15 Diesel Engine Exhaust Emissions

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15.1 General Background

The direct release of exhaust gas components from combustion processes into the environment, i.e. emission, is the primary and most important process in the chain of emission, transmission, pollutant input and impact. Naturally, a basic distinction is made between emissions from vegetation, oceans, volcanic activity or biomass decomposition for instance and anthropogenic emissions, i.e. emissions caused or influenced by humans, from power generation, traffic, industry, households and farming for instance. The following deals exclusively with anthropogenic emissions from diesel engine combustion processes. Figure 15-1 depicts the functional chain with the major anthropogenic sources [15-1]. Exhaust gas components may be harmful or harmless as well as gaseous, liquid or solid.

Figure 15-2 is an overview of anthropogenic emissions and their sources in Germany.

Influenced by topography, climatic conditions, temperatures, moisture and air movements, exhaust gas components are diluted and subjected to physicochemical reactions and dispersed over large distances by atmospheric transport (transmission).

Pollutant input (air quality) is the concentration that ultimately manifests itself after being transmitted to a particular location where measurements are taken, e.g. at an intersection. Pollutant input is the contamination of humans or nature engendered by exhaust emission and transmission.

Impact denotes the consequences of pollutant input on the environment, organisms or goods. The complex processes of emission transport cause pollutant input readings to fluctuate daily and seasonally. Therefore, there are emission limits on exhaust pollutants, e.g. from vehicles or household heating systems, as well as air quality limits on sulfur dioxide, particulates, lead and ozone [15-2].

The exhaust pollutants produced during combustion processes can be divided into harmless exhaust gas components, which are unavoidable natural products of combustion, and harmful exhaust gas components, which may or may not be subject to limits. Figure 15-3 presents the composition of exhaust gas for ideal and complete combustion with pure oxygen, which only produces carbon dioxide and combustion water in addition to the desired heat that the internal combustion engine converts into mechanical energy. Both components are harmless but relevant to the climate. Aside from the aforementioned harmless components, exhaust gas from combustion with air under ideal conditions only contains nitrogen and additionally oxygen in the case of diesel engines with excess air.

However, real combustion produces other components that are harmful and therefore partly subject to limits, e.g. carbon monoxide CO, unburned hydrocarbons HC, nitrogen oxides NO, NO2 (NOX), particulates, sulfur compounds, aldehydes, cyanide, ammonia, special hydrocarbons such as benzene and polycyclic aromatic hydrocarbons such as phenatrenne, pyrene and fluorene [15-3].

Figure 15-4 presents the raw emission from real combustion and its composition in percent by weight. Diesel engines have substantially smaller fractions of pollutants than gasoline engines. However, diesel engines also produce additional particulates, i.e. solids (predominantly soot) and components present as condensate, since their mixture formation is inhomogeneous. Their particular composition greatly depends on an engine’s operating point. Particulate emission also has to be allowed for in gasoline engines with charge stratification, i.e. inhomogeneous mixture fractions.

All in all, harmful exhaust gas components subject to limits have been reduced dramatically over the past years and projections up through 2020 confirm this trend will continue in the future too. Figure 15-5 clearly indicates that vehicles powered by diesel engines are particularly responsible for nitrogen oxide and particulate emission. Reduction measures will have to concentrate on this.

In light of the projected and highly probable increase of the earth’s mean temperature by approximately 1.5–5°C by the end of this century, greenhouse gases will also be limited in the future. Above all, carbon dioxide CO2 and methane CH4 (predominantly from agriculture) are responsible for the
“greenhouse effect”. Other greenhouse gases, e.g. fluorohydrocarbons FCKW, nitrogen dioxide N2O and sulfur compounds, have in part a significantly higher global warming potential (GWP) than CO2. However, they appear in substantially smaller concentrations and are therefore less relevant.

CO2 accounts for 65% of the projected temperature increase. Figure 15-6 presents the development of global CO2 emission of which traffic is estimated to produce between 15 and 20% (see Fig. 15-7).

Along with already existing air quality limits (Climate Conference, Kyoto Protocol and EU laws), intensive political and economic debates and efforts are also establishing limits on the CO2 emission of motor vehicles. A fleet standard of 120–130 g/km of CO2 is planned for cars by 2012.

In practice, only an integrated approach, i.e. the interaction of various measures, can effectively reduce harmful or climatically relevant emissions. Such measures may include the:

- provisions of legislation (emission limits in conjunction with the underlying test cycles),
- promotion of environmentally compatible vehicles through incentive systems (tax advantages, increased attractiveness of public transportation, etc.),
- reduction of emissions at their place of origin by improving combustion processes and exhaust gas aftertreatment,
- increase of efficiency of energy conversion,
- use of low emission fuels,
- power train and vehicle improvements (transmission design, road load and aerodynamics),
- power train energy management utilizing optimized drive systems (hybridization of vehicle propulsion),
- dynamic traffic routing (traffic flow control adjusted to the particular volume of traffic) and
- low emission and fuel economizing operation by drivers (driver training).

Transmission and pollutant input interact closely. Influencing factors are:

- local emission,
- road routing,
- development,
- traffic density,
- climatic influences such as
  - wind speed,
  - wind direction,
  - temperature and
  - solar irradiation and
- physicochemical reactions.

The expected air quality in particular geographic locations can be projected on the basis of dispersion models and by incorporating the aforementioned influencing factors. This is important, for instance, when planning new residential areas and routing the connected roads. While carbon monoxide and hydrocarbon emission have now reached a low level, not least because of the introduction of catalytic converter technology in gasoline powered vehicles (three-way catalytic
Fig. 15-2 Anthropogenic emission in Germany based on sources: (a) all sources (source: UBA 2009); (b) traffic (source: UBA 2007)
converters), particulate emission (fine particulate matter) and NOX emission remain particularly relevant for cars and commercial vehicles powered by diesel engines. Ozone $\text{O}_3$, which only forms in the atmosphere, is another factor.

Important because they affect air hygiene and humans, these three components are examined in more detail below.

## 15.1.1 Fine Particulate Matter

Particulate matter is one of the air pollutants that determine air quality. Regardless of their chemical composition, all the solids distributed in the air are subsumed under the terms "particulate matter" or "particulates". Primarily fine particulate matter that is no longer perceptible with the human eye is significant for humans. Such suspended particulates are relevant to health and classified according to their aerodynamic diameter $d_{\text{Aero}}$.

The mass of all the particulates with aerodynamic diameters of up to 10 $\mu$m contained in the total particulate matter is denoted as fine particulate matter (PM10) and represents the overwhelmingly inhalable proportion of the total mass of particulate matter. Fine particulate matter may have natural (e.g. soil erosion) or anthropogenic origins (i.e. human action). Power and industrial plants, stationary firing plants, metal and steel production and bulk material handling produce fine particulate matter. Road traffic is often the dominant source of particulate matter in urban areas.

Although not applied uniformly in the literature, the following designations are employed:
suspended particulates (total suspended particulates, TSP): particulates up to a $d_{\text{Aero}}$ of around 30$\mu$m (total particulate matter, all airborne particulates) fine particulate matter (PM10): particulates that pass through a size-selective air inlet with a 50% filtration rate for $d_{\text{Aero}} = 10$ $\mu$m coarse fraction: particulates larger than 2.5 $\mu$m (and smaller than 10 $\mu$m) fine fraction (PM2.5): particulates that pass through a size-selective air inlet with a 50% filtration rate for $d_{\text{Aero}} = 2.5$ $\mu$m ultrafine fraction (PM0.1): particulates smaller than 100 nm nanoparticulates: particulates smaller than 50 nm The particulate fraction PM2.5 is also designated as respirable fine particulate matter.

The aerodynamic diameter $d_{\text{Aero}}$ of a particulate of any shape, chemical composition and density is equal to the diameter of a sphere with the density of 1 g/cm$^3$, which has the same settling velocity in air as the particulate being analyzed.

In the European Union, the air quality framework directive (96/62/EC on ambient air quality assessment and management) concretized by a subsidiary directive (1999/30/EC relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air) mandates strict limits for air quality. These limits (air quality values) have a legally binding character, i.e. in order to prevent harmful environmental impacts, they may not be

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**Fig. 15-5** Development of emissions produced by road traffic in Germany (2006 VDA Annual Report)
exceeded. A revision of Directive 96/62/EC and the three subsidiary directives was planned for 2007.

As of January 1, 2005, the limits were:
- 50 μg/m³ for the 24 h mean value of PM10 with 35 exceedances allowed per year and
- 40 μg/m³ for the annual mean value of PM10.

Limits as of January 1, 2010 were:
- 50 μg/m³ for the 24 h mean value of PM10 but with only seven exceedances allowed per year and
- 20 μg/m³ for the annual mean value of PM10.
The limits mandated in the subsidiary directive are based on WHO studies and are normally below the values of earlier regulations. Thus, the new limits for fine particulate matter (PM10) supersede the previous limits for total suspended particulates (TSP with particulate diameters up to 40 \( \mu m \)). The German 22nd Federal Ambient Pollution Control Act (22. BimSchV) of September 11, 2002 [15-2] implemented the air quality framework directive and the first two subsidiary directives as federal law.

A distinction is usually made between anthropogenic and natural sources. Both sources can be divided into primary and secondary sources.

Primary anthropogenic sources directly produce and release dust particulates and include stationary sources such as combustion plants that supply power (power plants and district heating plants), waste incineration plants, domestic heating (gas, oil, coal and other solid fuels), industrial processes (e.g. metal and steel production, sintering plants), agriculture and bulk material handling.

The dominant sources in urban areas are mobile sources such as road traffic, e.g. diesel commercial vehicles and cars. In addition to soot particulates from exhaust, abraded particles from tires, brakes and clutch linings and stirred up particulate matter have to be factored into road traffic as diffuse emissions. Rail traffic, shipping (with diesel engines) and aviation are other mobile sources with appreciable emissions of particulate matter.

Secondary anthropogenic sources release reactive gases (including sulfur and nitrogen oxides and ammonia), which atmospheric reactions convert into secondary dust particulates. Among others, these include ammonia sulfates and ammonia nitrates, which bind to fine particulates already present in the atmosphere and thus form secondary aerosols.

Natural sources include volcanoes, oceans (salt water aerosols), forest fires and biological organic material (e.g. plant pollen). Such particulates may be transported from their original source region over long distances and thus contribute to long distance transport. The size of the particulates essentially determines their residence time in the atmosphere and potential transport routes. Thus, small particulates may be transported several 1,000 km within a few days. Saharan dust for instance can reach Europe or America depending on the wind direction.

Particulate matter emissions in Germany have dropped dramatically in the last 15 years. However, mainly total particulate matter was measured until 2001. Figure 15-8 plots the development of particulate matter emissions with the following boundary conditions.

![Figure 15-8 Development of particulate matter emission in Germany from 1990 to 2002 (source: UBA 2004)](image)
- It includes emissions from combustion processes caused and not caused by transportation and from industrial processes and bulk material handling.
- It does not include dust and grit from road surfaces stirred up by road traffic nor the large amount of abraded particles from tires and brakes.

The proportion of diesel soot particulates in fine particulate matter is difficult to estimate. The local percentage can be relatively high in urban regions with a high volume of traffic. Authorities are taking action against increased traffic with high diesel soot emissions. In addition, stricter emission limits (Euro 5 and 6) and tax incentives are stepping up the outfitting of diesel vehicles with diesel particulate filters.

Figure 15-9 presents a source analysis of PM10 in a measuring station in Berlin near heavy traffic. 49% of the total particulate matter load can be attributed to road traffic but only 11% stems from the exhaust of vehicles in local traffic (approximately 8% from trucks and 3% from cars).

Regulations for the reduction of fine particulate matter in conformance with the World Health Organization’s (WHO) recommendations were implemented in the wake of various studies that demonstrated they are a health hazard.

Ultrafine particulates constitute only a low percentage of PM by mass but possess a sizeable particulate surface area because of their large numbers (up to 90%). Harmful substances (e.g. heavy metals or organic materials such as polycyclic aromatic hydrocarbons or dioxins) can bind to them. The soot from a diesel vehicle’s exhaust system also consists of ultrafine fractions.

Suspended particulate fractions can act as irritants that cause inflammation whenever they deposit in the human body as foreign bodies. The smaller the particulates, the deeper they are able to penetrate the respiratory tract. Particulates that are over 10 µm in size hardly get past the larynx and only a small fraction can reach the bronchial tubes and the alveoli. However, particulates under 10 µm and under 2.5 µm can do so. Ultrafine particulates that are less than 0.1 µm in size can even reach the blood stream through the pulmonary alveolus and disperse in the body through the bloodstream.

Increasing evidence in recent years has indicated that – contrary to earlier assumptions – there is no threshold as of which suspended particulate matter adversely affects health. Findings from cohort studies indicate that the inhalation of fine particulate matter can be expected to shorten humans’ life expectancy [15-5]. Such studies are not undisputed though.

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**Fig. 15-9** Fine particulate matter loads in a measuring station in Berlin near heavy traffic [15-4]
15.1.2 Nitrogen Oxides NOx

The combustion process mainly produces NO (approximately 60–90%) and little NO2 in the combustion chamber. They are considered a mixture called NOX but only NO2 is relevant for air hygiene as a pollutant input. Diesel engines systematically produce NO2 from NO in catalytic converters. deNOx systems use it to oxidize and efficiently reduce soot particulates. In air, NO oxidizes to NO2, a gas that irritates mucous membranes and is caustic when combined with moisture (acid rain). It increases asthma sufferers’ physical stress, especially when they exert themselves physically. NO2 has a “fertilizing” effect on plants, i.e. it promotes growth.

According to [15-2], a limit concentration of NO2 of 40 μg/m2 will be in force in the EU in 2010. Figure 15-10 presents the current concentration of NO2, which has remained constant since around 1997 regardless of location. Achieving the aforementioned limits will necessitate considerable efforts in all sectors, i.e. not only in the transportation sector.

15.1.3 Ozone O3

Two domains of ozone activity are distinguished:

a) The ozone layer: Ozone at an altitude of 30–40 km (stratosphere) acts as a filter against harsh UV radiation (UV-C and UV-B) and is therefore essential to life. Increasing thinning of the ozone layer caused by FCKW and halones has been observable over the last 20 years. The O3 concentration over the Antarctic (ozone hole) declines particularly dramatically during southern spring (September and October). Exhaust emissions do not play any part. According to the latest calculations, the ozone hole will have closed again by around 2040–2050.

b) Low level ozone: This is summer smog that forms from atmospheric oxygen influenced by photooxidants (NOX, VOC, CO) when there is strong solar irradiation. It is toxic and, hence, undesired. Since the precursor substances partly stem from motor vehicle exhaust gases, information is passed along to motorists as of certain O3 concentrations and even driving bans are imposed to reduce motor vehicle traffic. On the one hand, nitrogen oxides trigger the formation of O3 but, on the other hand, they also facilitate its disintegration. A higher ozone concentration can actually appear in rural regions than in urban regions with heavy traffic.

Ozone is an irritant gas that alters the transport of oxygen in the human body. It reduces resistance to viral infections, impairs plant growth and affects breathing.
15.2 Emission Control Legislation

15.2.1 Emission Control Legislation for Car Engines

The USA issued the first emission control standards for diesel vehicles in the early 1970s. Japan and Europe followed somewhat later. Legislation is still focused on limiting diesel smoke, particulate emission and nitrogen oxide emission. An emission test performed on a chassis dynamometer with standardized driving cycles is intended to deliver quantitative information on vehicle emissions under representative operating conditions. However, different driving cycles for the measurement of exhaust gas and fuel consumption have also been developed in parallel since driving conditions in the USA, Europe and Japan differ. Figure 15-11 presents the major driving cycles.

Although higher nitrogen oxide emissions from diesel vehicles were initially accepted, the development of emission control standards is now heading toward treating gasoline and diesel engines equally, i.e. toward technology-independent limits.

The beginnings of emission control legislation in the USA, Europe and Japan were followed by the development of national emission standards in many other countries and emission control standards of varying stringency now exist in over 30 countries. Since these standards basically rely on American, European and Japanese models, the following remarks concentrate on the standards in these three regions.

15.2.1.1 Diesel Smoke

Initially also meaningful for the evaluation of new vehicles, diesel smoke measurement now only makes sense for tests of vehicles in service since smoke levels have become so low overall.

Basically, two types of diesel smoke tests are employed, full load measurement (4–6 points on the engine’s full load curve) and free acceleration (the engine is accelerated to its maximum governed speed). The metrology applied is either light absorption or filter measurement. However, the results of these measurements do not allow direct and clear conclusions.
about the level of particulate emission in a chassis dynamometer test. A diesel smoke test is only able to effectively identify high emission vehicles and, in certain cases, also detect tampering with an injection system.

15.2.1.2 Gaseous Emissions and Particulate Emission

New vehicle type approval testing requires the determination of the HC, CO, nitrogen oxide and particulate emissions during the driving cycle on a chassis dynamometer. Moreover, legislation mandates conformity of production testing and, in some countries, the testing of vehicles in use too (vehicles with a kilometrage of up to 100,000 km are currently being subjected to testing in the EU). Type approval testing also requires compliance with the emission limits over a vehicle’s useful life. To demonstrate compliance, manufacturers normally have the choice between applying fixed deterioration factors (Table 15-1) or conducting a durability test extrapolating emissions to the useful life by linear regression. In the USA however, the option of fixed deterioration factors only applies to small production runs and must be additionally adapted to the useful life distance. The useful life period is defined differently. Thus, while the USA requires demonstration of proof of compliance over 120,000 miles (193,000 km), Europe requires proof over 160,000 km.

A chassis dynamometer test analyzes the emissions from the diluted exhaust gas flow. Filter disks collect exhaust gas particulates from a partial exhaust gas flow and are weighed on a scale before and after the test. Debate over the potential health hazard of diesel soot particulates has raised questions about the real relevance of particulate mass as a metric when the number of particles may instead be the actual determinant of health risks. Hence, particle number limits will become mandatory for Euro 5 and 6 and thus supplement particulate mass measurement in Europe.

When particulate filter systems were launched on the market, European legislation specified a supplementary test for periodically regenerating particulate filters. Emission and fuel consumption are determined during both the particulate accumulation phase and the regeneration phase. The higher emissions during particulate filter regeneration are weighted in the final result based on the regeneration frequency.

15.2.1.3 American Emission Control Standards

The different emission limit levels in the USA are referred to as tiers, Tier 2 being the most recent. In turn, tiers contain different sets of limits or bins. Manufacturers may choose between several bins but must ensure that the NOX values of their vehicle fleets do not exceed 0.07 g/mile on average. This greatly limits the selection of bins since bin 5 must be reached on average. Bin 8 is the least stringent. The application of the same emission limits to both diesel and gasoline vehicle is a principal of American legislation. This is a particular challenge for diesel engine emission control (see Table 15-2). In addition, compliance with emission limits in additional test cycles, the Supplemental Federal Test Procedure (SFTP), is required.

Given its special situation with regard to climate, population density and traffic density, California has maintained its own emission standards until the present. The NMOG (non-methane organic gases) fleet standard supersedes the NOX fleet standard in force in the USA. A manufacturer’s average NMOG fleet value determines its production volume in the three limit classes, i.e. LEV (low emission vehicle), ULEV (ultra low emission vehicle) and SULEV (super ultra low emission vehicle) (see Table 15-3). California has the most stringent emission limits in the world.

15.2.1.4 European Emission Control Standards

The development of emission control standards in the European Union (EU) only caught up to the stringency of legislation in the USA relatively late with the Euro 1 emission level. In the meantime, Euro 4 (see Table 15-4) has been enacted and applied to all new types since January 1, 2005 and all newly approved vehicles since January 1, 2006. Further specifications already exist for Euro 5 (in force as of September 1, 2009) and Euro 6 (as of September 1, 2014). At present, the Euro exhaust levels still apply different limits to gasoline and diesel engines. What is more, cars are differentiated by their allowable total mass. Thus, vehicles with a gross vehicle weight rating of less than 2,500 kg must meet more stringent emission limits than vehicles of 2,500 kg and more. Mainly vans profit from this regulation.

EU emission control standards are proposed by the EU Commission and ratified by its institutions. Components of

<table>
<thead>
<tr>
<th>Table 15-1 European/Japanese deterioration factors</th>
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<tr>
<td>CO</td>
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<tr>
<td>-------</td>
</tr>
<tr>
<td>EU (Euro 4)</td>
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<tr>
<td>EU (Euro 5)</td>
</tr>
<tr>
<td>EU (Euro 6)</td>
</tr>
<tr>
<td>Japan</td>
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</table>

* To be set later
the legislation, e.g. test procedures, are being adopted from the work of the United Nations’ World Forum for Harmonization (UNECE) with increasing frequency. One example is the test procedure for vehicles with periodically regenerating exhaust gas aftertreatment systems such as diesel particulate filters. This procedure determines the regeneration factor \( k_i \) by measuring emissions before, during and after the regeneration of the exhaust gas aftertreatment system (Fig. 15-12). The measured values from the emission test with an unloaded particulate filter are multiplied by the value of \( k_i \).

