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Effect of Tampering on On-Road and Off-Road Diesel Vehicle Emissions

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Abstract: Illegal manipulation (i.e., tampering) of vehicles is a severe problem because vehicle emissions increase orders of magnitude and significantly impact the environment and human health. This study measured the emissions before and after representative approaches of tampering of two Euro 6 Diesel light-duty passenger cars, two Euro VI Diesel heavy-duty trucks, and a Stage IV Diesel non-road mobile machinery (NRMM) agricultural tractor. With tampering of the selective catalytic reduction (SCR) for NO_x, the NO_x emissions increased by more than one order of magnitude exceeding 1000 mg/km (or mg/kWh) for all vehicles, reaching older Euro or even pre-Euro levels. The tampering of the NO_x sensor resulted in relatively low NO_x increases, but significant ammonia (NH_3) slip. The particle number emissions increased three to four orders of magnitude, reaching 6–10 × 10^{12} #/km for the passenger car (one order of magnitude higher than the current regulation limit). The tampered passenger car's NO_x and particle number emissions were one order of magnitude higher even compared to the emissions during a regeneration event. This study confirmed that (i) tampering with the help of an expert technician is still possible, even for vehicles complying with the current Euro standards, although this is not allowed by the regulation; (ii) tampering results in extreme increases in emissions.

Keywords: tampering; high emitters; emulator; ECU flashing; tuner; NO_x emissions; DPF removal; NO_x sensor; SCR; diesel exhaust fluid (DEF); urea

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1. Introduction

Road vehicles contribute significantly to air pollution, especially in cities. During the type approval of vehicles, their emissions have to respect limits, the so-called Euro standards in European Union (EU). For example, the Euro 1 (1992) Diesel passenger cars limit for hydrocarbons plus NO_x was 970 mg/km, while the current Euro 6 (2014) is 170 mg/km. The latest Diesel passenger cars emit less than half of the Euro 6 NO_x limit (80 mg/km) even on the road [1]. For heavy-duty engines, the Euro I (1992) NO_x limit for the steady cycle in the laboratory was 8000 mg/kWh, while the latest Euro VI (2013) standard is 400 mg/kWh, a twenty-fold reduction. Limits to non-road mobile machinery (NRMM) (i.e., off-road engines) were introduced later: Stage I (1999) had a NO_x limit of 9000 mg/kWh, while the latest Stage V (2018) aligned the levels with the heavy-duty engines (400 mg/kWh). Particulate matter (PM) mass limits have also decreased by more than 95% for all vehicle categories. Despite the stricter limits, the environmental benefits for these two pollutants, even though not of the same magnitude, were still evident: the latest European environment agency's (EEA) report mentioned 40% ambient air NO_x reduction between 1990 and 2017 and 44% for PM between 2000 and 2017 [2]. There are various reasons for the less than expected decreases: increased contributions from other sources (such as heating and power production), increased number of vehicles and higher emissions of vehicles under real-world driving conditions (e.g., Dieselgate) [3]. Recently the contribution of high emitters has been under the focus [4]. Each vehicle has an onboard diagnostic (OBD) system, which consists of sensors designed to detect, record, and report malfunctions of all monitored emission systems or components. Nevertheless, a vehicle can perform poorly because of undetected malfunctioning, tampering, deterioration, or poor maintenance of its exhaust aftertreatment system [5–7].

Vehicles owners sometimes tamper (i.e., illegally manipulate) their vehicles to avoid costs of consumables, maintenance, and/or the repair of the emissions control systems [8]. Other reasons are reducing costs due to downtime, improving fuel economy, performance tuning, and exhaust sound level. In the EU "tampering" 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" (Regulation (EC) 595/2009). In the United States of America (USA), the term "aftermarket defeat device" refers to parts and components which bypass, defeat or render inoperative any emissions-related components of the vehicle [9]. The term "tampering" refers to the actual removal or rendering inoperative of emissions-related components. In this paper, the term tampering refers to both.

Tampering occurs mainly in Diesel vehicles, which is the focus of this paper. Tampering exists in Europe, but the magnitude of the problem is largely unknown. An internet review in 2017 identified 87 separate sites supplying Europe with tampering devices for Euro IV, V, and VI vehicles [10]. Reports of roadside inspection or plume chasing mentioned that up to 25% of the vehicles have tampered devices [8,11–14]. There is scarce information regarding the level of tampering on different markets and geographic areas. In general, it is expected that countries with stricter emissions standards, but looser technical inspection mechanisms should suffer more. It is reported that within Europe, trucks from certain countries have higher percentages of tampering based on roadside inspections [11]. Although the exact reasons are not clear, these findings may be related to fewer and less strict roadworthiness checks and inspections, and lower fines in these regions. They could also be associated with a higher relative fuel cost compared to countries where fuel prices are comparatively lower considering the higher gross domestic product (GDP) and service cost. There is no proper enforcement against tampering in place anywhere in Europe [15], unlike the USA, where it is clearly stated that it is a crime to knowingly falsify, tamper with, render inaccurate, or fail to install any "monitoring device or method" [9].

1.1. Achieving Low Emissions

The low tailpipe emission levels are achieved by optimizing the engine calibration and with emission control devices.

1.1.1. Engine Calibration

Manufacturers calibrate the engine control functions to optimize fuel consumption and power performance while maintaining low emission levels and safety. The calibration of the electronic control unit (ECU) results in a series of, usually tabulated, parameter values that govern the operation of actuators and systems in the engine and exhaust after-treatment system, also known as engine or ECU maps. The calibration considers regional parameters (extreme heat or cold, pressure/altitude ranges) and driveability. Therefore, sometimes there is room to improve one parameter (e.g., power output) in the cost of others (e.g., driveability or emissions).

1.1.2. NO_x and PM Emissions Control Devices and Customer Concerns

NO_x are formed at high exhaust gas temperatures. With exhaust gas recirculation (EGR), exhaust gas is added to the intake air, regulated by a valve. This results in lower peak combustion temperature and lower NO_x. EGR can make combustion less efficient, compromising fuel economy and power [16]. The most common problem of EGR is the accumulation of soot on the EGR valve and passages. Soot in combination with oil vapor from a closed crankcase ventilation system can result in valve sticking due to deposit build-up. However, with Euro 6 vehicles, the EGR issues have been addressed by the automotive manufacturers.

Selective catalytic reduction (SCR) converts NO_x to N_2 and H_2O with a catalyst and a reagent [17]. Due to the hazardous nature of the pure anhydrous ammonia, a Diesel exhaust fluid (DEF) (commercial name AdBlue®), which is a 32.5% aqueous urea solution, is widely used in the industry for this application as a reagent. The consumption is estimated to be 1–2 L of reagent per 1000 km, depending on the engine-out emissions [18,19]. An optimal ratio between NO_2 and NO is needed for a high NO_x reduction efficiency at low exhaust gas temperatures (e.g., during low load, low-speed operation in cities). This ratio is achieved with an upstream Diesel oxidation catalyst (DOC) which converts NO to NO_2. The EGR ratio can also affect the NO/NO_2 ratio mainly because the NO_x reduction is achieved by NO decrease [20].

