Abridged final report

Euro5 diesel vehicles and their operation and performance in everyday traffic following a hardware retrofit

Driving over 50,000km in everyday traffic
incl. exhaust emissions measurements in the WLTC
and real driving emissions (RDE) measurements

Project managers:

ADAC Württemberg e.V.

ADAC e.V. Test & Technical Services

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Recipient:

ADAC Württemberg e.V.

Content

1 Introduction

People’s health has always been a first priority for ADAC. Hence, ADAC supports the idea of running through the full gamut of measures suitable to reduce urban air pollution, ideally without limiting individual mobility by introducing driving bans.

ADAC therefore continues its efforts to promote hardware retrofits for the reduction of nitrogen oxide (NO_x) emissions of diesel vehicles. ADAC Württemberg e.V. and ADAC e.V. have launched a joint project which is funded by the Baden-Wurttemberg Ministry of Transport. The project aims at assessing the functionalities and effectiveness of SCR systems in long-term everyday driving.

With this second test series, ADAC continues a project carried out by ADAC Württemberg e.V. in the winter of 2017/18 and funded by the Baden-Wurttemberg Ministry of Transport. The results were published at a press conference in Stuttgart on 20 February 2018 [1]. The measurements conducted at the ADAC technical centre at Landsberg/Lech with and without the retrofit system provide clear proof that the technology is, in principle, effective since it reduced NO_x emissions by at least 50 to 70% in 4 retrofitted Euro5 diesel vehicles.

The current project is designed as a long-term test, i.e. the retrofitted/optimised vehicles assessed in the first funding project of ADAC Württemberg e.V. had to cover at least 50,000km in everyday traffic – on urban and extra-urban roads as well as on motorways. The focus of the assessment was on the systems’ reliability in different weather conditions such as heat, cold, rain and snow. To be able to regularly measure the vehicles’ NO_x emissions, we subjected the vehicles every 10,000km to a lab test based on WLTC. In addition, we conducted several RDE measurements.

In the framework of the project, we also took a series of special measurements including, for instance, of pollutants such as ammonia (NH_3) to which no limit applies or the greenhouse gas nitrous oxide (N_2O), and conducted testing at low temperatures.

The test line-up included an Opel/Vauxhall 1.7 CDTI that was retrofitted by Twintec Baumot and 2 light commercial vehicles (VW T5 retrofitted by Oberland Mangold and Fiat Ducato retrofitted by HJS). Since the Fiat Ducato was damaged beyond repair in a road accident, it was no longer available to continue the long-term test after 33,000km. The Mercedes B 180 CDI equipped with a system from Dr Pley SCR-Technology GmbH was pulled back from our current project for company-internal reasons.

As a first step, we invited the participating retrofitters in July/August 2018 to give their prototypes in the test vehicles a technology update. To comply with the requirements set out in the statement of work, amongst other things, the retrofitters had to equip the vehicles with systems that provide information on the AdBlue® fluid level as well as continuously monitor and display the operational condition of the SCR catalytic converter. Carrying the improved systems on board, the vehicles were subjected to initial emissions tests both in the lab and on the road; the results were compared with those of the systems of the first development stage.

Since the long-term test started in late August 2018 and ended in January 2019, it covered different kinds of weather conditions ranging from summer heat to cold winter weather.

1.1 Project participants

Project management:	ADAC Württemberg e.V. Carl-Eugen Metz, Board Member Transport and Environment Am Neckartor 2 70190 Stuttgart, Germany
	ADAC e.V. Test &Technical Services Dino Silvestro, Senior Manager ADAC Vehicle Testing Otto-Lilienthal-Strasse 2 86899 Landsberg am Lech, Germany
Project participants:	HJS Emission Technology GmbH & Co. KG Dieselweg 12 58706 Menden/Sauerland, Germany
	Oberland Mangold Katalysatortechnik GmbH In der Enz 1 82438 Eschenlohe, Germany
	Twintec Baumot Group BAUMOT Technologie GmbH Stockumer Str. 28, B14 58453 Witten, Germany
Scientific support:	Prof Dr-Ing Hermann Koch-Gröber Automotive Systems Engineering (ASE) Heilbronn University of Applied Sciences Max-Planck-Str. 39 74081 Heilbronn, Germany

2 Objectives

The project entitled *Reduction of NO_x emissions from Euro5 diesel vehicles by hardware retrofits* showed that retrofit SCR systems are, in principle, effective [1].

In our current follow-up project, we verified whether after the hardware retrofit the Euro5 diesel vehicles achieved permanent reductions in NO_x emissions in everyday driving and whether their performance changed when they were used during a specified period of time under different framework conditions. The purpose of the project was to provide exemplary documentation of the operation and effectiveness of the SCR exhaust gas aftertreatment systems installed in the tested prototypes rather than to conduct a comprehensive functional and long-term test with a view to ensuring functional safety in line with the standards applicable to the automotive industry.

50,000km in everyday traffic to assess mechanical reliability and system stability

In the retrofitted test vehicles, we covered at least 50,000km, documenting any incidents or system failures in a test log. To verify the effectiveness of the SCR systems during the test period, we took the vehicles to our lab every 10,000km for emissions testing in the WLTC and motorway cycles.

Documentation of NO_x reduction and AdBlue® consumption in different temperatures

We used a data logger to continuously record relevant emissions data during testing in everyday traffic. In addition to the NO_x emissions in front of and behind the SCR system, we recorded the exhaust temperatures and AdBlue® consumption. It was our aim to collect the NO_x reduction and AdBlue® consumption data during the test period in different outside temperatures.

Performance in low and high temperatures

To document the system's effectiveness in different outside temperatures, we conducted PEMS measurements in specific temperature/weather conditions (summer, autumn, winter). The test route also took us through built-up areas where engine load is high and exhaust temperatures are low. We also made a number of cold starts in different outside temperatures.

Measurement of uncontrolled pollutants

Under certain circumstances, catalytic exhaust gas aftertreatment or an AdBlue® overdose may cause secondary emissions which should absolutely be avoided. Therefore, we also measured uncontrolled pollutants such as ammonia (NH_3) and nitrous oxide (N_2O).

3 Summary of findings

On 21 December 2018, the German Federal Ministry of Transport and Digital Infrastructure (BMVI) adopted the requirements for SCR retrofit systems in passenger cars. The Directive *Technical specifications for nitrogen oxide (NO_x) reduction systems with increased reduction performance for retrofits on passenger cars and similar vehicles* defines the properties and reduction performance of retrofit systems. It was published in the German Federal Gazette on 11 January 2019 [2].

Quintessentially, the directive specifies the NO_x limit of 270mg/km which was established in the draft amendment of the Federal Immission Control Act (BImSchG) in autumn 2018 [3]. To pass testing and obtain approval, RDE NO_x emissions must not exceed the above limit between 5°C and 30°C. In lower temperatures (4°C to -3°C), a factor of 2 increases the stricter NO_x limit to 540mg/km, and if temperatures exceed 30°C, the factor is 1.6 (432mg/km). The directive also specifies that the increase in CO_2 emissions of vehicles retrofitted with an SCR system must not exceed 6%.

According to the directive, manufacturers must prove that their NO_x reduction systems have a long service life. If a system is used for its intended purpose, it must endure 100,000km or up to 5 years (whichever occurs first).

While the SCR retrofit systems are highly effective also after 50,000km, their reliability needs to be improved for standard production use

The tested vehicles took 5 months to travel 50,000km in everyday traffic. They followed the 700km route of our long-term test 72 times. When the test drives were completed, the results varied significantly.

It was good to see that with similar reduction rates, the SCR catalytic converters were, in principle, as effective after 50,000km as at the beginning of the test. There was no steady decline in performance as, for instance, the SCR systems aged during the 50,000km test.

Reliability was less impressive: after installation, which took a few weeks, and adaptation to the respective test vehicle, the SCR systems were in a development stage in which long-term functional reliability could not be ensured. We saw temporary system failures and mechanical defects of SCR components as well as temporary instability in the energy management. Consequently, the retrofitters had to make several improvements to mechanical components, the sensor systems and the energy supply.

With a view to the potential standard production use of SCR retrofit systems, the greatest challenges so far seem to be the service life of mechanical SCR components, the issue of how to prevent deposition as well as stable and efficient energy management. These are the issues which the retrofitters need to tackle to comply with the service life/mileage requirements set out in the above retrofit directive and to design their systems in a way that they are warranted against defects/failure. Because motorists must be able to rely on having purchased a reliable and durable product that ensures carefree mobility in the years to come at no consequential cost.

SCR retrofit systems whose components were tried and tested in standard production systems were more reliable in our test than systems comprising specifically designed components

The SCR system in the Fiat Ducato mostly comprised components which had been tried and tested in standard production systems. According to our test log, there were 2 temporary system failures (for details, refer to the test log) but no other relevant incidents. NO_x reduction was stable up to 30,000km (intermediate measurement), and there were no defects worth mentioning during our test. However, soon after going into leg 4 of the long-term test, the vehicle was involved in an accident that was not the driver's fault. Since the vehicle was beyond repair, we had to abort the test with this vehicle. Although it did not do the final 20,000km, the vehicle left a positive impression: in the Ducato, HJS installed mostly series production parts of the Euro6b model series. Usually working reliably, this concept offers the potential for development into a series production SCR retrofit system in the short term.

