Bundesanstalt für Straßenwesen (BASt)
(Federal Highway Research Institute)

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Examination of pollutants emitted by vehicles in operation and of emission relevant components

- Replacement catalytic converters

Final Report

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by

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Drive/Emissions

Cars/Motorcycles

On behalf of Federal Highway Research Institute (BASt)

Contents

List of abbreviations

ADAC	German Automobile Association
AECC	Association for Emissions Control by Catalyst
AU	Periodic Exhaust Gas Inspection
BAT	Bench Ageing Time Calculator; Environmental Protection Agency
CAP	Compliance Assurance Program; EPA
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EUDC	Extra Urban Driving Cycle
EPA	Environmental Protection Agency
Euro 4	Type approval test according to Directive 98/69/EC
IUC	In-Use Compliance
HC	Hydrocarbons
KBA	German Type Approval Authority
NEDC	New European Driving Cycle
NO_X	Nitrogen Oxides
OBD	On Board Diagnostics
OEM	Original Equipment Manufacturer
SBC	Standard Bench Cycle
SRC	Standard Road Cycle
TÜV NORD	TÜV NORD Mobilität GmbH & Co. KG
UBA	German Federal Environment Agency
UDC	Urban Driving Cycle
UNECE	United Nations Economic Commission for Europe
ZDK	Zentralverband Deutsches Kraftfahrzeuggewerbe e.V.

1 Introduction

An extensive package of measures has been developed to reduce the air pollution caused by motor vehicles. It includes not only the type approval of new types of vehicle, but also examination of the conformity of the production of new vehicles, examination of the conformity of vehicles in operation (in-use compliance), on-board diagnostics, periodic inspection of all vehicles in operation and more stringent requirements regarding fuel quality.
The stricter requirements regarding emission behaviour have demanded advanced vehicle and exhaust gas after treatment technologies. One major component of current exhaust gas after-treatment systems is the catalytic converter. It facilitates the elementary conversion of the gaseous pollutants resulting from the combustion process. In the three-way catalytic converter unburnt hydrocarbons and carbon monoxide are oxidised to form carbon dioxide and water and nitrogen oxides are reduced to nitrogen. Under optimum operating conditions conversion rates of almost 100 % are achieved.
If a catalytic converter is damaged or its effectiveness deteriorates, it can be replaced by a replacement converter. Basically a distinction can be drawn between original replacement catalytic converters which have been approved in the context of the vehicle type approval and which are normally replaced in repair shops of authorised dealers, on the one hand, and replacement converters available on the independent aftermarket.
Replacement catalytic converters from the aftermarket are approved on the basis of Regulation No 103 of the UNECE – United Nations Economic Commission for Europe. According to this regulation the replacement catalytic converter shall be designed, constructed and capable of being mounted so as to enable the vehicle to comply with the provisions taken as a basis for its type approval. Furthermore the pollution emissions must be effectively limited throughout the entire normal service life of the vehicle under normal operating conditions. The ECE Regulation No 103 provides for an examination of the durability of such systems over 80,000 km, but as an alternative it is possible under the regulation to use fixed deterioration factors. In practice the durability of the replacement systems for exhaust after-treatment is guaranteed by their manufacturers but independent checks of those systems take place relatively rarely in the context of the approval. No in-use compliance provisions are laid down in the relevant regulations for replacements systems for the after-treatment of exhaust gases.
The German type approval authority (KBA) does not have any inventory data with regard to replacement systems, for the after-treatment of exhaust gases. It is therefore not known to what extent and in what versions such exhaust gas after-treatment systems are present in the field and what the effectiveness of such systems actually is on the roads. There are indications for considerable differences in quality in replacement systems for the after-treatment of exhaust gases, which may impair the durability of such systems in actual road traffic. A study of the durability of replacement systems for the after-treatment of exhaust gases is therefore urgently necessary.
Within the framework of this project the durability of various replacement catalytic converters for a vehicle with spark-ignition engine was examined. For this purpose exhaust gas after-treatment systems in new condition were measured, then aged and checked again in aged condition. For this check a suitable test vehicle was selected. The prime objective of this project is to gain an overview of the current situation and not the assessment of individual replacement catalytic converters. /1/

2 Starting situation / state of knowledge

In order to estimate to what extent and in what versions replacements systems for exhaust after-treatment are present in the existing vehicle inventory, numerous discussions took place, licences under the ECE Regulation No 103 were analysed at the KBA and internet searches were made.
There are no precise figures on the replacement catalytic converters sold in Germany and on the market shares of the different catalytic converter manufacturers. It can be assumed that catalytic converters are replaced due to mechanical damage or anomalies found during the periodic exhaust gas inspection (AU). But there is no inventory data available to the German type approval authority relating to the spread of replacement systems for exhaust after-treatment. Neither the ADAC nor the Zentralverband Deutsches Kraftfahrzeuggewerbe (Central Association for the German Automotive Trade) has any sales data for replacement catalytic converters. The Association for Emissions Control by Catalyst (AECC) can also give no details of the sales figures and market shares of the different manufacturers of replacement systems for the after-treatment of exhaust gases in Germany, and secondly because not all manufacturers of replacement catalytic converters are members of the AECC.
Concerning the sales figures for replacement catalytic converters and the market shares of the different suppliers there are estimates by the individual catalytic converter manufacturers. Relevant

figures were made available. But they only give a general overview of the market situation. The total market for replacement catalytic converters in Germany is estimated at about 300,000 a year. It can be assumed that about half of these are original spare parts which are installed in repair shops of authorised dealers. Accordingly the estimated figure for replacement catalytic converters sold on the open market is about 140,000 to 160,000. No figures are available for the market shares relating to replacement catalytic converters for individual vehicle types. It can be assumed, however, that the share accounted for by OEM replacement catalytic converters for higher grade vehicles is greater than for inexpensive vehicles.
In the current version of the ECE Regulation No 103 there is at present no specified procedure for examining the durability of replacement systems for the after-treatment of exhaust gases, which may lead to distortions in competition and disadvantages for serious manufacturers. There are indications that in past years the market share of quality suppliers has declined because of the aggressive pricing policy of some competitors. So-called universal catalysts are being offered at prices from € 50 upwards. In addition catalytic converters are being marketed via the internet without indication of the manufacturer. Some catalytic converters do not display a licence number, and others are promoted with statements such as "very good permeation rates (…) for more power in the vehicle".

3 Project implementation

3.1 Statutory basis

Basis for the approval of replacement catalytic converters is Regulation No 103 of UNECE - United Nations Economic Commission for Europe, where the "Uniform provisions concerning the approval of replacement catalytic converters for power-driven vehicles" are laid down. This regulation applies to the type approval of catalytic converters as separate technical units for installation in vehicles of categories M1 and N1. This regulation distinguishes between "Original equipment catalytic converters", "Replacement catalytic converters" and "Original replacement catalytic converters:

- "Original equipment catalytic converter" means a catalytic converter or an assembly of catalytic converters covered by the type approval delivered for the vehicle and whose types are indicated in the documents related to Annex 2 to Regulation No 83.
- Replacement catalytic converter' means a catalytic converter or an assembly of catalytic converters for which approval can be obtained according to ECE Regulation No 103, other than those defined as "original equipment catalytic converters".
- Original replacement catalytic converter' means a catalytic converter or an assembly of catalytic converters whose types are indicated in the documents related to Annex 2 to Regulation No 83, but are offered in the market as separate technical units by the holder of the vehicle type-approval.