Diesel particulate filters (DPFs) trap the soot emitted by Diesel vehicles with >90% filtration efficiency [21,22]. The accumulated PM deposited in the inlet channels of the DPF leads to increased backpressure and fuel penalty; for this reason, the deposited soot has to be periodically removed (oxidized to CO_2). The trapped soot can be oxidized passively at high exhaust gas temperatures (e.g., high-speed driving). Actively, the exhaust gas temperature can increase, e.g., with late fuel injection: the unburnt fuel is oxidized in the DOC increasing the exhaust gas temperature. In addition to the fuel penalty due to the soot accumulation in the DPF, or the regeneration process, there is the risk for uncontrolled regenerations that can damage the DPF. Uncontrolled regenerations can sometimes happen due to excessive soot loading or injected fuel [23], for example, when driving too frequently in city areas [24]. A final concern is that, over time, the accumulated ash (mainly due to bad lubricant and fuel) that cannot be oxidized during the regeneration results in a more frequent need for regenerations.

1.2. Tampering Approaches

In general, tampering involves changes to the emission system hardware and modifications to the engine management software [25,26].

To increase (electronically "tune") the performance of an engine (higher power or better fuel economy) two approaches are used: (i) onboard diagnostics (OBD) tuning, i.e., directly accessing and reprogramming the ECU (also called ECU flashing or remapping); (ii) tuning boxes, i.e., optimization with auxiliary control devices (also called performance/tuning chips, piggybacks or power chips/boxes). Tuning boxes work by connecting to existing sensors on the engine and manipulating one or more signals that they send to the vehicle's ECU. Two sensors that are commonly taken into consideration are the intake air and coolant temperature sensors.

The main type of tampering for the latest generation of aftertreatment devices is ECU reprogramming (or flashing or remapping) which changes the engine control software and overrides the OBD system. Emulators, which are devices that manipulate control signals and messages without reprogramming the engine, are also used, but less often. They can be easily found in the market, and they are cheaper but there are a lot of operating issues and they are prone to visual inspections or other roadside checks. Both approaches can be accompanied by "delete" hardware kits (delete tuners) for emission control systems and/or sensors and actuators modifications (called modifiers). Examples are spacers for lambda or temperature sensors. In parallel, diagnostic trouble code (DTC) deletion tools are offered to support tampering by erasing error codes detected by the OBD (DTC erasers or OBD suppressors).

EGR tampering is completed by software manipulation (e.g., valve positioning) and/or mechanically. For SCRs, except ECU reflashing, SCR (or DEF) emulators are sometimes used at light commercial vehicles and trucks, which imitate the SCR system components (e.g., signals related to the temperature of the exhaust system and the availability and quality of DEF) or "modifying" the NO_x sensors values (called NO_x emulators). Regarding DPFs, removal methods include replacing the DPF with a piece of exhaust pipe ("DPF delete"), cutting the DPF canister, removing the filter from inside, then welding the canister back together. Alternatively, tampering with the DPF includes drilling out the DPF, with a drill into the DPF's inlet and outlet pipes ("DPF drilled/gutted") [27]. In addition to removing the DPF, the sensor measuring the pressure difference across the DPF or the ECU will be modified to disable the regenerations. Depending on the vehicle architecture, the DPF removal requires in some cases the deactivation of the SCR because the two aftertreatment devices are connected in terms of control.

The tampering is either offered as a service in workshops or as a product with instructions for installation provided in webshops, online shopping areas, forums, and social media.

1.3. Environmental Consequences of Tampering

Tampered vehicles can have very high emissions. Depending on the frequency of tampering, the fleet emissions can increase significantly. There is not much data published on actual emissions degradation after tampering and most published studies focused on two-wheelers (mopeds and motorcycles) [28,29]. Studies have shown that 10–25% of the high emitters contribute 50–80% of the fleet emissions [4,30,31]. Tampering will be even more important for the latest and future technologies due to their low tailpipe emissions, resulting in huge emissions increases if their emission control systems are deactivated. The Horizon 2020 project diagnostic anti-tampering systems (DIAS) aims at achieving a strong reduction or total elimination of tampering emissions-relevant systems using high resistance to hardware and software manipulation and detection of tampering [32].

1.4. Tampering vs. Retrofitting

It should be added that tampering is in many ways opposite of retrofitting, i.e., the installation of various emission control technologies to improve emissions from older existing vehicles [33–35]. Retrofitting is covered in regulations: for example, United Nations Economic Commission for Europe (UNECE) Regulation 115 on CNG and LPG retrofitting, or Regulation 132 for the approval of retrofit emission control (REC) devices for heavy duty vehicles, agricultural and forestry tractors, and non-road mobile machinery equipped with compression ignition engines. Various programs encourage users to retrofit their vehicles.

1.5. Aims of the Study

This paper aims to present the application of tampering devices at the latest generation Diesel vehicles (two Euro 6 passenger cars, two Euro VI trucks, and a Stage IV tractor) and their impact on emissions. The study tries to shed light to the following topics for which there is lack in the literature:

- what is the environmental impact of tampering of new generation vehicles (including light duty, heavy-duty and off-road machines) that there is no information of their engine out emissions?
- what are the tampering installation costs and savings?

The paper, following this introduction (Section 1), presents the vehicles and the tampering approaches (Section 2). Then, at the results section (Section 3), the impact of tampering is presented for each vehicle. At the discussion section (Section 4) the environmental impact of tampering, the cost and savings and the tampering availability are discussed. The last section (Section 5) summarizes the findings of this study.

2. Materials and Methods

The following sections describe the vehicles' characteristics, tampering approaches, testing equipment, and protocols. All vehicles were restored after finishing the project on evaluation of tampering.

2.1. Light Duty Vehicle Euro 6d-Temp

2.1.1. Vehicle

The vehicle was a Euro 6d-Temp passenger car (M1) with a 1.6 L Diesel engine and 11,000 km at the odometer. In addition to EGR, the vehicle had an aftertreatment with DOC, DPF and SCR. Market Diesel B7 fuel was used.

2.1.2. Tampering Approach

The tampering occurred with various steps of ECU flashing: initially only for the EGR valve, then only for the SCR dosing. Finally, the DPF was removed, and the SCR was deactivated, but the EGR valve was not tampered.

2.1.3. Testing

All tests were conducted on the road at the premises of the Joint Research Centre (JRC) of the European Commission, in Italy, following a real-driving emissions (RDE) regulation-compliant route (Regulation (EU) 2017/1151). The route and the characteristics are summarized in Figure 1 (see also [36]). The tests were conducted in the following order: original configuration, EGR disabled, SCR disabled, and SCR plus DPF tampered. At least two repetitions from each configuration were conducted. The tests that had DPF regeneration were not repeated, and they helped in assessing the impact of regenerations on emissions. The ambient temperature during the tests was 25 ± 3 °C.

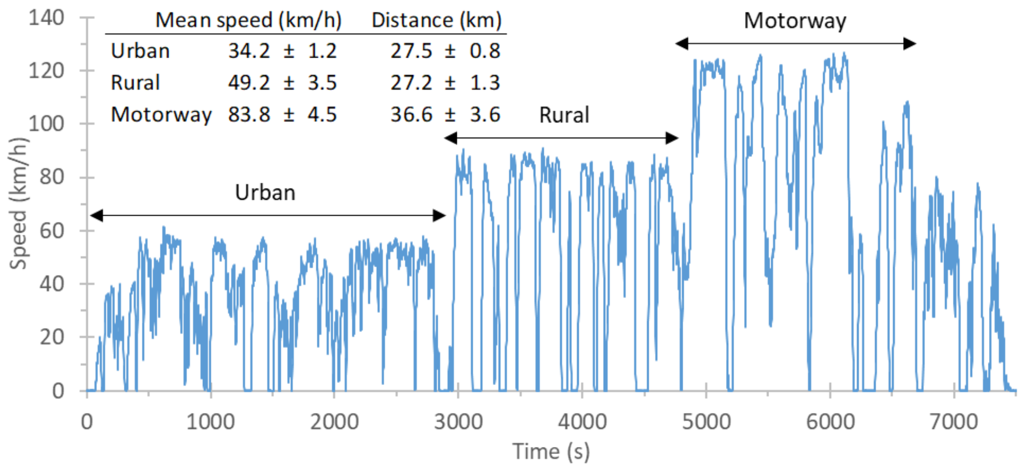


Figure 1. Typical on-road speed profile followed by the passenger car. The route is compliant with the real driving emissions (RDE) regulation for light-duty vehicles.

