Advanced Technologies to Reduce Motor Vehicle Pollution: The Critical Role of Low Sulfur Fuel

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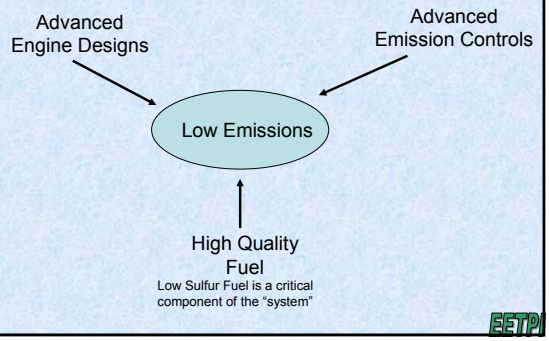
Introduction

- In several countries, pollution from new gasoline and diesel motor vehicles will be reduced by up to 99 percent by 2010 compared to uncontrolled vehicles
  - The U.S., Europe, Japan and other countries are adopting increasingly stringent standards
- Achieving very low emissions from motor vehicles requires a "systems approach" and low sulfur fuel is very important
- Sulfur in diesel and gasoline fuel adversely affects reduction of motor vehicle pollution

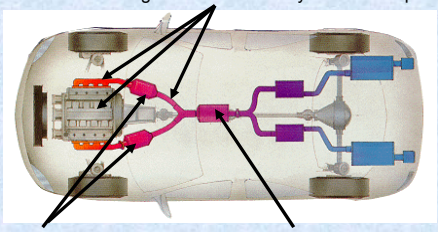
Significantly Reducing Harmful Emissions from Engines Requires a ***Systems Approach***



The Impact of Sulfur in Gasoline Fuel on Motor Vehicle Emission Control

The Three-Way Catalytic Converter is the Critical Component of Emission Control Technology

Air-gap Manifolds, Exhaust Pipes, Coolant Heat Storage for Efficient Engine and Exhaust System Heat-up



Close-coupled Converters for Fast Heat-up

Underfloor Converter for High NOx Efficiency

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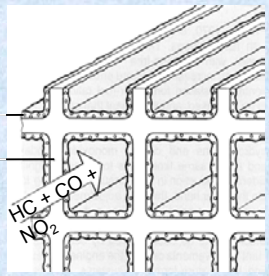
Method of Operation of the Three-Way Catalytic Converter

1 Catalyst Layer Containing Platinum and Rhodium
2 Ceramic or Metal Substrate



Chemical Reactions:

$2\ CO + O_2 \longrightarrow 2\ CO_2$

$2\ C_2H_6 + 7\ O_2 \longrightarrow 4\ CO_2 + 6\ H_2O$

$2\ NO + 2\ CO \longrightarrow N_2 + 2\ CO_2$

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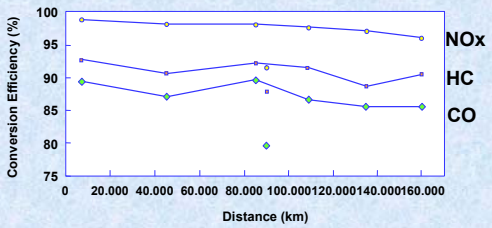
TWC Catalysts Are Durable Even Under Extreme Use Conditions, If Properly Fueled and Maintained



PM-Loading = 105 g/ft³; PM Ratio = Pt/Pd/Rh 1/14/1
50 g/ft³; PM-Ratio = Pt/Rh 5/1
European Testcycle Evaluation (MVEG-Cycle)

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Fuel Sulfur Negatively Affects Catalyst-Based Emission Control Technology

- Sulfur inhibits emission control performance
- Sulfur inhibition is a serious problem in meeting tighter emission control standards
- Low sulfur gasoline will allow recovery of catalyst performance of in-use on-road vehicles by up to 25% to 35% -- *the result is an immediate and significant reduction in pollution from catalyst-equipped vehicles that are currently being used in Central America*

