

Exhaust-gas measuring techniques

Exhaust-gas test for type approval

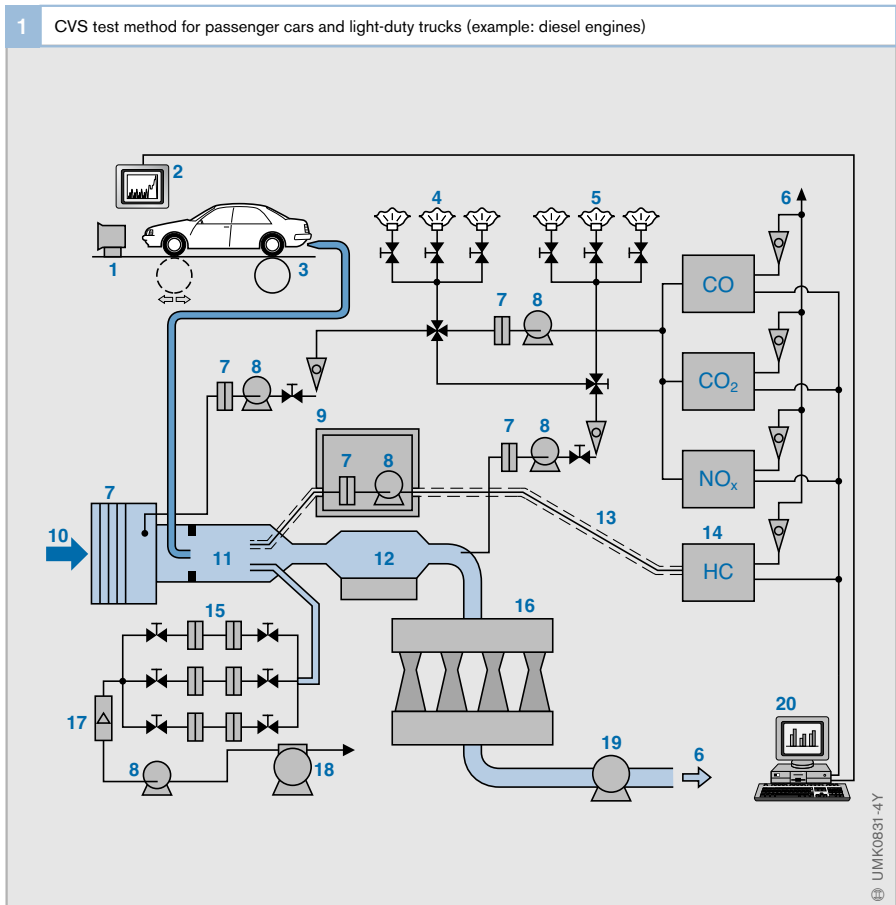
During type-approval testing to obtain General Certification for passenger cars and light-duty trucks, the exhaust-gas test is conducted with the vehicle mounted on a chassis dynamometer. The test differs from exhaust-gas tests that are conducted using workshop measuring devices for in-field monitoring.

For the type approval of heavy-duty trucks, exhaust-gas tests are carried out on engine test benches.

The prescribed test cycles on the chassis dynamometer stipulate that practical on-road driving mode must be simulated as closely as possible. Testing on a chassis dynamometer offers many advantages compared with on-road testing:

- The results are easy to reproduce since the ambient conditions are constant.
- The tests are comparable since a specified speed/time profile is driven irrespective of traffic flow.
- The required measuring instruments are set up in a stationary environment.

Fig. 1
 1 Cooling fan
 2 Driver display monitor
 3 "Rolling road" with dynamometer
 4 Air-sample bag
 5 Exhaust-gas bag
 6 Extraction
 7 Filter
 8 Pump
 9 Heated prefilter and pump
 10 Dilution air
 11 Dilution tunnel
 12 Heat exchanger
 13 Heated pipe
 14 Gas analyzers
 15 Measuring filter
 16 Quadruple venturi tubes
 17 Flow meter
 18 Gas meter
 19 CVS blower
 20 PC with monitor



Besides type-approval testing, exhaust-gas measurements on the chassis dynamometer are conducted during the development of engine components.

Test setup

The test vehicle is placed on a chassis dynamometer with its drive wheels on the rollers (Fig. 1, 3). The test cycle is repeated by a driver. During this cycle, the required and current vehicle speeds are displayed on a driver monitor. In some cases, an automated driving system replaces the driver to increase the reproducibility of test results by driving the test cycle with extreme precision.