The portable emissions measurement system (PEMS) was the OBS-ONE from Horiba (Kyoto, Japan). The PEMS equipment comprised an exhaust gas flow meter, exhaust gas analyzers, a global positioning system (GPS) device, a weather probe with ambient gas and pressure, a power supply device, and an OBD data acquisition device (not always). The exhaust flow meter was based on the Pitot tube principle. The analyzers measured CO_2 and carbon monoxide CO with heated non-dispersive infrared detection (NDIR), NO_x with heated chemiluminescence detection (CLD), and particle number with a condensation particle counter (CPC) after a hot catalytic stripper [37–39].

2.2. Light Duty Vehicle Euro 6b

2.2.1. Vehicle

The vehicle was a Euro 6b passenger car (M1) with a 1.6 L Diesel engine and 45,000 km at the odometer. In addition to EGR, the vehicle had an aftertreatment with DOC, SCR, and DPF. Market Diesel B7 fuel was used.

2.2.2. Tampering Approach

The tampering consisted of ECU flashing for the EGR valve, and the SCR dosing. The EGR valve power supply was also disconnected, while the urea dosing module was not deactivated; it was rather modified via some internal maps of the ECU.

2.2.3. Testing

The testing took place at the Laboratory of Applied Thermodynamics premises in Thessaloniki, Greece. The route was RDE compliant, consisting of the characteristics of Table 1. The car started with the engine hot. One baseline repetition was conducted and one with the tampered vehicle. As it will be shown, the tampering was not entirely successful, and no additional repetitions were performed.

Table 1. On-road RDE-complaint trip characteristics. U = urban; R = rural; M = motorway.

Trip Characteristics	Original	Tampered
Ambient temperature (°C)	25	22
Coolant temperature (°C)	92	84
Mean speeds U/R/M (km/h)	26.1/80.0/99.1	30.3/76.0/106.6
Distances U/R/M (km)	22.6/26.0/25.3	23.1/26.0/25.0

The portable system was the smart emissions measurement system (SEMS) from TNO (Delft, Netherlands) which includes an OBD connection, GPS signal, and NO_x, NH_3, O_2, and temperature sensors connected to the tailpipe [40]. The exhaust flow rate was calculated from the fuel consumption and the air-to-fuel ratio. The CO_2 was calculated based on the fuel carbon–hydrogen ratio and the fuel flow rate. Studies have shown that the results are well comparable with PEMS [41].

2.3. Heavy-Duty Vehicle N2

2.3.1. Vehicle

The vehicle was a Euro VI Step D, N2 category truck with a 5L Diesel engine. In addition to EGR, the vehicle had an aftertreatment with DOC, DPF, SCR, and ammonia slip catalyst. Market B7 Diesel fuel was used.

2.3.2. Tampering Approach

The tampering device was an AdBlue® (or DEF) emulator. A unique characteristic was that it remained functional but with very low reagent consumption (<2% of the nominal consumption). It was installed by an expert technician without any permanent modification to the vehicle exhaust aftertreatment system and was difficult to detect by visual inspection. The intercepted modules were the vehicle diagnostic plug and after treatment control module. The tampering signals involved two CAN channels and two control units:

- Engine CAN: Communication with ECU and ACM (after treatment control module). The emulator reduced the DEF dosing command on ACM, but at the same time, it fed back a higher DEF value to ECU to avoid faults on diagnostics as ACM controls the DEF consumption. In parallel, the device emulated the downstream NO_x sensor by reducing its signal.
- Diagnostic CAN: The emulator carried out a DTC erase operation immediately after the dashboard key was switched on to ensure that the whole system worked correctly.

2.3.3. Testing

The tests were conducted at the vehicle emissions laboratory (VELA 7) of the JRC. The gas analyzers were AMA i60 from AVL (Graz, Italy), measuring hydrocarbons with a flame ionization detection (FID), NO_x with CLD, and CO and CO_2 with NDIR. Particle number measurements were performed using an AVL particle counter. The World Harmonized Vehicle Cycle (WHVC) was used to test [42], both with the original configuration and the tampering device installed. Only hot engine start tests were conducted. The cycle was divided into three parts depending on the vehicle's speed (Figure 2). The WHVC was developed based on the same set of data used to develop the type approval Worldwide Harmonized Test Cycle (WHTC) for heavy-duty engines.

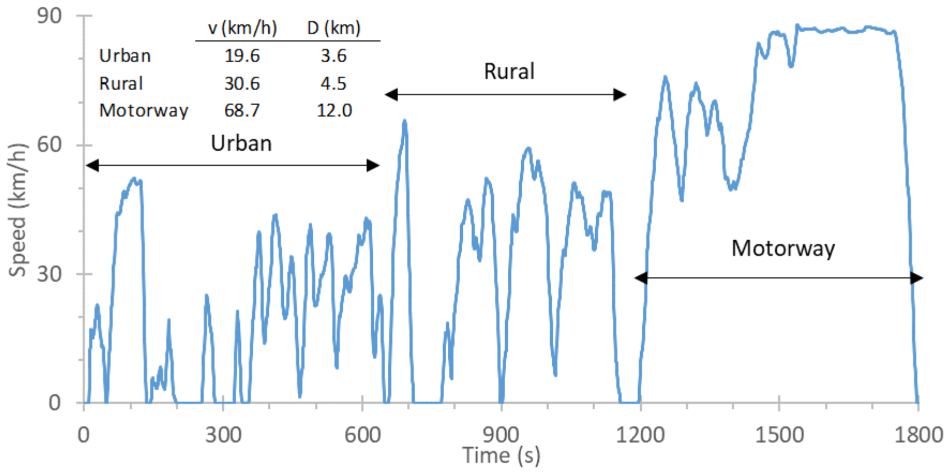


Figure 2. Speed profile followed by the N2 truck in the laboratory. The route is standardized and based on the same data used for the engines type-approval cycle. The differentiation to urban, rural, and motorway parts is only specific to this study. The mean speed (v) and distance per phase (D) is given in the inset.

2.4. Heavy Duty Vehicle N3

2.4.1. Vehicle

The vehicle was a Euro VI Step C, N3 category truck with a 12.8 L Diesel engine. In addition to EGR, the vehicle had an aftertreatment with DOC, DPF, SCR, and ammonia slip catalyst. Market B7 Diesel fuel was used.

2.4.2. Tampering Approach

The tampering devices were one NO_x sensor emulator and three different SCR emulators. The NO_x sensor emulator, which is typically used to prevent replacement of broken NO_x sensors and downtime, emulated only the downstream NO_x sensor.

