

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

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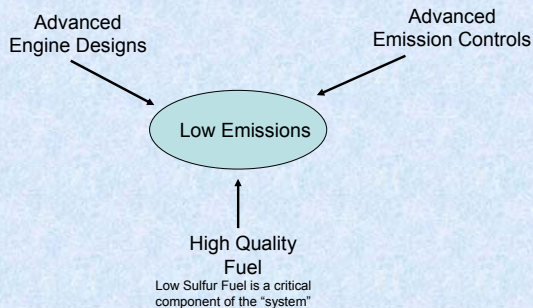
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### Introduction

- 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

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



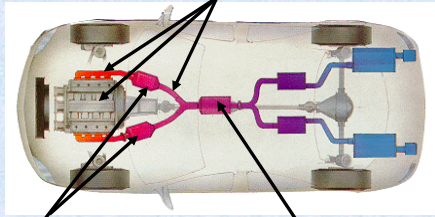
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### The Impact of Sulfur in Gasoline Fuel on Motor Vehicle Emission Control

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### 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

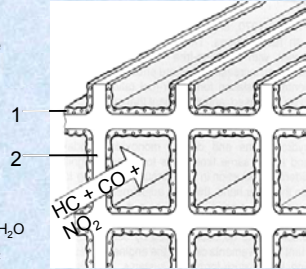
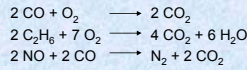
Underfloor Converter for High NOx Efficiency

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### Method of Operation of the Three-Way Catalytic Converter

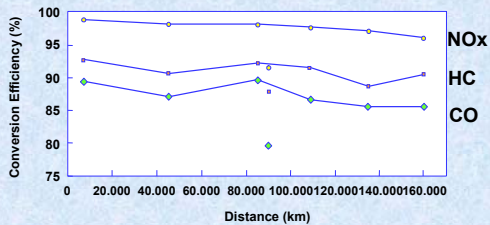
- 1 Catalyst Layer Containing Platinum and Rhodium
- 2 Ceramic or Metal Substrate

Chemical Reactions:



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



PM-Loading = 105 g/ft<sup>3</sup>; PM Ratio = Pt/Pd/Rh 1/14/1  
50 g/ft<sup>3</sup>; PM-Ratio = Pt/Rh 5/1  
European Testcycle Evaluation (MVEG-Cycle)

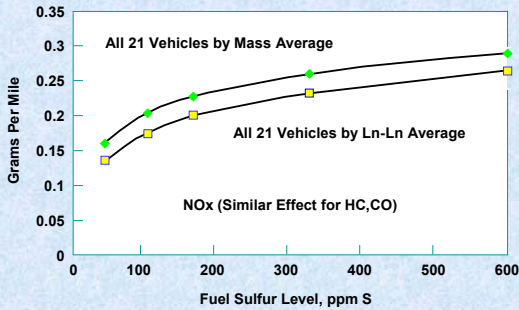
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### Fuel Sulfur Negatively Affects Catalyst-Based Emission Control Technology

- 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



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

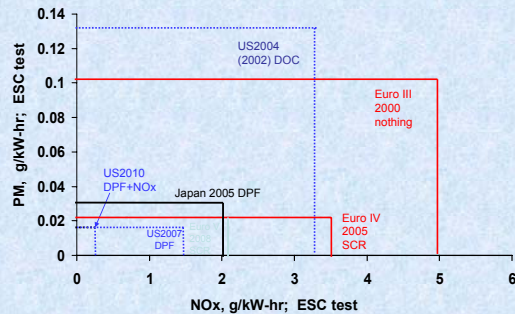
- No Emission Control Requirements or First Level of Emission Control – 1000 ppm max.
- Stringent Emission Control Requirement (e.g. U.S. 1982 standards) – 200 ppm max.
- Advanced Emission Control Requirements (e.g., U.S. Tier 2 standards) – 30 ppm max.
- Future Advanced Requirements to Enable Sophisticated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

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### The Impact of Sulfur in Diesel Fuel on Emission Control

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### Heavy-duty Diesel Regulations are Progressively Tightening Around the World



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### 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

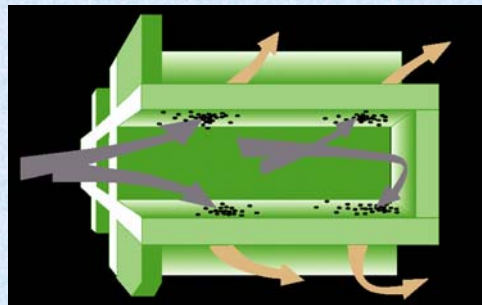
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### Diesel Particulate Filters Are Efficient and Are Developing an Impressive Track Record

- 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

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## Reducing PM from Existing Diesels



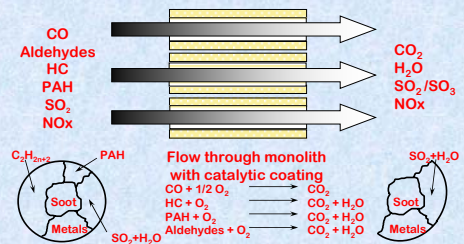
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## Diesel Oxidation Catalysts Are Efficient and Have Excellent Operating Experience

