FINAL DRAFT

INTERNATIONAL STANDARD

ISO/FDIS 8178-5

ISO/TC **70**/SC **8**

Secretariat: DIN

Voting begins on:
2021-01-19

Voting terminates on:
2021-03-16

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 5:
Test fuels

Moteurs alternatifs à combustion interne — Mesurage des émissions de gaz d'échappement —

Partie 5: Carburants d'essai

Reference number
ISO/FDIS 8178-5:2021(E)

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 70 *Internal combustion engines*, Subcommittee SC 8, *Exhaust gas emission measurement*.

This fourth edition cancels and replaces the third edition (ISO 8178-5:2015), which has been technically revised.

The main changes compared to the previous edition are as follows:

— the addition of reference fuels from EU Regulation 2017/654 exhaust emission requirements for internal combustion engines in non-road mobile machinery

— the addition of California Air Resources Board (CARB) E10 emissions certification fuel

— the addition of US Environmental Protection Agency Tier 3 E10 emissions certification fuel

— updates of fuel specifications from ISO 8217

A list of all parts in the ISO 8178 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

In comparison with engines for on-road applications, engines for off-road use are made in a much wider range of power output and configurations and are used in a great number of different applications.

Since fuel properties vary widely from country to country a broad range of different fuels is listed in this document — both reference fuels and commercial fuels.

Reference fuels are usually representative of specific commercial fuels but with considerably tighter specifications. Their use is primarily recommended for test bed measurements described in ISO 8178-1.

For measurements typically at site where emissions with commercial fuels, whether listed or not in this document, are to be determined, uniform analytical data sheets (see Clause 5) are recommended for the determination of the fuel properties to be declared with the exhaust emission results.

Reciprocating internal combustion engines — Exhaust emission measurement —

Part 5:
Test fuels

1 Scope

This document specifies fuels whose use is recommended for performing the exhaust emission test cycles given in ISO 8178-4.

It is applicable to reciprocating internal combustion engines for mobile, transportable and stationary installations excluding engines for vehicles primarily designed for road use. This document is applicable to engines used, e.g. earth-moving machines and generating sets, and for other applications.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 4259, *Petroleum and related products – Precision of measurement methods and results – Part 1: Determination of precision data in relation to methods of test*

ISO 6974 (all parts), *Natural gas – Determination of composition and associated uncertainty by gas chromatography*

ISO 6976, *Natural gas — Calculation of calorific values, density, relative density and Wobbe indices from composition*

ISO 8178-1, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 1: Test-bed measurement systems of gaseous and particulate emissions*

ISO 8178-4:2020, *Reciprocating internal combustion engines — Exhaust emission measurement — Part 4: Steady-state and transient test cycles for different engine applications*

ISO 8216-1, *Petroleum products — Fuels (class F) classification — Part 1: Categories of marine fuels*

ISO 8217, *Petroleum products — Fuels (class F) — Specifications of marine fuels*

ASTM D 4815, *A method for the determination of oxygenated compounds in reformulated fuels*

ASTM D 8221-18, *Standard Practice for Determining the Calculated Methane Number (MNC) of Gaseous Fuels Used in Internal Combustion Engines*

EN 228, *Automotive fuels – unleaded petrol – Requirements and test methods*

EN 15376, *Automotive fuels – ethanol as a blending component for petrol – Requirements and test methods*

EN 15489, *Ethanol as a blending component for petrol – Determination of water content – Karl Fischer coulometric titration method*

EN 16726, *Gas infrastructure - Quality of gas - Group H*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

Note 1 to entry Also see any applicable definitions contained in the standards listed in the tables in Annex B.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
carbon residue
residue remaining after controlled thermal decomposition of a product under a restricted supply of oxygen (air)

Note 1 to entry: The historical methods of Conradson and Ramsbottom have largely been replaced by the carbon residue (micro) method.