Recently adopted Euro 5 and future Euro 6 emission control legislation are further tightening the limits on NO\(_X\) emissions from diesel engines in particular to close the gap between gasoline and diesel limits. Future levels of EU emission standards may well harmonize them. EU legislative bodies are also contemplating revising the particulate emission limits and there is movement toward not only measuring the quantity of particulate mass but also determining the number of particles emitted.

Any revisions of the test cycle are still open. Statements from legislators to the effect that the current NEDC test cycle is no longer representative seem to suggest they are likely. Such activities may be coordinated with those at the UNECE.

### 15.2.1.5 Japanese Emission Control Standards

For some time now, major Japanese cities and their metropolitan areas have been suffering from the problem of smog caused by high concentrations of hydrocarbons and nitrogen oxides. Road traffic contributes to this substantially. Hence, the development of emission control legislation has particularly concentrated on reducing NO\(_X\) emissions. Along with emission limits for the entire country, the NO\(_X\) Control Law contains more stringent limits for the approval of diesel vehicles in metropolitan areas. However, revisions of the exhaust emission standard in Japan are also moving toward treating gasoline and diesel vehicles equally. The implementation dates are staggered for Japanese made vehicles and imports. However, this practice may be discontinued in the future. Moreover, two different limit are being defined, one for mass production and another for small lots or low numbers of imports (a maximum of 2,000 vehicles per type and calendar year) (see Table 15-5).

### On-Board Diagnostics (OBD)

Legislation requires on-board diagnostics that monitors the function of components related to emission during vehicle operation. California required this first with OBD I in 1988. The current Californian version is OBD II. Euro 3 legislation (EOBD) introduced on-board diagnostics in the EU in 2000. The function of OBD is to inform drivers of malfunctions or failures of components relevant to emissions through an optical malfunction indicator. Detected malfunctions are entered in a fault memory and can be retrieved by an external diagnostic tool through a standardized interface. American and European OBD have different monitoring parameters and OBD thresholds at which a malfunction is indicated.

### 15.2.2 Emission Control Legislation for Commercial Vehicle Engines

#### 15.2.2.1 Test Mode and Emission Limits

The diversity of types of commercial vehicles, their evolution into component trucks and tire and brake wear during chassis
dynamometer operation gave rise to emission testing for heavy commercial vehicles on engine test benches. The European Union’s vehicle classes are listed in Table 15-6.

Since it is impossible to test every engine application profile, an engine must be run through a test cycle that matches the application profile as closely as possible in order to evaluate emissions and keep the time and effort required for engine certification within limits. A test measures the emissions of the following components:

- nitrogen oxides (NOx),
- hydrocarbons (HC),
- carbon monoxide (CO),

Table 15-5  Japanese diesel car emission limits

<table>
<thead>
<tr>
<th></th>
<th>HC [g/km]</th>
<th>CO [g/km]</th>
<th>NOx [g/km]</th>
<th>PM [g/km]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Emissions in the 10.15-mode</td>
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<td>Long-term targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>since 2004</td>
<td>0.12</td>
<td>0.63</td>
<td>0.28</td>
<td>0.052</td>
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<tr>
<td></td>
<td>(0.24)</td>
<td>(0.98)</td>
<td>(0.43)</td>
<td>(0.11)</td>
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<tr>
<td>Emission in the 11/10.15-mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>As of 2008: emissions in the JC08/10.15-mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>New long-term targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>as of Sept. 1, 2007</td>
<td>0.024</td>
<td>0.63</td>
<td>0.14</td>
<td>0.013</td>
</tr>
<tr>
<td></td>
<td>(0.032)</td>
<td>(0.84)</td>
<td>(0.20)</td>
<td>(0.017)</td>
</tr>
<tr>
<td>Emissions in the JC08/10.15-mode</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Post new long-term targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>as of 2010</td>
<td>0.024</td>
<td>0.63</td>
<td>0.08</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>(0.032)</td>
<td>(0.84)</td>
<td>( *)</td>
<td>( *)</td>
</tr>
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| Parenthetical values apply to small lots/small volumes of imports up to a maximum of 2000 vehicles per type and calendar year. (*) To be set later.
– particulates (PM) and
– visible emission (exhaust gas opacity).

Tables 15-7 and 15-8 present the emission limits applied in the different regions. All over the world, emission legislation is exhibiting a clear trend toward ever tighter emission limits. Since engines must be tuned for the particular test cycle, a direct comparison of the individual regions’ limits is impossible.

The most important test procedures are described below.

### 15.2.2.2 US Test Cycle

A transient test procedure (US-FTP) has been mandatory for commercial vehicle engines in the USA since 1985 (see Fig. 15-13). The US-FTP test cycle is specified in a standardized form (percentage speed and percentage torque), lasts 20 min and is run twice (cold start test and hot start test). The cold start test is weighted as 1/7 and the hot start test as 6/7 of the final result. The operating frequencies of the cycle are concentrated on the higher engine speed range. The range around the maximum torque speed applied in real operation to reduce fuel consumption is only represented very little. Therefore, European legislation has not adopted US-FTP.

The test cycle’s failure to capture typical in-use driving conditions has been exploited to design engines that obtain good fuel consumption in the field at the expense of NOX emission while meeting the NOX limit in the test cycle. This abuse (cycle beating) led to a significant tightening of American legislation. Along with additionally implementing Euro III ESC tests, a region of the engine map was stipulated in which emissions may not exceed the respective limits multiplied by one of the NTE factors, which are dependent on the

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**Table 15-6** Vehicle classes according to Directive 70/156/EEC for diesel-powered vehicles. Test requirements for gaseous emissions and particulates

<table>
<thead>
<tr>
<th>Class</th>
<th>Seats</th>
<th>Gross vehicle weight rating</th>
<th>Test cycle</th>
<th>Class</th>
<th>Gross vehicle weight rating</th>
<th>Test cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>M₁</td>
<td>≤ 8</td>
<td>≤ 3.5 t</td>
<td>NEDC⁴</td>
<td>N₁</td>
<td>≤ 3.5 t</td>
<td>Either NEDC⁴ or ESC, ELR; ETC</td>
</tr>
<tr>
<td>M₂</td>
<td>&gt; 8</td>
<td>≤ 5 t</td>
<td>ESC; ELR; ETC</td>
<td>N₂</td>
<td>3.5 t &lt; . . . 12 t</td>
<td>ESC, ELR (NEDC⁴)</td>
</tr>
<tr>
<td>M₃</td>
<td>&gt; 8</td>
<td>&gt; 5 t</td>
<td>ESC; ELR; ETC</td>
<td>N₃</td>
<td>≥ 12 t</td>
<td>ESC; ELR; ETC</td>
</tr>
</tbody>
</table>

ESC: European Steady State Cycle; ETC: European Transient Cycle; ELR: European Load Response test.

1 Applicable to vehicles with at least four wheels and a maximum speed of more than 50 (25) km/h (without driven machines).
2 Without driver.
3 New chassis dynamometer test cycle up to 120 km/h in compliance with Directive 70/220/EEC.
4 Chassis dynamometer test can be performed for M₂ and N₂ vehicles when the reference mass of 2,840 kg is not exceeded.

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**Table 15-7** Development of the limits for gaseous and particulate emissions of commercial vehicles over 3.5 t in the EU

<table>
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<tr>
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<tbody>
<tr>
<td>CO g/kWh</td>
<td>4.5 (4.9)</td>
<td>4.11</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>HC g/kWh</td>
<td>1.1 (1.23)</td>
<td>1.1</td>
<td>0.66</td>
<td>0.46</td>
<td>0.13</td>
<td>0.16</td>
</tr>
<tr>
<td>NMHC g/kWh (gas engines)</td>
<td>0.78</td>
<td>0.55</td>
<td>0.55</td>
<td>0.416</td>
<td>0.416</td>
<td></td>
</tr>
<tr>
<td>NOₓ g/kWh</td>
<td>8.0 (9.0)</td>
<td>7</td>
<td>5</td>
<td>3.5</td>
<td>3.5</td>
<td>2</td>
</tr>
<tr>
<td>PM g/kWh</td>
<td>0.61 (0.68)</td>
<td>0.25</td>
<td>0.13</td>
<td>0.21</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>CH₄ g/kWh</td>
<td>0.36 (0.4)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.16</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>ELR smoke m⁻¹</td>
<td>1.6</td>
<td>1.1</td>
<td>1.1</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
level of the emission limits. This is called the NTE (not-to-exceed) zone (Fig. 15-14).

A dynamic test cycle that includes the different motoring, loading and deceleration phases (Fig. 15-15) has been specified to limit visible emissions (exhaust gas opacity).

### European Test Cycle

Headquartered in Geneva, the UN Economic Commission for Europe (ECE) introduced the first European test cycle (13-mode test) in 1982 as part of its regulation ECE R49, which was in force until Euro III.

The European Union then implemented a new test cycle for Euro III in 1999. Its operating points were determined by taking extensive measurements of in-use driving [15-6]. Engines are tested on the new ESC (European Steady State Cycle) together with the ELR (European Load Response test) at three test speeds and several load points (Fig. 15-16). The test range is determined from the engine’s full load curve (Fig. 15-17). NO\textsubscript{X} emission is measured in three measuring points randomly selected by the approval authority within the test range to validate the homogeneity of the NO\textsubscript{X} map. The ELR limits dynamic particulate emission (Fig. 15-18).

Engines with exhaust gas aftertreatment systems (particulate filters and deNO\textsubscript{X} systems), gas engines and all Euro IV and Euro V engines must be additionally tested on the ETC (European Transient Cycle) derived from the same base of data (Fig. 15-19). Like the US transient test, the ETC is specified on the basis of normalized speed and torque values but it is only run as a hot start test and lasts thirty minutes.

### Table 15-8 Development of the limits for gaseous and particulate emissions of diesel powered commercial vehicles over 3.5 t in the USA and over 2.5 t in Japan

<table>
<thead>
<tr>
<th>Effective date</th>
<th>Test cycle</th>
<th>FTP [g/kWh]</th>
<th>ESC [g/kWh]</th>
<th>D 13 [g/kWh]</th>
<th>JE05 [g/kWh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1998</td>
<td>NO\textsubscript{x}</td>
<td>5.4</td>
<td>4.5</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td>HC</td>
<td>1.7</td>
<td>2.9</td>
<td>0.17</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>CO</td>
<td>20.8</td>
<td>7.4</td>
<td>2.22</td>
<td>2.22</td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>0.13/0.07</td>
<td>0.25</td>
<td>0.027</td>
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</tr>
<tr>
<td>1999</td>
<td>NO\textsubscript{x}</td>
<td>3.35 (NO\textsubscript{x} + HC)</td>
<td>3.38</td>
<td>2.0</td>
<td></td>
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<tr>
<td></td>
<td>HC</td>
<td>20.8</td>
<td>0.87</td>
<td>0.17</td>
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<tr>
<td></td>
<td>CO</td>
<td>0.13/0.07</td>
<td>2.22</td>
<td>2.22</td>
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<tr>
<td></td>
<td>PM</td>
<td></td>
<td>0.18</td>
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<tr>
<td>2004</td>
<td>NO\textsubscript{x}</td>
<td>1.5</td>
<td>1.5</td>
<td>0.7</td>
<td></td>
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<tr>
<td></td>
<td>HC</td>
<td>0.19</td>
<td>0.19</td>
<td>0.17</td>
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<tr>
<td></td>
<td>CO</td>
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<td>20.8</td>
<td>2.22</td>
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<tr>
<td></td>
<td>PM</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
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</tr>
<tr>
<td>2005</td>
<td>NO\textsubscript{x}</td>
<td>0.27</td>
<td>0.27</td>
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<tr>
<td></td>
<td>HC</td>
<td>0.19</td>
<td>0.19</td>
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<tr>
<td></td>
<td>CO</td>
<td>20.8</td>
<td>20.8</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>PM</td>
<td>0.02</td>
<td>0.02</td>
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</tbody>
</table>

USA | Japan
The European regulation ECE-R24 limits visible full load smoke as a function of the theoretical engine air flow rate (Fig. 15-20). Smoke is additionally measured during free engine acceleration from idle to full load to test the effectiveness of the smoke limiter. The certified smoke value is indicated on the engine nameplate and serves as the basis for periodic inspection implemented in some EU countries.
15.2.2.4 Japanese Test Cycle

As in Europe, a steady state 13-mode test (D 13) was originally also implemented in Japan. Its testing points chiefly cover the range of maximum torque and idling (Fig. 15-21). A transient test cycle (JE 05) has been in effect since 2005. Unlike the US-FTP and ETC, it is specified as a vehicle cycle in km/h like that for cars (Fig. 15-22). As in the EU and the USA, the emission test is performed on the engine. Japanese legislation additionally provides a computer program that converts the vehicle cycle into the engine cycle as a function of vehicle type.

![Fig. 15-15](image1)

American smoke test

![Fig. 15-16](image2)

ESC (European Steady State Cycle)
Rated power: $P_N$

Engine operating range Engine speed

Fig. 15-17 Determination of the ESC (European Steady State Cycle) test range

Torque

Fig. 15-18 ELR (European Load Response test)

Fig. 15-19 ETC (European Transient Cycle)
**Fig. 15-20** Swedish smoke limit curves based on ECE-R 24 and A30

**Fig. 15-21** Modes and weighting factors in the Japanese 13-mode cycle (D 13)
15.2.2.5 Worldwide Harmonized Test Cycle (WHDC)

American, European and Japanese test cycles have significantly different operating ranges (Fig. 15-23). For globally operating commercial vehicle manufacturers, the ever stricter and converging limits translate into disproportionately high costs for the development of emission control technology that is identical in principle.

Therefore, prompted by the European commercial vehicle industry, the UN Economic Commission for Europe (ECE)
developed a global test procedure in 1997 for the certification of heavy commercial vehicle engines. This WHDC procedure was adopted as a global technical regulation (gtr No. 4) in 2006 and is intended to harmonize test procedures and measuring equipment worldwide. It will be implemented in Europe with Euro VI in 2012–2013. The cycle was developed from driving data from over 80 vehicles worldwide and is a compromise between European, Japanese and American driving profiles (Fig. 15-24). Thus, it is not representative for specific vehicle usage (e.g. long-distance traffic) but facilitates the development and use of efficient exhaust gas control technology across the entire range.

Like the US-FTP and ETC, the transient test cycle (WHTC) is specified in normalized speed and torque (Fig. 15-25). The main engine speed range has clearly been shifted to lower speeds also found in actual in-use driving. Normalization is now substantially more complex than in the US-FTP and ETC, thus minimizing the risk of cycle bypass. In addition, there is also a steady state test cycle WHSC since the combination of transient and steady state testing has established itself worldwide.

15.2.2.6 New Elements of Emission Control Legislation

Until Euro III was phased out, emission legislation basically only consisted of the test cycle(s) and the respective emission limit(s). Already familiar from passenger cars, OBD (on-board diagnostics) systems became mandatory for commercial vehicles in the EU for the first time as of Euro IV (2005). When a malfunction of an emission-related component is detected, a malfunction indicator informs the driver to find a garage for repairs. The ECE has already formulated a global regulation (WWH-OBD) in this field too. It was adopted as gtr No. 5 in 2006 and is expected to be applied worldwide by 2013–2014.

Another key point of future emission control regulations will be emissions monitoring of customer vehicles in the field (in-use compliance and in-service conformity). Commercial vehicles will be breaking new ground here. Since the test cycle is based on the engine but removing an engine from a vehicle for the test is inexpedient, emission will be measured directly under real vehicle operation with a portable emission measurement system (PEMS). While such regulations were already adopted in the USA in 2008, the technicalities of implementation are currently still being sorted out in the EU and adoption for Euro V vehicles is foreseen in 2010.

15.2.3 Emission Control Legislation for Nonroad Engines

Engines not installed in a road vehicle are referred to as non-road engines. Since this category covers an extremely wide range from small lawnmower engines through large marine diesel engines, the following can only address the most relevant regulations. An ISO committee formulated the standard ISO 8178 [15-7] (see Standards and Guidelines for Combustion

![Fig. 15-24](image-url) Comparison of the frequency of road categories in the USA, EU and Japan WTVC - World-wide Transient Vehicle Cycle
Engines in the appendix) as the basis to establish emission limits for this broad range of applications under the appropriate operating conditions. Specific test cycles are assigned to specific applications (see Table 15-9). Table 15-10 summarizes the relevant test modes and weighting factors.

The standard does not address the emission limits with which these engines must comply. They will be set by regulators and legislation.

15.2.3.1 Stationary Engine Plants: Technical Instructions on Air Quality Control

The German Federal Ambient Pollution Control Act (BImSchV) limits the emissions of stationary combustion engines, e.g. emergency power units, cogeneration plants, combined heat and power stations and the like. Known as TA Luft, the Technical Instructions on Air Quality Control from July 24, 2002 specify the measures for implementing the Federal Ambient Pollution Control Act and provide instructions for practical implementation and examples of existing laws (Table 15-11).

TA Luft has different nitrogen oxide and particulate matter limits for gasoline, diesel and dual fuel engines. An adjustment clause for emissions (e.g. particulate matter, CO, NOx, SO2 [for biogas and sewage gas] and organic substances) exists for some fuels (sewage, biogas and landfill gas). It demands that every option be exhausted to further reduce emissions with measures that reflect state-of-the-art emission control technology (cf. TA Luft 2002). The limits
## Table 15-9 Test cycles for nonroad engines: application ranges

<table>
<thead>
<tr>
<th>Test cycle</th>
<th>Example applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>Off-road diesel engine</td>
</tr>
<tr>
<td>C2</td>
<td>Off-road gasoline engines</td>
</tr>
<tr>
<td>D1</td>
<td>Cruising speed</td>
</tr>
<tr>
<td>D2</td>
<td>Cruising speed</td>
</tr>
<tr>
<td>E1</td>
<td>Marine</td>
</tr>
<tr>
<td>E2</td>
<td>Marine</td>
</tr>
<tr>
<td>E3</td>
<td>Marine</td>
</tr>
<tr>
<td>E4</td>
<td>Marine</td>
</tr>
<tr>
<td>E5</td>
<td>Marine</td>
</tr>
<tr>
<td>F</td>
<td>Rail</td>
</tr>
<tr>
<td>G1</td>
<td>Small engines (lawnmowers and the like)</td>
</tr>
<tr>
<td>G2</td>
<td>Small engines</td>
</tr>
<tr>
<td>G3</td>
<td>Small engines</td>
</tr>
</tbody>
</table>

### Test cycle Example applications

- **C1**: Off-road diesel engine
- **C2**: Off-road gasoline engines
- **D1**: Cruising speed
- **D2**: Cruising speed
- **E1**: Marine
- **E2**: Marine
- **E3**: Marine
- **E4**: Marine
- **E5**: Marine
- **F**: Rail
- **G1**: Small engines (lawnmowers and the like)
- **G2**: Small engines
- **G3**: Small engines

### Example applications
- **Construction equipment, agricultural equipment, material transport**
- **Construction equipment, agricultural equipment, material transport**
- **Power plants, irrigation pumps**
- **Gas compressors, generators**
- **Ships with diesel engines less than 24 m in length**
- **Oceangoing ships with constant speed**
- **Oceangoing ships with propeller curve**
- **Sport boats with gasoline engines less than 24 m in length**
- **Ships with diesel engines less than 24 m in length (propeller curve)**
- **Locomotives, railcars, switch engines**
- **Intermediate speed applications**
- **Rated speed applications**
- **Handheld equipment**

## Table 15-10 Test cycles for nonroad engines: operating modes and weighting factors

<table>
<thead>
<tr>
<th>Rated speed</th>
<th>Intermediate speed</th>
<th>Idle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque/power* [%]</td>
<td>Torque/power* [%]</td>
<td>Torque/power* [%]</td>
</tr>
<tr>
<td>Type</td>
<td>100</td>
<td>75</td>
</tr>
<tr>
<td>C1</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>C2</td>
<td>0.30</td>
<td>0.50</td>
</tr>
<tr>
<td>D1</td>
<td>0.05</td>
<td>0.25</td>
</tr>
<tr>
<td>E1</td>
<td>0.08</td>
<td>0.11</td>
</tr>
<tr>
<td>E2</td>
<td>0.20</td>
<td>0.50</td>
</tr>
<tr>
<td>*E3</td>
<td>0.20</td>
<td>0.50</td>
</tr>
<tr>
<td>*E4</td>
<td>0.06</td>
<td>0.14</td>
</tr>
<tr>
<td>*E5</td>
<td>0.08</td>
<td>0.20</td>
</tr>
<tr>
<td>F</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>G1</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td>G2</td>
<td>0.09</td>
<td>0.20</td>
</tr>
<tr>
<td>G3</td>
<td>0.09</td>
<td>0.20</td>
</tr>
</tbody>
</table>

* Values for test cycles E3, E4 and E5 are power values. The values for the other test cycles are torque values.
are based on an exhaust gas oxygen content of 5% by volume.