The SCR emulators emulated the CAN signals between ECU and the ACM. The vehicle had separate control units for engine (ECU) and aftertreatment devices (ACM). As the whole ACM module needed to be disconnected, all signals were emulated. Some signals were constant with either a fixed value (e.g., temperatures) or zero (e.g., DEF dosing). Because all three SCR emulators required disconnection of the control unit of the aftertreatment devices, active regeneration of the DPF was not working. Hence, according to the installation instructions of the emulators, the DPFs (2 pieces) needed to be removed to prevent clogging of the filters. The particulate emissions were not measured, and only the impact on NO_x was demonstrated with these measurements, but due to the required removal of the DPF, the particulate emissions increased to unfiltered very high levels (based on the optical black smoke). As all three SCR emulators worked similarly, their results will be averaged in the Section 3.

2.4.3. Testing

The tests were conducted on road near the premises of TNO in The Hague with a SEMS (see details in Section 2.2.3). The test cycles used were a "short" cycle and an in-service conformity (ISC) cycle (Figure 3). The details of the cycles are summarized in Table 2. The ambient temperature was around 12 °C at the baseline measurements and about 9 °C with the tampering devices.

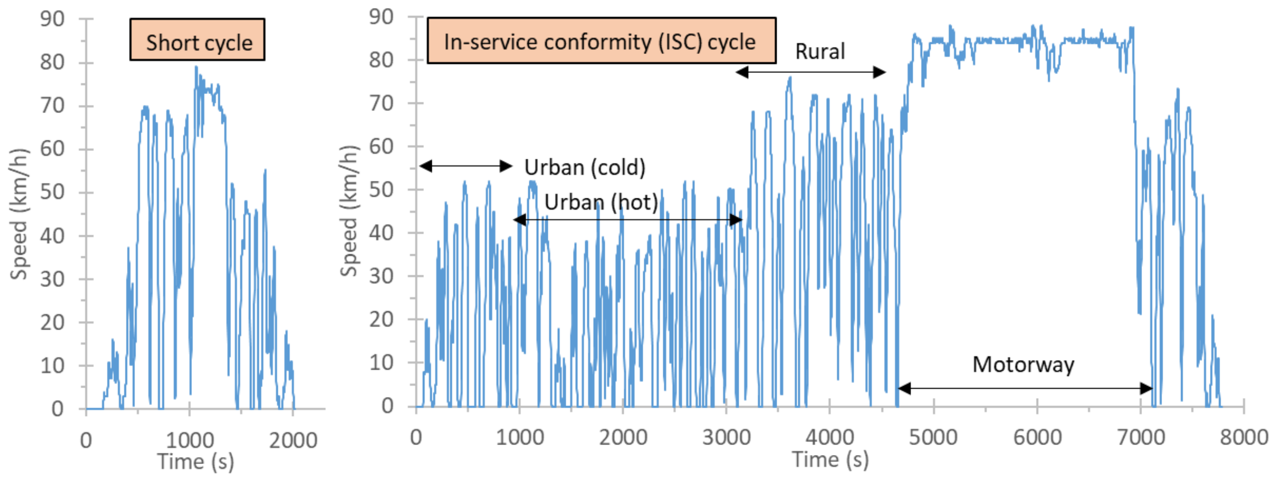


Figure 3. Speed profile of the short cycle and the in-service conformity (ISC) cycle (N3 truck).

Table 2. Characteristics of the two tested cycle (short cycle) and in-service conformity (ISC) cycle. All ISC cycles were started with cold engine, while the short cycles with cold or hot engine.

Parameter	Short Cycle	ISC Cold Start	ISC Urban	ISC Rural	ISC Motorway
Distance	18.1 ± 0.1	5.0 ± 0.6	13.1 ± 0.6	18.3 ± 0.6	52.7 ± 0.2
Mean speed	34.4 ± 1.4	20.1 ± 2.6	20.0 ± 3.2	38.0 ± 7.6	72.3 ± 7.0
kWh/km	1.83 or 1.67 [1]	2.46 ± 0.16	2.12 ± 0.05	2.04 ± 0.20	1.09 ± 0.10

[1] The higher value for the cold start test.

2.5. Non-Road Mobile Machinery

2.5.1. Vehicle

The vehicle was an agricultural tractor with a 88 kW power 3.6 L common rail four cylinders Diesel engine, compliant to Stage IV regulations. It was equipped with a DOC and an SCR. Market Diesel B7 fuel was used.

2.5.2. Tampering Approach

The tampering device was a prototype developed for the latest NRMM models. An expert technician installed it without causing any permanent modification to the vehicle. Even after installation, it was difficult to detect it upon visual inspection.

The SCR tampering device was a DEF emulator. It consisted of a control unit with a central processing unit (CPU) to elaborate signals to emulate and input/output (I/O) ports to interact with the rest of the vehicle. The emulator intercepted two CAN bus lines and the pump module. The first CAN only gave information about the vehicle when the engine was operating. The second CAN was dedicated to the upstream and downstream NO_x sensors: the downstream was disconnected and was emulated so that the ECU would not recognize any anomaly. The pump module had one serial line to detect the initialization of the pump, digital output to switch on and off the DEF pump and emulation of the DEF pressure transductor.

As a separate tampering, ECU flashing (reprogramming) was performed independently to increase the engine's power output.

2.5.3. Testing

The tractor was connected to an eddy current dynamometer (Dyno tractor-trailer from Dimsport, Serralunga, Italy), and the tests were performed with and without the emulator. During the tests with the emulator, no DTC occurred. The tests included the full power curve and a constant engine speed mode (1500 rpm, 290 Nm) corresponding to approximately 50% of maximum power.

The emissions were measured with a Semtech DS PEMS from Sensors (Saline, MI, USA). The NO_x emissions were measured via the non-dispersive ultraviolet (NDUV) principle, while CO and CO_2 emissions were measured via NDIR principle. The exhaust flow meter was based on the Pitot tube principle.

3. Results

This section describes the results for the three vehicles with and without tampering.

3.1. Light Duty Vehicle Euro 6d-Temp

The on-road emissions of the passenger car are summarized in Figure 4. The emissions of the original configuration, the regeneration (whenever available), the tampered EGR, tampered SCR, and the tampered SCR and DPF are given separately for the route's urban, rural, and motorway parts.

