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Further development of exhaust emissions testing

Short version

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Fortentwicklung der Abgasuntersuchung

Short version

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1 Rationale for this report

1.1 Background

Maximum permissible nitrogen oxide (NO_x) immission levels are regularly exceeded in Germany, especially in urban areas. In addition to the threat of infringement procedures brought by the European Commission, the most heavily polluted cities also potentially face legally mandated driving bans for diesel vehicles. For the past several months, the media, the general public, and politicians have been increasingly focused on the issue of 'exhaust emissions from diesel vehicles'. Increased concentrations of pollutants in the ambient air result in greater health risks [1]. Among the most harmful pollutant components emitted by modern diesel vehicles besides diesel particulates are nitrogen oxides (NO_x) [2]. Overall, the transport sector accounts for about 40% of European NO_x emissions, about 80% of which are emitted by diesel vehicles. The high NO_x emissions of diesel engines ($\lambda > 1$) are caused by their high temperature peaks during combustion in conjunction with the excess oxygen inherent to their mode of operation.

Directive 2014/45/EU provides the legal framework for all Member States of the European Union to conduct periodic technical vehicle inspections. Recital 4 of the Directive allows Member States to define test criteria of their which go beyond those set out in the Directive. Recitals 7 to 9 recognise that vehicles with poorly functioning emissions control systems contribute more to pollution than properly maintained vehicles. Consequently, a system of regular technical monitoring ensures better environmental protection by reducing average vehicle emissions. Furthermore, Member States are urged to take appropriate measures to prevent tampering which could compromise the required safety-related and environmental properties of a vehicle. Periodic technical monitoring is assigned particular importance in this context.

Recital 9 of Directive 2014/45/EU effectively provides the underlying mandate for the present research report: *"Possibilities for improving test cycles to match on-road conditions should be closely examined in order to develop future solutions, including the establishment of test methods for the measurement of NO_x levels and of limit values for NO_x emissions."*

1.2 Type approval testing

Some of the NO_x immissions can be explained by comparing exhaust emissions in the type approval test cycle NEDC (New European Driving Cycle) in the laboratory with actual emissions in on-road traffic. This comparison has established that CO_2 emissions and thus fuel consumption are increased by 20 to 40% in on-road operation [3]. The difference is even more pronounced in the case of NO_x – and continues to increase given the ever-stricter emissions guidelines set out in new emissions standards (EURO classes) [4]. Actual NO_x emissions from diesel vehicles have barely improved over the period from 2000 to 2016, which is also reflected in air quality data.

This is partly due to the NEDC test cycle applied in vehicles up to the EURO 6b emissions standard, which is hampered by a rather unrepresentative driving profile for driving in road traffic. The lack of practical test procedures despite ever-stricter limits on CO_2 and other pollutant emissions has further exacerbated the gap between laboratory tests and reality.

To address these issues, regulations for the type approval of new vehicles have been tightened: starting with the EURO 6c standard, vehicles are subject to the emissions limits set out in the WLTP (Worldwide Harmonised Light Vehicles Test Procedure) test cycle, which covers a significantly broader load and speed range.

In addition, the EURO 6d-Temp emissiona standard also introduced the RDE (Real Driving Emissions) test procedure – to complement to WLTP bench testing. In this test, emissions limits must be maintained under realistic driving conditions. The test vehicle is fitted with PEMS (Portable Emission Measurement System) devices, which directly measure the level of pollutants in the exhaust emissions produced in an on-road driving scenario.

The first diesel vehicles to undergo this RDE test procedure have been on the market since 2018. A substantial market penetration of these vehicles of around 50% – bringing about a significant reduction in emissions – is not to be expected until about 2030, given that the average age of the European vehicle fleet is around 13 years (or around 10 years in Germany). Therefore, this measure will only have an impact in the longer term.

1.3 Periodic exhaust emissions testing

In addition to the more elaborate emissions measurements conducted during the type approval process, periodic exhaust emissions testing plays a crucial role in improving air quality. Its purpose is to ensure that a vehicle's exhaust aftertreatment systems remain in working order for the duration of its life cycle by identifying and, if necessary, remedying any deterioration in a vehicle's emissions behaviour, e.g. due to ageing, wear, or tampering with the exhaust gas aftertreatment system. The primary focus of exhaust emissions testing is on so-called 'high emitters'.

Although exhaust emissions testing has undergone continuous development in recent years, it has been unable to keep pace with developments in modern engine and exhaust gas aftertreatment technology.

The following stricter national guidelines were established in Verkehrsblatt 19/2017 [7], among others:

- As of 01/01/2018: Mandatory measurement of exhaust gas flow (tailpipe measurement)
- As of 01/01/2019: New exhaust gas opacity limit for Euro 6 diesel vehicles: 0.25 m-1
- As of 01/01/2021: Introduction of a procedure for particle number measurement

The first two points have already been implemented. These additional, stricter regulations are designed to improve the informative value of exhaust emissions testing.