According to VDI 2066, particulate matter emissions must be measured close to the point of emission, i.e. in the hot exhaust gas, while measurement of particulate emission mandated for commercial vehicle engines and nonroad mobile machinery is based on diluting the exhaust gas.

The thermal outputs (P_{th} in MW_{th}) specified in Table 15-11 are based on the overall fuel flow rates of the specific systems.

### 15.2.3.2 Nonroad Mobile Machinery and Agricultural and Forestry Tractors

Nonroad mobile machinery (NRMM) encompasses such applications as front loaders, excavators, forklifts, road construction equipment, etc. The C1 cycle is applied to diesel engines implemented in these applications. In keeping with the aforementioned principle of transient and steady state testing, the USA and the EU intend to introduce a transient cycle (NRTC) for these engines in addition to the C1 cycle as of 2011. The NRTC is also the basis for a newly developed global technical regulation (GTR) set to be adopted in 2009.

The emission limits are specified as a function of engine power. After long negotiations, test cycles and limits have largely been harmonized worldwide. The limits specified in Table 15-12 apply to engines in nonroad mobile machinery and agricultural and forestry tractors [15-8, 15-9].

### 15.2.3.3 Marine Engines


The European Commission also extended the scope of its emissions Directive 97/68/EC to inland marine engines in the amendment 2004/26/EC. Since their levels of technology are virtually identical, mutual recognition of EU and ZKR directives is assured.
Table 15-12  Limits for engines in nonroad mobile machinery NRMM

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<td>Power (kW)</td>
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<td>&gt; 560</td>
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<td>130 = &lt; 560</td>
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<td>19 = &lt; 37</td>
<td>NOx + HC: 9.5 / PM: 0.4</td>
<td>NOx + HC: 7.5 / PM: 0.6</td>
<td>NOx + HC: 7.5 / PM: 0.3</td>
<td>NOx + HC: 4.7 / PM: 0.03</td>
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<td>8 = &lt; 19</td>
<td>NOx + HC: 9.5 / PM: 0.8</td>
<td>NOx + HC: 7.5 / PM: 0.8</td>
<td>NOx + HC: 7.5 / PM: 0.40</td>
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<td>&lt; 8</td>
<td>NOx + HC: 10.5 / PM: 1.0</td>
<td>NOx + HC: 7.5 / PM: 0.8</td>
<td>NOx + HC: 7.5 / PM: 0.40</td>
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<tr>
<td>130 = &lt; 560</td>
<td>NOx: 6.0 / PM: 0.2</td>
<td>Oct 06</td>
<td>NOx: 3.6 / PM: 0.17</td>
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<tr>
<td>75 = &lt; 130</td>
<td>Oct 2003</td>
<td>NOx: 6.0 / PM: 0.3</td>
<td>Oct 07</td>
<td>NOx: 3.6 / PM: 0.2</td>
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<tr>
<td>56 = &lt; 75</td>
<td>Oct 2003</td>
<td>NOx: 7.0 / PM: 0.4</td>
<td>Oct 08</td>
<td>NOx: 4.0 / PM: 0.25</td>
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<tr>
<td>37 = &lt; 56</td>
<td>Oct 2003</td>
<td>NOx: 7.0 / PM: 0.4</td>
<td>Oct 08</td>
<td>NOx: 4.0 / PM: 0.3</td>
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<tr>
<td>19 = &lt; 37</td>
<td>Oct 2003</td>
<td>NOx: 8.0 / PM: 0.8</td>
<td>Oct 07</td>
<td>NOx: 6.0 / PM: 0.4</td>
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The IMO (International Maritime Organization) imposed limits on NOx emissions for marine diesel engines with power outputs >130 kW as of January 1, 2000 (Table 15-14 [15-10] and Fig. 15-26). It plans to later adapt the limits determined from the test cycles dependent on use (main propulsion or auxiliary engine) and the mode of operation (constant speed or propeller drive) specified in Fig. 15-27 to its technical program and environmental policies.

Sweden has been charging emission-related harbor fees based on the IMO Code since January 1, 1998 [15-11]. However, the incentive to use emission reducing exhaust gas after-treatment largely failed because of the imbalance between the additional operating costs and the potential reductions in fees.

### Table 15-13 RheinSchUO emission limits for inland waterway engines as a function of rated power \( P_N \) and rated speed \( n_N \)

<table>
<thead>
<tr>
<th>Level I</th>
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<tbody>
<tr>
<td>Rated power ( P_N ) [kW]</td>
<td>CO [g/kWh]</td>
<td>HC [g/kWh]</td>
<td>NOx [g/kWh]</td>
<td>PM [g/kWh]</td>
</tr>
<tr>
<td>37 ( \leq P_N &lt; 75 )</td>
<td>6.5</td>
<td>1.3</td>
<td>9.2</td>
<td>0.85</td>
</tr>
<tr>
<td>75 ( \leq P_N &lt; 130 )</td>
<td>5.0</td>
<td>1.3</td>
<td>9.2</td>
<td>0.70</td>
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<tr>
<td>( P_N \geq 130 )</td>
<td>5.0</td>
<td>1.3</td>
<td>( n_N \geq 2,800 ) rpm = 9.2 &amp; ( 500 \leq n_N &lt; 2,800 ) rpm = 45 ( n_N^{-0.2} ) &amp; 0.54</td>
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<th>Level II</th>
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<tbody>
<tr>
<td>( P_N ) [kW]</td>
<td>CO [g/kWh]</td>
<td>HC [g/kWh]</td>
<td>NOx [g/kWh]</td>
<td>PM [g/kWh]</td>
</tr>
<tr>
<td>18 ( \leq P_N &lt; 37 )</td>
<td>5.5</td>
<td>1.35</td>
<td>8.0</td>
<td>0.8</td>
</tr>
<tr>
<td>37 ( \leq P_N &lt; 75 )</td>
<td>5.0</td>
<td>1.3</td>
<td>7.0</td>
<td>0.4</td>
</tr>
<tr>
<td>75 ( \leq P_N &lt; 130 )</td>
<td>5.0</td>
<td>1.0</td>
<td>6.0</td>
<td>0.3</td>
</tr>
<tr>
<td>130 ( \leq P_N &lt; 560 )</td>
<td>3.5</td>
<td>1.0</td>
<td>6.0</td>
<td>0.2</td>
</tr>
<tr>
<td>( P_N \geq 560 )</td>
<td>3.5</td>
<td>1.0</td>
<td>( n_N \geq 3,150 ) rpm = 6.0 &amp; ( 343 \leq n &lt; 3,150 ) rpm = 45 ( n_N^{-0.2} ) = 3 &amp; ( n &lt; 343 ) rpm = 11.0 &amp; 0.2</td>
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</table>

### Table 15-14 IMO emission limits for marine diesel engines with a power of 130 kW and up

<table>
<thead>
<tr>
<th>Rated speed ( n_N ) in rpm</th>
<th>NOx emission in g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 0 \leq n_N \leq 130 )</td>
<td>17</td>
</tr>
<tr>
<td>( 130 &lt; n_N \leq 2,000 )</td>
<td>45 ( n_N^{-0.2} )</td>
</tr>
<tr>
<td>( n_N &gt; 2,000 )</td>
<td>9.8</td>
</tr>
</tbody>
</table>

### 15.3 Pollutants and Their Production

Apart from the desired heat energy, the only products produced by ideal combustion of hydrocarbons (HC) in an engine are water (H\(_2\)O) and carbon dioxide (CO\(_2\)), their mass ratio being a function of the fuel’s H:C ratio. Both diesel fuel and gasoline may be specified with the empirical formula \( C_xH_y \).

An ideal stoichiometric combustion process yields:

\[
C_xH_y + \left( x + \frac{y}{4} \right) O_2 \rightarrow x \cdot CO_2 + \frac{y}{2} \cdot H_2O. \tag{15-1}
\]

The water produced is environmentally harmless. CO\(_2\) is nontoxic but contributes significantly to the greenhouse effect. Lowering the specific fuel consumption (\( b_o \)) reduces CO\(_2\) emissions during engine combustion.

Combustion does not proceed ideally in gasoline or diesel engines and it produces other byproducts, which are in part harmful to the environment. Incomplete combustion during homogeneous gasoline engine operation (\( \lambda = 1 \)) not only produces nitrogen oxides (NO\(_x\)) and unburned hydrocarbons (HC) but also chiefly carbon monoxide (CO) as pollutants. Combustion is incomplete because the flame front quenches on the cold combustion chamber wall or in squish gaps. Inhomogeneous combustion cycles where \( \lambda > 1 \), typical diesel engine combustion and stratified operation of direct injection gasoline engines produce another pollutant, soot (Fig. 15-28).
Fig. 15-26  IMO limit curve for the NOx emissions of marine diesel engines with $P_n > 130$ kW and test results based on CLEAN

Fig. 15-27  IMO test cycles for marine engines according to ISO 8178
The main advantages of diesel engines – lower fuel consumption and high torque at low speed – especially unfold in direct injection turbocharged engines. Their combustion systems are characterized by locally strongly fluctuating air/fuel ratios. There is a deficiency of air ($\lambda \ll 1$) inside the individual flames that form around the injection sprays. There is an excess of air ($\lambda \gg 1$) between injection sprays and on the combustion chamber wall. Soot is produced in the air deficient regions. Nitrogen oxides are chiefly produced directly behind the locally extremely hot flame front. Thus, the production of the two main pollutants during diesel engine combustion is directly connected with the combustion system.

Diesel engine development remains focused on continually reducing these pollutants while continually lowering fuel consumption and optimizing performance at the same time [15-12]. Before emission reduction measures in and downstream from the engine are described in Sects. 15.4 and 15.5 (exhaust gas aftertreatment), the production of the different pollutants is treated in detail below.

### 15.3.1 Nitrogen Oxides (NO\(_x\))

Of the different nitrogen oxides (NO, NO\(_2\), N\(_2\)O, N\(_2\)O\(_3\), N\(_2\)O\(_5\)), only the compounds NO and NO\(_2\) (nitrogen monoxide and nitrogen dioxide) are produced in appreciable quantities and the designation NO\(_x\) (nitrogen oxides) is frequently employed as shorthand for the total NO and NO\(_2\).

The most important mechanism for the production of NO\(_x\) is the formation of thermal NO. It was described for the first time by Zeldovich in 1946 [15-13]. Specifically, the following elementary reactions occur:

\[
\begin{align*}
O_2 & \Leftrightarrow 2 \cdot O & (15-2) \\
N_2 + O & \Leftrightarrow NO + N & (15-3) \\
O_2 + N & \Leftrightarrow NO + O & (15-4) \\
OH + N & \Leftrightarrow NO + H & (15-5)
\end{align*}
\]

Equations (15-3) and (15-4) describe the Zeldovich chain reaction: When elementary oxygen (O) is present, N\(_2\) produces NO and N. The molecular nitrogen (N) formed reacts with O\(_2\) in the following step to become NO and O. This completes the cycle and the reaction chain begins all over again. Equation (15-5) describes the formation of NO in fuel-rich zones like those located behind the flame front.

The presence of atomic oxygen, which forms from molecular oxygen at temperatures above 2,200 K (see Eq. (15.2)), is the basic condition for the start of the Zeldovich reactions that follow Eqs. (15-3) and (15-4). Thus, one prerequisite for the formation of NO is peak temperatures, explicitly, local peak temperatures, not mean combustion chamber temperatures. The second prerequisite for the formation of NO is the presence of excess oxygen, i.e. local excess air [15-13].
Ideal conditions for the formation of NO\(_X\) are present in gasoline engines when \(\lambda = 1.1\). The maximum concentration of NO\(_X\) in diesel engine exhaust gas shifts toward a somewhat higher air/fuel ratio. The concentrations of the different pollutants are plotted as a function of the air/fuel ratio \(\lambda\) in Fig. 15-28 [15-14]. The curve of the NO\(_X\) concentration rises continuously as \(\lambda\) drops. This can be attributed to the increasing exhaust gas temperature. Despite the diminishing oxygen content, the increasing process temperature facilitates an increase in the NO\(_X\) concentration up to a value of \(\lambda = 2\). When the exhaust gas temperature continues to increase, free oxygen is no longer sufficiently available below \(\lambda = 2\). The gradient of the NO\(_X\) concentration decreases as a function of the air/fuel ratio and a local maximum is produced.

Zeldovich reactions are equilibrium reactions. Their equilibrium parameters are established as a function of temperature. However, engine combustion processes are so rapid that the equilibrium concentrations are usually not obtained and the actual NO\(_X\) concentrations are below what would be obtained at thermal equilibrium. On the other hand, the drop in combustion chamber temperature during the expansion phase causes reverse reactions to “freeze” according to Eqs. (15-3) and (15-4). NO no longer reforms significantly below approximately 2,000 K. As a result, the NO\(_X\) concentrations in the actual exhaust gas are above the equilibrium concentrations. Consequently, NO\(_X\) emissions cannot be predicted by equilibrium reactions alone. They can only be predicted with the aid of the reaction kinetics and by incorporating the time sequence of the combustion that actually occurs.

The process sequence can strongly influence NO\(_X\) emissions in diesel engines. Thus, the combustion temperature may be limited by cooling the charge air and recirculated exhaust gas as well as by retarding injection and combustion after TDC. Exhaust gas recirculation lowers the oxygen supply and, thus, directly reduces the formation of NO\(_X\). At the same time, the lower oxygen concentration reduces the rate of combustion, which in turn limits the local peak temperatures. The higher specific heat capacity of the triatomic gases (CO\(_2\) and H\(_2\)O) in the recirculated exhaust gas further reduces the local peak temperatures during exhaust gas recirculation. Different engine processes that reduce NO\(_X\) emissions are discussed in detail in Sect. 15.4.

NO\(_2\) makes up 1–10\% of the total NO\(_X\) emissions in gasoline engines and 5–15\% in diesel engines. Higher concentrations are also detectable in the lower part load range at correspondingly low exhaust gas temperatures [15-14]. In an engine, NO\(_2\) forms from NO by reacting with HO\(_2\) and OH radicals. The most probable equation is:

\[
\text{NO} + \text{HO}_2 \rightleftharpoons \text{NO}_2 + \text{OH} \quad (15-5a)
\]

At ambient temperature, the chemical equilibrium for NO\(_2\) is virtually complete. When there is incident light, NO reacts in the atmosphere with ozone to become NO\(_2\). Equilibrium is established after a few hours to days, depending on the ambient conditions.

Other mechanisms of NO formation such as prompt NO from the reaction of N\(_2\) with fuel radicals, NO from fuel-based nitrogen or the formation of NO from N\(_2\)O tend to be of secondary importance for diesel engine combustion.

### 15.3.2 Particulate Matter (PM)

According to the statutory test specifications, a vehicle’s particulate matter emissions are the total mass of solids and attached volatile or soluble constituents. The test conditions are defined precisely: an exhaust gas sample is diluted with filtered ambient air and cooled to a maximum of 52°C [15-15]. The particulate matter is separated onto a defined and conditioned sample holder and the total mass is determined by weighing under defined conditions.

Figure 15-29 presents the typical composition of particulate matter [15-16]. The particulates mainly consist of soot, i.e. of elementary carbon. This is addressed in more detail.
below. Organic compounds consisting of unburned hydrocarbons that may stem from the lubricating oil or the fuel itself constitute the second largest fraction. The dew point of numerous hydrocarbons is fallen below under the aforementioned conditions for particulate matter sampling and weighing: the compounds condense and bond to the solid cores.

The particulates' sulfate fraction is basically determined by the sulfur content of the fuel and the engine oil. During combustion, the sulfur oxidizes into SO$_2$ and, at exhaust gas temperatures above 450°C, into SO$_3$. The latter oxidation process can also be facilitated by downstream exhaust gas aftertreatment in an oxidation catalytic converter [15-17]. Interaction with water causes the formation of sulfate ions to produce sulfuric acid (H$_2$SO$_4$), which condenses on the particulates in the cooled exhaust gas. Metal oxides are produced as products of lubricating oil or fuel additives and are only present in particulate emissions in traces. These oxides can assume a significant proportion of the particulate mass when an additive is blended into fuel for particulate filter regeneration.

The composition of particulate matter presented in Fig. 15-29 corresponds to the mean value of measurements in various cars and can vary greatly depending on vehicle operation and type. Thus, a commercial vehicle engine run at high load has a larger fraction of elementary carbon. The fraction of hydrocarbons in cars operated at part load can significantly exceed the value presented in Fig. 15-29.

Soot constitutes the largest fraction of particulate matter relative to mass. This fraction can be controlled by engine measures described in more detail below. Soot is generally produced in air deficient zones. In older model prechamber engines, these zones include wall films in which fuel coking partly produces large soot particulates [15-18], which then become visible in the exhaust gas. The particulates in modern direct injection diesel engines are usually significantly smaller and consequently no longer visible in the exhaust gas. The production processes also differ distinctly. Two hypotheses of soot production exist and are presented here in greatly simplified form [15-19]:

15.3.2.1 Elementary Carbon Hypothesis

This hypothesis assumes that the fuel dissociates at high combustion temperatures, i.e. breaks down into its basic elements of carbon and hydrogen. Hydrogen molecules diffuse in the oxygen-containing environment significantly faster than larger carbon atoms. Their quadruple valences enable them to form clusters, primarily hexagonal and pentagonal structures, very quickly when they are deoxygenated. Curved shells form and grow to typical particulate sizes of approximately 10 nm within milliseconds.

15.3.2.2 Polycyclic Hypothesis

This hypothesis assigns critical importance to ethyne (formerly known as acetylene C$_2$H$_2$). Ethyne is formed by pyrolysis – the decomposition of fuel under O$_2$ exclusion – of aliphatics and aromatics while cleaving hydrogen. Assuming the structure is polycyclic, repeated bonding of ethyne molecules can cause a graphitic structure to grow [15-20]. Advanced growth through repeated ethyne bonding is number 1 in Fig. 15-30. The occasionally quintuple rings curve the macromolecules produced. Several of these molecules accrete in layers atop one another, producing primary particulates. Figure 15-30 depicts the formation process. The primary particulates produced typically have a size of 2–10 nm.

![Formation of soot particles according to Siegmann (based on [15-21]).](image)
According to both hypotheses of formation, primary particulates with diameters of less than 10 nm form first, are approximately spherical and have a density of 1.8 g/cm$^3$. These primary particulates subsequently agglomerate into the actual soot particulates, the individual particulates continually adhering to one another. Some SEM micrographs of typical agglomerates are pictured in Fig. 15-31. Very loose agglomerates only have a density of 0.02–0.06 g/cm$^3$ [15-21].

The bonding of highly mobile primary particulates causes the agglomerates to grow very rapidly at first. However, as the concentration of primary particulates decreases and the mobility of larger agglomerates diminishes [15-22], their growth in size decreases and a typical agglomerate size distribution appears. The size distribution is quite uniform even for different engines and is normally a log-normal distribution with a value of approximately 80–100 nm. Figure 15-32 presents the size distributions of particulate emissions of different vehicles at a constant operating point corresponding to a vehicle speed of 100 km/h [15-23]. The absolute number of particulates corresponds to the different emissions of the vehicles in the operating point and displays fluctuations that are three times as large in the maximum. However, the shape of the distribution and the position of the maximum are virtually independent of the vehicle and considered characteristic of all modern combustion systems.

A majority of the soot produced during combustion oxidizes while still in the combustion chamber. This afterburning takes place at temperatures above 1,000 K as soon as the combustion gases mix with the remaining fresh air, i.e. when
sufficient oxygen is available again. Unlike in gasoline engines, the mixture temperature in lean burn diesel engines rapidly drops below a critical value during the expansion phase and post-oxidation is frozen. The remaining particulates are discharged and can only be eliminated by exhaust gas aftertreatment with a particulate filter (see Sect. 15.5) [15-17].