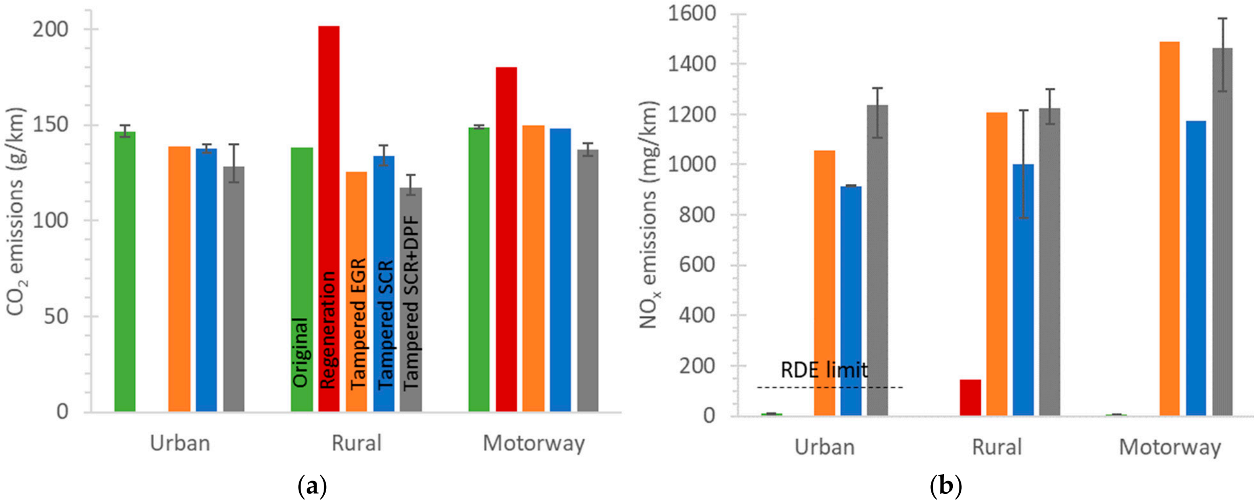


Figure 4. Impact of regeneration (red bars), tampering of the EGR (orange bars), SCR (blue bars) and/or the DPF (grey bars) on the emissions of the original vehicle configuration (green bars), indicated with different colored bars: (**a**) CO_2; (**b**) NO_x. Error bars give min-max values of two or three repetitions. Test: On-road routes (Figure 1). To convert (m)g/km to (m)g/kg fuel multiply by 22.5. DPF = Diesel particulate filter; EGR = exhaust gas recirculation; SCR = selective catalytic reduction.

The CO_2 emissions of the tampered EGR and the tampered SCR cases were similar (Figure 4a) and exhibited a 3–9% reduction compared to the vehicle baseline for the urban and rural routes. There was no evident decrease at the motorway route. The CO_2 benefit is associated with the no or reduced EGR of the tampered vehicle. At the motorway part it is highly likely that the use of EGR was low also for the original configuration. The CO_2 emissions with the removed DPF were 8–15% lower, indicating considerable fuel savings due to the lower backpressure without the DPF. The DPF regeneration increased the CO_2 emissions by 20–45%. The vehicle regenerated on average every 350–450 km, and the distance during the regeneration events was 16–29 km, thus, the 20–45% CO_2 increase was equivalent to an average 2.4–3.0% CO_2 increase for the CO_2 emissions with the original configuration (the so called ki factor).

Figure 4b presents the NO_x emissions. With the original configuration, they were close to the detection limit of the onboard measurement system. During the regeneration route at the rural part, NO_x increased and reached 144 mg/km. The whole trip emissions were 44 mg/km, well below the regulation Euro 6 limit (80 × 1.43 = 114 mg/km) for this vehicle. The conformity factor is 1.43 and considers the measurement uncertainty of the on-road equipment [43]. The routes with tampered SCR had emissions 900–1200 mg/km, while with tampered EGR or SCR plus DPF around 1100–1500 mg/km. There is no clear explanation for the high emissions of the tampered EGR. The SCR should be functioning, but the results showed that this was not the case. Probably internal conflicts due to the blocked EGR, disabled the SCR or the SCR calibration could not be set to compensate for situations where EGR was malfunctioning or disabled. The functioning of the EGR can explain the relative lower NO_x emissions of the tampered SCR case. In all cases, the emissions were almost ten times higher than the Euro 6 on-road limit for Diesel passenger cars, and even higher than any previous limit: for Euro 1 vehicles, the limit was 970 mg/km, including hydrocarbons. The latter finding reveals that tampering can result in almost a complete cancellation of the benefits provided by advanced modern aftertreatment systems, effectively reducing the vehicle to a pre-Euro standard.

The impact of tampering on the particle number emissions is given in Figure 5a, which plots the integrated emissions of the urban, rural, and motorway parts of each route (see Figure 1) for the baseline/original configuration, the original configuration when a regeneration event took place, the tampered EGR, SCR, or SCR + DPF cases.

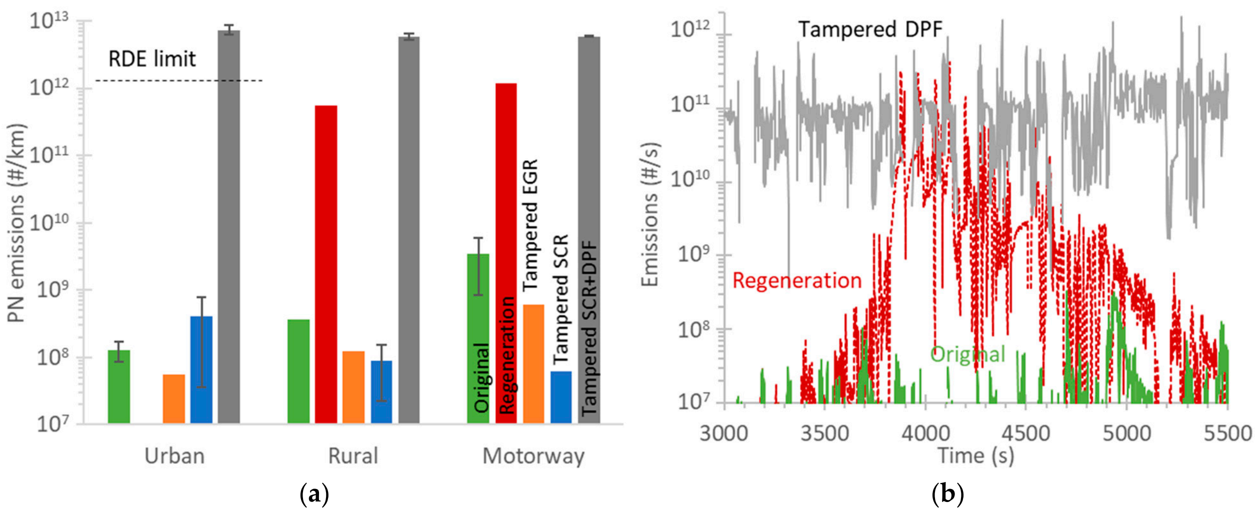


Figure 5. Impact of regeneration, tampering of the EGR, SCR and/or the DPF on the particle number (PN) emissions of the original vehicle configuration: (**a**) integrated PN emissions. Error bars give min-max values of two or three repetitions; (**b**) real-time PN emissions.

The vehicle's emissions with the original configuration were extremely low, three to four orders of magnitude below the Euro 6 limit ($6 \times 10^{11} \times 1.5 = 9 \times 10^{11}$ #/km). The 1.5 is the conformity factor for particle number [39]. During regeneration, the particle emissions reached the limit (but no limit is applicable). The EGR and SCR tampering did not affect the particle number emissions, which remained at very low levels. However, tampering (removal) of the DPF resulted in emissions 5–6 times higher than the RDE limit. The specific tampered vehicle with emissions 6–10 × 10^{12} #/km had idle particle number concentration (as determined by the PEMS) just above 2.5×10^5 #/cm^3, which is the future limit during periodical technical inspection (PTI) in Germany. The vehicle with the original configuration had weighted emissions (i.e., sum of emissions including one regeneration event) around 0.4–1.4 × 10^{12} #/km, well below the current particle number limit.

Figure 5b plots real-time emissions during the rural part of the trip for three cases: (i) original configuration, (ii) regeneration, and (iii) tampered DPF. Comparing the original and tampered DPF signals, the filtration efficiency of the specific DPF was >99.99%.

The emissions during regeneration remained below the emissions without the DPF. The filtration efficiency during the regeneration event was 84%.