In the VW T5, Oberland Mangold install several series production parts of the VW T6. These parts comprise the AdBlue® tanks including all lines. They had already been subjected to a long-term test and proved to be durable in our test. The VW breezed through the test for quite a long time. After 30,000km, however, NO_x emissions suddenly deteriorated. Why? In the external hydrolysis reactor which Oberland Mangold developed for AdBlue® treatment, deposits are left over time which impair the system's effectiveness. Oberland Mangold could easily remedy this defect by removing the deposits. However, this would not be a solution for a series production system. The retrofitter still needs to do some research and development to ensure the long-term operation of their system. The NO_x reduction rates require further enhancement, too, since they are very low at higher (motorway) speeds.

The Opel/Vauxhall Astra was number 3 in our test line-up. Independent of the SCR retrofit system, we found this car to be rather unreliable in our long-term test as it required several unscheduled visits to the workshop. However, among the vehicles tested the Astra had the highest mileage (140,000km). Already in the first project – conducted in 2017/2018 on the basic feasibility and efficiency – the retrofitter Twintec had to design an all-new SCR system and adapt it because there were no SCR series production components available for the Opel. Greatest challenges were the limited space and the suboptimal position of the exhaust system. In our test we identified quite some potential for improvement. According to our test log, several failures occurred including a leak in the coolant hose, a defective AdBlue® gauge and a mechanical defect in a line that directs the exhaust gas to the hydrolysis reactor. The energy management and/or energy supply were equally insufficient for series production use. The on-board generator was not capable of reliably charging the additional battery in the boot in all operating conditions. Consequently, as a precaution, the SCR system was deactivated, and/or the dosing rates were lowered in certain driving situations so as not to compromise the stable energy supply to (safety-relevant) vehicle systems by an overloaded on-board electrical system.

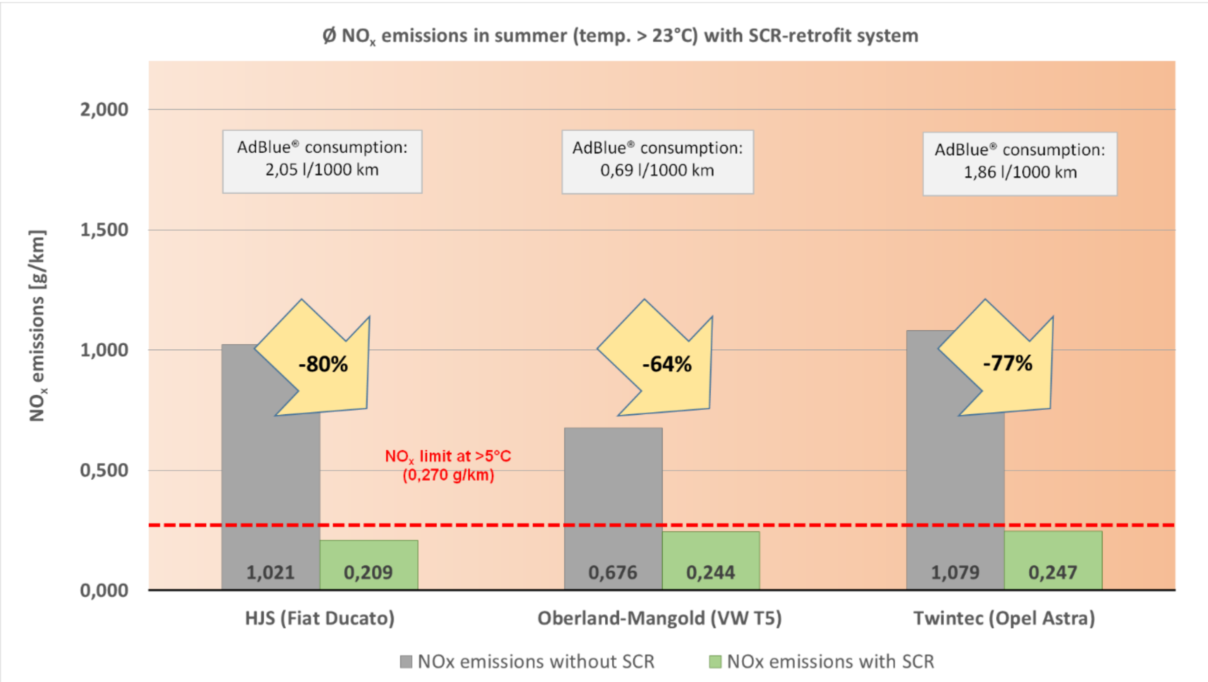
Despite these serious problems, the Twintec system shows that SCR retrofit systems can be successfully implemented also in less convenient vehicle types. It will still require creative engineers as well as some time to develop series production systems for such vehicles.

In summer heat, SCR retrofit systems take RDE emissions to or below the NO_x limit of 270mg/km

Before our test, we took a drive on a warm day in late August to measure RDE in summer mode. While emissions were shockingly high without SCR system, they made us hopeful when we took the measurements with SCR retrofit system.

At or beyond 23°C, the 3 test vehicles produced untreated RDE NO_x emissions of approx. 700 to 1,100mg/km even when external conditions were good. Although emissions were much higher than the Euro5 lab test limit, the SCR systems in any of the 3 cars clearly lowered emissions thanks to an exhaust gas aftertreatment system that relies on catalytic converters and the AdBlue® urea solution. Reduction rates in the RDE measurements were between 64 and 80% and brought the NO_x emissions of the tested vehicles to or below the limit of 270mg/km which – as required by the above directive on retrofit systems – vehicles must not exceed in a temperature range from +5°C to +30°C.

Figure 1 RDE NO_x emissions in summer



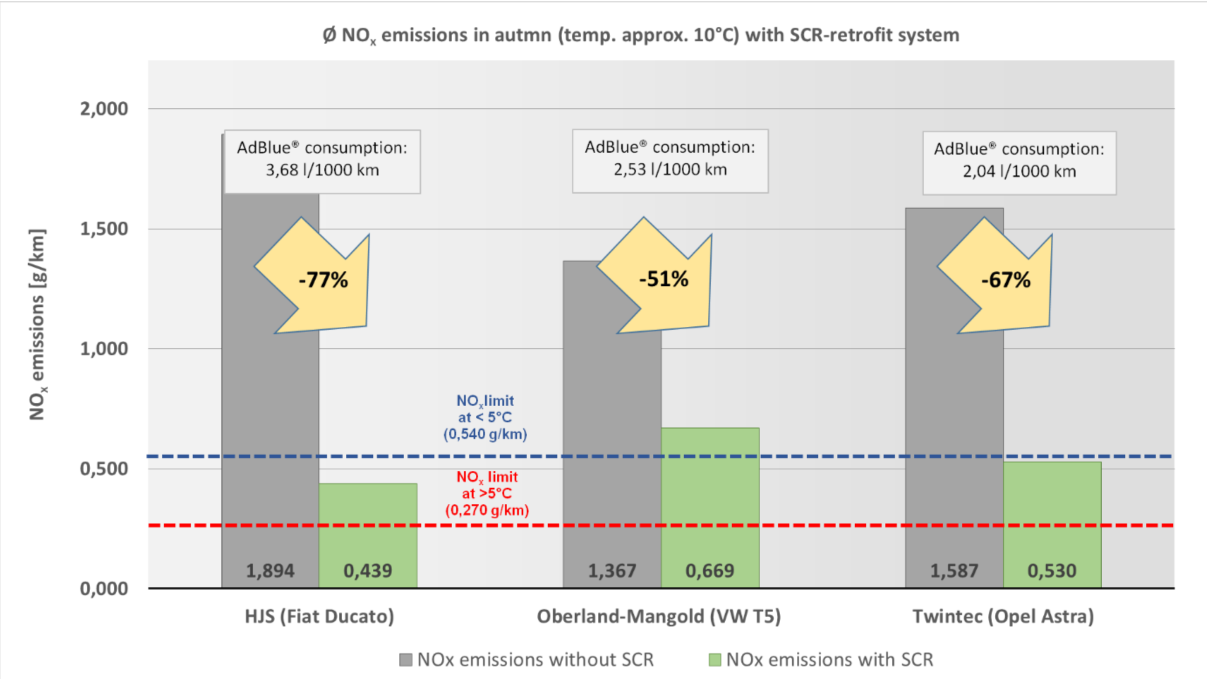
In autumn temperatures, emissions soar drastically without SCR system. Impressive NO_x reduction rate with SCR retrofit system

Without SCR systems, the 3 tested vehicles produced much higher emissions in low outside temperatures. Climbing to almost 2g/km, NO_x emissions were partly twice as high as the RDE emissions in summer temperatures. And this despite the fact that the autumn measurements were taken at temperatures that correspond to the annual average temperature in Germany (approx. 9.5°C). At an outside temperature of 10°C, the SCR retrofit systems effectively reduced emissions, however, not as effectively as in summer temperatures. This is mostly due to the fact that the SCR systems work independently of the engine control units and take their time to reach operating temperatures after a cold start. The measured NO_x reduction rates were still high, ranging between 51 and 77%. While this was a significant decrease, NO_x emissions in absolute terms still amounted to at least 400mg/km.

