS	Emission After Treatment System
EC	European Commission
ECM	Engine Control Module
ECU	Engine Control Unit
EEV	Enhanced Environmentally Friendly Vehicle
EGR	Exhaust Gas Recirculation
EOBD	European On-Board Diagnostics
EPA	Environmental Protection Agency
EPS	Environmental Protection System
EU	European Union
FTIR	Fourier-Transform Infrared Spectroscopy
GPS	Global Positioning System
HC	Hydrocarbon
HD	Heavy Duty
HDV	Heavy-Duty Vehicle
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
I/M	Inspection and Maintenance
IoT	Internet of Things
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCV	Light Commercial Vehicle
LDV	Light-Duty Vehicle
LEZ	Low Emission Zone
LPG	Liquefied Petroleum Gas
MIL	Malfunction Indicator Light
ML	Machine Learning
MOT	Ministry of Transport
MySQL	My Structured Query Language

Abbreviation	Meaning
NO	Nitrogen Oxide
NOx	Nitrogen Oxides
NRMM	Non-Road Mobile Machinery
OAPC	Ordinance on Air Pollution Control
OBD	On-Board Diagnostics
OBD-I (or OBD 1)	On-Board Diagnostics, first revision (in U.S.)
OBD-II (or OBD 2)	On-Board Diagnostic, second revision (in U.S.), *see also EOBD*
OBM	On-Board Monitoring
OBFCM	On-Board Fuel and/or Energy Consumption
OC	Occurrence Counter
OEM	Original Equipment Manufacturer
OTL	OBD Threshold Limits
OS	Operating System
OVU	On-Vehicle Unit
PCA	Principal Component Analysis
PCD	Particulate Control Diagnostics
PCV	Positive Crankcase Ventilation
PEMS	Portable Emissions Measurement System
PGN	Parameter Group Number (J1939)
PID	Parameter ID (OBD II)
PM	Particle Matter
PN	Particle Number
PTI	Periodic Technical Inspection
RPM	Revolutions Per Minute
SCR	Selective Catalytic Reduction
SEMS	Smart Emission Monitoring
THC	Total hydrocarbons
TRAP	Traffic-Related Air Pollution
TWC	Three-Way Catalyst
UDS	Unified Diagnostic Service
URL	Uniform Resource Locator
VIN	Vehicle Identification Number
WHTC	World harmonized transient cycle
WHVC	World Harmonised Vehicle Cycle
WLTP	Worldwide harmonised Light vehicles Test Procedures
WP	Work Package
XML	Extensible Mark-up Language

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Executive Summary

This deliverable is part of Work Package 4 on the Effectiveness of inspections and depollution systems, which is one of the five technical WPs of MODALES project. The aim of WP4 is to propose and validate possible solutions that will contribute to lower emissions by involving (a) OBD data, (b) periodic inspections and anti-tampering solutions and (c) retrofits for passenger cars, light- and heavy-duty vehicles (LDVs/HDVs). More specifically, the purpose of D4.2 is to investigate the detection of tampering or malfunctions by considering a wide range of technical, behavioural and legal criteria, in order to clarify the current and future capabilities of the EOBD protocol.

Drawing on the results, the current characteristics of the EOBD protocol have been studied in order to suggest improvements, e.g. on sensitivity factors, which may result in an enhanced detection of tampering and malfunctions. Study on other user behaviours, given by technicians, garages and tuning centres on poor maintenance or tampering has been conducted, taking into account the real effectiveness of OBD and periodic inspections. Additionally, an in-depth analysis of the vehicle inspection data has been performed with data provided from Turkey, Finland and Spain. By analysing Periodic Technical Inspection (PTI) data, one might conclude that a year-on-year increase in random emission checks (leading to a greater number of penalties being issued for violations), has a positive effect on reducing emission failures. Also, overloading of trucks and buses may be one of the reasons for increased failure percentages. More specific controls and higher penalties for overloading would help combat this.

Two options for vehicle modification and/or manipulation were studied in Task 4.2: Engine Control Unit (ECU) reprogramming and/or tampering of the vehicle Engine After-Treatment System (EATS). The results acquired from this demonstration suggests that the effect of different ECU remapping and EATS tampering solutions may change the vehicle performance characteristics relatively significantly. The ECU reprogramming versions adapted in this study were found to affect especially the EATS thermal control, increasing the delay of catalyst activation. No effect on particulates was found for ECU reprogramming with the Diesel Particulate Filter (DPF) installed. On contrary, removal of vehicle EATS neglects totally the suppression of any exhaust pollutants, resulting in exhaust emissions which correspond to engine raw emissions.

Necessary software has been created and demonstrated for passenger cars. The software combines EOBD codes that indicate potential tampering violations or improper maintenance. The proposed system can be a multiple actor, to: allow predictive maintenance so that the necessary precautions can be taken as to encourage drivers to intervene; inform the periodic inspection technician that an irregular vehicle behaviour is spotted that might lead to tampering or improper maintenance; transfer the fault codes through IoT to a central database to discourage tampering and assess the vehicle maintenance levels.

Besides the above technical aspects, an overview of best practices and recommendations based on the legal research (from MODALES WP2) was carried out on vehicle tampering. Analysis of the current situation provided evidence of the need to strengthen regulations and monitoring processes. Regulatory improvements for more rigorous inspection controls all over Europe, together with a tougher sanction system for both vehicle owners and technician violators have been discussed. The recommendations also suggest that Member States may consider applying rules outside the context of the type approval process in order to prohibit a wider scope of tampering conducts.

1. Introduction

1.1. Project overview

The MODALES project works towards reducing air pollution from all types of on-road vehicles by encouraging the adoption of low-emission driving behaviour and proper maintenance choices.

MODALES pursues a user-centric approach to address all the challenges, which, on the one hand enhance low-emission practices, and on the other hand, suppress high-emission behaviour by researching, developing, and testing several innovative and complementary solutions in four key areas (driver, retrofits, EOBD and inspection) to reduce vehicle emissions from three main sources: powertrain, brakes and tyres.

The scope of vehicles covers all vehicle types, ranging from passenger cars to buses and trucks.

The main activities of MODALES are:

- Measurement of real-world vehicle emissions and driving behaviour to produce accurate correlations between them using advanced mathematical and statistical techniques.
- Exploration of the most advanced technologies for retrofits designed to substantially reduce powertrain emissions from all types of vehicles and validate their effectiveness under different real-world traffic and environment conditions, and by various drivers.
- Undertaking an in-depth analysis of OBDs, periodic inspection and legal issues on tampering in Europe to help regulatory authorities put in place effective anti-tampering legislation, and help owners properly maintain their vehicles.
- Conducting extensive low-emission user trials (with both driving and maintenance practices), supported by awareness campaigns, to enhance public engagement and help drivers better understand the impact of their driving and maintenance behaviours in all situations.

1.2. Scope

This deliverable is part of Work Package 4 (WP4) on the **Effectiveness of inspections and depollution systems**, which is one of the five technical WPs of MODALES (the two “non-technical” WPs are WP1 on Project Management and WP7 on Awareness, Communication and Dissemination). The five “technical” WPs of MODALES are the following:

- **WP2: Defining low-emission factors**, which explored driving behaviour variability using existing available data. This WP delivered a first approach on driving behaviour patterns and powertrain, brake and tyre emissions. It also addressed the state-of-the-art in retrofits, inspection, and maintenance (I/M) and legal issues regarding tampering in various EU member states.
- **WP3: Impact of user behaviours**, which undertook a series of measurement campaigns to establish the interconnection between driving behaviour and powertrain exhaust emissions, as well as fine particulates from brakes and mass-loss from tyres. Measurement campaigns were also carried out to address the impact of poor maintenance and deliberate tampering of the emission control system.
- **WP4: Effectiveness of inspections and depollution systems**, which uses the findings of WPs 2 and 3 as a basis to investigate and propose solutions that will contribute to emission monitoring via the

EOBD protocol and systems that detect a lack of maintenance and tampering. It has also investigated the potential of enhancing existing retrofit systems.

- **WP5: Guidelines and tools for low-emission training**, which takes into consideration results from the above WPs in order to define guidelines for low-emission driving and specify the technical requirements for a smartphone application. The app is developed and tested in this WP. Online training materials were also designed to ensure consistency with existing learning processes and serve as input for on-road trials and awareness campaigns.
- **WP6: User trials and evaluation**, which develops an evaluation plan to test and evaluate, with real-world trials, the functionality of the innovations developed in MODALES, their effects on driver acceptance and performance and their potential wider impact (their predicted overall effects on vehicle emissions).

The figure below shows how these deliverables fit into the project and highlights related deliverables which will consider the content of this one.

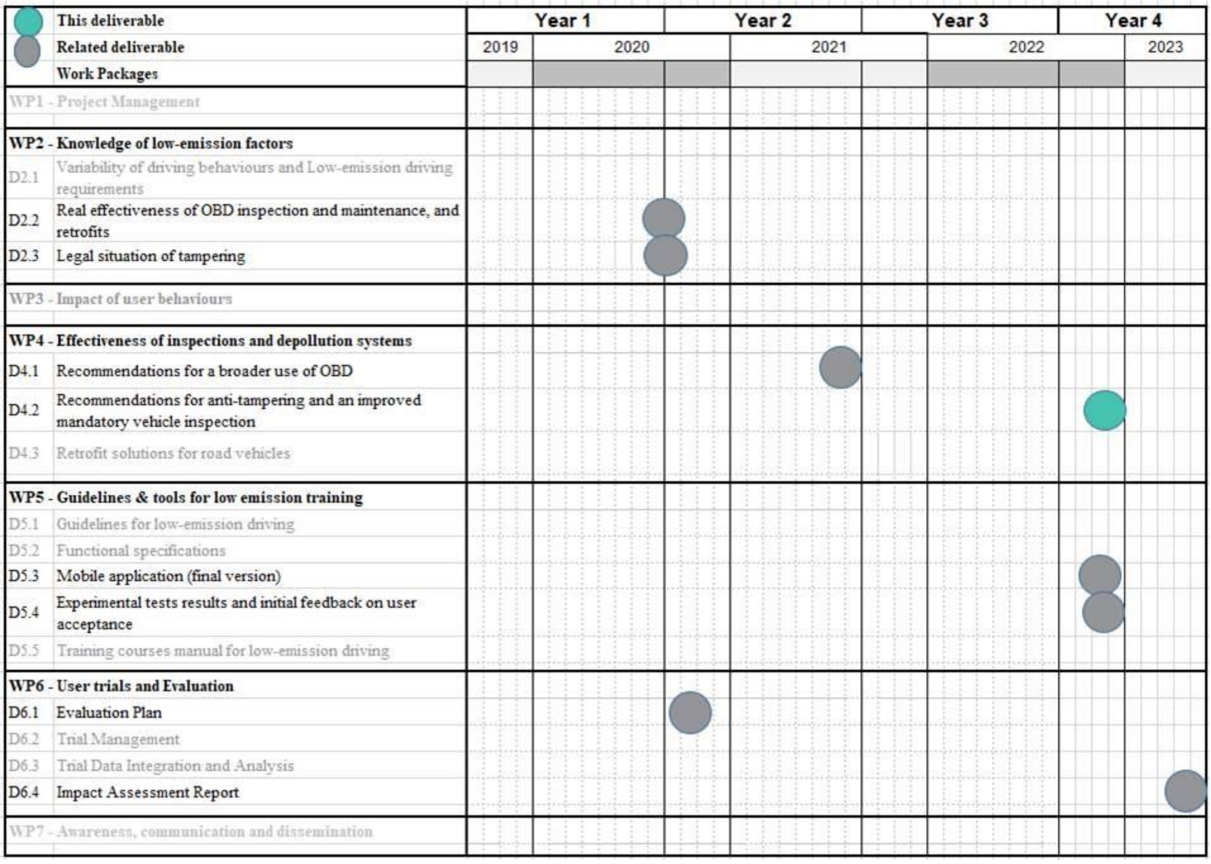

Figure 1: D4.2 in the context of related MODALES tasks and deliverables

1.2.1. MODALES WP4 on the effectiveness of inspections and depollution systems

The aim of WP4 is to propose and validate possible solutions that will contribute to lower emissions by involving (a) OBD data, (b) periodic inspections and anti-tampering solutions and (c) retrofits for passenger cars, light- and heavy-duty vehicles (LDVs/HDVs). Taking WP2's findings as inputs, WP4's objectives are to:

- Study user behaviours concerning poor maintenance or tampering, taking into account the real effectiveness of OBD and periodic inspections;
- Demonstrate solutions that will allow the detection of poor maintenance and/or tampering;
- Propose regulatory improvements for more rigorous inspection controls all over Europe, together with a tougher sanction system for both vehicle owners and technician violators;
- Investigate the feasibility and potential of retrofit emission controls and expand their practicality to heavy-duty/non-road mobile machinery (NRMM) applications, light-duty trucks and large vans;
- Study and experiment with prototype technologies, not yet released to the market, that will be used to retrofit LDVs/HDVs, targeting a dramatic reduction of NO_X from diesel engines.

1.2.2. Scope, structure and intended audience of this deliverable

This deliverable is the outcome of MODALES Task 4.2 “Periodic inspection and other anti-tampering solutions”. The purpose of D4.2 is to investigate the detection of tampering or malfunctions by considering a wide range of technical, behavioural and legal criteria, in order to clarify the current and future capabilities of the EOBD protocol.

The deliverable consists of 10 Sections (chapters), starting from this introduction and continuing with Section 2 which briefly describes the outcome of Task 4.1 that is linked with Task 4.2. Section 3 addresses the owner motivation for the vehicle tampering. Sections 4, 5 and 6 are mainly literature reviews about the findings of the PTI inspections, the road vehicle and the NRMM tampering. Sections 7 describes a series of tests for quantifying the effects on emissions of a heavy-duty engine for different tampering phases. Section 8 presents a system developed in Task 4.2 for the identification of potential vehicle tampering. In Section 9, a number of recommendations for the poor maintenance and tampering problems are listed which derived from a review of best practices but also by interviewing local authorities and country experts. The report ends with the “Conclusions” Section 10.

The officially submitted version of this deliverable was Confidential (CO), as per the DoA. However, as the authors agreed that it contains no sensitive content, it has been made public.

1.3. Deviations from the Description of Action (DoA)

This deliverable is aligned with the content of the DoA. In addition, chassis dyno tests have been conducted with the aim to quantify the emissions of a heavy-duty vehicle engine that underwent different stages of tampering.

However the 2022 Contract Amendment included a reschedule from Month 28 to Month 37 (further delayed by two months to Month 39). This is due in particular to:

- COVID-19 pandemic and the limited access to vehicles and experts to interview.
- Delays with the PTI data provision.
- The chassis dyno tests that have not initially planned as part of the original Grant Agreement, but were included in the Amendment to add value to this task.

It should be noted that this deliverable is a “stand-alone” one and its delay does not influence the progress of any other task or deliverable in the project.

2. Summary of results from Task 4.1: OBD logging

Task 4.1 considered recommendations for a broader use of On-Board Diagnostics (OBD). The origins of OBD lie in the identification of emission-related deviations to reduce environmental impact. This project foresees the use of data that is accessible via OBD, with additional information from third party devices, to identify driver behaviour which might have an impact on engine emissions, as well as on brake and tyre wear.

The Task began by investigating potentially relevant diagnostic parameter that can be accessed via OBD Identifiers (OBD PIDs), to attempt to gain insights into driving behaviour. On basis of this, we analysed the availability of these PIDs in a random set of cars with different types of fuel and years of manufacture, ranging from 2007 to 2019. The lessons learned were that newer cars support more PIDs but from our list of potentially relevant PIDs, only quite a small number of PID was widely supported. This will have an impact on decisions about what age cars we support in the later field test or on what basis we model driving behaviour.

Before performing the field tests, we needed to select a suitable OBD dongle for this task. Dongles support different protocols, might contain additional sensors, and are accessed in different ways. Based on a small market study, we identified all potentially relevant properties, from which we selected some that we need to develop our own application.

A deeper look at the modelling of the powertrain, brakes and tyres of a car was done, to identify driving behaviour. These models list some of the properties that might be accessible via OBD or which have to be accessed via additional sensors. If these sensors prove to be emission-relevant, they might be made available in a future OBD standard.

Finally, potential recommendations for a broader use of OBD have been discussed, not only from a legal point of view, but also regarding the lack of available services or the avoidance of vehicle tampering.

3. User behaviour analysis

3.1. Introduction

A primary aim of Task 4.2 was to identify the reasons of people tuning their vehicles. For this purpose, interviews were conducted with companies making such conversions. Interviews took place in Finland and China. It should be noted that the participation of the companies was small, because the owners viewed the description of their customers' needs with a negative attitude, since such information could be against their interests. This fear was also supported by the fact that the findings of the project would be known to the EU.

3.2. Interviews in Finland

In Finland, the project attempted to interview three tuning shops. However only one provided complete and useful information through the set questions (common questions were proposed for all three).

The first company did not respond to several calls and the second one answered but then declined to respond to the questions because the owner stated: "this call does not bring any value to the company".

Therefore the answers below relate to the third company only (which we promised would remain anonymous). A comprehensive telephone discussion took place with the owner of this company, who shared very openly the situation on current tuning markets. This company does software tunings for light- and heavy-duty vehicle and NRMM applications, but concentrates currently on HDV and NRMM markets due to better profitability and less competition.

The answers to the questions by this company are as follows:

1. Customers' motivation for tuning their vehicles?

According to its owner, the company has been in the tuning scheme (especially LDVs) for decades, therefore they have a long experience in the field and have a clear view of the market and how the competitors perform software tunes. The essential comments related to aftermarket software tuning were divided as listed below:

General comments regarding the passenger car tuning scheme and market since the beginning of software tuning (commented by company 3):

- The company focused on software tunings related to diesel cars, not gasoline (petrol) vehicles.
- According to this company, especially older vehicles (early 2000) had a lot of room for improvements related to engine maps/calibrations that could lead to easy to fix/update later with software tuning
- The methods for passenger car tunings are divided based on technology types and the age of the car (pre-or post-2008), as followings:
    1. Pre-2008 era

    Customers often requested simple power upgrades, as less complicated EATS were present in these vehicles. At that time, fuel injectors were also often "oversized" making software power maps easy by increasing injector duty time, increasing boost pressure and removing the Exhaust Gas Recirculation (EGR). Due to the absence of DPFs, no major changes in the hardware was required.

2. Post- 2008 era

These vehicles are more complicated and require a better understanding of the complete powertrain system. More EATS malfunction related requests took place (EGR and DPF deletes) in order to decrease maintenance costs and EATS related errors/issues (often caused by improper software tunes or poor maintenance). Still power upgrades were requested, but many (especially VAG Group) software upgrades post 2008 era required that the ECUs were physically opened for reading/flashing the software (the ECUs were sealed in order to prevent software changes). However, due to the more complicated ECU, risks of failure and required workload increased which lead to less profitable customer requests.

2. Software requests depends on which parameters?

Current (or newer) passenger cars tend to have enough power for several car buyers, therefore fewer tunes are performed on newer cars, albeit still some demand exists. Some customers are still tempted to increase power and pursue for a decrease in fuel consumption, therefore utilise software "optimisation" and there are many software tuning companies often promise both.

Older, high mileage (post 2008) vehicles may also suffer from EATS failures, hence customers sometimes requests for "DPF-delete" software kits. E.g. the price for DPF replacement may be very high in relation to car price on the market; therefore, the customers think that EATS maintenance is not worthwhile for older cars.

Several competitors provide the customers with "pre-tuned" general software packages that are not individually calibrated for the specific vehicle. These software tunes, according to the company respondent, are more or less "incomplete". Many general software upgrades provided by competitors promise lower fuel consumption simultaneously with increase in power, but this statement may be false due to injector map (injector duty time is extended) manipulation and as the recalibrated injector maps are not in line with actual flow. The ECU thinks that the fuel flow is lower than actual, leading into higher fuel consumption compared to the value declared by ECU/dashboard, higher PM emissions and DPF clogging as required interval for regeneration is insufficient

Due to increase in fuel injection quantity (and lower AFR or EGR removal), DPFs are often removed in order to prevent premature filter clogging. Several competitors remove the EGR that affect the air path/gas exchange. This should however be taken into account in software tuning if proper upgrades are made. If not accounted for, AFR is changed and the engine does not work "properly" in the long term and may also clog the DPFs.

3. Is tampering harmful for the engine?

Some tuners disable error codes in order to "hide or manipulate" engine diagnostics for avoiding limp-mode. Company 3 believes that no changes in factory injection maps should be made, therefore the maximum allowed torque curve is only manipulated to increase power (max torque limit). Due to engine wear and different existing power grades for same engine family, the engine manufacturer calibrates engine maps with fairly large margins (the actual torque curve is lower than the actual power/torque potential existing in the total ECU map). Company 3 named several cases where the customer brings a defect vehicle (and tuned by others) for restoring OEM maps or updates the "falsely tuned" ECU. Any software changes should always be performed using a chassis dynamometer.

4. What is the profile of your customers?

Current customers (on HD- and NRMM sectors) are divided typically into three categories:

1. Those who face NRMM EATS failures, which will increase downtime. In such case, the EATS is disabled either temporarily or permanently depending on spare parts price and delivery time.

2. Customers who believes that the engine power is lower than rated by the manufacturer, as engine response may be "slow" or lack power in relation to the workload. The requests are for power improvements which will lead to improvements in work efficiency and consequently in time saving.
3. Customers who buy a "rescue kit". In this case, a backup ECU-flash is used if any error codes appear that increase the downtime during the workdays. These customers want to get the job done in time and will then return the machinery for service after the work is complete.

As the profit of the customers on the HD- and NRMM sectors solely rely on the work done by the machines (operation time), they try to avoid limp-modes and EATS related errors as long as possible. Company 3 often gets requests to upgrade or restore OEM maps for badly tuned software on passenger cars that have a general software tune or EGR/DPF removed. Company 3 aims to upgrade all software so that OEM EATS or engine diagnostics are not affected by the software tunes In order to prevent EATS deletes; Company 3 believes that the manufacturers should be responsible for the costs that are caused by EATS malfunctions.

3.3. Interviews in China

1. General questions about construction machinery in Nanjing:

- ***a. Where are the main applications of construction machinery in Nanjing?***
- ***b. What is the current status, e.g. fuel type, etc.?***

Received answers from the staff of Nanjing Motor Vehicle Exhaust Pollution Inspection and Management Centre.

They are mainly distributed in construction sites, port terminals and chemical companies. Port machinery has basically changed to electricity, using shore power. For example, Longtan port has very few machineries using fuel oil. In the city, there are not many loaders and bulldozers, and the ratio of excavators to bulldozers is about 10:1. The sites are equipped with generator sets, which are generally used very rarely and have high pollutant emissions when they are on. Because they are seldom used, there is no strict monitoring of their emission…

2. Are there any inspection and maintenance related programmes available for NRMM in Nanjing? If yes,

- ***a. What are the emission-related components that need to be tested?***
- ***b. Which emission-related components are most frequently repaired and replaced, and at what cost?***
- ***c. Where is the required test location (on-site or field, or repair centre)?***
- ***d. What are devices, tools and methods used in the test for emission components, and how do they differ when used on older and newer engines?***
- ***e. What are the common faults or malfunctions associated to emissions, and which of these will cause of the test to fail?***
- ***f. Other comments?***

Received answers from the staff of Nanjing Motor Vehicle Exhaust Pollution Inspection and Management Centre.

The use of construction machinery is intensive, and they are often not properly maintained.

3. What types of vehicles have more frequent replacement of emission-related components?

a. Cars: Private cars and taxis

b. Buses
c. Heavy-duty vehicles
d. NRMM
e. Others

4. **What is the difference between vehicles with and without routine maintenance in the inspection (e.g., probability of passing inspection, price required for repair if not passed, etc.)**

No answer received.

5. **What are the most common problems in inspections?**

The inspection centre has installed blackness detectors on more than 1,000 construction machinery vehicles in the city. However, the accuracy of the measurement cannot be guaranteed due to poor maintenance.

6. **What are common types of tampering?**

No answer received.

7. **What are the methods of tampering? (the answers to the question are for on-road vehicles, not NRMM)**

Received answers from the staff of Vehicle Repair workshop.

Example 1: There is a special disposable wire ball used for annual inspection, which is commonly known as "fire lotus". This wire ball is placed inside the muffler pipe of the three-way catalytic converter before the annual inspection. This wire ball can be used once or twice to bring the motor vehicle up to standard in the OBD test (HC and NO_X). The image below is a metal soft carrier wire ball suitable for annual inspection.

Figure 2: Wire ball example, known as "fire lotus"

Example 2: The muffler is removed directly, and the exhaust is smoother and more powerful after removing the muffler and exhaust catalytic device, while OBD does not limit the use of the vehicle by the driver after modification.

4. Outcomes of road vehicles PTI

4.1. Literature review

Typically, in developed countries, all private car owners must get their vehicles' emission tested biennially [1]. This policy is generally known as the inspection and maintenance (I/M) programme [2]. In a typical I/M programme, owners are required periodically to take vehicles subject to regulation at an inspection and maintenance station [3]. Based on result of emission test, vehicles which fail to pass an emissions test under inspection programme are suggested to perform a maintenance process and then re-test their emissions. In most cases, the test consists of tailpipe emission test called idle emission test, an examination of certain components of evaporative emission system and a check to ensure that vehicle has not been tampered with. Any motor vehicle with emission rates of Hydrocarbon (HC) and Carbon Monoxide (CO) that exceed a set of emission standards in EU must be repaired to meet those standards in order to extend vehicle registration [4][5].

According to Autonettv [6] over 80 percent of the vehicles on the road have one or more service or repair that is needed, but has not been taken care of. That translates into roughly over 160 million vehicles in the US alone. Some of the neglected items are minor. Others are serious safety concerns. The most common car problems that tend to pop up are: [7]and [8].

Warning lights: A warning or check engine light is the most common issue for car, truck and SUV owners. These lights illuminate when the ECU (engine control unit) detects an error code triggered by a sensor. Since there are more than 200 possible warning code, the light does not tell the operator what the problem exactly is. Having a professional mechanic complete a warning light inspection is the best way to determine the source and make the right repairs.

Sputtering engine: The engine runs best when air and fuel properly mix and burn in the combustion chamber. If this process is not efficiently completed this, engine sputtering or misfiring might occur.

Poor fuel economy: When the engine is running efficiently, it burns fuel at a rate that helps improve fuel economy. However, several fuel system parts like fuel filters, air filters, mass air flow sensors, and O_2 sensors will eventually get dirty or wear out. If this happens before they are replaced, it will cause the engine to consume more fuel than usual which can also lead to higher emissions.

Dead battery: Most car batteries should last about three years or 80,000 km. A dead battery is usually caused by reduced capacity which naturally decrease as the battery loses its ability to maintain a charge. A damaged alternator, battery temperature sensor, or other charging system components can expedite this issue. It is suggested that the replacement of the battery should take place every 80,000 km or three years, even if is not showing signs of damage.

Tyre wear: In order to create even wear to tyres, Bridgestone suggests the rotation of tyres every 8,000 km (or as suggested by the vehicle manufacturer).

Brakes squeaking or grinding: Brake wear is natural and proper maintenance is vital for the brake system to work as intended. The brakes wear sometimes unevenly or due to poor maintenance or long service periods, may seize. A soft pedal is an issue of fluid leakage or air in the system, which should be taken care of immediately.

Alternator failure: The alternator is the part on the vehicle that keeps all electrical systems running once the car starts. It is also responsible for supplying a charge to the battery to keep it in peak condition. A check should be done during recommended service intervals and the alternator should be replaced before it breaks.

Broken starter motor: The started motor is used for staring the ICE. When this component fails, the main reason is usually because the electrical solenoid has been damaged or motor brushes wear out, the starter motor breaks, or another electrical fault occurs. While a starter can be replaced before it fails, it is difficult to predict when this will happen.

Steering wheel shaking: Multiple issues can cause the steering wheel to shake while driving. If it happens right after starting the car and beginning to drive, wheel bearings or damaged suspension components are often the source. If it happens at higher speeds, it is typically a tyre/wheel balance issue. A professional mechanic inspection could solve the problem.

Failed emissions test: Most countries require an emissions test to register the car, and a failed test can occur for many reasons. If the vehicle fails the emissions test, a professional mechanic inspection is required.

Overheating: In most modern cars, the cooling system is very complex, containing multiple sensors that monitor coolant temperature, flow and other components. By regularly servicing the coolant system, e.g. flushing the coolant ensures a longer coolant system lifespan.

Slipping Automatic Transmission: When properly maintained, an automatic transmission can have a long lifespan without a trouble. The modern automatic transmission is a hydraulic system comprised of several seals, gaskets, and lines that can become damaged, clogged with debris, or leak. They are relatively complex systems with several potential parts that could fail. When this happens, a transmission will slip or not shift smoothly.

As described above, there are many problems that may occur in a vehicle. For that reason, inspection maintenance programmes are important to keep the vehicles in their normal operation as they have been designed by the manufacturers. Below are listed the most common causes of inspection failure on personal vehicles [9]:

- Air to fuel mixture may be incorrect.
- Positive Crankcase Ventilation (PCV) valve may be malfunctioning or missing
- Vacuum leak present
- Exhaust Gas Re-Circulation (EGR) may be malfunctioning
- Ignition timing may be incorrect
- One or more worn, damaged, or fouled sparkplugs are present
- Catalytic converter is clogged, missing, or ineffective
- Malfunctioning oxygen sensor
- Internal engine parts may be malfunctioning or damaged
- Dirty or contaminated engine oil
- Clogged air filter.