This means that the forces acting on the vehicle, i.e. the vehicle's moments of inertia, rolling resistance, and aerodynamic drag, must be simulated so that the test cycle on the test bench reproduces emissions comparable to those obtained during an on-road test. For this purpose, asynchronous machines, direct-current machines, or even electrodynamic retarders on older test benches, generate a suitable speed-dependent load that acts on the rollers for the vehicle to overcome. More modern machines use electric flywheel simulation to reproduce this inertia. Older test benches use real flywheels of different sizes attached by rapid couplings to the rollers to simulate vehicle mass. A blower mounted a short distance in front of the vehicle provides the necessary engine cooling.

The test-vehicle exhaust pipe is generally a gas-tight attachment to the exhaust-gas collection system – the dilution system is described below. A proportion of the diluted exhaust gas is collected there. At the end of the test cycle, the gas is analyzed for pollutants limited by law (hydrocarbons, nitrogen oxides, and carbon monoxide), and carbon dioxide (to determine fuel consumption).

In addition, and for development purposes, part of the exhaust gas flow can be extracted continuously from sampling points along the vehicle's exhaust-gas system or dilution system to analyze pollutant concentrations.

The complete sampling system, including the exhaust-gas measuring instrument for hydrocarbons, is heated to 190°C to avoid any condensation of hydrocarbons that boil at high temperatures.

There is also a dilution tunnel with high internal flow turbulence, and a particulate filter whose loading is analyzed to determine particulate emissions.

CVS dilution procedure

The most commonly used method of collecting exhaust gases emitted from an engine is the Constant Volume Sampling (CVS) method. It was introduced for the first time in the U.S.A. in 1972 for passenger cars and light-duty trucks. In the meantime it has been updated in several stages. The CVS method is used in other countries, such as Japan. It has also been in use in Europe since 1982.

During the dilution process, exhaust gas is mixed with air, then part of this mixture is collected in bags. The exhaust gas is only analyzed at the end of the test. Dilution avoids condensation of water vapor contained in the exhaust gases and also prevents the loss of gas components that are dissolvable in water. Dilution also avoids secondary reactions in the collected exhaust gas, and simulates actual dilution conditions in the atmosphere.

Principle of the CVS method

Exhaust gas emitted by the test vehicle is diluted with ambient air (10) at an average ratio of 1:5...1:10, and extracted using a special pump setup (7, 8). This ensures that the total volumetric flow, comprising exhaust gas and dilution air, remains constant. The admixture of dilution air is therefore dependent on the momentary exhaust-gas volumetric flow. A sample is continuously extracted from the diluted exhaust-gas flow and is collected in one or more (5) exhaust-gas sample bags. Filling the sample bags generally corresponds to the phases in which the test cycles are divided (e.g. the ht phase in the FTP 75-test cycle).

As the exhaust-gas sample bags are filled, a sample of dilution air is taken and collected in one or more (4) air-sample bags in order to measure the pollutant concentration in the dilution air.

The sampling volumetric flow is constant during the bag-filling phase. The pollutant concentration in the exhaust-gas sample bags at the end of the test cycle corresponds to the average value of the concentrations in the diluted exhaust gas for the sample-bag filling period. The pollutant masses emitted during the test are calculated from these concentrations and from the total air/exhaust gas mixture conveyed from the volume – taking into account the pollutants contained in the dilution air.

Dilution systems

There are two alternative methods to obtain a constant volumetric flow of diluted exhaust gas:

- Positive Displacement Pump (PDP) method: A rotary-piston blower (Roots blower) is used.
- Critical Flow Venturi (CFV) method: A venturi tube and a standard blower are used in the critical state.

Advances in the CVS method

Diluting the exhaust gas causes a reduction in pollutant concentrations as a factor of dilution. As pollutant emissions have dropped significantly in the past few years due to the growing severity of emission limits, the concentrations of some pollutants (in particular hydrogen compounds) in the diluted exhaust gas are equivalent to concentrations in diluted air in certain test phases (or are even lower). This poses a problem from the measuring-process aspect, as the difference between the two values is crucial for measuring exhaust-gas emissions. A further challenge is presented by the precision of analyzers used to measure small concentrations of pollutants.

To confront these problems, more recent CVS dilution systems apply the following measures:

- Reduce dilution: This requires precautions to avoid the condensation of water, e.g. by heating parts of the dilution system.
- Reduce and stabilize pollutant concentrations in the dilution air, e.g. by using activated charcoal filters.
- Optimize the measuring instruments (including dilution systems), e.g. by selecting or preconditioning the materials used and system setups; by using modified electronic components.
- Optimize processes, e.g. by applying special purge procedures.

