Malfunctions in Selected Emissions-Related Components of Euro 4 Passenger Cars: Emissions Increase and OBD System Response

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ABSTRACT

As new passenger cars are constantly getting cleaner, their contribution to air pollution is in large part defined by the in-use emissions degradation. In this respect, malfunctions in emissions-related components may play an important role to the contribution of passenger cars in air pollution. This paper assesses the impact of malfunctions of selected emissions related components to the pollutant emissions and evaluates the response of the OBD system to these malfunctions, under legislated and non-legislated driving cycles. The emissions-related components subjected to malfunctions are, for gasoline fuelled cars oxygen sensor and catalytic converter, and for diesel cars Exhaust Gas Recirculation system (EGR) and diesel Particulate Filter (DPF). For gasoline cars, the results show that total malfunctions of the above components result in up to two orders of magnitude increase in pollutant emissions. For diesel cars, total malfunctions in the EGR system lead to 2-6 times increase of NO_x emissions. Removal of the DPF leads to 20 times increase of PM emissions, in terms of PM mass, and up to 3 orders of magnitude increase in terms of particle number. The OBD system detected these malfunctions accurately in the legislated driving cycle. However, the ability of the OBD system to detect the malfunctions in the non-legislated driving cycles presented a high variability between the different cars tested.

INTRODUCTION

The demand for improvement in air quality together with the tightening of the emission standards has resulted in the development of passenger cars, which emit only a

fraction of the mass of legislated pollutants, compared to their predecessors of two decades ago. As a result, pollutant emissions from road transport tend to depend more on the small portion of vehicles in the fleet, which present high emission levels due to poor maintenance, rather than on the large number of properly functioning, low-emitting vehicles. The problem of in-use deterioration of a car's engine and emission control system has been well demonstrated with the aid of laboratory measurements, on-board measurements, roadside vehicle inspections, tunnel studies and remote sensing observations [1,2,3,4].

The increase of pollutant emissions in the course of a vehicle's lifetime may come as a combined result of a) the normal wear of the engine components and gradual ageing of the exhaust aftertreatment system components, mainly the catalytic converters and b) the unpredictable malfunctions in emissions related components. The effect of the normal wear and ageing has been demonstrated in several experimental studies [5,6]. These studies confirmed that normal wear and ageing usually do not result in tailpipe emission levels higher than the type-approval limits. On the other hand, the environmental impact of malfunctions in emissions related components has not been extensively documented so far. This impact is rather complex to estimate, as it relies on the following parameters:

1. The nature and severity of each malfunction.
2. The frequency of the malfunctions in a vehicle's lifetime.
3. The timeliness of the detection of the malfunction, which relies on the performance of the vehicle's On Board Diagnostic (OBD) system, and the frequency

and efficiency of the Inspection and Maintenance (I/M) periodic testing.

Currently, limited knowledge exists on the impact of emissions-related malfunctions on the in-use vehicle emissions. The aim of the present paper is to examine the upper range of the emissions increase, which can be caused by malfunctions in selected emissions-related components of Euro 4 gasoline and diesel-fuelled cars. The emissions increase is examined under legislated and non-legislated driving conditions, and covers the most important of the legislated pollutants i.e. HC, NO_x and particulate mass (PM), as well as the particle number, for which an emission standard is to be introduced in the European legislation at the Euro 5 stage. In addition, the response of the OBD system to the introduction of these malfunctions is evaluated.

EXPERIMENTAL

VEHICLES AND TEST PROTOCOLS

Emission measurements were conducted on four Euro 4 level vehicles with low accumulated mileage, and were repeated on the same vehicles after introducing real or artificial malfunctions on selected emissions-related components. The small test fleet consisted of two gasoline-fuelled and 2 diesel-fuelled Euro 4 level cars. The main characteristics of the vehicles tested are described in Table 1. All measurements were conducted on the chassis dynamometer of the University of Thessaloniki.