In case of commercial vehicles, **Error! Not a valid bookmark self-reference.** presents the most common reasons of inspection failure [10]:

Table 1: Common Causes of Inspection Failure—Commercial Vehicles

Vehicle Documents and Miscellaneous Items	Vehicle Body	Vehicle Safety
• Missing or incorrect tags • Non-operational HVAC • Damaged or torn upholstery • Unacceptable sanitation • Damaged lift wheel • Incorrect tag mounting	• Damaged or rusted doors • Damaged and/or rusted quarter panel • Damaged and/or rusted bonnet (hood) • Damaged and/or rusted and/or missing bumpers (fenders) • Damaged and/or missing bumper guards • Incorrect tag mounting • Missing or improper petrol (gas) cap • Damaged bodywork	• Missing or damaged mirrors • Missing or damaged horn • Missing or damaged seatbelts • Missing or damaged speedometer • Missing or damaged gear indicator • Missing or damaged safety chains • Missing or damaged chain guard
Vehicle Lights	**Vehicle Glass**	**Vehicle Suspension**
• Non-operational indicator (turn signal) lights • Non-operational backup lights • Non-operational tail lights • Non-operational stop lights • Non-operational tag lights • Non-operational clearance lights • Non-operational marker lights • Non-operational fog lights • Incorrect lens colour • Damaged or missing side reflectors • Damaged or missing rear reflectors • Non-operational headlights	• Cracked or damaged windscreen (windshield) • Cracked or damaged side window • Cracked or damaged rear window • Non-operational window controls • Unacceptable window tint • Missing or non-operational windscreen wipers • Missing or damaged wiper blades	Damaged or unacceptable: • Kingpin • Shocks • Ball joints • Control arm • Rack and pinion • Tie rod ends • Idler arm • Pitman arm • Sleeve • Springs • Steering box • Steering wheel • Bearings • Steering linkage • Column • Alignment • Power steering • Bellows • CV joints
Vehicle Exhaust	**Vehicle Tyres**	**Vehicle Brakes**
• Leaking exhaust • Tampered exhaust • Missing or damaged exhaust converter • Loose exhaust • Flexible piping exhaust • Excessive exhaust noise • Excessive exhaust smoke	• Unacceptable or worn tyre tread • Unacceptable or cut tyre • Mixed tyre types • Unacceptable knots and bulges in tyres • Over- or under-inflated tyres • Visible tyre cord	• Worn or warped rotors • Damaged or worn front brakes • Damaged or worn rear brakes • Excessive brake noise • Leaking or damaged master cylinder

• Excessive exhaust hydro carbon • Excessive exhaust carbon monoxide	• Tyre recap/tread front • Missing lug nuts	• Leaking or damaged wheel cylinder • Damaged or non-operational vacuum booster • Non-operational parking brake • Non-operational brake warning light • Incorrectly adjusted pedal reserve • Missing and/or damaged pedal pads
Tail Pipe Test – Typical causes for failing a tailpipe test include:		
• Air to fuel mixture may be incorrect. • Positive Crankcase Ventilation (PCV) valve may be malfunctioning or missing * • Vacuum leak present • Exhaust Gas Re-Circulation (EGR) may be malfunctioning * • Ignition timing may be incorrect • One or more worn, damaged, or fouled sparkplugs are present • Catalytic converter is clogged, missing, or ineffective * • Malfunctioning oxygen sensor • Internal engine parts may be malfunctioning or damaged • Dirty or contaminated engine oil • Clogged air filter * Indicates items that may or may not be standard equipment		

From all the described inspection failures the most important are the exhaust and emission control system because they are strongly related with the emissions of the vehicle and thus related to this study. Suspension, brakes and tyres are crucial to maintain proper safety. Five percent of all new cars had a problem with their exhaust or emission control system [8]. When a vehicle is emitting excess levels of smoke, chances are that it is not properly tuned or maintained. When a vehicle is poorly tuned or maintained, the equipment on the vehicle designed to control the level of pollutant emissions also may not function properly. Smoke from petrol engine vehicles (most cars) is mainly due to excessive wear. Diesel vehicles (most trucks) may emit smoke from poor injector maintenance, excessive fuel delivery rates or poor driving technique (for example, lugging which is labouring the engine in too high a gear). Smoke emissions mean that the vehicle is wasting fuel and engine damage is probably occurring. Routine servicing will eliminate many problems that cause smoke emissions and save time and money. However, problems can and do occur after vehicle servicing or in vehicles in an apparent state of good repair, and even in relatively new vehicles.

The following problems may be the cause of smoke from a vehicle [11][12]:

Fuel-engine vehicles: Four-stroke or rotary petrol and LPG engines may emit blue/grey smoke or black smoke. Blue smoke normally means engine wear or damage. Black smoke results from an excessively rich fuel mixture. Where this occurs, the following components may be at fault.

- Air cleaner: A rich mixture can be caused by excessive build-up of dirt or oil. Replace the filter element at regular service intervals. Rags or paper caught in the air cleaner intake pipes can also cause black smoke emissions.

- Fuel system: Carburettor (most common in PTWs nowadays) and engine management system faults leading to black smoke include:
    - choke butterfly unable to open fully
    - carburettor flooding
    - incorrect grade of oil in dashpots
    - incorrectly adjusted or faulty automatic choke
    - air cleaner winter/summer lever set in wrong position
    - manual choke operated incorrectly or when the engine is warm
    - worn or loose jets or needles
    - sticking diaphragm
    - faulty engine management system
    - faulty oxygen sensor or other engine management sensors
    - faulty fuel injector.

Diesel-engine vehicles: Blue smoke from diesel engines normally means engine wear or damage. Black and grey smoke results from incomplete combustion and may be caused by many factors that can usually be rectified during routine maintenance. Some bases reasons for smoky diesel engines are listed below [11]:

- Over-fuelling: this is a common cause of smoke emissions. Adjusting the fuel system in an attempt to increase the power output of an engine which may be too small for the job, or to compensate for power loss in a worn or poorly maintained engine, will lead to more fuel being injected into the combustion chamber than the engine can efficiently use. The excess fuel that cannot be burnt is then emitted as black smoke. If fuel settings have been increased beyond those specified by the manufacturer, readjustment to the proper settings should be made.
- Injector servicing: It is essential that injectors be regularly serviced by a reputable diesel specialist, according to the manufacturer's recommendations.
- Crankcase breathers: As with petrol-engine vehicles, worn or broken rings or pistons allow gases from the cylinders to pass into the crankcase and out in to the atmosphere via the crankcase breather. Excessive smoke from a diesel vehicle's crankcase breather indicates serious engine problems.
- Lugging: Lugging the engine, which is labouring the engine in too high a gear, will also cause excessive smoke emissions. Drivers should be made aware of the minimum engine speed that must be used to avoid smoke emissions. Overloading a vehicle or operating the engine 'on the governor' (that is, at maximum engine speed) for long periods when prevailing conditions require less may cause smoke emissions.

Maintenance is best carried out in a fully equipped garage or service centre by qualified service personnel. Service manuals supplied by the vehicle manufacturer provide information on the control of smoke through good maintenance practices and should be studied when planning preventive maintenance schedules [13]. The fuel-injection pump or fuel injectors should only be repaired by the manufacturer, its manufacturer's representative or a reputable specialist.

To conclude the current section, it has been shown by several studies that the exposure to traffic-related air pollution (TRAP) increases health problems, such as obesity, asthma, cardiovascular diseases and cancer [14][15][16][17]. It is estimated that around 1.3 billion trucks, buses, and cars are registered and running worldwide. Therefore, air pollution is directly related to vehicular emissions, mainly in megacities [18][19][20][21]. In order to reduce and control air pollution from mobile sources, considering the adverse health effects on the population, it has become increasingly important to have I/M programmes for all types of vehicles.

4.2. Analysis of PTI (Periodic Technical Inspection) data

4.2.1. Introduction

This subsection aims to provide analysis results from PTI data that have been available to the consortium. The consortium tried to have access to as many data sources as possible, through its members, however the provision of such –sensitive– data from the transport authorities requires the consent from different departments so this is not always possible. Within MODALES, the consortium analysed data from Turkey, Finland and Spain. It should be noted that the data have not been provided in a similar format or level of aggregation. This fact did not allow us to make a direct comparison of results between these three countries.

4.2.2. Turkish PTI data analysis

According to the Turkish Legislation (6th of January 2021 no: 31356), the periodic inspection intervals are as follows:

- For passenger cars and LCV's after the first three years and later every two years.
- For tractors after the first three years and later every three years.
- For two and three wheel vehicles after the first three years and later every two years
- For all the other vehicles including taxis, trucks and buses after the first year and later every year

These inspection periods are in line with EU Directive 96/96/EC. For passenger cars and LCVs, they are even stricter, as the EU directive specifies four years after first registration.

The data have been made available through the relevant administration of the Ministry of Transport.

- **Periodic emission inspections**

Emission Inspections are being carried out according to the legislation dated 11th March 2017 with no 30004. The legislation is in line with the EU legislation.

The results below show that passenger cars have the highest percentage of failures. This may be due to stricter limits or due to tampering. Of course, it could also be related to the number of light vehicles (much greater numbers than HDVs) on the road and to the fact that the proper service is neglected. Also, the incentives to keep HDVs in proper condition are higher and they are often operated and taken care of by professionals. Another reason maybe that all the passenger vehicles are inspected after the first three years and later every two years whereas all the other vehicles are to be inspected every year. However, there is no detailed information about these findings.

There is an obvious trend of failure rate reduction from 2017 to 2021. Starting from the legislation of 2017, random emission checks have increased and every year related penalties are being increased. This may have positive effect on the reduction of the emission failures.

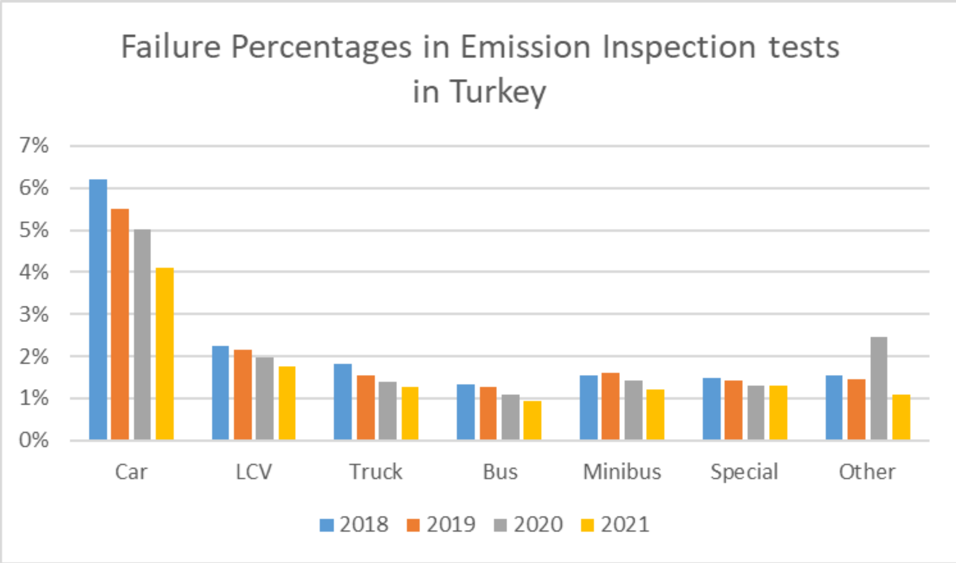

Figure 3: Emission inspections failure rate (Turkey)

- **Brakes and tyres**

The dataset consists of inspections carried out the years 2017-2021. The results in Figure 4 to Figure 7 show that for trucks and bus is much higher both for tyres and brake deviation compared with other type of vehicles. Brake deviation failures for other type of vehicles are also near 4 % which is also high. Brake deviation will impose harder braking than necessary causing more brake induced particles. For brakes maximum deviation allowed is 30% and for tyres minimum groove depth is 4 mm for buses and trucks and for other vehicles it is 1.6 mm which is in line EU directives.

For tyre failures again, the percentages of trucks and buses are very high compared with other type of vehicles. Overloading of trucks and buses may be one of the reasons for such a high failure percentage which requires for more specific controls and higher penalties for overloading.

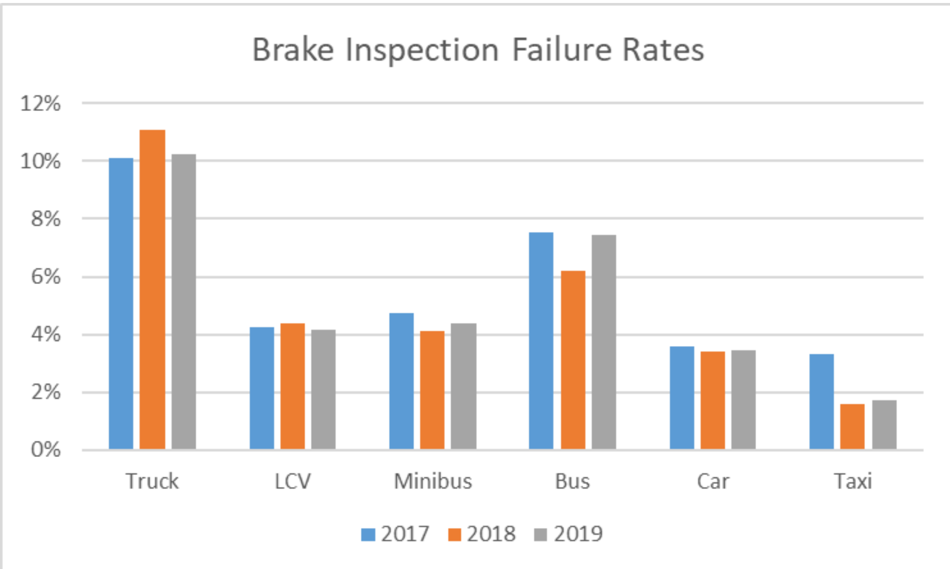

Figure 4: Brake inspection failure rate (Turkey)

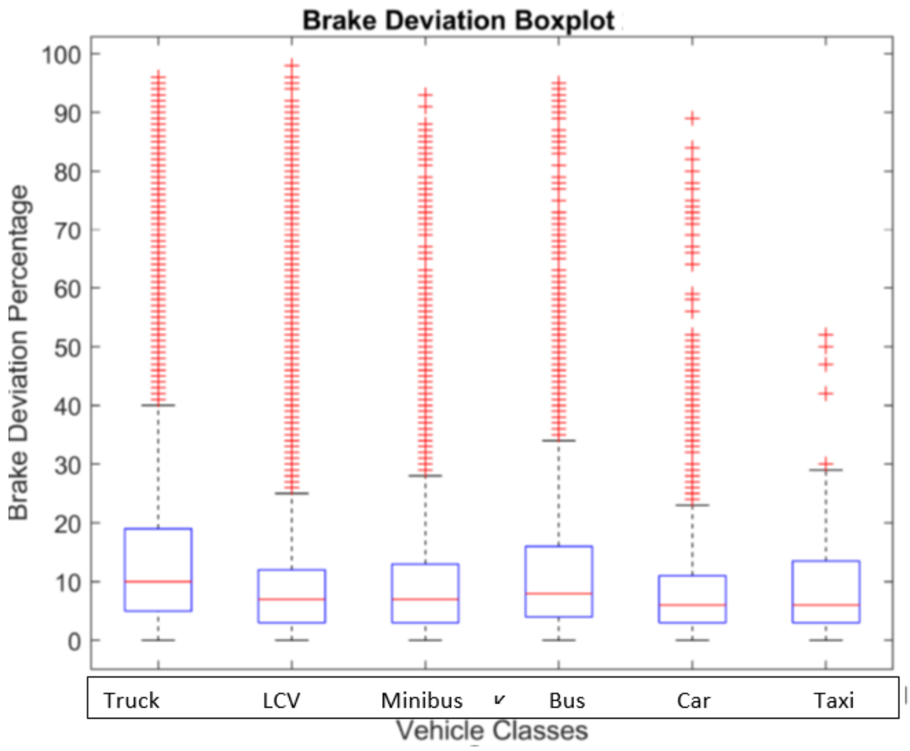

Figure 5: Brake deviation per vehicle category (Turkey)

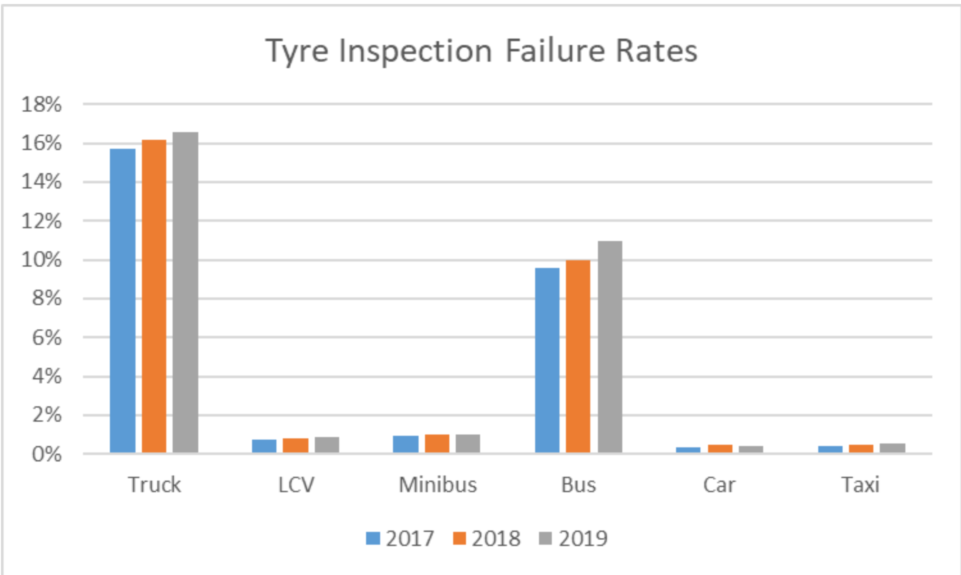

Figure 6: Tyre inspection failure rate (Turkey)

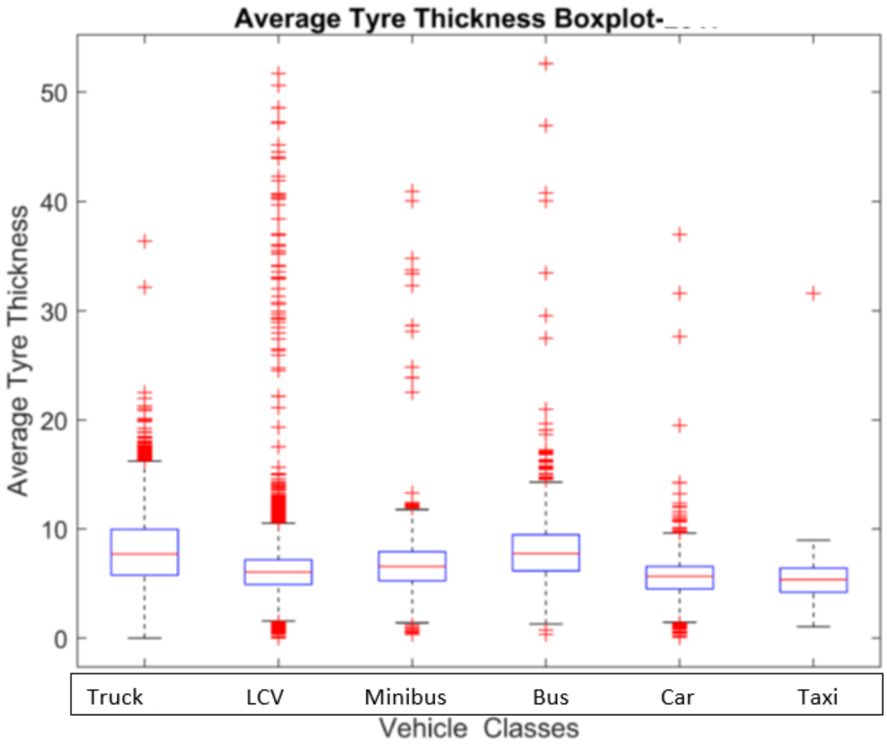

Figure 7: Average tyre thickness per vehicle type (Turkey)

4.2.3. Finnish PTI data analysis

The Finnish data were available through the Finnish Transport and Communication Agency (TRAFICOM) portal (https://trafi2.stat.fi/PXWeb/pxweb/en/TraFi/TraFi__Katsastuksen_vikatilastot/020_kats_tau_102.px/?rxid=8ea72f0e-5e16-4d50-849a-45770a8dd5a6). The analysis included the inspection years from 2017-2020. Regarding the vehicle age, 3-15 year-old passenger cars are included. Only model series that have had 100 or more inspections in the reference year are included. The analysis was split into three parts: the first one that refers to faults associated to environment, the second one that presents info regarding axle hazards in general and the third one about brake faults.

- **Periodic environment-related inspections**

This type of inspections concerns the emission measurement, fuel, oil and hydraulic leaks, noise, and checks through the OBD. Figure 8 shows that the vehicle age is a parameter that strongly influences the occurrence of faults that are relevant with environmental issues. The 10th year of the vehicle age seems to be a critical one, according to the graph. The distribution of the number of bans in relation to the vehicle registration years follows an exponential function.

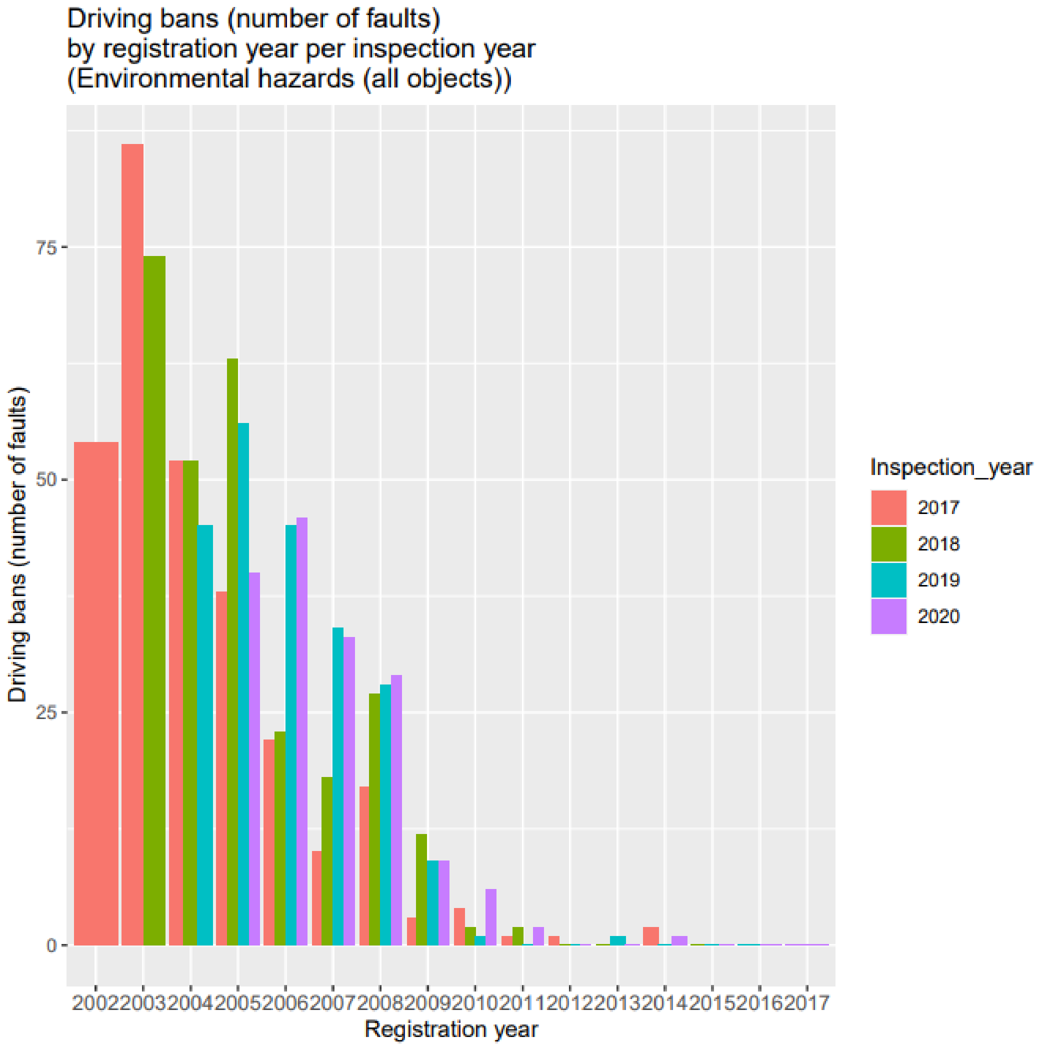

Figure 8: Number of environmental hazards from PTIs (Finland)

- **Periodic axle-related inspections**

This type of inspections concerns the front and rear axle condition, suspension and sock damping, wheels and rims. The distribution of faults has a linear development since very new vehicles of three years old that grows until the 10th year since the first registration. After that point, the distribution remains almost the same per inspection year, that is interpreted as reaching a certain limit of about 470-500 fault on average per inspection year.

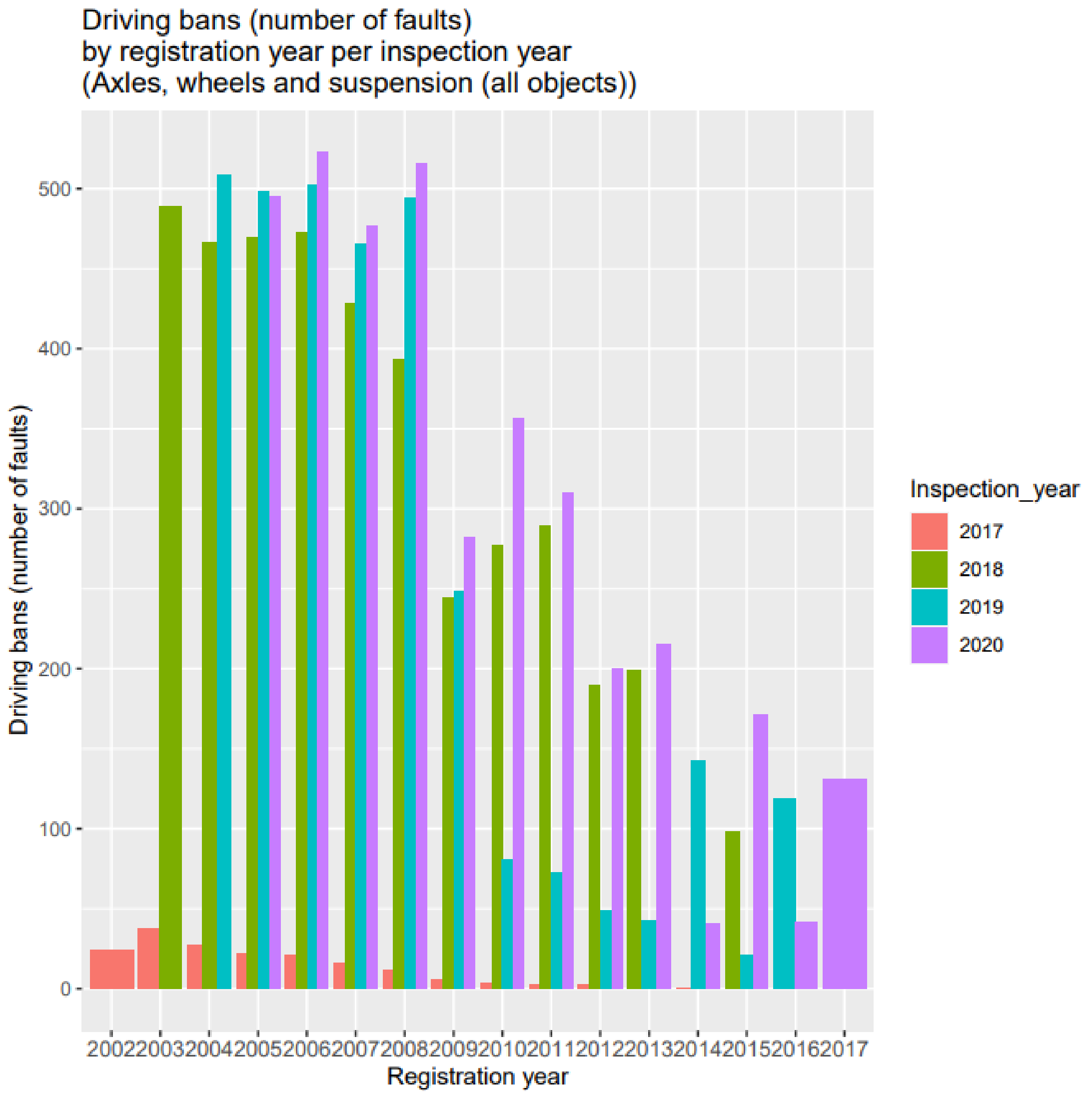

Figure 9: Number of axle hazards from PTIs (Finland)

- **Periodic brake-related inspections**

This type of inspections concerns the front and rear brakes optical checks, the stability control check and the service and parking brakes performance on the dynamometer. According to Figure 10, the brake hazards follow an exponential function with an increasing slope towards the older vehicles, and again with the critical point at about the 10th years of vehicle age since the first registration.