3.2. Light Duty Vehicle Euro 6b

The on-road emissions of the passenger car for the different parts of the routes with and without tampering are summarized in Table 3. In general, the CO_2 had a small decrease in the urban and motorway parts, while NO_x a significant increase: NO_x almost doubled at urban and rural routes (but with relatively low absolute levels), and increased 18% at the motorway part where the absolute levels were high. Note that there is no RDE limit for this car, which was introduced with Euro 6c. The results clearly reflect the EGR deactivation, however there are doubts about the SCR deactivation. Even for the original configuration the SCR efficiency was low at motorway conditions. The ECU flashing did not fully deactivate the SCR, as the urban and rural emissions remained relatively low.

Table 3. Results of the Euro 6b passenger car tampering.

Emissions	Original	Tampered	Difference
Urban CO_2 (g/km)	128.5	122.6	−4.6%
Rural CO_2 (g/km)	113.5	114.7	1.1%
Motorway CO_2 (g/km)	154.4	148.2	−4.0%
Urban NO_x (mg/km)	127.4	234.1	84%
Rural NO_x (mg/km)	133.1	291.0	119%
Motorway NO_x (mg/km)	771.4	912.4	18%

3.3. Heavy-Duty Vehicle N2

The impact of SCR tampering on the truck's emission is summarized in Figure 6a for CO_2 and Figure 6b for NO_x. CO_2 emissions marginally decreased over urban conditions while there was no significant change in rural and motorway driving. The NO_x emissions increased to high levels (600–1000 mg/km or 1000–1700 mg/kWh). Although not applicable to vehicles, and not directly comparable due to the differences between engine and vehicle test cycles, the limit for the type approval of Euro VI heavy-duty engines is 460 mg/kWh, while for Euro V it was 2000 mg/kWh.

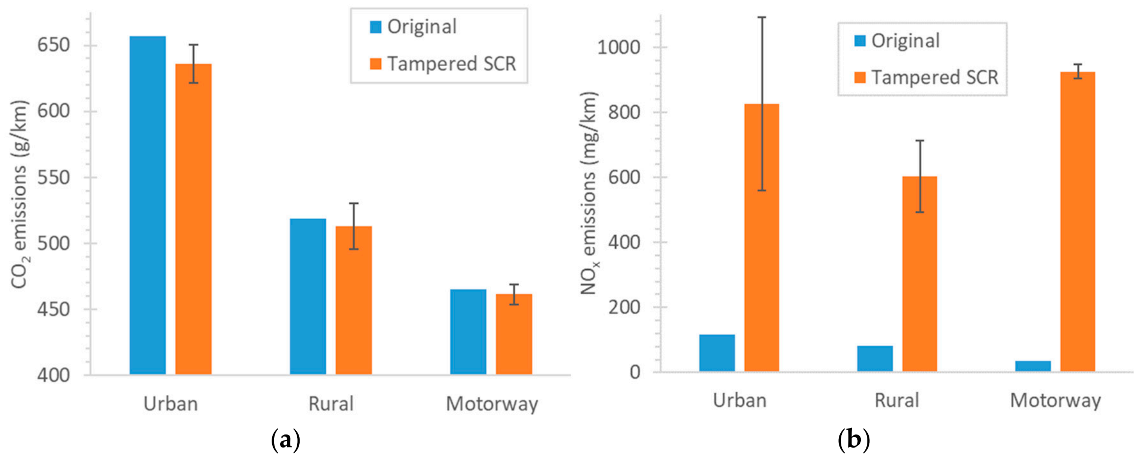
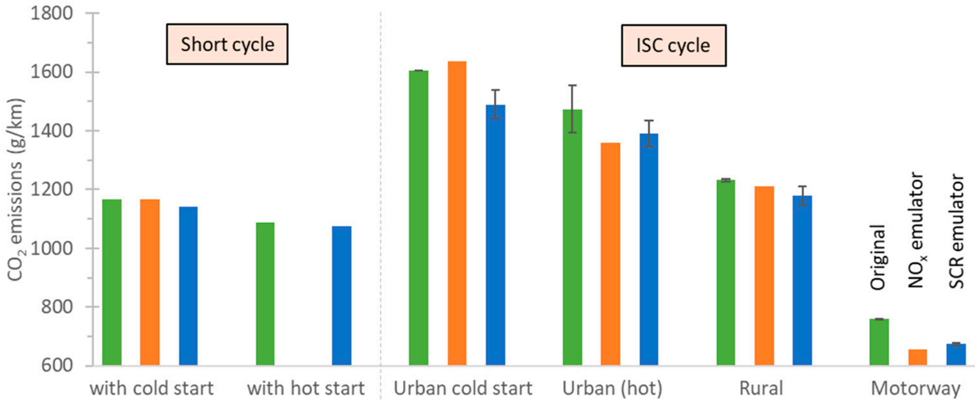


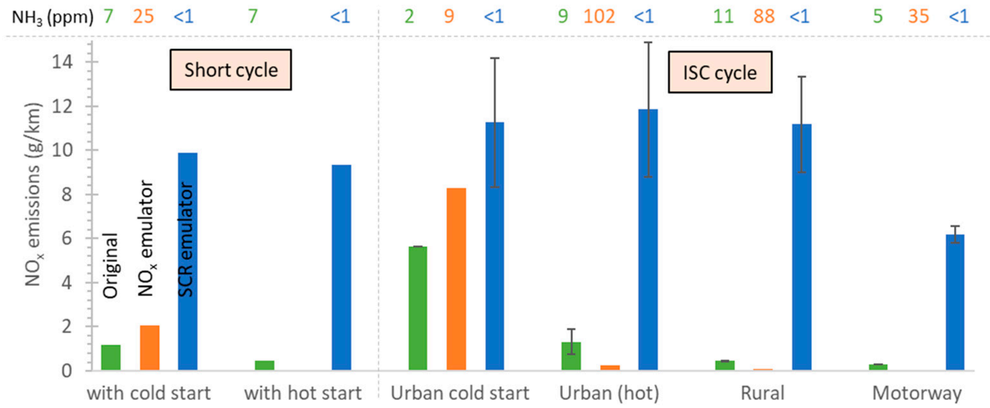
Figure 6. Impact of SCR tampering on the emissions of the original vehicle configuration: (**a**) CO_2; (**b**) NO_x. Error bars give min-max values of two repetitions. Test: Hot start WHVC (Figure 2). To convert (m)g/km to (m)g/kg fuel multiply by 6.1. To convert to (m)g/kWh divide by 0.63 (urban), 0.57 (rural), and 0.58 (motorway). SCR = selective catalytic reduction for NO_x; WHVC = world harmonized vehicle cycle.

3.4. Heavy-Duty Vehicle N3

The results of the N3 truck are summarized in Figure 7. The CO_2 emissions (Figure 7a) varied from 600 to 1600 g/km, depending on the cycle. There was a minimal difference between original and tampered configurations for the short cycles (2%), while there was a 6% decrease for the ISC urban and rural parts and 11% for the motorway part. The variability of the results can partly be attributed to the test trip variability. It should be recalled that the DPF was removed when the SCR emulators were tested.



(**a**)



(**b**)

Figure 7. Results of the N3 truck: (**a**) impact of NO_x and SCR emulators on: (**a**) CO_2; (**b**) NO_x and NH_3 emissions. To convert to (m)g/kWh divide by the kWh/km factors of Table 2.