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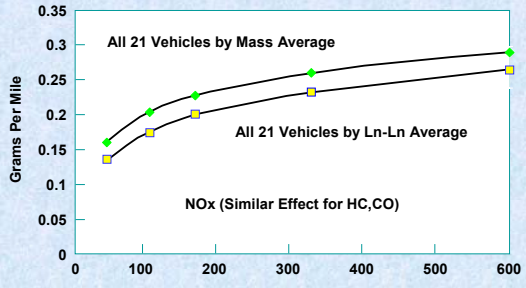
Fuel Sulfur Level Affects Catalyst NOx Performance

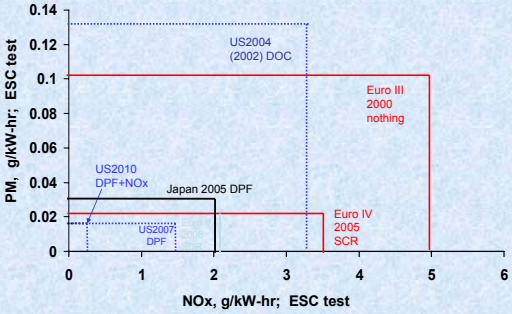


Vehicle/Engine Manufacturers Call for Reducing Sulfur in Gasoline: *World-Wide Fuel Charter* – December 2002

- No Emission Control Requirements or First Level of Emission Control – 1000 ppm max.
- Stringent Emission Control Requirement (e.g. U.S. 1982 standards) – 200 ppm max.
- Advanced Emission Control Requirements (e.g., U.S. Tier 2 standards) – 30 ppm max.
- Future Advanced Requirements to Enable Sophisticated NOx control technologies (lean burn engines) – 5-10 ppm max.

The Impact of Sulfur in Diesel Fuel on Emission Control

Heavy-duty Diesel Regulations are Progressively Tightening Around the World



Early Emission Reductions Were Achieved with Engine Design Changes

- Heavy-duty:
  - High Pressure Injection
  - Electronic Fuel Injection
  - Advanced Injection Timing
  - Turbo Charger
  - Turbo Charger with Intercooler
- Light-duty:
  - Common Rail Fuel Injection

But Advanced Emission Control Technology Is Needed For a Truly Clean Diesel Engine

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Advanced Emission Control Technologies

- PM, CO, HC, and Toxics
  - Diesel Particulate Filters (DPFs)
  - Diesel Oxidation Catalysts (DOCs)
  - Crankcase Emission Controls
- Oxides of Nitrogen (NOx)
  - Lean NOx Catalysts
  - NOx Adsorbers
  - Selective Catalytic Reduction with Urea Injection

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Diesel Particulate Filters Are Efficient and Are Developing an Impressive Track Record

- Filter Control Capabilities
  - PM reductions with ultra-low sulfur fuel
    - PM mass - >85%; fine PM - >99%
  - CO and HC - up to 90% Reduction
  - Toxic HCs - up to 90% Reduction
- Filter Operating Experience
  - 750,000 Passenger Cars in Europe
  - Over 150,000 Trucks and Buses
  - Over 20,000 Off-Road Engines

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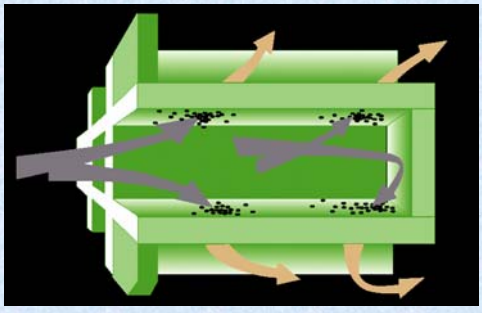
Diesel Particulate Filter