In order to test a replacement catalytic converter under ECE Regulation No 103 the test vehicle shall be fitted with a new original catalytic converter (see paragraph 3.3.1) which shall
be run in with 12 extra urban cycles (test type I part 2). After this preconditioning, the vehicle shall be kept in a room in which the temperature remains relatively constant between 293 and 303 K (20 and 30 °C). This conditioning shall be carried out for at least six hours and continue until the engine oil temperature and coolant, if any, are within ± 2 K of the temperature of the room. Subsequently three exhaust gas tests type I shall be made. The test vehicle with the original catalytic converter shall comply with the limit values according to the type approval of the vehicle including — if applicable — the deterioration factors applied during the type approval of the vehicle.
Then the original catalytic converter of the test vehicle shall be replaced by the replacement catalytic converter which shall be run in with 12 extra urban cycles (test type I part 2). The test procedure described above must be repeated.
According to point 5.2.3 of the ECE Regulation No 103 the requirements regarding emissions of the vehicle equipped with the replacement catalytic converter shall be deemed to be fulfilled if the results meet for each regulated pollutant (CO, HC, NOx and particulates) the following conditions:

1. $M \leq 0.85S + 0.4G$
2. $M \leq G$.

where:

- M: mean value of the emissions of one pollutant (CO, HC, NOx and particulates) or the sum of two pollutants (HC + NOx) obtained from the three type I tests with the replacement catalytic converter.
- S: mean value of the emissions of one pollutant (CO, HC, NOx and particulates) or the sum of two pollutants (HC + NOx) obtained from the

three type I tests with the original catalytic converter.

- G: limit value of the emissions of one pollutant (CO, HC, NOx and particulates) or the sum of two pollutants (HC + NOx) according to the type approval of the vehicle(s) divided by - if applicable - the deterioration factors.

The main criterion for the type approval of replacement catalytic converters is to fulfil the relevant limits during type 1 test.
In order to ensure the durability of the replacement catalytic converters so-called deterioration factors are applied. With these factors it is intended to take account of the ageing of the catalytic converter over a certain distance (e.g. 80,000 km for limit value stage Euro 4) and any related deterioration in the exhaust emissions. For this purpose the emission measured with the new catalyst are multiplied with the deterioration factors. The resulting values for the exhaust gas emissions must be lower than the limits. The limit values laid down must consequently also be complied with by a catalytic converter which has been aged over the distance laid down in the requirements for durability. For a new catalytic converter the measured emissions must comply with correspondingly limit values including the deterioration factors.
The deterioration factors may be determined with the help of an ageing test over 80,000 km following the procedure described in ECE Regulation No 83 on a test track, on the road or on a test rig. As an alternative to an ageing test the deterioration factors mentioned may be applied which are laid down in ECE Regulation No 103 and are shown in Table 3.1. In the case of the table values applicable up to exhaust standard Euro 4 it is assumed that the pollutant emissions CO, HC and NOx will deteriorate by 20 % compared to the new condition in vehicles with spark ignition engines over a travelling distance of 80,000 km.
In practice the values given in the table are applied, the durability of the replacement systems for exhaust after-treatment is guaranteed by their manufacturers, but only in the rarest of cases is a check performed as part of the approval.

Type of engine	**Deterioration factors**				
	CO	HC	NOx	HC+NOx	Particulates
Spark ignition	1.2	1.2	1.2	-	-
Compression ignition	1.1	-	1	1	1.2

Table 3.1: Deterioration factors according to ECE Regulation No 103

3.2 Examination programme

Within the framework of this research project the durability of different replacement systems for after-treatment of exhaust gases was examined. For this purpose a suitable test vehicle was first selected and procured. To ensure that the test vehicle was in a proper condition with respect to exhaust emissions, the exhaust emissions were measured in as-delivered condition, i.e. with the exhaust gas after-treatment system originally installed in the New European Driving Cycle (type I test, Figure 3.2).
Then an original replacement catalytic converter was purchased for the test vehicle from an authorised dealer and furthermore 4 different replacement catalytic converters approved for this vehicle according to ECE Regulation No 103 were bought covertly from the independent aftermarket. The exhaust gas after-treatment systems were subsequently installed in the test vehicle and run in according to point 5.2.2 of the ECE regulation No 103 with twelve extra-urban driving cycles.
After the conditioning an initial measurement was conducted on the replacement catalytic converters, during which the exhaust gas emissions were determined in the New European Driving Cycle (type I test). If anomalies were found during the initial measurement, i.e. with the exhaust gas after-treatment system in new condition (one or more limit values exceeded), the examination of the system concerned was terminated and rated as not passed.
If the initial measurements did not reveal any emission anomalies, the exhaust gas after-treatment systems to be tested were removed from the test vehicle and subjected to ageing on a burner test rig. The procedure for the burner ageing is described in detail in section 3.5.
In all, ageing of the replacement exhaust gas after-treatment systems was simulated over 80,000 km. In order to check the effectiveness of the replacement catalytic converters during the ageing process, the burner ageing was interrupted after 10,000 km and 40,000 km and intermediate measurements were conducted. For this purpose the aged catalytic converters were re-installed in the test vehicle and the exhaust gas emissions were measured in the type I test.
If one or more limit values were exceeded the examination was terminated. If no emission anomalies arose in the intermediate measurement, the exhaust gas after-treatment system was again removed from the test vehicle and the burner ageing process was resumed in the way described above. After 80,000 km burner ageing a final measurement was conducted in the NEDC. If this did not reveal any emission anomalies, the examination was concluded and rated as passed.
In the final phase the emissions of the test vehicle in original condition, i.e. with the catalytic converter originally installed, were measured in the NEDC (type I test) to check whether there had been any deterioration in the emission behaviour of the test vehicle during the testing procedure or in order preclude any impairment of the examination results by the vehicle. Figure 3.1 shows a diagram of the examination programme.