For the aforementioned reasons, however, it would appear necessary to integrate the NO_x emissions test into future periodic exhaust emissions testing guidelines.

1.4 Vehicular NO_x conversion systems

In the diesel engine combustion process, excess oxygen in combination with a high combustion temperature, results in an increased production of nitrogen oxides (NO_x). Since an increased engine load leads to an increased combustion chamber pressure, and thus a higher combustion chamber temperature, there is a direct correlation between engine load and nitrogen oxide emissions in the raw exhaust gas.

Internal engine solutions are designed to reduce the production of NO_x during the combustion process, most prominently exhaust gas recirculation (EGR). With EGR, a defined amount of exhaust gas is recirculated and added to the fresh intake air. This causes a reduction in the oxygen content of the air-fuel mixture in the combustion chamber and lowers the combustion temperature. This effect is supported by the high heat capacity of the principal components of exhaust gases, carbon dioxide, and water. Since both pollutants are subject to statutory limits under the type approval framework, exhaust gas recirculation must be implemented with extreme care.

Exhaust gas recirculation has to be deactivated at high speeds and under full load, otherwise particle emissions become too high due to a lack of fresh air. As such, the recirculation rate is heavily reliant on the operating point. The EGR valve is controlled by the engine control unit, which uses prestored engine maps to optimise performance.

A frequent cause of failure in the EGR system is coking of the EGR valve due to build-up of soot particles in the recirculated exhaust gas.

However, current exhaust gas limits cannot be met by internal engine-based solutions alone. Exhaust gas aftertreatment is indispensable. Storage catalysts or SCR catalysts are therefore used to reduce the nitrogen oxides from raw exhaust gas.

A lean NO_x trap (LNT) is a catalytic converter designed to adsorb nitrogen oxides during lean engine operation. As soon as the maximum adsorption capacity has been reached, the nitrogen oxides are reduced to nitrogen and water in a short period of rich engine operation. An LNT is less efficient than an SCR system with an NO_x conversion rate of approx. 80% and is therefore mainly used in small cars where an SCR system would require too much space to install. However, LNTs are not suitable for meeting future emissions standards [3].

The SCR catalyst currently shows the greatest potential in reducing NO_x. Ahead of an SCR catalyst, urea (AdBlue) is fed into the exhaust tract, where it is converted to ammonia. The SCR catalyst uses the ammonia to reduce nitrogen oxides to elemental nitrogen and water. The amount of urea must be precisely dosed in order to prevent the release of unreacted ammonia. Under optimum operating conditions (temperature, engine operating condition, etc.), NO_x conversion rates can exceed 90%. On the other hand, if the operating conditions are not met, the NO_x conversion rate is significantly lower. Furthermore, there is an incentive to tamper with the urea injection to cut out the additive (urea) altogether, without which the SCR catalyst has no NO_x-reducing effect whatsoever.

2 Research design and approach

In the first step, existing test procedures for measuring NO_x emissions were researched. These test procedures were identified and evaluated. In the next step, test procedures were derived that were deemed suitable for exhaust emissions testing in Germany.

These test procedures differ in terms of whether an additional load (roller test bench / on-road test) is applied to the engine – or whether it is only accelerated against the rotational mass (inertia) of the engine at idling speed while the vehicle is stationary.

Advantages of test procedures **with** an externally applied load:

- Higher engine loads significantly increase NO_x emissions
- Cut-off speed has no effect when idling

Disadvantages of test procedures **with** an externally applied load:

- Longer test setup times (e.g. securing the vehicle)
- Test equipment is generally more expensive and requires more space (test bench/test track)
- Conducting the tests is generally more time-consuming

The inverse advantages and disadvantages apply to test procedures **without** an externally applied load.

The test procedures were compared and evaluated on the basis of various criteria (e.g. purchasing costs, time requirements, correlation, error rate, acceptance, error indication). Using our own measurements, the function and effect of the best-rated test procedures were then examined to determine whether and how they are suitable for periodic exhaust emissions testing. The evaluation was based on two test procedures **with** an externally applied load (ASM2050 / road travel with Mini-PEMS) and one test procedure **without** an externally applied load (CAPELEC).

The test vehicle used was a Peugeot 308SW (2.0d) with a EURO 6b emissions standard. The primary NO_x-reducing systems, i.e. the EGR and SCR systems, were deliberately tampered with to assess whether and how reliably the test procedures would be able to detect possible faults: exhaust gas recirculation of the exhaust gas was blocked by an orifice plate, thereby suppressing the EGR (EGR error). The urea injection valve was removed so that urea could no longer be injected into the SCR catalytic converter (SCR error).