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Filter from Bus Application

Filter Inlet Section

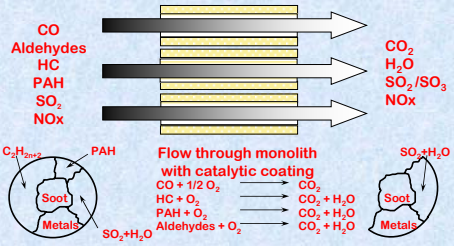
Filter Outlet Section

Reducing PM from Existing Diesels

Diesel Oxidation Catalysts Are Efficient and Have Excellent Operating Experience

- Oxidation Catalyst Control Capabilities
  - PM - 20-50% Reduction Organic PM
  - CO and HC - up to 90% Reduction
  - Toxic HCs - up to 70% Reduction
  - Diesel Odor Eliminated
- Oxidation Catalyst Operating Experience
  - >250,000 Off-Road Engines
  - >1,500,000 Heavy Trucks and Buses
  - >1,500,000 Class 1 & 2 Vehicles (Pick-Ups)
  - >50,000,000 LDD Vehicles in Europe

Diesel Oxidation Catalyst



Lean NOx Catalyst Technology

- Flow-Through Catalyst Technology. Formulated for NOx control, it incorporates ceramic micro cages that allow NOx reduction with HC even though the surrounding exhaust gas is lean (excess oxygen)
  - Most lean NOx catalyst systems inject a small amount of diesel fuel or other reductant into the exhaust to enhance NOx control
- Lean NOx catalysts can achieve a 10 percent (without fuel injection) to >40 percent (with fuel injection) NOx reduction
- Lean NOx catalyst technology has been utilized on new passenger cars (without fuel injection) in Europe for a number of years and is being developed for diesel retrofit applications in California

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NOx Adsorber Technology

- NOx adsorbers look and act much like a 3-way catalyst (TWC).
- The TWC stores and releases oxygen under cyclic stoichiometric conditions to control HC, CO, and NOx.
- The challenge is to control NOx emissions in the oxygen-rich exhaust environment of a diesel engine
- The solution is a specially designed TWC catalyst that
  - Stores NOx emissions during lean (oxygen rich) modes
  - Releases and reduces NO_x to nitrogen during rich operation

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SCR Is Very Successful Worldwide on Stationary Sources and Is Now Applied to On-Road Engines

- SCR Control Performance (with Integral Oxidation Function)
  - PM - 20-50% reduction of organic PM
  - CO and HC - up to 90%
  - Toxic HCs - up to 70%
  - NOx - 50 to 90%
- SCR Operating Experience
  - HD truck demonstration in Europe since 1995 with mileage exceeding 400,000 miles
  - Expected to be used to meet the HDE Euro 4 standards in 2005
  - Some use on locomotives and marine vessels

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Advanced Emission Control Technology Can be Retrofitted on Existing Diesel Engines

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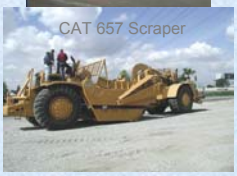
Off-Road Engines Can Be Retrofitted



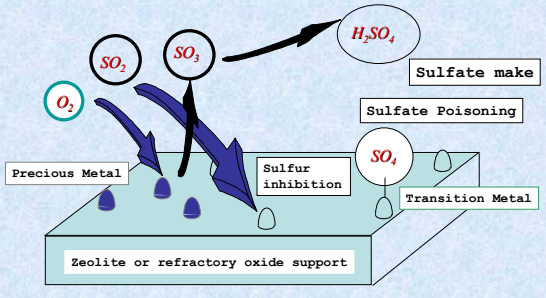
Sulfur Is *the* Problem

- Of All Fuel Constituents that Affect Engine-Out Emissions, Low Sulfur Fuel Is the Most Important for Best Results from Catalyst-Based Emission Control Technology
- Fuel Sulfur Adversely Affects Performance of All Catalyst-Based Emission Control Technologies
- Near Zero Sulfur Levels (<15 ppm Sulfur) Enables the Application of the Full Range of Catalyst Technologies and Provides for Optimization of Each Technology for Maximum Emission Control Performance