The original configuration had NO_x emissions 300–1300 mg/km (240–650 mg/kWh) (Figure 7b). The NO_x emissions were high only during the 15 min cold start of ISC (5.6 g/km or 2.3 g/kWh), but when the SCR was at appropriate working temperature the emissions were very low (250 mg/kWh). The on-road NOx limit is 690 mg/kWh (1.5×460) for the specific vehicle, but excluding cold start for the ISC cycle. The 1.5 value is the conformity factor for on-road tests (Regulation (EU) No. 582/2011) [44].

With the NO_x emulator, the NO_x emissions remained at similar levels with the baseline configuration. The differences at the NO_x levels are due to the different ambient temperature and the variability of the on-road testing. However, with the NO_x sensor emulator mounted, ammonia concentration increased substantially (up to 102 ppm average) from 5–9 ppm with the original configuration. Note that the laboratory limit is an average of 10 ppm over a WHTC engine test cycle and is not controlled on the road. It is possible that the emulated NO_x signal caused the reagent dosing to be off (open loop) and this caused increased slip of ammonia.

On the other hand, the NO_x emissions with the SCR emulators were extremely high, ranging 6–15 g/km (5–6 g/kWh). The Euro I limit in 1992 was 8 g/kWh, the Euro II limit in 1996 was 7 g/kWh, and the Euro III in 2000 was 5 g/kWh. NH_3 was close to zero ppm due to stopped dosing of reagent.

3.5. Non-Road Mobile Machinery (NRMM)

The results of the tractor's tampering are summarized in Figure 8. Figure 8a plots the CO_2 and NO_x emissions at constant engine mode (around 50% of max power). While the CO_2 emissions remained identical, the NO_x emissions from negligible levels (23 mg/kWh) increased to very high levels (4839 mg/kWh): more than ten times above the limit for the specific tractor (Stage IV: 400 mg/kWh for NO_x). The emission levels were even higher than the limit of Stage III engines (3300 mg/kWh), but lower than Stage II (6000 mg/kWh).

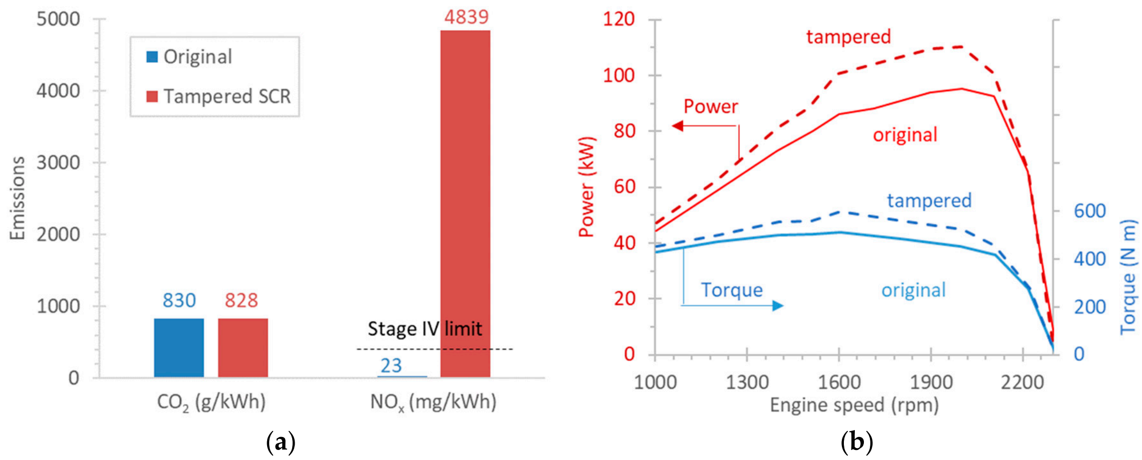


Figure 8. Results of the tractor: (**a**) impact of SCR tampering on the CO_2 and NO_x emissions of the original vehicle configuration. To convert (m)g/km to (m)g/kg fuel multiply by 3.8.; (**b**) full power curve.

Figure 8b shows that after tampering (ECU reprogramming) the maximum power and torque increased around 15%. This finding confirms that tampering can increase power and torque in some cases, but the consequences to emissions, safety, durability, and driveability were not investigated.

4. Discussion

Our study provides useful information for the quantification of the impact of tampering on environment and user (as cost savings). The data can be used for detailed environmental impact of tampering on the current fleet by using more accurate emissions factors (tampered or not vehicles). The results of the impact assessment will allow the adoption of legislative guidelines considering the costs and benefits of the various countermeasures. The data can also be used for more detailed calculations on the installation of the tampering device or software and cost avoidance of parts or consumables. In the following sections these topics are discussed in more details.

4.1. Tampering and Increase of Emissions

This study demonstrated the serious environmental impact of tampering. Table 4 summarizes the vehicles, the tampering approaches and the impact on CO_2 and NO_x. The NO_x emissions of the Euro 6d-Temp passenger car, when the SCR was tampered, increased 120–850 times, or around 30 times when considering the NO_x emissions during regeneration. The absolute emissions reached 1500 mg/km exceeding any Euro standard level. Only EGR tampering of the Euro 6b car had smaller effect (up to a factor of 2). The tampered NO_x levels reached what was measured from some Diesel vehicles during the Dieselgate scandal [34,45], or malfunctioning SCR [6]. For the Euro VI heavy-duty trucks under hot engine conditions, the NO_x increased 7–28 times for the N2 and 50–220 times for the N3 truck. The absolute levels reached 1.7 g/kWh (Euro V) for the N2 truck and 5–6 g/kWh (Euro II) for the N3 truck. These levels are lower than a China IV tampered truck (6–8 g/kWh) [46]. The tampered tractor increased the NO_x emissions >200 times, reaching 4.8 g/kWh (Stage II) levels.

Table 4. Tampering approaches of this study and impact on emissions.

Category	Description	Target	Approach	CO_2	NO_x
LD (Euro 6d-Temp)	Passenger car	EGR	ECU flashing [1]	3–9%	1.1–1.5 g/km
		SCR (DEF)	ECU flashing	3–9%	0.9–1.2 g/km
		SCR + DPF	ECU flashing	8–15% [2]	1.1–1.5 g/km
LD (Euro 6b)	Passenger car	EGR + SCR	ECU flashing [3]	<5%	0.2–0.9 g/km
HD (Euro VI D)	N2 truck	SCR (DEF)	DEF emulator	no impact	1.0–1.7 g/kWh
HD (Euro VI C)	N3 truck	NO_x sensor	NO_x emulator	2–11%	No impact [4]
		SCR + DPF	SCR emulator	2–11%	5–6 g/kWh
NRMM (Stage IV)	Agrigultural tractor	SCR	DEF emulator	no impact	4.8 g/kWh
		Power	ECU flashing	+15% power	n/a

[1] The EGR tampering affected the SCR negatively and resulted in high NO_x emissions; [2] plus 2.4–3.0% benefit from the regeneration; [3] the SCR tampering was probably not successful and resulted in relatively low increases of NO_x; [4] ammonia slip was measured. DEF = Diesel exhaust fluid; DPF = Diesel particulate filter; ECU = electronic control unit; EGR = exhaust gas recirculation; HD = heavy duty; LD = light duty; NRMM = non-road mobile machinery; SCR = selective catalytic reduction.

The NO_x/CO_2 ratios of the original vehicles (except the Euro 6b) were 0.1–1.8 $\times 10^{-4}$, while of the tampered 9–107 $\times 10^{-4}$. Such ratios are in line with the ratios determined with remote sensing to detect high emitters [47–50].