[SOURCE: ISO 1998-2:1998, 2.50.001]

3.2
cetane index
number, calculated to represent the approximate *cetane number* (3.3) of a product from its density and distillation characteristics

Note 1 to entry: The formula used for calculation is reproduced from statistical analysis of a very large representative sample of world-wide diesel fuels, on which cetane number and distillation data are known, and thus is subject to change at 5 to10 year intervals. The current formula is given in ISO 4264. It is not applicable to fuels containing an ignition-improving additive.

[SOURCE: ISO 1998-2:1998, 2.30.111]

3.3
cetane number
number on a conventional scale, indicating the ignition quality of a *diesel fuel* (3.5) under standardized conditions

Note 1 to entry: It is expressed as the percentage by volume of hexadecane (cetane) in a reference mixture having the same ignition delay as the fuel for analysis. The higher the cetane number, the shorter the delay.

[SOURCE: ISO 1998-2:1998, 2.30.110]

3.4
crude oil
naturally occurring form of petroleum, mainly occurring in a porous underground formation such as sandstone

Note 1 to entry: Crude oil is a hydrocarbon mixture, generally in a liquid state, which may also include compounds of sulfur, nitrogen, oxygen, metals and other elements.

[SOURCE: ISO 1998-1:1998, 1.05.005, modified — Note 1 to entry has been added.]

3.5
diesel fuel
gas-oil that has been specially formulated for use in medium and high-speed diesel engines, mostly used in the transportation market

Note 1 to entry: It is often referred to as “automotive diesel fuel”.

[SOURCE: ISO 1998-1:1998, 1.20.131, modified — The alternative term "automotive gas-oil" has been removed.]

3.6
liquefied petroleum gas
LPG
mixture of light hydrocarbons, consisting predominantly of propane, propene, butanes and butenes, that may be stored and handled in the liquid phase under moderate conditions of pressure and at ambient temperature

Note 1 to entry: The historical methods of Conradson and Ramsbottom have largely been replaced by the carbon residue (micro) method.

[SOURCE: ISO 1998-1:1998, 1.15.080, modified — The abbreviated term has been added; Note 1 to entry has been added.]

3.7
octane number
number on a conventional scale expressing the knock-resistance of a fuel for spark-ignition engines

Note 1 to entry: It is determined in test engines by comparison with reference fuels. There are several methods of test; consequently the octane number should be accompanied by reference to the method used.

[SOURCE: ISO 1998-2:1998, 2.30.100]

3.8
oxygenate
oxygen containing organic compound which may be used as a fuel or fuel supplement, such as various alcohols and ethers

3.9
natural gas
NG
complex gaseous mixture of hydrocarbons, primarily methane, but generally includes ethane, propane and higher hydrocarbons, and some non-combustible gases such as nitrogen and carbon dioxide

[SOURCE: ISO 14532:2014, 2.1.1.1, modified — Note 1 to entry has been removed.]

3.10
methane number
rating indicating the knocking characteristics of a fuel gas

Note 1 to entry: It is comparable to the octane number for petrol. One expression of the methane number is the volume percentage of methane in a methane-hydrogen mixture, that in a test engine under standard conditions has the same tendency to knock as the fuel gas to be examined.

[SOURCE: ISO 14532:2014, 2.6.6.1]

4 Symbols and abbreviated terms

The symbols and abbreviated terms used in this document are identical with those given in ISO 8178-4:2020, Clause 4. Those which are essential for this document are repeated below in order to facilitate comprehension.