Fuel Sulfur Negatively Affects Catalyst-Based Emission Control Technology

- Impacts of Sulfur
  - SO_2 Sticks to Catalyst Sites (Chemisorption)
    - Inhibits Gaseous Catalytic Reactions
  - Catalytic Oxidation of SO_2 to SO_3
    - Catalyst Increases this Reaction Under Exhaust Conditions
    - SO_3 Adds to Tailpipe PM Emissions – Up to 40 to 50% of SO_2 Can Be Oxidized to SO_3
    - SO_3 Reacts with Catalyst Base Metal Oxides to Form Metal Sulfate that is Not Catalytic
    - For Catalyst-Based Diesel Particulate Filters, Sulfur Adversely Effects the Regeneration of the Filter
    - For NOx Adsorbers, Sulfate Clogs Up and Shuts Down the NOx Storage Mechanism

Sulfur Effects

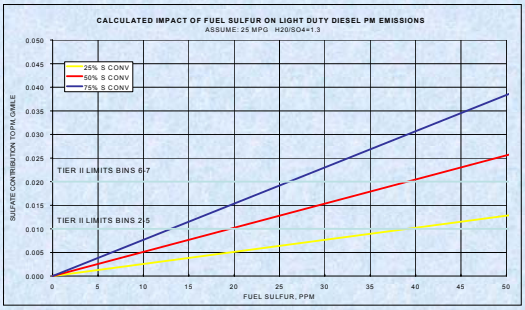


Summary of Influence of Fuel Sulfur on Diesel Exhaust Emission Control Devices

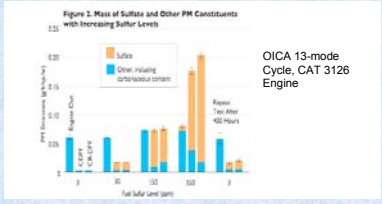
Control Technology	Sulfur Effects
– Oxidation Catalyst	– Inhibition, form SO_3 PM
– Lean NOx Catalyst	– Inhibition, form SO_3 PM
– SCR with Urea	– Inhibition, form SO_3 PM
– Catalytic Filters	– Inhibition, form SO_3 and Affects Regeneration
– NOx Adsorbers	– Clogging, form SO_3 and store as sulfate – requires periodic removal

All Catalyst Technologies Adversely Affected

Impact of Sulfur on PM Emissions on Light-Duty Vehicle Equipped with a Catalyst-Based Diesel Particulate Filter



The DECSE Study Showed that Low Sulfur Diesel Is Critical to Achieving a 0.01 g/bhp-hr PM Standard



OICA 13-mode Cycle, CAT 3126 Engine

95% filtration efficiency at 3 ppm sulfur
74% filtration efficiency at 30 ppm sulfur

From DOE website: Diesel Emission Control - Sulfur Effects; Sponsored by DOE, EMA, MECA, and National Labs

Vehicle/Engine Manufacturers Call for Reducing Sulfur in Diesel Fuel: *World-Wide Fuels Charter* – December 2002

- No Emission Control Requirements or First Level of Emission Control – 3000 ppm max.
- Stringent Emission Control Requirement (e.g. U.S. 1991 standards) – 300 ppm max.
- Advanced Emission Control Requirements (e.g., U.S. 2004 standards) – 30 ppm max.
- Further Advanced Requirements to Enable Sophisticated PM and NOx control technologies (e.g., U.S. 2007 Standards) – 5-10 ppm max.