Bag Mini Diluter

As an alternative to advances in CVS technology described above, a new type of dilution system was developed in the U.S.A.: the Bag Mini Diluter (BMD). Here, part of the exhaust-gas flow is diluted at a constant ratio with dried, heated zero gas (e.g. cleaned air). During the test, part of the diluted exhaust-gas flow that is proportional to the exhaust-gas volumetric flow is filled in (exhaust-gas) sample bags and analyzed at the end of the driving test. Diluting the exhaust gas with a pollution-free zero gas dispenses with air-sample bag analysis followed by taking the difference between the exhaust-gas and air-sample bag concentrations. However, a more complex procedure is required than for the CVS method, e.g. one requirement is to determine the (undiluted) exhaust-gas volumetric flow and the proportional sample-bag filling.

Testing commercial vehicles

The transient test method for testing emissions from diesel engines in heavy-duty trucks over 8,500 lb. (U.S.) or 3.5 t (Europe) is performed on dynamic engine test benches and also uses the CVS test method. This test came into force in the U.S.A. starting model year 1986 and is slated for 2005 in Europe. However, the size of the engines demands a test setup with a substantially higher throughput in order to keep to the same dilution ratios as for cars and light-duty trucks. Double dilution (by means of a secondary tunnel) permitted by law helps to minimize equipment costs.

Under critical conditions, the volumetric flow rate of diluted exhaust gas is controllable, either using a calibrated Roots blower, or venturi tubes.

Exhaust-gas measuring devices

Emission-control legislation in the EU, the U.S.A., and Japan defines standard test procedures for emission-limit pollutants in order to measure the pollutant concentrations in exhaust-gas and air-sample bags:

- Measurement of CO and CO₂ concentrations with Non-Dispersive InfraRed (NDIR) analyzers.
- Measurement of NO_x concentrations (aggregate of NO and NO₂) using Chemi-Luminescence Detectors (CLD).
- Measurement of total hydrocarbon concentrations (THC) using Flame Ionization Detectors (FID).
- Gravimetric measurement of particulate emissions.

NDIR analyzer

The NDIR (Non-Dispersive InfraRed) analyzer uses the property of certain gases to absorb infrared radiation within a narrow characteristic wavelength band. The absorbed radiation is converted into vibrational and rotational energy of the absorbing molecules.

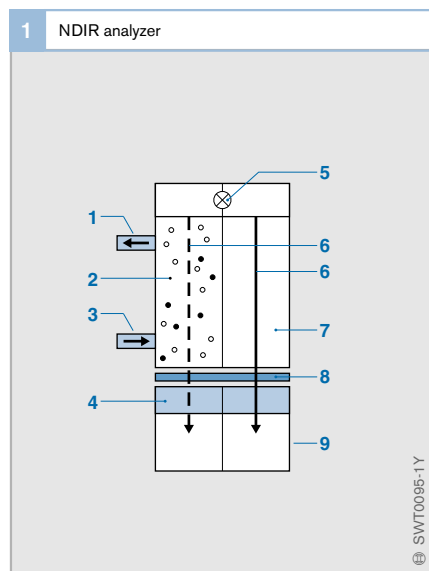


Fig. 1

- 1 Gas outlet
- 2 Absorption cell
- 3 Test-gas inlet
- 4 Optical filter
- 5 Infrared light source
- 6 Infrared radiation
- 7 Reference chopper
- 8 Rotating chopper
- 9 Detector

In the NDIR analyzer, the analysis gas flows through the absorption cell (vessel) (Fig. 1, 2) where it is exposed to infrared radiation. The gas absorbs radiation energy within the characteristic wavelength band of the pollutant, whereby the radiation energy is proportional to the concentration of the pollutant under analysis. A reference cell (7) arranged in parallel to the absorption cell is filled with an inert gas (e.g. nitrogen (N_2)).

The detector (9) is located at the opposite end of the cell to the infrared light source and measures the residual energy from infrared radiation in the measurement and reference cells. The detector comprises two chambers connected by a membrane and containing samples of the gas components under analysis. The reference-cell radiation characteristic for this component is absorbed in one chamber. The other absorbs radiation from the test-gas vessel. The difference between the radiation received and the radiation absorbed in the two detector chambers results in a pressure difference, and thus a deflection in the membrane between the measuring and reference detectors. This deflection is a measure of the pollutant concentration in the test-gas vessel.

A rotating chopper (8) interrupts infrared radiation cyclically, causing an alternating deflection of the membrane, and thus a modulation of the sensor signal.

NDIR analyzers have a strong cross-sensitivity¹⁾ to water vapor in the test gas since H_2O molecules absorb infrared radiation across a broad wavelength band. This is the reason why NDIR analyzers are positioned downstream of a test-gas treatment system (e.g. a gas cooler) to dry the exhaust gas when they are used to make measurements on undiluted exhaust gas.