2.1 ASM2050 (Acceleration Simulation Mode)

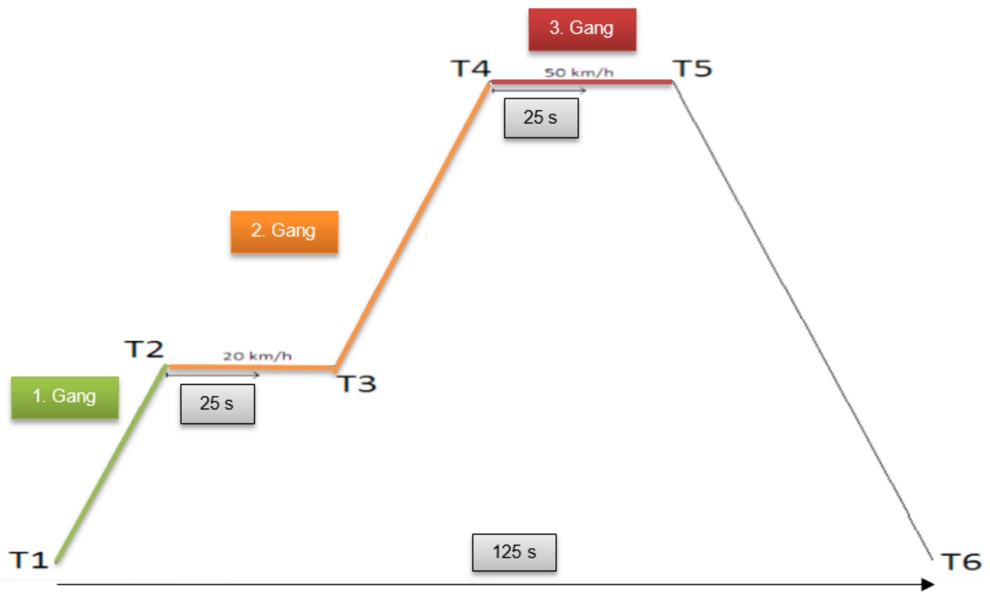
In the ASM2050 test procedure, a vehicle with a defined is accelerated to 20 km/h and maintains this speed for 25 seconds. In the next step, the vehicle is accelerated to 50 km/h and maintains this speed for another 25 seconds. Then the vehicle is brought to a standstill. The speed curve is shown in Figure 1. The nitrogen oxide emissions measured during the respective constant speed phases are used to calculate the mean value. The first five seconds of each constant speed phase are reserved for stabilisation. The measurement itself lasts 20 seconds per constant speed phase.

A constant roller load of 50 N, 200 N, and 1000 N was set for the tests in the evaluation phase. It was found that the built-in fault in the EGR system was clearly identifiable even at a low load. The SCR system, on the other hand, requires higher loads until it comes into operation and can be evaluated.

Advantages of the ASM2050:

- Very good fault indication: vehicles with deliberately introduced faults measured four times higher NO_x values than factory condition vehicles [6]
- Relatively low requirements on the test bench

Figure 1: Speed curve over the time for the ASM2050 cycle



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2.2 On-road testing with mini-PEMS

So-called mini-PEMS, which use sensors to measure exhaust gas concentrations, are currently in development. These devices are much more compact, lighter, and cheaper than the PEMS used for emulsion type approval testing. Based on these properties, it is conceivable that mini-PEMS could be used for periodic exhaust emissions testing. The measurement could be combined with the on-road test required by the periodic technical inspection (PTI).

Installing the mini-PEMS itself is relatively simple. In order to determine pollutant emissions per kilometre, however, the exhaust gas mass flow must also be determined using an exhaust flow meter (EFM). The effort required to install an EFM depends on the type and position of the exhaust tailpipe and can take several hours. Alternatively, an exhaust gas sampling probe can be used to measure only the NO_x volume concentration. This reduces the time required for installation to just a few minutes. It was found that the determination of the volume concentration was sufficient for the measurement procedures examined and did not have to be converted to "g/km" as was the case in the type approval test. Therefore, the mass flow/volume flow of the exhaust gas does not have to be measured.

It was found that there is a good correlation between the mini-PEMS and the PEMS used to measure exhaust emissions during type approval testing.

The evaluation phase for the mini-PEMS produced the following findings:

- Speed and distance travelled can be measured with sufficient accuracy using a GPS system.
- NO_x concentrations can be measured with sufficient accuracy.
- CO_2 concentrations can be measured with sufficient accuracy.
- The exhaust gas mass flow can be measured with sufficient accuracy via the signal from the intake air sensor and the fuel flow.
- Based on the exhaust concentrations, conclusions can be drawn regarding the condition of the vehicles. This eliminates the need for a time-consuming installation of an EFM.
- NOx emissions [mg] can be estimated based on NO_x to CO_2 concentration ratios [%].
- Mini-PEMS is a viable alternative / supplement to the roller test bench.
- Installation of a mini-PEMS is possible with minimum effort (without mass flow measurement).
- A vehicle's NO_x, CO, and particle emissions can be measured by means of a short on-road test.
- Built-in faults are reliably detected.
- The given concentrations are sufficient for the evaluation, a determination of the exhaust gas mass flow is not compulsory.
- Environmental conditions and vehicle conditioning affect the results.
- OBD data increase reliability during evaluation (e.g. exhaust gas temperature, SCR catalyst temperature, ambient temperature, AdBlue dosage).
- All-wheel drive vehicles can be tested without additional effort.