REDUCTION OF DIESEL FUEL SULFUR (FROM 2500 ppm TO 500ppm MAX S) HAS SIGNIFICANT BENEFITS

- Reduced PM Emissions
- Reduced Corrosive Engine Wear (Less Iron Particles in the Lubrication Oil)
  - Result: Estimated 30%-50% Longer Engine Life
- 500 ppm Sulfur Diesel Allows for Application of Selected Emission Control Technology – Potential 70 to 90% reduction

But to maximize the benefits of available emission controls, 150 ppm S would be a better first step

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Conclusion

- Fuel Quality Is an Integral Part of a Complete Emission Control System for Both Gasoline- and Diesel-Powered Vehicles
- Fuel Sulfur Adversely Effects All Catalyst-Based Emission Control Technology and Needs to Be Reduced
- Using a Systems Approach with Ultra-Low Sulfur Fuel Combined with Advanced Engine Designs and Advanced Emission Control Technology, Cars, Trucks, and Buses Will Emit 99% Less Pollution As Compared to Vehicles in the 1960s

Fuel Sulfur Content: The Lower, the Better

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Conclusion (continued)

- Introducing Low Sulfur Gasoline Fuel Will Immediately Improve the Emission Control Performance of Existing Catalyst-Equipped Vehicles
- Introducing Low Sulfur Diesel Fuel Will Enable Existing Engines to be Retrofitted with Advanced Control Technology
- Where Possible, EEPTI Recommends:
  - Gasoline – First Step Reduction <1000 ppm and Next Step 30 ppm
  - Diesel -- First Step Reduction <150 ppm and Next Step <15 ppm

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Appendix

World-Wide Fuels Charter
Recommended Diesel Fuel Quality Specifications

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CATEGORY 1. UNLEADED GASOLINE

Markets with no or first level of emission controls; based primarily on fundamental vehicle/engine performance and protection of emission control system

Properties		Units	Limit Min.	Limit Max.
'91 RON' [1]	Research Octane Number	--	91.0	
	Motor Octane Number	--	82.0	
'95 RON' [1]	Research Octane Number	--	95.0	
	Motor Octane Number	--	85.0	
'98 RON' [1]	Research Octane Number	--	98.0	
	Motor Octane Number	--	88.0	
Sulfur Content		mg/kg		1000[2] max
Metal Content (Fe,Mn,Pb[3],other)		g/l	Non-Detectable[4]	
Oxygen Content[5]		%m/m		2.7 max
Aromatics Content		%v/v		50 max
Benzene Content		%v/v		5 max

[1] See note 1. for Category 2. [2] The unit mg/kg is often expressed as ppm. Lower sulfur content preferred for catalyst-equipped vehicles [3] No intentional lead addition. Maximum level of 0.005 g/l is acceptable during the transition period [4] Metal-containing additives are accepted for valve seat protection on non-catalyst cars only. In this case, potassium-based additives are recommended. [5] See Category 3 Note 4.

CATEGORY 2. UNLEADED GASOLINE

Markets with stringent requirements for emission controls or other market demands

Properties		Units	Limit Min.	Limit Max.
'91 RON' [1]	Research Octane Number	--	91.0	--
	Motor Octane Number	--	82.5	--
'95 RON' [1]	Research Octane Number	--	95.0	--
	Motor Octane Number	--	85.0	--
'98 RON' [1]	Research Octane Number	--	98.0	--
	Motor Octane Number	--	88.0	--
Sulfur Content		mg/kg		200[2] max
Metal Content (Fe,Mn,Pb,Others)		g/l	Non-Detectable[3]	
Oxygen Content[4]		%m/m		2.7 max
Aromatics Content		%v/v		40 max
Benzene Content		%v/v		2.5 max

[1] Adequate Labeling of Pumps Must Be Defined and Used; Fuel Should Be Dispensed through Nozzles Meeting SAE J285, 'Recommended Practice Gasoline Dispenser Nozzle Spouts'. Three Octane Grades Defined for Maximum Market Flexibility. Availability of All Three Not Needed. [2] The unit mg/kg is often expressed as ppm. [3] At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. [4] See Category 3 Note 4.