Symbol	Definition	Unit
A/F_{st}	stoichiometric air to fuel ratio	—
λ	excess air factor (in kilogrammes dry air per kilogramme of fuel)	kg/kg
c_{gasd}	concentration of gas on a wet basis	% (V/V)
c_{gasw}	concentration of gas on a dry basis	% (V/V)
k_f	fuel specific factor for exhaust flow calculation on wet basis	—
k_{CB}	fuel specific factor for the carbon balance calculation	—
k_w	dry to wet correction factor for the raw exhaust gas	—
k_{wr}	dry to wet correction factor for the raw exhaust gas	—
k_f	fuel specific factor	—
H_a	absolute humidity of the intake air (g water/kg dry air)	g/kg
p_b	total atmospheric pressure	kPa
p_r	water vapor pressure after cooling bath	KPa
q_{mad}	intake air mass flow rate on dry basis	kg/h
q_{maw}	intake air mass flow rate on wet basis[a]	kg/h
q_{mew}	exhaust gas mass flow rate on wet basis[a]	kg/h
q_{mf}	fuel mass flow rate	kg/h
q_{ved}	exhaust gas volume flow rate on dry basis	m^3/s
q_{vew}	exhaust gas volume flow rate on wet basis	m^3/s
q_{vH20}	H_20 volume flow rate	m^3/s
w_{ALF}	mass fraction of hydrogen in the fuel	%
w_{BET}	mass fraction of carbon in the fuel	%
w_{GAM}	mass fraction of sulfur in the fuel	%
w_{DEL}	mass fraction of nitrogen in the fuel	%
w_{EPS}	mass fraction of oxygen in the fuel	%
z	fuel factor for calculation of w_{ALF}	—

[a] At reference conditions (T = 273,15 K and p = 101,3 kPa).

5 Choice of fuel

5.1 General

As far as possible, reference fuels should be used for certification of engines.

Reference fuels reflect the characteristics of commercially available fuels in different countries and are therefore different in their properties. Since fuel composition influences exhaust emissions, emission results with different reference fuels are not usually comparable. For lab-to-lab comparison of emissions even the properties of the specified reference fuel are recommended to be identical as far as possible. This can theoretically best be accomplished by using fuels from the same batch.

For all fuels (reference fuels and others), the analytical data shall be determined and reported with the results of the exhaust measurement.

For non-reference fuels, the data to be determined are listed in the following tables:

— Table 5 (Universal analytical data sheet — Natural gas);

— Table 9 (Universal analytical data sheet — Liquefied petroleum gas);

— Table 17 (Universal analytical data sheet — Engine gasolines);

— Table 21 (Universal analytical data sheet — Diesel fuels);

— Table 23 (Universal analytical data sheet — Distillate fuel oils);

— Table 25 (Universal analytical data sheet — Residual fuel oils);

— Table 26 (Universal analytical data sheet — Crude oil).

An elemental analysis of the fuel shall be carried out when an exhaust mass flow measurement or combustion air flow measurement, in combination with the fuel consumption, is not possible.

In such cases, the exhaust mass flow can be calculated using the concentration measurement results of the exhaust emission and using the calculation methods given in ISO 8178-4:2020, Annex D. In cases where the fuel analysis is not available, hydrogen and carbon mass fractions can be obtained by calculation. The recommended methods are given in Annex A: A.2.2, A.2.3 and A.2.4.

Emissions and exhaust gas flow calculations depend on the fuel composition. The calculation of the fuel specific factors, if applicable, shall be done in accordance with ISO 8178-4:2020, Annex D.

NOTE For non-ISO test methods equivalent to those of International Standards mentioned in this document, see Annex B.

5.2 Influence of fuel properties on emissions from compression ignition engines

5.2.1 General

Fuel quality has a significant effect on engine emissions. Certain fuel parameters have a more or less pronounced influence on the emissions level. A short overview on the most influencing parameters is given in 5.2.2 to 5.2.4.

5.2.2 Fuel sulfur

Sulfur naturally occurs in crude oil. The sulfur still contained in the fuel after the refining process is oxidized during the combustion process in the engine to SO_2, which is the primary source of sulfur emission from the engine. Part of the SO_2 is further oxidized to sulfate (SO_4) in the engine exhaust system, the dilution tunnel, or by an exhaust aftertreatment system. Sulfate will react with the water present in the exhaust to form sulfuric acid with associated water that will condense and finally be measured as part of the particulate emission (PM).

Consequently, fuel sulfur has a significant influence on the PM emission.

The mass of sulfates emitted from an engine depends on the following parameters:

— fuel consumption of the engine (BSFC);

— fuel sulfur content (FSC);

— $S \Rightarrow SO_4$ conversion rate (CR);

— weight increase by water absorption standardized to $H_2SO_4 \cdot 6{,}651H_2O$.