15.3.3 Carbon Monoxide (CO)

Carbon monoxide (CO) emissions from diesel engines are normally very low and only increase during a conventional combustion process when the stoop limit is approached. The remaining area of the map contains sufficient oxygen to completely oxidize the fuel. However, the prerequisite for this is good intermixing of the partially burned gases with the remaining fresh air at sufficiently high temperatures. Prechamber engines have particularly low CO emissions because of their intensive mixture turbulence during the flow from the prechamber into the main combustion chamber [15-18]. Modern combustion systems have swirl and/or squish flows, which help support air side mixture formation. Adjusting the combustion chamber air flow, the combustion chamber geometry and the injection geometry to one another minimizes CO emissions. The entire map must be optimized, paying particular attention to the lower part load range since lower temperatures cause the post-oxidation of CO to come to a standstill earlier [15-24]. In some engines, one of the charge ports is closed in this range to promote swirl, i.e. air side mixture formation.

The latest studies [15-24] have demonstrated that the fraction of CO from the rich spray core in the total CO emissions is low. The temperature in this range is high enough to assure that CO completely oxidizes to CO$_2$ when it is mixed with air after the end of combustion.

15.3.4 Hydrocarbons (HC)

Diesel engines may emit unburned hydrocarbons (HC) when inadequately prepared fuel reaches regions where the temperature no longer suffices for combustion. Such conditions exist in the lower part load range when there is substantial excess air. The function of an injection system is to prepare the fuel by atomizing it well so that it can evaporate completely even at low temperatures.

Locally very rich mixture zones can be other sources of HC emissions, e.g. when fuel sprays strike the combustion chamber wall. Complete evaporation cannot be assured during cold start and HC emissions increase. Misfires similar to the combustion of leaner mixtures in gasoline engines are usually not observed in diesel engines since direct injection always establishes a range with approximately stoichiometric mixing and thus with ideal conditions for auto-ignition.

Fuel contained in the nozzle holes and the injection nozzle’s sac hole after the end of injection is a further source of HC emissions. This fuel evaporates during the expansion phase at temperatures far below the limit necessary for oxidation and is forced into the exhaust system unburned. This source of HC emissions has been reduced significantly in recent years by minimizing the volume of the sac hole [15-25].

An oxidation catalytic converter (see Sect. 15.5) can further reduce both hydrocarbons and carbon monoxide [15-17].

15.4 In-Engine Measures for Pollutant Reduction

The optimization of diesel engines generally entails a conflict of objectives between fuel consumption and emission reduction. Only a few additional measures allow simultaneously optimizing both parameters and a solitary measure is seldom able to simultaneously reduce every legally limited pollutant in equal measure. Fine tuning an engine requires a compromise. Other important parameters for engine tuning are comfort (noise) and engine dynamics. Since the impact of some measures is limited to certain ranges of the map and can reverse in other ranges, one challenge is tuning the engine in the entire map – for the entire speed range at different loads.

The numerous optimization parameters are weighted according to the legal requirements for pollutants and according to customer demand when the objectives of comfort and fuel consumption conflict. Thus, for example, combustion noise is increasingly receiving attention as a parameter for cars engines. Fuel consumption is generally the crucial parameter for customer utility in commercial vehicles with high mileage. Of course, the costs must be considered for every engine type in order to be able to offer a competitive product.

Table 15-15 provides an overview of different, currently common methods to optimize engines and their influence on pollutant emissions as well as specific fuel consumption and combustion noise. The principal correlations are identical for all vehicle types. Only the weighting changes according to market requirements. Thus, the different measures always have to be reevaluated on an individual basis. An advanced DI combustion system provides the basis for evaluation.

No one measure affects every parameter positively. Frequently, a combination of several measures is required to compensate a detrimental effect. Thus, for example, an increase in injection pressure only has a positive effect on NO$_x$ emissions when it is combined with exhaust gas recirculation. Selected measures are discussed in detail below.

15.4.1 Start of Injection

The start of injection was the first parameter of diesel engine injection on which influence could be systematically exerted as a function of the operating point. Some distributor injection pumps were already able to control the start of injection,
initially mechanically and later by an electrically actuated solenoid valve.

Figure 15-33 visualizes the importance of the start of injection for engine emissions. The NO\textsubscript{X} and PM emissions are plotted for different starts of injection, the crank angle of 0° (0° CA) denoting top dead center. The steady rise of particulate emissions and the continuous drop of NO\textsubscript{X} emissions are clearly discernible. The measurements are based on a commercial vehicle engine at mean load and 1,425 rpm.

Figure 15-34 presents the cylinder pressure curves measured during engine operation for four starts of injection selected from Fig. 15-33. The rise in pressure after top dead center (TDC) indicates the start of combustion. The pressure rises more steeply when the start of injection is advanced than when injection and combustion are long after TDC. The flatter rise in pressure in retarded combustion can be attributed to the continuing expansion. On the one hand, it directly limits the rise in pressure. On the other hand, the expansion causes combustion chamber temperatures to drop and thus combustion to proceed more slowly. The pressure curves also allow the inference that the peak temperatures occurring in the cylinders will also be lower when the start of injection is retarded since the heat generated by slower combustion has more time to disperse from the zone of direct combustion. As explained in Sect. 15.3.1, not only the oxygen supply but also the local peak temperature is a crucial parameter for the formation of NO\textsubscript{X}. Thus, the decreasing NO\textsubscript{X} emissions (Fig. 15-33) when the start of injection is retarded can be explained by the cylinder pressure curves in Fig. 15-34.

<table>
<thead>
<tr>
<th>Measure</th>
<th>NO\textsubscript{X}</th>
<th>HC/CO</th>
<th>Soot</th>
<th>bsfc</th>
<th>Noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retarded start of injection</td>
<td>+</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>+</td>
</tr>
<tr>
<td>Exhaust gas recirculation</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Cooled EGR</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Supercharging</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Intercooling</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Pilot injection</td>
<td>0</td>
<td>+</td>
<td>−</td>
<td>0</td>
<td>+</td>
</tr>
<tr>
<td>Added post-injection</td>
<td>+</td>
<td>0</td>
<td>+</td>
<td>−</td>
<td>0</td>
</tr>
<tr>
<td>Injection pressure increase</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Lower compression ratio</td>
<td>+</td>
<td>−</td>
<td>+</td>
<td>0</td>
<td>−</td>
</tr>
</tbody>
</table>

Symbols: +: reduction; −: increase; 0: no change

**Fig. 15-33**
Influence of the start of injection on PM- and NO\textsubscript{X} emissions of a commercial vehicle engine at 1,425 rpm and mean load
An increase in particulate matter when the start of injection is retarded is discernible in Fig. 15-33. This is a typical example of the aforementioned conflicts of objectives when every emission parameter is minimized. The increase in particulate matter applies to the majority of the map with the exception of the low load ranges and is caused by the decrease in the quality of mixture preparation as mixture density decreases and the reduced post-oxidation of the particulates due to lower temperatures in the combustion chamber.

A decrease in particulate emissions when the start of injection is retarded is also observable in the lower load range because the temperatures in the combustion chamber drop. This prevents particulates from forming at all [15-24]. However, a significant increase in the CO and HC emissions as well as fuel consumption must be accepted in this case. Thus, this strategy to simultaneously reduce NOX and particulates can only be implemented to a certain extent.

Furthermore, the retarded start of injection affects brake specific fuel consumption adversely (not represented here). The consumption disadvantage can also be inferred from the cylinder pressure curves in Fig. 15-34. The rapid combustion near TDC when the start of injection is advanced resembles isochoric combustion that is optimal for consumption, while a convergence with isobaric combustion when injection is retarded worsens consumption.

15.4.2 Injection Pressure

Technical advances since the introduction of direct injection diesel engines have steadily increased the maximum injection pressure [15-25]. Figure 15-35 presents the influence of injection pressure on NOX and PM emissions (the parameter black smoke (SN) being specified here) and brake specific fuel consumption $b_{fs}$ for a car engine’s part load point at 50% load and $n = 1,400$ rpm.

The rise in brake specific fuel consumption for the retarded start of injection discussed above is recognizable for every injection pressure in the lower portion of the figure. A significantly more retarded start of injection without any disadvantage in fuel consumption can be set when injection pressures are higher than when they are lower. In this example, the minimum brake specific fuel consumption shifts from $–19^\circ$CA at 500 bar injection pressure to $–12^\circ$CA at 1,100 bar injection pressure because the duration of injection is shorter – since the injection rate increases with the injection pressure – and the quality of the mixture preparation improves as the injection pressure increases. Thus, the position of the center of combustion, which essentially determines brake specific fuel consumption, can be kept approximately constant.

The crucial advantage of higher injection pressure is evident in the clearly reduced particulate emission – the smoke number SN – in the center section of Fig. 15-35. When the start of injection is constant, soot emissions decrease significantly as injection pressures increase. An increase as injection pressure increases is only observable when the starts of injection are retarded considerably. Once again, the reason is the improved mixture preparation. On the one hand, less soot is produced because atomization improves at a higher injection pressure. On the other hand, the higher energy of mixture formation facilitates post-oxidation.
However, a higher injection pressure as a function of higher local peak temperatures affects NO\textsubscript{X} emissions adversely. When the start of injection is constant, NO\textsubscript{X} emissions increase significantly as injection pressures increase. On the other hand, any comparison of NO\textsubscript{X} emissions becomes relative when brake specific fuel consumption is constant (e.g. at minimum brake specific fuel consumption, NO\textsubscript{X} emissions have roughly constant values of approximately 16 g/kWh for 500 bar injection pressure at −19°CA and for 1,100 bar injection pressure at −12°CA). Combining increased injection pressure with exhaust gas recirculation (see Sect. 15.4.3) can significantly reduce NO\textsubscript{X} emissions. This strategy has its limits though. Further elevation of the pressure fails to generate any further advantages above an upper limit on injection pressure, which is dependent on the combustion system and load point.

15.4.3 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) is now employed in cars everywhere as an important means to reduce NO\textsubscript{X}. The exhaust gas recirculation rate $x_{\text{AGR}}$ is defined as the ratio of the recirculated exhaust gas mass flow to the total mass flow in the intake tract:

$$x_{\text{AGR}} = \frac{m_{\text{AGR}}}{m_{\text{AGR}} + m_{\text{Luft}}}$$  \hspace{1cm} (15-6)

It may be as much as 50% in state-of-the-art combustion systems and is controlled by an electrically or pneumatically activated valve. A hot film air-mass flowmeter determines the mass of the fresh air.

Figure 15-36 presents the influence of exhaust gas recirculation on brake specific fuel consumption, noise and HC and PM emission as a function of the NO\textsubscript{X} emissions. The measured NO\textsubscript{X} emissions were selected as the abscissa and the other parameters were plotted on the ordinates in the individual graphs as dependent values. The experimentally determined individual points came from varying the EGR rate. The typical PM-NO\textsubscript{X} trade-off hyperbolae in the lower right graph are produced as a function of the EGR rate. Two different injection pressures were investigated. The EGR rate rises from right to left in each of the individual graphs, from 0% to the maximum value of 40%.

A continuous reduction of NO\textsubscript{X} emissions as the EGR rate increases is identifiable for both injection pressures in all the graphs. Slower combustion, retarded timing of the start of combustion by prolonging the ignition delay time and enlarged specific heat capacity through the higher percentage of triatomic gases (inert gas) in the cylinder charge all reduce the maximum local peak temperature and thus NO\textsubscript{X} emissions. The influence of the EGR rate on HC emissions turns out to be quite slight in the engine tested here. On the other hand, an increase in both PM emission and brake specific fuel consumption are recognizable in the two lower graphs. Slower combustion and thus the shift of the position of the center of combustion toward retardation cause the increase in fuel consumption. The limitation of the oxygen necessary for soot oxidation is also a primary reason for the higher soot emissions. The oxygen content reduced by EGR always acts to reduce NO\textsubscript{X} emissions and increase soot emissions. The hyperbolae produced in the lower right graph are characteristic of the conflicts of objectives when optimizing diesel engines.

Discussed in Sect. 15.4.2, the increase in NO\textsubscript{X} emissions when injection pressure is increased without other measures is also discernible in Fig. 15-36. The circled points denote the
experiments in which emissions without EGR were measured. The increase in NO\textsubscript{X} emissions with the injection pressure is clearly recognizable. The PM emissions clearly exhibit lower values.

When the EGR rate is increased, the curve of the PM-NO\textsubscript{X} trade-off for 800 bar injection pressure is clearly below the trade-off for 600 bar. This effect is called enhanced EGR compatibility. Since the energy of mixture formation is predominantly obtained from the injection spray, increasing the EGR rate can reduce \textit{O\textsubscript{2}} more substantially without increasing PM emissions too much. However, these approaches are subject to limits that are dependent on the combustion system.

The straight line in the lower right graph in Fig. 15-36 denotes a 10:1 ratio of NO\textsubscript{X} emissions to PM emissions. This corresponds to typical Euro 4 car application engineering since the legally mandated emission limits have exactly this ratio. The trade-offs’ intersections with the straight line indicate that an increase of injection pressure from 600 to 800 bar reduces NO\textsubscript{X} and PM emissions by approximately 35%. A roughly 3\% reduction of the specific fuel consumption for this operating point is recognizable in the lower left graph.

An increase in injection pressure solely has an adverse effect on noise (upper left graph). The increase in noise can be attributed to the large mass of fuel injected during injection delay, which burns virtually instantaneously at the start of combustion. When the EGR rate is constant, the chemical ignition delay is constant and the physical ignition delay is slightly reduced by the smaller droplets. However, the effect of the higher injection rate outweighs this at higher injection pressure.

The following discusses the most important in-engine measure to reduce combustion noise, i.e. pilot injection.

15.4.4 Pilot Injection

Pilot injection (PI) has established itself as an effective measure to reduce noise in DI diesel engines. Small quantities of fuel (1–3 mm\textsuperscript{3} per injection) are injected in a short time interval before the main injection. This small quantity typically starts to combust shortly before TDC, resulting in an increase of temperature and pressure in the combustion chamber before the start of the main injection. Figure 15-37 presents typical cylinder pressure curves for a part load point with different pilot injected fuel quantities at a constant ratio of soot to NO\textsubscript{X} of 1:10.

The lower portion of the graph represents the stroke of the injector needle. The pilot injected fuel quantity is the parameter for the different curves. The prolongation of the duration of the pilot injection as the pilot injected fuel quantity increases is evident. The duration of the main injection is shortened accordingly to keep the load set on the test bench constant.

The black curve in the upper portion of the graph represents the pressure curve measured in the cylinder during operation without pilot injection. This pressure curve corresponds to that of a motored engine (motored curve) until the start of combustion of the main injection (approximately 12°CA after TDC). The steep rise in pressure at the start of combustion until approximately 15°CA after TDC causes undesired high noise emission. Pressure oscillations after the end of combustion are artifacts attributable to the method of measurement.

The three curves of differing grays were determined with differently sized pilot injected fuel quantities. The start of the control of the main and pilot injection was kept constant. The
The start of pilot injection combustion is discernible in the increase in pressure at approximately 12°CA before TDC where the pressure curve begins to deviate significantly from the motored curve. A local pressure maximum is reached at approximately TDC in each case. The absolute value is a function of the parameter of the pilot injected fuel quantity and increases with it.

The cylinder pressures and temperatures that increase when the pilot injected fuel quantity increases shorten the chemical ignition delay for the main injected fuel quantity. This is indicated in Fig. 15-37 by the increase in pressure, which characterizes the start of main injection combustion (6–12°CA after TDC), and moves closer and closer after TDC as pilot injected fuel quantities increase. The gradient of the increase in pressure of the main injection always grows smaller as pilot injected fuel quantities increase – at approximately constant maximum pressure in this example. The reasons have already been discussed: a shorter ignition delay decreases the quantity of fuel injected during the ignition delay. The rapid combustion of this fuel quantity at the start of combustion affects the increase in pressure and the combustion noise. Therefore, the cylinder pressure gradient is a measure of the level of combustion noise.

The influence of the pilot injected fuel quantity on noise and emissions as a function of the exhaust gas recirculation rate is represented in Fig. 15-38 as a function of the NOX emissions.
This type of representation is already familiar from Fig. 15-36: the different parameters have been represented as a function of the NOX emissions by varying the EGR rate. The upper left graph plots the aforementioned decrease in combustion noise brought about by the pilot injection. A minimum is already obtained at a pilot fuel quantity of 0.5–1 mg per injection. Another increase of the pilot fuel quantity to 1.5 mg causes an increase in noise: The combustion of the pilot injected fuel quantity itself determines the combustion noise. Moreover, an increasing EGR rate slightly reduces noise for every pilot injected fuel quantity. This can be attributed to the slower combustion caused by the combustion air’s reduced oxygen content.

As the upper right graph indicates, pilot injection lowers HC emissions. This effect greatly depends on the combustion system and the operating point.

As the lower right graph indicates, the combustion system’s significantly reduced EGR compatibility is a negative effect of PI. The larger the pilot fuel quantity, the more detrimental the effect is. This underscores the importance of precise injection of the minutest pilot fuel quantities for the combined optimization of noise and particulates [15-25]. Since the increased combustion noise must be compensated by a pilot injection in some cases of application, part of the advantages for the PM-NOX trade-off and brake specific fuel consumption obtained by increasing the injection pressure are lost. Thus, optimization of the overall system again requires a weighted analysis of every influencing variable.

Advanced combustion systems apply a second pilot injection and/or a post-injection positioned shortly after main injection for further optimization. While the second pilot injection is applied to further optimize noise, the added post-injection reduces soot emissions. Increased turbulence in the combustion chamber caused by the added post-injection facilitates soot oxidation. At the same time, the temperature at the end of combustion is increased. This also has a positive effect on soot oxidation. The efficacy of the added post-injection greatly depends on the combustion system and the map range being analyzed.

### 15.4.5 EGR Cooling and Intercooling

A minimum charge air temperature before the intake valves is advantageous for several reasons. On the one hand, charge air density that increases as the temperature drops produces efficient cylinder charging. This is called thermal engine dethrottling. As a consequence, the EGR compatibility increases and NOX and PM emissions can be lowered further. In addition, thermal dethrottling produces a consumption advantage through the air/fuel ratio. This underscores the positive influence of EGR and intercooling on an engine’s thermodynamic performance.

Both the compression of the charge air in the turbocharger and the recirculation of hot exhaust gas increase the air temperature in the cylinder intake. Therefore, processes have been developed to limit the temperature. These include the use of intercoolers virtually all over and the use of processes to cool the recirculated exhaust gas for cars in particular. The latter can entail long line length, line routing through the cylinder head and/or a heat exchanger cooled with cooling water. Numerous applications are able to control the cooling capacity or bypass the refrigeration unit to quickly heat up the engine cooling water to heat the passenger cell during a cold start or to prevent unduly low combustion chamber temperatures from increasing HC and CO emissions during operation in the lower part load range.

Whether the gas temperature in the intake valves is reduced by cooling the recirculated mass of exhaust gas or by cooling the compressed charge air is irrelevant thermodynamically.

Figure 15-39 presents the NOX and particulate emissions for two different temperature levels after the compressor (T2) as a function of the EGR rate. The upper graph plots the resultant air/fuel ratio. Specific fuel consumption and noise emissions as well as boost pressure and exhaust back pressure were equalized during the measurements. The higher value of $\lambda$ for an EGR rate of 0% on the far right in the top graph indicates that the lower temperature causes better cylinder charging. The lower graph displays lower NOX emissions for colder intake air when EGR is disabled. This can be attributed to the low peak temperatures that result. Improved emission performance with exhaust gas recirculation is also recognizable for the lower temperature in Fig. 15-39: significantly higher EGR rates with commensurately lower NOX emissions can be applied without an unduly high increase in particulate emissions.

### 15.5 Exhaust Gas Aftertreatment

#### 15.5.1 Introduction

Emission limits for diesel vehicles have dropped steadily in recent years and further reductions for the future have already been agreed upon. Emission reduction refers to every technology and system that is instrumental in lowering vehicle and engine emissions. Emission reduction systems not only have to satisfy legal requirements but also other technical boundary conditions (e.g. structural space and exhaust gas temperatures) and economic requirements.

Emission reduction can be divided into engine measures and downstream measures, which are frequently also combined as exhaust gas aftertreatment.

In the past, it was initially possible to lower emission limits by improving engine combustion with corresponding decreases of raw emissions (see Sect. 15.4). Although raw emissions are continuing to decrease, this will no longer suffice in the future.

The term exhaust gas aftertreatment subsumes the systems located in the exhaust gas system with the primary function of reducing engine emissions. They include catalytic converters,
sensors, particulate filters and auxiliary systems that may introduce a reductant or support particulate filter regeneration. Exhaust gas aftertreatment systems primarily reduce pollutant concentrations through chemical processes. Particulate filters also employ physical separation.

Apart from the desired conversion of pollutants, a number of additional technical requirements must be considered when selecting a system. The boundary conditions are briefly presented below before the individual components are described.