The equipment for regulated emissions measurement in legislated driving cycles was used to obtain emission measurements compatible to the current EU regulations. Additionally, particle number measuring equipment was used for vehicles C and D, including an Electrical Low Pressure Impactor (ELPI), a Condensation Particle Counter (CPC) and a Scanning Mobility Particle Sizer (SMPS). A schematic representation of the measurement protocol is shown in Figure 1. The first part of the measurement consists of 3 repetitions of the European legislated driving cycle (NEDC). This part resembles the legislated procedure followed during the certification test of the OBD system. The second part consists of three “real-world” modes, forming the Common Artemis Driving Cycle (CADC, or simply “Artemis”). This is a driving cycle derived based on statistical data from road traffic, and generally involves higher speeds and more severe transient conditions compared to the NEDC [7]. The CADC includes three modes (CADC-Urban, CADC-Road and CADC-Motorway). Each of them approximates the respective driving pattern under urban, extra-urban and motorway conditions. Each mode has a duration of 18-21 minutes. In our tests, each mode was performed as a separate driving cycle, with an engine shut-off of 2-3 minutes between two modes. All modes start with a hot engine.

Table 1: Description of the vehicles tested

	Fuel type	Engine	Exhaust aftertreatment technology	Mileage [km]*
A	Unleaded gasoline, 95 RON	Naturally aspirated 1.4 [ℓ]	Close-coupled 3-way Catalytic converter, dual O2 sensors	1285
B	Unleaded gasoline, 95 RON	Naturally aspirated 1.3 [ℓ]	Close-coupled (main) and underfloor (secondary) 3-way Catalytic converter, dual O2 sensors	4239
C	Diesel (<50 ppm S)	Turbo-charged, cooled EGR (electrically operated) 2.0 [ℓ]	Underfloor DOC and DPF, with pressure sensors upstream and downstream of the DPF. Regeneration assisted by fuel-borne catalyst	96
D	Diesel, low sulphur (<10 ppm S)	Turbo-charged, cooled EGR (electrically operated) 2.0 [ℓ]	Close-coupled DOC, close coupled DPF, catalytically coated, with NO _x storage capacity, underfloor DOC.	344

*Vehicle mileage at the beginning of the baseline measurement. Includes conditioning which was done in the Lab.

Figure 1: Schematic description of the experimental protocol

CRITICAL EMISSION RELATED MALFUNCTIONS

A large variety of emissions-related malfunctions may cause the increase of tailpipe emission levels of a modern passenger car. In the framework of this study, it

was not feasible to test the effect of all possible malfunctions of all emissions related components on the pollutant emissions. Therefore, the most critical emissions related components for gasoline and diesel vehicles were identified, according to a combination of the following criteria:

1. *Effect on pollutant emissions*: malfunctions in critical components should result to a significant increase in pollutant emissions.
2. *Frequency of malfunctions observed in the field*.
3. *Difficulty level of diagnosis by the vehicle's OBD system*: Malfunctions with the highest environmental burden are typically the ones that are most difficult to detect by the OBD system. An electrical failure of a sensor, for example, is very easy to diagnose, and therefore the vehicle user will be soon prompted by the OBD system to have the malfunction repaired. On the other hand, monitoring of other components, e.g. catalytic converters, relies on indirect assessment of the component's performance. In this case, the diagnostic strategy may affect the detection time of a malfunction, thus affecting the environmental burden.