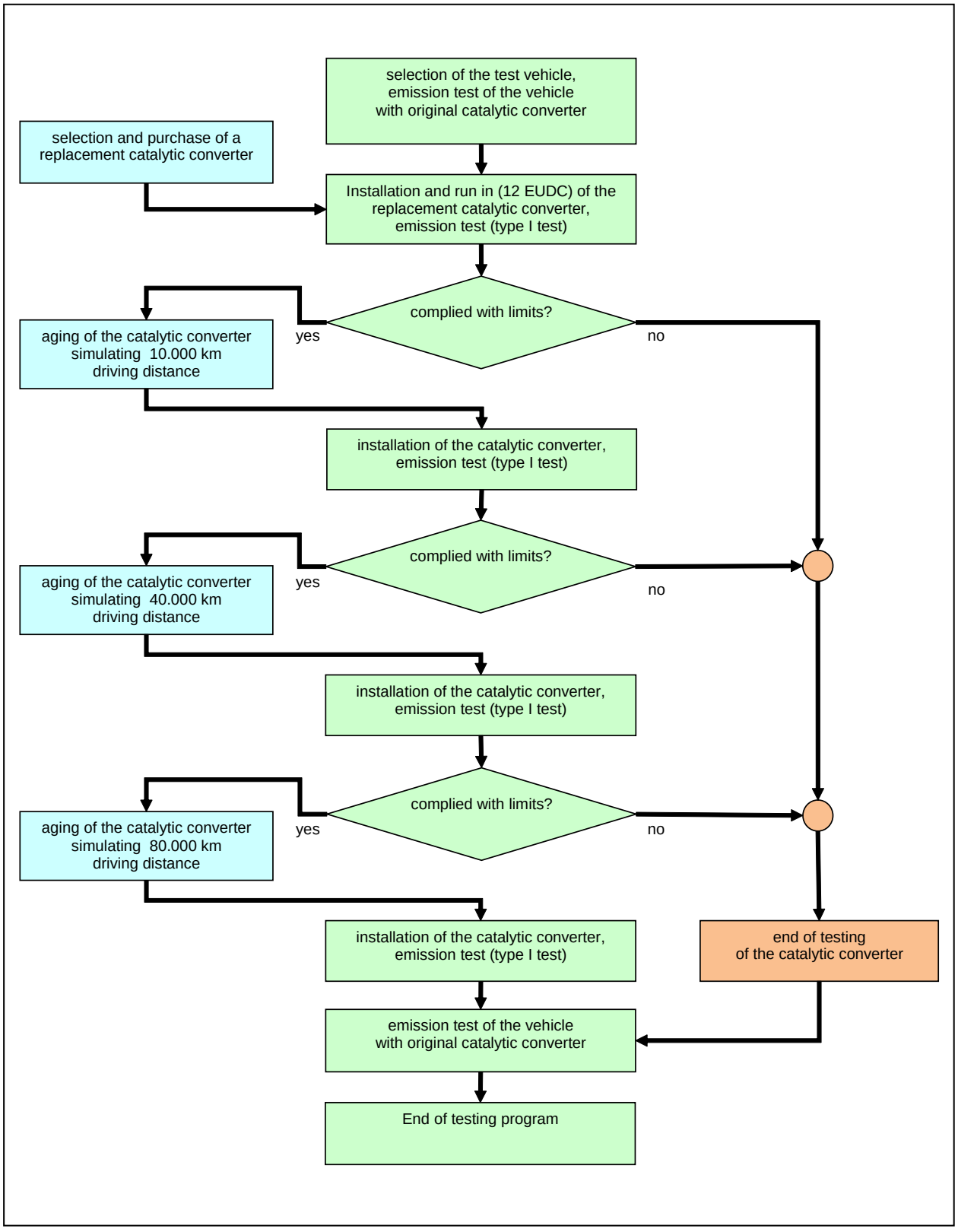

Figure 3.1: Diagram of the examination programme

3.3 Selection of test vehicle and replacement catalytic converters

For the examination the intention was to select a representative vehicle type which has been certified in the type approval test in accordance with Euro 4 emission standards. A further criterion in the selection was the availability of an adequate number of different replacement catalytic converters for the test vehicle. For the selection of the test vehicle the inventory data of the German type approval authority (KBA) was taken as a basis.

For the examination of the durability of replacement systems for the after-treatment of exhaust gases a VW Golf, 1.4l, 55kW with emission standard Euro 4 was selected. The Volkswagen Golf 1J with 1.4l petrol engine occurs very frequently in Germany with more than 400,000 and at the time of the examination it had the highest inventory figures in absolute terms /2/. The vehicle data is summarised in Table 3.2.

Vehicle manufacturer:	VOLKSWAGEN
Manufacturer code:	0603
Type:	1J
Trade name:	Golf IV
Type code:	419
Engine type:	BCA
Operating principle:	spark ignition
Cubic capacity:	1390 cm^3
Engine power:	55 kW
Emission standard	Euro 4
First licensed:	27.11.2002
mileage at the start of measurements:	75,500 km

Table 3.2: Vehicle data

At the start of the examinations the test vehicle showed a mileage of 75,500 km. After the test vehicle had been received, a check was made of compliance with the specified servicing intervals and the proper state of the vehicle. During the receiving inspection no anomalies were found. The vehicle selected was regularly serviced in accordance with the manufacturer's specifications. Evidence of this was provided in the form of service logs. The OBD system had not logged any defects relating to the exhaust system.
For the measurements initially an original replacement catalytic converter was purchased from an authorised dealer for approx. 850 €. In the context of the present research programme furthermore 4 replacement catalytic converters from different manufacturers were examined. Only replacement catalytic converters were considered for which an approval to ECE Regulation No 103 had been granted. For the selected test vehicle replacement catalytic converters with corresponding approvals were on offer at prices of approx. 150 € to approx. 550 €. Replacement catalytic converters without an approval number and which were partly on offer for the test vehicle on the internet for 50 € were not considered. For the examinations replacement catalytic converters with costs of approx. 250 €, approx. 300 € and two catalytic converters costing approx. 450 € were selected and purchased covertly from the independent aftermarket. All the costs quoted are given inclusive of value added tax.

3.4 Measurement of the exhaust gas emissions

The basis for the approval of replacement catalytic converters within the framework of the ECE Regulation No 103 is the New European Driving Cycle (NEDC).