2.3 Capelec

The test without external load developed by the electronics manufacturer Capelec uses five criteria to test the functionality of the EGR valve. The position and function of the EGR valve are determined by the engine filling ratio. The engine filling ratio p is calculated using OBD data and the combustion chamber size, which must be entered manually by the person administering the test.

The results of the SCR error show a similar exhaust emissions behaviour as the measurement in factory condition, as the operating range for urea injection is not reached. Therefore, this method is not suitable for the evaluation of the exhaust aftertreatment system and was not examined any further.

- Poor fault indication: increase of measured values by a factor of 1.2 [6]
- Only 2 criteria applicable to vehicles with limited cut-off speed

- Focus on EGR, no informative value for exhaust aftertreatment systems such as the SCR catalytic converter

3 Execution

The evaluation of the procedures found that the functionality of all emissions control systems can only be reliably tested if an external load is applied to the engine. This is partly due to the aforementioned relationship between engine load and NO_x raw emissions. Another reason is that exhaust aftertreatment systems such as SCR catalytic converters often do not run in the temperature-dependent operating range when idling and thus cannot be tested for their functionality.

Therefore, in the next step, the ASM2050 was tested and validated using a mini-PEMS both on a roller test bench and on the road. The validation was carried out with the following test vehicles:

- Peugeot 308 BlueHDi 180 EAT8 GT (2.0d) – Euro 6d-TEMP emissions standard
- Mercedes Benz A-Class 180 – Euro 6d-TEMP emissions standard
- VOLVO XC60 – Euro 6d-TEMP emissions standard

The measurements for the three selected test vehicles were carried out as follows:

- in factory condition (= without pre-installed faults)
- with EGR fault
- with SCR fault
- with EGR and SCR faults

The respective test vehicle was conditioned before each measurement:

- Engine temperature > 80 °C
- SCR catalyst temperature > 200 °C
- No faults stored in the OBD trouble-code memory

At least five ASM2050 cycles were run in succession – with a pause of 10 seconds between the cycles. The evaluation included the constant runs of cycles 3, 4, and 5. In these cycles, the systems were active in all measurements and vehicles. All measurement results are summarised in Table 1 in the Appendix.

4 Findings

4.1 ASM2050 – Test bench

Even if only one of the two faults was installed, there was a significant increase in NO_x emissions (averaged values from constant runs or peak values). The SCR fault also led to higher emissions values than the EGR fault. Emissions increased disproportionately if both faults were installed at the same time. This would suggest that if only one exhaust gas purification system fails, the functioning system will partially compensate for the failure. Whether the applied load is 500 N or 1000 N only has a minor impact on the NO_x emissions measured at the tailpipe. The increased measured values after installation of the fault are sufficiently significant at 500 N compared to the original condition to be able to detect faults. Applying a load of 1000 N does not provide any additional information and therefore does not appear necessary. The situation is similar with the different speeds of 20 km/h and 50 km/h. With an existing manipulation, the increased values measured at 20 km/h are already sufficiently significant compared to the factory condition to be able to detect faults. Testing at a speed of 50 km/h does not appear necessary in view of the additional effort involved and the information gained. This result is independent of whether testing is carried out on the test bench or via a short on-road test.

4.2 ASM2050 – On-road test with Mini-PEMS

The short on-road tests following the ASM2050 cycle showed very similar results to the simulated drives on the roller test bench. The installation of a single fault already results in significantly higher NO_x emissions. If both faults are installed at the same time, NO_x emissions increase disproportionately. On-road testing with speeds of 50 km/h do not appear necessary in relation to the additional effort required and the information gained.

4.3 Short on-road test with Mini-PEMS

In addition to the ASM2050, mini-PEMS were used for the "short on-road test". A similar behaviour was observed during this shortened test drive of approx. 10 s and an acceleration to only approx. 20 km/h (with the exception of the Peugeot 308 with an EGR fault) – with sufficient significance for fault detection. The "short on-road test" provided similar results to the longer ASM2050 cycle.