CATEGORY 3. UNLEADED GASOLINE

Markets with advanced requirements for emission controls or other market demands

Properties		Units	Limit Min.	Limit Max.
'91 RON' [1]	Research Octane Number	--	91.0	--
	Motor Octane Number	--	82.5	--
'95 RON' [1]	Research Octane Number	--	95.0	--
	Motor Octane Number	--	85.0	--
'98 RON' [1]	Research Octane Number	--	98.0	--
	Motor Octane Number	--	88.0	--
Sulfur Content		mg/kg		30[2] max
Metal Content (Fe,Mn,Pb,Others)		g/l	Non-Detectable[3]	
Oxygen Content[4]		%m/m		2.7 max
Aromatics Content		%v/v		35 max
Benzene Content		%v/v		1.0 max

[1] See note for Category 2. [2] The unit mg/kg is often expressed as ppm. [3] At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. [4] Where oxygenates are used ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and pH_e 6.5-9) is permitted the blended fuel must meet Category 1 requirements and fuelling pump labeling is recommended. Higher (C> 2) alcohols are limited to 0.1% max by volume. Methanol is not permitted.

CATEGORY 4. UNLEADED GASOLINE

Markets with further advanced requirements for emission control, to enable sophisticated NOx technologies

Properties		Units	Limit Min.	Limit Max.
'91 RON' [1]	Research Octane Number	--	91.0	--
	Motor Octane Number	--	82.5	--
'95 RON' [1]	Research Octane Number	--	95.0	--
	Motor Octane Number	--	85.0	--
'98 RON' [1]	Research Octane Number	--	98.0	--
	Motor Octane Number	--	88.0	--
Sulfur Content		mg/kg		Sulfur-free[2] max
Metal Content (Fe,Mn,Pb,Other)		g/l	Non-Detectable[3]	
Oxygen Content[4]		%m/m		2.7 max
Aromatics Content		%v/v		10 max
Benzene Content		%v/v		1.0 max

[1] Same as Note 1 for Category 2. [2] 5-10 mg/kg Maximum Depending on Applicable Emission Standard. The unit of mg/kg is often expressed as ppm. As More Data Becomes Available, a More Specific Maximum Will Be Defined. [3] At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. [4] See Category 3 Note 4.

CATEGORY 1. DIESEL FUEL

Markets with no or first level of emission controls; based primarily on fundamental vehicle / engine performance and protection of emission control systems

Properties	Units	Limit	
		Min.	Max.
Cetane Number[1]	--	48.0[2]	--
Cetane Number[1]	--	45.0[3]	--
Density @ 15 °C	kg/m^3	820[4]	850
Viscosity @ 40 °C	mm^2/s	2.0[5]	4.0
Sulfur Content	ppm	--	3000[6]
T95	°C	--	370
Flash Point	°C	55[7]	--

[1] Compliance with either cetane index or number is allowed. [2] The Minimum Limit Can Be Relaxed to 45.0 When Ambient Temperatures Are Below -30°C. [3] The Minimum Limit Can Be Relaxed to 42.0 When Ambient Temperatures Are Below -30°C. [4] The Minimum Limit Can Be Relaxed to 800 kg/m^3 When Ambient Temperatures Are Below -30°C. [5] The Minimum Limit Can Be Relaxed to 1.5 mm^2/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm^2/s When Ambient Temperatures Are Below -40°C. [6] Limit of 3000 ppm Commonly Referred to as 0.30 mg/kg. [7] Compliance Either with T90 or T95 Is Required, Not Both.