The exhaust gas temperatures of diesel engines are now usually so low that the chemical processes are frequently limited kinetically even when high quality catalytic converters are used. In addition, the exhaust gas temperatures greatly depend on the engine operating conditions, especially torque. Temperatures can reach values between the outside temperature (immediately after engine start) and up to over 700°C at full load. Temperatures in the front underbody area of the exhaust gas system are typically between 150 and 250°C, e.g. during the European driving cycle. Therefore, not only the optimization of the chemical reaction rate but also the protection of the components must be considered when designing and positioning components.

The exhaust gas mass flow also largely depends on engine operating conditions, particularly engine speed, the supercharging rate and the exhaust gas recirculation rate. These operating conditions can change considerably within a few seconds, thus changing the space velocity (the ratio of the volumetric exhaust gas flow to the volume of the individual catalytic components) to the same extent. Space velocity is a measure of the residence time of exhaust gas in catalytic converters. When residence times are too short, the gas is only able to react inadequately and conversion is diminished. Therefore, catalytic converters must be sized to ensure sufficiently large conversion even at high exhaust gas mass flows. However, the components’ thermal mass increases as their sizes increase. This affects the temperature curve of upstream components. The allowance for such interactions and the optimization of the overall system for all requirements are the object of system development and discussed after the description of the components.

Exhaust gas aftertreatment components represent aerodynamic obstacles that generate exhaust back pressure as a function of the volumetric exhaust gas flow. This exhaust back pressure must be overcome by the engine and increases the energy loss of gas exchange. In a bad case, this causes measurably increased fuel consumption, which translates into increased operating costs as well as increased CO2 emission. Therefore, minimal flow losses are important in the design of exhaust gas aftertreatment systems.

In addition, the flow restriction damps engine noise induced by exhaust gas. Vehicle operation transmits acceleration torque to the exhaust gas system. These mechanical stresses must be factored into the engineering of structural elements and the overall system and are treated elsewhere (see Sect. 13.2).

Engine exhaust gas contains vapor, which condenses while the exhaust gas system cools after the engine has been cut off. This exhaust condensate also contains corrosive constituents formed in reactions with the nitrogen oxides and sulfur dioxide contained in the exhaust gas. Engineering and material selection must include corrosion protection.

A suitable exhaust gas aftertreatment system that incorporates the aforementioned restrictions meets the requirements of reducing several pollutants at minimum cost. The design must also ensure the system’s service life is long enough.
Along with the aforementioned corrosive and mechanical stresses, the deterioration of catalytic coats must also be considered.

The multitude of requirements and interactions require complex design optimization customized for each vehicle model.

The individual components of an exhaust gas aftertreatment system are treated below first. Usually, they also have secondary functions in addition to their primary function. Suitable designs of exhaust gas aftertreatment systems with properly adjusted raw engine emission reduce the complexity and cost of overall emission reduction. The following section addresses this aspect of system design.

15.5.2 Exhaust Gas Aftertreatment Components

15.5.2.1 Diesel Oxidation Catalyst (DOC)

Diesel oxidation catalysts (DOC) were the first catalytic converters installed in diesel vehicles as standard. Their primary function is to oxidize engine carbon monoxide (CO) and hydrocarbon (HC) emissions with the residual oxygen of the exhaust gas into the harmless gases H₂O and CO₂. Precious metal coatings are employed for this. Advanced exhaust gas aftertreatment systems also include additional components and the DOC in these systems also assumes other functions:

- It oxidizes the volatile constituents of the particulate matter (adsorbed hydrocarbons), thus reducing particulate mass by up to 30%.
- It improves the ratios of nitrogen dioxide (NO₂) to nitrogen monoxide (NO). This step is conducive to nitrogen oxide reduction, especially for the SCR process.
- It releases heat by oxidizing deliberately supplied hydrocarbons and CO (as a so-called catalytic burner). This increases the temperature of an exhaust gas system after DOC. It is applied to facilitate the increase in temperature necessary for particulate filter regeneration and is additionally utilized for temperature management measures that bring deNOx systems to the operating temperature as quickly as possible after a start. This improves NOX conversion.
- When suitable coated, it additionally reduces NOX slightly (approximately 5–10%) by reacting with HC and CO.

All these functions are performed by the same principle made possible by the catalytic converter’s basic structure. The converter body consists of a ceramic or metallic honeycomb structure in which the exhaust gas is routed through channels approximately 1 mm in width. The channel walls consist of a ceramic or metal substrate structure covered with a catalyst washcoat containing precious metal. Exhaust gas components diffuse onto this catalyst coat when they flow through the converter body and are oxidized.

The basic variables influencing conversion are the:
- activity of the catalyst coating,
- size and inner geometry of the catalytic converter to which the residence time of the gas and the space velocity are related,
- catalytic converter temperature and
- concentration of the reaction partners.

The washcoat’s catalytic activity is basically defined by the type and quantity of its material and the spatial structure of its surface. DOCs utilize precious metals from the platinum group (platinum and palladium), which are dispersed on an oxide washcoat (aluminum oxide, cerium oxide or zirconium oxide) in the form of very small particulates (with a size of a few nm). The washcoat furnishes a very large internal surface area, stabilizes the precious metal particulates against sintering and supports the course of reactions either directly by reacting on the boundary between particulates and the substrate or indirectly by adsorbing catalyst poisons. Also frequently called catalyst loading, the quantity of catalyst utilized is in the range 50–90 g ft⁻³ (1.8–3.2 g l⁻¹).

The external dimensions (diameter and length), the density of the channels (specified in channels per square inch or cpsi) and the strength of the walls between the individual channels are the basic structural properties of a converter body. These properties determine a catalytic converter’s mechanical stability, exhaust back pressure and heating performance.

Typical values for the space velocity are between 150,000 and 250,000 h⁻¹. The volumetric exhaust gas flow depends on the engine displacement among other things. Placing the volume of a catalytic converter in relation to displacement yields values of \( V_{\text{Katal}} / V_{\text{Hub}} = 0.4 - 0.8 \).

As already mentioned in the introduction, a catalytic converter’s temperature is dependent on the engine’s operating state. If the exhaust gas temperature increases after the turbine of the turbocharger, then the catalytic converter temperature also follows with a delay induced by the exhaust gas system’s thermal mass. Figure 15-40 presents a typical conversion
curve for CO oxidation. A very steep increase in conversion is discernible. The exhaust gas temperature at 50% conversion is referred to as the catalytic converter’s light-off temperature and is 150–200°C, depending on the catalyst composition, flow velocity and exhaust gas composition. Over 90% of the CO is then converted at higher temperatures. The oxidation of hydrocarbons proceeds similarly but at somewhat higher temperatures and specifically depends on the composition of the hydrocarbons. Thus, for example, methane is only converted at very high temperatures, while short-chain alkenes already react at low temperatures.

A basic function of a DOC is to improve the ratio of NO₂ to NO. NO₂ is beneficial for a number of exhaust gas after-treatment systems (DPF, NSC and SCR). In the presence of oxygen, NO and NO₂ are in equilibrium with each other, at low temperatures (<250°C) on the NO₂ side and at high temperatures (>450°C) on the NO side. Depending on the operating point, there is somewhere between 5 and 50% NO₂ in NOₓ in the engine exhaust gas. This is far under the equilibrium value effective for the exhaust gas temperatures for most operating conditions. Therefore, a DOC can use catalytic reactions to increase the ratio of NO₂ to NO toward equilibrium as of 180–230°C and above. At high temperatures (>450°C), the NO₂ concentration commensurates with the thermodynamic equilibrium drops as the temperature rises. Aside from the exhaust gas temperature, the HC and CO concentration is also a significant factor that influences NO oxidation. Thus, HC or CO reduction can lower the percentage of NO₂ below the initial value, even in the mean temperature range.

Given its low concentration, the reaction heat released during oxidation does not cause any appreciable increase in the exhaust gas temperature. Additional hydrocarbons must be introduced before the DOC when an increase in temperature is desired, e.g., to initiate particulate filter regeneration. Then, the DOC assumes the function of a catalytic heating component (a catalytic burner). HC may either be introduced by an engine post-injection or by a device downstream from the engine. In both cases, the fuel quantity to be introduced can be calculated from the desired increase in temperature and the exhaust gas mass flow. A 1% increase in the CO concentration for an approximately 90°C increase in temperature is the approximation applied. The energy is released on the catalytic surface area, which transfers the heat to the exhaust gas by convection. The maximum permissible washcoat temperature (e.g., 800°C) limits the heat output.

Engine post-injection must be applied so that, as far as possible, it no longer plays a role in combustion. Otherwise it would cause an undesired increase in torque. However, unduly retarded injection causes part of the diesel fuel to reach as far as the cylinder wall. This would dilute the lubricating oil.

When HC is introduced downstream from the engine, the required quantity must disperse throughout the flow cross section as homogeneously as possible and reach the catalytic converter fully vaporized. Various approaches are in development:
- liquid introduction of the diesel sprays with a metering valve,
- the introduction of vaporized diesel fuel and
- the introduction of gases with low light-off temperatures, e.g., from H₂/CO mixtures preferably generated from diesel fuel directly in the vehicle.

Operation can diminish the effectiveness of catalytic converters over the course of time. This is known as catalyst deterioration. Two deterioration mechanisms are fundamental. On the one hand, the precious metal particulates can agglomerate at very high exhaust gas temperatures. This reduces the specific surface area of the precious metals. On the other hand, catalyst poisons can either coat the precious metal surface directly or make them inaccessible to the requisite diffusion processes by forming voluminous layers on the washcoat. The best-known catalyst poison is the sulfur contained in the fuel. It forms sulfates on the surface, which inhibit the precious metal’s accessibility. Today’s fuels are sulfur-free or at least low-sulfur. This reduces the risk of DOC sulfurization.

Part of the processes of deterioration are irreversible. Such processes must be prevented by selecting appropriate exhaust gas temperatures and fuel qualities. However, some catalyst poisoning can be reversed by selecting appropriate operating conditions.

### 15.5.2.2 Particulate Filters

The function of diesel particulate filters (DPF) is to separate a very large fraction of particulates from the exhaust gas flow. Given the small size of the particulates (the majority being smaller than 100 nm; see Sect. 15.3.2), only filtration provides sufficiently large filtration efficiency with relative ease.

Over time, the increasing quantity of filtrate increases the flow restriction through a filter. This causes higher fuel consumption. Therefore, a filter requires regeneration in certain intervals, i.e., utilizing appropriate operating conditions to oxidize the combustible filtrate constituents (incombustible filtrate constituents remaining behind as ash). Thus, operation can be divided into long phases of particulate filtration interrupted by short phases of regeneration. Therefore, particulate filter operation requires an operation strategy and other components that collectively form the DPF system. The following describes the structure of the DPF, which is important for the filtration phase, then examines the regeneration phase and finally explains the other elements of a DPF system.

The requirements for a particulate filter are:
- a high filtration rate even for extremely small particulates (50–95% depending on the law and raw emission),
- low flow restriction,
- high temperatures strength against temperatures of up to 1,000°C, which occur during regeneration, and
Four filter types in are in use at present:
(a) ceramic extrudates made of cordierite,
(b) ceramic extrudates made of silicon carbide (SiC),
(c) sintered metal filters (particularly for the retrofit market) and
(d) particle separators with open structures.

The first three filter types are based on the wall-flow filter principle (closed filter systems), which routes the complete quantity of exhaust gas through a porous wall. Every other channel in the ceramic extrudate is closed on the front and back (Fig. 15-41). This makes the extrudate walls a porous filter surface with a very large surface area (approximately 1 m$^2$). When particulates pass through the porous wall, they initially diffuse onto the inside pores. After a short time, a thin surface filtration layer begins forming on the surface of the walls, which have significantly smaller pores than the substrate structure and consequently trap the majority of the particulates. The thickness of the filtrate layer increases with the loading time. This initially increases the flow restriction and then also increases the flow restriction in the filter’s inlet channels as it continues. Flow restriction and filtration efficiency are a function of wall thickness (0.3–0.4 mm) and pore size. Moreover, channel density (100–300 cpsi) is important for flow restriction. While high channel density increases the inner surface area and thus reduces the wall’s resistance to penetration, it also results in smaller channel diameters. This increases the flow restriction in the channels, especially when the surface filtrate additionally constricts the cross section of the inlet channels. In a new development, the diameters of the ingoing channels are larger than the diameters of the outgoing channels. This improves the flow loss induced by surface filtrate and the compatibility with ash deposits.

Sintered metal filters are composed of filter cells with large inlet cross sections that increasingly taper in the direction of flow. This geometry also reduces the inlet flow loss and increases ash compatibility.

Wall-flow filters filter the entire exhaust gas, producing filter efficiencies above 95% for the entire relevant size range (10 nm$^{-1}$). When a filter cannot be regenerated in due time, e.g. because a retrofit solution fails to provide every measure to trigger regeneration, then the exhaust back pressure can increase so much that engine operation is impeded. Such filter blockage is impossible in an open particle separator.

Instead of imperatively routing the exhaust gas through a wall, the structure of an open particle separator initially deflects it into the cells protruding into the filter channels. This delivers a pulse to the gas, thus accelerating it toward a porous channel wall. When filter loading is low, the majority of it penetrates the channel wall much like in a wall-flow filter and filtrate builds up. As the resistance to penetration increases, the fraction of gas that penetrates the wall decreases and the fraction in the channel that bypasses a cell increases. Therefore, the filtration efficiency in such structures is a function of loading and between approximately 30 and 70% in real applications.

Similar to a DOC, the filter’s manufactured size and thus its surface area are oriented toward displacement (typically $V_{DFP}/V_{Dipl} = 1.2–2.0$).

Depending on the design and the raw emissions, filter regeneration is necessary after 300–600 km. Above approximately 600°C, soot burns with the oxygen contained in the exhaust gas to become CO$_2$, releasing heat. The design point for regeneration is the accumulated quantity of soot (5–10 g l$^{-1}$ depending on the filter material). If this quantity is too large, then local temperatures can peak during exothermic regeneration and damage the substrate or the catalytic coating as the case may be.

The temperatures necessary for regeneration only exist in an engine’s rated power range. Therefore, additional measures must be planned, which facilitate timely filter regeneration even under ordinary in-use driving.

The following regeneration strategies exist:
1. uncatalyzed oxidation by residual oxygen at 550–650°C,
2. additively supported regeneration,
3. regeneration with NO$_2$ and
4. regeneration with catalyzed diesel particulate filters (CDPF).

Non-catalytic Oxidation

Uncatalyzed oxidation employs various measures to raise the filter temperature to the ignition temperature. In principle, the temperature of the DPF can be increased by degrading the engine efficiency (changing the injection characteristic), reducing the exhaust gas mass flow (lowering boost pressure or throttling) or increasing the temperature downstream from the engine (e.g. by a catalytic burner in the DOC). All these measures must ensure that the residual oxygen content in the DPF is high enough for rapid regeneration (>5%). The measures are a function of the engine operating point and assembled into packages of measures (Fig. 15-42).
The engine temperatures in range 1 (rated power range) are already so high that no other measures must be introduced. This range is very rarely found in car operation.

The very high torques required in range 2 must be available despite regeneration measures. The main injection is shifted to be somewhat more retarded. This degrades engine efficiency and increases the exhaust gas temperature as desired. In addition, an added (advanced) post-injection takes place, which still plays a part in combustion and delivers another torque contribution. These measures aimed at increasing the engine exhaust gas temperature by degrading efficiency are called engine burners.

The supercharging in range 3 is low and the air/fuel ratio already below 1.4 when combustion is optimal. In this case, an added post-injection would locally cause very low air/fuel ratios and thus a strong increase of black smoke. Therefore, the post-injection is retarded long enough that it no longer plays a part in combustion (retarded post-injection). The additional HC and CO emissions are converted into heat in the DOC (catalytic burner).

Various measures are combined with one another in range 4. However, lowering the boost pressure reduces the exhaust gas mass flow. Retarding the main injection and adding a post-injection further increases the exhaust gas temperature in range 2. The proportion of individual measures must be optimized for noise, emissions and consumption and are usually not all required simultaneously.

A sizeable temperature increase of 300–400°C is required in range 5. A throttle valve additionally reduces the air mass in this range. This necessitates further measures to stabilize combustion, e.g. increasing the pilot injected fuel quantity and adjusting the interval between the pilot and main injection.

The very small torques in range 6 make it impossible to trigger regeneration at temperatures >600°C.

The scope of the measures in every range significantly depends on the temperature generated. The thermal loss between the engine and filter should be kept to a minimum to fully maximize the effect of the heat generated in the engine in the filter. Therefore, many applications place the filter as close to the engine as possible.

Catalytically supporting soot oxidation is another option to lower the required regeneration temperature.

**Additive Systems**

Additive systems blend additives (usually cerium or iron compounds) into fuel. The metal bonds to the soot during engine combustion. This produces a surface area of soot in the filter that is doped with mixed oxides that lower the ignition temperature to 450–500°C, which allows reducing the scope of the aforementioned measures. After the soot oxidizes, the metal oxide remains in the filter as residue and thus increases the ash fraction that thermal regeneration is unable to remove. Therefore, additive regeneration requires the removal and mechanical cleaning of conventional wall-flow filters every 120,000–180,000 km.

**NO₂ Regeneration**

NO₂ is an extremely active oxidant that already oxidizes soot as of temperatures of 250–350°C. Such temperatures are frequently reached in commercial vehicle applications and in car applications during highway driving for instance. NO forms during soot oxidation.

\[
2\text{NO}_2 + \text{C} \rightarrow 2\text{NO} + \text{CO}_2 \tag{15-7}
\]
\[
\text{NO}_2 + \text{C} \rightarrow \text{NO} + \text{CO} \tag{15-8}
\]
\[
\text{CO} + \text{NO}_2 \rightarrow \text{CO}_2 + \text{NO} \tag{15-9}
\]
\[
\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2 \tag{15-10}
\]

The equations indicate that eight times the mass of NO₂ must be present to completely oxidize soot. On average, the amount of soot that oxidizes and new soot that is separated is the same when the temperature and mass ratio are high enough (\(T > 350°C\)). This is referred to as a CRT® (continuous regenerating trap). The required NO₂ forms from
Catalyzed Diesel Particulate Filter (CDPF)

Catalyzed diesel particulate filters (CDPF) can lower the regeneration temperature slightly. While their catalytic coating has far less of an effect than the use of fuel additives, it does not produce any additive ashes.

Catalytic coating performs several functions:
- oxidizing CO and HC and
- oxidizing NO to NO$_2$.

Just like a DOC, a CDPF can also oxidize HC and CO while releasing heat. In this case, the temperature lift produced acts directly in the point where high temperatures are required to ignite soot. The heat losses that may occur when an upstream catalytic burner is employed can be prevented. Just as for a catalytic burner, either engine post-injection or a metering unit downstream from the engine supplies the requisite HC and CO to the exhaust gas system.

In addition, NO oxidizes to NO$_2$ in the catalytic coating. In small quantities, it can support soot oxidation at low temperatures.

A DPF system consists of the particulate filter and other components:
- a DOC employed as a catalytic burner and to boost the NO$_2$ fraction,
- a temperature sensor before the DOC that determines the convertability of HC in the DOC (light-off state),
- a differential pressure sensor that measures the differential pressure through the particulate filter from which the flow restriction can be calculated with the volumetric exhaust gas flow and
- a temperature sensor before the DPF that determines the DPF temperature important to control regeneration.

Moreover, a DPF system must have appropriate control unit functions to control and monitor regeneration. First, a particulate filter’s loading state must be measured during the loading phase (loading detection). Various methods are employed to do this. The flow restriction, which increases as the filter load increases, is determined with the aid of a differential pressure sensor. A function of the preceding operating conditions, the influence of the soot coat’s morphology (e.g. equipartition of the coat thickness over the filter and filtrate porosity) interferes with the correlation between the quantity of soot and the flow restriction.

Therefore, the quantity of included soot arrived at by integrating the engine soot mass flow is additionally modeled mathematically. Moreover, the removal of soot by the CRT is also incorporated. The soot burn-off is calculated during the regeneration phase as a function of the filter temperature and the oxygen mass flow.

A so-called coordinator determines the soot mass decisive for the regeneration strategy from the soot mass values calculated with both methods.

The regeneration strategy determines when regeneration is triggered and what measures are initiated. To prevent thermal damage to the substrate during regeneration, a threshold at which regeneration should take place is defined for the soot mass as a function of the material used. Advancing regeneration is expedient when particularly favorable conditions exist (e.g. highway driving). A regeneration strategy defines the regeneration measures to be executed as a function of the soot mass and the operating state of the engine and vehicle. These are transmitted to the other engine control functions as a status value.

The DPF temperature is regulated during regeneration to prevent uncontrolled overheating in a filter or uncontrolled termination of regeneration. The injection characteristic and the air mass are available as manipulated variables.