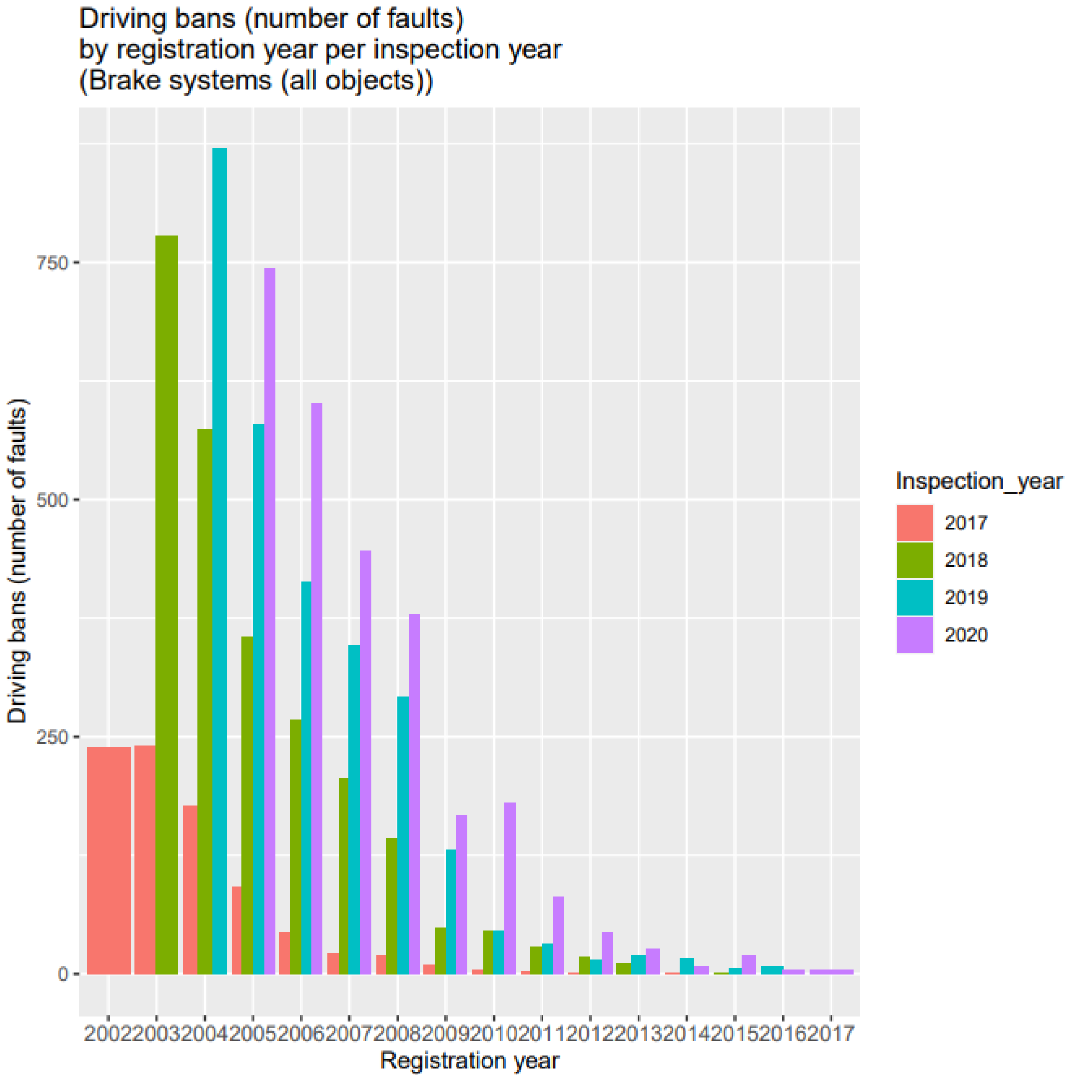

Figure 10: Number of brakes hazards from PTIs (Finland)

4.2.4. Spanish PTI data analysis

The Spanish data were made available though one of the major PTI inspection companies in the country. The data provided to the consortium had less aggregation with regard to the other two datasets, however there was not sufficient support by a local data expert to interpret all parameters and values correctly. Taking this limitation into account, the consortium analysed the data to a certain extent, so as to avoid any wrong results and conclusions. The dataset includes inspections from 1st March 2017 to 1st March 2022.

Similarly to the Finnish data, the number of fault codes for both engine and brakes increases exponentially with the age of the vehicle. The distribution of the tyre related codes follows a more linear trend, again increase with the age of the vehicle.

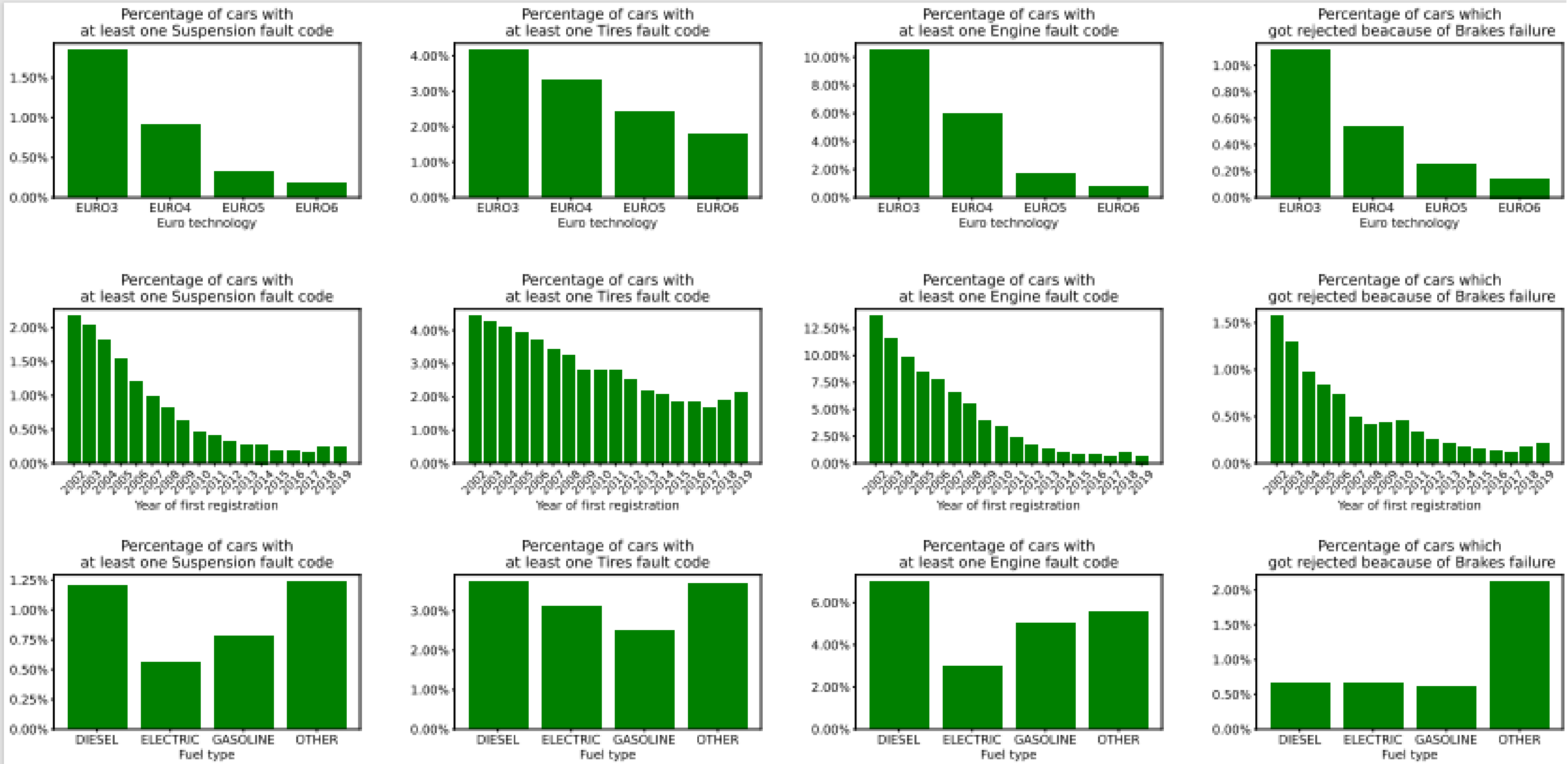

Figure 11: Percentage of cars with a least one fault code (Spain)

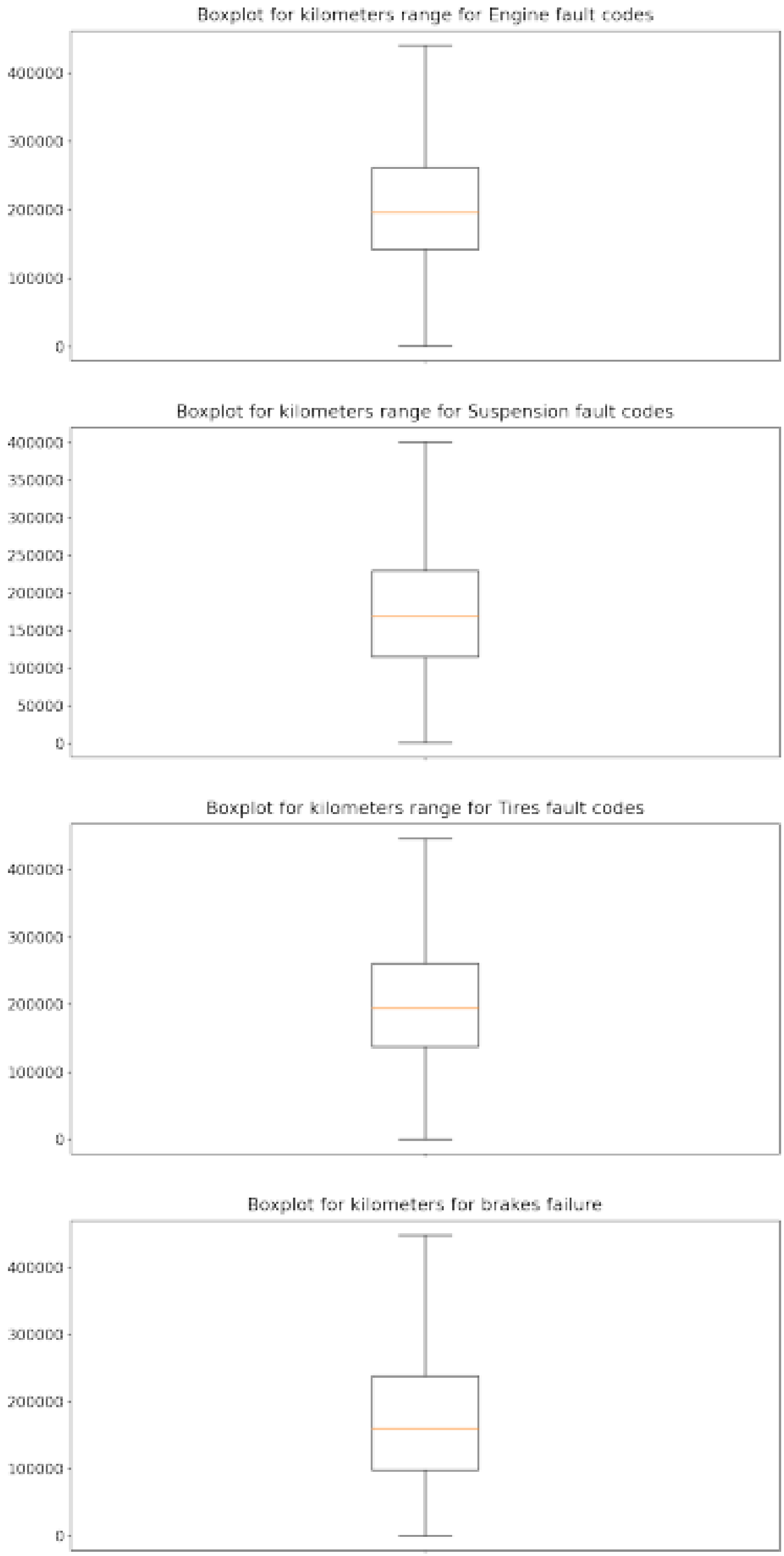

Figure 12: Kilometres driven per vehicle fault code (Spain)

In Figure 12, we see that the mean value of km driven for engine and tyre fault codes is about 200,000. For suspension and brakes, the mean values are about 170,000 km and 150,000 km respectively. The range between the first and the third quartile is about 110,000 km (ranging approximately from 140,000 – 250,000 km) in the four categories of faults.

5. Review of road vehicles tampering

5.1. Tampering Techniques and Anti-Tampering Suggestions literature review

Protection of the environment and improvement of air quality is an important objective of the European Commission. In the automotive industry, EU legislation and standards aim to reduce the emission of CO_2, NO_X and particulate matter. To that aim vehicles manufacturers have installed the EATS to the vehicles. This System is fitted to a vehicle and it is designed to reduce any (pollutant) emissions of that vehicle. Examples of such systems are the exhaust gas recirculation (EGR), the diesel particulate filter (DPF), the selective catalytic reduction (SCR), three-way catalyst (TWC), diesel oxidation catalyst (DOC), NO_X absorber, evaporative emission control system (EECS) and others. The use of EPS has 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 [22][23]. The manipulation of these systems is called tampering and it is very common for many vehicle owners to manipulate the EPS for various reasons with the most important the money savings by avoiding repair costs 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. Today, there is a big market where tampering is offered for both light- and heavy-duty vehicles and non-road mobile machinery.

In general, there are four tampering techniques that used today for manipulating the EPS:

- Electronic control unit (ECU) re-flashing
- Emulators
- Modifiers
- OBD suppressors.

ECU re-flashing: is flashing modified software in the memory of the ECU. There are different tampering ways that can be applied depending from the modification goals. Some examples of ECU re-flashing are: the deactivation of reagent dosing, deactivation of the EGR valve, removal of DPF or of the whole after-treatment unit. Another typical tampering motivation is to increase the power rating of the engine which is mostly related to performance tuning. ECU re-flashing usually requires both software and hardware changes to be made and thus it is a work that has to be made by specialized personnel. Today, there are many workshops all over the world that provide such services with expert engineers in this field. ECU re-flashing is the best way of tampering as the ECU flashing is immune to visual inspections since no observable changes are made to the tampered vehicle. In addition, another advantage is that the ECU re-flashing is completely reversible, however, the reverse procedure must be carried out by a highly experienced mechanic specialist as well. 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.

Emulators: They are devices that mostly attack the SCR system. These devices communicate with the vehicle through the CAN-bus and thus are CAN devices. The installation of the emulators is an easy process as these devices are installed in the OBD port or are attached directly to the CAN-bus. However, some types of emulators require the emulation of analogue signals like AdBlue pump pressure or temperature signals in order to successfully tamper the EPS. Tampering via emulators is common in both light and heavy-duty vehicles. As these devices need to be installed in the OBD port, the authorities have gained sufficient experience with such devices that they can be easily identified.

Modifiers: Modifiers are hardware that aim to alter the control state of an EPS. The way that these devices works is by changing individual signals that are part of emissions control system logic. There is a specific range or a certain criterion that these signals have to meet in order for the emissions control system to work effectively. The modifiers emulate these signals in such a way that the value is outside the range of normal operation and herewith deactivates a critical part of the system. An example of this technique is on SCR system in which these modifiers change the signal for the conditions that have to be met in order for the reagent to be dosed. Thus, a modified signal can set an inactive state for reagent dosing by faking the signal to a value outside the boundary for the normal base emission strategy. It is easily observed that modifiers are similar to emulators, however, they are simpler in design compared to emulators.

OBD Suppressors: In general, if a vehicle has a problem, the on-board diagnostics system usually detects the issue and generates the appropriate code that you can use to identify the issue. These codes are commonly known as DTC or diagnostic trouble codes. OBD suppressors sent specific CAN-bus messages to suppress the on-board diagnostics of the vehicle (by periodically erasing the fault code storage). For example, to remove the AdBlue refill message, or suppress power inducement deactivation. The described tampering techniques are summarised in the following Table 2.

Table 2: Tampering techniques

Tampering technique	Work description
ECU re-flashing	A workshop alters the ECU flash and checks using test drives or dyno tests if any errors or problems arise. In the end, the workshop alters the ECU code in such a way that the requested EPS is deactivated, and no MILs are activated or OBD fault codes are stored. (Mostly LDs)
Emulators	The majority of the emulators offered for HD vehicles are devices that attack the SCR system. Most of these SCR or NO_2 sensor emulators are CAN only, meaning they only communicate with the vehicle through the CAN-bus.
Modifiers	Specific hardware solutions that are simpler to emulators in design and mainly aim to alter the control state of an EPS
OBD Suppressors	These devices sent specific CAN-bus messages to suppress the onboard diagnostics of the vehicle (by periodically erasing the fault code storage).

Tampering is observed in all kind of vehicles including light-duty, heavy-duty and non-road mobile machinery (NRMM). A short description of different tampering ways for each category will be presented below:

Light-duty vehicles: The most common method of tampering in light duty vehicles is to disable the EGR or DPF system. The reason is that in case of malfunction it costs less to disable the system than repairing it. Furthermore, the lack of control on tampering and a low chance of getting caught this is the frequently chosen solution for emission control problems. An example of such tampering is a large scandal in Netherlands where the Bo-rent company has removed diesel particulate filters from their Mercedes-Benz Sprinter vans to save on maintenance costs [24]. In order to avoid similar situations, the Government of the Netherlands added an additional check in the roadworthiness test. A visual inspection is performed during the periodic inspections to check for the presence of the DPF [25]. However, with a simple visual inspection, even during PTI, the presence of the filter in the DPF system can hardly be checked and thus, this measure turned out to be ineffective. Although the visual inspection turned out to be ineffective, also other EU countries have adopted this technique for the investigation on the removal of DPF's [26][27][28][29]. Similar to the DPF removal, another common technique is the EGR tampering by removing the EGR system and making changes to the vehicle's software. Although tampering with the EGR system is illegal in Europe, normally only the fault codes of the vehicle are checked during periodic inspections [30]. Finally, the last but not least emission control system that is commonly tampering on light-duty vehicles, is the selective catalytic reduction (SCR) system. Today, 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 [31].

Heavy-duty vehicles: in case of trucks, the most common system that is tampered is the SCR. For that reason, the Europe has enhanced the road inspections which are focused in this type of tampering [32]. In addition to SCR, DPF tampering is also another common technique for heavy-duty vehicles, however, the focus of Europe on DPF tampering via inspections is less compared to SCR tampering. Some common reasons that push the owners to tamper the DPF system are that the DPF removal increases fuel efficiency, improves the engine performance, increases the service life of the engine and reduces vehicle repair costs.

Non-road mobile machinery: In general, there is not much information and data that deals with the inspection of NRMM. However, it is highly likely that especially non-road mobile machinery used for agriculture and construction work are being tampered with on a similar scale as are light-duty and heavy-duty vehicles [33].

From the above analysis, it is easily noticed that tampering of light-duty, heavy-duty as well as of NRMM is very common in many European countries. The main motivation for tampering is the avoidance of repairing cost. Thus, new innovative measures have to be taken by authorities to prevent tampering.

As far as the ECU re-flashing tampering method is concerned, the current security techniques have proven to be insufficient to prevent unauthorised flashing of an ECU. In order to prevent the re-flashing of the ECU the improvement of security has to be enhanced through encryption with secure key generation and storage, intrusion detection, code signing, authentication and data integrity checks [34].

In case of emulators, they can inject false digital signals via the CAN or via SENT protocol to the ECU. For digital signals, it is recommended to consider secure communication e.g. through message authentication. To prevent tampering of sensor and actuator signals, advanced algorithms should be developed to check the integrity of the signals. Analog sensor signals can't be protected by authentication. This means that these signals need to be checked by an advance integrity/plausibility/rationality check.

Finally, tampering abuses the vulnerability of the simple diagnostic service commands by which the OBD fault code memory with diagnostic trouble codes can be erased. A recommended anti-tampering procedure is the development of a function that aims to specifically detect and prevent only the malicious DTC (Diagnostic Trouble Code) deletion. Several options could be considered such as setting a permanent fault or checking or limiting the frequency of a DTC reset. Since current OBD does not foresee in functionality to detect and report tampering it is advised to consider requirements for dedicated tampering checks to be performed and reported at (periodic) inspections.

6. NRMM inspection, maintenance and tampering

6.1. Introduction

Non-road mobile machinery (NRMM) is a broad category covering a wide range of engine sizes for a variety of applications, including construction machinery, agricultural machinery, gardening equipment, inland waterway vessels, and locomotives, most of which run on diesel fuel. In response to the increasingly tighter emission standards, various NRMM engines have been equipped with innovative emission control technologies to effectively reduce emissions [42][61]. These emission control devices should be operated properly over the lifespan of the engine under different operating conditions to meet the required emission standards of in-use NRMMs. However, poor maintenance or tampering with these devices can lead to a significant increase in harmful air pollution. This section briefly reviews current practices to prevent excess emissions due to malfunctioning, defeat devices or tampering, using information obtained from publicly available sources and interviews with staff at several maintenance centres in Nanjing (China). Although understandably, the interviewees were reluctant to share much of the information requested due to sensitivity and confidentiality concerns, they did shed much light on how easily tampering can occur and how difficult it is for anti-tampering measures to be effective in the absence of effective regulations.

Compared with on-road vehicles, emission-control strategies for non-road mobile machinery (NRMM) have lagged years behind. NRMM emission standards were first introduced in the US in 1996, followed by the EU in 1999. Several other countries such as Japan, Canada and China tend to adopt the US and EU standards and test methods. Legislations have been set for NRMM emissions, progressively covering a wider range of machinery engines and bringing in more stringent emission limits, along with fuel quality and durability provisions. These requirements come into effect in stages, such as in the EU or China, and in tiers, such as in the US or Canada.

In the EU, after the Directive 97/68/EC for mobile machinery was first published, it has been amended several times and led to the adoption of Regulation (EU) 2016/1628 to become the first of the regulated countries to set the most stringent NRMM emission standards. Legislative emission control of new NRMM engines set emission standards for type-approval before NRMM engines are placed on the market. The standards have been progressively tightened over the past few decades. After pre-production testing of examples of the engine, type approval is granted once the corresponding standards required have been met. To represent emissions under real-world conditions, in-service monitoring was introduced for certain categories of NRMM engines to determine the difference between the test cycle and the real-world performance of the engine. Figure 13 shows the progressive tightening of NRMM emission standards for the 130-560 kW engine category in the EU, US and China. The upcoming China Stage IV emissions limits follow the EU Stage IIIB standards, but include PN limits for 37-560 kW power-rated engines and DPF is mandatory.

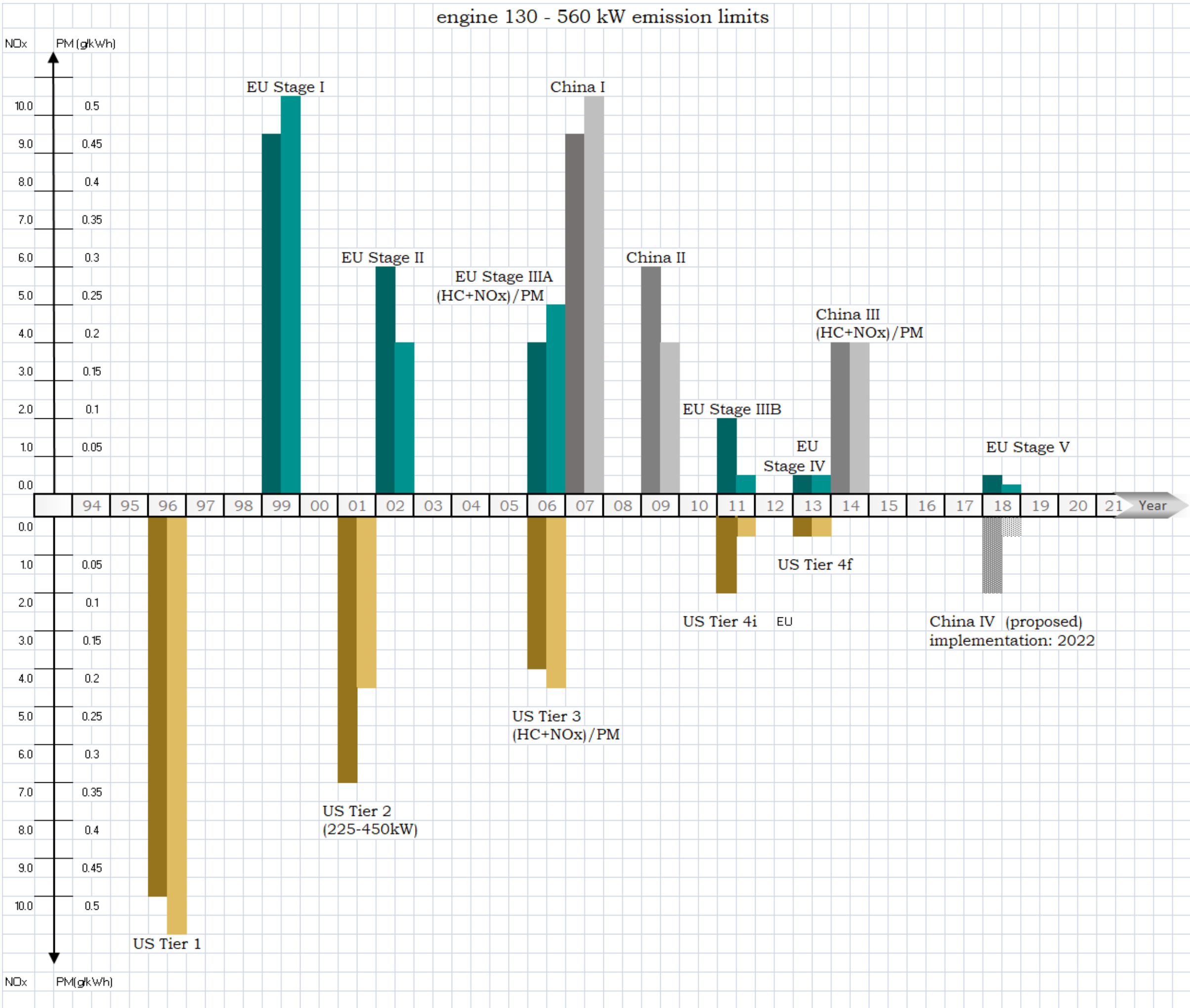

Figure 13: Examples of NRMM emission standards for NOx and PM for the 130- 560 kW power-rated engine category

The increasingly stringent regulatory requirements are pushing the boundaries of emission compliance technologies to produce ever-lower levels of exhaust pollutants, from engine design, and fuel and lubricant related technologies, to exhaust gas after-treatment. To adhere to the new standard, the use of diesel particulate filters (DPFs), exhaust gas recirculation (EGR), diesel oxidation catalysts (DOC), and/or selective catalytic reduction (SCR) systems may be required for the newly regulated engines or as retrofit systems for the existing NRMM. These technological advances have played an important role in significantly reducing emission and improving engine efficiency, while also facing challenges such as wear, ageing, and the risk of manipulation and tampering with emission control systems. Keeping these emission control components operating efficiently helps ensure compliance with emissions standards over the lifetime of a vehicle or engine.

To address these potential problems, measures to keep the emission control systems working properly include early detection of malfunctions or defects in emission control components, quickly diagnosis of them, and repair or replacement. In order for these measures to be effectively implemented, the aforementioned regulations set out requirements to be followed through enforcement mechanisms. For example, the Regulation (EU) 2016/1628, which is further reinforced by detailed requirements of Regulation (EU) 2017/654, and the administrative requirements of Regulation (EU) 2017/656, provides detailed technical requirements for preventing malfunctions that may be caused by tampering and ensuring the proper functioning of emission control systems. These regulations require the manufacturer to provide the approval authority with a description of the provisions taken to prevent tampering with, and modification of the adjustable parameters of the emission control system. Tamper resistant components, such as carburettor limiter caps, or sealing of carburettor screws or special screws not adjustable by users, are required to be included [51]. For engines regulated under 40 CFR Part 89 (Nonroad CI Engines) in the US, if the manufacturer intends to seal adjustable parameters to prevent adjustment, the method of sealing must provide both a visual and a physical deterrence to tampering [46]. These tamper resistance (or anti-tampering) techniques will make tampering more difficult, and help indicate the existence of tampering, which can be easily identified through visual inspection or other period inspection programmes.

Monitoring of NRMM emissions and compliance can facilitate effective control measures where necessary and identify high emitters that may be caused by malfunction or tampering. To ensure that the regulatory requirements are put into practice, measures include, for instance, monitoring, developing inspection and maintenance related programmes such as I/M or periodic technical inspection (PTI), and by taking advantage of technological advances.

Figure 14 outlines some examples of inspection, maintenance, anti-tampering and associated practices related to emission controls.

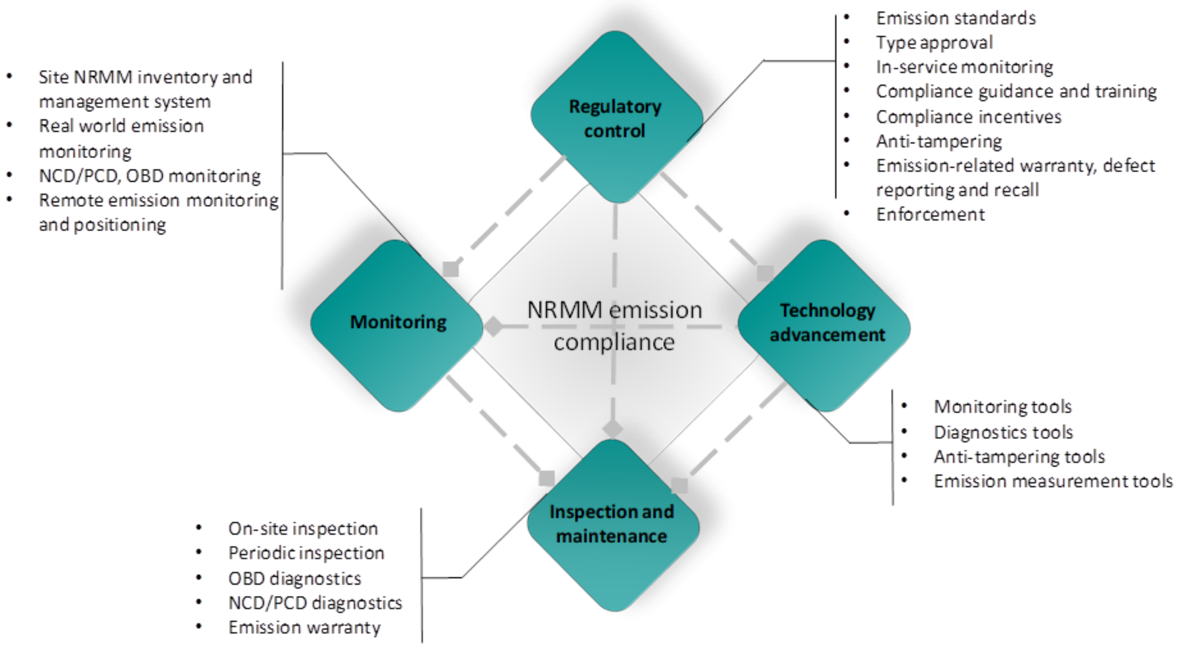

Figure 14: Examples of emission control measures and related measures through inspection, maintenance and anti-tampering

6.2. Emission measurement and monitoring

While many regulatory compliance efforts are focused on controlling emissions at the new/pre-production stage of NRMM, there are also actions in place that have an impact on emissions from the in-use NRMM fleet [57]. Real-world emission measurements provide insight into the emissions from engines. Examining the difference between certified test performance and real-world vehicles or engines emissions is essential for controlling those emissions, regardless of the cause of the performance gap: equipment failure, normal deterioration with use, or a deliberate effort to deceive regulations. If high emissions are observed, the cause and defeat device triggers can be identified through testing and data analysis.