The short on-road acceleration test needs to be examined in more detail in further studies. The advantages of an on-road test compared to a bench test are that the actual driving resistances act on the vehicle and, independent of the drive concept, the test requires no additional effort. Furthermore, exhaust emissions testing facilities do not need to find additional space for another roller test bench. On the other hand, every exhaust emissions testing facility needs to be able to carry out on-road testing with reasonable effort. The specifications and boundary conditions for such an on-road test must be precisely defined. With the caveat that only three vehicles were tested, both procedures – bench testing and short on-road testing – are suitable, based on the measured NO_x emissions, for testing the operation of the exhaust aftertreatment systems within the framework of periodic exhaust emissions testing. The installed faults were detected due to increased NO_x concentrations.

4.4 Conditioning as an important boundary condition

The NO_x concentration measured at the tailpipe depends to a large extent on the NO_x conversion efficiency achieved by the SCR catalyst. This efficiency depends on the temperature of the SCR catalytic converter, which reaches its optimum operating range between approx. 200 °C and 400 °C. The temperature of the SCR catalyst must therefore be within this temperature range during the measurement. It should be noted that the measurement must be started immediately after conditioning, as the SCR catalyst cools down very quickly when idling. If the temperature is too low, significantly increased NO_x emissions are measured although the SCR system is not defective. This finding shows that it is necessary to specify the correct conditioning for the vehicle.

It must also be possible to identify circumstances which might prevent the successful application of exhaust emissions testing, e.g. during the regeneration phase of the diesel particulate filter. In addition, information on the system concept of the exhaust aftertreatment is required in order to identify any conditions in which the systems may be partially or fully deactivated (e.g. low ambient temperatures).

The vehicle must be verifiably rendered ready for testing in order to reduce the possibility of misinterpreting the results. Correct conditioning of the vehicle is essential for transparent and reproducible measurement.

4.5 Expansion of the standardised OBD data

The on-board diagnostics (OBD) system stores important information (e.g. urea injection quantity, SCR catalyst temperature, EGR valve activity) on the condition of a vehicle. These data also need to be analysed when testing the conditioning parameters of the systems (e.g. catalyst temperature). The current

OBD standard SAE J 1979 provides for many data which would allow for more efficient and targeted exhaust emissions testing. An overview of the required parameters (PID) is provided in the Appendix. For this purpose, the OBD system must grant access to the necessary data, as is common practice for diagnostic devices in workshops. OBD could also be used to detect vehicle conditions during which exhaust emissions testing cannot be carried out, e.g. during the regeneration phase of the diesel particulate filter.

In addition, the currently valid software version must be compared with the software version available in the vehicle, e.g. to detect any tampering with the electronics.

4.6 Vehicle-specific limit values and testing specifications

The three vehicle types studied in this research project each have different exhaust aftertreatment concepts and engines. However, in order to statistically secure the information gained, it is necessary to increase the sample size. After all, it was found that the absolute NO_x emissions of the three vehicles studied were already very different. Compilation of suitable benchmark data during type approval testing would therefore be very useful in the evaluation of NO_x concentrations of diesel vehicles within the framework of periodic exhaust emissions testing. A definition of the appropriate test, including the collection of data for technical monitoring, would have to be included in the European regulations for exhaust emissions type approval testing. In addition to the measured NO_x concentrations, the conditions that need to be taken into account in technical monitoring, e.g. the engine temperature and the temperature at the SCR catalytic converter, also need to be determined. Type-specific limit values could be used for periodic exhaust emissions testing to evaluate the NO_x concentrations in vehicles with compression ignition engines. General limit values would also need to be defined, but should only be applied in the absence of type-specific values.

4.7 Measurement equipment requirements

In some tests, NO_x concentrations were measured that were within the range of permissible measurement errors. Regulation (EU) 2017/1151 specifies for the Type 1 test: *„If not defined otherwise, measurement errors shall not exceed ± 2 per cent (intrinsic error of analyser) disregarding the reference value for the calibration gases."* In other words, the permissible measurement error depends on the measuring range used. The use of suitable measurement equipment must therefore be ensured for measuring NO_x concentrations in these orders of magnitude. Currently, analysers with measurement ranges of 10 ppm or 3 ppm are available for laboratory use.