Fuel consumption and fuel sulfur content are measurable parameters, whereas the conversion rate can only be predicted, since it can vary from engine to engine. Typically, the conversion rate is approximately

2 % for engines without aftertreatment systems. Formula (1) has been applied for estimating the sulfur impact on PM:

$$S_{PM} = e_{fuel} \times \frac{X_{FSC}}{1{,}000{,}000} \times \frac{E}{100} \times 6{,}795\,296 \qquad (1)$$

where

S_{PM} is the brake specific contribution of fuel sulfur to PM, expressed in grams per kilowatt-hour (g/kw-h);

e_{fuel} is the brake specific fuel consumption, expressed in grams per kilowatt-hour (g/kW-h);

X_{FSC} is the fuel sulfur content, expressed in milligrams per kilogram (mg/kg);

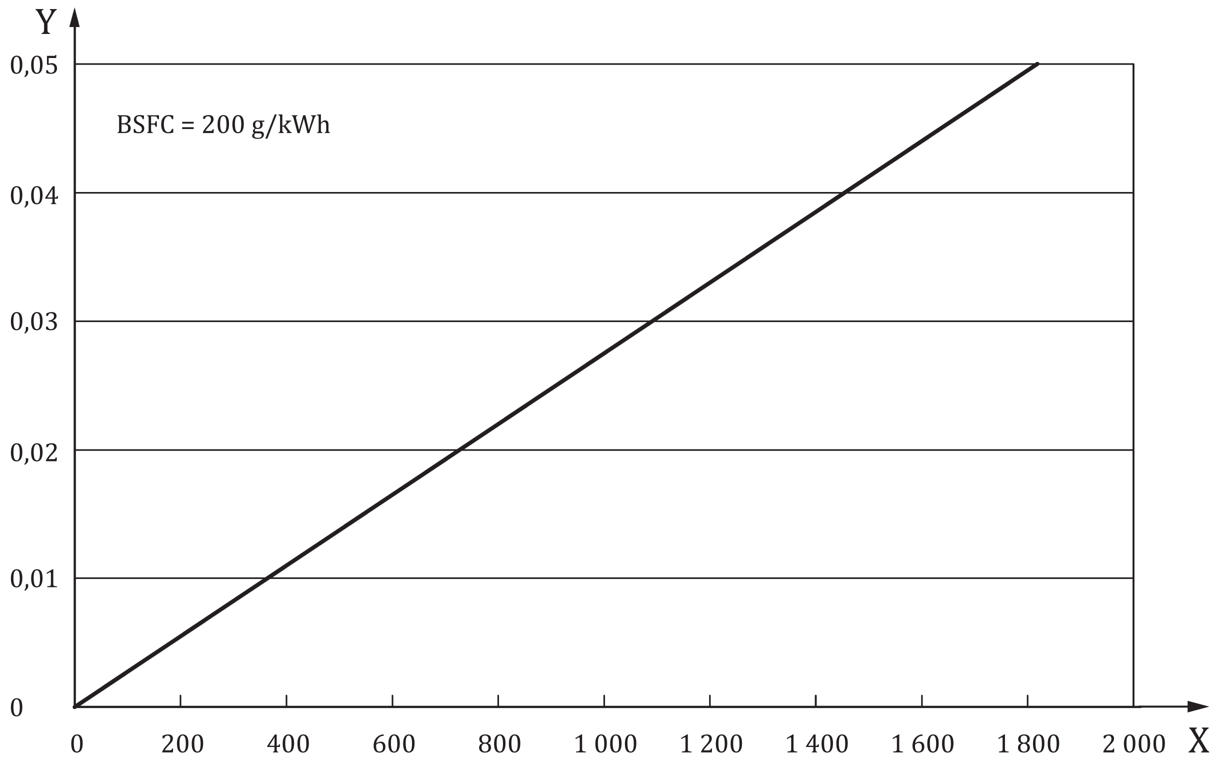
E is the $S \Rightarrow SO_4$ conversion rate, expressed in percent %;

6,795 296 is the $S \Rightarrow H_2SO_4 \cdot 6{,}651H_2O$ conversion factor.