15.5.2.3 NO$_X$ Reduction Catalysts

Like methods of particulate matter reduction, only some of the theoretically conceivable methods of NO$_X$ reduction are implementable in vehicles.

Effectively installed in gasoline engines, three-way catalytic converters in which NO$_X$ reacts with HC and CO with very high conversion at $\lambda = 1$ to become N$_2$, H$_2$O and CO$_2$ cannot be implemented in lean diesel exhaust gas. The desired reduction of NO$_X$ relies with the reduction of the residual oxygen, which is present in an approximately thousand-fold concentration.

Two systems (SCR and NSC) are being launched on the market at present.

Selective Catalytic Reduction (SCR)

Using ammonia (NH$_3$) as the reductant, selective catalytic reduction (SCR) reduces NO$_X$ to nitrogen in a suitable catalytic converter. SCR has proven itself in large firing plants and is found in commercial vehicles that have been launched widely on the market (since around 2005). Initial applications in cars are even planned (starting around 2007).

Basically, the actual SCR reaction proceeds according to the following reaction equations:

$$4 \text{NO} + \text{O}_2 + 4 \text{NH}_3 \rightarrow 4 \text{N}_2 + 6 \text{H}_2\text{O} \quad (15-11)$$
$$\text{NO} + \text{NO}_2 + 2 \text{NH}_3 \rightarrow 2 \text{N}_2 + 3 \text{H}_2\text{O} \quad (15-12)$$
$$6 \text{NO}_2 + 8 \text{NH}_3 \rightarrow 7 \text{N}_2 + 12 \text{H}_2\text{O} \quad (15-13)$$

The reductant does not react with oxygen in the SCR catalyst at ordinary vehicle temperatures below 550°C, i.e.
the selectivity for NO\textsubscript{X} reduction is 100%. The first two reactions are dominant in most cases. The required quantity of reductant can then be calculated directly from the desired NO\textsubscript{X} reduction. Based on one refueling interval, this would produce a substantial NH\textsubscript{3} requirement (approximately 0.3–1% of the fuel quantity, depending on the raw emission). Its safe storage in a vehicle is questionable because NH\textsubscript{3} is toxic.

However vehicles can also produce NH\textsubscript{3} from a number of precursor substances relatively easily. Such precursor substances differ from one another in terms of storage density, toxicity, availability and stability. In the 1990s, the European automotive industry reached an agreement to use a 32.5% aqueous urea solution (with the brand name AdBlue\textsuperscript{®}) in commercial vehicles. Used industrially as fertilizer, urea is sufficiently chemically stable for environmental conditions. Moreover, urea is easily soluble in water and, as a 32.5% solution, forms a eutectic mixture with a freezing point of \(-11^\circ\text{C}\).

The urea/water solution is metered in before the SCR catalyst and, an intermediate product, isocyanic acid hydrolyzes the urea to NH\textsubscript{3} in a two stage process in the exhaust gas system at temperatures of approximately 250°C and above.

\[
(NH_2)_2CO \rightarrow NH_3 + HNCO \quad \text{(thermolysis)} \quad (15-14)
\]

\[
HNCO + H_2O \rightarrow NH_3 + CO_2 \quad \text{(hydrolysis)} \quad (15-15)
\]

Solid deposits (biuret and higher molecular compounds) can be produced from the isocyanic acid in a secondary reaction. Appropriate catalytic converters and sufficiently high temperatures (of approximately 250°C and above) must be selected so that the hydrolysis reaction proceeds with sufficient speed to prevent solid precipitates.

The ammonia produced is adsorbed in the SCR catalyst and then available for SCR reactions. High conversions can be obtained with NH\textsubscript{3} in the temperature range of 180–450°C. Allowing for the upstream hydrolysis reaction, stable high conversion with the urea/water solution is possible only at 250°C and above.

The reaction mainly proceeds through Eq. (15-12) at low temperatures (<300°C). Therefore, an oxidizing catalytic converter that elevates the ratio of NO\textsubscript{2} to NO\textsubscript{X} to around 50% is located before the SCR catalyst and the metering point to boost conversion. The oxidation catalytic converter may be either a DOC or a CDPF.

The SCR and hydrolysis reactions directly link the reduction of NO\textsubscript{X} to the amount of AdBlue metered in. The mass ratio of required AdBlue to reduced NO\textsubscript{X} is \(2 \frac{\text{gAdBlue}}{\text{gNO}_x}\). The metering ratio \(\alpha\) (also called a feed ratio) is defined as the molar ratio of the NH\textsubscript{3} equivalent metered into the NO\textsubscript{X} present in the exhaust gas. The theoretically possible maximum reduction of NO\textsubscript{X} corresponds to the metering ratio \(\alpha\). Theoretically, NO\textsubscript{X} can be eliminated completely when \(\alpha = 1\). If it is metered at \(\alpha > 1\) over a longer time, then the catalytic converter’s adsorptive capacity will be exceeded and unconverted NH\textsubscript{3} will leave the SCR catalyst (NH\textsubscript{3} slip). NH\textsubscript{3} has a very low odor threshold (15 ppm in air). Excessive NH\textsubscript{3} would cause an odor nuisance in the environment. Therefore, not only conversion optimized by maximizing the metering ratio but also minimum NH\textsubscript{3} slip is important. In addition to limiting slip by a sufficiently small metering ratio, a downstream oxidation catalytic converter (trap catalyst) can also remove escaping NH\textsubscript{3}.

The conversion achieved in existing systems may be less than the theoretical potential for conversion defined by the metering ratio. There are a number of possible reasons for this discrepancy:

- NH\textsubscript{3} slip can occur even at \(\alpha < 1\) when insufficient homogenization of the AdBlue solution in the exhaust gas produces an inhomogeneous concentration of reductant in the SCR catalyst inlet. The quantity of NH\textsubscript{3} that passes through reduces the NO\textsubscript{X} conversion achieved.
- When hydrolysis is incomplete, the formation of precipitates causes the reductant to be lost for the SCR reaction.
- At high temperatures, part of the NH\textsubscript{3} can react with oxygen by oxidizing.
- When the NO\textsubscript{2} to NO\textsubscript{X} ratio is unduly large, part of the NO\textsubscript{2} reacts according to Eq. (15-13). 30% more NH\textsubscript{3} is required for this fraction than for reactions that follow Eqs. (15-11) and (15-12).

Just like a DOC and DPF, an SCR catalyst is dependent on the volume after displacement (\(V_{\text{SCR}}/V_{\text{Displ.}} = 1.0–2.5\)). When implemented in the field, 90% NO\textsubscript{X} conversion can be achieved when the NH\textsubscript{3} slip is <20 ppm.

The achievable conversion greatly depends on the metering strategy. In the simplest design, the reductant is metered at a constant ratio. The required quantity of reductant yielded by the NO\textsubscript{X} mass flow can be determined in engine or vehicle tests. The metered amount is released when the temperature in the SCR catalyst has reached the operating temperature (e.g. 250–450°C). This simple metering strategy is suitable for stationary engine operation. It is not suited for high NO\textsubscript{X} conversion at low NH\textsubscript{3} slip under the dynamic operating conditions common in vehicle operation.

SCR catalysts have excellent NH\textsubscript{3} storage capacity (approximately 1 g l\(^{-1}\)), which greatly depends on the temperature (e.g. only 10% of the low temperature value is retained as of 350°C and above). The advantage of such storage capacity is that overmetering of AdBlue does not directly cause NH\textsubscript{3} slip and NO\textsubscript{X} conversion can proceed with the stored NH\textsubscript{3} even at temperatures that are too low for a hydrolysis reaction. However, the storage capacity’s dependence on the temperature harbors a risk that part of the adsorbed NH\textsubscript{3} desorbs should the temperature increase too rapidly. This causes NH\textsubscript{3} slip. To control this characteristic, an extended metering strategy includes a storage model that incorporates the SCR catalyst’s storage capability and storage level. The SCR catalyst’s storage level is increased by the reductant metered in and decreased by
the NO\textsubscript{X} conversion and the NH\textsubscript{3} slip that occur. The goal is to attain high NO\textsubscript{X} conversion with an optimal storage level as a function of temperature. Therefore, the metered quantity is reduced by metering with a constant metering ratio in phases of decreasing storage capability and it is increased when the temperature decreases.

Higher conversion with low NH\textsubscript{3} slip is only possible when the calculation of the storage level is correct. In real systems, drifts in reductant metering and deviations in the raw NO\textsubscript{X} emissions cause the calculated storage level to deviate from the real state. Insufficient NO\textsubscript{X} or excessive metering ratios would cause continuous NH\textsubscript{3} slip. Maximum conversion can be achieved when the NO\textsubscript{X} and NH\textsubscript{3} concentrations are measured after the SCR catalyst and the metering is readjusted commensurately.

A complete AdBlue SCR system includes the following components and subsystems (Fig. 15-43):

- a DOC or CDPF that increases the NO\textsubscript{2} to NO\textsubscript{X} ratio,
- a temperature sensor downstream from the SCR catalyst, which determines the SCR temperature,
- an NO\textsubscript{X} sensor downstream from the SCR (optional), which determines the NO\textsubscript{X} concentration and, when appropriately cross sensitive, the NH\textsubscript{3} concentration,
- an NO\textsubscript{X} sensor upstream from the SCR (optional), which improves the control quality,
- a tank system that stores the urea/water solution, an integrated level sensor, a heater, a temperature sensor (optional) and a quality sensor (optional),
- a delivery module consisting of a pump that conveys the urea/water solution from the tank to the metering module and, when mixture formation is air-supported and, additionally an air control valve and an air pressure sensor to establish an appropriate air mass flow from the air tank (commercial vehicle system) to the metering module,
- a metering module in which a solenoid valve regulates the exact quantity of urea/water solution. (In an air-supported system, this quantity together with the compressed air reaches a mixing chamber whence a line transports the aerosol to the metering point in the exhaust pipe; in systems without air support, an appropriate nozzle atomizes and forms the mixture directly at the exhaust pipe.) and
- a control unit that reads the sensors and controls the relevant actuators according to the metering strategy, while appropriate diagnostic functions monitor the components; communication with the engine control unit takes place through a CAN bus.

\textbf{NO\textsubscript{X} Storage Catalyst (NSC)}

An NO\textsubscript{X} storage catalyst (NSC or lean NO\textsubscript{X} trap LNT) facilitates the reduction of NO\textsubscript{X} without having to replenish any additional agent (Fig. 15-44).

NO\textsubscript{X} is decomposed in two steps:

- a \textit{loading phase} in which NO\textsubscript{X} is stored in the lean exhaust gas in the catalytic converter’s storage components and
- a \textit{regeneration phase} in which the stored NO\textsubscript{X} is discharged and reduced to N\textsubscript{2} in the rich exhaust gas.

A function of the operating point, the loading phase lasts approximately 30–300 seconds, the regeneration phase approximately 2–10 seconds. This operating mode initially concentrates the nitrogen oxides to be reduced. In the extremely short regeneration phase, the reductant only reduces the concentrated NO\textsubscript{X} together with the residual oxygen. This reduces the fraction of oxygen that acts parasitically during NO\textsubscript{X} reduction. Thus, the reductant required can be limited to a 2–4% increase in fuel consumption.

\textbf{NO\textsubscript{X} Storage}

An NSC is coated with chemical compounds with a high propensity to enter stable but chemically reversible bonds with nitrogen oxides. Examples are oxides and carbonates of alkali and alkaline earth metals. Barium compounds are employed particularly frequently because of their thermal characteristics.

NO must progressively oxidize to form nitrate. NO is initially oxidized to NO\textsubscript{2} in a catalytic coating. The NO\textsubscript{2} reacts with the storage compounds in the coating and afterward with oxygen (O\textsubscript{2}) to become nitrate:

\[ \text{BaCO}_3 + 2 \text{NO}_2 + \frac{1}{2} \text{O}_2 \rightleftharpoons \text{Ba(NO}_3)_2 + \text{CO}_2 \]  \hspace{1cm} (15-16)

Thus, an NO\textsubscript{X} storage catalyst stores the nitrogen oxides emitted by an engine. Storage is only optimal in a material-dependent exhaust gas temperature interval between 250 and 450°C. The NO oxidizes to NO\textsubscript{2} very slowly. The nitrate formed is unstable above 450°C and NO\textsubscript{X} is discharged thermally.

Apart from its aforementioned capability to store NO\textsubscript{X} as nitrate, a catalytic converter also has a limited capability to bind NO\textsubscript{X} in surface storage at low temperatures. Such storage systems are sufficient to adequately store nitrogen oxides with low catalytic converter temperatures, e.g. during the start phase.

Nitrate forms from carbonates in an equilibrium reaction. The catalyst’s ability to bind more nitrogen oxides decreases as the quantity of nitrogen oxides stored increases (loading). Thus, the quantity of NO\textsubscript{X} allowed through increases over time. There are two ways to recognize when a catalyst is so loaded that the storage phase must be terminated:

- a model-aided method incorporating the state of the catalyst calculates the quantity of nitrogen oxides stored and, from this, the remaining storage capacity, the storage efficiency and thus the quantity of NO\textsubscript{X} allowed through or
- an NO\textsubscript{X} sensor after the NO\textsubscript{X} storage catalyst measures NO\textsubscript{X} in the exhaust gas and thusly determines the current fill level.
A storage catalyst must be regenerated after the storage phase to limit the passage of NOX.

**NSC Regeneration**

During regeneration, the stored nitrogen oxides are discharged from the storage components and converted into the harmless components of nitrogen and carbon dioxide. The processes of NOX discharge and conversion proceed separately.

To this end, oxygen deficiency ($\lambda < 1$, also called a rich exhaust gas condition) must be established in the exhaust gas. The components of carbon monoxide (CO) and hydrocarbons (HC) present in the exhaust gas serve as the reductant. Discharge – presented below in an example with CO as the reductant – proceeds so that CO reduces the nitrate (e.g. barium nitrate $\text{Ba(NO}_3\text{)}_2$) to NO and, together with barium, reforms the carbonate originally present.

$$\text{Ba(NO}_3\text{)}_2 + 3\text{CO} \rightarrow \text{BaCO}_3 + 2\text{NO} + 2\text{CO}_2 \quad (15-17)$$

CO$_2$ and NO are produced in the process. In a method familiar from three-way catalytic converters, a rhodium coating subsequently uses CO to reduce the nitrogen oxides to N$_2$ and CO$_2$:

$$2\text{NO} + 2\text{CO} \rightarrow \text{N}_2 + 2\text{CO}_2 . \quad (15-18)$$

Less nitrogen oxide is discharged as regeneration advances and thus less reductant is consumed.

There are two methods to recognize the end of the discharge phase:

- a model-aided method calculates the quantity of nitrogen oxides still present in the NOX storage catalyst or
- a lambda oxygen sensor after the catalytic converter measures the excess oxygen in the exhaust gas and indicates a change of $\lambda$ to $\lambda < 1$ when discharge has ended (CO breakthrough).

The rich operating conditions ($\lambda < 1$) required for regeneration can be established in diesel engines by retarding injection and throttling the intake air. The efficiency of engine operation is poor during the regeneration phase because of throttling losses and the suboptimal introduction of fuel. Therefore, the ratio of the duration of the regeneration phase to the duration of the storage phase should be minimized to keep increased fuel consumption low. Unlimited drivability as well as the constancy of torque, response and noise has to be assured when switching from lean to rich operation.

Rich operating conditions may also be established by introducing the reductant downstream from the engine. Similar to the operation of a catalytic burner (see Sect. 15.5.2.1), it may be introduced as diesel spray, vaporized fuel or a highly reactive species, usually a reformate gas (H$_2$/CO mixture). Intervention in engine combustion, in particular application engineering of retarded injection, can be reduced commensurately. However, the air mass should to be reduced, e.g. by lowering the boost pressure or throttling, to reduce the reductant requirement.
Desulfation

One problem with NOX storage catalysts is their sulfur sensitivity. Sulfur compounds in the fuel and lubricating oil are oxidized to sulfur dioxide (SO₂) during combustion. The compounds utilized in NSC to form nitrate (BaCO₃) have very high bonding strength (affinity) to sulfate, which exceeds the bonding strength of the nitrate. Normal regeneration does not remove the sulfates. Thus, the quantity of sulfate stored gradually increases during the operating life. As a result, less space exists for NOX storage and NOX conversion decreases. Therefore, storage catalysts require the use of sulfur-free fuel (≤10 ppm).

The decreasing NOX storage capability after a driven distance of between 500 and 2,500 km necessitates sulfur regeneration (desulfation) even during operation with fuel with a sulfur content of 10 ppm. Typically, the catalyst is heated to over 650°C for a period of more than five minutes and pulses of rich exhaust gas (λ < 1) are applied. The potential measures to increase the temperature correspond to those for DPF regeneration. These conditions reconvert the barium sulfate to barium carbonate. Appropriate process control (e.g. oscillating λ by 1) must be selected to ensure that the deficiency of residual oxygen does not reduce the discharged SO₂ to hydrogen sulfide (H₂S) during desulfation. (Alternatively, an appropriate trap catalyst must be designed in.)

In addition, the conditions established during desulfation must be selected to avoid excessive increase of catalyst deterioration. While, high temperatures (typically >750°C) accelerate desulfation, they also intensify catalyst deterioration. Therefore, desulfation optimized for a catalytic converter must occur in a limited temperature and excess air coefficient window and not interfere with a vehicle’s in-use driving in the process.

Above all, the storage process is significant for the design of storage catalysts. Storage efficiency is a function of the catalyst temperature, precious metal loading, space velocity and available amount of storage. The ratio of catalytic converter volume to displacement (V_{NSC}/V_{Hub}) is 0.8:1.5. Efficient oxidation of NO to nitrate by NO₂ and maximum recovery of HC compounds during regeneration require high precious metal loading of approximately 100 g ft⁻³. An NSC mounted as closely to the engine as possible can assume the functions of the DOC, which may then be dispensed with.

NSC catalysts allow a 50–80% reduction of NOX throughout their service life.

NOX Reduction Systems in Comparison

NSC and SCR systems have a multitude of different properties. Any decision on which system to implement in a vehicle greatly depends on the requirements and boundary conditions. The most important differences are examined below.

- At present, SCR systems are able to achieve greater maximum efficiency than NSC systems. This criterion is fundamental when compliance with extremely ambitious NOX limits is required.
- SCR systems require another agent (e.g. AdBlue®). This has three consequences that must be borne in mind:
  (a) The agent must be approved for NOX reduction in the region concerned.
  (b) Replenishment in appropriate intervals must be assured.
  (c) The agent must be stored in the vehicle. This requires space and – depending on the agent – necessitates cold flow and defrosting measures.

An AdBlue infrastructure for commercial vehicle systems is currently being set up throughout Europe, which will make replenishment possible in the fueling interval. An approximately 20–25 l tank could also suffice for a servicing interval for cars, thus making replenishment at garages possible.

- Proportional to displacement, SCR systems cost less than NSC systems. However, AdBlue systems generate fixed costs. Therefore, NSC systems cost less for cars with small displacement, while SCR systems are less expensive for commercial vehicles.

- The type and amount of operating costs differ. An SCR system consumes AdBlue. An NSC system increases fuel consumption by 2–4% depending on the NOX reduction and the system design. When their NOX reduction is comparable, SCR systems cost less to operate than NSC systems.

15.5.3 Exhaust Gas Aftertreatment Systems

Knowledge of the function of every individual system module is required to completely design an exhaust gas aftertreatment system (Fig. 15-45). Additionally understanding the interaction of the exhaust gas aftertreatment components is also essential. Moreover, dependable, highly efficient pollutant reduction must be obtained with minimum complexity by a good correspondence between engine measures for emission reduction and the exhaust gas aftertreatment system.

The following first explores the interaction of exhaust gas aftertreatment components and then explains the link with engine emission reduction.

15.5.3.1 Interaction of Exhaust Gas Aftertreatment Subsystems

Exhaust gas aftertreatment components are arranged serially in an exhaust gas system, i.e. one component’s physicochemical performance has an effect on downstream components. Allowing for a slight delay (with a magnitude of 0.1–1 s), the exhaust gas mass flow is identical for every component.
Thermal Coupling

Uncoupled from their chemical function, all exhaust gas aftertreatment components including pipes possess heat capacity. A change in the temperature of the exhaust gas before one of the components causes a change in the temperatures of the components and a damped temperature change of the gas downstream from the components (thermal low pass with a time constant in the magnitude of 10–100 seconds). At the same time, outer walls (pipe wall and catalytic converter housing) release heat from the exhaust gas system to the environment. Thus, components further downstream have a lower mean temperature than upstream components.

As described in the preceding section, every chemical process requires a minimum operating temperature of 150°C (light-off CO oxidation) to 250°C depending on the components (CRT\textsuperscript{1}). Since conversion cannot take place below these temperatures, high conversion necessitates that the components reach their operating temperature as rapidly as possible after the engine starts. Therefore, the components are mounted as closely to the engine as possible. The use of insulated pipes can reduce their heat losses.