Our autumn measurements showed that in vehicles without SCR systems, emissions increase dramatically already when temperatures are around 10°C. Although the tested retrofit systems were quite effective in this temperature range, they reduced emissions only to a level that was clearly above 270mg/km; however, emissions would not exceed 540mg/km, which is the limit for low temperatures. From the measurements we see that depending on the model, vehicles without SCR may produce much higher emissions already at approx. +13°C (key word: thermal window). The factor that takes into account adverse conditions, however, does not apply before the temperature is +5°C or lower, though.

Obviously, compliance with the emissions limit is most challenging in the temperature range between +5°C and +13°C. When adopting the above retrofit directive, it was assumed that the vehicle is still operating at normal temperatures so that a factor to compensate for adverse conditions was not needed. Practical experience has shown that carmakers have a different notion of low outside temperatures, strongly slowing down the performance of EXW emissions control systems already in this temperature range. Consequently, emissions in cars without SCR systems are way too high for high-quality retrofit systems to be effective even if NO_x emissions in absolute terms decrease by up to 1,400mg/km. For SCR retrofit systems to be able to clearly reduce emissions in absolute terms, carmakers should update their engine control units improving, for instance, exhaust gas recirculation in this temperature range.

Figure 2 RDE NO_x emissions in autumn

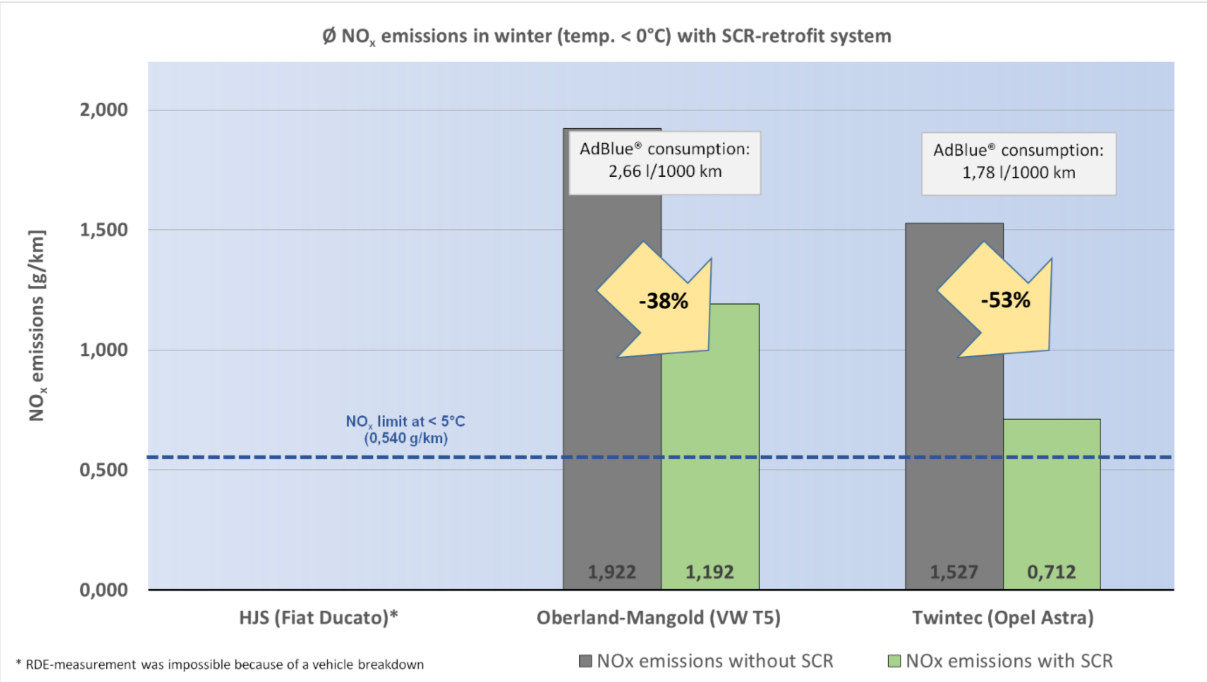


SCR retrofit systems are much less effective in winter but still achieve acceptable reductions of NO_x emissions

As was the case with the VW T5 Multivan, without SCR system emissions can increase further at freezing point temperatures in the winter. On the other hand, in the Opel/Vauxhall Astra we saw that as soon as a certain temperature level is reached, emissions remain stable. This means that the outside temperature has only marginal effect on NO_x emissions. What does have an effect, however, is the carmaker's strategy of when and to what extent the exhaust gas aftertreatment system should slow down. Not being familiar with this strategy, retrofitters have a very challenging job installing a system that is effective throughout the entire temperature range.

Reduction rates in winter are still acceptable, ranging between 38 and 53%. Lowered NO_x emissions in absolute terms range between 700mg (Opel/Vauxhall) and 1,200mg (VW). This may clearly be above the low-temperature NO_x limit of 540mg/km, but in the case of Opel/Vauxhall we see that it is within a technically feasible range. What helps to reach this ambitious limit are a sophisticated energy management, an efficient heating strategy of the SCR system and an effective thermal insulation of the SCR components.

Figure 3 RDE NO_x emissions in winter



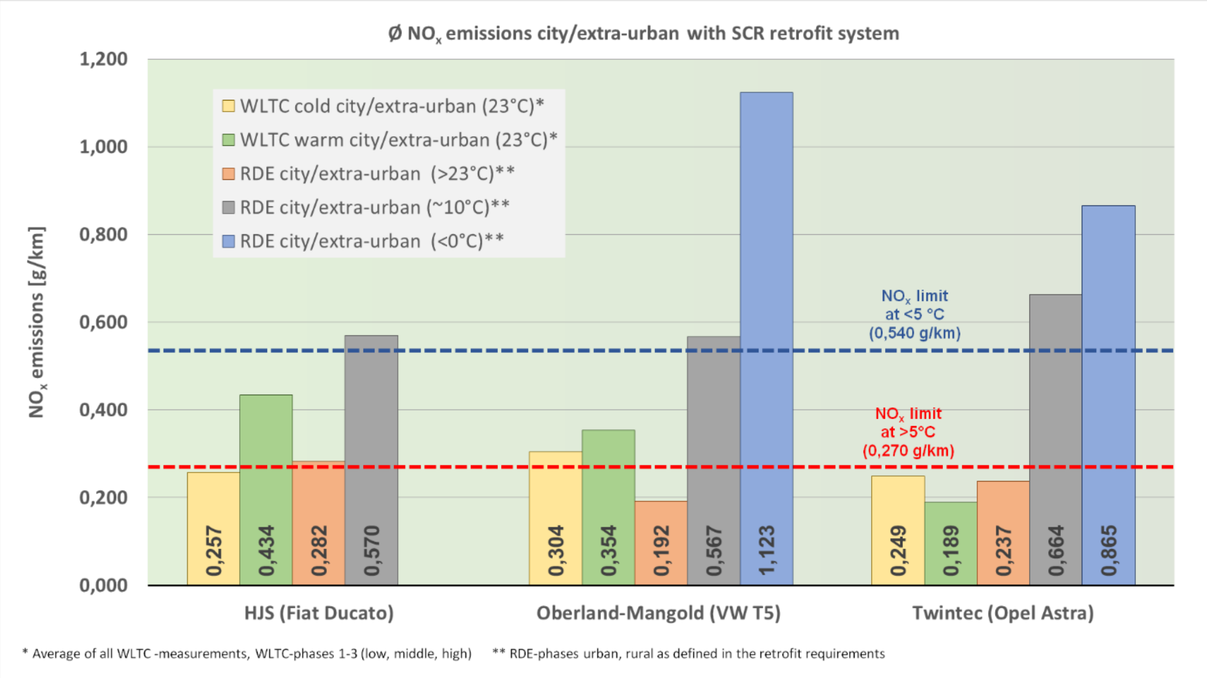
In low outside temperatures, emissions in front of the SCR system are higher and SCR systems take longer to warm up

In the city and extra-urban driving modes, the NO_x emissions of the Opel/Vauxhall Astra clearly exceeded the limit of 270mg/km in the WLTC cycle both right after engine start and with a warm engine. The RDE measurements at summer temperatures confirm this. Despite impressive NO_x reduction rates in the WLTC, both vans failed to fully comply with the limit. Please note, however, that the Fiat Ducato and the VW T5 were type-approved to the Euro5 N1 III and the Euro 5 M1 (specific social needs) standards, respectively. This means that to obtain type approval, the vehicles have to comply with a NO_x limit of 280mg/km (rather than the 180mg/km limit for passenger cars). Applying a factor of 1.5 to the type-approval limit in analogy to passenger cars, then a vehicle must not emit more than 420mg/km of NO_x in order to be exempt from driving bans.

In autumn, emissions increase strongly without SCR system. In addition, the vehicles take longer to warm up and reach exhaust temperatures high enough for the SCR retrofit systems to operate effectively. Consequently, emissions in absolute terms in urban/extra-urban traffic are much higher than in warmer weather.