This is based on the assumption that 1,221 6 grams of water is associated with each gram of H_2SO_4 because of the dew point temperature of 9,5 °C in the weighing environment. This corresponds to $6{,}651H_2O$.

The relationship between fuel sulfur content and sulfate emission is shown in Figure 1 for an engine without aftertreatment and a S to SO_4 conversion rate of 2 %.

Many aftertreatment systems contain an oxidation catalyst as an integral part of the overall aftertreatment system. The major purpose of the oxidation catalyst is to enhance specific chemical reactions necessary for the proper function of the aftertreatment system. Since the oxidation catalyst will also oxidize a considerable amount of SO_2 to SO_4, the aftertreatment system is likely to produce a high amount of additional particulates in the presence of fuel sulfur. When using such aftertreatment systems, the conversion rate can drastically increase to about 30 % to 70 % depending on the efficiency of the catalytic converter. This will have a major impact on the PM emission, as shown in Figure 2.

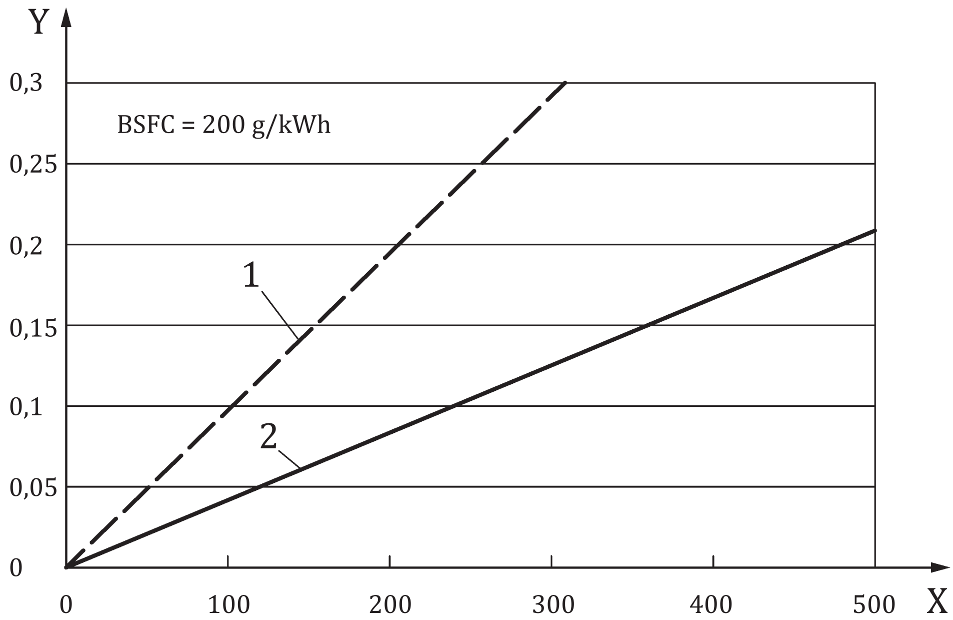


Key

X sulfur content, in mg/kg

Y sulfur PM, in g/kW · h

Figure 1 — Relationship between fuel sulfur and sulfate emission for engines without aftertreatment



Key

X sulfur content, in mg/kg

Y sulfur PM, in g/kW · h

1 70 % conversion

2 30 % conversion

Figure 2 — Relationship between fuel sulfur and sulfate emission for engines with aftertreatment

5.2.3 Specific considerations for marine fuels

For marine fuels (distillate and residual fuel oils), sulfur and nitrogen have a significant impact on PM and NO_x emissions, respectively.

Typically, the sulfur content is higher than that for onroad or nonroad diesel fuels by a factor of approximately 10, as shown in Table 22. Even without any aftertreatment system, the PM sulfur level will be approximately 0,4 g/kWh for a 2 % sulfur fuel. In addition, the high ash, vanadium and sediment fractions will significantly contribute to the total PM emission. As a consequence, the inherent engine PM emission, which is mainly soot, is only a very small fraction of the total PM emission. In the application of aftertreatment systems, 5.2.2 should be carefully considered.