The particle number emissions increased three to four orders of magnitude when the DPF was removed. Even when considering the regeneration, the weighted emissions over the regeneration distance remained more than four times below the 6 $\times 10^{11}$ #/km limit, while the engine-out emissions were much higher than ten times the limit.

Even though the contribution of tampered vehicles to air pollution is out of the scope of this paper, the results showed that depending on the vehicle (light-duty, heavy-duty, and NRMM), driving (urban, rural, and motorway) increases by more than one order of magnitude occur.

4.2. Tampering Cost Motives

One of the main motives for tampering is cost savings. Cost savings can be achieved on multiple levels, fuel consumption reductions, as observed in the case of the light-duty vehicle, savings in SCR reagent, and in maintenance, repair, replacement parts, and downtime [8]. For a few cases, power increase could be a motive. Based on the tampering cases examined in this study, some cost savings estimations can be made.

The passenger car tests showed 3–9% reduction in fuel consumption (CO_2) in the urban phases, probably due to the no or reduced EGR [16]. Annual mileage of 10,000 km in urban and rural roads would translate to about 30–100 Euros yearly savings at a fuel price of 1.5–2.0 Euros per liter and 5.5 L/100 km fuel consumption. The benefit increases when considering professional cars or commercial vehicles where the annual mileage can easily be doubled or tripled, also proportionally increasing cost savings.

Assuming a 2 L DEF consumption per 1000 km for high engine-out emissions and 25 Euro per 10 L reagent, the annual cost for 10,000 km would be 50 Euro. A similar value (70 Euro) is calculated by assuming DEF consumption equal to 5% of the fuel consumption. In the case of the truck, the cost would be more than ten times higher: according to Regulation (EU) 2019/1242 the majority of the fleet (category 5-LH) drives on average 116,000 km annually.

Removal of the DPF for the passenger car of this study resulted in 8–15% lower CO_2 due to lower backpressure plus 2.4–3.0% savings for the regeneration fuel penalty. The 10–18% saving for this vehicle's 5.5 L/100 km fuel consumption translates to 100–180 Euro annually (1.5–2.0 Euro per liter price range). For the heavy duty truck the fuel saving was from negligible (urban and rural) up to 11% (motorway). For 50,000 km driven in motorways (from the 100,000 km driven annually), a 5% fuel saving translates to 1100–1500 Euros annually (based on 30 L/100 km fuel consumption under motorway conditions).

The cost of tampering for a passenger car can start from 50 Euro (only an emulator), but ECU flashing costs are estimated to be around 300–600 Euro. For tractors and heavy-duty vehicles, the cost is similar or slightly higher. The removal of the DPF costs 1500–2000 Euro for heavy-duty vehicles [8]. Thus, the "investment" return would need around 3–6 years for EGR and SCR tampering (assuming 100 Euros reduced costs per year). For DPF tampering a cost of 1500 Euro would take 10 years to pay back for a passenger car, but probably 1 year for a heavy duty vehicle. However, the cost of tampering becomes marginal if the owner has to replace a damaged DPF (cost >1500 Euro) or other parts of the vehicle (EGR valve, NO_x sensors, DEF pump, and injectors). Thus, based on this simple analysis, light-duty vehicles tampering is likely to appear in vehicles requiring repair or replacement of exhaust aftertreatment components, thus already some years in the market, or in professional or commercial vehicles performing a significant number of kilometers annually. For heavy-duty vehicles DEF and fuel savings could be a motive even early in the vehicles' life.

4.3. Tampering Availability

Finding a workshop willing to tamper the vehicle is not very uncommon. Furthermore, there are many sites and forums available if one wants to install the tampering device independently [8,26]. Most importantly, at the moment, there are no robust procedures to detect tampering: the periodical technical inspection (typically every two years after four years from the purchase) does not include NO_x testing [51]. The threshold of the DPF smoke opacity test is very high. Efforts are taking place to add a NO_x test, while for DPFs, a much more sensitive particle number methodology will be introduced in the Netherland, Belgium, Germany, and Switzerland [52,53]. However, as most tampering methods are reversible, the user might restore the vehicle before the PTI test. This could be the case with some emulators which have a switch to be deactivated.

However, ECU re-flashing is not easy to undo. Then most importantly, to restore a removed DPF would cost significantly. PTI controls report <1% tampered vehicles [54], while roadside inspections up to 25%, but typically 5–10% [8,12]. Thus, roadside inspections are important as other monitoring programs (e.g., remote sensing) [48,50]. Finally, there is a need for stricter OBD requirements to detect tampering attempts [55–59]. In the future, the vehicle gathered data could be transmitted to a cloud backend, where a more complex analysis over longer time frames would be possible [60]. Another possibility is secure onboard tampering diagnostics and reporting. Even more importantly, there is no proper legal framework to deal with tampering today, particularly for light-duty vehicles [61]. Regulation (EC) 715/2007 on the emissions of light-duty vehicles does not mention tampering, but provisions for the electronic system security are required from manufacturers of light-duty vehicles according to the implementing Regulation (EU) 2017/1151. Even though Regulation (EC) 595/2009 on the emissions of heavy-duty vehicles foresees penalties for manufacturers, repairers and even operators of vehicles that perform tampering, such penalties are never applied in practice. Combining all these measures may already lead to a less attractive 'environment' for tampering.

5. Conclusions

Five latest technology Diesel vehicles equipped with Diesel particulate filter (DPF) and selective catalytic reduction (SCR) for NO_x were tampered: two Euro 6 light duty passenger cars (EGR, SCR, and DPF), two Euro VI heavy duty trucks (NO_x sensor and SCR), and a Stage IV NRMM agricultural tractor (SCR, and power increase). Tampering included market NO_x, SCR, and Diesel exhaust fluid (DEF) (commercial name AdBlue®) emulators and ECU reprogramming for the SCR and EGR, removal of the DPF, and electronic control unit (ECU) reprogramming for the power increase. The results showed a very high increase of NO_x (>1000 mg/km), reaching older or even pre-Euro standards levels for all vehicles. For the few cases that the tampering was not successful, the NO_x increases were smaller, and in one case NH_3 slip was noticed reaching 10 times the laboratory limit. EGR tampering had a small fuel consumption (CO_2) benefit. The particle number emissions of the passenger car with tampered DPF increased three to four orders of magnitude, reaching levels one order of magnitude above the current limit. The passenger car tests also included regeneration events with the original configuration. The DPF filtration efficiency was still 84% during the regeneration period. It increased the CO_2 emissions by 2.4–3.0% over the regeneration distance. Removal of the DPF reduced the CO_2 emissions by 8–15%. The maximum power of the tractor increased around 15% with the ECU reprogramming. The key message of this study is that tampering is still possible even for the latest (Euro 6/VI, Stage IV) generation vehicles with serious environmental consequences.

The study is part of an EU-funded research project (DIAS) for the development of novel anti-tampering technologies. In this respect the findings will serve as the foundation for further research for creating more robust and resilient exhaust aftertreatment systems and vehicle control. This study also highlighted the broader need to find solutions for tampering: starting from regulatory level to vehicle manufacturers, from users to service providers. Finally, the quantification of the tampering effect is a necessary input for assessing the impact of the anti-tampering countermeasures. This will allow the adoption of the most efficient technical solutions and legislative actions in terms of cost and benefit.

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