ChemiLuminescence Detector (CLD)

Due to its measuring principle, the CLD is limited to determining NO concentrations. Before measuring the aggregate of NO_2 and NO concentrations, the test gas is first routed to a converter that reduces NO_2 into NO .

The test gas is mixed with ozone in a reaction chamber (Fig. 2) to determine the nitrogen monoxide concentration (NO). The nitrogen monoxide contained in the test gas oxidizes in this environment to form NO_2 ; some of the molecules produced are in a state of excitation. When these molecules return to their basic state, energy is released in the form of light (chemiluminescence).

1) The absorption of infrared radiation within a particular wavelength band is possible not only with the gas component measured, but also with water vapor.

Fig. 2

- 1 Reaction chamber
- 2 Ozone inlet
- 3 Test-gas inlet
- 4 Gas discharge
- 5 Filter
- 6 Detector

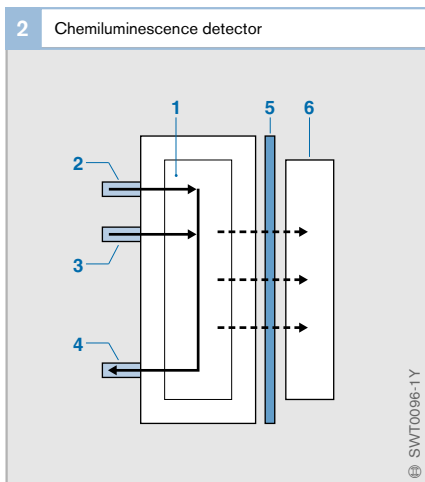
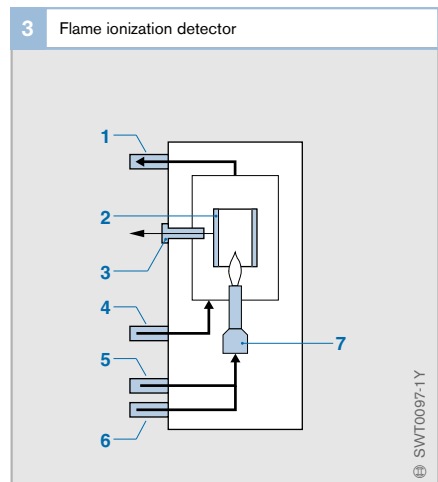


Fig. 3

- 1 Gas discharge
- 2 Collector electrode
- 3 Amplifier
- 4 Combustion air
- 5 Test-gas inlet
- 6 Combustion gas (H_2/He)
- 7 Burner



A detector, e.g. a photomultiplier, measures the emitted luminous energy; under specific conditions, it is proportional to the nitrogen-monoxide concentration in the test gas.

Flame Ionization Detector (FID)

The hydrocarbons present in the test gas are burned off in a hydrogen flame (Fig. 3). This forms carbon radicals; some of the radicals are ionized temporarily. The radicals are discharged at a collector electrode; the current produced is measured and is proportional to the number of carbon atoms in the test gas.

Measuring particulate emission

A gravimetric process is a process specified by law to measure particulate emissions during type-approval testing.

Gravimetric process (particulate filter process)

Part of the diluted exhaust gas is sampled from the dilution tunnel during the driving test and then channelled through particulate filters. The quantity of particulate emissions is calculated from the increase in weight of the (conditioned) particulate filter, taking into account volumetric flow. The gravimetric process has the following disadvantages:

- Relatively high detection limit, only reducible to a limited extent by using intensive instrument resources (e.g. to optimize tunnel geometry).
- It is not possible to measure particulate emissions continuously.
- The process requires numerous resources since the particulate filter requires conditioning to minimize environmental influences.
- Only particulate mass is measured; however, it is not possible to determine the chemical composition of the particulate or particle size.

Due to the disadvantages discussed above, as well as the drastic reduction in limits for particulate emissions anticipated in future, the lawmakers are considering replacing the gravimetric process, or supplementing it in order to determine particle-size distribution or particle quantity. However, an alternative process has not yet been found.

The measuring instruments that show particulate-size distribution in exhaust gas include the following:

- Scanning Mobility Particle Sizer (SMPS)
- Electrical Low Pressure Impactor (ELPI)
- Photo-Acoustic Soot Sensor (PASS)

Exhaust-gas measurement in engine development

For development purposes, many test benches also include the continuous measurement of pollutant concentrations in the vehicle exhaust-gas system or dilution system. The reason is to capture data on emission-limit components, as well as other components not subject to legislation. Other test procedures than those mentioned are required for this, e.g.:

- GC FID and Cutter FID to measure methane concentrations (CH_4).
- Paramagnetic method to measure oxygen concentrations (O_2).
- Opacity measurement to determine particulate emissions.