In very low winter temperatures, an efficient heating strategy and good insulation of SCR components are of the essence. Emissions right after a cold start are very high.

Figure 4 NO_x emissions city/extra-urban in WLTC cold/warm and RDE



Increased energy consumption of SCR retrofit systems leads to increased fuel consumption – series production systems require efficient energy management

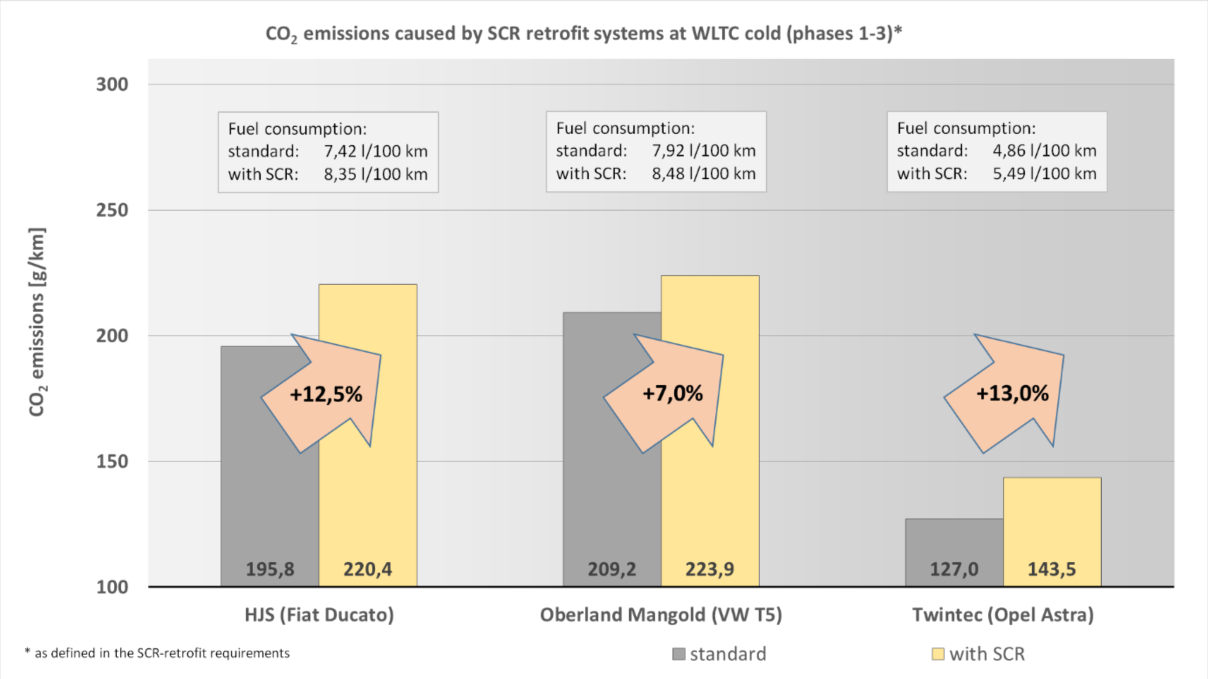
According to the directive on the retrofitting of passenger cars, fuel consumption and/or CO_2 emissions must not increase more than by 6%. This fuel consumption limit is a reasonable measure to limit the increase in the emissions of the greenhouse gas CO_2 and, first and foremost, to keep the additional cost for motorists for higher fuel consumption as low as possible.

The directive makes a lab test both with and without the retrofit system mandatory. This seems reasonable because only lab tests render reproducible, i.e. comparable, fuel consumption data. RDE measurements are no suitable options since the traffic conditions and driving style strongly affect fuel consumption. In the WLTC, the first 3 phases specifically analyse the increase in fuel consumption when right after the cold start the SCR system needs more energy to heat up. All this is quite challenging for the retrofitters. And the WLTC measurements during our test in everyday traffic confirm this. In all 3 vehicles, the increased fuel consumption and CO_2 emissions partly exceeded the admissible factor considerably. While at 7%, increased fuel consumption of the Oberland Mangold system in the VW T5 is almost within the acceptable range, we saw much stronger increases in the Fiat Ducato (HJS) and the Opel/Vauxhall Astra (Twintec) at 12% and 13%, respectively. In the Astra, this is due to the energy management system which needs to be improved. In the Fiat Ducato, we were unable to identify the reason because the vehicle was involved in an accident and had to be removed from the test line-up. One reason may be the heated catalytic converter whose job is to increase the exhaust temperature after a cold start. Please note that we were unable to assess whether or not the fuel consumption in the Ducato's standard configuration changed during our test and part of the increase in fuel consumption was vehicle-related.

Taking into account all our measurements and all operating modes, we see that the increase in fuel consumption is much lower than in the type approval test which represents the worst case scenario, i.e. cold start. Considering all measurements, the average increase amounts to approx. 9%. Depending on the test cycle, the fuel consumption increase in absolute terms ranges between 0.46l (Opel/Vauxhall Astra) and 0.68l (Fiat Ducato) per 100km. While the increase in fuel consumption is the highest after a cold start, the vehicle needs hardly any additional energy when driving on the motorway with a warm engine. On motorways, fuel consumption increases only between 2% to 4%.

The retrofit directive only specifies the tolerated percentage of increased CO_2 emissions rather than an absolute figure. This comes at a disadvantage for very fuel-efficient vehicles because the tolerable fuel consumption increase in absolute terms is very low. In absolute terms, the fuel consumption increase is similar in the Opel/Vauxhall Astra and the VW T5. However, because the VW T5 needs much more fuel in the standard configuration, the increase translates into only 7.0% while the increase in the Opel/Vauxhall Astra is 13%. Bottom line: developing an SCR retrofit system for fuel-efficient vehicle models is a much greater challenge than for less efficient vehicles.

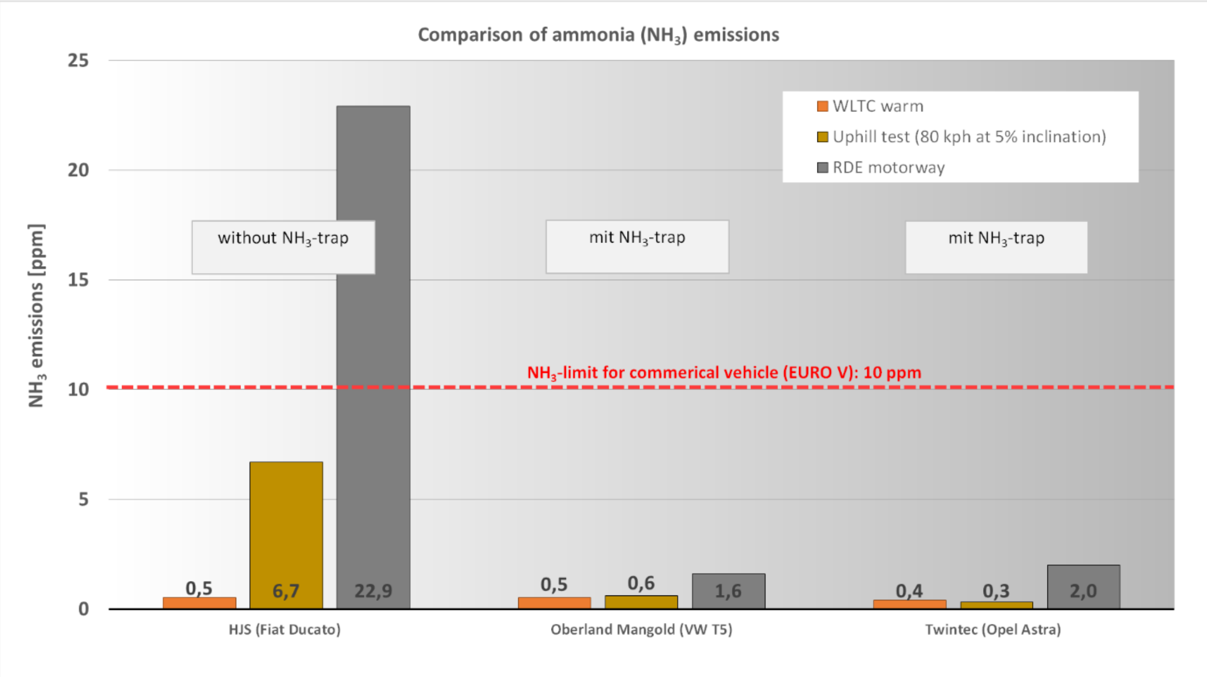
Figure 5 CO_2 emissions caused by SCR retrofit systems



SCR retrofit systems reliably prevent secondary emissions such as ammonia or nitrous oxide – provided they use the right technology

The catalytic converter first decomposes the urea in the vehicle to ammonia (NH_3). Overdosage of ammonia and its discharge into the environment must be avoided at all costs. The retrofit directive in fact specifies the requirements for the installation of an NH_3 trap [2]. The Fiat Ducato shows that the integration of an ammonia trap is a reasonable measure to reliably avoid ammonia slip and make sure that any NH_3 overdose is safely oxidised. The Ducato's SCR catalytic converter (series production part of the Ducato Euro6b) does not yet come with such a trap. In the WLTC cycle, which represents typical urban driving conditions, we did not measure any NH_3 emissions. The measurements were within measurement tolerance. There is a risk of temporary overdosage and a potential increase in NH_3 emissions in driving situations such as going uphill at high load for a long period or real-life motorway driving. As in the case of the Fiat Ducato, in vehicles not equipped with an NH_3 trap, NH_3 emissions may rise to above 20ppm. For your orientation: the limit for EURO V commercial vehicles is 10ppm. Our measurements with the VW T5 and Opel/Vauxhall Astra show that the installation of an NH_3 trap can reliably prevent ammonia slip.