4.8 Benefit-cost analysis (BCA)

As part of the economic analysis, a benefit-cost analysis (BCA) should be used to determine whether the modified exhaust emissions test is beneficial from a macroeconomic point of view. The BCA is an established procedure for assessing the use of public funds or the implementation of regulatory measures. It is also designed to ensure that the measures will definitely improve social welfare. A benefit-cost ratio (BCR) is calculated. If the BCR is greater than 1, the use of public funds or the implementation of regulatory measures is deemed desirable from a social point of view. If it is less than 1, spending should be stopped, and regulatory measures should not be implemented. Exhaust emissions testing is a regulatory measure because it acts as a market control mechanism (= technical verification that NO_x emissions limit values are actually met). In order to determine the benefit-cost ratio for future exhaust emissions tests, it is necessary to determine both the economic costs of carrying out exhaust emissions testing and the economic benefits resulting from reduced NO_x emissions. The viability threshold for a measure is a benefit-cost ratio greater than 1. A benefit-cost ratio greater than 3 is considered excellent. In order to investigate the benefits of exhaust emissions testing for diesel passenger cars with Euro 6d-TEMP, the number of diesel passenger cars that have to be regularly inspected from 2024 onwards was first determined. A fault ratio of 1% was assumed for EGR faults, SCR faults, or EGR and SCR faults. Furthermore, the amount of additional NO_x emissions released due to faults in the catalytic converters was calculated. The emissions measurements carried out within the framework of this project were used for this purpose. In order to determine the economic costs, the personnel costs resulting from the time spent on exhaust emissions testing were calculated. Furthermore, the investment costs for the measurement equipment were calculated. Overall, an average BCR of 3.7 was calculated for the testing period from 2024 to 2033.

Therefore, introducing exhaust emissions testing will result in significant positive macroeconomic effects and an excellent BCR. However, it should be noted that this project broke new ground both theoretically and empirically, so that a number of assumptions had to be made. Although these assumptions were deemed plausible, they may still be subject to critical interrogation. It was therefore examined how sensitively the benefit-cost analysis reacts to changes in important input variables. For this purpose, so-called reaction elasticities were calculated to determine the effect of, for example, a variation in the distance travelled by a defective vehicle, the time required to carry out exhaust emissions testing, the personnel costs, or the investment costs for the measurement equipment. It was found that partial changes in time requirements, personnel costs and equipment costs only have a disproportionately low effect on the BCR. If all three variables were to increase by 10% at the same time, the BCR would decrease from 3.7 to 3.3, which is still an excellent value. If the number of kilometres travelled with a fault in the exhaust aftertreatment system is reduced by 10%, the BCR is reduced by 9.7%, but is still greater than 3.

Overall, the BCR shows that the introduction of exhaust emissions testing is desirable from a macroeconomic point of view. The sensitivity analysis also confirms a high stability of the benefit-cost ratio against changes in important input variables. However, the main limitations are that it is difficult to predict how the diesel passenger car population with Euro 6d will continue to develop.

The research report clearly shows that the addition of the air pollutant NO_x to the exhaust emissions testing measurement programme using the aforementioned measurement procedures is fundamentally feasible in terms of measurement technology and makes sense from a macroeconomic point of view. The present measurement programme was exclusively designed to develop a technically feasible measurement procedure. The measurement results show that the measurement must be carried out under load – either on a roller test bench or via an on-road test. However, further studies are needed to statistically secure this procedure.

According to an estimate, the future price for exhaust emissions testing of diesel vehicles (consisting of PN and NO_X measurements, including the additional equipment costs of approx. €1.90) would increase by approx. €12.80 (incl. VAT). As a result, the vehicle owner would have to pay an additional €6.40 per year (incl. VAT).

4.9 Legal amendments

The revision proposals for Directive 2014/45/EU and the German exhaust emissions guideline can be found in the Appendix in Table 3.

5 Appendix

5.1 OBD-PIDs

The OBD-PIDs listed below are already included in the SAE J 1979 standard and should be accessible in a standardised readable format in the future:

PID 01 Readiness codes (non-continuous)

bit 1 (NO_x), **bit 5** (exhaust gas sensor monitoring), **bit 6** (PM filter monitoring), and **bit 7** (EGR system monitoring)

PID 2C Commanded EGR (EGR rate)

PID 2D EGR Error

PID 78/79 Exhaust Gas Temperature (EGT) Bank 1/2

PID 7A/7B Diesel Particulate Filter Pressure (DPF) Bank 1/2

PID 7C Diesel Particulate Filter Temperature (DPF)

PID 7D NO_x NTE Control Area Status

PID 7E PM NTE Control Area Status

PID 83 NO_x Sensor (supported and concentration)

PID 85 NO_x Control System (information about Reagent)

PID 86 Particulate Matter Sensor (PM)

PID 88 SCR Inducement System Actual State

PID 8B Diesel Aftertreatment System

PID 8F Particulate Matter Sensor Output

5.2 Measurement results

Table 1: Overview table of all measurement results for ASM2050 cycle

Load [N]	Fault	NO_x constant MV 20 km/h [ppm]	FI constant MV 20 km/h	NO_x constant MV 50 km/h [ppm]	FI constant MV 50 km/h
			Peugeot 308		
500	Factory	**9.26**	1.00	**17.25**	1.00
500	AGR	**16.62**	1.80	**24.90**	1.44
500	SCR	**35.20**	3.80	**54.66**	3.17
500	AGR+SCR	**128.52**	13.88	**199.93**	11.59
1000	Factory	**4.45**	1.00	**8.74**	1.00
1000	AGR	**10.97**	2.46	**9.43**	1.08
1000	SCR	**47.21**	10.61	**113.40**	12.97
1000	AGR+SCR	**207.54**	46.62	**327.93**	37.52