Table 2: Malfunctions imposed to the vehicles tested

Veh.	Malfunction	Malfunction description
A	Total lambda sensor malfunction	Replacement of upstream lambda sensor with defective, provided by the local dealership
	Intermediate catalyst malfunction	Replacement of catalytic converter with defective, provided by the local dealership
	Total catalyst malfunction	Complete removal of catalytic converter monolith (de-catting)
B	Intermediate lambda sensor malfunction	Artificial poisoning of the upstream lambda sensor with silicone spray
	Intermediate catalyst malfunctions	1 st stage oven ageing of close coupled catalytic converter (19h at 900°C)
		2 nd stage oven ageing of close coupled catalytic converter (24h at 940°C)
C	Total EGR malfunction	Tampering of the EGR system by connecting the EGR cable to an EGR valve not installed in the engine
	Intermediate DPF malfunction	Replacement of Diesel Particulate Filter with a similar defective filter. The Defective filter had been used for 120000 km on a similar car, and showed signs of clogging by ash
	Total DPF malfunction	Removal of Diesel Particulate Filter (replacement with an empty canning)
D	Total EGR malfunction	Tampering of the EGR system by connecting the EGR cable to an EGR valve not installed in the engine
	Intermediate DPF malfunction	Thermal ageing of the catalytically coated Diesel Particulate Filter (24h at 850°C)
	Total DPF malfunction	Removal of Diesel Particulate Filter (replacement with an empty canning)

Based on the above, the components on which this experimental study has focused are:

1. For gasoline engines, lambda sensor and 3-Way Catalyst: Malfunctions in these two components

represent approximately 50% of all MIL illuminations in vehicles with mileage higher than 75000 miles (120700 km) in the USA [8]. The performance of these two components can be estimated only based on indirect assessment methods. Moreover, malfunctions in these components may result in a broad range of increase of pollutant emission levels, depending on the severity of each malfunction.

2. For diesel engines, EGR system and DPF: these two components play a major role at the reduction of the most important pollutants for diesel engines. EGR is the main measure used to control NO_x emissions. The DPF on the other hand, is an aftertreatment device with a reported efficiency of more than 90% on PM emissions.

The malfunctions introduced to the vehicles tested are summarised in Table 2. The idea behind the selection of the malfunctions was to introduce to each component one "total" malfunction that would cause the maximum increase in the emission levels. Since the effect of each malfunction was not known in advance, it turned out that some of the malfunctions imposed were not as severe as it had been anticipated. Therefore, "total" malfunctions were not imposed on all tested components. The introduced malfunctions, with the exception of the lambda sensor malfunction, had no noticeable effect on the driveability of the vehicle. Thus, detection of these malfunctions would rely either on the OBD system, or on the periodic inspection program. Further details on the malfunctions introduced and on the experimental procedure can be found in reference [9].

EMISSION MEASUREMENTS

This section presents the emission measurements for the gasoline and diesel-fueled vehicles. The distinction is made between emissions measured in the legislated cycle and in the non-legislated cycle. The emissions of the non-legislated cycle refer to the average emissions of all 3 modes of the CADC cycle. Moreover, emissions are presented as average of the different vehicles tested.

GASOLINE-FUELLED VEHICLES

Figure 2 presents the average HC emissions from the two gasoline-fueled vehicles tested. HC emissions at the baseline configuration were well below the type approval limit of 0.1 g/km, and were in fact lower for the non-legislated cycle, due to the absence of a cold-start phase. The introduction of the total lambda sensor malfunction had a significant impact on HC emissions, which climbed to 0.53 g/km in the NEDC, approximately 10 times higher than the baseline measurement. This effect was even more pronounced in the real-world cycles, where HC emissions reached 2.72 g/km, approximately 27 times above the emission standard and 270 times above the baseline measurement. This malfunction was a real in-use malfunction: the damaged sensor that we installed in vehicle A had been provided by the local dealership, and came from a private car, which had it replaced for having the same malfunction.

The malfunctions characterized as “Intermediate catalyst malfunctions” generally had low impact on HC emissions. The total removal of the catalyst though resulted in HC emissions one order of magnitude higher than the type-approval limit, and at least 30 times higher than the emission levels in the respective baseline cycles.