Figure 6 Ammonia (NH3) emissions



Under certain circumstances, catalytic exhaust gas aftertreatment may produce secondary emissions such as nitrous oxide (N_2O). Reasons for this include an AdBlue® overdose, an unfavourable NO_2/NO_x ratio or coatings of the SCR catalytic converters. Retrofitters must make sure that the formation of this climate-damaging greenhouse gas is prevented to the largest extent possible. Our measurements show that nitrous oxide emissions are next to zero in all vehicles. Even in the worst case scenario (motorway in the RDE cycle), the Opel/Vauxhall Astra's nitrous oxide concentration was only 8ppm. While nitrous oxide is 298 times more climate-harming than CO_2, its concentration here is too low to be of relevance. Expressed in CO_2 equivalents, this means maximum additional CO_2 emissions on motorways of approx. 3g/km.

The directives on the retrofitting of passenger cars and commercial/delivery vehicles inadequately specify their scope of application, causing uncertainty and unnecessary delays in the introduction of NO_x reduction systems for series production use

The results of our test show that the directive on the retrofitting of passenger cars almost fully defines the relevant requirements for a prompt and successful introduction of NO_x reduction systems. Retrofits can effectively contribute to cleaner air while preventing driving bans. The same applies to the directive on the retrofitting of commercial and delivery vehicles [4].

Both directives leave room for interpretation as to the scope of application, causing uncertainty among retrofitters and delaying developments. The directive applicable to passenger cars fails to elaborate on why the permissible maximum weight is 2.8t. The key issue is whether or not the limit applies only to commercial vehicles or also to passenger cars of the categories M1 and M2. Plus, it is not yet clear whether retrofits are possible for >2.8t commercial vehicles used for private travel since the annex includes the technical specifications of the funding directive which only targets commercial vehicles used by craftspeople or for delivery purposes.

Therefore, the legislator should clearly specify without delay the directives' scope of application to improve the legal certainty over SCR retrofit options for retrofitters and motorists.

4 Procedure and methodology

4.1 Prerequisites:

The retrofitted vehicles were subjected to a long-term test in everyday traffic. ADAC Württemberg e.V. purchased the 3 tested vehicles and verified that they were in perfect working condition before the test.

All emissions measurements were performed at the ADAC technical centre in Landsberg am Lech/Germany. This in-house emissions laboratory has been certified by the KBA (German Federal Motor Transport Authority, no. KBA-P 00069-07) and complies with the requirements of DIN EN ISO/IEC 17025:2005 as well as DIN EN ISO/IEC 17020:2012.

4.2 Tested vehicles

The test line-up included an Opel/Vauxhall 1.7 CDTI that was retrofitted by Twintec Baumot and 2 light commercial vehicles (VW T5 retrofitted by Oberland Mangold and Fiat Ducato retrofitted by HJS). The Mercedes B 180 CDI equipped with a system from Dr Pley SCR-Technology GmbH was pulled back from the test for company-internal reasons.

The 1.7l diesel engine of the Opel Astra is used in many different Opel/Vauxhall models. Under the Euro5 (M1) emissions standard, which applies to these vehicles, their NO_x limit is 180mg/km.

Both panel vans – type approved in the NEDC cycle – are also Euro5-compliant, albeit with a NO_x limit of 280mg/km. The type approval procedure is identical with that for passenger cars, except that higher limits apply to light commercial vehicles. We selected a Fiat Ducato 130 Multijet panel van with an engine capacity of 2.3l and a VW T5 Multivan with the very common 2.0 TDI diesel engine. The higher NO_x limit of 280mg/km also applies to the VW T5 because the selected vehicle is homologated in accordance with Euro5 M1 (M1 fulfilling specific social needs).

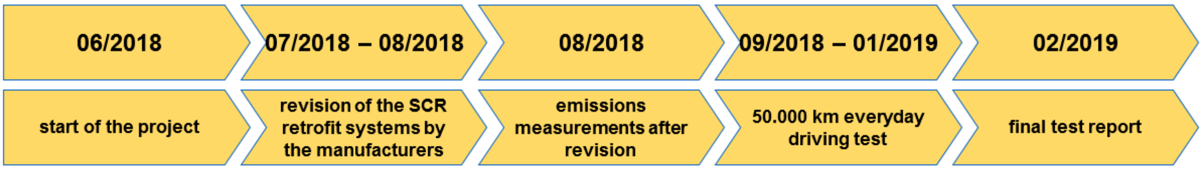
4.3 Hardware retrofits

The hardware retrofits were performed by retrofitters in the framework of our first project [1]. Each retrofitter was given a maximum of 4 weeks to retrofit a vehicle with technology for reducing nitrogen oxide emissions. The objective was to show the effectiveness and feasibility of various SCR systems in different vehicles. Accordingly, all 4 retrofitted vehicles are prototypes intended to demonstrate the basic feasibility of the retrofits. For the operation of the vehicles with the retrofitted SCR systems, the Stuttgart regional council issued the required temporary special authorisations under Section 70 of the German Traffic Licensing Regulation (StVZO). The relevant expert reports under Section 19 (2) / 21 StVZO and Section 70 StVZO are available. Before we started our test, the retrofitters were given 6 weeks to further develop their retrofit systems.

4.4 Test methodology

Before our test, the retrofitters had the opportunity to improve their SCR retrofit systems, i.e. to update the software of the SCR control units and install new technologies (see detailed reports). In addition, they had to install information systems that display the AdBlue® fluid level and the SCR operating status. Subsequently, the vehicles were equipped with data loggers whose sensors continuously recorded exhaust emissions during the long-term test, including NO_x emissions in front of and behind the SCR system, exhaust temperatures and AdBlue® consumption.

Figure 7 Project planning and milestones



Before starting the 50,000km test, we conducted exhaust emissions tests based on the ADAC Ecotest. Lab tests are indispensable in terms of obtaining unrestrictedly comparable and reproducible measurement results before and after hardware retrofitting. Test lab measurements are the only way to ensure that both environmental conditions (temperature, air humidity, air pressure) and the driving profile are always identical and, consequently, the results of several measurements are produced under precisely the same conditions. For the test lab measurements, we selected the WLTC driving cycle which has been in effect since 1 September 2017 for all new vehicle models. Testing in the ADAC motorway cycle was conducted to cover higher engine loads.

In compliance with type approval requirements, the emissions tests were performed at an air temperature of 23°C. We performed measurements while the engine was still cold (WLTC cold) and measurements with the engine at operating temperature. This helped us to reveal the differences in emissions between a cold and a warm engine. Since typical SCR systems do not work until the exhaust gas has reached a specific temperature, the cold start test also shows to what extent emissions can be reduced directly after a cold start.

Measurements were performed both on a test bench in the emissions lab and in real road traffic using a portable emissions measurement system (PEMS). As far as applicable for Euro5 vehicles, the test lab and RDE measurements are based on the emissions legislation effective since 1 September 2017 (WLTP, RDE).