On-road	Factory	**7.30**	1.00	**12.17**	1.00
On-road	AGR	**6.68**	0.92	**5.97**	0.49
On-road	SCR	**75.82**	10.39	**129.22**	10.61
On-road	AGR+SCR	**194.06**	26.60	**225.14**	18.49
			Mercedes A180d		
500	Factory	**0.01**	1.00	**0.04**	1.00
500	AGR	**1.62**	144.32	**5.32**	132.57
500	SCR	**3.55**	316.96	**5.06**	126.16
500	AGR+SCR	**32.85**	2934.06	**62.92**	1569.21
1000	Factory	**0.02**	1.00	**0.03**	1.00
1000	AGR	**5.41**	357.21	**10.75**	331.22
1000	SCR	**3.17**	208.91	**12.26**	377.94
1000	AGR+SCR	**51.70**	3411.00	**140.63**	4333.91
On-road	Factory	**0.25**	1.00	**2.35**	1.00
On-road	AGR	**9.78**	39.04	**27.00**	11.49
On-road	SCR	**24.23**	96.70	**40.37**	17.18
On-road	AGR+SCR	**153.85**	613.94	**284.95**	121.22
			VOLVO XC60		
500	Factory	**0.22**	1.00	**0.33**	1.00
500	AGR	**0.36**	1.60	**1.89**	5.68
500	SCR	**1.30**	5.88	**5.24**	15.72
500	AGR+SCR	**3.72**	16.81	**27.03**	81.16
1000	Factory	**0.33**	1.00	**0.79**	1.00
1000	AGR	**3.37**	10.37	**9.88**	12.52
1000	SCR	**5.73**	17.63	**19.48**	24.67
1000	AGR+SCR	**24.50**	75.33	**92.39**	117.05
On-road	Factory	**0.57**	1.00	**4.07**	1.00
On-road	AGR	**16.27**	28.57	**55.05**	13.52
On-road	SCR	**34.16**	59.99	**57.95**	14.23
On-road	AGR+SCR	**87.85**	154.25	**132.43**	32.52

Table 2: Overview table of all measurement results for the “short on-road test”

Test	Fault	Mean NO_x [ppm]	Peak NO_x [ppm]	Error factor Mean value NO_x
		Peugeot 308		
1	Series	**9.65**	17.94	
2	Series	**9.23**	19.57	
3	Series	**10.53**	24.11	
Mean	Series	**9.80**	20.54	1.00
1	AGR	**10.68**	21.14	
2	AGR	**10.52**	35.23	
3	AGR	**12.37**	37.18	
Mean	AGR	**11.19**	31.18	1.14
1	SCR	**115.12**	189.34	
2	SCR	**117.44**	177.78	
3	SCR	**110.30**	180.32	
Mean	SCR	**114.29**	182.48	11.66
1	AGR+SCR	**208.42**	365.19	
2	AGR+SCR	**216.26**	364.82	
3	AGR+SCR	**205.52**	421.78	
Mean	AGR+SCR	**210.07**	383.93	21.43
		Mercedes A180d		
1	Series	**0.93**	5.46	
2	Series	**1.45**	7.19	
3	Series	**3.70**	17.52	
Mean	Series	**2.03**	10.05	1.00
1	AGR	**13.25**	46.41	
2	AGR	**9.66**	45.63	
3	AGR	**35.91**	121.37	
Mean	AGR	**19.61**	71.13	9.67

1	SCR	**104.39**	317.13	
2	SCR	**93.81**	203.87	
3	SCR	**114.00**	266.63	
Mean	SCR	**104.07**	262.54	51.32
1	AGR+SCR	**252.44**	812.41	
2	AGR+SCR	**268.73**	859.75	
3	AGR+SCR	**272.04**	858.40	
Mean	AGR+SCR	**264.40**	843.52	130.40

5.3 Proposed revisions for the amendment of Directive 2014/45/EU and the Exhaust Emissions Directive

Table 3: Amendment of Directive 2014/45/EU

Item	Method	Reason for failure	Assessment of deficiencies: Minor	Major	Dangerous
8.2.2.3 NO_x Measurement	For vehicles as of emission class Euro 6d-TEMP: NO_x concentration to be measured under load with a force of at least 500 N and a speed of 20 km/h. Alternatively, a short on-road test may be carried out with an acceleration to 20 km/h and subsequent deceleration to 0 km/h (1st gear). 1. Vehicle preconditioning: The engine shall have reached the full operating temperature of at least 80 °C. The SCR catalyst shall have reached the operating temperature as per the manufacturer's specifications. NO_x test readiness indicated (EOBD Mode 1 – readiness code). Measurement to be carried out immediately (avoid cooling). 2. Test procedure: Measurement of the NO_x	NO_x concentration exceeds the value specified by the manufacturer. If this value is not applicable/available: NO_x concentration exceeds the value of (40) ppm		X	