Monitoring emissions from in-service NRMM engines (ISM) for engine manufacturers, using portable emissions measurement systems (PEMS) to measure real-world emissions, has been brought into Regulation (EU) 2016/1628 to ensure that emission performance continues during normal usage pattern, thus more closely reflecting real operating conditions. It is currently used in Stage V NRMM engines in EU countries. However, the purpose of ISM is to assess the engine design, not the impact of incorrect maintenance, tampering or faults [54].

A study using PEMS to measure emissions from tampered or malfunctioning heavy duty (HD) diesel vehicles [77] showed that at 0%, 50% and 75% load, the tested HD diesel vehicle with SCR system failure had NO_X emission factors 2.14, 2.10 and 2.47 times higher than those of the normal SCR vehicle, respectively, while urea consumption was much lower than the normal one. The measurements can be used to single out high emitters for more in-depth study of defeat devices, deterioration effects, and malfunctions, etc. Similarly, real-world emissions measurements for NRMM carried out in London [43] showed that the failure of a SCR could only be detected with PEMS if the machine did not give a warning indicating an SCR malfunction. However, the real-world emissions measurement method using PEMS is both time consuming and resource intensive [43][59][72]. A simpler, easy-to-use, and cost-effective alternative, Smart Emission Monitoring (SEMS), has been developed and used for real-world NRMM emissions measurement.

Emission controls are further enhanced by amendments or supplements of the current regulations in the EU, e.g. Regulation (EU) 2016/1628 [53]. The regulations include functional requirements of NO_X control diagnostics (NCD) and Particulate Control Diagnostics (PCD) to ensure detection of malfunction or failure of NO_X or PM control systems. In addition to the NCD/PCD requirements, the amended China IV regulations require the installation of GPS tracking systems for NRMM with engines between 37-560 kW power rating, allowing management platforms to track the location of the machinery over its lifecycle [60]. Some local environment and ecological bureaus in China are conducting DPF retrofit programmes for older vehicles and NRMM engines with high salvage values. In such programmes, local governments usually provide financial subsidies. The Shenzhen Environmental Protection Bureau issued technical regulations for DPF retrofits for on-road vehicles and NRMM, requiring each retrofitted vehicle and NRMM to be connected to a real-time remote monitoring system. Through the system, essential information including geographical location, temperature, pressure at the inlet/outlet of the DPF, and alert information will be reported to the bureau. The DPF supplier is responsible for ensuring the in-use compliance of the DPF systems within their useful life [75]. Thus, high emitters that may be caused by malfunctioning, failed emission control devices, or tampering will be able to be identified remotely.

6.3. NRMM related inspection and maintenance programmes

NRMM engines and retrofit devices require regular emission inspection and maintenance to achieve proven and durable emission reductions, and without proper maintenance, deterioration may occur, resulting in a shorter life span. Therefore, NRMM owners should have their machines serviced or maintained regularly in accordance with manufacturer's recommendations.

Commonly used policies to control emissions through regular inspection and maintenance practices, such as I/M programmes and PTI programmes, complemented by random roadside inspections and coupled with enforcement, are usually targeted at on-road vehicles because the current NRMM regulatory programmes lag behind them. They are designed to ensure the proper operation of in-use vehicle emission control systems throughout their life cycle. These programmes for road vehicles are considered to be useful for identifying certain emissions violation issues such as broken parts, poor durability of components, and inadequate maintenance [58]. Evidence from a study [45] suggests that enhanced I/M programmes in the US could reduce tailpipe Hydrocarbon (HC) emissions from light-duty fleets by 14% to 28%. For the NRMM fleet, however, there are very few examples of on-road vehicle equivalent regulation programmes that regularly track the emission compliance specifically for in-use machinery. In China a new I/M regulation for NRMM was developed and implemented to identify high-emitting engines and reduce their emissions [75]. However, according to interviews with the staff at several maintenance centres in Nanjing, as of up to now, most construction machinery is still not yet regularly maintained.

Emission warranty covers any repair, replacement, or adjustment the emission control equipment and related components fail during the warranty period. However, engine owners are responsible for performing the necessary maintenance listed in their manual. Manufacturers may deny the owner warranty coverage if a component fails due to abuse, neglect or improper maintenance, incorrect or contaminated fuel, improper cooling concentration or unapproved modifications, etc [58][65][67]. Therefore, performing all scheduled maintenance is necessary to maintain warranty coverage and ensure the validity of the emissions warranty.

Some registration programmes, such as in London, allow for on-site inspections, while providing guidance on the processes and procedures to be followed by all relevant sites to help achieve regulatory compliance [57][63].

6.4. On-site monitoring

NRMM engines have long lifecycles and, in many cases, can operate for more than 30 years. Fleet replacement takes a long time. Currently, there are many NRMM that still run on Stage III and IIIB engines. These previous Stage/Tier engines fulfil their respective emission standards at the time of type approval. However, some areas, such as the Central Activities Zone, Low Emission Zones and Opportunity Areas in London, require a higher standard for all machinery on sites, which means that many of them are non-compliant for these specified regions. If the machinery does not meet the requirements, solutions such as retrofitting, replacing the engine with a new or used one or filing a waiver application can be taken to comply with the standards. In order to track emissions compliance for on-site equipment covered by regulations, NRMM registration is essential to gather the information needed for inspections to identify non-compliant machinery.

On-site fleet registration tools have been used to register a new site or to register machinery on an existing site or to register machinery at someone else's site if an invitation is accepted. In London, a registration process is required for most NRMM operating within the London Low Emission Zone. To ensure that the registration process takes place on development sites, the site operators need to register their NRMM vehicles through an online registration tool [63][64] in order to obtain an exemption, or approval to use a retrofitted or specialist equipment [63].

Site inspections include book audits, inspection of machinery, engine emission stages and types of retrofits to check that registration information is correct and that all the requirements for the site have been fulfilled. If the machinery meets the requirements, a certificate of compliance will be issued for the site. The local authority, enforcement officers or inspectors are able to access the NRMM online register through a dedicated web form to review these registered NRMM vehicles, they will also regularly visit the site to check compliance, and the local planning department will take action if machinery is found to be in violation of the regulations. As for retrofits equipped on NRMM, copies of certificates for all retrofits on-site need to be readily accessible for inspection, either on paper or kept electronically. This ensures that the machinery on-site uses robust and high-quality retrofit systems. However, the registration records, enforced by periodic site audits, do not track the use of NRMM, nor is there any emissions monitoring to confirm the emissions performance of the engines used at the construction site.

Similarly, some cities in China have implemented a NRMM labelling programme [75]. All new and in-use NRMM are expected to be registered, and emission labels are issued upon registration. Required registration includes owner, machinery and environmental information. To ensure that road vehicles and NRMMs meet the required emission standards within the specified lifetime, national and provincial ecological and environmental authorities are in charge of monitoring and inspecting emissions of newly produced and in-use road vehicles as well as NRMM through on-site inspection and sampling tests.

Created by California's Air Resources Board (CARB) as an on-line reporting system (DOORS) [57], NRMM fleet owners must annually fill out information about the equipment they own to track the NRMM emissions compliance covered by the relevant regulations. For retrofitted engines, the system automatically calculates the adjusted emissions rating. Once the NRMM is registered in DOORS, the fleet owner will receive an equipment identification number from CARB, which is checked versus database information at initial on-site inspection. CARB does not use this database to track how or where NRMMs are used.

Site NRMM inventory and management tools are used to centralize storage of all relevant NRMM emissions information and documentation to facilitate enforcement of regulations [63]. For example, in London's Low Emission Zone (LEZ), the information provided by subcontractors will be documented centrally by the primary contractor in the site NRMM inventory spreadsheet, including actions taken when non-compliant NRMM are identified on site. All the NRMM are expected to be regularly serviced; service/maintenance logs are required to be kept on-site for scrutiny by local authority officers.

6.5. NRMM diagnostic tools

For the EU Stage V NRMM engines, a NO_X control diagnostic (NCD) system and a particulate control diagnostic (PCD) system for NO_X and PM control respectively are required under Regulation (EU) 2016/1628. In addition, when the NO_X control malfunction or a PM control malfunction (possibly due to tampering) is detected, the warning or inducement torque reduction systems will be activated.

The on-board diagnostic (OBD) system allows the vehicle's computer system to communicate with external hardware and software tools to detect and diagnose problems and to assist a technician in detecting and repairing malfunctions, and has proven to be powerful tools for identifying in-use compliance issues. Recent study [68] has shown that OBD is reliable in monitoring NRMM engine emissions and can be widely used in NRMM sector. Integration of OBD in emission control schemes, such as I/M programmes, improves test accuracy and credibility. However, current OBD regulations apply to road vehicles, there is no OBD requirement for NRMM engines, and it is not yet widely used in NRMM.

6.6. Periodic in-use testing

In addition to safety testing, Periodic Technical Inspections (PTI) also include checking exhaust emissions. It is a regulatory measure in Europe and some other countries to promote road safety and potentially detect excessive emissions from road vehicles that may be caused by technical problems or tampering with emission control devices. Current PTIs monitor smoke emissions and are effective for older diesel vehicles that produce high emissions. Modern diesel vehicles are fitted with DPF, SCR and other high-performance technologies that can eliminate more than 95% NO_X and PM emissions. These new technologies can fail by ageing, poisoning or manipulation [74]. For emission control components, such as DPF, EGR and/or SCR inspections in most inspection and maintenance I/M or PTI programmes for diesel engines that rely mainly on visual inspection and/or a tailpipe measurement of opacity for vehicle emission, it is difficult to tell by observation alone whether a device has been removed when Ministry of Transport (MOT)/PTI-friendly and hard-to-notice services are used on these components. The vehicle's software can be modified to prevent the occurrence of fault codes stored for these devices. Moreover, as the test methods are not sensitive enough to measure emissions of fine particulate (PM2.5) and NO_X from modern vehicles, which are invisible and smoke emission levels are very low. Therefore, a new PTI is proposed, which involves the use of a particle counting to identify the removal/tampering, disabling or failure of DPF devices or other DPF malfunctions using a relatively inexpensive particle counting device. Checking particle filters by measuring the number of soot particles in diesel exhaust with a particle counter was first introduced in Switzerland for the inspection of construction machinery. From 1 July 2022, the new PTI test with particle counter will be introduced in the Netherlands to check the particulate filters of diesel vehicles [44].

Most EU stage IIIB and IV NRMMs are not equipped with a DPF because their corresponding PM limits can be met without the use of a DPF. The introduction of PN limits in EU Stage V makes it inevitable that DPF technology will be used for regulated NRMM, and will be a requirement for the upcoming Chinese Stage IV emission standards. Engines with previous standards can benefit from the DPF technology by retrofitting the engines with approved DPF devices to bring them up to the required standard. Countries such as Switzerland or some regions in Austria and Germany require old NRMM engines at construction sites to be equipped with a certified DPF to meet the required standards.

The Swiss government enacted the Ordinance on Air Pollution Control (OAPC), the first legislation worldwide, to effectively limit PN emissions from NRMM used on construction sites for machine homologation and periodic on-site emission control, which effectively brings PN emission testing from the test bench environment into the field. All NRMM vehicles equipped with DPFs are subject to a biannual field inspection and must be tested and certified for their PN emission [36]. Tampering with the DPF will also become more difficult due to PN-based period inspection tests, thus ensuring that the DPF continues to function throughout the life of the device [37][44].

However at present, in most cases, there are no periodic inspections of NRMM. NRMM engines that have undergone type approval testing prior to production have not been inspected for proper emission levels after years of operation [71], thus the most important variable for the emission control and diagnostic systems to be effective is for operators to repair the engine when the diagnostic light comes on.

6.7. Tampering

Technological advances in engine design, emission control components and fuel formulation have made it possible to meet increasingly stringent emission requirements, while facing the challenge of increased operating, repairing, or maintenance costs, fuel economy penalty, and limited engine power. Various forms of tampering including hardware and software have emerged to avoid the need to service and maintain emission control related components, to increase engine power, and to reduce fuel costs. Common approaches of such tampering involve unauthorised removal, deactivation, alteration, or in any way rendering them ineffective for emission control devices, reprogramming engine software to eliminate diagnostic trouble codes, etc. This allows engines to operate without emissions controls, and ultimately cause excessive toxic exhaust emissions. In response to widespread tampering, many efforts have been made to prevent tampering with emission control systems, ranging from regulatory and policy development to technological advances to monitor, detect, and eliminate tampering.

6.8. Tampering with emission control systems, benefit and their impact

As emission limits tighten, emission control technologies, such as in-cylinder approach aiming to limit pollutant formation through developments and modifications of the fuel injection and air handling systems and after-treatment systems (Figure 15) for removing pollutants from the exhaust gas stream [42], many of which were first developed for on-road diesel engines, have been introduced into NRMM engines. Diesel engines used in NRMM applications are available in a wide range of power ratings, from below 8 kW to over 560 kW power rating. Emission control strategies and technologies vary significantly by engine power categories under different emission requirements [42]. Table 3 shows an overview of emission control technologies used in NRMM.

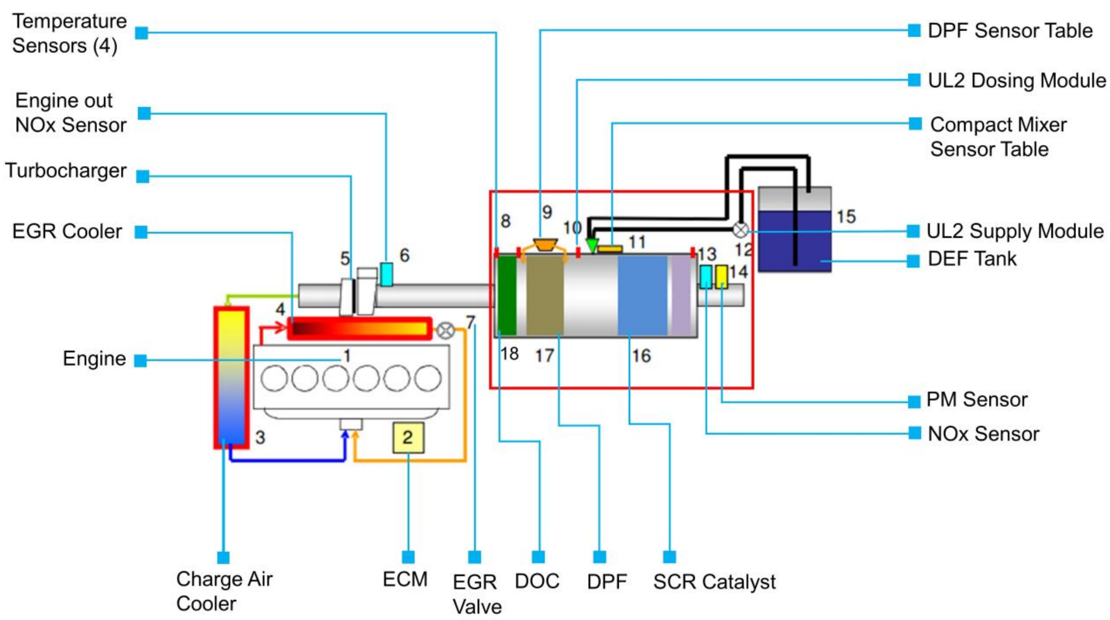

Figure 15: Example of after-treatment system, Source from [41]

Table 3: Overview of emission control technologies used in NRMM (adapted from [42][61]

	Name Technology	Short name	Pollutants targeted	Description
In-cylinder technologies - fuel injection system	Fuel injection	FIE	PM, NOx, HC, CO	Increased injection pressure promotes fuel atomization and better air and fuel mixing, resulting in improved combustion efficiency.
	Rate of fuel injection, multiple injections	FIE	NOx	Fine tuning of fuel injection by varying rate of injection or using multiple injections. Multiple injection strategies require electronically controlled high-pressure unit injectors or common rail injection systems
	Fuel injection timing advanced	FIE	PM, CO, HC	Advanced or delayed fuel injection to tune combustion process. Advanced timing increases combustion pressures and temperatures resulting in improved fuel efficiency. Delayed fuel injection timing reduces NOx emissions at
	Fuel injection timing delayed	FIE	NOx	
In-cylinder technologies - air handling	Turbocharger	TC	PM, CO, HC	Compressor used to boost intake air pressure. Wastegated, multiple-stage, and variable geometry turbochargers developed to improve turbocharger performance over a broad range of engine operating conditions.
	Charge air cooling		NOx	Heat exchanger used to lower temperature of gases entering combustion chamber to reduce peak combustion temperatures
	Exhaust gas circulation	EGR	NOx	Portion of exhaust gas mixed with intake air to serve as diluent and reduce peak combustion temperatures. In internal EGR (iEGR) residual exhaust is retained within the combustion chamber, and external high pressure loop systems where exhaust gas is routed from upstream of the turbocharger exhaust turbine to the intake manifold. Cooled EGR (cEGR) systems incorporate a cooler to increase system NOx reduction efficiencies.
Aftertreatment devices	Diesel oxidation catalyst	DOC	PM, HC, CO	Flow-through catalytic converter composed of a monolith honeycomb substrate coated with a platinum group metal catalyst
	Diesel particulate filter	DPF	PM (organic soluble)	Wall-flow filtration device. Filters are regenerated using active and/or passive regeneration methods to oxidize and remove collected particles.
	Selective catalytic reduction	SCR	NOx	Catalytic reduction of NO and NO2 to N2 and H2O using ammonia as reducing agent. Catalysts types include vanadium, iron-exchanged zeolite, and copper-exchanged zeolite. Catalysts vary in effective temperature ranges, exhaust NO2/ NOx sensitivity, and sulfur tolerance. Ammonia is generated from the decomposition of a urea solution, which is referred to as diesel exhaust fluid in the United States and by the brand name AdBlue in Europe.
	Ammonia slip catalyst	ASC	NH	Oxidation catalyst used for the control of ammonia passing through the SCR system.

These efficient emission removal technologies allow NRMM to meet its corresponding legislative requirements, while they become targets for tampering, often to improve performance or reduce maintenance costs. Common emission control devices tampered with include EGR, DOC, DPF and SCR or a combination thereof, which are phased into NRMM vehicles to regulate emissions based on their related emission limit requirements, as shown in Figure 16.

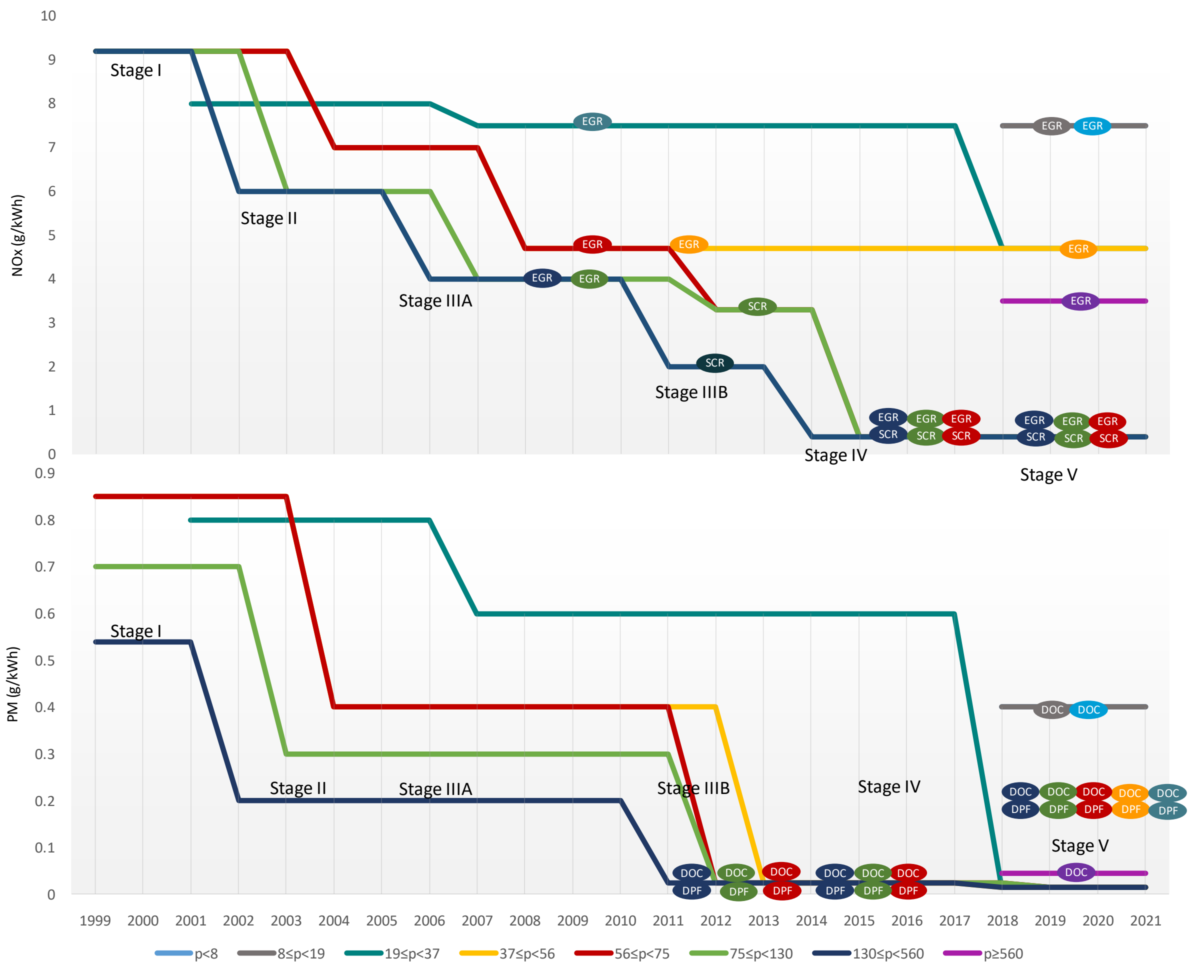

Figure 16: The EU NRMM NO_x and PM limits by engine power, incorporated with EGR and after-treatment devices

The devices have their own design life, but this can vary greatly depending on the use of the vehicle/equipment, the condition of the engine and maintenance. For example, DPFs are highly effective at capturing soot particles from diesel exhaust. To remove particulates from the filter to restore its soot collection capacity, the particulates or deposits are burned into smaller, finer soot through a regeneration process. Over time, the fine soot content accumulates to the point where regeneration cycles can no longer be taking place, which can lead to exceeding the emission limits and may require a replacement of the device. Regular maintenance, such as emptying the filter in the DPF system, can prevent soot build-ups to avoid costly replacement and prolong its lifespan.

However, removing or tampering with the emission control devices from the exhaust engine is considered the most cost-effective solution to the problems, avoiding maintenance, repair and replacement costs, while manufacturers and service providers can profit from the production, sale, and installation of aftermarket defeat devices. As a consequence, there are many commercial services or individuals worldwide who have been trying to defeat the required emission controls, which could have a very significant impact on NRMM emissions.

Table 4: Examples of tampering with EGR, DPF and SCR, issues and motives

Tampered component/system	Exhaust Gas Recirculation (EGR) valves	Diesel Particulate Filter (DPF)	Selective Catalytic Reduction (SCR)
Functionality of component/system	allows exhaust gases to be recirculated back into the engine intake manifold to help reduce NOx emission.	traps the particles from exhaust, preventing them from being released into the atmosphere.	injects a liquid-reductant agent through a special catalyst into the exhaust stream of a diesel engine, converting nitrogen oxides into nitrogen, water and tiny amounts of CO2, achieving a NOx reduction of up to 90%.
Frequent problems with related devices	over time, the EGR valve will wear and tear; becoming clogged from a gradually build-up of oil residue and exhaust soot, causing engine stalling at idle, rough idle, detonation; EGR gases cause engine oil to become contaminated rapidly, resulting in more frequent oil changes; reduced efficiency; increased fuel consumption, etc.	the DPF can become blocked with a residue of ash from the soot trapped in the filter being burnt off in a regeneration process; too dirty to function to its maximum efficiency, causing higher diesel fuel consumption, lack of power or torque;leaking injectors and engines burning oil can significantly reduce the life of the DPF; deterioration of DPF, etc.	Wearing; clogging of the urea injection nozzle causing under-dosing of urea, etc.
Defeat device /tampering example	remove, delete/disable, e.g. blocking off the gas tube with a baffle/blanking plate or an EGR delete kit; EGR emulator allowing to electronically disable EGR flow, without physically blocking off the EGR pipe	remove/cut open; drilling/perforation inside the DPF to allow the exhaust gases to flow more freely through the honeycomb structure; disable hardware from the ECU by the remapping process, etc.	disconnectting the circui; removing the fuse from SCR system; SCR /ECU emulator to disable SCR system,etc.
Example of tampering services	sale and installation of EGR delete kits; teach and demonstrate how to delete EGR on the web; remove the structures and falt codes from the ECU software etc.	sale and installation of DPF delete kits; teach how to delete DPF on the web; advertise DPF removal to make it look like a viable solution to DPF blockage, etc.	advertising AdBlue removal, delete and bypass services for NRMM on the web;
Reason of tampering	reduce costs and time of necessary maintenance or repairing and replacement; improve the performance and fuel economy of an engine	reduce costs and time of necessary maintenance or replacement of the filter; improve fuel economy	reduce costs and time of necessary maintenance or repairing and replacement; avoid the need to replenish urea solutions (AdBlue, DFF)
Effects of tampering	allows more harmful pollutants to enter into the environment, e.g higher amount of NOx; in the long run, it will jeopardize the engine system;	affects reliability of the devices; PM increase greatly	result in a higher NOx emissions from vehicle/engine than non-SCR.
Possible methods to identify the likely emission control malfunctions /tampering	visible modifications or replacement of physical change e.g. inserted blanking plates, modify the original design; real emission measurement tool, e.g. Mini-PEMS; diagnostic tools such as NCD for NOx control malfuction; PCD for particulate control malfunction.	visible signs of physical change of the filter, e.g. cut open or missing filter; differential pressure sensor; temperature sensor, e.g. if, based on the engine operating conditions, no significant temperature rise is detected throughout the DPF during regeneration, it is considered to have been tampered with.	visible signs of reagent tank gauge, soldered wire, or modified wires in harness, etc. ; real emission measurement tools, e.g. Mini-PEMS; using diagnostic techniques base on sensor values, etc..

Tampering with emission control systems has become a growing problem [40][47]. In general, it can take two basic forms to allow a vehicle or engine to operate without emission controls, i.e., removing hardware or installing aftermarket defeat devices, and altering or manipulating software. For example, Adblue is a diesel exhaust fluid used in vehicles/engines with SCR systems to reduce NO_X emissions. It must be constantly topped-up as most of these engines are designed not to restart if it runs out. ECU reprogramming can be used to electronically disable the AdBlue system while eliminating the associated dashboard lights and warning messages to avoid problems caused by AdBlue. Since the removal of emission control components such as EGR/DPF in many countries is an offence and drivers are likely to be fined mostly for road vehicles only, many services are available and advertised to bypass or eliminate the effectiveness of NRMM emission control system. Examples include the sale and installation of EGR delete kits, DPF delete kits and/or and engine computer reprogramming for NRMM engines.

Table 2 shows common targets for tampering, such as EGR, SCR, DPF, and lists some of the problems caused related to these components, as well as the motivation, types and impact of tampering, and some possible measures to detect tampering.

6.9. Preventing tampering

Emissions from engines installed in NRMM have been regulated through emission limits. The regulation sets out the procedures of engine manufacturers have to follow in order to obtain type - approval of their engines before they are placed on the market. A variety of emission control technologies have been equipped to reduce emissions to the levels required while ensuring that the engines pass type-approval emission testing. However, the effectiveness of these systems could be compromised if they are tampered with or removed, or if aftermarket parts designed to defeat those controls are installed. Measures to avoid tampering or make tampering more difficult include providing the right information, such as marking of OEM and self-diagnostic software features; access to the systems, such as visual access, mechanical access, sensors' readings and actuators operation, etc. Anti-tuning control unit, which makes tampering more difficult, would register all the activities performed and can be read, but not manipulated [40].

Some tampering activities can be identified via existing monitoring systems. For example, a DPF system contains pressure and temperature sensors for monitoring the soot levels and overheating protection respectively. They can also be used to identify tampering by destroying and removing of DPFs or by drilling/perforation holes inside the DPF [70].

In addition, various legislative and regulatory efforts have been made to help limit tampering with them. Examples of current legislation include the following:

- **Regulations on tamper resistance of emission control systems**

  EU regulation 2016/1628 requires "*Engine types and engine families shall be designed and fitted with emission control strategies in such a way as to prevent tampering to the extent possible*"

  This is further supplemented by Delegated Regulation 2017/654 [51], which provides more detailed technical requirements relating to NO_X and PM control strategies for different NRMM engine categories and the methods to demonstrate these strategies, including diagnostic and maintenance of the control systems, and monitoring for failures that may be attributed to tampering. In addition, Regulation 2017/656 sets out administrative requirements on the protection of ECUs in accordance with Regulation (EU) 2016/1628 [52]. These protections are intended to prevent tampering and to ensure that the required after-treatment systems perform as designed.