Figure 8 VW T5 with PEMS on board

Figure 9 WLTC driving cycle

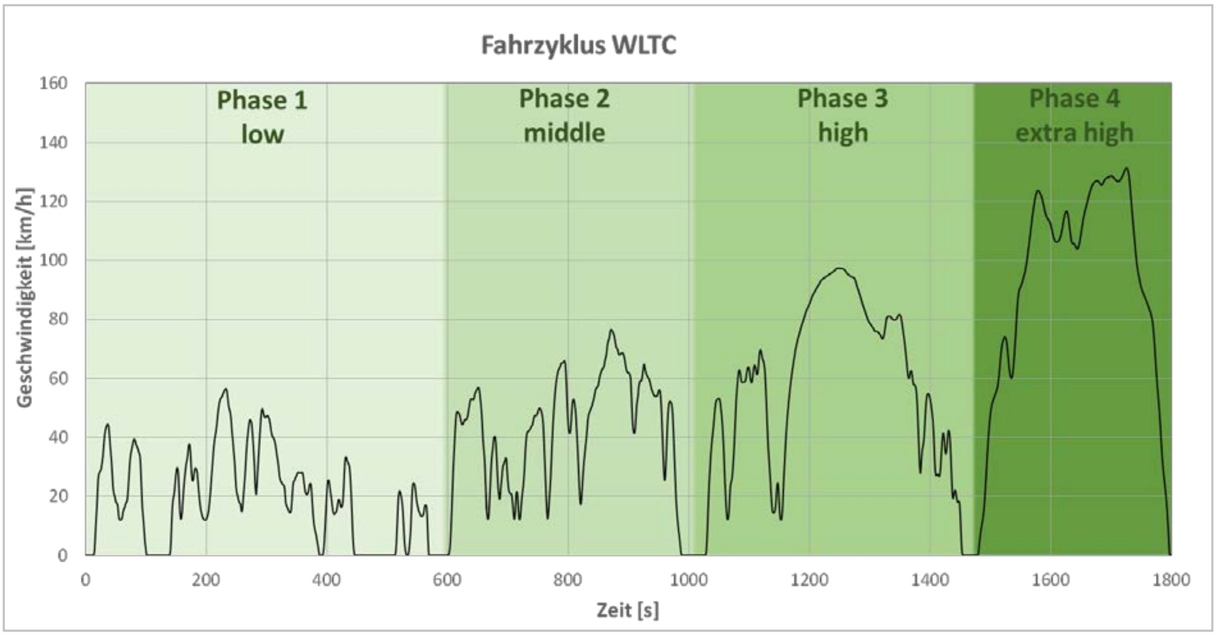
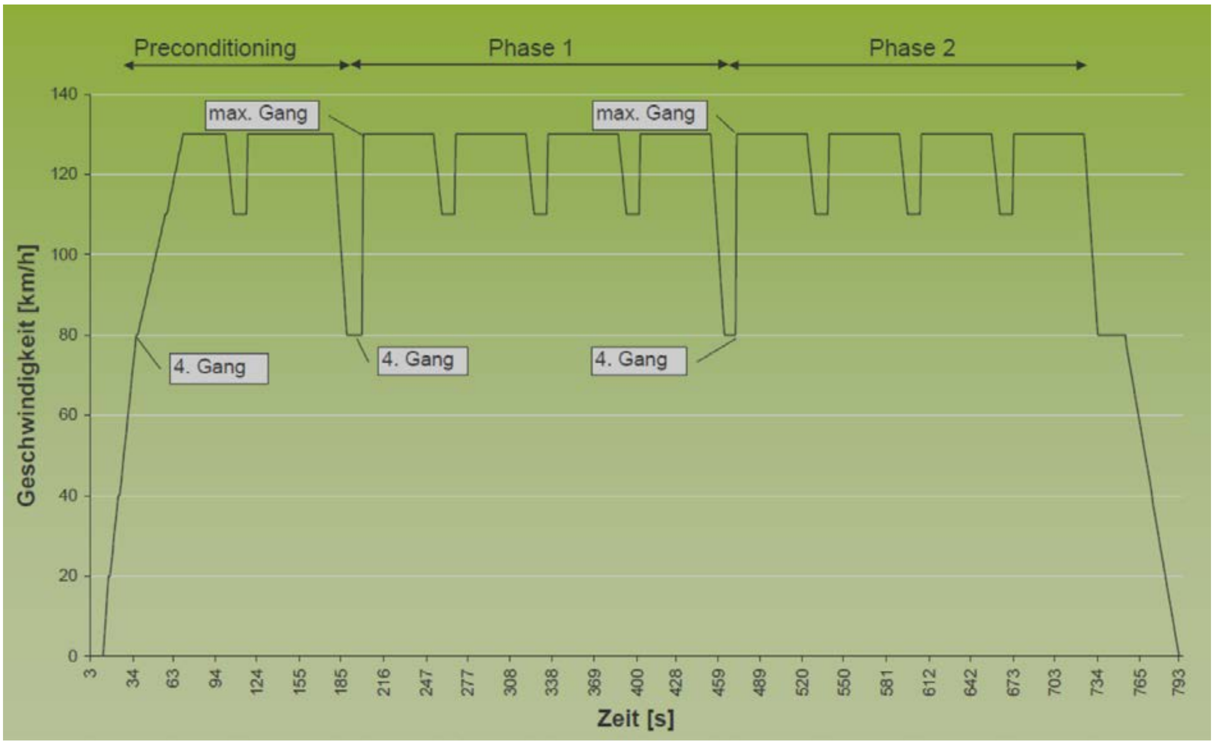


Figure 10 ADAC motorway cycle



To confirm the efficiency of the retrofits in real-life traffic, RDE tests using a portable emissions measurement system (PEMS) are required as well. However, it should be noted that RDE tests serve, first and foremost, to examine the robustness of the systems in real-world conditions. Thus, it must be ensured that emission levels do not exceed a certain limit even under extreme conditions. Since the changing environmental conditions affect not only vehicle emissions but also the measurement accuracy of the mobile exhaust systems, we took into account the stricter requirements specified by the legislator for portable measurement systems. Therefore, Euro6d-TEMP emission laws allow a conformity factor (CF) of 2.1 for RDE measurements with respect to the limit for nitrogen oxide emissions.

We analysed and evaluated the following exhaust gas components in the lab tests:

Table 1 Exhaust gas components measured in WLTC

Fuel consumption*	FC [l/100km]
Carbon dioxide	CO_2 [g/km]
Carbon monoxide	CO [g/km]
Hydrocarbon	HC [mg/km]
Nitrogen oxides	NO_x [g/km]
Nitric oxide	NO [g/km]
Nitrogen dioxide	NO_2 [g/km]
Particulate matter	PM [g/km]
Particle number	PN [1/km]

* calculation factors in the carbonaceous exhaust gas components

In the RDE tests, we measured and analysed the following emissions:

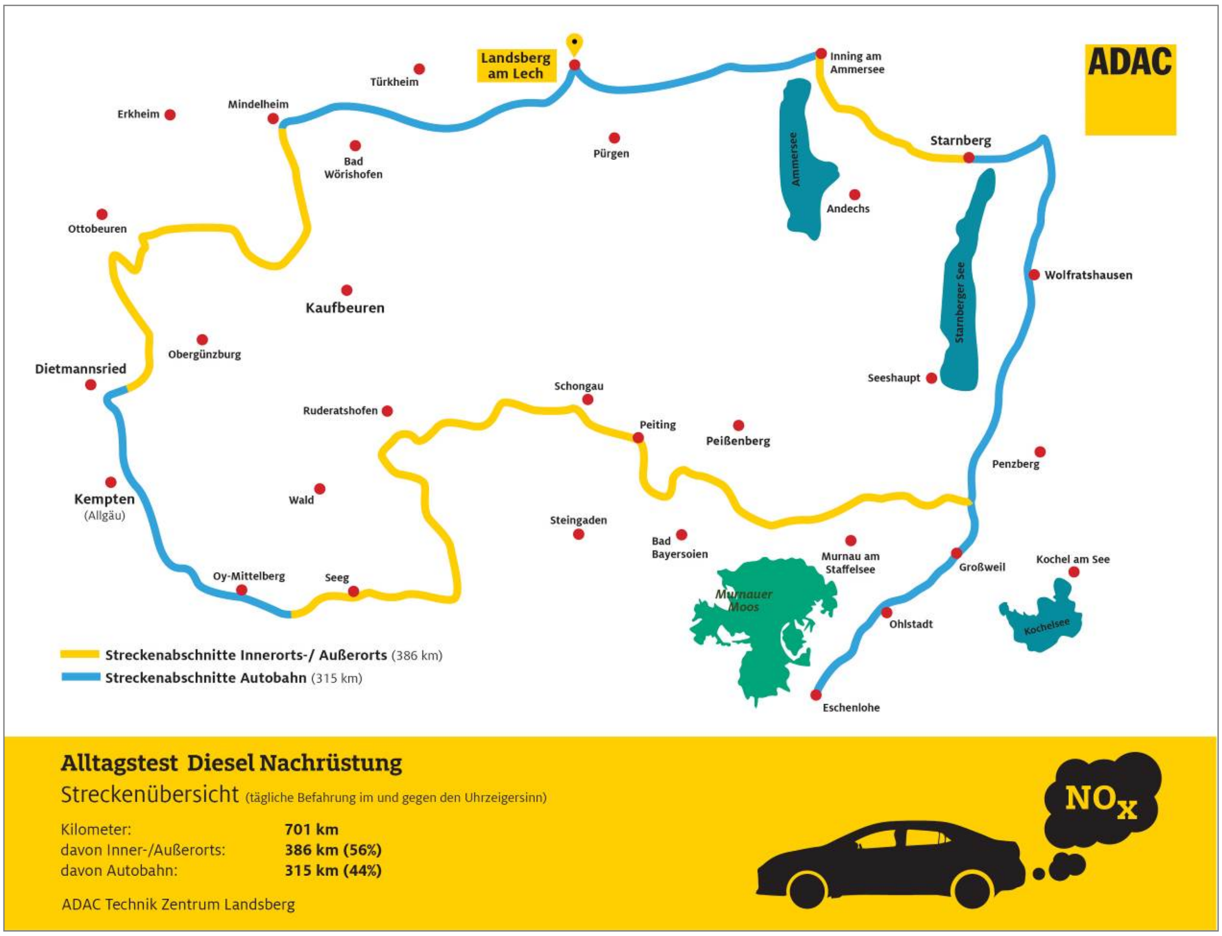
Table 2 Exhaust gas components measured in RDE

Fuel consumption*	FC [l/100km]
Carbon dioxide	CO_2 [g/km]
Carbon monoxide	CO [g/km]
Nitrogen oxides	NO_x [g/km]
Nitric oxide	NO [g/km]
Nitrogen dioxide	NO_2 [g/km]
Particle number	PN [1/km]

* calculation by factoring in the carbonaceous exhaust gas components

Afterwards, we started the long-term test, driving the vehicles on a defined approx. 700km route each day with the following mix of roads: 56% urban and extra-urban roads, approx. 44% motorways. Each day we performed cold starts in different outside temperatures. The route was approx. 350km long and was run twice a day, once clockwise and once anti-clockwise. It is the same route ADAC has been using for approx. 10 years for tyre wear testing. Behind the wheel were experienced drivers who regularly swapped vehicles so that we achieved maximum comparability of driver profiles. The drives took place in normal everyday traffic; the driving style was as defensive and proactive as possible. In addition to the data collected by the data logger, we documented the daily fuel consumption data and outside temperatures.