Figure 2: Average HC emissions for the two gasoline-fuelled vehicles tested

Figure 3: Average NO_x emissions for the two gasoline-fuelled vehicles tested

NO_x emissions for the gasoline-fuelled cars are displayed in Figure 3. In the baseline configuration, the emissions of the CADC cycle were almost double compared to the emissions of the legislated cycle. This is attributed to the higher engine load and speed involved in the CADC. The malfunction of the lambda sensor resulted in emission levels higher than the type-approval limit, which for Euro 4 is 0.08 g/km. Primarily the NEDC emissions were affected by this malfunction, while no increase was observed in the CADC emissions. This, combined with the high HC emissions in the CADC, can be an indication that this malfunction caused the engine

to operate with very rich mixture. The catalyst removal resulted in very high NO_x emissions, approximately 60 times higher than the respective baseline emissions. This increase factor was practically the same for the NEDC and the CADC cycle.

The above results indicate clearly that malfunctions either in the lambda sensor or in the catalytic converter may result in up to two orders of magnitude increase of pollutant emissions. The small number of vehicles tested, and the fact that the introduced malfunctions were not the same in the two vehicles, does not allow us to reach more specific conclusions on the effect of each malfunction.

DIESEL-FUELLED VEHICLES

The malfunctions introduced in the diesel-fuelled vehicles were a total deactivation of the EGR system and a total removal of the DPF. These malfunctions were the same in both vehicles, therefore the emissions of the two vehicles are directly comparable.

In the baseline configuration, NO_x emissions in the real-world CADC cycle were more than double, compared to the legislated NEDC cycle. This is caused by the higher engine load and speed involved in the CADC. The malfunction of the EGR system is considered to be the primary malfunction affecting NO_x emissions. Figure 4 shows that deactivating the EGR system resulted in approximately 6 times higher emissions in the NEDC cycle, and 2 times higher emissions in the real-world cycles compared to the baseline configuration. It is worth mentioning that the emissions with the EGR system deactivated were lower than the current OBD threshold, which is 1.2 g/km. The removal of the DPF had only a small effect on NO_x emissions. This effect primarily concerned vehicle D, whose DPF had a NO_x storage capability.

Figure 4: Average NO_x emissions for the two diesel-fuelled vehicles tested

The average measured PM emissions from the two diesel-fuelled cars are displayed in Figure 5. In the baseline configuration the mass of particulate matter emitted was not only well below the Euro 4 emission standards (0.025 g/km), but also below the future Euro 5 standards (0.003 g/km), both in the legislated and in the real-world cycles. This was a result of both vehicles being equipped with a DPF. The emissions in the real-world CADC cycle were approximately two times the emissions in the legislated cycle, but even this value is low. The EGR malfunction had no noticeable effect on PM emissions. When the DPF was removed, the PM emissions climbed to values around 0.04-0.05 g/km. These values correspond to the raw PM emissions of current generation vehicles. However, these values are only a fraction of the current OBD threshold, which is set to 0.18 g/km, i.e., approximately 4 times higher than the measured raw PM emissions.

Figure 5: Average PM emissions for the two diesel-fuelled vehicles tested

A particle number (PN) emission standard is scheduled to be included in the European legislation from the Euro 5 stage. In order to measure the particles emitted in each driving cycle, and investigate the effect of malfunctions on the number of particles emitted, an experimental protocol resembling the PMP protocol was used. Particle number counts were conducted on vehicles C and D. Figure 6 presents the total particle number, measured using a condensation particle counter (CPC), for vehicles C and D, averaged for each cycle. Although the emissions performance of the two vehicles presented significant variability, the average shows that in the baseline configuration, CADC emissions were almost an order of magnitude higher than the respective emissions in the NEDC cycle. The EGR malfunction resulted in an order of magnitude increase in PN emissions, both in the legislated and in the real-world cycles. The level of "raw" particle number emissions, reflected by the total removal of the DPF, for both vehicles was approximately the same, in the order of 1^{14} [particles/km]. Compared to the baseline measurement, this corresponds to

approximately 3 orders of magnitude increase. It is also interesting to notice that the "raw" number of particles emitted, i.e. the number of particles without DPF presented a very small variability between the different driving cycles, while the respective number with DPF presented variations of up to 2 orders of magnitude between the different driving cycles. A possible explanation for that could be found in the differences in the soot loading state of the filter, which could affect the filtration performance of ultrafine particles. This variability will need to be taken into account when establishing thresholds for evaluating the in-use particle number emissions of DPF equipped cars, for example OBD thresholds.