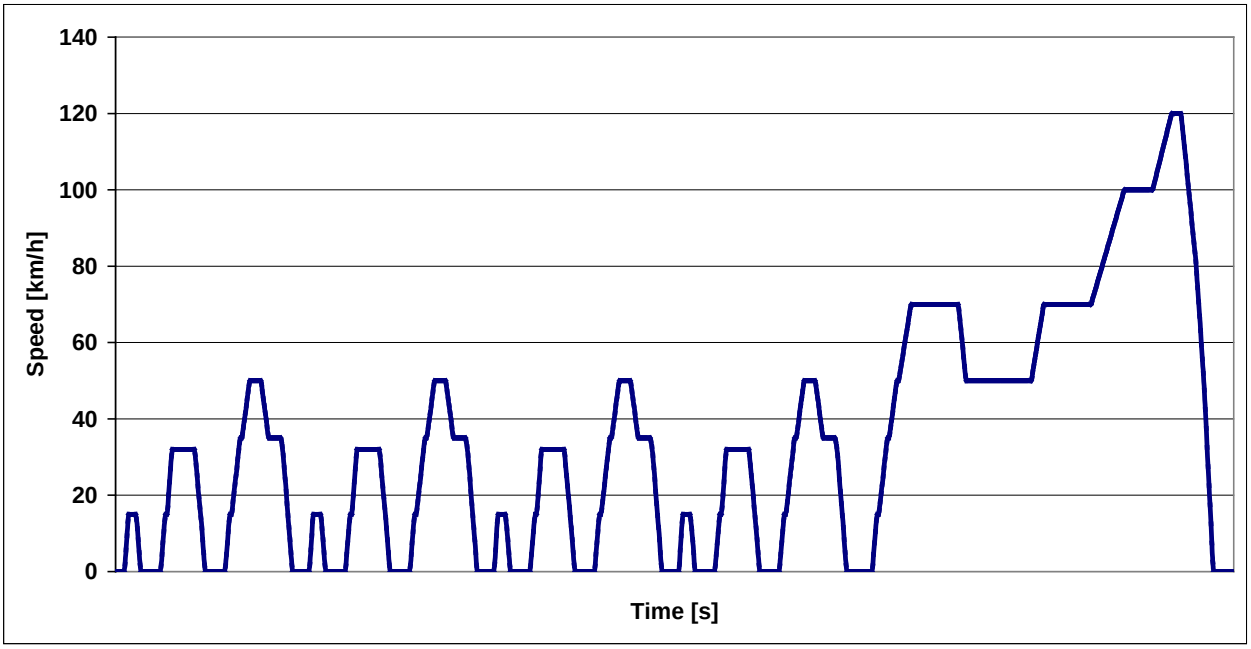

Figure 3.2: Driving curve of the NEDC /6/

This driving cycle is mandatory under ECE Regulation No 103 for the type approval of new vehicle types in Europe and also for the approval of replacement catalytic converters. The driving cycle is described in the ECE Regulation No 83. The NEDC comprises two part-cycles, an urban part (part 1 or urban driving cycle UDC) and an extra-urban part (part 2 or extra-urban driving cycle EUDC), the urban driving cycle being made up of 4 basic urban driving cycles to be run successively. In all, a distance of about 11 km is travelled in 1180 seconds. Figure 3.2 shows the speed profile of the NEDC. /3/

During the measurements conducted on the exhaust gas roller test bench the regulated pollutants carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxides (NO_x) were determined. Furthermore the carbon dioxide emissions (CO_2) were measured in order to check the plausibility and comparability of the measurements. For the load adjustment of the dynamometer the same values were used as for the homologation of the test vehicle.

3.5 Catalytic converter ageing on the burner test rig

For replacement three-way catalytic converters used in Euro 4 vehicles with petrol engine, ageing over 80,000 kilometres in real vehicle operation (continuous run) was to be simulated. There is no standardised procedure for ageing of exhaust gas after-treatment systems. Various methods are available. Vehicle manufacturers have various specifications for these types of tests. The supplier of original spare parts must meet the requirements of vehicle manufacturers and carry out durability tests in accordance with their specifications.

One possibility for ageing replacement catalytic converters is carrying out continuous operation in a real vehicle. Only one system can be aged per vehicle, which makes this approach complex and expensive. Furthermore, the comparability of the results of different systems when ageing in different vehicles is not necessarily given. It must also be checked whether any deterioration of the exhaust gas behaviour can be attributed only to the exhaust gas after-treatment system or additionally to a modification of the vehicle.

A usual type of ageing, both for the OEMs and the manufacturers of replacement catalytic converters is thermal ageing in the oven. In some cases, in addition to oven ageing, a hot shake test to check mechanical stability is carried out on a second catalytic converter. The combination of oven ageing and hot shake test is a practical and relatively cost-effective method for making statements for an estimate of the durability of replacement catalytic converters. The temperature profile for oven ageing must be adapted to the requirements of the vehicles used as a basis. Direct contact with the respective vehicle manufacturer is important here. Certain ageing processes, however, such as corrosion of the housing or thermal load during cold starts, cannot be simulated during ageing on a test bench, or only to a limited extent.

Another alternative is ageing of the exhaust gas after-treatment systems on a burner test rig. With burner ageing, exhaust gas emissions, which are generated in a burner and should correspond to the actual emissions arising during vehicle operation, are applied to the exhaust gas after-treatment systems. In this procedure, the exhaust gas after-treatment systems are subjected to both thermal and chemical stress.

In 2005 a standard procedure to demonstrate the durability of emission-reducing devices of passenger and light commercial vehicles was introduced by the US EPA as part of the Compliance Assurance Program (CAP 2000). The Standard Road Cycle (SRC) and the Standard Bench Cycle (SBC) are major components of this procedure. With the Standard Road Cycle, the complete vehicle is aged by driving a specified speed profile. As an alternative to SRC, with the help of the Standard Bench Cycle (SBC) accelerated ageing of the emissions-relevant components can be effected on a test bench. Here, exhaust gas generated by an engine or a burner is applied on a test bench to the exhaust gas after-treatment system to be tested. The SBC was especially designed for ageing catalytic converters and lambda sensors. The number of SBCs to be driven is based on the temperature profiles of the catalytic converter determined in the SRC and SBC calculated with the help of a formula specified by the EPA. This procedure is tried and tested and was adopted into European emissions legislation with the Regulation (EC) No 692/2008 of the Commission implementing and amending the Regulation (EC) No 715/2007 for conducting the ageing test (Type 5 Test) for exhaust after-treatment systems on petrol engines (Appendix 7, Section 1.3, 2.2 and Appendix 1), /4/, /5/, /6/

It was agreed with the customer and the research-supporting steering group that burner ageing is to be used for examining durability of replacement catalytic converters within the context of this project. This procedure provides meaningful and reliable measurement results. Ageing of the replacement catalytic converters was effected by FEV GmbH in the Standard Bench Cycle. The FEV burner test rig had already been used for homologation testing of several well-known vehicle manufacturers. The ageing procedure is explained in the following.

- Equipping of an original replacement catalytic converter with measurement technology for data collection in the SRC
- Installation of the original replacement catalytic converter with measurement technology in the test vehicle
- Recording of the catalytic converter temperature curve in the SRC on a vehicle dynamometer
- Removal of the catalytic converter from the vehicle
- Set-up of the original replacement catalytic converter with measuring technology on the burner test rig.
- Recording the catalytic converter temperature curve in the SBC on the burner test rig
- Evaluation of data and establishment of ageing time for the SBC using the catalytic converter temperature curves in the SRC and SBC
- Equipping the catalytic converters to be aged with measuring technology
- Carrying out SBC ageing on the burner test rig in several steps

- After each step, an emissions test is driven and evaluated.

An additional original replacement catalytic converter was used for recording temperatures in the SRC and adjusting the burner test rig.

Standard Road Cycle (SRC):

The SRC is a mileage accumulation cycle that can be driven on a test track or on a chassis dynamometer. The cycle consists of 7 sections of 6 km each. The cycle must be repeated until the required mileage has been reached. In Figure 3.3 a complete SRC run, whose driving distance amounts to a total of 42 km, can be seen.

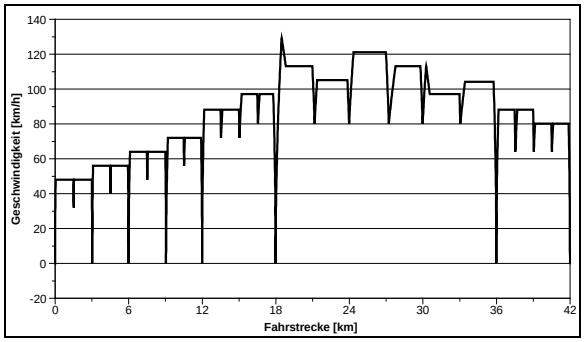

Figure 3.3: Driving cycle of the Standard Road Cycle (SRC)

The SRC driven by the test vehicle can be seen in Figure 3.4. Here the target speed (black), the actual speed of the test vehicle (red) and the highest temperature in the catalytic converter (blue) are shown.