- 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

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## Diesel Oxidation Catalyst



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### 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



### 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 NOx to nitrogen during rich operation



### 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



### Advanced Emission Control Technology Can be Retrofitted on Existing Diesel Engines



## Off-Road Engines Can Be Retrofitted



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## 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

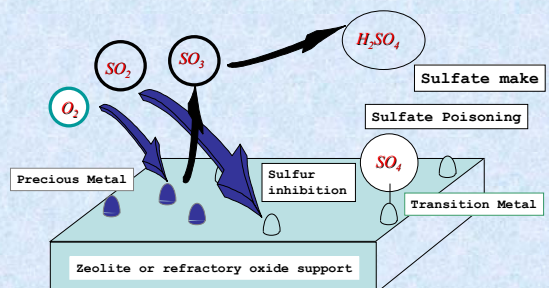
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## Fuel Sulfur Negatively Affects Catalyst-Based Emission Control Technology

- Impacts of Sulfur
  - $\text{SO}_2$  Sticks to Catalyst Sites (Chemisorption)
    - Inhibits Gaseous Catalytic Reactions
  - Catalytic Oxidation of  $\text{SO}_2$  to  $\text{SO}_3$ 
    - Catalyst Increases this Reaction Under Exhaust Conditions
    - $\text{SO}_3$  Adds to Tailpipe PM Emissions – Up to 40 to 50% of  $\text{SO}_2$  Can Be Oxidized to  $\text{SO}_3$
    - $\text{SO}_3$  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  $\text{NO}_x$  Adsorbers, Sulfate Clogs Up and Shuts Down the  $\text{NO}_x$  Storage Mechanism

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## Sulfur Effects



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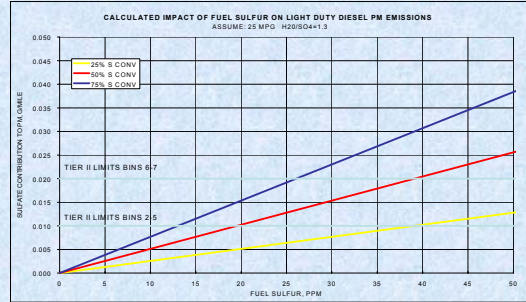
## Summary of Influence of Fuel Sulfur on Diesel Exhaust Emission Control Devices

- **Control Technology**
  - Oxidation Catalyst
  - Lean NOx Catalyst
  - SCR with Urea
  - Catalytic Filters
  - NOx Adsorbers
- **Sulfur Effects**
  - Inhibition, form SO<sub>3</sub> PM
  - Inhibition, form SO<sub>3</sub> PM
  - Inhibition, form SO<sub>3</sub> PM
  - Inhibition, form SO<sub>3</sub> and Affects Regeneration
  - Clogging, form SO<sub>3</sub> and store as sulfate – requires periodic removal

All Catalyst Technologies  
Adversely Affected

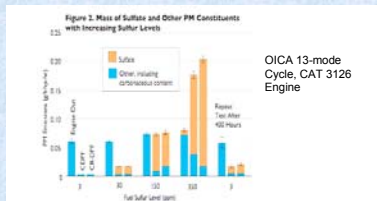
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## Impact of Sulfur on PM Emissions on Light-Duty Vehicle Equipped with a Catalyst-Based Diesel Particulate Filter



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



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

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## 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.

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

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



### CATEGORY 2. UNLEADED GASOLINE

Markets with stringent requirements for emission controls or other market demands

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

<sup>1</sup> 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. <sup>2</sup> The unit mg/kg is often expressed as ppm. <sup>3</sup> At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. <sup>4</sup> See Category 3 Note 4.



### CATEGORY 3. UNLEADED GASOLINE

Markets with advanced requirements for emission controls or other market demands

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

<sup>1</sup> See note for Category 2. <sup>2</sup> The unit mg/kg is often expressed as ppm. <sup>3</sup> At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. <sup>4</sup> Where oxygenates are used ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and pH, 6.5-9) is permitted the blended fuel must meet Category 1 requirements and fuelling pump labeling is recommended. Higher (> 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.	Max.
'91 RON' <sup>1</sup> Research Octane Number Motor Octane Number	--	91.0	--
	--	82.5	--
'95 RON' <sup>1</sup> Research Octane Number Motor Octane Number	--	95.0	--
	--	85.0	--
'98 RON' <sup>1</sup> Research Octane Number Motor Octane Number	--	98.0	--
	--	88.0	--
Sulfur Content	mg/kg	Sulfur-free <sup>2</sup> max	
Metal Content (Fe,Mn,Pb,Other)	g/l	Non-Detectable <sup>3</sup>	
Oxygen Content <sup>4</sup>	%m/m	2.7 max	
Aromatics Content	%v/v	10 max	
Benzene Content	%v/v	1.0 max	