	concentration using suitable measurement equipment under load with a force of at least 500 N and 20 km/h (0-20 km/h in 15 s, 25 s constant, 20 km/h to 0 in 15 s) or alternatively: Short on-road test with acceleration from 0 to 20 km/h (approx. 3 s constant 20 km/h) and deceleration to 0 km/h (corresponds to a measuring distance of approx. 40 m) The test shall only be considered failed if the arithmetic mean of at least three measurement cycles exceeds the limit value. When calculating this value, measurements that deviate significantly (> 30 %) from the averaged measured value or the result of other statistical calculations which take into account the dispersion of the measurements shall be disregarded. Member States may place limits on the number of test cycles to be carried out. To avoid unnecessary testing, Member States may decide that a vehicle with measured values significantly below the limit (< 30 %) after less than three measurement cycles has passed the test.		

To adapt/amend the German exhaust emissions guideline, an adaptation proposal for NO_x measurement is made below. The exhaust emissions guideline should be amended to include the performance test “exhaust gas with NO_x measurement”:

Performance test with NO_x measurement (for vehicles as of Euro 6dtemp)

- Vehicle conditioning:
  1. Coolant temperature at least 80 °C
  2. Determine NO_x test readiness by reading the readiness codes (NO_x supported and executed)
  3. Carry out NO_x measurement immediately after conditioning, avoid cooling, immediately drive onto the test bench without switching off the engine or taking a short drive
- Place vehicle on test bench and execute test cycle (with 500 N load, 20 km/h)
  1. Accelerate the vehicle from 0 to 20 km/h (within 15 s)
  2. Maintain a constant speed of 20 km/h for 25 s
  3. Then decelerate from 20 km/h to 0 km/h within 15 s
  4. Wait 15 s
- Evaluation test cycle – load roller
  1. 5 s after reaching the test speed of 20 km/h, begin NO_x measurement and calculate mean over 20 s
- If no test bench is available, the measurement may also be carried out via a short on-road test
  1. Accelerate the vehicle from standstill to 20 km/h (in max. 5 seconds)
  2. Maintain speed at 20 km/h for approx. 3 s
  3. Then reduce vehicle speed down to 0 km/h
- Evaluation test cycle – short on-road test
  1. Begin NO_x measurement immediately after the acceleration of the vehicle and calculate mean over the entire movement cycle of the vehicle
- Repeat test cycle until the last three test cycles are within a range of +/- 20% (or a fixed value of e.g. 10 ppm) of the mean of the three test cycles
- Evaluation overall result
  1. Calculate the mean of the last three test cycles
  2. Result < manufacturer value OK
  3. Result > manufacturer value not OK
  4. If manufacturer value unavailable, NO_x limit value 40 ppm

6 List of references

[1] Umweltbundesamt [German Environmental Agency]. (2017). Wirkungen auf die Gesundheit [Effects on health]. Accessed on 01/11/2017 at https://www.umweltbundesamt.de/themen/luft/wirkungen-von-luftschadstoffen/wirkungen-auf-die-gesundheit.

[2] Landesanstalt für Umwelt, Messungen und Naturschutz Baden-Württemberg [Baden-Württemberg State Institute for the Environment, Survey and Nature Conservation]. Wirkungen auf den Menschen [Effects on humans]. Accessed on 01/11/2017 at https://www4.lubw.baden-wuerttemberg.de/servlet/is/18796/.

[3] Yang, L., Franco, V., Campestrini, A., German, J. & Mock, P. (2015). NOX control technologies for Euro 6 Diesel passenger cars: Market penetration and experimental performance assessment. ICCT 2015, International Council on Clean Transportation, Neue Promenade 6, 10178 Berlin.

[4] Tietge, U., Diaz, S., Mock, P., German, J., Bandivadekar, A., Ligterink, N. (2016). From laboratory to road. A 2016 update of official and 'Real-world' fuel consumption and CO2 values for passenger cars in Europe. White Paper ICCT November 2016. Accessed on 02/11/2017 at https://cleantechnica.com/2016/11/21/icct-average-gap-official-fuel-consumption-figures-actual-fuel-use-eu-hit-42/.

[5] European Environment Agency. (2016). Explaining road transport emissions: A non-technical guide. Accessed on 02/11/2017 at https://www.eea.europa.eu/publications/explaining-road-transport-emissions/at_download/file.

[6] CITA International Motor Vehicle Inspection Committee. (2017). CITA SET II Project: Sustainable Emissions Testing.

[7] Bundesministerium für Verkehr und digitale Infrastruktur [Federal Ministry of Transport and Digital Infrastructure]. (2017). Verkehrsblatt [Transport gazette] 19/2017.