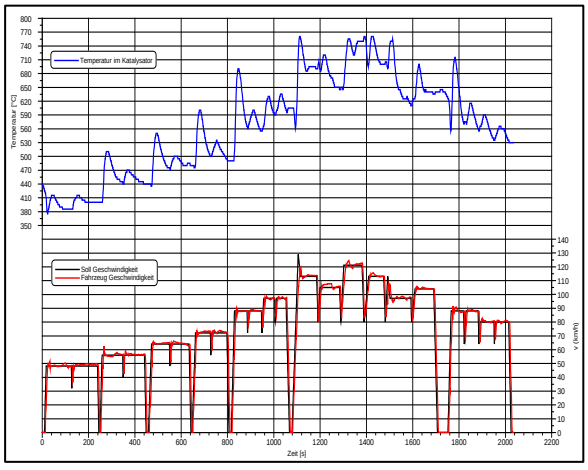

Figure 3.4 Speed and maximum catalytic converter temperature in the SRC

Standard Bench Cycle (SBC)

The SBC was designed to carry out a durability test of emission-reducing devices on an ageing test bench. In the SBC, it is not the whole vehicle that is aged, only the exhaust system. For the ageing test according to the SBC specifications, the catalytic converter is set up with the lambda sensors on an engine or burner test rig and exhaust gas is applied. The most important variables are the temperature in the catalytic converter and lambda. An SBC run lasts a total of 60 seconds. In the first 40 seconds, the test is operated at 800°C and lambda 1. Subsequently, the adjustment is made to lambda less than 1 and after a further 5 seconds, secondary air dosing takes place. The airflow is set in such a way that 3% oxygen is generated in the stable stoichiometric mixture. As a result of this air injection, an exothermic reaction takes place, with which the temperature in the test object rises to 890°C. The maximum temperature can be varied by adjusting the fuel-air ratio. The total period for which lambda is less 1 lasts 15 seconds, the burner subsequently delivers a stoichiometric mixture again. At 60 seconds the secondary air dosing is then also finished and one cycle is at an end. Figure 3.5 shows lambda and the secondary air injection in the SBC.

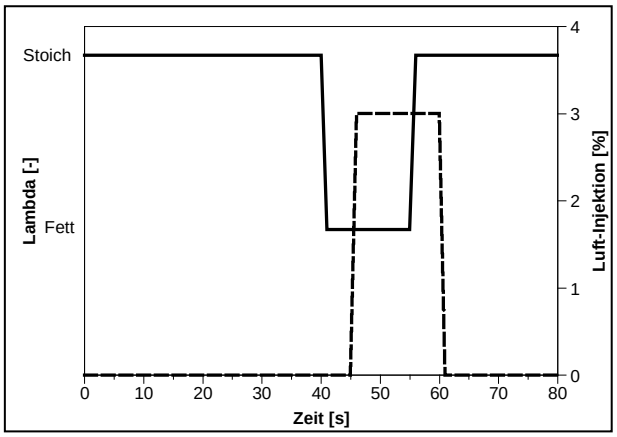

Figure 3.5 Standard Bench Cycle (SBC)

Figure 3.6 shows a section from the ageing of the original replacement catalytic converter. The cycle jump starts at second 51507, here lambda (green and red line) is changed to 0.94. In this point, the oxygen is discharged from the monolith and the monolith flooded with HC molecules. At second 51513, secondary air is dosed directly in front of the monolith. The unburnt HC molecules react with the surplus oxygen whereby an exothermic reaction takes place in the monolith and the temperature rises to 890°C. At second 51523, the lambda in front of catalytic converter again rises towards 1 and the temperature lowers again to 800 °C. After a further 5 seconds the secondary air is switched off.

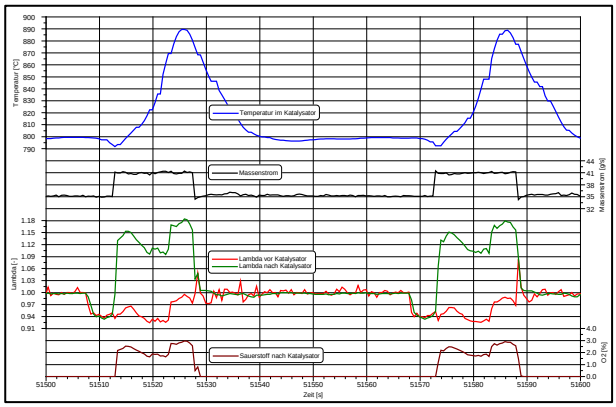

Figure 3.6: Section SBC ageing VW catalytic converter (CAT 83)

With the SBC, the system to be tested should be aged in such a way that the ageing corresponds to a specified run in the SRC. The catalytic converter temperature serves as a reference value. The catalytic converter temperature profile is initially determined on a roller-type test bench in a test vehicle. Through an SRC run and through recording all temperatures on the test object, it can be seen how the catalytic converter behaves in the vehicle. The temperatures are measured with a sampling rate of at least one Hertz in the SRC in order to create the temperature profile. The exhaust system is subsequently mounted on a test bench and operated in the SBC. Here, too, the temperature in the catalytic converter is recorded with a sample rate of at least one Hertz. Using the catalytic converter temperature curves in the SBC and SRC, with the help of a calculation program provided by EPA, the number of SBC that must be driven to simulate the specified travel distance is determined. The burner test rig is shown in Figure 3.7. /7/