Figure 6: Average number of particles or the two diesel-fuelled vehicles tested

OBD SYSTEM RESPONSE

The response of the OBD system to the introduction of the malfunctions is characterized by the following two factors:

1. The OBD system *readiness status*: by checking the OBD system memory after each driving cycle, using the scan tool, we record if monitoring for the components of interest has been completed during the driving cycle.
2. The MIL activation: in this case, we check:
  - If the MIL has activated by the end of the 1st part of the experiment, i.e. by the end of the 3rd NEDC cycle, which is the legislated requirement for vehicles with an emission related malfunction.
  - If the MIL activates inside the 2nd part of the experiment, i.e. under non-legislated driving conditions.

Below, we present the results of the OBD system response, along these lines.

READINESS STATUS IN THE BASELINE MEASUREMENT

Typically the diagnostic algorithms, which monitor the performance of emissions related components on a non-continuous basis, require the engine to operate at a defined range of operating and ambient conditions. These conditions, referred to as "enable conditions", may include for example engine speed and load, ambient temperature etc. Moreover, certain amount of time is required, with the engine operating inside the enable conditions, for the monitor to complete. The readiness status recorded during the baseline measurement shows whether the OBD system has completed the monitoring of each particular component, by the end of each driving cycle. We expect that the all monitors will complete inside the NEDC, since this is the cycle used for OBD system certification, therefore the enable conditions will essentially be fulfilled inside the NEDC, and enough time will be given for the diagnostic algorithms to complete monitoring. This is a pre-requisite for the certification of the OBD system, however it presents little practical interest for real-world applications: in real-world a car is being driven at random, transient operating conditions, and in a variety of ambient conditions too. The enable conditions need to be broad enough to allow frequent execution of the monitors under real-world driving conditions. Therefore, we also investigated the monitor readiness outside the NEDC. Certainly, different alternative approaches for this investigation could have been adopted. Our approach was to test the vehicles on the chassis dyno, under non-legislated driving cycles, and check the readiness status of the non-continuous monitors at the end of the driving cycle.

Table 3: OBD readiness status during the measurements performed with the baseline configuration of the vehicles tested

Veh.	Component	1 st Part			2 nd Part		
		NEDC hot	NEDC hot	NEDC cold	CADC Urban	CADC Road	CADC Motorway
A	O2 sensor	✓	✓	✓			
	O2 sensor heater	✓	✓	✓	✓	✓	✓
	Catalyst	✓	✓	✓			
B	O2 sensor	✓	✓	✓		✓	✓
	O2 sensor heater	✓	✓	✓	✓	✓	✓
	Catalyst	✓	✓	✓	✓	✓	✓
C	EGR	✓	✓	✓	✓	✓	
	DPF	✓	✓	✓	(?)	(?)	
D	EGR	✓	✓	✓	✓	✓	(?)
	DPF	✓	✓	✓		✓	✓

The results of the monitor readiness status are summarized in Table 3. For each vehicle, the status of the non-continuous monitors of interest is recorded. The tick (✓) in the box corresponding to each driving cycle, denotes that this particular monitor was completed. If the box is left blank, the monitor was not completed. The grey shading in vehicles C and D indicates that the respective monitor readiness status was not available through the scan tool used.

In the case of Vehicle A, we observe that all monitors completed inside the first NEDC cycle, and the oxygen sensor heater monitor actually completed every time the engine was turned on. However, the oxygen sensor and catalyst monitors did not complete in any of the non-legislated driving cycles. This means, that the monitor enable conditions were not met for sufficient time during these cycles, to allow detection of possible malfunctions. This finding poses several questions regarding the ability of this particular OBD system to diagnose malfunctions under real-world operating conditions. In the case of Vehicle B, all monitors completed in almost all driving conditions, even under non-legislated driving cycles. The only exception is the lambda sensor monitor, which did not complete during the CADC-Urban driving cycle, a cycle which involves low speeds and severe transient conditions. Interestingly, the catalyst monitor completed in the same cycle. The fact that vehicle B presented monitor readiness under practically all driving conditions is an encouraging fact, indicating the ability of the OBD system to diagnose malfunctions even under non-legislated conditions.