Other analyses can be conducted using multi-component analyzers:

- Mass spectroscopy
- FTIR (Fourier Transform InfraRed) spectroscopy
- IR laser spectroscopy

GC FID and Cutter FID

There are two equally common methods to measure methane concentration in the test gas. Each method consists of the combination of a CH_4 -separating element and a flame ionization detector. Either a gas-chromatography column (GC FID), or a heated catalytic converter, oxidizes the non- CH_4 hydrocarbons (cutter FID) in order to separate methane. Unlike the cutter FID, the GC FID can only determine CH_4 concentration discontinuously (typical interval between two measurements: 30...45 seconds).

ParaMagnetic Detector (PMD)

There are different designs of paramagnetic detectors (dependent on the manufacturer). The measuring principle is based on inhomogeneous magnetic fields that exert forces on molecules with paramagnetic properties (such as oxygen), causing the molecules to move. The movement is proportional to the concentration of molecules in the test gas and is sensed by a special detector.

Opacity measurement

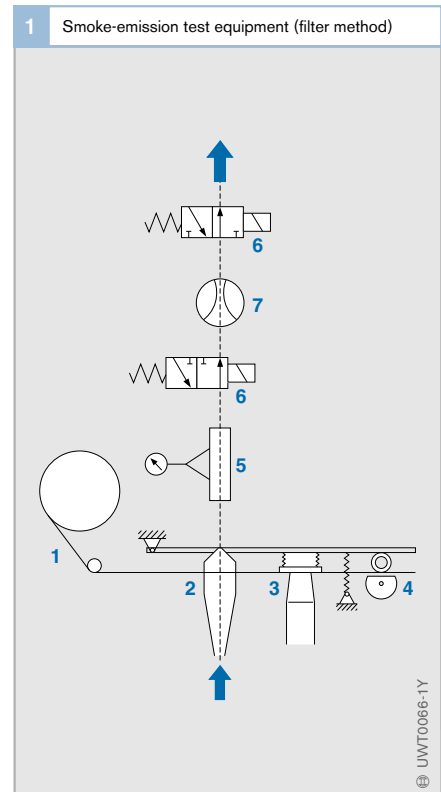
An opacity meter (opacimeter) is used in development and in diesel smoke-emission testing in the workshop during exhaust-gas testing (see the section entitled "Emissions testing (opacity measurement)").

The smoke-emission test equipment (Fig. 1) used in development extracts a specified quantity of diesel exhaust gas (e.g. 0.1 or 1 l) through a strip of filter paper. As a requirement for the high-precision reproducibility of results, the volume extracted is recorded for every test sequence and converted to the standardized quantity. The system also takes account of pressure and temperature impacts, as well as dead volume between the exhaust-gas sample probe and the filter paper.

The blackened filter paper is analyzed optoelectronically using a reflective photometer. The results are generally indicated as the Bosch smoke number or mass concentration (mg/m^3).

Fig. 1

- 1 Filter paper
- 2 Gas penetration
- 3 Reflective photometer
- 4 Paper transport
- 5 Volume measuring device
- 6 Purge-air switchover valves
- 7 Pump



Emissions testing (opacity measurement)

The procedure for emissions testing in the workshop comprises the following steps for a diesel-engined vehicle:

- Identifying the vehicle.
- Visually inspecting the exhaust-gas system.
- Testing engine speed and temperature.
- Detecting the average idle speed.
- Detecting the average breakaway speed.
- Opacity measurement: Initiating at least three accelerator bursts (unrestricted acceleration) to determine exhaust-gas opacity. If opacity figures are below the limit, and all three measured values are within a bandwidth of $< 0.5 \text{ m}^{-1}$, the vehicle passes the emissions test.

With effect from 2005 Germany also stipulates an on-board diagnosis as part of the emissions test.

Opacity meter (absorption method)

During unrestricted acceleration, a certain amount of exhaust gas is taken from the vehicle's exhaust pipe (without vacuum assistance), using an exhaust-gas sampling probe and a hose leading to the measuring chamber. This method avoids impacts arising from exhaust-gas backpressure and its fluctuations on test results, since pressure and temperature are controlled (Hartridge tester).

In the measuring chamber, a light beam passes through the diesel exhaust gas. Attenuation of the light is measured photoelectrically and displayed as a percentage opacity T or absorption coefficient k . High precision and good reproducibility of test results are dependent on a specific measuring-chamber length and keeping the inspection windows free from soot.