  NCD and PCD are diagnostic systems on-board the engine that are capable of detecting NO_X and PM control malfunctions, respectively, and identifying the likely cause of the malfunctions by storing the information in computer memory and/or communicating that information off-board [51]. Once a failure and/or malfunction of NO_X control is detected, the operator warning and/or inducement torque reduction functions are activated [60]. For example, an operator warning system required for NCD should be activated in the event of a low reagent level, incorrect reagent quality, dosing interruption or a malfunction. This includes one or more lamps or a message display system to alert the operator and show the time remaining before activation of inducements, the amount of torque reduction, etc., to indicate the cause of the malfunction (e.g. AdBlue dosing malfunction) and the need for emergency repairs. If ignored or not resolved within the predetermined engine operating time, the operator inducement system will be activated, resulting in restricted performance or effective disablement of NRMM operation, depending on the severity of the fault discovered by the diagnose function. For an NCD system, total number and duration of all incidents of engine operation with inadequate reagent injection or quality are required to be stored in non-volatile electronic memory or counters for national inspection authorities to read with a scan tool. Similarly, for a PCD system, a warning system is activated once a particulate control malfunction is detected. PCD systems also include non-volatile computer memory or counters to store incidents of engine operation with a Diagnostic Trouble Code (DTC) confirmed and active in a manner to ensure that the information cannot be intentionally deleted [51]. These detailed technical requirements help prevent tampering by making emission control systems difficult to tamper with.

In the United States, both EPA and CARB have an emission defect reporting programme to help reduce in-use emissions by identifying and replacing defective emission control components. As manufacturers are required to guarantee some emission control components in their new engines for a minimum number of years of use or operating hours of NRMM engines to protect owners from repair costs incurred during the warranty period, these warranty claims, along with other information, are used by manufacturers to investigate possible defects. Under the CARB's emission defect reporting program, manufactures are required to review warranty claim records for each engine family or test group on a quarterly basis. If a larger share or number of warranty claims are caused by a specific emissions problem, those engine families, vehicle or test groups are subject to recall [58][62]. However, the manufacturer will not honour the engine's warranty if the engine's emissions controls have been tampered with.

Although warranties provide a degree of protection against tampering, it is still possible to avoid invalidating them through some tampering attempts. For example, by removing EGR operation from an ECU without physically removing the EGR valve from the engine, there is no visible indication that this has been done and therefore does not void the warranty.

In addition to the tampering resistant requirements for manufacturers, various tamper-prohibiting are also included in the regulations to ensure that vehicles and engines remain compliant with their respective requirements at type approval over their useful life. For example, the US Clean Air Act (CAA) 203(a)(3)(B) prohibits *the manufacturing or selling, or offering to sell, or installing, any part or component intended for use with, or as part of, any motor vehicle or motor vehicle engine where a principal effect of the part or component is to bypass, defeat, or render inoperative any device or element of design installed on or in a motor vehicle engine, and where the person knows or should know that such part or component is being offered for sale or is being installed for such use* [62]. The EPA's prohibition against defeat devices also applies to NRMM products.

- **Anti-tampering enforcement**

Despite legislative efforts, concerns still remain that the regulated entities continue to ignore the prohibitions against tampering, and many individuals and companies are still producing, selling and installing aftermarket defeat devices.

Following an EPA study [47], which revealed tampering with diesel emissions systems and detailed the removal of emission control devices from more than 550,000 diesel trucks over the past decade, resulting in hundreds of thousands of tons of excess emissions, the EPA issued a revised tampering policy that also applies to NRMM. This involves civil enforcement of the CAA for tampered and aftermarket defeat devices. For example, under the regulation, those who sell or install devices to defeat emission controls can be fined up to $48,192 (for manufacturers and dealers) or $4,819 (for individuals) for each act of tampering, and $4,819 for each aftermarket defeat device [48]. Moreover, many states have online portals where citizens can report violations of the CAA regulations prohibiting tampering and aftermarket defeat devices.

As a result of the enforcement strategies, the CARB and EPA has been actively enforcing their anti-tampering laws and have recently reached settlements with several dealerships and body shops that tampered with or installed deficient aftermarket emission control devices [50]. EPA's current National Compliance Initiative (NCI fy2020 - 2023), which focuses on stopping the manufacture, sale and installation of defeat devices on vehicles and NRMM engines, has addressed serious violations through enforcement actions that have achieved measurable pollutant reductions and improving air quality, resolving 31 civil enforcement cases for tampering and aftermarket defeat devices in the first year (year 2020) [49].

Under the UK government's proposals, new offences would be created to prevent modifications that negatively impact the environment, such as supplying, installation and/or advertising a tampered product for NRMM or road vehicles in order to strengthen enforcement capacities in the area [73].

7. Assessment of the effect of tampering solutions on HDV tail-pipe emissions

7.1. Action background and description

This chapter describes experimental studies that were performed to demonstrate the effects of tampering, especially on commercial vehicles, which is the most common example. Specifically, in this work, the effect of different Engine After-treatment System (EATS) tampering methods and reprogramming (also known as remapping) of engine control unit (ECU) software in heavy duty vehicle (HDV) applications. The aim of the work was to study the direct effect in respect to changes in exhaust emissions and vehicle performance by testing typical tampering and ECU reprogramming methods, thus enabling to increase the knowledge of the potential gains and penalties obtained with the different vehicle modifications. The data of this study was also analysed for improving the knowledge regarding detection of EATS tampering and ECU reprogramming.

7.2. Test equipment and testing methodology

The tests conducted in this work were executed in VTT's vehicle laboratory in Espoo, Finland. For this study, a chassis dynamometer specifically designed for heavy-duty applications was utilised. The tests were conducted by studying a city bus that underwent several ECU software versions/EATS tampering configurations between the measurements. Each modification/configuration (e.g. ECU software reprogramming or EATS removal) the emissions were measured during several consecutive WHVC drive cycles. Additionally, acceleration tests to demonstrate the maximum power output of the vehicle driveline with each software version were carried out. The main focus in this study was on the exhaust emission components CO_2, CO, HC, NO_X and particulates (PN, PM). The effects of different software versions and other tampering actions on fuel consumption were also demonstrated.

The emission measurement system in the VTT test laboratory consist of a CVS-based emission sampling system, where the exhaust emissions are introduced and diluted into a full flow dilution tunnel, enabling sampling of exhaust emissions without the need to separately measure the engine exhaust mass flow. In addition to CVS sampling, a Fourier-transform infrared spectroscopy (FTIR) gas analyser was used for measuring upstream EATS exhaust emissions in all conditions. The overview of the test cell and the test bench instrumentation with applicable analysers is presented in Figure 17.

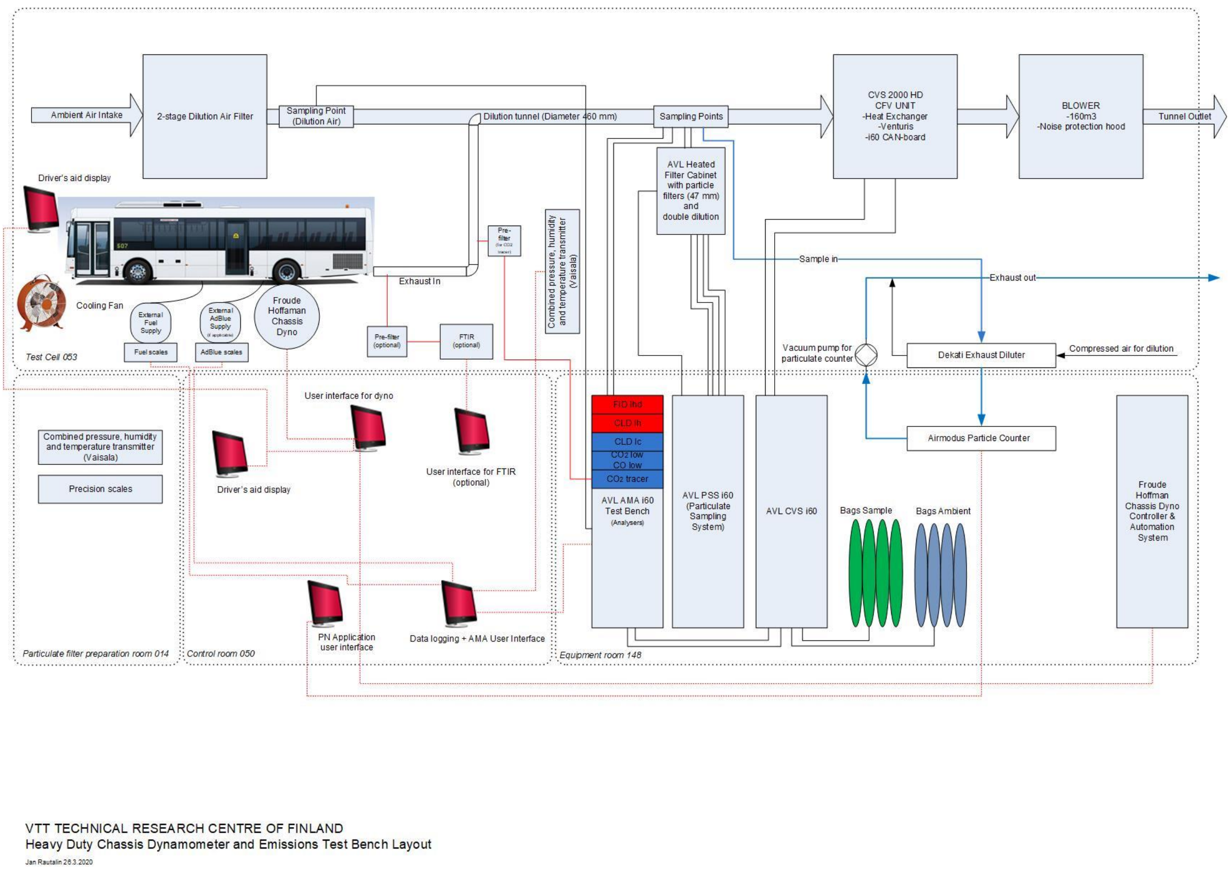

Figure 17: Overview of VTT heavy-duty test cell and test bench instrumentation

The following equipment was used in the measurements:

Heavy-duty chassis dynamometer

Manufacturer: FroudeConsine Ltd
Maximum power: ± 300 kW (54 – 110 km/h)
Excess power capacity: 120 % / 300 s
Maximum traction force: ± 20 000 N (0 – 54 km/h)
Inertia simulation range: 2 500 – 60 000 kg
Diameter of the rolls: 2 500 mm
Maximum axle load: 20 000 kg

Emission sampling and dilution system:

Manufacturer: Pierburg AG
CVS: CVS-12-WT (AVL CVS i60)
Multiple (3) critical flow venturi system
Tunnel flow: 30 – 120 m^3/min
Dilution tunnel: VT-458
Particle collector: AVL PSS i60

Emission analyser system: AVL AMA i60, with the following analysers:

FID LHD, THC: 0 – 1 000 ppm (C3)
FID LHD, CH_4: 0 – 1 000 ppm (C1)
CLD LHD SLQ, NO_X: 0 – 1 000 ppm
CLD LHD SLQ, NO: 0 – 1 000 ppm
IRD L, CO_2: 0 – 6 %
IRD L ,CO: 0 – 5 000 ppm
IRD H, CO_2 tracer: 0 – 20 %

Fuel scale:

Manufacturer: Sartorius Combics 1
Model: Combics 1, CW1P1-60FE-I
Weighting capacity: 60 kg
Resolution: 2 g
Calibration interval: 1 year

Fourier Transformation Infra-Red (FTIR): Gasmet Cr-2000

Temperature controlled sample cell (180 °C)
Liquid nitrogen cooled MCT detector
Resolution: 8 cm^{-1}
Path length: 2.0 m
Sample cell volume: 0.22 l
N2O detection limit: 4 ppm
NH3 detection limit: 3 ppm

Butanol Condensation Particle Counter (bCPC): Airmodus A23

Particle size range: 7 nm – > 1 µm
Particle concentration: 0 – 100 000 particles per cubic centimetre
Response time: 3 s
Sampling speed: 1 Hz
Inlet flowrate: 1 l/min

The World Harmonised Vehicle Cycle (WHVC) was used as the primary driving cycle in these tests. WHVC is a chassis dynamometer test cycle derived from the HDV type approval engine test cycle, World Harmonised Transient Cycle (WHTC). Meanwhile the WHVC tests cycle replicates the WHTC profile, the two tests are not directly identical, and due to the addition of the powertrain and vehicle factors, are not completely comparable with each other. However, WHVC is occasionally used for expressing directional vehicle behaviour in respect to vehicle emission performance (compared to type approval values). The speed profile of the WHVC cycle is presented in Figure 18. Each individual test sequence consisted of one “cold start” WHVC cycle followed by two consecutive “hot start” WHVC cycles. The two hot start cycles were driven after a 10 minutes pause following the end on the cold start cycle. There was no pause between the hot cycles, thus enabling the drivetrain to maintain its operational temperature between the hot start tests. Cold start in this context means that the vehicle/engine was soaked overnight in the test cell prior to each test sequence. However, in order to build up sufficient air pressure for the braking system the engine had to be started to idle before the beginning of the drive cycle. This took usually took 2 - 3 minutes.

After these three WHVC cycles the maximum power output from the driveline was measured by executing acceleration tests.

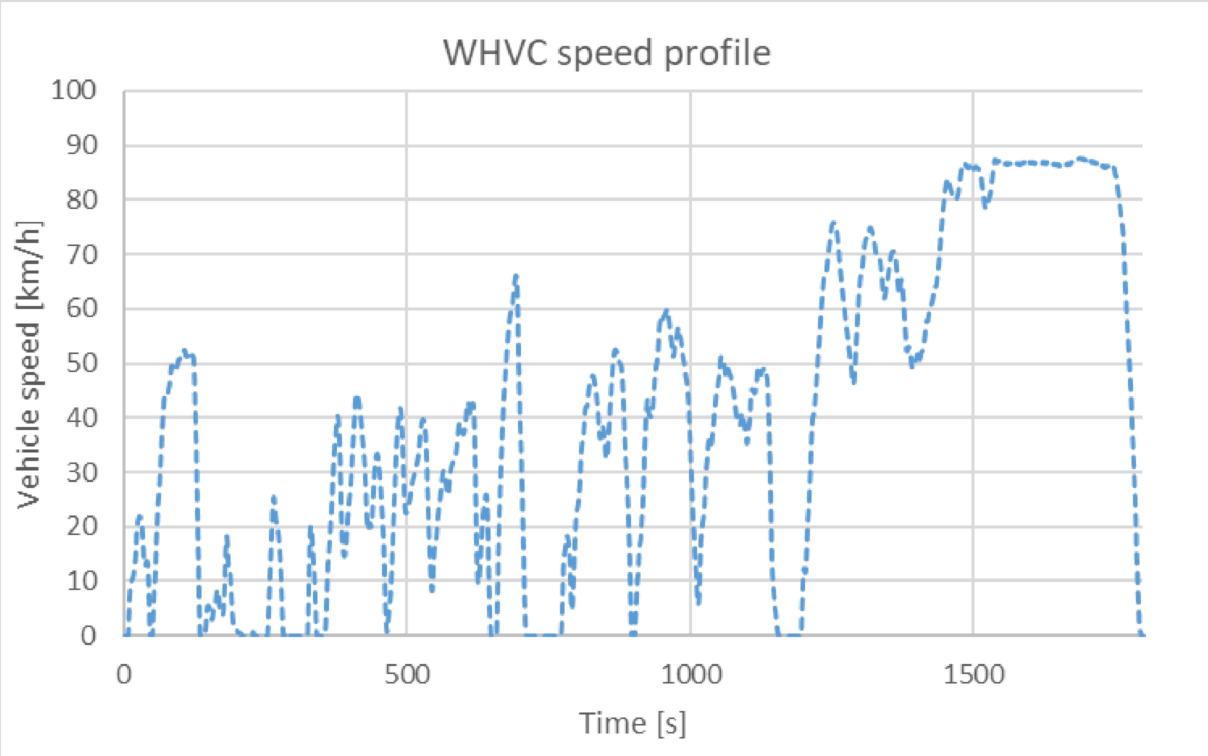

Figure 18: Vehicle speed plot during World Harmonised Vehicle Cycle

7.3. Acceleration tests

After the WHVC emission tests were successfully carried out, the peak power output from the driveline was measured for each test configuration by executing acceleration tests. The measurements were done shortly after the emission tests so the engine and driveline were properly warmed up. Because the test vehicle was equipped with a fully automatic gearbox, the driver had no control over the gear selection or shifting points. This is not an optimal situation for acceleration measurements, although it ensures a good repeatability compared to manual shifting. The acceleration tests were conducted by accelerating the vehicle with full throttle from standstill until the vehicle speed limiter was met (set to 85 km/h). The acceleration tests were done three times consecutively. The lowest and highest values of each attempt were dropped and the remaining results were accounted as valid acceleration tests for further analysis.

7.4. Test vehicle and test configurations

Experimental tests on the dynamometer were executed with a model year 2010 three-axle city bus with a 12 litre, six-cylinder diesel engine with a six-speed automatic gearbox. The bus was originally type approved as an EEV vehicle. However, the vehicle was later retrofitted with a more modern EATS (by Proventia) that now consists of a diesel oxidation catalyst (DOC), a diesel particulate filter (DPF) and a selective catalytic reduction system (SCR). The retrofitting was performed initially for the bus in order to meet the emission requirements set by the Helsinki regional transport. The predominant vehicle EATS layout is comparable and similar to later Euro VI versions of the same engine family. The vehicle odometer reading in the beginning of the first test was 910,000 km. The unladen weight of the test vehicle was 15,100 kg. The dynamometer load parameters were set to emulate 50% payload of the vehicle and are shown in Table 5.

Table 5: Settings used on the VTT chassis dynamometer

Inertia [kg]	f0 [N]	f1 [N/(km/h)]	f2 [N/(km/h)^2]
19725	500	6.001	0.1458

There were few reasons to choose this type of engine for this test series. Firstly, the engine has quite large displacement compared to the maximum power output, thus offering good potential for demonstrating the effect of ECU reprogramming (e.g. increasing the maximum power output). The brand of the test vehicle (Volvo) was known to be common in the Nordic countries, therefore making the market potential for ECU reprogramming or EATS tampering relatively feasible. Secondly this engine represents and simulates a generally common engine family widely used (vertically installed in trucks) in other HD applications throughout Europe. Furthermore, the EATS system applied in the test vehicle was seen to cover elements typically found in Euro V and IV applications and was seen as a good example to demonstrate the effect of EATS tampering. The test vehicle placed in the test cell is portrayed in Figure 19.

In order to be able to implement various ECU software versions, a local independent third-party specialist was commissioned as consultant for producing the different ECU versions. The specialist in question was found through the surveys aimed for software tuning centres conducted earlier in the work related to T4.2. The company that assisted with the reprogramming was the only operator in Finland responding to the survey, and thus being the only operator found capable of flexible ECU reprogramming of HDVs to a significant extent.

In addition to OEM ECU program, two different ECU program versions was adapted to the vehicle. The reprogramming was conducted through reconfiguring the ECU software using a dedicated flash-tool designed for aftermarket software modifications. In practice, the updated ECU flash replaced the complete data set of the original ECU. Using this method, no error codes, nor any traces of ECU reprogramming could be found for any of the modifications. A copy of the original ECU program was captured as a backup prior to any reprogramming. The process of ECU reprogramming is illustrated in Figure 19. According to the specialist the main characteristics of the different ECU software versions used in this study were:

OEM: Factory-made original ECU software for this particular engine.

ECU reprogram 1: Typical upgrade of the OEM ECU software, reprogrammed similar to higher power output versions of the same engine family. Optimised and fine-tuned by the reprogramming specialists. The main fuel injection parameters were not specifically calibrated apart from fuel injection quantity on higher loads, which is increased in the range for higher torque limit.

ECU reprogram 2: An example of a reprogram aiming for peak-performance and low fuel consumption. In addition to ECU reprogram 1, adjustments were made in respect to injection calibration parameters, such as fuel injection timing.

Figure 19: Illustration of the ECU reprogramming process

To demonstrate the effects of EATS tampering, the whole EATS package was passed by (referred in report as *"no EATS"*) and the exhaust sample was routed to CVS tunnel directly from exhaust pipeline after the turbocharger and before the EATS. In addition, for the purpose of simulating a situation where the urea system would be deactivated, the urea nozzle was removed and the temperature sensor relocated to avoid accidental dosing of urea into the cold unused SCR system. The untampered and tampered versions of exhaust path (i.e. EATS) are shown in Figure 22 and Figure 23.

Figure 20: Test vehicle installed in the HD-chassis dynamometer environment

Figure 21: Test vehicle placed in the test cell

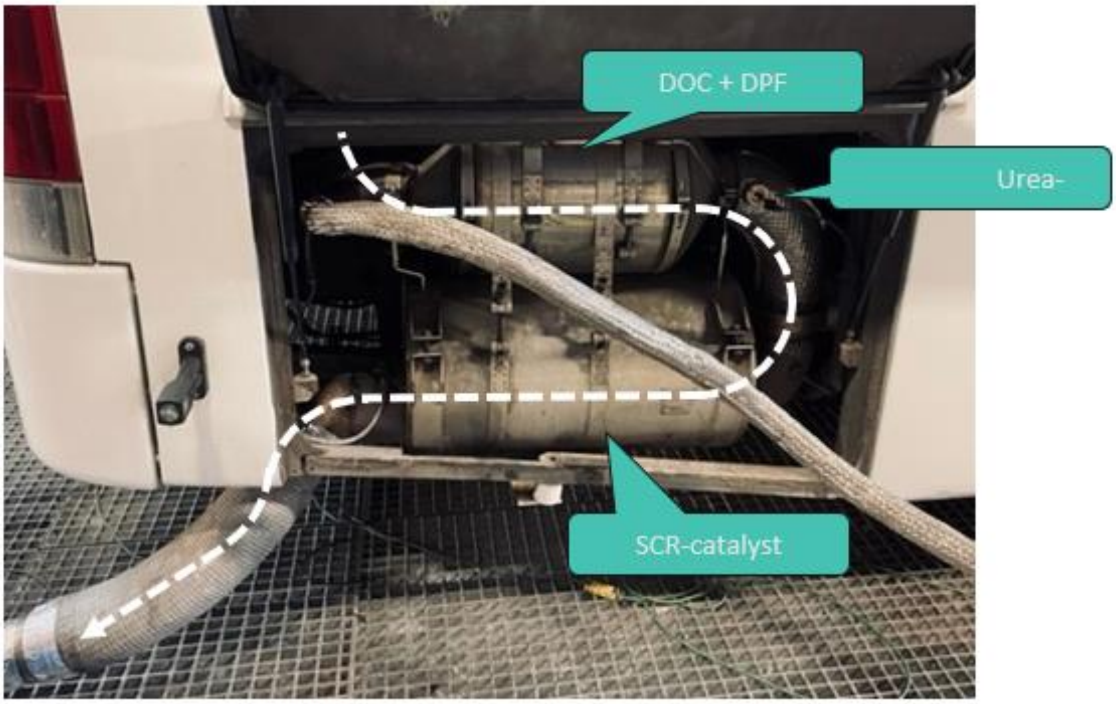

Figure 22: Untampered exhaust path via EATS components to CVS tunnel

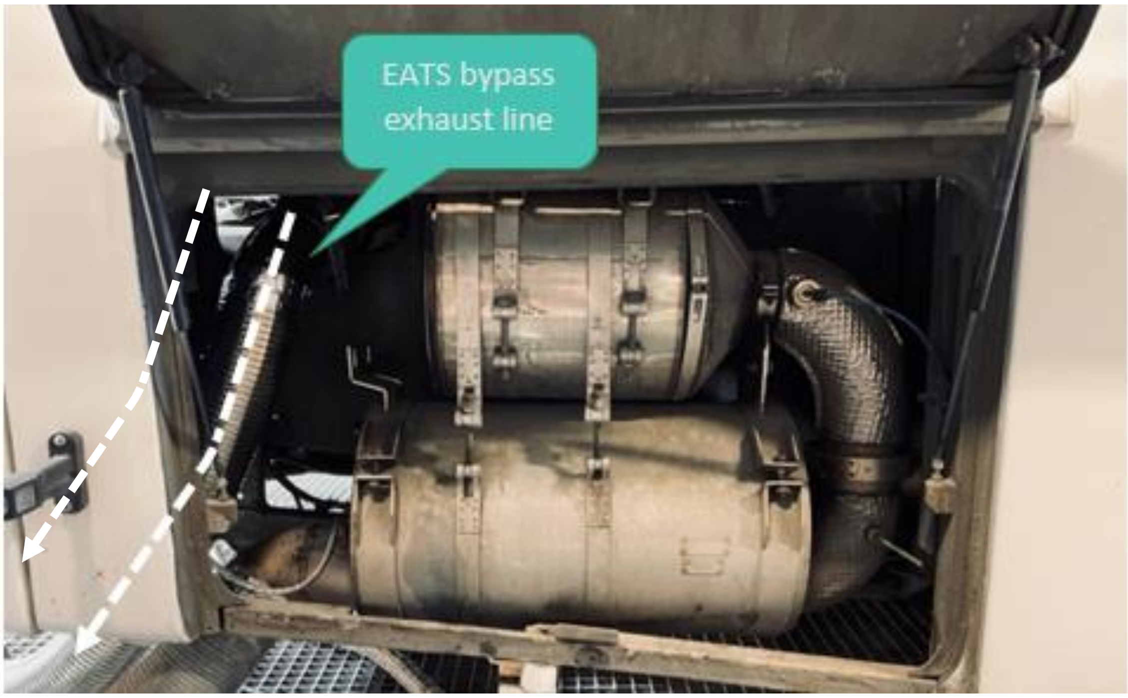

Figure 23: Tampered EATS bypass route to CVS tunnel (with normal route depicted in figure 2-3 now disconnected)

7.5. Test matrix

All of the ECU versions described in the previous chapters were tested with and without EATS. After the two ECU versions had been tested, the vehicle was restored to the original condition. After the restoration, an additional baseline test was conducted to ensure proper function of the vehicle. Furthermore, one set of tests were conducted with the urea injection for the SCR disabled. The test matrix and applicable test conditions are presented in Table 6.

Table 6: Assessment of effect of tampering solutions: Test matrix and test conditions

VTT test id	*Date*	*Drive Cycle*	*ECU Software*	*EATS*	*Remarks*
22R004	15.8.2022	WHVC cold	OEM	Complete	Baseline
22R005	15.8.2022	WHVC warm	OEM	Complete	Baseline
22R006	15.8.2022	WHVC warm	OEM	Complete	Baseline
22R009	16.8.2022	Acceleration test	ECU reprogram 1	Complete	
22R010	17.8.2022	WHVC cold	ECU reprogram 1	Complete	
22R011	17.8.2022	WHVC warm	ECU reprogram 1	Complete	
22R012	17.8.2022	WHVC warm	ECU reprogram 1	Complete	
22R013	17.8.2022	Acceleration test	ECU reprogram 2	Complete	
22R014	18.8.2022	WHVC cold	ECU reprogram 2	Complete	
22R015	18.8.2022	WHVC warm	ECU reprogram 2	Complete	
22R016	18.8.2022	WHVC warm	ECU reprogram 2	Complete	
22R017	19.8.2022	WHVC cold	ECU reprogram 2	No EATS	
22R018	19.8.2022	WHVC warm	ECU reprogram 2	No EATS	CAN recording failed
22R019	19.8.2022	WHVC warm	ECU reprogram 2	No EATS	
22R020	22.8.2022	WHVC cold	ECU reprogram 1	No EATS	
22R021	22.8.2022	WHVC warm	ECU reprogram 1	No EATS	
22R022	22.8.2022	WHVC warm	ECU reprogram 1	No EATS	
22R023	22.8.2022	Acceleration test	ECU reprogram 1	No EATS	
22R024	22.8.2022	Acceleration test	ECU reprogram 2	No EATS	
22R025	23.8.2022	WHVC cold	OEM	No EATS	
22R026	23.8.2022	WHVC warm	OEM	No EATS	
22R027	23.8.2022	WHVC warm	OEM	No EATS	
22R028	23.8.2022	Acceleration test	OEM	No EATS	
22R029	24.8.2022	WHVC cold	OEM	Complete	
22R030	24.8.2022	WHVC warm	OEM	Complete	
22R031	24.8.2022	WHVC warm	OEM	Complete	
22R032	24.8.2022	Acceleration test	OEM	Complete	
22R033	26.8.2022	WHVC cold	OEM	Complete	
22R034	26.8.2022	WHVC warm	OEM	Partial, No urea injection	Urea nozzle removed, temp sensor relocated
22R035	26.8.2022	WHVC warm	OEM	Partial, No urea injection	Urea nozzle removed, temp sensor relocated
22R036	29.8.2022	WHVC cold	OEM	Partial, No urea injection	Urea nozzle removed, temp sensor relocated
22R037	30.8.2022	Acceleration test	OEM	Partial, No urea injection	Urea nozzle removed, temp sensor relocated

7.6. Test results

7.6.1. Acceleration tests

The acceleration tests indicate the effect of different ECU program versions and tampering configurations on overall vehicle driving behaviour. The conclusive test results are shown both as absolute performance values and as relative change in respect to baseline in Table 7. Furthermore, the acceleration curves for each attempt showing the gear changes are plotted in Figure 24. The summary graph of the peak power output is shown in Figure 25. The power output measured from the driveline increased significantly when modified ECU software was implemented. Figure 26 illustrates the relative changes for the different test configurations. When using "ECU reprogram 1" software the maximum power increased by 27% and when using "ECU reprogram 2" software the measured peak power increased with 31%. Furthermore, when the EATS components were completely passed by, the power further increase with 33% and 36% respectively. Solely by removing the EATS, an increase of ca. 8% was gained with standard ECU program. It was found that the maximum power output was present with 5th gear at the speed of approximately 50 - 60 km/h.