Figure 11 Test route



We conducted emissions tests in our lab every 10,000km to document the effectiveness of the SCR retrofit systems and changes in exhaust emissions, if any, in the test period.

The 3 retrofitted Euro5 diesel vehicles were subjected to several additional tests. They ranged from measurements of uncontrolled pollutants such as ammonia (NH_3) and nitrous oxide (N_2O) to testing at low temperatures to assessing the mechanical stress of SCR components on poor surfaces.

To measure the uncontrolled pollutants (NH_3 and N_2O) we used a Fourier transform IR spectrometer (FTIR) from Ansyco Gasmet. Our measurement instrumentation did not allow any reliable measurements of isocyanic acid (HNCO).

4.5 Analysis of results

During the entire test between early September 2018 and January 2019, the sensors of the data loggers in the vehicles daily recorded the NO_x concentration in front of and behind the SCR systems, the average outside temperature and the amount of the injected AdBlue® solution. In a test log, we documented all incidents during the test period plus comments, if any.

In our assessment of the NO_x reduction, based on the ADAC Ecotest procedure, we compared both the WLTC cold (with cold start) and the WLTC warm (with engine at operating temperature) before and after the retrofit. For a near-realistic representation of urban traffic, we specifically evaluated the first 3 phases of the WLTC (low, middle, high) in compliance with the test procedures described in the directive on the retrofitting for passenger cars. The fourth phase (extra-high) represents the typical extra-urban traffic (extra-urban roads and motorways) and is therefore shown separately. We also analysed NO_x emissions at high load in motorway traffic (ADAC motorway cycle).

To represent the typical urban operation in RDE tests as well, we specifically analysed the urban and rural phases. These 2 phases are within a similar load/rpm spectrum as the above-mentioned WLTC phases. The motorway phase of the RDE tests is shown separately. The experts cited in the German Federal Environment Agency's report (UBA) on NO_x retrofit technologies from July 2017 recommended a similar approach [5].

Since emissions in a standard-configuration vehicle strongly depend on outside temperatures, other than in a lab where conditions do not change, it is possible with limitations only to compare RDE measurements before and after the retrofit. Therefore, we calculated the NO_x RDE emissions in front of the SCR system based on the NO_x concentration recorded by the data logger. Please note that the data recorded by the data logger are for information only; they have not been confirmed by measurements.

5 List of figures

6 List of tables

7 Sources

[1] Final report "*Reduction of NOx emissions from Euro5 diesel vehicles by hardware retrofits" of* 20 February 2018. Published at www.adac.de/scr

[2] Bundesministerium für Verkehr und digitale Infrastruktur BAnz AT 11.01.2019 B3: "*Bekanntmachung der Technischen Anforderungen an Stickoxid (NOx)-Minderungssysteme mit erhöhter Minderungsleistung für die Nachrüstung an Pkw und Pkw-ähnlichen Fahrzeugen (NOxMS-Pkw)"* vom 21.12.2018 [German Federal Ministry of Transport and Digital Infrastructure, Federal Gazette AT 11 January 2019 B3: *technical specifications for nitrogen oxide (NO_x) reduction systems with increased reduction performance for retrofits on passenger cars and similar vehicles* of 21 December 2018]

[3] Gesetzentwurf der Bundesregierung: *Entwurf eines Dreizehnten Gesetzes zur Änderung des Bundes-Immissionsschutzgesetzes,* Stand: 30.10.2018 https://www.bmu.de/gesetz/gesetzesentwurf-eines-dreizehnten-gesetzes-zur-aenderung-des-bundes-immissionsschutzgesetzes/ [draft amendment of the German Federal Pollution Control Act, last amended: 30 October 2018]

[4] Bundesministerium für Verkehr und digitale Infrastruktur BAnz AT 28.12.2018 B6: "*Bekanntmachung der Förderrichtlinie für die Nachrüstung von mit Selbstzündungsmotor angetriebenen gewerblichen leichten Handwerker- und Lieferfahrzeugen der Klassen N1 und N2 mit einer zulässigen Gesamtmasse von 2,8 Tonnen bis zu 3,5 Tonnen der Schadstoffklassen Euro 3, 4, 5 und 6 mit Stickoxidminderungssystemen"* vom 10.12.2018 [German Federal Ministry of Transport and Digital Infrastructure, Federal Gazette AT 28 December 2018 B6: *publication of the funding directive on the retrofitting of light (2.8t-3.5t) Euro3, 4, 5 and 6 diesel vehicles with nitrogen oxide reduction systems used by craftspeople or for delivery purposes* of 10 December 2018]

[5] Umweltbundesamt: *Ergänzung der Bewertung zu marktverfügbaren fahrzeugseitigen NO_x-Nachrüsttechnologien und Bewertung der Nachbesserung,* Stand: Juli 2017 https://www.umweltbundesamt.de/sites/default/files/medien/2546/dokumente/uba_bericht_nachruestung_ii_0.pdf [German Federal Environment Agency: *assessment of available on-board NO_x retrofit technologies and assessment of the retrofit,* last amended: July 2017]

8 Glossary of terms

Emission test laboratory	In order to ensure maximum reproducibility and comparability, emissions tests must be carried out on approved dynamometers. The vehicle to be tested is mounted on a roller type test stand. The rollers are permanently controlled so that they continuously reproduce the road loads, i.e. rolling resistance and aerodynamic drag as well as inclines and acceleration. In order to represent the behaviour of each vehicle as accurately as possible, so-called road load data (see glossary of terms) are applied.
Exhaust gas recirculation (EGR)	A valve permanently mixes cooled exhaust gases with the intake air to lower the oxygen content in the combustion chamber and, consequently, the combustion temperature. This reduces nitrogen oxide levels.
AdBlue®	AdBlue® is a registered trademark of the Verband der Automobilindustrie (VDA) [German Association of the Automotive industry] for AUS 32, an aqueous urea solution used to reduce nitrogen oxide emissions (NO_X) by means of SCR systems. This is an ultrapure, limpid, synthetically produced 32.5% urea solution (chemical formula: $H_2N\text{-}CO\text{-}NH_2$). The requirements for AdBlue® are laid down in ISO 22241.
Ammonia (NH_3)	Ammonia (NH_3) is a chemical compound consisting of nitrogen and hydrogen. It is a colourless, toxic gas with a very pungent smell, which causes tearing and choking even at low concentrations.
Ammonia trap catalytic converter	By arranging an oxidation catalytic converter (trap catalytic converter) at the downstream end of the SCR unit, any unreacted ammonia can be converted to N_2 and H_2O.
CAN bus	Controller Area Network: usually 2 copper wires connecting different control units to which the control units can “transmit” information and where they can “receive” information from other control units.
Diesel particulate filter (DPF)	System in diesel engines, which filters noxious soot particles out of the exhaust gas and initiates a regeneration process from time to time to burn off the accumulated soot.

Emissions	This term refers to the discharge of gaseous or solid substances which may cause air, soil or water pollution. Substances causing emissions are called emitters (polluters). Traffic is considered to be one of the main causes of air pollution.
Emission factors	The Handbuch Emissionsfaktoren des Straßenverkehrs (HBEFA, Handbook of road traffic emission factors) provides emission factors (specific emissions in g/km) for all common vehicle categories (passenger cars, panel vans, heavy duty vehicles, buses and motorcycles). These emission factors cover a wide selection of traffic situations, vehicle sizes and emission levels for various European countries. The database includes all regulated air pollutants and the most important unregulated air pollutants as well as fuel efficiency and greenhouse gas emissions. The HBEFA is a tool developed by the German Federal Environment Agency on behalf of the German government and in cooperation with scientists in Austria and Switzerland in order to develop emissions cadastres, for example.
Emission classes	Certain emission limits are stipulated in the European type approval directive for the approval of new vehicle types. Together with the required test procedures, the limits ranging from Euro1 to Euro6d are a core element of the EU legislation for the reduction of emissions from passenger cars.
Road load data	The road loads of a vehicle in road traffic comprise resistance to pulling away, aerodynamic drag, internal friction (drive train, bearings) and the rolling resistance of the tyres. Through coast-down testing, a road load curve is generated using the coefficients f0, f1, f2. These parameters allow dynamometer simulation of the load to be overcome by the vehicle in real-life operation. Taking advantage of the permitted tolerances during testing (e.g. tyre pressure) produces good lab test results, especially in fuel consumption tests, because road load is rather low. If no such road load data are available, vehicles may be alternatively classified by their equivalent inertia according to Directive 70/220/EEC (Annex III, 2, “Alternative method”). The vehicles will then be assigned to an equivalent inertia class according to their weight, and the coefficients for the road load curve will be drawn from the table.
Homologation	Type approval of vehicles and vehicle components granted by an authority (in Germany: Motor Transport Authority, KBA) for market authorisation.