<sup>1</sup> Same as Note 1 for Category 2. <sup>2</sup> 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. <sup>3</sup> At or Below Detection Limit of Test Method Used. No Intentional Addition of Metal-Based Additives. <sup>4</sup> 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 <sup>1</sup>	--	48.0 <sup>2</sup>	--
Cetane Number <sup>1</sup>	--	45.0 <sup>3</sup>	--
Density @ 15 °C	kg/m <sup>3</sup>	820 <sup>4</sup>	850
Viscosity @ 40 °C	mm <sup>2</sup> /s	2.0 <sup>5</sup>	4.0
Sulfur Content	ppm	--	3000 <sup>6</sup>
T95	°C	--	370
Flash Point	°C	55 <sup>7</sup>	--

<sup>1</sup> Compliance with either cetane index or number is allowed. <sup>2</sup> The Minimum Limit Can Be Relaxed to 45.0 When Ambient Temperatures Are Below -30°C. <sup>3</sup> The Minimum Limit Can Be Relaxed to 42.0 When Ambient Temperatures Are Below -30°C. <sup>4</sup> The Minimum Limit Can Be Relaxed to 800 kg/m<sup>3</sup> When Ambient Temperatures Are Below -30°C. <sup>5</sup> The Minimum Limit Can Be Relaxed to 1.5 mm<sup>2</sup>/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm<sup>2</sup>/s When Ambient Temperatures Are Below -40°C. <sup>6</sup> Limit of 3000 ppm Commonly Referred to as 0.30 mg/kg. <sup>7</sup> 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 <sup>1</sup>	--
Cetane Number	--	50.0 <sup>2</sup>	--
Density @ 15 °C	kg/m <sup>3</sup>	820 <sup>3</sup>	850
Viscosity @ 40 °C	mm <sup>2</sup> /s	2.0 <sup>4</sup>	4.0
Sulfur Content	ppm	--	300 <sup>5</sup>
Total Aromatics Content	%m/m	--	25
Polyaromatics Content (di+tri+)	%m/m	--	5
T90 <sup>6</sup>	°C	--	340
T95 <sup>6</sup>	°C	--	355
Final Boiling Point	°C	--	365
Flash Point	°C	55	--

<sup>1</sup> The Minimum Limit Can Be Relaxed to 48.0 When Ambient Temperatures Are Below -30°C. <sup>2</sup> The Minimum Limit Can Be Relaxed to 45.0 When Ambient Temperatures Are Below -30°C. <sup>3</sup> The Minimum Limit Can Be Relaxed to 800 kg/m<sup>3</sup> When Ambient Temperatures Are Below -30°C. For Environmental Purposes, a Minimum of 815 kg/m<sup>3</sup> Can Be Adopted. <sup>4</sup> The Minimum Limit Can Be Relaxed to 1.5 mm<sup>2</sup>/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm<sup>2</sup>/s When Ambient Temperatures Are Below -40°C. <sup>5</sup> Limit of 300 ppm Commonly Referred to as 0.03 %m/m. <sup>6</sup> 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 <sup>1</sup>	--
Cetane Number	--	52.0 <sup>2</sup>	--
Density @ 15 °C	kg/m <sup>3</sup>	820 <sup>3</sup>	840
Viscosity @ 40 °C	mm <sup>2</sup> /s	2.0 <sup>4</sup>	4.0
Sulfur Content	ppm	--	30 <sup>5</sup>
Total Aromatics Content	%m/m	--	15
Polyaromatics Content (di+tri+)	%m/m	--	2.0
T90 <sup>6</sup>	°C	--	320
T95 <sup>6</sup>	°C	--	340
Final Boiling Point	°C	--	350
Flash Point	°C	55	--

<sup>1</sup> The Minimum Limit Can Be Relaxed to 50.0 When Ambient Temperatures Are Below -30°C. <sup>2</sup> The Minimum Limit Can Be Relaxed to 47.0 When Ambient Temperatures Are Below -30°C. <sup>3</sup> The Minimum Limit Can Be Relaxed to 800 kg/m<sup>3</sup> When Ambient Temperatures Are Below -30°C. For Environmental Purposes, a Minimum of 815 kg/m<sup>3</sup> Can Be Adopted. <sup>4</sup> The Minimum Limit Can Be Relaxed to 1.5 mm<sup>2</sup>/s When Ambient Temperatures Are Below -30°C, and to 1.3 mm<sup>2</sup>/s When Ambient Temperatures Are Below -40°C. <sup>5</sup> Limit of 30 ppm Commonly Referred to as 0.003 mg/kg. <sup>6</sup> 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 <sup>1</sup>	--
Cetane Number	--	52.0 <sup>2</sup>	--
Density @ 15 °C	kg/m <sup>3</sup>	820 <sup>3</sup>	840
Viscosity @ 40 °C	mm <sup>2</sup> /s	2.0 <sup>4</sup>	4.0
Sulfur Content	%m/m	--	Sulfur-Free <sup>5</sup>
Total Aromatics Content	%m/m	--	15
Polyaromatics Content (di+tri+)	%m/m	--	2.0
T90 <sup>6</sup>	°C	--	320
T95 <sup>6</sup>	°C	--	340
Final Boiling Point	°C	--	350
Flash Point	°C	55	--

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