The increase in power when removing the EATS originates from reduced backpressure of the exhaust system, improving the engine gas exchange and reducing pumping losses [78]. No significant gain in power was found for the case when the EATS was installed, but without the urea injection system active. From driver's point of view the most noticeable feature was overall increased powertrain performance. The reprogrammed ECU configurations allowed the usage of higher engine speeds prior to gear change, thus increasing the power band for each gear (e.g. 5th, see Figure 24). Furthermore, the acceleration with the reprogram was significantly improved. E.g. accelerating time from 0 to 50 km/h speed (taking off from a bus stop) is approximately 2 - 2.5 seconds shorter than with the OEM configuration.

Table 7: Results of acceleration tests

Summary of acceleration tests	22R008(2.) OEM Baseline (1st test)	22R009(3.) ECU reprogram 1	22R013(2.) ECU reprogram 2	22R023(3.) ECU reprogram 1 No EATS	22R024(1.) ECU reprogram 2 No EATS	22R028(4.) OEM No EATS	22R032(1.) OEM Baseline (2nd test)	22R037(3.) OEM No urea injection
Maximum Power [kW]	201.2	256.1	264.1	267.5	274.6	216.6	208.3	201.3
Change vs. baseline		27 %	31 %	33 %	36 %	8 %	4 %	0 %
Speed (max power) [km/h]	50.7	65.8	61.6	65.3	61.8	51.8	52.2	48.4
Change vs. baseline		30 %	21 %	29 %	22 %	2 %	3 %	-5 %
Time (max power) [s]	15	20.1	17.2	19.1	17	15.5	15.7	13.9
Change vs. baseline		34 %	15 %	27 %	13 %	3 %	5 %	-7 %
Accel 0 to 50 km/h [s]	14.6	13.4	12.6	13	12.5	14.8	14.6	14.5
Change vs. baseline		-8 %	-14 %	-11 %	-14 %	1 %	0 %	-1 %

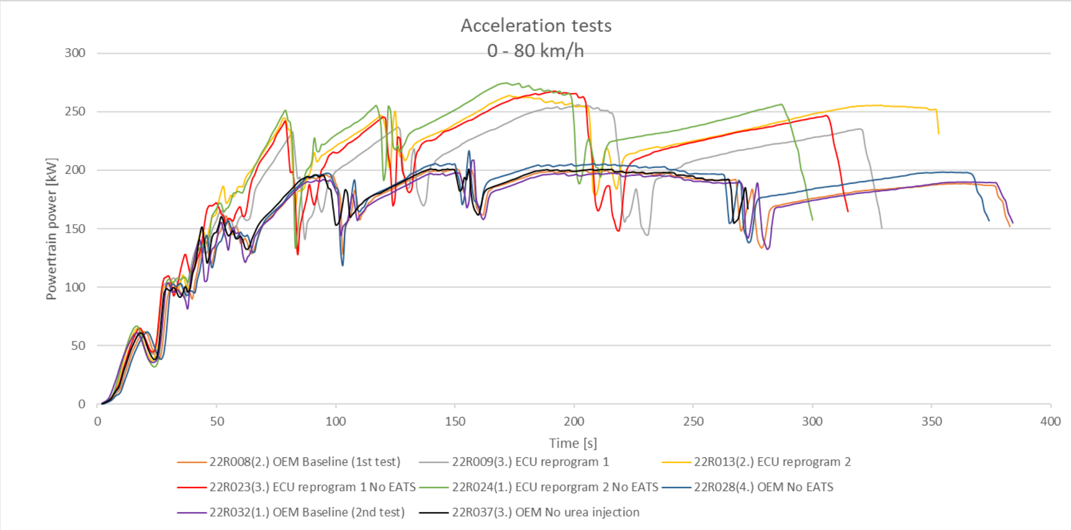

Figure 24: Acceleration curves with each test configuration

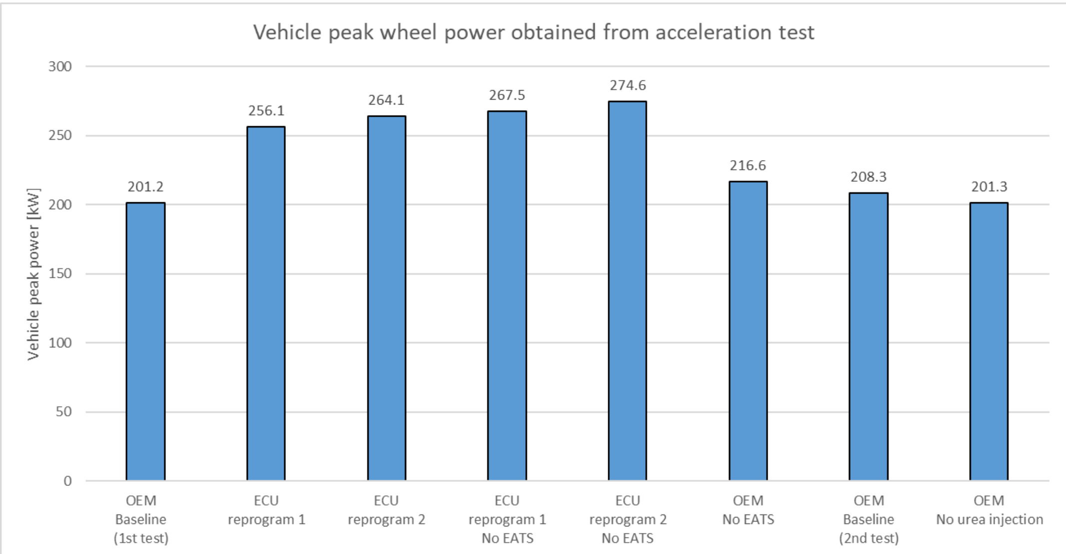

Figure 25: Peak power output of each test configuration

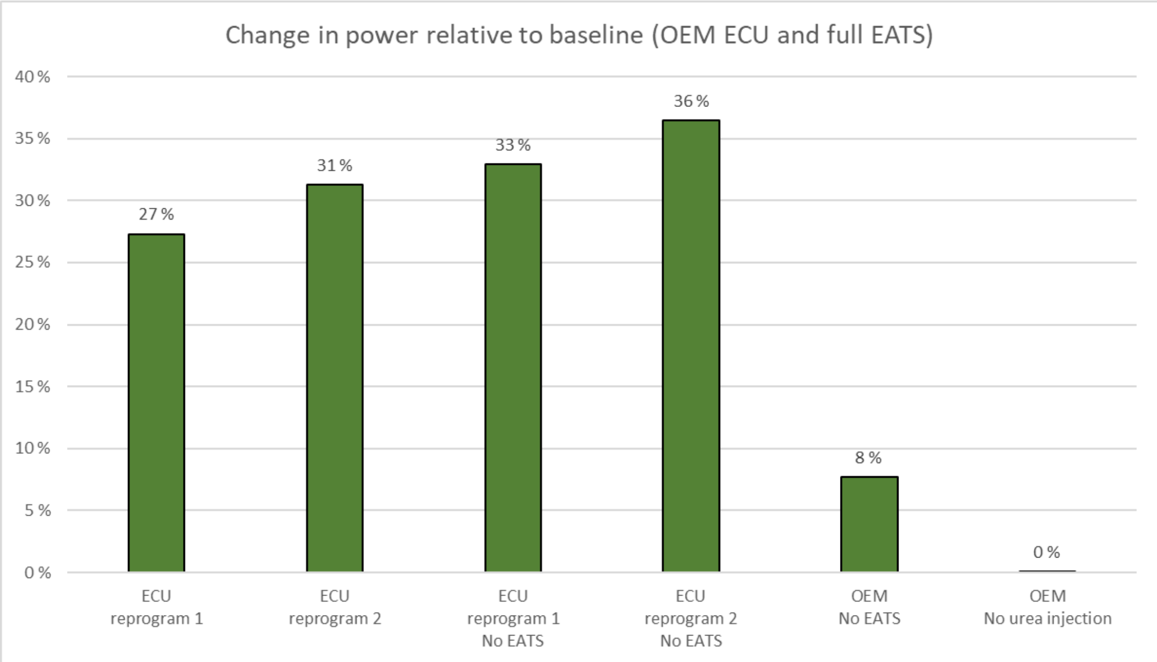

Figure 26: Change in power relative to baseline

7.6.2. Effect on exhaust emissions and other vehicle performance indicators

Vehicle exhaust emissions are dependent of both engine calibration parameters and EATS configuration and its efficiency. CO_2 (not total GHG) emissions are solely dependent on engine efficiency and correlate directly with fuel economy. The OEM engine calibration is typically optimised for highest fuel efficiency without compromising the engine raw exhaust pollutants [79] upstream the EATS and powertrain durability. Other exhaust tail pipe emissions (such as CO, NO_X and particulates) are not only dependent on the engine characteristics (or raw exhaust concentrations), as the emissions are generally further reduced by using sophisticated EATS configurations, i.e. a series of different catalysts and filters. The configuration and design of the vehicle EATS is generally determined by the exhaust matrix (concentration of exhaust pollutants), exhaust mass flow and limitations set by the local emission regulation. By removing the EATS system, the vehicle lacks its abilities to reduce its corresponding exhaust emissions that the removed EATS component is designed to reduce.

- **Effect on CO2 emissions and fuel economy**

The results for CO_2 emissions over cold start WHVC, two hot start WHVCs and for the average WHVC results over all three tests are shown in Figure 27. The CO_2 emissions for the baseline configuration were 1040 g/km for WHVC cold start and between 970 - 976 g/km for hot start WHVC tests. Solely by ECU reprogramming, the corresponding values was in this case reduced to 1010 - 1015 g/km for the cold start tests and between 944 - 959 g/km for the hot start WHVC tests. No significant difference between the two ECU reprogramming methods was found when the EATS system remained untampered, and the difference between the averages (WHVC results) were some 8 g/km.

When removing the EATS, the CO_2 emissions/fuel consumption was further reduced in all cases. Interestingly, the greatest change was found with OEM ECU program and ECU reprogram 2. With the OEM ECU software, the CO_2 emissions were reduced from an average WHVC value from 995 g/km to 934 g/km, correspondingly from 977 g/km to 931 g/km with ECU reprogram 2. The effect remains somewhat lower for the case of ECU reprogram 1, as the change in CO_2 emissions were found lower (average results from ca. 969 g/km to 951 g/km) than for both OEM ECU software configuration and ECU reprogram 2. The dominant reason for this phenomenon remains unknown, as no other indications from the engine performance or the exhaust emission data was found.

Lastly, no significant effect on CO_2 was found over cold start WHVC emissions with OEM ECU software but with urea injection disabled. However, the CO_2 emissions were reduced on both hot start WHVC tests. As the fuel consumption for the vehicle was determined from the CO_2 emissions, the effect on fuel consumption is directly proportional as seen in Figure 28. The relative changes in fuel consumption compared to baseline is illustrated in Figure 29. The greatest reduction in fuel consumption was found for OEM ECU software and for ECU reprogram 2 with the EATS removed, improving fuel economy with 5.8 - 6.2 %. The achievable fuel reduction with solely ECU the urea injection disabled (and EATS still installed) was found on average 1.7 %.

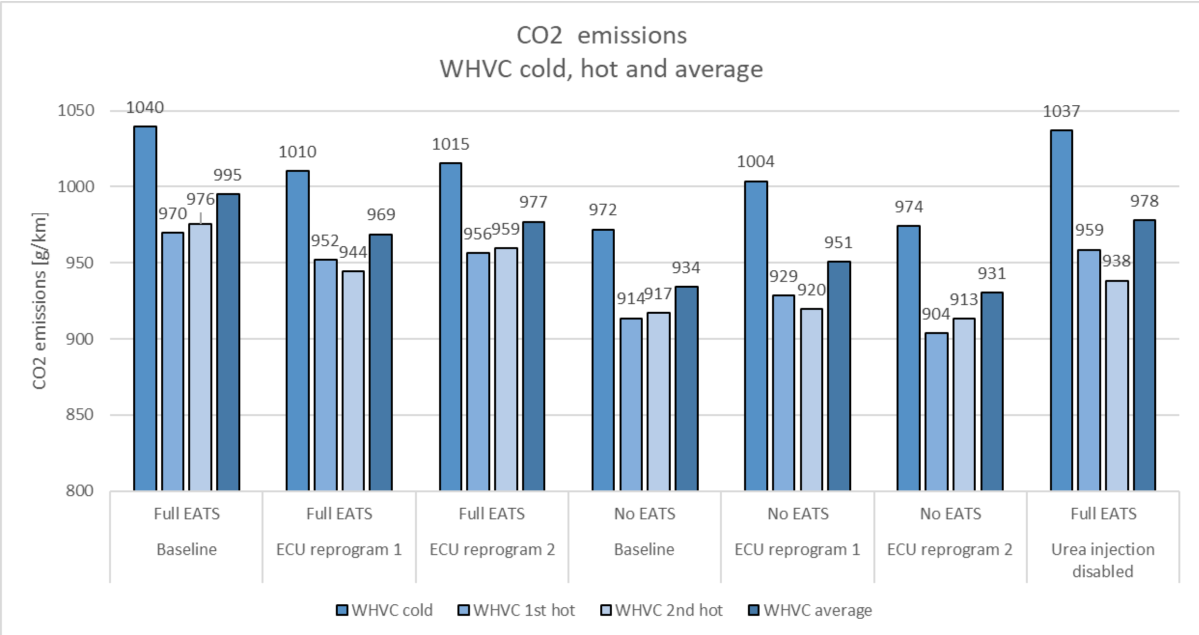

Figure 27: CO_2 results over WHVC test cycle with the different test configurations

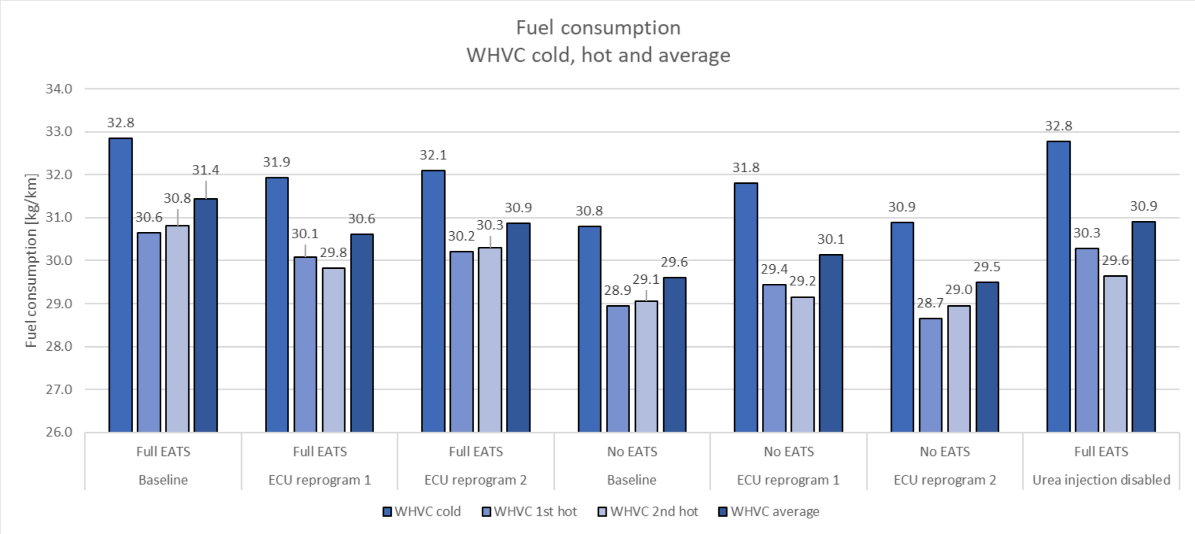

Figure 28: Fuel consumption in WHVC test cycle calculated from CO_2 emissions for the different test configurations

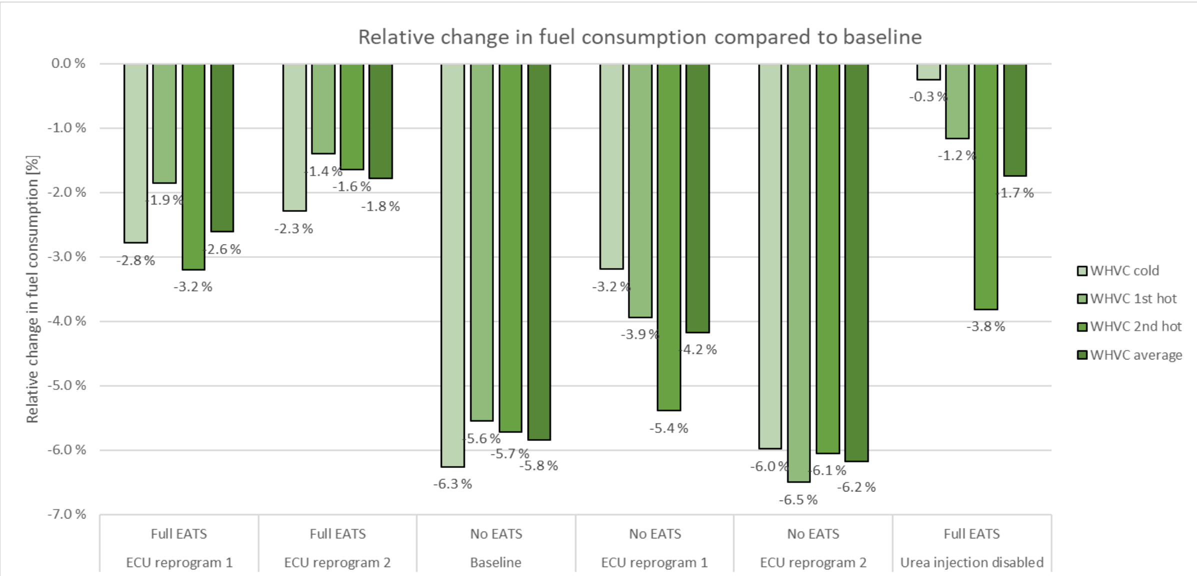

Figure 29: Change in fuel economy for the test configurations in relation to baseline tests

- **Effect on local exhaust emissions**

The emissions results acquired from the emission testing campaign may be categorised based on the main technical configurations: emissions for configurations with the EATS installed and tests where the EATS had been removed or tampered. Generally, with configurations where the EATS was present, the influence of ECU reprogramming was found significantly lower compared to the cases where the complete EATS was removed. Although ECU reprogramming may influence the engine out emission concentrations, the efficiency of modern EATS is due to catalyst sizing and system optimisation being typically relatively high. However, it should still be noted that ECU reprogramming may influence the upstream EATS emission so that the exhaust emissions may exceed the maximum potential of the given EATS components. Furthermore, as the different catalysts used in modern EATS are highly dependent on the light-off temperature (i.e. the temperature at which the system or catalysts activate) and the thermal management of the catalysts, reprogramming may affect the EATS system efficiency by reducing thermal control for the intentions of improvements in fuel economy. This part of the report describes the effect of ECU reprogramming and/or EATS tampering on local exhaust emissions.

Figure 30 illustrates the CO emissions for the different configurations in WHVC conditions. The most evident increase in CO was seen when removing the EATS system. Nevertheless, both ECU reprogramming methods were found increasing the CO emission by ca. 100 % even with the EATS system installed, despite the absolute CO emissions remain generally low. In comparison, removing the DOC catalyst was found to raise the CO emissions by 500 - 4500 %, depending on test conditions. No effect in CO was found with the urea injection disabled. The increased engine out CO emissions for ECU reprogramming were not corresponding with HC emissions, which remain relatively stable over the different ECU program versions (Figure 31). These trends indicate that the HC emissions on lean operating combustion engines (such as diesels) are less influenced by the injection parameters, rather the used air-fuel ratio. Furthermore, it should be noted that the presence of an efficient DOC catalyst reduces the HC emissions virtually on a level that was close to detection limit of used measurement system as seen in Figure 31. For the OEM-calibrated software and ECU reprogram 2, the HC emissions with the full EATS installed, the HC emissions were found practically same or below the ambient (background) HC-emissions.

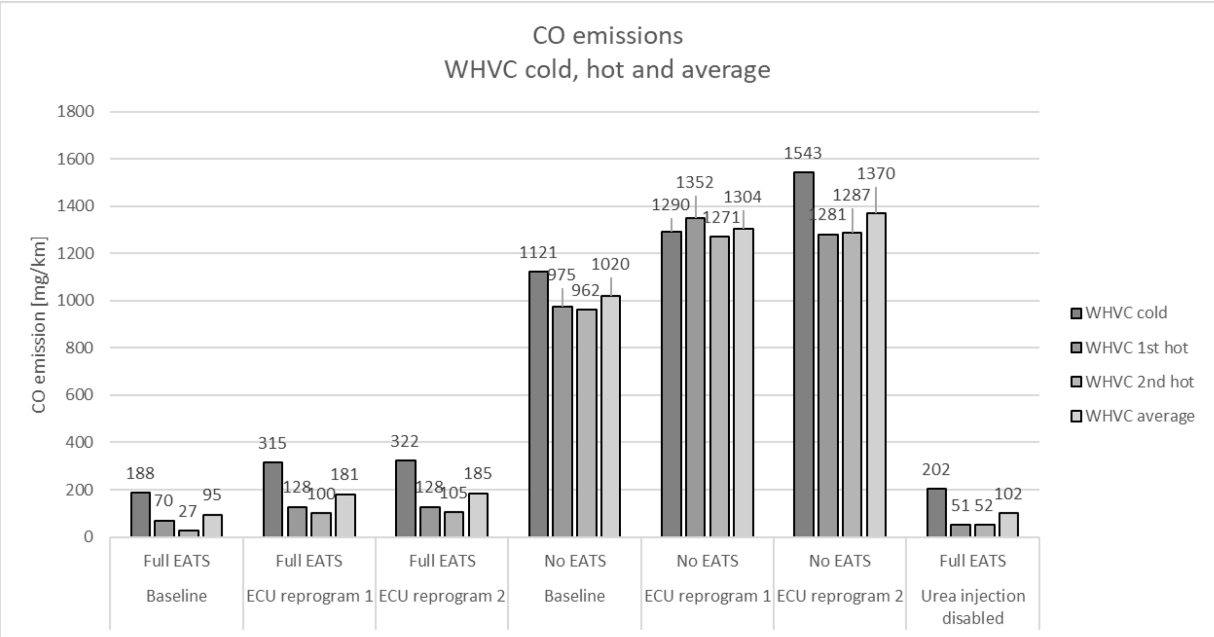

Figure 30: CO tail pipe emissions for all configurations over WHVC

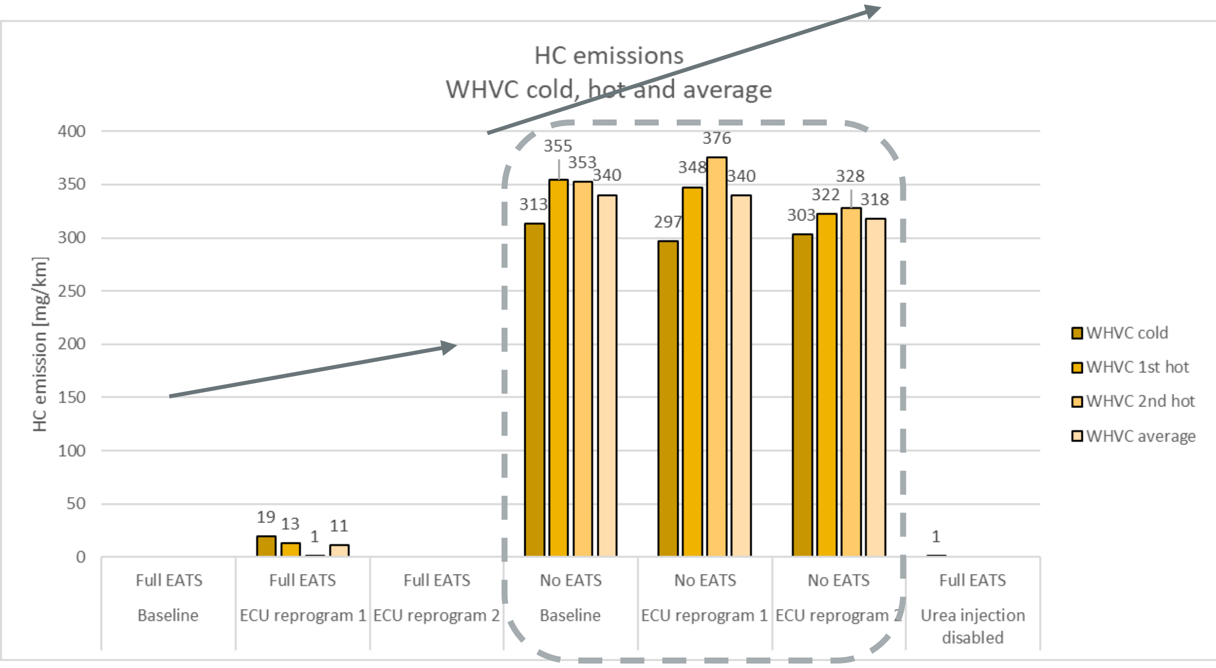

Figure 31: HC tail pipe emissions for all configurations over WHVC

The formation of NO_X emissions (engine raw emission) in a diesel engine is a complex thermochemical process where the NO_X formation is highly dependent on engine hardware and fuel injection system configuration and fuel injection calibration parameters. Typically, the efficiency of a diesel engine may be improved by advancing the fuel injection timing, simultaneously increasing NO_X emissions due to higher combustion temperatures, promoting the formation of thermal NO_X [79]. i.e. the fuel economy may to a certain extent be improved through advancing the injection timing with a penalty in engine raw NO_X emissions using ECU reprogramming. OEM ECU calibrations are often balanced between the best achievable fuel economy with respect to sufficiently low engine raw NO_X emissions. In modern diesel vehicles, the NO_x emissions are then further reduced by utilising a SCR system applied as a part of the vehicle EATS. The magnitude of achievable NO_x reduction in an SCR is highly dependent on several factors: maintaining sufficient catalyst temperature (often supported by engine exhaust gas thermal control), upstream SCR NO_X concentration, NO/NO_2 balance, catalyst volume and quantity of urea injection. Meanwhile EATS thermal control does not necessarily remarkably influence the absolute engine out NO_X emissions, the tail pipe (downstream EATS) emissions may be affected by injection parameters by influencing the EATS catalysts light-off temperature.

Figure 32 illustrates the observed average WHVC engine raw NO_X emissions measured using a FTIR and Figure 33 expresses the corresponding tail pipe NO_X emissions. As expected, the highest NO_X tail pipe emissions were obtained with the EATS removed (and additionally with urea injection disabled). When removing the EATS, the NO_X emissions corresponds to engine raw (upstream EATS) NO_X emissions and practically no NO_X suppression was found. The engine raw (and upstream SCR) NO_X emission were found increasing somewhat with ECU reprogramming 2, but not with ECU reprogramming 1, thus resulting in virtually equal NO_X results compared to baseline configuration (ca. 10.5g/km). This suggests that if the engine peak power is solely increased without introducing significant changes in injection advance, such as with ECU reprogram 1, the increase in top end power does not significantly increase engine out NO_X emissions in normal (type approval like) operation such as in WHVC conditions. Due to the nature of the test programme, the NO_X characteristics during other test conditions, e.g. under higher loads, remain unknown. With advanced injection timing used with ECU reprogram 2, NO_X emissions were observed to increase by some 12 % on average. These results demonstrate that the general increase in engine power are not necessarily increasing the engine raw emissions throughout the complete engine operation map, rather is more dependent of the reprogramming strategy. In this case, no significant change in engine raw NO_X emissions were found by removing the engine EATS.

Despite that the engine out NO_X emissions were found virtually equal for ECU reprogramming 1 compared to OEM ECU calibration, the average tail pipe NO_X emissions increased for both ECU reprograms with the EATS system installed. Both ECU reprogram versions resulted in an increase in NO_X tail pipe emissions of ca. 35 - 39 %, equivalent of ca. 300 mg/km. The reason for the increase in NO_X emissions is explainable through analysing the cumulative NO_X results shown in Figure 34. As the overall potential of EATS NO_X suppression is highly dependent on the EATS thermal control and SCR system optimisation (urea injection quantity and SCR efficiency among other parameters), the thermal control used by both ECU reprogram cases was suspected to influence the light off threshold and start of urea injection. Generally, no NO_X reduction is achievable prior to reaching the SCR light off temperature, as there is no urea injection, thus catalytic reaction may take place. Despite that the SCR may be even able to reduce the increased amount of absolute engine raw NO_X emissions caused by greater injection advance (absolute amount of NO_X reduced increased from 91.2 - 95.2 g/km NO_X) the SCR system is unable to fully operate close to engine start up or in low load (low exhaust temperature) conditions, as seen the cumulative, upstream/downstream NO_x emissions during the initial 4 km of the tests. This observation is supported by calculating absolute difference in NO_X formation, i.e. increase in cumulative tail-pipe NO_X over the different ECU reprograms compared to baseline results (Figure 35). The absolute NO_X emissions are remarkably higher for the first 4 km until the SCR system is activated. After SCR activation, the NO_X reduction for all ECU versions remain comparable. It should also be noted that the absolute amount of achievable NO_X reduction is determined by the ability of the SCR system to adapt with the changes in upstream EATS NO_X emissions (quantity of engine out NO_X emissions) and this may not necessarily be the case on all vehicles, as the flexibility of SCR systems may vary case by case.