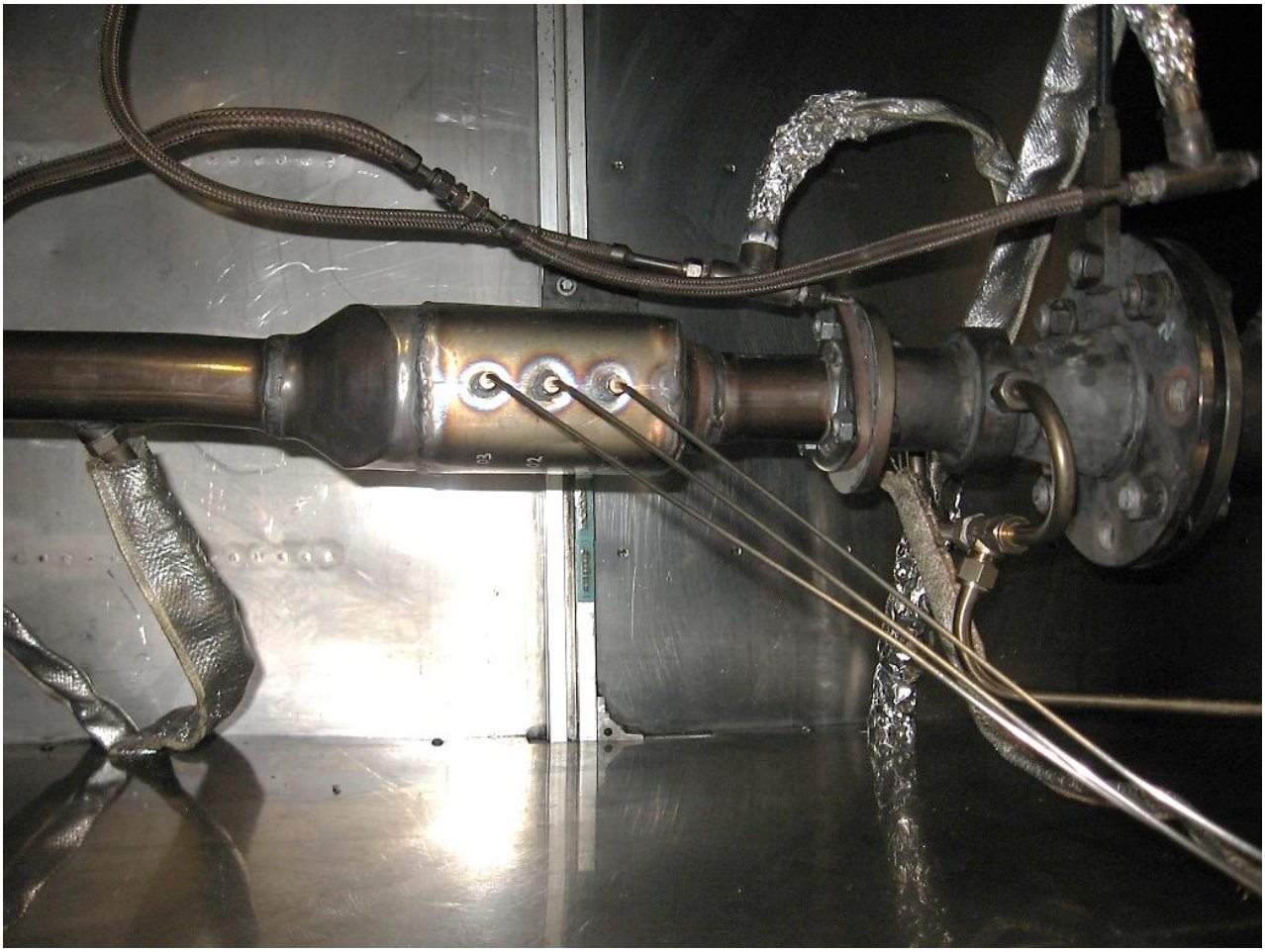

Figure 3.7 Test specimen with temperature measuring points on the burner test rig

4 Results

4.1 Exhaust gas emissions in as-delivered condition with the originally fitted catalytic converter

The test vehicle was delivered with a mileage of 75,000 km. In order to check the suitability of the vehicle for further examinations, the exhaust gas emissions in the NEDC were measured in as-delivered condition. The exhaust gas emissions of the test vehicle with the originally installed catalytic converter in the New European Driving Cycle are shown in Table 4.1.
The measurements of the test vehicle in as-delivered condition with the originally installed catalytic converter showed very good results, which were considerably below the Euro 4 limit values and achieve the level of the type test values. The results show that the vehicle is suitable for the test of replacement catalytic converters in accordance with ECE Regulation No 103. Over the entire duration of the research project, the emissions of the test vehicle were regularly checked with the original catalytic converter to ensure that the vehicle was in technical flawless condition.

Exhaust gas emissions in the NEDC	Regulated pollutants		
	CO [g/km]	HC [g/km]	NOx [g/km]
Test vehicles in as-delivered condition with original catalytic converter	0.271	0.040	0.049
Type approval test values of the test vehicle	0.172	0.066	0.055
Euro 4 Emission limits	**1.0**	**0.1**	**0.08**

Tab. 4.1: Exhaust gas emissions of the test vehicle in as-delivered condition with the originally installed catalytic converter

4.2 Exhaust gas emissions with the original replacement catalytic converter

For the test vehicle, an original replacement catalytic converter was purchased from an authorised dealer. After the initial measurement of the test vehicle with the genuine installed catalytic converter, this original replacement converter was installed in the test vehicle and conditioned in accordance with ECE Regulation No 103. The exhaust gas emissions were subsequently determined with the conditioned original replacement catalytic converter in 3 measurements in the NEDC. The mean values from these measurements are shown in Table 4.2.
The measurements with the conditioned original replacement catalytic converter (OEM) show excellent results. The values for the measurements with the new original replacement catalytic converters are even below the type approval test values

Exhaust gas emissions in the NEDC	Regulated pollutants		
	CO [g/km]	HC [g/km]	NOx [g/km]
Test vehicle in as-delivered condition with original catalytic converter	0.271	0.040	0.049
Test vehicle with the original replacement catalytic converter	0.119	0.035	0.029
Type approval test values of the test vehicle	0.172	0.066	0.055
Euro 4 Emission limits	**1.0**	**0.1**	**0.08**

Tab. 4.2: Exhaust gas emissions with the original replacement catalytic converter in new condition

4.3 Exhaust gas emissions with replacement catalytic converters from the independent aftermarket in new condition

From the independent aftermarket 4 replacement catalytic converters from various manufacturers were covertly purchased for the test vehicle, installed in the vehicle according to the manufacturer's specifications and conditioned according to ECE Regulation No 103. The exhaust gas emissions with the various replacement catalytic converters in new condition were measured three times each in the NEDC. The mean values of the measuring results are shown in Table 4.3.
For the measurements in new condition, 3 of the replacement catalytic converters satisfied the Euro 4 limit values. With replacement catalytic converter 4, the limit value for hydrocarbons (HC) was exceeded.

Exhaust gas emissions in the NEDC	Regulated pollutants		
	CO [g/km]	HC [g/km]	NOx [g/km]
Test vehicle in as-delivered condition with original catalytic converter	0.271	0.040	0.049
Test vehicle with the original replacement catalytic converter	0.119	0.035	0.029
Test vehicle with replacement catalytic converter 1	0.323	0.072	0.070
Test vehicle with replacement catalytic converter 2	0.135	0.058	0.046
Test vehicle with replacement catalytic converter 3	0.230	0.056	0.039
Test vehicle with replacement catalytic converter 4	0.234	0.112	0.057
Type approval test values of the test vehicle	0.172	0.066	0.055
Euro 4 Emission limits	**1.0**	**0.1**	**0.08**

Tab. 4.3: Exhaust gas emissions with replacement catalytic converters from the independent aftermarket in new condition

4.4 Exhaust gas emissions with replacement catalytic converters after ageing

The results of the catalytic converter ageing on the burner test rig are described in the following. The results of the emission measurements (Type I Test) in new condition of the systems and after 10,000 km, 40,000 km and 80,000 km burner ageing are listed in Table 4.4. The measurements and tests were performed according to the specifications of the examination programme described in Section 3.2.
With the original replacement catalytic converter and the replacement catalytic converters No 1, 2 and 3, ageing on the burner test rig was carried out. The replacement catalytic converter No 4 exceeded the Euro 4 emission limit for hydrocarbons already during exhaust gas measurements in new conditioned state. Therefore no further tests were carried out on this system and the examination was aborted before the ageing was started on the burner test rig.