CATEGORY 2. DIESEL FUEL

Markets with stringent requirements for emission controls or other market demands

Properties	Units	Limit	
		Min.	Max.
Cetane Number	--	53.0[1]	--
Cetane Number	--	50.0[2]	--
Density @ 15 °C	kg/m^3	820[3]	850
Viscosity @ 40 °C	mm^2/s	2.0[4]	4.0
Sulfur Content	ppm	--	300[5]
Total Aromatics Content	%m/m	--	25
Polyaromatics Content (di+tri+)	%m/m	--	5
T90[6]	°C	--	340
T95[6]	°C	--	355
Final Boiling Point	°C	--	365
Flash Point	°C	55	--

[1] The Minimum Limit Can Be Relaxed to 48.0 When Ambient Temperatures Are Below -30°C. [2] The Minimum Limit Can Be Relaxed to 45.0 When Ambient Temperatures Are Below -30°C. [3] The Minimum Limit Can Be Relaxed to 800 kg/m^3 When Ambient Temperatures Are Below -30°C. For Environmental Purposes, a Minimum of 815 kg/m^3 Can Be Adopted. [4] The Minimum Limit Can Be Relaxed to 1.5 mm^2/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm^2/s When Ambient Temperatures Are Below -40°C. [5] Limit of 300 ppm Commonly Referred to as 0.03 %m/m. [6] Compliance Either with T90 or T95 Is Required, Not Both.

CATEGORY 3. DIESEL FUEL

Markets with advanced requirements for emission controls or other market demands

Properties	Units	Limit	
		Min.	Max.
Cetane Number	--	55.0[1]	--
Cetane Number	--	52.0[2]	--
Density @ 15 °C	kg/m^3	820[3]	840
Viscosity @ 40 °C	mm^2/s	2.0[4]	4.0
Sulfur Content	ppm	--	30[5]
Total Aromatics Content	%m/m	--	15
Polyaromatics Content (di+tri+)	%m/m	--	2.0
T90[6]	°C	--	320
T95[6]	°C	--	340
Final Boiling Point	°C	--	350
Flash Point	°C	55	--

[1] The Minimum Limit Can Be Relaxed to 50.0 When Ambient Temperatures Are Below -30°C. [2] The Minimum Limit Can Be Relaxed to 47.0 When Ambient Temperatures Are Below -30°C. [3] The Minimum Limit Can Be Relaxed to 800 kg/m^3 When Ambient Temperatures Are Below -30°C. For Environmental Purposes, a Minimum of 815 kg/m^3 Can Be Adopted. [4] The Minimum Limit Can Be Relaxed to 1.5 mm^2/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm^2/s When Ambient Temperatures Are Below -40°C. [5] Limit of 30 ppm Commonly Referred to as 0.003 mg/kg. [6] Compliance Either with T90 or T95 Is Required, Not Both.

CATEGORY 4. DIESEL FUEL

Markets with further advanced requirements for emission control, to enable sophisticated NOx and PM emission control technologies

Properties	Units	Limit	
		Min.	Max.
Cetane Number	--	55.0[1]	--
Cetane Number	--	52.0[2]	--
Density @ 15 °C	kg/m^3	820[3]	840
Viscosity @ 40 °C	mm^2/s	2.0[4]	4.0
Sulfur Content	%m/m	--	Sulfur-Free[5]
Total Aromatics Content	%m/m	--	15
Polyaromatics Content (di+tri+)	%m/m	--	2.0
T90[6]	°C	--	320
T95[6]	°C	--	340
Final Boiling Point	°C	--	350
Flash Point	°C	55	--

[1] The Minimum Limit Can Be Relaxed to 50.0 When Ambient Temperatures Are Below -30°C. [2] The Minimum Limit Can Be Relaxed to 47.0 When Ambient Temperatures Are Below -30°C. [3] The Minimum Limit Can Be Relaxed to 800 kg/m^3 When Ambient Temperatures Are Below -30°C. For Environmental Purposes, a Minimum of 815 kg/m^3 Can Be Adopted. [4] The Minimum Limit Can Be Relaxed to 1.5 mm^2/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm^2/s When Ambient Temperatures Are Below -40°C. [5] 5-10 ppm Maximum, depending on the applicable emission standard. The unit ppm is often expressed as mg/kg. [6] Compliance Either with T90 or T95 Is Required, Not Both.