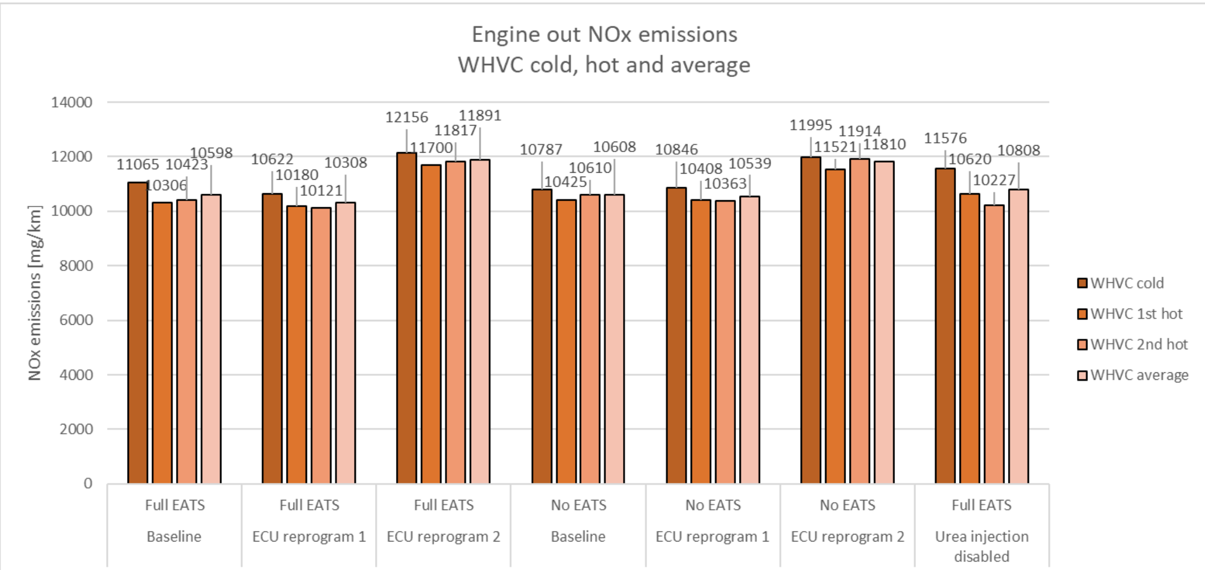

Figure 32: NO_X engine out emissions measured with FTIR for all configurations

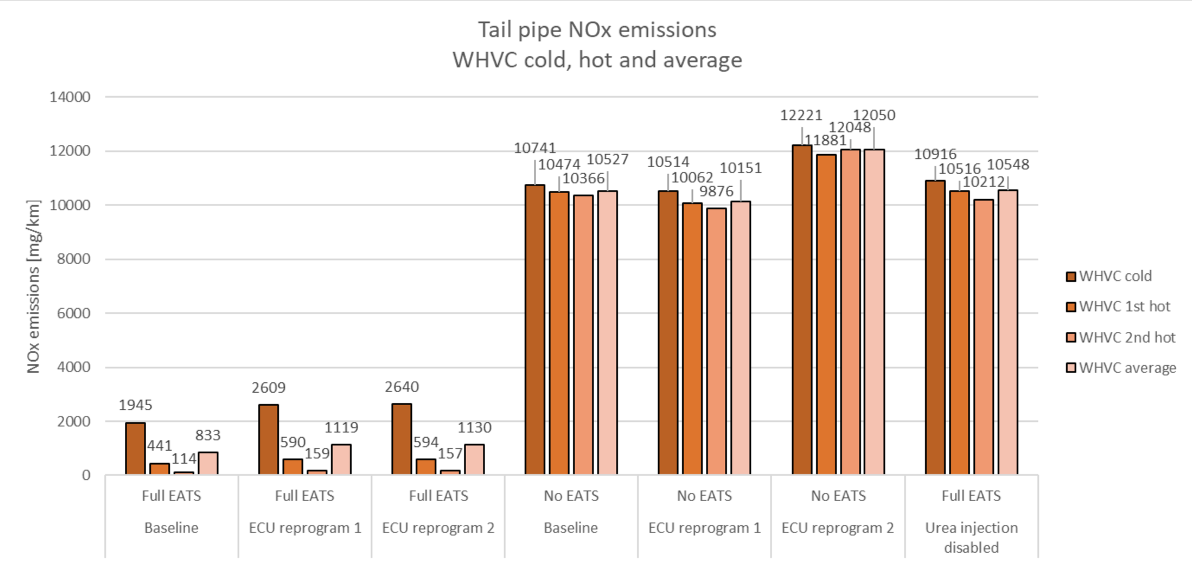

Figure 33: NOx tail pipe emission over the performed WHVC test for all configurations

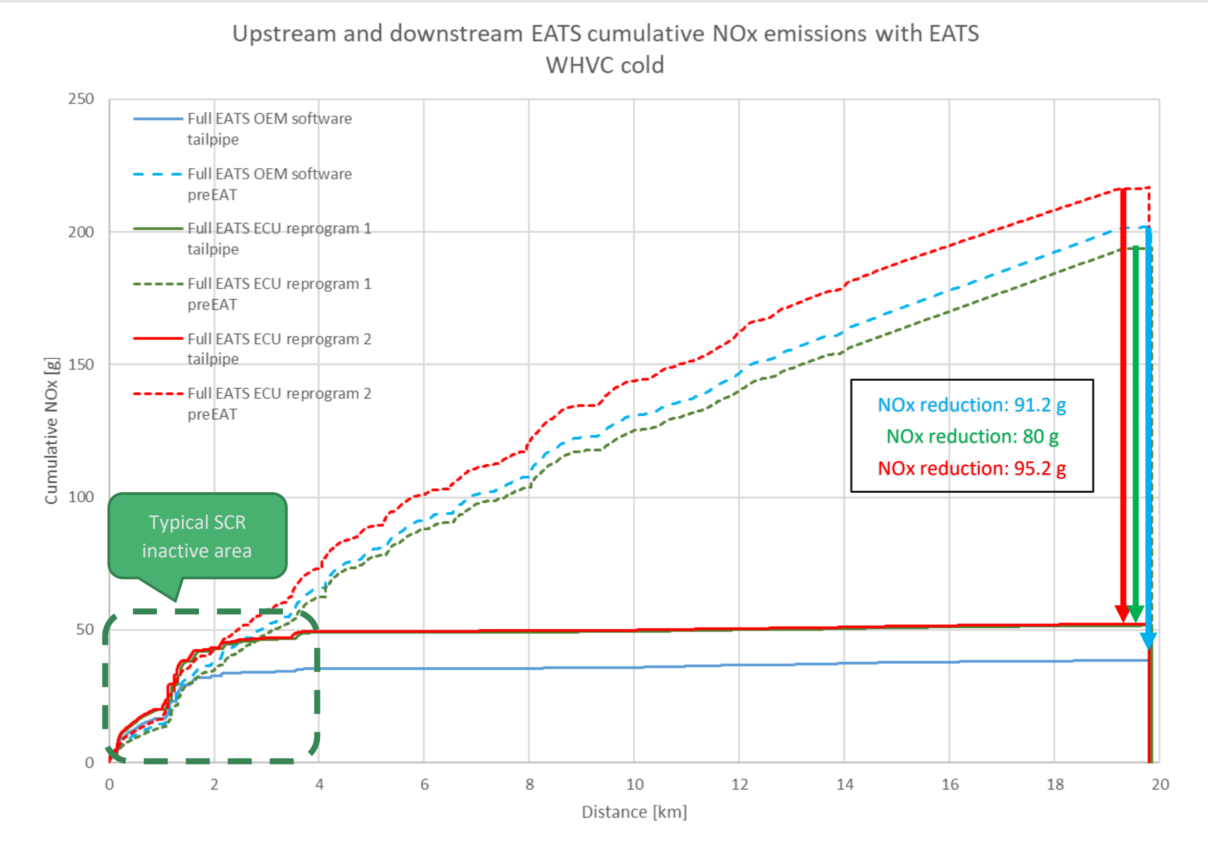

Figure 34: Cumulative NOx emissions, pre and post EATS for OEM ECU and both ECU reprogram strategies

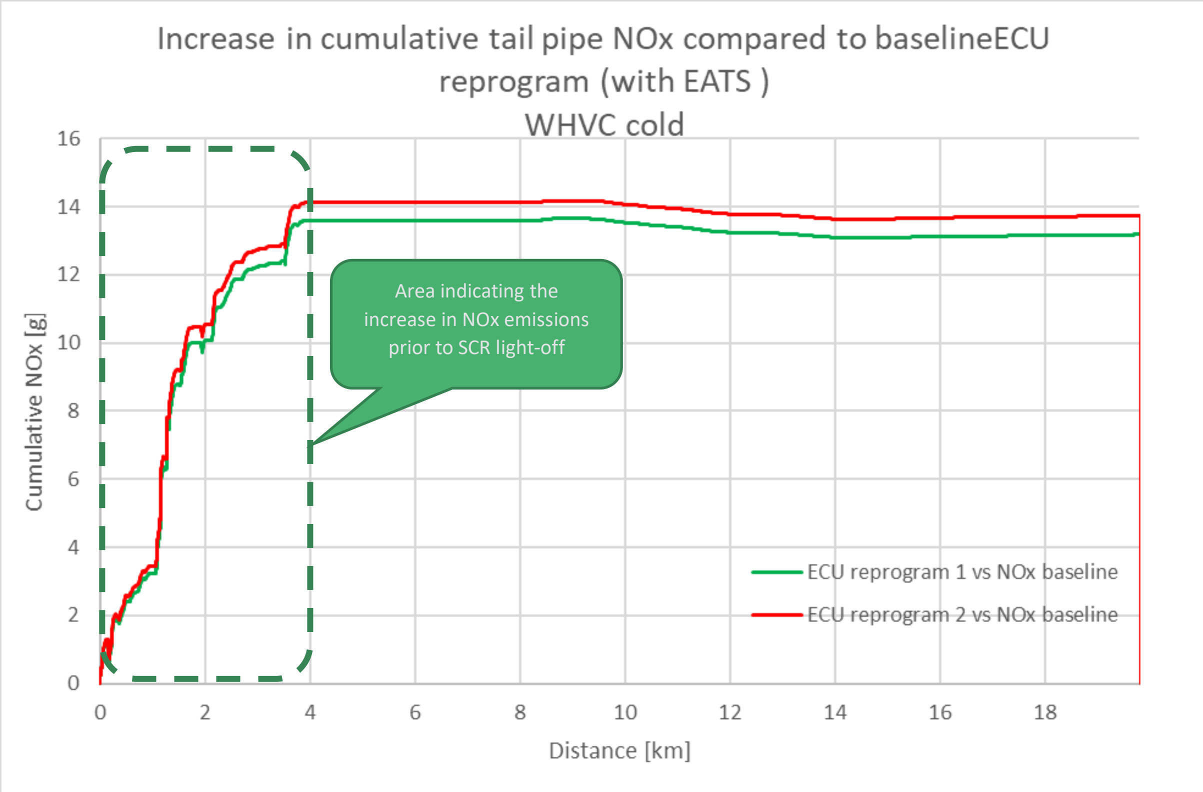

Figure 35: Difference in absolute cumulative tail-pipe NO_X emissions with ECU reprogramming in relation to OEM ECU parameters

Figure 36 illustrates the PN results obtained from the WHVC both in cold start and hot start conditions. Unfortunately, due to PN device malfunction, no result from ECU reprogram 1 with full EATS was achieved. However, based on the observed changes in PN emissions without the EATS system installed together with the tail pipe emission results obtained with ECU reprogram 2 (with full EATS), the relative effect of ECU reprogramming was possible to be evaluated without the need for further repetitions. Correspondingly, Figure 37 represents the trip-based PM emissions over the conducted WHVC tests. As the DPFs applied in Euro VI emission standard complying vehicles are typically highly sophisticated, the reduction of PN and PM emissions are generally efficient in various conditions despite changes in the upstream particulate emissions. This phenomenon may be demonstrated through the results obtained in these tests as virtually no change in tail pipe PN nor PM emissions was found between the reprogrammed ECU version(s) and baseline ECU parameters with the EATS attached.

With the EATS removed, the average increase in PN emissions were some 3 % for ECU reprogram 1 and 7 % for ECU reprogram 2 obtained from the WHVC tests compared to baseline. However, as the observed filtering efficiency for PN was high ca. 99.7 - 99.8 % in all conditions, the PN emissions were reduced for the tail pipe PN emissions to virtually an equal level with the baseline. Correspondingly for PM emissions, a filtering efficiency around 91.2 - 94.7 % was noted, thus like for PN emissions, no significant change in tail-pipe PM emissions were found with different setups with the EATS attached. Interestingly, with the EATS system attached but with urea injection disabled, PN and PM emissions were further reduced even below the baseline particulate emissions. The reduction in particulate emissions when disabling urea injection was suspected to be a cause of the absence of ammonia related particles, typically responsible for causing non-carbon originating particle emissions.

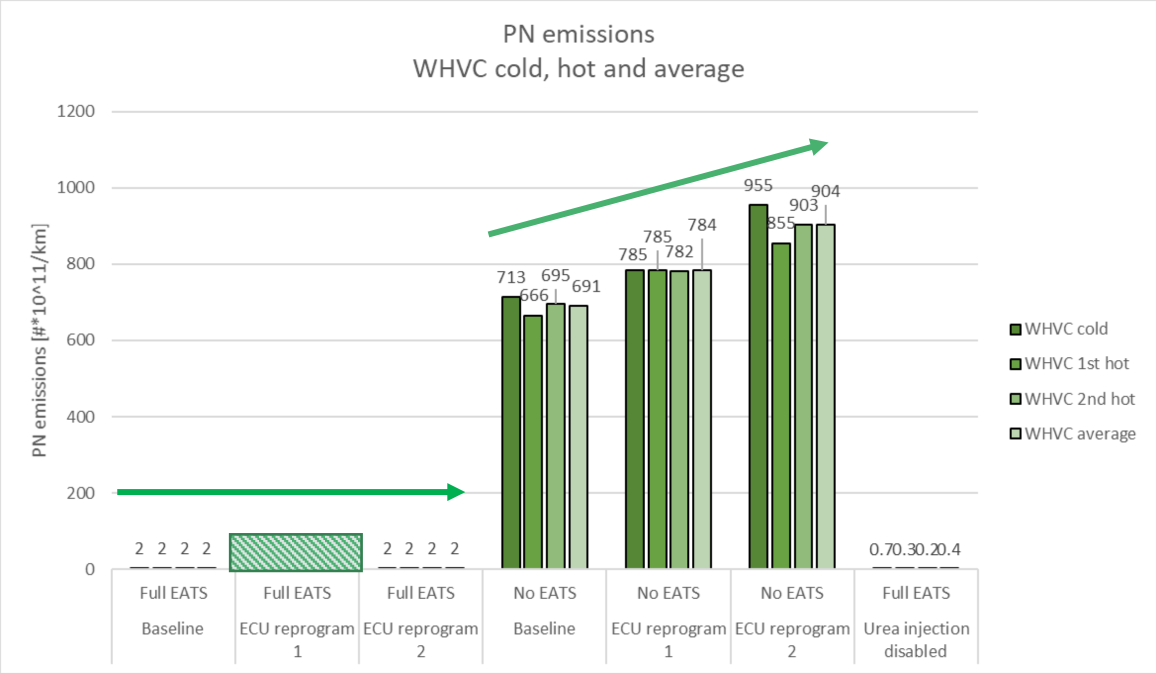

Figure 36: PN tail pipe emission over the performed WHVC test for all configurations

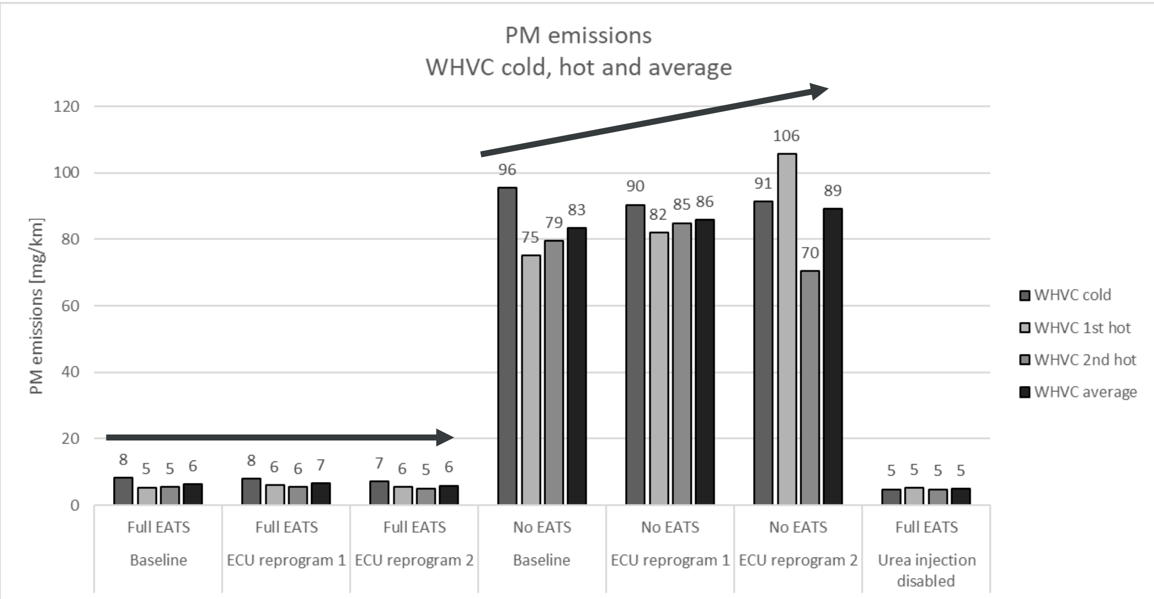

Figure 37: PM tail pipe emission over the performed WHVC test for all configurations

7.7. Conclusions

The results acquired from this demonstration suggests that the effect of different ECU remapping and EATS tampering solutions may change the vehicle performance characteristics relatively significantly. The results also indicate that the effect of ECU remapping had a lesser effect on exhaust pollutants compared to EATS tampering. Despite this, none of the tampering configurations tested in this study improved the overall vehicle emission behaviour. However, due to the nature of the test matrix, the effect on vehicle emissions outside WHVC conditions with different ECU remapping or EATS tampering methods remain unknown.

Based on these findings, the most likely reason for EATS tampering is to try to obtain a reduction in operational and maintenance related cost (e.g. savings in fuel or urea consumption) rather than gains in vehicle performance. On the other hand, the most evident gain of ECU remapping is increase in vehicle performance (whole power-band and peak power) together with reduction in fuel consumption. This demonstration shows that by ECU reprogramming, the potential gain in engine peak power may be increased with up to 30% simultaneously with a reduction of overall fuel consumption in the range of 5 - 6%, meanwhile EATS removal increase the peak power with some 4 - 8% with corresponding gains in fuel economy. With a sophisticated and adaptive EATS still in use, the effect (increase) on exhaust pollutants were lower than expected. However, this applies for engine families with multiple power level options and that the engine in question represents a version of a low powered model. As expected, the downside with ECU remapping is in any case seen as some increase in exhaust emissions, which typically tend to increase especially for CO, HC and NO_X emissions even with the EATS installed. The ECU reprogramming versions adapted in this study was found to affect especially the EATS thermal control, increasing the delay of catalyst activation. No effect on particulates was found for ECU reprogramming with the DPF installed. On the contrary, removal of vehicle EATS neglects totally the suppression of any exhaust pollutants, with resulting exhaust emissions corresponding to engine raw emissions.

Due to the nature of the work, no analysis regarding vehicle durability was performed. Nevertheless, as enhancements in drivetrain performance always increases the load and stress on the overall drivetrain and EATS system, a lower durability with ECU reprogrammed vehicles should always be expected. The vehicle tested in this study represented solely one example of an HDV with ECU and EATS tampering modifications. It is impossible to draw generalised conclusions from the tests apart from basic fundamentals. Despite the fact that vehicle technologies are comparable between different brands, the technical solutions may affect the response of ECU reprogramming or EATS tampering. Furthermore, the quality of ECU reprogramming is expected to have a significant role in determining the outcome of the modifications. The ECU reprograms provided by the specialist are always tailor-made case by case. Additionally, vehicle age, emission class, maintenance history and predominant ambient conditions are expected to affect the outcome of any modifications.

8. Vehicle anti-tampering system

8.1. Introduction

In Task 4.2, an attempt was made to create a system to identify and notify possible tampering or insufficient engine maintenance issue of a vehicle. The basic principle is based on comparing vehicle parameter values as available from OBD with factory values or vehicle performance values recorded by independent agencies/sources.

The system works as follows: a vehicle data collection and control unit sends information to a central server in which comparison routines run between OBD and manufacturer performance values in order to identify any significant discrepancies per vehicle. If discrepancies are large and occur on an ongoing basis, the vehicle authority information manager is notified of the discrepancies. From there it is up to the local bodies to decide how to manage the notifications. They could call that particular vehicle for immediate inspection at a random PTI centre. Should the PTI centre confirm the tampering or engine maintenance issue, it would inform the local authority of the findings and accordingly recommendations to the owner could be made for compliance or give fines commensurate with the severity of the problem.

8.2. Architecture description

The system follows a three-tier architecture. The presentation tier, or user interface, the application tier, where data is processed, and the data tier, where the application's associated data is stored and managed, are the three logical and physical computer tiers that make up the well-known three-tier architecture. Although, the system implements a mobile phone application and a website, the presentation tier comprises only the website. The system exploits the web services in the application tier for providing data from/to the database. The web services have been built according to the most popular architectural styles, i.e. Representational State Transfer (REST) architecture. Moreover, the application tier exploits the mobile application developed to collect data from the vehicles. The data tier includes the database that stores the raw data.

The system architecture consists of four major components (Figure 38). The first component is the On-Vehicle Unit (OVU) or a mobile application, in case there is no possibility of placing an application in the OVU, is responsible to read the data from the Controller Area Network (CAN) bus, pre-process it and then transmit it to the server. Due to the many different vehicle models from different manufacturers, developing an application that is capable of operating in different OVU environments is a very difficult task. For this reason, we developed a mobile phone application that receives vehicle data via the On-Board Diagnostic device and is responsible for sending it to the server.

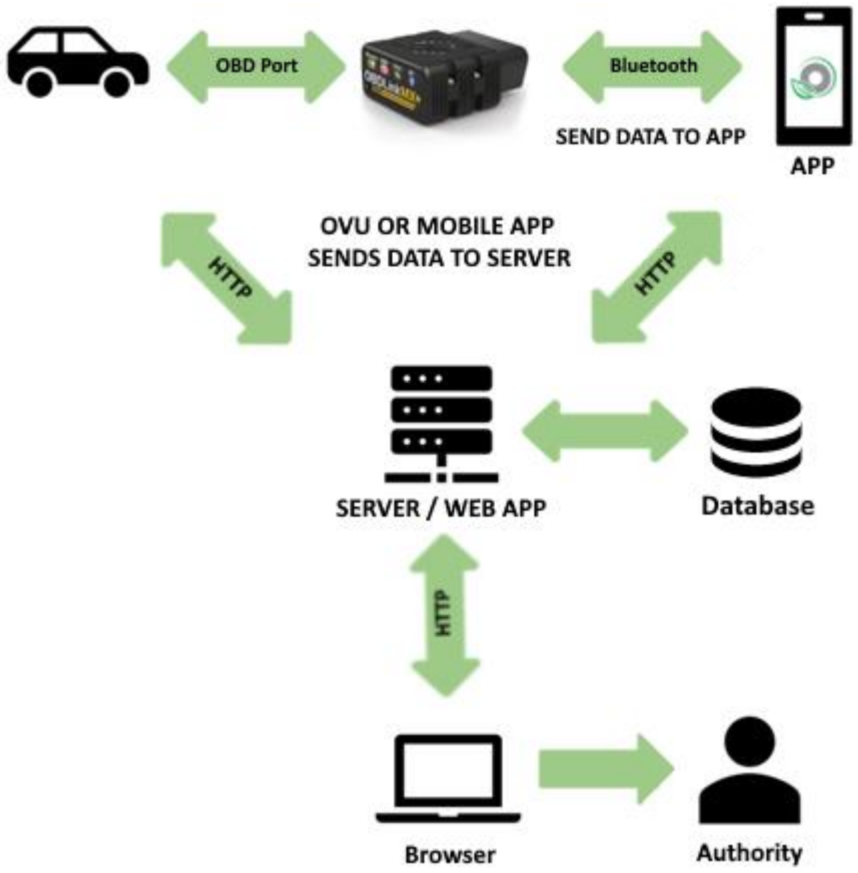

Figure 38: Anti-tampering System architecture

The mobile application has been developed on Android operating system. After the application reads the data, it stores it locally in csv format. The application has a background thread that runs continuously and every time a new file is created, it sends it to the server according to the HTTP protocol. At the same time, the application sends the VIN, make, model and variant information for each vehicle. The core parameters that are used as a reference for the identifications of potential issues are the vehicle speed and acceleration, engine power and torque, engine speed (RPM) and the Malfunction Indicator Light (MIL) on.

The second component is the server or else the web application that has been developed. The web application implements the following functionality:

- Implements the web services / Application Program Interface (API) in order to receives the data from the mobile application and stores the csv in the file system (Table 8)
- Processes the data (e.g. type casting, missing values)
- Transforms the data in the appropriate format according to the database
- Loads the data to the database
- Implements the web services / Application Program Interface (API) in order to serve the requests coming from the Presentation Layer (Table 9).

The implementation of the web services / API is based on Java programming language and more precisely on the Java Jersey framework and is executed on the Apache Tomcat web server. Additionally, the application tier exploits the Grafana open-source analytics and visualisation software. Grafana offers an open-source tool for building dashboards, query data sources, explore, monitor and visualise metrics. The application tier implements data analytics inside the Grafana and a dashboard that is incorporated in the user interface.

Table 8: API for receiving data (csv file) from the mobile application or the OVU

Operation Description	The web service module is responsible for receiving the raw data, process and store it in the database. The mobile application or the OVU sends to the server (Back-End API) a multipart form data containing the information from a trip. The mobile application or the OVU receives an HTTP code (e.g. 200, 400, 404, etc.) about the operation.			
URL	http://160.40.60.237:8080/modales.tampering.ws/rest/server/sendCsvFile			
Input	**Format**	**Name**	**Type**	**Comments**
	multipart/form-data (HTTP POST)	brand	String	The vehicle's brand
		model	String	The vehicle's model
		variant	String	The vehicle's variant
		fuel	String	The vehicle's fuel type (e.g. Petrol)
		vin	String	The vehicle's identification number (VIN)
		file	CSV	The CSV file containing raw data for a specific journey
		filetype	String	The file's type
		filename	String	The file's name

Usage Example	Example: Post the raw data
	http://160.40.60.237:8080/modales.tampering.ws/rest/server/sendCsvFile
	Input data formatted as:
	{
	"brand": "FIAT",
	"model": "Qubo",
	"variant": "Sport",
	"fuel": "diesel",
	"vin": "f4329u432942239",
	"filetype": "text/csv",
	"filename": "CSVLog_20220922_143855.csv"
	}			

Table 9: Anti-tampering system login operation

Operation Description	The web service module is responsible for receiving the user’s credentials from the presentation layer (website). The module runs the authentication procedure based on the user’s credentials and returns the appropriate HTTP code (e.g. 200, 400, 404, etc) and generic user information. It uses the basic access authentication to provide a username and password when making a request. The request contains a header field in the form of Authorization: Basic <credentials>, where credentials is the Base64 encoding of ID and password joined by a single colon.			
URL	http://160.40.60.237:8080/modales2.ws/rest/server/login			
Input	**Format**	**Name**	**Type**	**Comments**
	Basic Auth (HTTP POST)			
Output	**Format**	**Name**	**Type**	**Comments**
	JSON	user_id	Integer	The user’s identification number
		firstname	String	The user’s first name
		lastname	String	The user’s last name
		email	String	The user’s email
		authority_id	Integer	The user’s authority identification number
		authorityname	String	The user’s authority name
		userrole_id	Integer	The user’s role identification number
		rolename	String	The role name

Usage Example	Example: Login operation
	http://160.40.60.237:8080/modales2.ws/rest/server/login
	Output JSON formatted as:
	{
	"user_id": 1,
	"firstname": "Nikos",
	"lastname": "Dimokas",
	"email": "dimokas@certh.gr",
	"authority_id": 1,
	"authorityname": "Thessaloniki",
	"userrole_id": 3,
	"rolename": "director"
	}			

The third component is the database where the raw data are stored. Additionally, the database contains the appropriate stored procedures for processing the data and producing the aggregated information. The data storage has been implemented with MySQL Relational Database Management System. The data model developed as a relational schema consisting of various tables and the corresponding relations among them. The entity relational model (Figure 39) below presents the tables and the corresponding attributes (columns).

The "vehiclecharacteristics" table stores the unique characteristics (reference values) of all different vehicles. Among other things, the table stores information on vehicle's brand, model, variant, engine power, engine torque, top speed, acceleration, etc. On the other hand, the "vehicle" table stores information only for the vehicle running our system. The table contains information about VIN, brand, model, fuel type, etc. The table "tamperingdata" contains the raw data.