The EGR monitor of vehicle C completed in the 1st NEDC cycle. In fact, the only driving cycle, under which the EGR monitor did not complete is the CADC-Urban cycle. This corresponds to an overall good monitoring performance. Unfortunately it was not possible to check the readiness status of the DPF monitor, as no such byte is included in the current OBD protocols. However, we can indirectly derive that this monitor completed in the NEDC cycle, because when this cycle was performed with the total DPF malfunction, the MIL illuminated, as will be discussed below. CADC-Motorway driving cycle was not performed for this vehicle, due to technical restrictions of the experimental facility. In the case of vehicle D, we could again indirectly derive the readiness status in the baseline configuration, by observing the MIL illuminations in the case of malfunctioning components, as will be discussed below. This assessment indicates that the EGR and DPF monitors completed from the 1st NEDC cycle. In the non-legislated driving cycles, the EGR monitor completed in the Urban and Road cycle, but we had no indication for the Motorway cycle. The DPF monitor, completed in all but the Urban cycle. Again, this could be judged as a timely response of the OBD system.

MALFUNCTION DETECTION

The second criterion, along which the OBD system is evaluated, is the correct detection of the introduced malfunctions. Here we aimed at investigating whether the malfunctions, that according to the legislation requirements should trigger MIL illumination, are in fact detected by the OBD system. These malfunctions are the malfunctions that cause the NEDC emissions to exceed the OBD thresholds, and the removal of the DPF, irrespective of the resulting emissions. The effect of the introduced malfunctions, with respect to the expected OBD system response, is presented in Table 4.

Table 4: Effect of malfunctions, with respect to the expected OBD system response

Veh.	Malfunction	OBD threshold exceeded?
A	Total lambda sensor malfunction	NEDC and CADC
	Intermediate catalyst malfunction	No
	Total catalyst malfunction	NEDC and CADC
B	Intermediate lambda sensor malfunction	NEDC only
	Intermediate catalyst malfunctions	No
C	Total EGR malfunction	No
	Intermediate DPF malfunction	No
	Total DPF malfunction	No (OBD system required to detect a missing DPF though)
D	Total EGR malfunction	Yes
	Intermediate DPF malfunction	No
	Total DPF malfunction	No (OBD system required to detect a missing DPF though)

Table 5 shows the response of the OBD system to the introduced malfunctions, in terms of MIL illumination, during the legislated and non-legislated driving cycles.

In the case of vehicle A, MIL illuminated for both malfunctions at the 3rd NEDC cycle, but there was no MIL illumination at the non legislated cycles. For vehicle B, MIL again illuminated at the 3rd NEDC cycle. Due to the reversible nature of the malfunction introduced to the lambda sensor, the sensor had recovered by the time the non-legislated driving cycles were performed, therefore we do not know if the MIL would have illuminated at these cycles. The removal of the DPF of vehicle C was detected at the 3rd NEDC cycle, but was not detected at the non-legislated cycles. It must be pointed that before the CADC-Urban, 2 EUDC cycles were run for warm-up, without erasing the OBD system memory in between, therefore the OBD system had a total of 4 cycles to detect the malfunction. The performance of vehicle D was a positive finding: both in the case of the EGR and in the case of the DPF malfunction, the OBD system turned the MIL on from the first NEDC cycle, despite of the