The average nitrogen content of residual fuel oil is currently around 0,4 %, but steadily increasing. In some cases, nitrogen contents between 0,8 % and 1,0 % have been reported. Assuming a 55 % conversion rate at a nitrogen level of 0,8 % will increase the NO_x emission of the engine by more than 2 g/kWh. This is a significant portion of the total NO_x emission and shall therefore be carefully taken into account.

5.2.4 Other fuel properties

There are other fuel parameters that have a significant influence on emissions and fuel consumption of an engine. Contrary to the sulfur influence, their magnitude is less predictable and unambiguous, but there is always a general trend that is valid for all engines. The most important of these parameters are the cetane number (CN), density, poly-aromatic content, total aromatics content and distillation characteristics. Their influence is briefly summarized below.

For NO_x, total aromatics is the predominant parameter whereas the effect of poly-aromatics and density is less significant. This can be explained by an increase of the flame temperature with higher aromatics content during combustion, which results in an increased NO_x emission. For PM, density and poly-aromatics are the most significant fuel parameters. In general, NO_x will be reduced by 4 % if aromatics are reduced from 30 % to 10 %. A similar reduction is possible for PM when reducing poly-aromatics from 9 % to 1 %.

Increasing the CN will improve engine cold start and therefore white smoke emission. It has also a favourable influence on NO_x emission particularly at low loads, where reductions of up to 9 % can be achieved if CN is increased from 50 to 58, and fuel consumption with improvements of up to 3 % for the same CN range.

5.3 Influence of fuel properties on emissions from spark ignition (SI) engines

Fuel parameters that have a significant influence on emissions and fuel consumption of an SI engine include octane number, sulfur level, metal-containing additives, oxygenates, olefins and benzene.

Engines are designed and calibrated for a certain octane value or methane number. When a customer uses gasoline with an octane level lower than that required, or accordingly, a natural gas with a lower methane number, knocking can result which could lead to severe engine damage. Engines equipped with knock sensors can handle lower octane or methane number levels by retarding the spark timing.

As mentioned above, sulfur naturally occurs in crude oil. If the sulfur is not removed during the refining process, it will contaminate the fuel. Sulfur has a significant impact on engine emissions by reducing the efficiency of catalysts. Sulfur also adversely affects heated exhaust gas oxygen sensors. Consequently, high sulfur levels will significantly increase HC and NO_x emissions. Also, lean burn technologies, which require NO_x aftertreatment technologies, are extremely sensitive to sulfur.

Metal-containing additives usually form ash and can therefore adversely affect the operation of catalysts and other components, such as oxygen sensors, in an irreversible way that increases emissions. For example, MMT (methylcyclopentadienyl manganese tricarbonyl) is a manganese-based compound marketed as an octane-enhancing fuel additive for gasoline. The combustion products of MMT coat internal engine components, such as spark plugs, can potentially cause misfire which leads to increased emissions, increased fuel consumption and poor engine performance. They also accumulate and partly plug the catalyst causing an increased fuel consumption in addition to reduced emission control.

Oxygenated organic compounds, such as ethanol, are often added to gasoline to increase octane, to extend gasoline supplies, or to induce a lean shift in engine stoichiometry to reduce carbon monoxide emissions. The leaner operation reduces carbon monoxide emissions, especially with carbureted engines without electronic feedback-controlled fuel systems. However increased O_2 levels beyond that for which an open loop engine has been calibrated will typically increase NO_x emissions and combustion temperatures which can lead to premature engine failure.

Olefins are unsaturated hydrocarbons and, in many cases, are also good octane components of gasoline. However, olefins in gasoline can lead to gum and deposit formation and increased emissions of reactive (i.e. ozone-forming) hydrocarbons and toxic compounds.

Benzene is a naturally occurring constituent of crude oil and is also a product of catalytic reforming that produces high octane gasoline streams. It is also a known human carcinogen. The control of benzene levels in gasoline is the most direct way to limit evaporative and exhaust emissions of benzene from SI engines.

Proper volatility of gasoline is critical to the operation of SI engines with respect to both performance and emissions. Volatility is characterized by two measurements, vapour pressure and distillation.