Pollutant Coupling

Every active exhaust gas aftertreatment component reduces at least one pollutant component according to its primary function. The other pollutant components can disrupt or facilitate this process or also be partially converted in it. Tables 15-16 presents these interactions.

One particularly important coupling is the required reduction of particulates by NO\textsubscript{x} and especially by NO\textsubscript{2} through the action of the CRT\textsuperscript{1}. Furthermore, HC and CO compounds interfere with the storage of NO\textsubscript{x} in the NSC and the SCR process. In both cases, NO\textsubscript{2} is a key component that is reduced to NO in the presence of HC and CO.

Very rapid starting processes additionally require start assist measures that correspond in principle to the measures that increase the DPF temperature.

Frequently, part of the required temperature increase is reached by an upstream catalytic burner that thermally regenerates the DPF. For this reason, a DOC is always located upstream from a DPF.

**Fig. 15-45** Complete systems for exhaust gas aftertreatment (HCl–HC injection)
A decision about the relative arrangement of the components always has to be made whenever an exhaust gas system contains both a particulate filter and a nitrogen oxide reduction system. Along with thermal coupling, the pollutants’ influence on the function of the components is important. The following discusses both interactions together.

CRT® can reduce DPF loading when the DPF is located upstream from the NOX reduction system. Under favorable conditions, this can prolong the regeneration intervals considerably. Moreover, since it dispenses with the thermal low pass of an NSC or SCR catalyst, this arrangement makes it easier to bring the DPF to the regeneration temperature and keep it there. However, the DPF’s relatively sizeable heat capacity only allows the NOX reduction system to reach its operating temperature very late after start. Therefore, start assist measures must be designed in for high NOX conversion rates.

When a coated DPF is located downstream from an SCR system, then the DPF can simultaneously assume the function of a trap catalyst for potential NH3 slip. The abundance of arguments demonstrates the futility of a universal recommendation for a relative arrangement. The more beneficial arrangement for a particular vehicle frequently only becomes evident in combination with engine and vehicle design.

### 15.5.3.2 Interaction Between Engine Operating Parameters and Exhaust Gas Aftertreatment

The preceding section revealed the complexity of the interaction between the different components in an exhaust gas aftertreatment system. A number of correlations between engine combustion and exhaust gas aftertreatment also must be optimized for the purpose of overall system design.

Historically, exhaust gas aftertreatment systems were initially operated without intervention in engine combustion. The DOC reaches the light-off temperature necessary for CO and HC oxidation shortly after the engine starts and, with the exception of long motoring or idle phases, remains above this temperature until the engine is cut off. The SCR system is very similar. In the first applications, the metered quantity necessary for the targeted NOX conversion was determined by tests on engine test benches and in vehicles and metered in production vehicles according to the application engineering data obtained. Only as requirements for NOX reduction increased have allowances for fluctuations in engine NOX emission become so important that it is only possible to obtain the conversion values by controlling the metered quantity. However, the engine operating parameters are not adapted to the requirements of exhaust gas aftertreatment during operation here either.

The situation changes when storage catalysts or particulate filters are utilized. Both systems must be regenerated regularly, the operating parameters being set far outside the usual range for diesel engines. In addition, the exhaust back pressure also increases as particulate filters become more loaded. First, this causes the pressure after the turbocharger to rise and, then, the pressure before the turbine. This pressure increase not only increases the energy loss of gas exchange but also influences the pressure gradient through the EGR system. Therefore, a change in exhaust back pressure must be compensated by the air system. Consequently, the operating parameters change with the filter’s fill level.

Understandably, component costs as well as the complex interactions of components and their effects on engine operation have prompted attempts to achieve emission goals with a minimum number of components. Engine operating parameters (e.g. EGR rate and injection timing) can be utilized to change the ratio between soot and NOX emission (the so-called soot-NOX trade-off). They are employed in two main strategies to reduce complexity in exhaust gas aftertreatment:

(a) combustion optimized for soot with NOX reduction downstream from the engine and

(b) combustion optimized for NOX with particulate reduction downstream from the engine.

### Table 15-16 Interaction of exhaust gas aftertreatment systems

<table>
<thead>
<tr>
<th>Components</th>
<th>DOC</th>
<th>CDPF</th>
<th>NSC</th>
<th>SCR</th>
<th>Storage</th>
<th>Regeneration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pollutant</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HC</td>
<td>X</td>
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<tr>
<td>CO</td>
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<tr>
<td>Particulates</td>
<td>-</td>
<td>-</td>
<td>X</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>NO</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO2</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

X: primary purpose of the components; ––: pollutant is greatly reduced; --: pollutant is reduced; 0: no change; +: pollutant increases; 
↑: pollutant greatly facilitates process; ⇧: pollutant facilitates process; ⇫: pollutant impedes process.
Very good engine efficiency can be obtained when combustion is optimized for soot (and NOx rich). What is more, this eliminates a particulate filter’s back pressure contribution, which also causes perceptibly increased fuel consumption. Therefore, NOx reduction (with an SCR system) downstream from the engine is the preferred solution for commercial vehicle applications for which operating costs are extremely important.

However, particulate limits will be lowered considerably in the near future. Implementing a particulate filter with very high filtration efficiency and eliminating the complexity of NOx reduction downstream from the engine by (particulate rich) combustion optimized for NOX benefits overall system optimization when the particulate limits are not attainable in the engine or only with considerable complexity. This path is currently being pursued for European car applications.

Finally, some new markets for diesel vehicles, e.g. the USA, have such low particulate and NOx limits that every measure for emission reduction in and downstream from the engine must be implemented. Although the attendant complexity is considerable, this route may be worthwhile in light of the alternatives. Diesel engines are still significantly superior to gasoline engines in terms of efficiency. In the face of limited global fuel reserves and global CO2 emissions, this is an increasingly important argument for pushing to increase the number of diesel vehicles.

15.6 **Emissions Testing**

Exhaust measurement systems consist of exhaust measuring equipment and dilution systems. The determination of environmentally relevant mass emissions requires the determination of their concentrations as well as the engine’s exhaust gas volumes.

15.6.1 **Exhaust Measurement Systems for Gaseous Emissions**

Individual pollutant concentrations are measured by individual exhaust gas analyzers mounted in an exhaust measurement system. Such systems (Fig. 15-46) consist of a base unit that extracts an exhaust gas sample from the engine’s exhaust
system, transports the sample gas to the system, conditions it and feeds it to the individual gas analyzers to measure the concentrations. In addition, a multitude of valves that feed the different operating and calibration gases to the analyzers are also necessary. Sample conditioning prevents the composition of the sample from changing on its way to the analyzers, e.g. prevents water from condensing or certain hydrocarbon compounds from depositing. In addition, particulates are filtered out of the sample gas to protect the analyzers.

**Zero and Span Point Adjustment (Calibration):**
All gas analyzers require regular adjustment of their zero and span calibration point (Fig. 15-47) before every measurement or at least once a day depending on the application. A zero gas and a span calibration gas are supplied to the analyzer from gas cylinders and its measured value is adjusted to the known calibration gas concentration. Normally, calibration is fully automatic. The absolute accuracy of measurement significantly depends on the accuracy of the calibration gases.

**Linearization:**
Linearization is performed to ensure that the values measured between the analyzer’s zero and span points are accurate (Fig. 15-48). To this end, different gas concentrations dispersed throughout the measuring range are supplied to the analyzer and the measured values are compared with the expected concentrations. When the deviations are more substantial (>2%), the measured values are corrected mathematically (linearization curve). Such linearization is usually performed or at least checked in 3-month intervals. The reference concentrations are mixed together from zero and calibration gas in a highly precise multi-stage gas divider.

**Diagnostic Tests:**
Depending on the type of analyzer and the application, a multitude of diagnostic tests are performed, which assure the quality of the systems’ measurements. Among others, these include cross sensitivity tests, which verify that the measured value of a gas component is not influenced by other gas components at all or only minimally, and leak checks of the system.

### 15.6.1.1 Hydrocarbon Measurement

Hydrocarbons are measured with a flame ionization detector (FID) (Fig. 15-49). Exhaust gas contains a multitude of hydrocarbon compounds. Normally, it is important to measure their cumulative rather than their individual components. The FID measuring principle measures most different hydrocarbon compounds, thus allowing a cumulative result.

**FID Measuring Principle:**
A flame generated from a constant flow of synthetic air and a gas mixture of hydrogen and helium burns inside the measuring cell. The flame burns in an electrical field between the cathode and anode. This flame is blended with a constant sample gas flow. Hydrocarbon molecules are cracked and ionized in the process. The ions generated transport a very weak current between the cathode and anode (measurement signal). Ideally, every hydrocarbon molecule would decompose into ionized components, which only contain one carbon atom. Then, the ion flow in the exhaust gas sample would also be proportional to the number of carbon atoms with a bond to hydrogen. However, the cracking and ionization process does not fully function in practice. Nonetheless, its efficiency for the individual hydrocarbon molecules is constant. This is called structural linearity and is identified as response factors. The response factors specify the difference between the value measured by the FID and the real concentration of individual hydrocarbons. Typically, they are between 0.9 and 1.1.
When measuring hydrocarbons in diesel engine exhaust gas, the entire exhaust gas sample must be heated to 190°C from the sampling point to the FID since diesel engine exhaust gas contains hydrocarbons that would already condense below this temperature. Without heating, the condensed hydrocarbons would not be measured and the gas passages would also be contaminated. This is called HC hang-up.

15.6.1.2 Nitrogen Oxide (NO and NO₂) Measurement

Usually, the total content of nitrogen oxides NO and NO₂, referred to as NOₓ, is measured. Typically, a chemiluminescence detector (CLD) is employed to do this (Fig. 15-50).

**CLD Measuring Principle:**
Measurement is based on the chemiluminescence produced by blending NO and ozone O₃. A chemical reaction converts NO and O₃ into NO₂. Approximately 10% of these reactions
produce NO2 in an energetically excited state (NO2*). The molecules return from their energetically excited state to their base state after a brief time; the excess of energy is released as photons. The light generated is measured with photodiodes or photomultipliers. The light’s intensity is directly proportional to the concentration of NO in the measuring cell.

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2 + \text{O}_2 \quad (15-19)
\]

for approximately 90% of the NO molecules in the sample

\[
\text{NO} + \text{O}_3 \rightarrow \text{NO}_2^* + \text{O}_2 \quad (15-20)
\]

for approximately 10% of the NO molecules in the sample

\[
\text{NO}_2^* \rightarrow \text{NO}_2 + \text{hv} \quad (15-21)
\]

with h \ldots Planck constant \quad \text{hv \ldots photons} \quad (15-22)

An ozone generator in the analyzer itself generates the required ozone O3 from oxygen O2, which may be pure oxygen, synthetic air or ambient air depending on the type of analyzer.

A CLD is only able to measure NO. Therefore, every NO2 molecule is converted into NO before the CLD detector so that NOX (NOX = NO + NO2) can be measured. An NO2/NO converter performs this conversion much like a catalytic converter.

Since NO2 can also react with water, any water condensation must be prevented at least up to the NO2/NO converter. Otherwise, the NO2 being measured would be lost and aggressive acids would form. Therefore, the complete sample gas path and the analyzer are usually heated. Older analyzers often use an unheated CLD detector. Then, the sample has to pass through the NO2/NO converter first (to avoid NO2 to condensed water) and then proceed to a gas drier (to remove water).

NOX quenching occurs when NO2* molecules collide with other suitable molecules before they have released light. Then, the energy is not released as light but to the other molecules. Thus, less light is generated and the measured value is too small. In exhaust gas, such molecules are primarily H2O and CO2. The more molecules are in the measuring cell, the more often such collisions occur and, thus, the greater the quenching is. Hence, most CLD analyzers are operated in a vacuum (at approximately 20–40 mbar absolute). This significantly reduces the number of molecules and thus the potential for quenching.

In addition to analyzer calibration and linearization, two diagnostic tests are particularly important for CLD. The H2O and CO2 quench test measures the degree of quenching and the NO2/NO converter test measures convertibility and efficiency. Typically, the efficiency ought to be over 90%.

15.6.1.3 Carbon Monoxide (CO) and Carbon Dioxide (CO2) Measurement

Carbon monoxide CO and carbon dioxide CO2 are measured by nondispersive infrared analyzers (NDIR) (Fig. 15-51).

NDIR Measuring Principle:

An emitter emits a broad infrared spectrum and the radiation is sent through a bipartite measuring cell. One part of the measuring cell is filled with nonabsorbent gas (e.g. nitrogen N2) and
referred to as the reference cell. The sample gas flows through the other part. A chopper (e.g. a rotating perforated disk) intermittently disrupts the infrared radiation. When the sample gas contains gas molecules that are absorbent in the infrared range, e.g. CO or CO₂, part of the radiation from these molecules is absorbed. Thus, the radiation through the measuring cell is lower than the radiation through the reference cell.

A detector measures the difference in the intensity through the two cells. The detector also consists of two chambers. One receives the radiation from the reference cell and the other the radiation from the measuring cell. Both of the detector’s chambers are filled with the gas to be measured (e.g. CO or CO₂). Thus, the detector absorbs infrared radiation just like the measuring cell for these gas components. Depending on the concentration of the gas components being measured in the measuring cell, the infrared radiation through the measuring cell becomes weaker than the radiation through the reference cell since radiation has already been absorbed. The remaining radiation is also absorbed in the detector chambers since they are filled with the same gas that is being measured. The absorption increases the energy and thus the pressure in the sealed chamber. The two cells’ differing radiation cause a differential pressure in the two detector chambers, which is measured by a flexible diaphragm between them. The diaphragm’s movement is measured capacitively (as in Fig. 15-51). Alternatively, flow measurement of a compensating flow between the two chambers may be used.

The larger the concentration of the gas being measured in the measuring cell, the larger the measurement signal is. The correlation between the concentration and measurement signal corresponds to the Beer-Lambert law, which is a nonlinear function. Hence, NDIR detectors must always be linearized.

Many gases absorb in the infrared spectrum and the different gases’ absorption spectra also overlap. CO and CO₂ analyzers are particularly cross sensitive to H₂O vapor. CO analyzers are also cross sensitive to CO₂. Such cross sensitivity increases the measured value. Typically, the raw exhaust sample is dried first before it flows to the NDIR analyzers. Thus, cross sensitivity to water is no longer relevant. Wet gas only has to be measured from the bags of a constant volume sampling system (CVS). Such applications require the performance of water cross sensitivity tests (interference checks).

15.6.1.4 Oxygen O₂ Measurement

The oxygen concentration in exhaust gas is measured by a paramagnetic detector (PMD) (Fig. 15-52).

PMD Measuring Principle:
Oxygen is one of the few gases with paramagnetic properties. The sample gas flows through a strong magnetic field in a measuring cell. Their magnetic properties cause the oxygen molecules to move to the center of the magnetic field. However, a quartz sphere without any magnetic properties is in the center. Such detectors are designed
symmetrically with two magnetic fields and two quartz spheres. An arm connects both spheres. This is also referred to as a dumbbell. The dumbbell is mounted on a rotating axis. The oxygen molecules surging into the magnetic fields attempt to displace the dumbbell’s spheres. The higher the oxygen concentration, the greater its displacement force is. A mirror is mounted on the dumbbell’s rotating axis. A beam of light and a light detector measure the deflection. Either the deflection itself is the measurement signal or a controlled magnetic field always keeps the sphere centered and the required electrical current is then the measurement signal. In both cases, the measurement signal is directly proportional to the oxygen concentration in the sample gas.

The measuring principle is also slightly sensitive to NO, NO₂ and CO₂ because these gases are also slightly paramagnetic. Since these gases are measured in every exhaust measurement system, the slight cross sensitivity may be corrected mathematically. Since the cross sensitivity is relatively low, it also only plays a role in gasoline engines that have only a very low O₂ concentration at λ = 1 and below. Without a correction, errors of a magnitude of 5,000 ppm may occur.

### 15.6.1.5 Special Measurement Systems

The aforementioned measuring principles constitute the standard methods of measurement, often referred to as conventional measurement systems, as well as the measuring principles mandated in most emission control legislation [15-26-15-30]. Other methods of measurement are also required and utilized in research and development to obtain an even better picture of exhaust gas composition as well as to measure gas components that are not or are not yet covered by legislation. Some such methods of measurement are presented below.

**Fast Response Measurement Systems:**

Fast response measurement systems are based on the aforementioned conventional measuring principles but the measurement systems are trimmed to rapid signal response times of only a few milliseconds. However, this results in significantly shorter service lives and maintenance intervals.

**Nondispersive Ultraviolet Analyzers (NDUV):**

NDUV analyzers measure gas components much like NDIR analyzers. However, unlike an NDIR, ultraviolet light is used. Such analyzers are mainly employed to measure NO, NO₂ and NH₃.

**Fourier Transform Infrared Spectroscopy (FTIR):**

Fourier transform infrared spectroscopy is a method of optical measurement that measures a multitude of exhaust gas components simultaneously. Measurement is based on the individual gas components’ absorption of infrared light. FTIR are widely used, especially in modern diesel engine applications with exhaust gas aftertreatment systems, e.g. NOₓ storage and SCR catalysts and diesel particulate filters.

A differentiated measurement of NO, N₂O, NO₂, NH₃ and other exhaust gas components is particularly important in these applications.

FTIR employs a broad infrared waveband to capture all of an exhaust gas sample’s spectral information simultaneously. The intensity of the individual infrared wavelengths is varied continuously by means of a Michelson interferometer. A beam splitter divides the light source’s infrared radiation into two beams. One of the beams strikes a moveable mirror, the other a stationary mirror. Afterward, the two beams are rejoined into one beam. The mirror’s continuous movement produces differential path lengths, which in turn produce interference when the beam is reunited. Individual wavelengths may be cancelled or amplified depending on the moveable mirror’s position. The thusly continuously modified infrared beam is conducted through the measuring cell and individual wavelengths are absorbed by the different gas components in the exhaust gas sample. The Fourier transformation applies complex mathematical formulas to calculate an infrared spectrum (intensity as a function of wavelength) from the interferograms and special methods of analysis determine the concentrations of the individual gas components from them.

**Mass Spectrometers (MS):**

Mass spectrometers make it possible to measure many gas components in exhaust gas. The sample gas is ionized, e.g. by reactant gases or electrical ionization, and the ions are separated in the analyzer, according to their mass. There are several methods for this but all of them are based on the differences in ion motion in the analyzer as a function of their mass. These may be differential transit times or different curve radii during deflection. Given its complexity, such equipment is used more in labs than regular test bench operation. Mass spectrometer systems are especially used to measure sulfur components (SO₂, H₂S, COS) and hydrogen H₂.

**Diode Laser Spectroscopy (DIOLA):**

Diode laser spectroscopy is similar to the infrared measuring principle employed in NDIR analyzers but it produces very short signal response times. It is especially used for the development of catalytic converter applications.

**Exhaust Gas Dilution Systems:**

In principle, the masses of environmentally relevant pollutants in exhaust gas are determined from the concentration of the particular exhaust gas components, their density and the engine’s volumetric exhaust gas flow. While this is a relatively simple task in stationary engine operation, the method of measurement is relatively complicated in transient operation since it must follow both the rapid changes in the exhaust gas and accurately measure the concentrations over several powers of ten. In addition, the extremely dynamic volumetric exhaust gas flow must also be measured. Since every signal has different
time delays, the measured data must be accurately time aligned before further calculation. Since it was impossible to meet such requirements in the early days of emission control legislation, alternative methods were sought to perform the task with the instruments and computers available at the time. This was achieved by employing full flow dilution. Even though it is now possible to meet these requirements without dilution, full flow dilution is still mandatory in virtually all emission control legislation. The only exceptions are stationary and transient emission tests for commercial vehicles such as EURO IV (2005 [15-32]). The somewhat conservative position in legislation is also rooted in the ease with which the relatively simple full flow dilution method enables approval authorities to check the correctness of the mandatory emission test.