legislative requirement to do so by the end of the 3rd cycle. The EGR malfunction was also detected at the CADC-Urban driving cycle, and marginally at the CADC-Road (just a few seconds before the end of the cycle). The CADC-Motorway cycle was not performed, because the introduced malfunction resulted in too high exhaust gas temperatures (around 400°C) at the tailpipe, which posed a threat to the experimental facility. Malfunction DPF2 was not detected at the CADC-urban cycle, most probably due to the low exhaust gas mass flow in this cycle, which does not facilitate detection with pressure differential sensors, but was detected and turned the MIL on at the other two non-legislated cycles. Other circuit continuity malfunctions were also tested, without measuring emission levels, in order to simply check the response of the OBD system. These malfunctions included disconnection of the lambda sensor (vehicle A) and electrical disconnection of the EGR valve (vehicle C). After the introduction of the malfunction, the vehicle performed 3 consecutive NEDC cycles. In both cases, the OBD system illuminated the MIL in the 3rd cycle.

Table 5: MIL illuminations for the malfunctions that should have triggered the MIL

Veh.	Malfunction	1 st Part			2 nd Part		
		NEDC hot	NEDC hot	NEDC cold	CADC Urban	CADC Road	CADC Motorway
A	Total lambda sensor malf.			MIL			
	Total catalyst malfunction			MIL			
B	Total lambda sensor malf.			MIL			
C	Total DPF malfunction			MIL			
D	Total EGR malfunction	MIL	MIL	MIL	MIL	MIL	
	Total DPF malfunction	MIL	MIL	MIL		MIL	MIL

CONCLUSION

As the emission standards for new passenger cars are constantly becoming more stringent, the efforts for the reduction of air pollution from automobiles will need to be shifted towards controlling the in-use vehicle emissions. In the present paper, the maximum emissions increase as a result of malfunctions in selected emissions-related components has been investigated, by performing emission measurements on Euro 4 level cars, under legislated and non legislated driving cycles.

As a general trend from all vehicles and all configurations measured we can see that emissions in

the non-legislated CADC cycles are higher than the respective emissions in the legislated NEDC cycle. In the case of the two gasoline fuelled vehicles tested, the malfunctions introduced to each vehicle were not of the same nature, which does not allow to comparatively examine the emissions increase in each vehicle. In both vehicles though, it was observed that total malfunctions either of the lambda sensor, or of the catalytic converter result in up to two orders of magnitude increase in pollutant emissions. In diesel fuelled vehicles, total malfunctions of the EGR system were found to result in significant increase in NO_x emissions, in the order of 2-6 times of the baseline emissions on average. In the case of DPF malfunctions, the removal of DPF system leads to increases in PM emissions in the order of 15-30 times. The particle number counts show that the increase of particle numbers as a result of emissions related malfunctions lied in the range of 1-4 orders of magnitude. Significant variability in the number of particles emitted can be observed between different driving cycles, while at the same time the respective variability in terms of particulate mass emissions is low.

The above malfunctions, with the exception of the lambda sensor malfunction, had only minor, if any effects on the driveability of the vehicle. Therefore, the presence of an on-board system, which can timely detect such malfunctions under real-world driving conditions, and inform the driver accordingly, can significantly reduce their environmental burden. In this respect, the performance of the OBD system of the vehicles tested was analysed. It turned out that all vehicles fulfilled the legislated requirement to detect the malfunctions and illuminate the MIL during the legislated NEDC cycle. However, under the non-legislated CADC cycle, the response of the OBD system presented large variations from car to car. Some cars detected the malfunctions and illuminated the MIL under almost all of the real world sub-cycles tested, while others practically did not detect even severe malfunctions outside of the legislated driving cycle. Although the CADC cycle is only one of the possible real-world driving patterns, and therefore cannot be considered as the absolute criterion for the real-world performance of the OBD system, still the experimental results indicate that significant potential exists in the optimization of the real-world OBD system performance.

The small-scale experimental exercise presented in this work helps to gain some insight on the impact of selected malfunctions in emissions-related components. Other parameters are also important to determine the in-use emissions of a vehicle as a function of mileage. These include the frequency of malfunction and the pace of malfunction development. These parameters cannot be accurately estimated in the framework of such a small-scale exercise, but require a larger-scale experimental activity, which would be based on periodic emission measurements on larger fleets of vehicles. This could be a direction for future research.

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