Exhaust gas emissions in the NEDC	Original-replacement catalytic converter			Replacement catalytic converter 1			Replacement catalytic converter 2			Replacement catalytic converter 3			Replacement catalytic converter 4		
	CO [g/km]	HC [g/km]	NOx [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]	CO [g/km]	HC [g/km]	NOx [g/km]
New, after conditioning	0.119	0.035	0.029	0.323	0.072	0.070	0.135	0.058	0.046	0.230	0.056	0.039	0.234	0.112	0.057
After 10,000 km burner ageing	0.277	0.052	0.035	0.694	0.082	0.205	0.283	0.074	0.070	0.356	0.065	0.035	Not performed		
After 40,000 km burner ageing	0.221	0.054	0.036	Not performed			0.439	0.082	0.089	0.341	0.063	0.036	Not performed		
After 80,000 km burner ageing	0.278	0.059	0.040	Not performed			Not performed			0.291	0.066	0.041	Not performed		
Euro 4 Emission limits	**1.00**	**0.10**	**0.08**	**1.00**	**0.10**	**0.08**	**1.00**	**0.10**	**0.08**	**1.00**	**0.10**	**0.08**	**1.00**	**0.10**	**0.08**

Tab. 4.4: Mean values of the exhaust gas emissions with aged replacement catalytic converters

Figures 4.1 to 4.5 show the exhaust gas emissions related to the Euro 4 emission standards versus the ageing duration of the various catalytic converters.

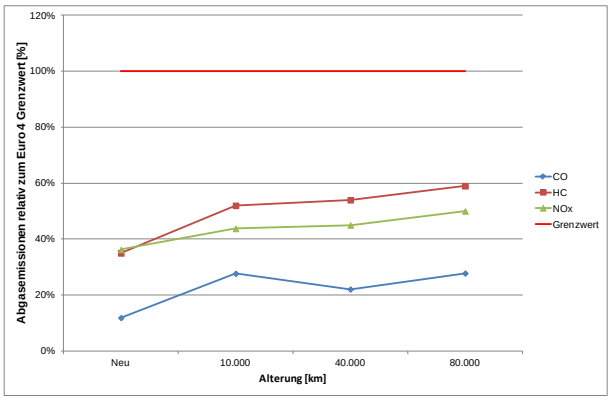

Figure 4.1: Exhaust gas emissions relative to the Euro 4 emission standards during ageing for the original replacement catalytic converter

In Table 4.5 and Figure 4.1 it becomes clear that with the original replacement catalytic converter a slight increase in emissions of all limited exhaust gas components appears after 80,000 km. Even after the run-through, however, the emissions lay well under the Euro 4 emission standards.

As indicated in the drawing of picture 4.2 replacement catalytic converter 1 exceeded the established nitrogen oxide limit value considerably already after 10,000 km. The examination was subsequently terminated.

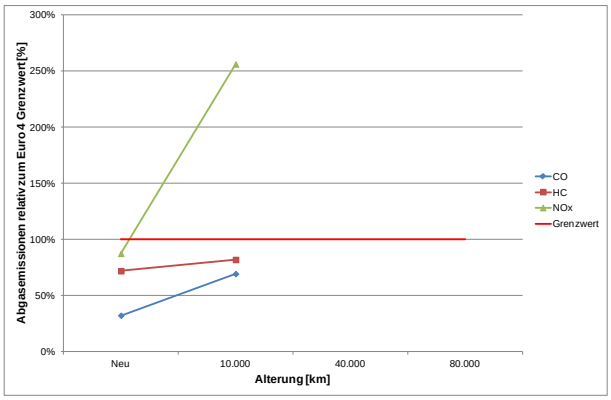

Figure 4.2 Exhaust gas emissions relative to the Euro 4 emission standards during ageing for replacement catalytic converter 1

Figure 4.3 shows the exhaust gas emissions measured with replacement catalytic converter 2. During ageing there is a detectable increase in the emissions of all limited pollutant components. After 40,000 km the limit value for the nitrogen oxide emissions was exceeded. The examination on this catalytic was subsequently ended.

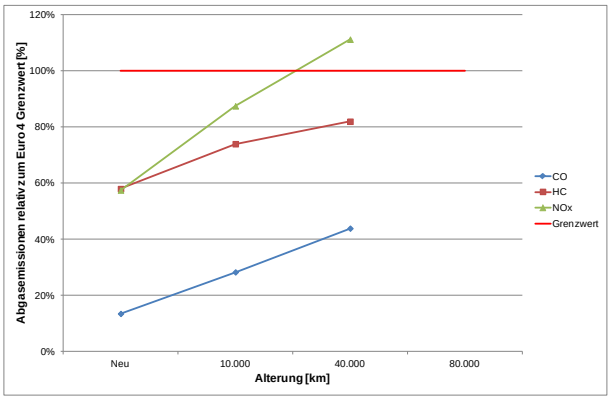

Figure 4.3: Exhaust gas emissions relative to the Euro 4 emission standards during ageing for catalytic converter 2

Figure 4.4 shows the exhaust gas emissions, which were measured with replacement catalytic converter 3 in the New European Driving Cycle in relation to the respective limit values. The exhaust gas values with this system were stable over the entire ageing and in the subsequent measurement were well below the Euro 4 emission standards after 80,000 km. With the replacement catalytic converter 3, comparable results to the original catalytic converter were achieved.

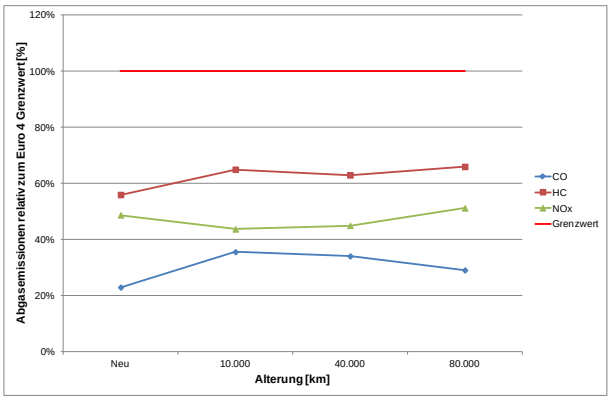

Figure 4.4: Exhaust gas emissions relative to the Euro 4 emission standards during ageing for replacement catalytic converter 3

Figure 4.5 shows the exhaust gas emissions relative to the limit values measured with replacement catalytic converter 4. As it was already established that the limit value had been exceeded in as-delivered condition, no ageing was performed. The measuring points shown in the diagram represent the values for the initial measurement after conditioning.

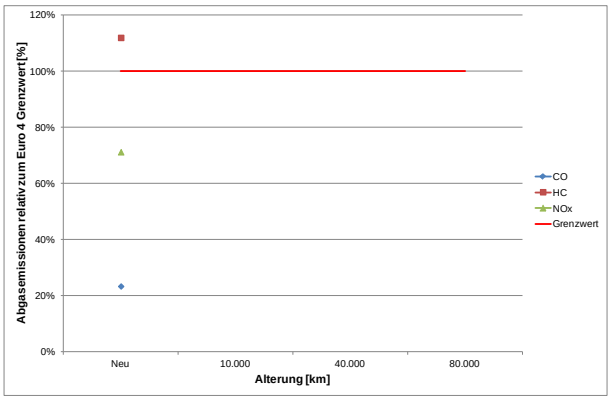

Figure 4.5: Exhaust gas emissions relative to the Euro 4 emission standards during ageing for replacement catalytic converter 4

The results in Table 4.4 and Figures 4.1 to 4.5 demonstrate that with the replacement catalytic converter No. 1, the examination was stopped after 10,000 km and with system No. 2 after 40,000 km burner ageing due to a limit value being exceeded. Only one system that originates from the free aftermarket (No. 3) and the original replacement catalytic converter of the OEM could satisfy all Euro 4 emission limits after burner ageing over 80,000 km. With replacement catalytic converter No.4 from the independent aftermarket the Euro 4 limit value for hydrocarbons was exceeded already in new conditioned state.