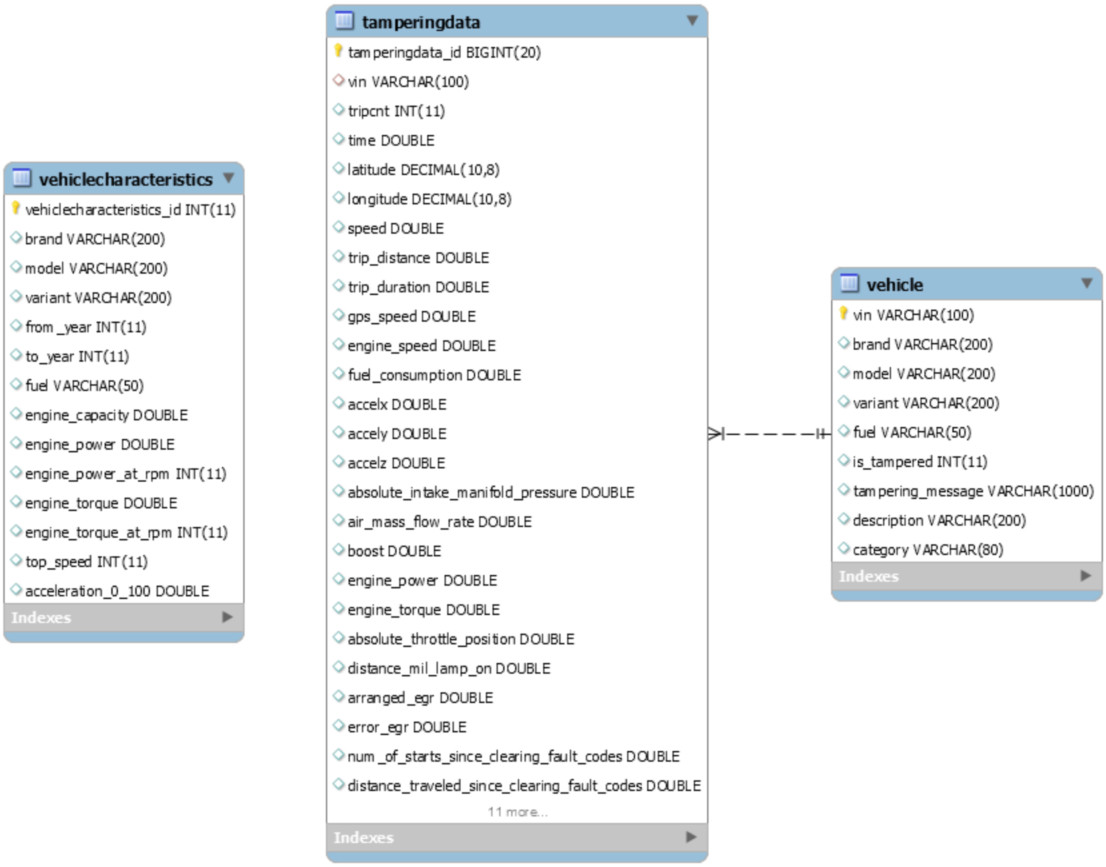

Figure 39: Entity Relational model

Finally, the fourth component is the user interface (presentation layer). It has been implemented based on the Grafana open-source analytics and visualisation software, the HTML, CSS and JavaScript programming languages.

The overall user interface, implemented for the overall dashboard web application, consists of three major sections/subsystems. The first, called *dashboard*, presents the overall dashboard. The second section, called *region*, provides also aggregated indicators according to the data gathered from a specific region. The third section, called *warnings* is related to the current system and provides valuable information about warnings. The subsystems of the dashboard and region are described in detail in the deliverable *D5.3 Low-emission driving assistance tools*.

This warnings page provides aggregated information on how many vehicles are experiencing possible tampering and maintenance issues. The user accessing this page can view detailed information about the vehicle's brand, model and the description for the warning. The warnings page can only be accessed by authorised users belonging to an authority.

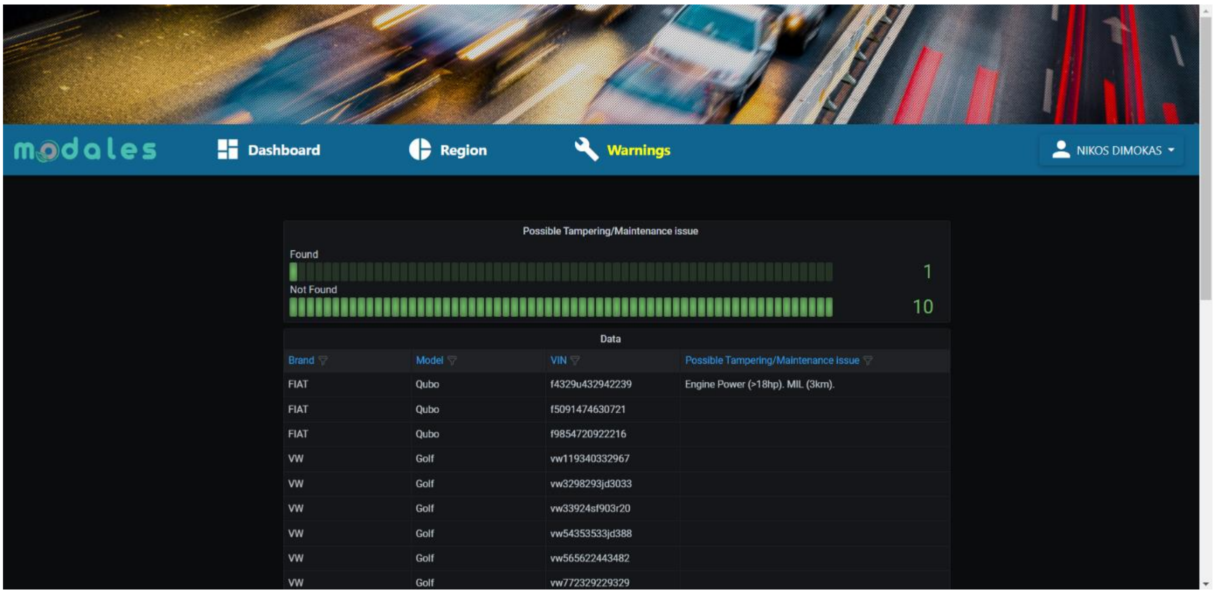

Figure 40: Warnings from anti-tampering system

8.3. System validation

Taking into account that the system can be validated when the tampering or poor maintenance of the vehicle is known, the validation phase was limited at this stage but it will continue until the end of the MODALES project.

In our cases, the system spotted an increased engine power of a vehicle for that variant. More specifically, the vehicle was a FIAT diesel with a Multijet engine which produces 75 hp at 4000 RPM. However, there were several logs with the engine power above 85 hp, with a maximum of 92 hp at 4300 RPM. Looking at potential engine tampering of this engine type, the current performance of the engine matches with a software tuning that increases the engine power to 95 hp at 5000 RPM. The owner of the vehicle was not aware of this issue because he had bought the vehicle second-hand from the first owner who has bought it new from an official dealer. From this example, the parameter of the total ownership of the vehicle is also of importance. However, when vehicle data is logged since the first date of registration (assuming that the data is not manipulated by a tampering software), any tampering will be associated with the owner of that period.

9. Recommendations for the use of OBD in maintenance and anti-tampering

Besides the aspects covered in previous chapters, the findings of Task 2.5 of MODALES (Legal issues on tampering) are also considered in order to propose ways to improve the EOBD protocol in relation to the legislation on maintenance and tampering in Europe and China. Analysis of the current situation will provide evidence on the immediate need to strengthen regulations on enhancement of the protocol. Potential future scenarios, identified in T2.5 (reported in MODALES Deliverable D2.3), are also investigated to identify the possible consequences of improving or deteriorating the protocol specifications. For example, adding or removing specific types of data, changing their sampling frequencies, etc.

9.1. Recommendations for maintenance

The test results in WP3 (Impact of user behaviours) demonstrated that within normal service intervals, the excess emissions are quite negligible, and post-service emission levels in most cases were at the same level as before service, especially taking into account the accuracy of this type of measurement. See MODALES D3.1 (Emission measurements, Section 5) for more details. Thus, the negligence of motorists regarding service must be quite severe before exhaust emissions are critically affected and could lead to the triggering of an event. It was also noted that the changes in fuel consumption due to service were somewhat ambiguous, with some cars reacting positively to the lowering of the consumption, others reacting in the opposite way, and some remaining more-or-less at the same level. However, changes in all cases were very small, and close to the level of the margin of error in this kind of chassis dynamometer tests. Therefore, the incentive for the motorist to properly maintain the vehicle's state-of-tune seems to be quite low.

Nevertheless, this statement was made on servicing focused only on the engine, yet mechanical items like binding brakes or weak shock absorbers can adversely affect the rolling resistance of the vehicle, which in turn increases energy and fuel consumption, with an expected upsurge also in tailpipe pollutants. However, within the scope of MODALES, this kind of testing was not performed, mainly due to the difficulty in finding suitable candidate vehicles.

Furthermore, the literature review in MODALES D2.2 (Real effectiveness of OBD inspection and maintenance, and retrofits) revealed that even if the Emissions after Treatment System (EATS) performance deteriorates resulting in elevated emissions that violate OTL and lead to MIL activation and one or more DTC is duly generated, the vehicle owner/operator can use inexpensive hardware dongles and readily available software to turn off the MIL and clear the DTCs. This can be made e.g., just before a Periodic Technical Inspection (PTI), in the hope of passing it, especially if the offset is only the cost of a PTI, normally less than €100, should the vehicle fail, whereas repairing the actual faults can be much costlier. This being the case, with the functionalities of present EOBD, there are few prospects for expanding the use of EOBD to expose excess emissions due to lack of maintenance and compel the motorists to rectify the situation.

As discussed in Section 4.1, maintenance is best carried out in a fully equipped garage or service centre by qualified service personnel. Service manuals supplied by the vehicle manufacturer provide information on the control of smoke through good maintenance practices and should be studied when planning preventive maintenance schedules. The fuel-injection pump or fuel injectors should only be repaired by the manufacturer, its agent or a reputable specialist.

By analysing the PTI data, one might conclude that positive effect on the reduction of the emission failures could have the increased random emission checks every year that consequently lead to increased related penalties. In addition, overloading of trucks and buses may be one of the reasons for increased failure percentages which requires for more specific controls and higher penalties for overloading.

9.2. Recommendations for anti-tampering

9.2.1. Road vehicle tampering detection potentials

The results acquired from the vehicle testing indicate the greatest change in any emissions are caused by removing any component of the EATS. Any changes made to the EATS is generally evidently distinguishable as a significant increase in exhaust emissions in question. Even with solely disabling the urea injection, the NO_X emissions increase to an equal level corresponding to the case of removing the complete SCR system. Furthermore, lesser gains in vehicle performance was found when removing the EATS compared to ECU reprogramming. Due to the remarkable increase in exhaust emissions, the removal of the EATS were in terms of exhaust pollutants easily distinguishable with the conducted tests and test layout. However, the study correspondingly demonstrated that if the EATS system is kept installed, is working as intended and would be sufficiently adaptive, ECU reprogramming has in typical operational conditions (in this case WHVC) a lesser role on increasing exhaust pollutants compared to EATS tampering. This means that detecting vehicles with reprogrammed ECUs based on exhaust concentrations may be difficult to point out even with sophisticated, laboratory grade testing methods, such as chassis dynamometer tests or PEMS equipment. This applies especially for older vehicles, because the relative changes in exhaust pollutants may have a similar effect compared to poor EATS durability and catalyst degradation.

It should be further noted that for the cases with ECU reprogramming, no error light, nor no change in software could be detected even with a workshop grade on-board diagnostics (OBD) reader. Due to these reasons, exclusively ECU remapping may be in the worst case be impossible to detect, albeit the effect of these reprogramming methods also seems to have a lesser negative environmental effect. The equipment and methods (test protocol) used in periodical inspections are typically less representative of real life emissions compared to laboratory grade measurements. Therefore, even major EATS tampering may be a challenge to detect, especially as the engine emissions are tested in unloaded conditions and with the engine pre-warmed.

9.2.2. NRMM anti-tampering potentials

As NRMM is a relatively new regulatory category, many efforts to maintain NRMM emission conditions currently are focused on methodologies and measures that fall under the responsibility of the manufacturers, such as requiring manufacturers to provide maintenance instructions for emission-related components, making tampering difficult, in-use or in-service testing, and providing warranties for faulty emission components that do not result from abuse, tampering or lack of maintenance. Measures to control emissions from NRMM throughout their lifespan by effectively monitoring, detecting, diagnosing and repairing high-emitting NRMMs remain scarce. While some studies (Bristol, 2020) suggest adopting minimum engine standards for construction sites as a measure to achieve significant emissions savings, the regularity of maintenance could also be taken into account as an indicator of engine condition.

Although tampering with emission control systems is an offence in many countries, it appears that commercial tampering services are not currently prevented by law, including in most EU Member States (EUROMOT, 2017). This is particularly prevalent in the NRMM sector, which has more lenient regulations than the road vehicles. More stringent regulations on NRMM may help to prevent tampering to some extent. More effective programmes, such as I/M or PTI for on-road vehicles, could be developed and implemented for NRMM to identify malfunctions or defects in the emission control system, and perform regular maintenance. This can be further enhanced by extending the road vehicle engine OBD requirements to NRMM engines and introducing a remote emission monitoring system for in-use machinery. NRMM emission controls could also benefit from tougher enforcement measures for activities related to tampering with emission controls devices, such as the sale and manufacture of defeat devices, and services to remove or install these devices. Current practice, such as on-site inspections, could be expanded to cover a broader range of applications or engine categories in a wider range of locations with more sophisticated procedures to identify malfunctioning and tampered devices.

9.3. Legal best practices and recommendations

9.3.1. Introduction

This section provides best practices and recommendations from a legal perspective which address the issue of tampering based on the research carried out by Spark Legal Network. This research was presented in Deliverable 2.3 (Legal situation of tampering) in the context of the project.

The best practices and recommendations are structured into four categories, namely the definition of tampering in the context of light duty vehicles, legal requirements placed on manufacturers, specific anti-tampering legislation, and enforcement and penalties. For each category, background information is provided, after which the recommendations are presented, and best practices relating to or even illustrating those recommendations are discussed.

A stakeholder survey with the objective of validating the recommendations from a legal perspective was created. This survey presented the recommendations (as discussed below), and asked the stakeholders completing it to indicate the extent to which each (legal) action should be prioritised (high priority/medium priority/low priority/do not know), as well as provide a reasoning for this indication. The survey was made available on EU Survey, an online survey-management system built for the creation and publishing of globally accessible forms [80], and an invitation to participate was sent out to the more than 300 governmental and industry stakeholders as well associations that were also asked to provide input in relation to the legal data collection exercise carried out by Spark Legal Network (see Deliverable 2.3 for more information). For most of the recommendations (eight out of 13), the majority of stakeholders indicated a high priority level was appropriate. For the remaining recommendations (five out of 13), the majority of stakeholders indicated a medium level of priority should be given. In addition, there were almost no indications of low priority levels. Thus, it was considered that all recommendations identified were validated through this stakeholder survey.

9.3.2. Definition of tampering in the context of light duty vehicles

Background information

EU safety, environmental, and conformity of production requirements of a vehicle are certified through the type approval process by national authorities before authorising the vehicle to be placed on the EU market. Manufacturers provide model vehicles that are used to test compliance with EU safety rules, noise and emission limits, and production requirements. With regard to the EU legal framework in place, Directive 2007/46/EC [81] makes type approval compulsory for all categories of whole vehicles and lays down the procedure to be followed for the approval of vehicles. Type approval processes are further divided into two main categories. Type approval in relation to light passenger and commercial vehicles are regulated by *Regulation (EC) No 715/2007 of the European Parliament and of the Council of 20 June 2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information* (hereinafter referred to as 'Regulation (EC) No 715/2007'), while *Regulation (EC) No 595/2009 of the European Parliament and of the Council of 18 June 2009 on type- approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information* (hereinafter referred to as 'Regulation (EC) No 595/2009') is applicable to heavy duty vehicles.

Regulation (EC) No 715/2007 on light passenger and commercial vehicles defines 'defeat devices' as "any element of design which senses temperature, vehicle speed, engine speed (RPM), transmission gear, manifold vacuum or any other parameter for the purpose of activating, modulating, delaying or deactivating the operation of any part of the emission control system, that reduces the effectiveness of the emission control system under conditions which may reasonably be expected to be encountered in normal vehicle operation and use". Defeat devices that reduce the effectiveness of emission control systems are prohibited by this Regulation and Member States are required penalise the use of such devices.

Regulation (EC) No 595/2009 on heavy duty vehicles prohibits the use of defeat strategies and thereby also prohibits the use of defeat devices that reduce the effectiveness of emission control equipment, and requires Member States to lay down provisions on penalties in this regard. However, unlike Regulation (EC) No 715/2007 on light duty vehicles – which does not provide any definition of tampering - it defines tampering as "means inactivation, adjustment or modification of the vehicle emissions control or propulsion system, including any software or other logical control elements of those systems, that has the effect, whether intended or not, of worsening the emissions performance of the vehicle".

Recommendations

As part of the EU legal framework on type approval, defeat devices are generally and explicitly prohibited. However, tampering is only defined in the context of heavy-duty vehicles; although Regulation (EC) No 595/2009 offers a definition in relation to the concept of tampering, Regulation (EC) No 715/2007 does not. If full alignment of the legislation on heavy and light duty vehicles on tampering activities is to be achieved, an update of Regulation (EC) No 715/2007 could be considered. Specifically, a definition of tampering corresponding to the one in Regulation (EC) No 595/2009 could be incorporated into Regulation (EC) No 715/2007.

Moreover, Regulation (EC) No 595/2009 specifies that tampering with systems which control NO_X emissions (including for example, tampering with systems which use a consumable reagent) by manufacturers, repairers and operators of the vehicles must be subject to a penalty. In order to avoid any further inconsistencies between the regulation of light and heavy-duty vehicles, Regulation (EC) No 715/2007 could be amended in order to include a similar provision.

9.3.3. Legal requirements on manufacturers

Background information

In most Member States, the type approval process is based on Directive 2007/46/EC (establishing a framework for type approval processes). The type approval process requires manufacturers to make prototypes available to the national type approval authorities. The manufacturer makes available approximately a dozen pre-production cars, which then are used to test compliance with EU safety rules (e.g. installation of lights, braking performance, stability control, crash tests with dummies), noise and emission limits, and production requirements of individual parts and components. The approval of a vehicle type in one EU Member State is valid EU-wide based on the mutual recognition of approvals.

In the majority of Member States, there seem to be no specific national legal requirements on manufacturers relating to the prevention of tampering in place (aside from those applicable in the context of type approval processes).

Best practices and recommendations

If Member States intend to enact stricter legal requirements on manufacturers that contribute to the effective fight against tampering, the following actions could be taken.

Extending manufacturers' responsibilities for all matters relating to the approval process ensures there is one point of contact, and the manufacturer remains involved and responsible (including in relation to the prevention of vehicle tampering) throughout the entire manufacturing process.

In Austria, the manufacturer is responsible to the approval authority for all matters relating to the approval process and for ensuring the conformity of production, even if it is not directly involved in all stages of the manufacture of the vehicle, the system, the component or the independent technical unit. In the case of a multi-stage type approval, each manufacturer is responsible for the approval and conformity of the production of the systems, components or independent technical units that it adds at the vehicle manufacturing stage.

Obliging manufacturers to disclose (additional) information enables national authorities and vehicle owners to take action based on the data provided (e.g. in relation to discovered defects). The broader set of data points available may be used to extend the requirements to be granted type approval and could prove to be useful in specifically targeting tampering.

Austria places an obligation on manufacturers to inform authorities in the event of recalling vehicles that have been granted type approval.

Belgian national legislation similarly requires manufacturers to disclose information on vehicles that have been recalled after manufacturing or when designing defects were discovered. The owners of such vehicles must be given notice that they should have their vehicle inspected.

In Germany, in some cases, the manufacturer shall make available to users all relevant information and necessary instructions indicating any special conditions or restrictions of use applicable to a vehicle, component or separate technical unit. The vehicle, component or separate technical unit may not be offered for sale, sold or placed on the market unless it is accompanied by the information and instructions supplied pursuant to the first sentence.

Requiring extensive on-board diagnostic (OBD) system usage can provide authorities with easily accessible data to uncover attempts of tampering with the vehicle or its parts.

In Belgium, vehicles must be equipped with an OBD system which diagnoses if some parts of the car are tampered with.

9.3.4. Anti-tampering legislation

Background information

In most Member States, vehicle tampering is prohibited under the national law. It may be noted, however, that this prohibition most often is derived from legislation on type approval processes, rather than adopted as a specific legal provision.

Best practices and recommendations

Vehicle tampering may take place following the granting of the type approval. Thus, in order to prohibit a wider scope of tampering conducts, Member States may consider applying rules in relation to the following outside the context of the type approval process.

Adopting rules prohibiting vehicle tampering will enable authorities to apply anti-tampering measures outside of the context of the type approval process.

In Germany, legislation prohibits vehicle tampering.

Post-type approval rules in Slovakia prohibit making, procuring or giving to another person equipment or software for the purpose of unauthorised manipulation of parameters evaluated during technical control, emission control or control of originality.

A general prohibition exists in Finland, according to which vehicle used in traffic may not be repaired, modified, allowed to change, or be equipped with an accessory after commissioning in such a way that the vehicle no longer meets the requirements that were in force in Finland at the time of the vehicle's first commissioning or later.

Laying down specific provisions in relation to emission levels or emission controls applicable after the type approval is obtained may contribute to the prevention of tampering.

In Belgium, second-hand cars sold by professionals or private persons must be granted a "Car-Pass" certificate. The certificate contains data on the CO_2 emissions of the vehicle, which aims at preventing any tampering with the emission control system or filter. The CO_2 emissions on the Car-Pass must comply with the certificate of conformity.

In France, it is prohibited to carry out transformations on a vehicle having the effect of removing a pollution control device, degrading its performance or masking its possible malfunction, or engaging in propaganda or advertising in favour of these transformations.

In the Netherlands, any modifications made to the emission control system of a vehicle must comply with the requirements laid down in the Vehicle Regulation (to the extent that those requirements are related to the modification made) unless the emission control system is replaced by the same original system or a system which has been approved under Regulation (EC) No 715/2007 or Regulation (EC) No 595/2009.

Laying down specific provisions applicable after the type approval regarding the tampering with aftermarket parts can ensure that aftermarket parts are not tampered with and they comply with road safety regulations.

In Belgium, there are some prohibitions regarding aftermarket parts, which are related to road safety (e.g. tampering with the brakes system, removing lights, etc.). For non-prohibited modifications, a validation report is required, ensuring that the modification has been approved.

In the Netherlands, in addition to the general prohibition on tampering, Chapter 6 of the Vehicle Regulation includes provisions in relation to modifications made to a vehicle. It specifies that modifications in the construction of a registered vehicle (with the exception of the installation of an electric drivetrain or a fuel system for gas) are subject to the requirements as stated at the time of the commissioning of the vehicle.

Establishing specific provisions applicable after the type approval regarding the tampering with the OBD system may allow authorities to check emission levels, detect malfunctioning, and verify the correct functioning of the OBD.

In Spain, technical inspection of vehicles (ITV) stations must have the necessary equipment to carry out an OBD port diagnosis in those vehicles that support it.

In Romania, the regular roadworthiness tests include OBD readings. Sub-optimal functioning detected is one of the types of tampering or malfunctions constituting major deficiencies.

9.3.5. Enforcement and penalties

Background information

In relation to type approval processes, most Member States have laid down various penalties and sanctions, mostly consisting of administrative fines. In cases where the approval is incomplete or there have been changes to the vehicle that result in non-conformity of the type for which approval has been granted, a withdrawal of the type approval is generally applicable in most Member States. The subjects of the penalties are generally the manufacturers of the vehicles or entities who possess the type approval certificate.

Post-type approval inspections include periodic roadworthiness tests and technical roadside inspections. Periodic roadworthiness tests are carried out in specific garages or centres and assess the road-safety of the vehicle and its compliance to environmental rules. Technical roadside inspections are conducted at random and are usually divided into an initial inspection and a further in-depth inspection, if necessary. Sanctions in relation to periodic roadworthiness tests generally entail fines to the drivers of the vehicle that was found not to be in compliance with the national requirements. The use of the vehicle is restricted or prohibited in all Member States if it poses a danger for road safety. Sanctions in relation to technical roadside inspection apply to the driver or the owner of the vehicle and are generally lower than those applicable to periodic roadworthiness inspections.

Best practices and recommendations

In terms of the effectiveness of the enforcement of the rules on tampering, the legal research shows that the main issues stem from the lack of severity of the sanctions. In order to increase the dissuasiveness of the sanctions, raising the amounts of the fines or punishments applicable to violations of rules on vehicle tampering may thus be considered. In addition, harmonisation of sanctions across Member States could contribute to effectively tackling conducts where tampered vehicles or their parts are sold in Member States with lower sanctions.

In relation to penalties concerning type approval, the expiration and revocation of the type approval certificate in case of change of circumstances can help remove these vehicles from operation on public roads. In addition, penalties going beyond fines may deter vehicle tampering. Lastly, broadening the scope of sanctions may enable the punishing of other parties that may be involved in tampering besides the manufacturers.

In Germany, the type approval certificate expires in cases where the type of vehicle approved in the type approval is modified, a danger to road users is to be expected, or the exhaust emission or noise behaviour has worsened. The certificate may be revoked or withdrawn, for example, if vehicles do not conform to the approved type or they pose a significant risk to road safety.

In Belgium prohibitions are available besides sanctions (e.g. prohibition of sale if the certificate of conformity is found to be incomplete). In Ireland, intentionally or recklessly making statements or declarations, as well as producing, providing, sending or otherwise making use of a document which that person knows to be false are punished as offences. Falsifying test results in connection with the type approval and various forms of withholding of data also constitute an offence.

In Spain, sanctions apply not only to manufacturers but to a wide range of people (e.g. owners, directors, managers, manufacturers, sellers, importers, organisation, entities, laboratories, etc.) Similarly, in Slovakia, recipients of fines are manufacturers or its representatives, the holders of the trial authorisation to vehicle operation and anyone without certificate or permission performing the activity of a manufacturer or its representative.

The adoption of penalties for the breach of post-type approval rules may deter tampering with the emissions control design.

In Finland, fines are applicable if the prohibition on the use of a device limiting the operation of an emission control system is violated. France laid out administrative penalties for carrying out or having carried out transformations on a vehicle having the effect of removing a pollution control device, degrading its performance or masking its possible malfunction, or engaging in propaganda or advertising in favour of these transformations.

Gradual sanctions to be applied in the context of periodic roadworthiness tests and technical roadside inspections can give drivers and owners the opportunity to rectify minor defects, while also allowing authorities to prohibit the use of vehicles that pose a greater degree of danger.

In Finland, for example, if defects are identified, or if the vehicle is not allowed to be on the road, the inspectors may withdraw its registration plates, transfer plates, registration certificate, test number certificate, transfer license or use any other appropriate means to prevent the vehicle from being on the road. In case the defect does not pose an immediate threat, a time limit within which it must be rectified is set. The driver of the vehicle will be fined if it fails to comply with the repair obligation, violates the prohibition on the use of a vehicle or the prohibition on driving, fails to comply with the obligation to keep the vehicle roadworthy, violates the obligation to allow the performance of a technical roadside inspection, and/or fails to comply with the inspection obligation.

In Belgium, the sanction depends on the gravity of the defect identified. If the vehicle poses a direct and immediate danger, its use will be restricted or prohibited as long as the defect is not repaired.

10. Conclusion

This deliverable is the outcome of MODALES Task 4.2 “Periodic inspection and other anti-tampering solutions”. The purpose of this task and D4.2 was to investigate the detection of tampering or malfunctions by considering a wide range of technical, behavioural and legal criteria, in order to clarify the current and future capabilities of the EOBD protocol.

From all the described failures the most important are the exhaust and emission control system because they are strongly related with the emissions of the vehicle and thus related to this study. Suspension, brakes and tyres are crucial to maintain proper safety. Maintenance is best carried out in a fully equipped garage or service centre by qualified service personnel. Service manuals supplied by the vehicle manufacturer provide information on the control of smoke through good maintenance practices and should be studied when planning preventive maintenance schedules. Additionally, an in-depth analysis of the vehicle inspection data revealed the positive effect on the reduction of the emission failures that the increased random emission checks could have every year.

The main motivation for tampering is the avoidance of repair costs. It is easily noticed that tampering of light-duty, heavy-duty as well as of non-road machineries is very common in many European countries. Thus, new innovative measures have to be taken from authorities to prevent tampering. As far as the common ECU re-flashing tampering method is concerned, the current security techniques have proven to be insufficient to prevent unauthorised flashing. In order to prevent the re-flashing of the ECU the improvement of security has to be enhanced through encryption with secure key generation and storage, intrusion detection, code signing, authentication and data integrity checks.

Two options for vehicle modification and/or manipulation were studied in this task: ECU reprogramming and/or tampering of the vehicle EATS. The results acquired from this demonstration suggests that the effect of different ECU remapping and EATS tampering solutions may change the vehicle performance characteristics relatively significantly. The results also indicate that the effect of ECU remapping had a lesser effect on exhaust pollutants compared to EATS tampering. Despite this, none of the tampering configurations tested in this study improved the overall vehicle emission behaviour. The ECU reprogramming versions adapted in this study were found to affect especially the EATS thermal control, increasing the delay of catalyst activation. No effect on particulates was found for ECU reprogramming with the DPF installed. On the contrary, removal of vehicle EATS neglects totally the suppression of any exhaust pollutants, resulting exhaust emissions corresponding to engine raw emissions.

This task demonstrated that a simple solution developed within the project could spot engine tampering as long as the OBD data are not manipulated by an aftermarket software. The notification of potential violations to the authorities could be a strong reason for discouraging such acts by the vehicle owners.

An overview of best practices and recommendations based on the legal research on vehicle tampering was carried. It provided that if harmonisation of the legislation on heavy and light duty vehicles is to be achieved, an update of Regulation (EC) No 715/2007 may be required. In this regard, it focused specifically on the alignment of the definitions of tampering and penalties. Secondly, it demonstrated the possible actions to be taken in relation to the obligations placed on manufacturers, which may prevent tampering with vehicles. The prohibition on tampering is most often derived from legislation on type approval processes rather than separate legal provisions. The recommendation suggests that Member States might consider applying rules outside the context of the type approval process in order to prohibit a wider scope of tampering conducts. Lastly, gradual sanctions to be applied in the context of periodic roadworthiness tests and technical roadside inspections can give drivers and owners the opportunity to rectify minor defects, while also allowing authorities to prohibit the use of vehicles that pose a greater degree of danger or damage to the environment.

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