Immissions	Under the Bundes-Immissionsschutzgesetz (BImSchG, German Federal Pollution Control Act), immissions are summarized as any form of air pollution, noise, vibrations, light, heat, radiation and similar environmental impacts acting on humans, animals and plants, the soil, the water, the atmosphere as well as cultural and other material goods. The permitted immission concentration of many substances (usually in mass per cubic metre of air) is defined by limits stipulated by law. The discharge from the source is called emission. Consequently, every immission can be traced back to one or more emitters.
Isocyanic acid (HNCO)	The thermal decomposition of urea does not only produce the ammonia required for the reaction in the SCR catalytic converter but also isocyanic acid (HNCO). It is a very reactive intermediate product that easily undergoes polymerisation and forms secondary products. Isocyanic acid also forms during a wildfire and is found in cigarette smoke. Isocyanic acid and cyanate ions easily dissolve in the human body; low concentrations (>1pptv) may cause health impairments such as arteriosclerosis, eye damage, inflammatory processes or rheumatism.
Carbon dioxide (CO_2)	Carbon dioxide (CO_2) is a chemical compound consisting of carbon and oxygen. It is an incombustible, acidic and colourless gas which is odourless at low concentrations. Carbon dioxide easily dissolves in water. Strictly speaking, CO_2 is not an air pollutant, but an approx. 0.04% constituent of “natural” air. CO_2 is a greenhouse gas whose emission contributes to the anthropogenic amplification of the natural greenhouse effect. CO_2 emissions are largely proportional to fuel consumption.
Carbon monoxide (CO)	Carbon monoxide (CO) is a chemical compound consisting of carbon and oxygen. It is a colourless, odourless and tasteless, toxic gas which forms, for instance, when insufficient admission of oxygen results in incomplete combustion of carbonaceous substances. CO is bound to haemoglobin 200 to 300 times more strongly than atmospheric oxygen; it hinders O_2 transport by the blood, thus affecting the body’s oxygen supply. If the concentration is higher than 0.5%, death may occur within minutes. CO is an important compound in the complex of chemical conversion processes which lead to summer smog.
Hydrocarbons (HC)	Hydrocarbons are a substance group of chemical compounds which consist only of carbon and hydrogen. This substance group is diverse, because hydrocarbons can contain carbon chains, rings or combinations thereof. There are several subgroups, such as alkanes, alkenes, alkynes and aromatic compounds (arenes). Hydrocarbons (HC) are the main constituent of fuel.
Conformity factor (CF)	This is the factor by which NO_x emissions are allowed to deviate from the Euro6 limit in RDE tests. It also takes into account the impact of inaccurate measurements.

Nitrous oxide (N_2O)	Nitrous oxide (N_2O), also known as laughing gas, is a chemical compound of nitrogen and oxygen from the group of nitrogen oxides. It is a colourless gas. At low concentrations, N_2O has an anaesthetic effect and was therefore frequently used as an anaesthetic for minor surgical procedures. While only trace amounts of the gas are present in the atmosphere, it is 298 times as effective as CO_2.
NEDC	Until 1 September 2017, the NEDC (New European Driving Cycle) was the basis for determining pollutant and CO_2 emissions as well as fuel and/or electric power consumption in the framework of the type approval procedure for passenger cars. Measurements were carried out on approved dynamometers. The first part of the NEDC (phase 1) represents urban driving, in which a vehicle is started in the morning (after being parked all night) and then driven in stop-and-go mode at a maximum speed of 50kph. The second part (phase 2) represents extra-urban driving at a maximum speed of 120kph. The total test duration is 1,180s over a total test distance of 11.01km (phase 1 approx. 4km; phase 2 approx. 7km). The average speed is 33.6kph (44.0kph not counting the idle phases). An acceleration of 26s from 0-50kph is not very realistic and means that engines operate at low loads.
OBD	On-board diagnostics: the diagnostic system, mandatory in all vehicles since 2004, monitors all components relevant in terms of exhaust gas emissions and indicates a malfunction to the driver. The fault memory of a vehicle can be read out from a standardised OBD2 interface via diagnostic tools. The OBD system accesses the CAN bus.
Oxidation catalytic converter (DOC)	Oxidation catalytic converters are used to clean diesel engine exhaust gases. The hydrocarbons (HC) and carbon monoxide (CO) contained in the exhaust gas are converted to water (H_2O) and carbon dioxide (CO_2). A suitable coating will increase the NO_2/NO ratio in the exhaust gas, which is necessary for stable functioning of the SCR catalytic converter.
PEMS	Portable emissions measurement system for measuring real driving emissions (RDE).

RDE	To improve the assessment of exhaust emissions in real-life operation, in addition to the mandatory type approval test cycles on a test bench, the EU legislators adopted the inclusion of direct emission metrics from a road test (real driving emissions or RDE) using portable emissions measurement systems (PEMS). This aims to ensure that carmakers equip their vehicles with emissions control technologies effectively lowering pollutant emissions under all operating conditions. RDE legislation also consists of a procedure for road testing that ensures a well-balanced mix of urban and extra-urban roads and motorways and prevents an extreme driving style.
Reference fuel	The requirements to be met by reference fuels for emissions measurements are laid down in Annex IX to Commission Regulation (EU) 2017/1151. This ensures that only approved quality fuels are used for the measurements.
SCR technology	In SCR (selective catalytic reduction) technology, nitrogen oxide emissions (NO_x) generated during the combustion process in the diesel engine are converted into elemental nitrogen (N_2) and water (H_2O) in a catalytic converter downstream of the engine. This requires ammonia, a reducing agent produced from AdBlue®, which is carried in a separate tank of the vehicle and injected into the exhaust system as needed.
Nitrogen oxides (NO_x)	Nitrogen oxides (NO_x) include both nitric oxide (NO) and nitrogen dioxide (NO_2). A chemical balance forms between NO and NO_2 after emission (within seconds to minutes in summer smog conditions). Therefore, the NO share in NO_x emissions also contributes to the NO_2 immission level.
Nitrogen dioxide (NO_2)	NO_2 is a gas that irritates the respiratory tract, is soluble in mucous membranes and increases vulnerability to pathogens. It is also the basis for other harmful substances associated with summer smog, such as ozone (O_3).
Nitric oxide (NO)	NO_2 may form from NO under the influence of oxygen and other oxidants. Consequently, it is essential that efforts to reduce NO_x emissions focus not only on NO_2, but also on reducing NO emissions, because they may quickly oxidise into NO_2 – with the adverse effects described above.

WLTC	The WLTC (Worldwide harmonized Light Duty Test Cycle) is the test cycle used in the new WLTP (Worldwide harmonized Light Duty Test Procedure), replacing the NEDC. Measurements were carried out on approved dynamometers. Depending on the vehicle class, the WLTC comprises various partial cycles that represent the typical driving from urban to motorway traffic (see WLTP). The duration of each partial cycle is identical in all 3 classes, i.e. low: 589s, medium: 433s, high: 455s, extra-high: 323s. However, the difference lies in the acceleration and speed values.
WLTP	To obtain more realistic fuel consumption specifications, the UNECE (United Nations Economic Commission for Europe) was mandated by the EU Commission to develop a new WLTC test cycle (Worldwide harmonized Light Duty Test Cycle) and a new WLTP test procedure (Worldwide harmonized Light Duty Test Procedure) for determining pollutant and CO_2 emissions as well as fuel or electric power consumption. The new test procedure was adopted into the type approval procedure by Commission Regulation (EU) 2017/1151 and has been mandatory for new car models since 1 September 2017. There are numerous conditions defined in the WLTP, such as gear shifting, total vehicle weight (including accessories, cargo and passengers), fuel quality, ambient temperature as well as tyre selection and pressure. The WLTP defines 3 vehicle classes based on P_{mr}, the weight-to-power ratio (engine power/kerb weight in W/kg) for which several WLTC test cycles were defined. The duration of each partial cycle is identical in all 3 classes, but they differ in the acceleration and speed values. Class 1: vehicles with P_{mr} <= 22W/kg; cycles: low, medium, low Class 2: vehicles with 22W/kg < P_{mr} <= 34 W/kg; cycles: low, medium, high, extra-high Class 3: vehicles with P_{mr} >34W/kg; cycles: low, medium, high, extra-high. Depending on the maximum speed, class 3 is further divided into classes 3-1 (<120kph) and 3-2 (>120kph). Usually only class 3b is relevant to the German car market where vehicles with a weight-to-power ratio of <34W/kg are rare and motorway speed exceeds 120kph.