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4.5 Assessment of the exhaust gas emissions in accordance with ECE-R 103

Approval of replacement catalytic converters is effected in accordance with the specifications of ECE Regulation No 103. The new replacement catalytic converters are conditioned according to the regulation and fitted in a suitable vehicle. The exhaust gas emissions with the replacement catalytic converters to be examined must satisfy the described criteria (see Section 3.1). In the ECE Regulation No 103, the application of deterioration factors is envisaged in order to ensure the durability of the replacement catalytic converters.
In Table 4.5, the exhaust gas emissions measured with the original (OEM) replacement catalytic converter and with 4 replacement catalytic converters from the independent aftermarket in new condition in the test vehicle are compared with both the (relevant) Euro 4 emission standards and the requirements as per point 5.2.3 of the ECE Regulation No 103.

For the measurement of the originally installed catalytic converter, consideration of deterioration factors is not relevant, since this system already reached a mileage of 75,000 km. Nevertheless, the vehicle in as-delivered condition also satisfied the requirements of the ECE regulation since the measured emissions complied with the emission limits including the deterioration factors.

Exhaust gas emissions in the NEDC	Regulated pollutants		
	CO [g/km]	HC [g/km]	NOx [g/km]
Test vehicle in as-delivered condition with original catalytic converter	0.271	0.040	0.049
Test vehicle with the original replacement catalytic converter **(S)**	0.119	0.035	0.029
Test vehicle with replacement catalytic converter 1 **(M)**	0.323	0.072	0.070
Test vehicle with replacement catalytic converter 2 **(M)**	0.135	0.058	0.046
Test vehicle with replacement catalytic converter 3 **(M)**	0.230	0.056	0.039
Test vehicle with replacement catalytic converter 4 **(M)**	0.234	0.112	0.057
Euro 4 Emission limits	1.0	0.1	0.08
Deterioration factor	1.2	1.2	1.2
Euro 4 Emission limits including deterioration factor (G)	**0.833**	**0.0833**	**0.067**
0.85 x S + 0.4 x G	**0.434**	**0.063**	**0.051**

Tab. 4.5: Exhaust gas emissions with the replacement catalytic converters in new condition compared with the requirements of ECE Regulation No 103

The values in Table 4.5 show that with the replacement systems for the after-treatment of exhaust gases, considerable quality differences can occur.
Considering the deterioration factors, the Euro 4 emission limit for the nitrogen oxide emissions is exceeded for replacement catalytic converter 1 in new condition. Moreover, replacement catalytic converter 1 does not satisfy the conditions $M \leq (0.85 \times S + 0.4 \times G)$ in relation to the hydrocarbon emissions and with regard to the nitrogen oxide emissions. With replacement catalytic converters 2 and 3, all criteria were met in new condition. The hydrocarbon emissions measured with the replacement catalytic converter 4 not only exceed the Euro 4 emission limit but also the corresponding limit value with deterioration factor. Moreover, replacement catalytic converter 4 does not satisfy the conditions $M \leq (0.85 \times S + 0.4 \times G)$ in relation to the hydrocarbon emissions and with regard to the nitrogen oxide emissions. Therefore besides the original replacement catalyst only two of the four examined replacement catalytic converters available on the independent aftermarket met the requirements of the ECE Regulation No 103 in new condition.

5 Summary

In the context of the research project, the durability of replacement catalytic converters was examined. A VW Golf with 1.4 l petrol engine was selected as a test vehicle. At the start of the examinations, the vehicle showed a mileage of 75,000 km. The selected vehicle was regularly serviced in accordance with the manufacturer's specifications. No emission-relevant faults were recorded by the OBD system. The initial control measurement of the vehicle in as-delivered condition with the originally installed catalytic converter showed that the corresponding emissions of the regulated pollutants were considerably below the Euro 4 emission limits to be applied.
Subsequently, an original replacement catalytic converter, which was purchased from an authorised dealer, and 4 replacement catalytic converters purchased in the independent aftermarket, were examined. The replacement catalytic converters were conditioned according to the specifications of ECE Regulation No 103 and then measured in new condition. The catalytic converters were then aged on a burner test rig. Here a total mileage of 80,000 km was simulated. After 10,000 km and 40,000 km, the ageing was interrupted and the exhaust gas emissions of the test vehicle with the aged catalytic converters were measured. The examination was ended as soon as a limit value had been exceeded.
The results of the project indicate that with the replacement systems for the after-treatment of exhaust gases available in the independent aftermarket considerable quality differences can occur. At the end of the ageing over a distance of 80,000 km only the original replacement catalytic converter and one replacement catalytic converter from the independent aftermarket complied with the Euro 4 emission limits. With one replacement catalytic converter, the Euro 4 emission limits were already exceeded in new condition. With another replacement catalytic converter, the examination was aborted after 10,000 km ageing and with a further catalytic converter after 40,000 km ageing due to the Euro 4 emission limits being exceeded.
Replacement catalytic converters offered from the independent aftermarket are approved on the basis of the ECE Regulation No 103. This regulation provides for a test of durability of such systems over 80,000 km, but also alternatively enables the use of fixed deterioration factors. In practice, the durability of the replacement systems for the after-treatment of exhaust gases is guaranteed by their manufacturers. However, replacement catalytic converters are rarely inspected as part of the approval. In-use compliance provisions for replacement systems for the after-treatment of exhaust gases are not mentioned in the corresponding specifications. The results of this study indicate that the requirements in the ECE Regulation No 103 are not adequate to ensure the durability of replacement catalytic converters.

6 Literature

/1/	Official Journal of the European Union	Regulation No 103 of the United Nations Economic Commission for Europe - UNECE “Uniform provisions concerning the approval of replacement catalytic converters for power-driven vehicles”
/2/	German type approval authority (KBA)	Vehicle licensing, inventory, emissions, fuels, 1 January 2009
/3/	Official Journal of the European Union	Regulation No 83 of the United Nations Economic Commission for Europe - UNECE “Uniform provisions concerning the approval of vehicles with regard to the emission of pollutants according to engine fuel requirements”, Official Journal of the European Union
/4/	Official Journal of the European Union	Regulation (EC) No 715/2007 on type approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 and Euro 6) and on access to vehicle repair and maintenance information, Official Journal of the European Union, 2007
/5/	Official Journal of the European Union	Regulation (EC) No 692/2008 of the Commission of 18 July 2008 implementing and amending Regulation (EC) No 715/2007 of the European Parliament and of the Council on type-approval of motor vehicles with respect to emissions from light passenger and commercial vehicles (Euro 5 und Euro 6) and on access to vehicle repair and maintenance information, Official Journal of the European Union, 2008
/6/	Federal Register	Emission Durability Procedures for New Light-Duty Vehicles, Light-Duty Trucks and Heavy-Duty Vehicles; ENVIRONMENTAL PROTECTION AGENCY, 40 CFR Part 86; Federal Register / Vol. 71, No 10 / Tuesday, January 17, 2006 / Rules and Regulations
/7/	ENVIRONMENTAL PROTECTION AGENCY	Bench Aging Time Calculator (BAT); http://www.epa.gov/otaq/regs/ld-hwy/durability/index.htm#bat, Status 2013