Simplified calculation of a pollutant component’s mass in exhaust gas employs the following terms:

- $Q_{\text{exh}}$: volumetric flow rate of the engine
- $Q_{\text{CVS}}$: volumetric flow rate of the CVS
- $V_{\text{CVS}}$: total volume of the diluted exhaust gas over the sample time
- $q$: dilution ratio of the CVS
- $\text{Conc}_{\text{raw}}$: concentration of the pollutant component in the undiluted exhaust gas
- $\text{Conc}_{\text{dil}}$: concentration of the pollutant component in the diluted exhaust gas
- $\text{Conc}_{\text{Bag}}$: concentration of the pollutant component in the exhaust sample bag
- $\rho$: density of the pollutant component
- $T$: sample time (duration of the test cycle)
- $m$: mass of the pollutant component

**Undiluted exhaust gas** (see scheme ①, Fig. 15-53) is

$$m = \int_0^T \text{Conc}_{\text{raw}} \cdot Q_{\text{exh}} \cdot \rho \, dt \quad (15-23)$$

With the following, diluted exhaust gas (see scheme ②, Fig. 15-53) from Eq. (15-23) becomes

$$Q_{\text{exh}} = \frac{Q_{\text{CVS}}}{q}$$

$$m = \int_0^T \text{Conc}_{\text{raw}} \cdot Q_{\text{CVS}} \cdot \rho \, dt$$

and the following with

$$\text{Conc}_{\text{raw}} = \text{Conc}_{\text{dil}} \cdot q$$

$$m = \int_0^T \text{Conc}_{\text{dil}} \cdot Q_{\text{CVS}} \cdot \rho \, dt$$

and the following with

$$Q_{\text{CVS}} = \text{const. and } \rho = \text{const.}$$

$$m = Q_{\text{CVS}} \cdot \rho \cdot \int_0^T \text{Conc}_{\text{dil}} \, dt \quad (15-24)$$

Dilution of engine exhaust gas also lowers the water concentration in the diluted exhaust gas so far that no water condenses in the measurement system. Sufficiently high dilution is the prerequisite. Dilution also simulates chemical reactions of the individual exhaust gas components in ambient air (real operation). This is particularly crucial for particulate formation.

Since no exhaust gas is removed, exhaust gas dilution fully retains the entire mass of the pollutants in the exhaust gas. However, the addition of dilution air also introduces small quantities of pollutants that are already contained in the ambient air. To prevent this from skewing the test result, the dilution air is also collected in a sample bag and analyzed. The pollutant mass added by dilution is subtracted when the final result is computed. Pollutants fed to the engine with the intake air are not corrected and are considered to be vehicle emissions.
CVS Full Flow Dilution:
The main function of constant volume sampling (CVS) is to dilute all of the engine’s exhaust gas (full flow) and maintain a constant volumetric flow of diluted exhaust gas (exhaust gas and dilution air). This can be accomplished with various methods:
- CFV critical flow venturis,
- PDP positive displacement pumps or Roots blower
- SSV subsonic flow venturis and
- UFM ultrasonic flowmeters.

CFV (Critical Flow Venturi):
A blower sucks the diluted exhaust gas through a venturi nozzle. Constricting the cross section in the nozzle increases the flow velocity. Sonic speed is reached in the narrowest point when the differential pressure between the nozzle inlet and the narrowest point has the factor of approximately two. Since the speed cannot be increased any further, a constant flow is produced, regardless of the strength of the blower after the nozzle. This state is referred to as critical and, hence, the nozzle as a critical venturi nozzle.

The exact flow can be calculated from the nozzle’s calibration parameters, the pressure and the temperature in the nozzle inlet (Fig. 15-54):

\[ V_s = K_v \cdot \frac{p_v}{\sqrt{T_v}} \]  

where:
- \( V_s \) is the volumetric flow rate normalized to the standard conditions at 20°C and 1,013 mbar in force for American legislation or to normal conditions at 0°C and 1,013 mbar in force for European legislation
- \( K_v \) is the venturi calibration factor as a function of the narrowest nozzle cross section
- \( p_v \) is the absolute pressure before the venturi nozzle
- \( T_v \) is the temperature before the venturi nozzle in Kelvin

Since the pressure downstream from the venturi nozzle does not influence the flow in any way, the blower does not have to be controlled. However, it must be strong enough to generate critical flow conditions in the nozzle.

Depending on the engine and test, usually three or four venturi nozzles are connected in parallel to establish different flows. Ideally, each next larger venturi nozzle has twice the flow than the preceding venturi nozzle. Thus, as in the binary numeral system, a combination of four nozzles produces fifteen different flow rates and three nozzles seven flow rates.

PDP (Positive Displacement Pump):
Also known as a Roots blower, a positive displacement pump PDP is another option to keep the flow through a CVS constant. Two rotary pistons in the housing transport the gas. The volume is not compressed though and the volumetric flow is directly proportional to the speed of the pump.

This advantage of this CVS variant is the adjustability of the flow rate by the pump motor’s speed control. CVS systems are no longer constructed with PDP primarily because of the high costs.

Flow Measurement and Active Control:
Some more recent legislation also allows the use of flow measurement and active blower control.

The flow is measured with a subsonic venturi (SSV). Unlike CFV, sonic speed is not reached in this nozzle and the flow is therefore calculated with the differential pressure according to the Bernoulli equation. Alternatively, ultrasonic flowmeters (UFM) are used.

Common CVS Flow Ranges:
CVS with differing flow ranges are implemented depending on the application and engine size. The flow must be large enough to prevent water from condensing in the system and, for diesel engines, to keep the temperature of the diluted exhaust gas below 52°C during particulate measurement:
- commercial vehicle engines 120 … 180 m³/min
- passenger cars 10 … 30 m³/min
- motorcycles 1 … 5 m³/min

CVS Sampling:
Only a small quantity of gas is extracted from a CVS to analyze the diluted concentrations in it. It is filled in sample bags that are evacuated before and analyzed after the test. The exhaust gas concentration in the sample bag yields a mean value over time throughout the test. To measure particulate emissions, the diluted exhaust gas is drawn through analysis filters that trap the particulates from the
sample taken. The analysis filters are weighed before and after the measurement to determine the quantity of particulates trapped.

The total masses of emissions from the total volumetric CVS flow during the measurement are calculated from the averaged concentrations in the sample bag and the particulate mass trapped in the filter. Thus, the sample flow into the sample bag and through the particulate filter must be proportional to the flow in the CVS.

The flow in a CVS is not absolutely constant and can vary slightly as a function of pressure and temperature. Therefore, either the sample flow must follow these variations proportionally or the flow through the CVS must be kept sufficiently constant. A CFV-CVS satisfies this requirement for gaseous exhaust gas components by also filling the sample bag by a CFV. Thus, any influence of pressure or temperature is identical for both nozzles (CVS and sample nozzles) and establishes the proportionality required. Sampling nozzles may not be utilized for particulate measurement since the nozzle hole traps particulates and the lower pressures after the nozzle can alter particulate formation. Either the CVS (state-of-the-art particle sampler) actively readjusts the particulate sampling to be proportional to the flow or a heat exchanger before the CVS venturi keeps the temperature constant. Thus, the flow through the CVS venturi is also constant. Since a CVS is always open to the environment through the dilution air inlet, significant changes in pressure that would alter the flow do not occur (Fig. 15-55).

**Requirements for Diesel Engine Measurement:**

Additional requirements exist for the measurement of particulate and hydrocarbon emissions from diesel engines (see Fig. 15-56).

A dilution tunnel is added to a CVS to measure particulates. Basically, this is simply a long, straight stainless steel pipe, which is intended to form particulates realistically. Its diameter must be selected so that the flow is always turbulent and the Reynolds number (measure of the turbulence) is above 4,000. Its length should be such that the diluted exhaust’s residence time in the tunnel is long enough to simulate particulate formation in the environment. The dilution tunnel’s length is usually 10 times its diameter. Dilution must also be high enough to maintain the temperature of the diluted exhaust gas in the point of particulate measurement below \(52\) \(^\circ\)C. Already very large, CVS systems are usually unable to dilute sufficiently to do this for commercial vehicles. Then, double dilution is performed in which a small flow sampled from the CVS is diluted a second time. This is referred to as secondary dilution.

Particulate measurement is performed at the end of the dilution tunnel by a particle sampler (PTS). It draws diluted exhaust gas through analysis filter disks. The filters are weighed before and after the measurement and the particulate emissions are calculated from the increase in weight and the flows.

Hydrocarbon compounds have a significantly higher boiling point in diesel engine exhaust gas than in gasoline engine exhaust gas. This stems from the fuel production. Put simply,
gasoline consists of hydrocarbons that vaporize at up to 200°C and diesel consists of hydrocarbons that vaporize at between 200 and 400°C. Hence, hydrocarbons from diesel exhaust gas can condense at higher temperatures and are thus no longer measured as gaseous components and contaminate the measurement systems. Referred to as HC hang-up, this would affect subsequent measurements. Therefore, the hydrocarbons are measured directly from the CVS dilution tunnel rather than out of sample bags as for gasoline engines. All lines and components that transport gas for hydrocarbon measurement, including the analyzer (FID), are heated to 190°C. This inhibits such condensation.

In addition to hydrocarbon measurement, nitrogen oxide measurement for commercial vehicle engines is also heated and performed directly from the dilution tunnel.

15.6.2 Measurement of Particulate and Dust Emissions

15.6.2.1 Particulate Emission: Dilution Tunnel

The limits on particulate emission specified in every mandatory regulation are based on an integral measurement by gravimetric determination of the particulate mass after dilution in a full flow or partial flow tunnel as first defined by the Environmental Protection Agency (EPA) [15-26] and then adopted worldwide [15-27, 15-28]: Based on the principle of the CVS, exhaust gas is mixed with filtered air and a partial flow of the diluted exhaust gas, which must have a temperature of <52°C, is drawn through inert filters with a >99% filtration rate. The emission is calculated from the filter’s increase in weight. Figure 15-56 depicts this schematically for a type of system with secondary dilution usually employed for commercial vehicles. In principle, car emissions are measured identically in a chassis dynamometer but without secondary dilution.

Particulates are composed of soot, adsorbed organic components, condensed and adsorbed sulfuric acid and solid constituents such as grit, ash, etc. Condensed and adsorbed substances basically only form in a dilution tunnel. However, other than initially expected, the soot concentration is not completely stable between the engine and reference filter [15-29]. Understandably, small modifications of the dilution and particle sampler system already influence the particulate mass measured.

The EPA specified the dilution, particulate sampling and weighing system more precisely in 2007 to also increase the repeatability and reproducibility of the measurement method as particulate and, above all, soot emissions decrease [15-30, 15-31].

The EU (and thus nearly every Asian and Latin American country) allows the use of partial flow dilution tunnels for commercial vehicles [15-32], which dilute a constant fraction of the exhaust gas as specified in the standard ISO 16183 [15-33]. The space and cost advantages of these systems (see the schematic in Fig. 15-57) are offset by the complex control of the mass flows. In addition, several boundary conditions must be observed to obtain the same emission as measured in a full flow system [15-34].

15.6.2.2 Particle Number Counting

Since only very sensitive instruments are able to capture the particulate emissions of modern combustion engines, the UNECE GRPE’s informal group on the Particle Emission Programme (PMP) is working on new methods of particle
measurement. The group’s recommendation for future homologation procedures includes modified EPA particulate measurement (2007) as well as particle number counting [15-35, 15-36].

The PMP group has defined a complex system to condition already diluted exhaust gas, which is presented schematically in Fig. 15-58. First, coarse particles that stem from reintroduced wall deposits rather than directly from combustion are separated. Second, the exhaust gas is diluted and subsequently heated to 400°C. Third, dilution is performed once more before the particle number counter (PNC) to cool the exhaust gas and lower the particle number further. A particle number is obtained in a condensation particle counter (CPC) and volatile nanoparticles are eliminated. Thus, only nonvolatile particles, i.e. chiefly soot particles, are counted. This requirement is rooted in two factors. On the one hand, nonvolatile particles are toxicologically more relevant to human health. On the other hand, reproducible measurement of volatile particle emissions has proven to be extremely difficult. This is not a problem with the measurement per se since volatile particles can be counted just like solid particles. However, the formation of homogeneously condensed hydrocarbons and sulfates after particulate filters is extremely sensitive to the slightest changes in engine or exhaust gas conditioning.

The conditioned exhaust gas may also be analyzed for such particle properties as size distribution, active surface area, etc. (not required by PMP).

Although not explicitly required by PMP, condensation particle counters (CPC) are the most common and most sensitive systems for particle number counting in the range of submicrons to a few nanometers. Figure 15-59 presents the principle of a CPC. Heterogeneous condensation of supersaturated vapor generates microparticles from nanoparticles, which are subsequently counted by the light scattering method.

15.6.2.3 Dust Measurement

In Germany, stationary diesel engines are subject to the regulations of TA Luft. Sampling is performed according to VDI 2066 [15-38]. A sample is taken from the exhaust gas without prior dilution so that, for all intents and purposes, the particulates do not contain any substances condensed and adsorbed onto the soot. Hence, this "dust mass" does not correlate with the particulates measured from diluted exhaust gas. Depending on the load point, the difference can be between 10 and 90%.

15.6.2.4 Alternative Methods

Gravimetric determination of particulate emission has serious disadvantages: it is a tedious, time consuming and integrating method. However, a rapid measurement and/
or the allocation of the time of emission to the dynamic driving conditions are frequently needed for engine development. Hence, a number of simpler and/or more dynamic methods of measurement have been developed. However, the measured quantities generally deviate from the particulates measured in compliance with the law and the established correlations only have limited validity. The measurement of soot emission assumes a special role here since it is an important indicator for the quality of combustion. Several measuring methods generally based on soot’s strong absorption of radiation have been developed. New methods have excellent time resolution and/or very high sensitivity.

The most important alternative measurement methods are summarized in Table 15-17 and presented schematically in Figs. 15-60–15-67. Generally, there are different designs and commercial providers for all of the methods of measurement.

### Table 15-17 Advantages and disadvantages of alternative methods of particulate/soot measurement

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opacimeter [15-39]</td>
<td>- Mandatory for some certification tests, e.g. ELR</td>
<td>- Sampling systems require sampling flows of up to 40 l/min</td>
</tr>
<tr>
<td></td>
<td>- Reliable, cost efficient, established method to measure exhaust gas opacity</td>
<td>- High sensitivity necessitates sophisticated system design: long optical path length L, good thermal conditioning</td>
</tr>
<tr>
<td></td>
<td>- Excellent time resolution of 0.1 s</td>
<td>- Relatively strong cross sensitivity to NO₂</td>
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<tr>
<td></td>
<td>- High sensitivity (0.1% opacity, corresponding to approximately 300 µg/m³ soot)</td>
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<tr>
<td></td>
<td>- Usable with special sample conditioning up to exhaust gas pressures of 400 mbar; higher pressure add-on available</td>
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<tr>
<td></td>
<td>- Acceptable soot concentration correlation (mg/m³) can be found for families of engines</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Sampling systems require sampling flows of up to 40 l/min</td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td>- Relatively strong cross sensitivity to NO₂</td>
<td></td>
</tr>
<tr>
<td>TEOA (Tapered Element Oscillating Microbalance) [15-48]</td>
<td>- Measurement of particulate (not soot) emission</td>
<td>- Replaces the particulate filter but requires exhaust gas dilution</td>
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<tr>
<td></td>
<td>- Result is similar to the statutory method of particulate measurement</td>
<td>- Generally not fully equivalent to the mandatory method</td>
</tr>
<tr>
<td></td>
<td>- Time resolution in the second range</td>
<td>- Sensitivity depends on the time resolution, typically 1 mg/m³</td>
</tr>
<tr>
<td>DMM (Dekati Mass Monitor) [15-41]</td>
<td>- Measurement of particulate (not soot) emission</td>
<td>- Expensive</td>
</tr>
<tr>
<td></td>
<td>- Result is similar to the mandatory method of particulate measurement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Time resolution in the second range</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Sensitivity of approximately. 1 µg/m³</td>
<td></td>
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<tr>
<td></td>
<td>- Additional estimation of mean particulate size</td>
<td></td>
</tr>
<tr>
<td>Smokemeter [15-39]</td>
<td>- Reliable cost efficient</td>
<td>- Replaces the particulate filter but requires high exhaust gas dilution</td>
</tr>
<tr>
<td></td>
<td>- Established method</td>
<td>- Frequently not really equivalent to the mandatory method</td>
</tr>
<tr>
<td></td>
<td>- High sensitivity (0.002 FSN, corresponding approximately to 20 µg/m³ soot) during longer sampling times</td>
<td>- Expensive</td>
</tr>
<tr>
<td></td>
<td>- With special sampling equipment, exhaust gas can be measured before the diesel particulate filter</td>
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<tr>
<td></td>
<td>- Good soot concentration correlation (mg/m³), minimal cross sensitivity to other exhaust gas components</td>
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<tr>
<td></td>
<td>- Integrating method</td>
<td></td>
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<tr>
<td></td>
<td>- Time resolution of approximately 1 min.</td>
<td></td>
</tr>
<tr>
<td>Photoacoustic soot sensor [15-42–15-44]</td>
<td>- High sensitivity – typically &lt; 5 µg/m³ soot</td>
<td>- Requires exhaust gas dilution</td>
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<tr>
<td></td>
<td>- Sensor signal is directly and linearly sensitive to soot concentration, minimal cross sensitivity</td>
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<tr>
<td></td>
<td>- Good time resolution, ≈ 1 s</td>
<td>- Method of calibration is not rigorously established</td>
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<tr>
<td></td>
<td></td>
<td>- Measurement upstream from the DPF requires exhaust gas conditioning</td>
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</tbody>
</table>
### Table 15-17 (Continued)

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>– Applicable for diesel particulate filter tests</td>
<td>– Regular servicing is easy but necessary</td>
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<tr>
<td></td>
<td>– Moderately expensive</td>
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<td></td>
<td>– High dynamic range (1: 10,000)</td>
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</tr>
<tr>
<td>Laser induced incandescence [15-45]</td>
<td>– High sensitivity – typically &lt; 5 μg/m³ soot</td>
<td>– Very expensive</td>
</tr>
<tr>
<td></td>
<td>– Sensor signal is directly and linearly sensitive to soot concentration</td>
<td>– Method of calibration is not established.</td>
</tr>
<tr>
<td></td>
<td>– Minimal cross sensitivity</td>
<td>– High dynamic range is only achievable with optical attenuators (insertion of absorber filters)</td>
</tr>
<tr>
<td></td>
<td>– Good time resolution, ≤ 1 s</td>
<td></td>
</tr>
<tr>
<td>Photoelectric aerosol sensor [15-46]</td>
<td>– Compact, cost effective system</td>
<td>– Time resolution, ≤ 10 s</td>
</tr>
<tr>
<td></td>
<td>– High sensitivity – typically &lt; 1 μg/m³ soot</td>
<td>– Strongly influenced by substances with high photoemission (PAH)</td>
</tr>
<tr>
<td></td>
<td>– An empirical correlation with the soot emission of diesel engines can be established in most cases</td>
<td></td>
</tr>
<tr>
<td>Diffusion charging sensor [15-41, 15-46, 15-47]</td>
<td>– Compact, cost effective system</td>
<td>– Not proportional to particulate mass</td>
</tr>
<tr>
<td></td>
<td>– Measures the active particulate surface (Fuchs surface)</td>
<td>– Time resolution of a few seconds</td>
</tr>
<tr>
<td></td>
<td>– High sensitivity – typically &lt; 1 μg/m³ particulates</td>
<td></td>
</tr>
<tr>
<td></td>
<td>– The signals have been found to empirically correlate with the particulate emission of diesel engines in some cases</td>
<td></td>
</tr>
</tbody>
</table>

![Fig. 15-60](principle-of-the-smokemeter.png)

*Fig. 15-60* Principle of the smokemeter [15-39]

![Fig. 15-62](principle-of-photoacoustic-measurement.png)

*Fig. 15-62* Principle of photoacoustic measurement [15-44]

![Fig. 15-61](principle-of-the-opacimeter.png)

*Fig. 15-61* Principle of the opacimeter [15-39]
Fig. 15-63  Principle of laser induced incandescence, LII [15-45]

Fig. 15-64  Principle of photoelectric measurement [15-46]

Fig. 15-65  Principle of a diffusion charging sensor [15-41]
The references [15-47–15-50] contain further and/or summarized information on unconventional state-of-the-art methods of diesel particulate measurement.

**Literature**

15-2 22nd Federal Ambient Pollution Control Act of September 18, 2002
15-11 SJÖFS: Swedish Maritime Administration Decree (1997) 27

**Fig. 15-66** TEOM (Tapered Element Oscillating Microbalance): tapered glass tube with the filter at the tip. The tube’s vibration frequency changes with the filter’s load [15-40]

**Fig. 15-67** Schematic of the sensor and data processing systems of a Dekati mass monitor DMM [15-41]
15-15 Directive 70/220/EEC (Measures to be taken against air pollution by emissions from motor vehicles)
15-23 ACEA report on small particle emissions from passenger cars (1999)
15-30 Code of Federal Regulations: Control of Emissions from new and In-Use Highway Vehicles and Engines. 40 CFR 86.007-11
15-40 Thermo Electron Co.: TEOM Series 1105 Diesel Particulate Monitor Data Sheet (www.thermo.com)


Further Literature