



# WORLD-WIDE FUEL CHARTER

DECEMBER 2002



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European Automobile  
Manufacturers Association



Alliance of  
Automobile Manufacturers



Engine Manufacturers  
Association



Japan Automobile  
Manufacturers Association

December 2002

Dear World-Wide Fuel Charter Recipient:

Subject: **World-Wide Fuels Harmonisation**

On behalf of automobile and engine manufacturers from around the world, the World-Wide Fuel Charter Committee is pleased to present the newest edition of the World-Wide Fuel Charter. The Charter was first established in 1998 to promote greater understanding of the fuel quality needs of motor vehicle technologies and to harmonise fuel quality world-wide in accordance with vehicle needs.

Regions of Asia, Europe and North America have been adopting stringent new requirements for lowering vehicle emissions and continuing to explore the opportunity for reducing fuel consumption. To cope with these emerging needs, automobile and engine manufacturers have concluded from existing research that the sulfur levels of both gasoline and diesel fuel must be dramatically lowered to enable advanced and future motor vehicle technologies to meet these new requirements. The most stringent of these requirements led to the recommendation for sulfur-free fuels in Category 4, which the Committee adopted in 2000. We are pleased that so many countries around the world have begun taking steps to reduce the sulfur content in gasoline and diesel fuel.

At the other end of the spectrum, numerous countries around the globe continue to allow the use of lead in their gasoline. Leaded gasoline poses a serious, direct threat to public health and is a barrier to the introduction of automotive emission control systems that can reduce exhaust emissions by 90 percent or more over uncontrolled levels. It also impedes global harmonisation of vehicle technology. Automakers and engine manufacturers around the world support efforts to end the use of lead in gasoline. The key change in this 3rd edition of the Fuel Charter is the elimination of any allowance for lead use anywhere in the world.

Some areas that are reducing the use of lead may be using metallic or ash-forming substitutes that also may harm emission control systems. This Charter revision recommends against the use of any metal-based additives replacing lead in commercial fuels to avoid potential health risks and damage to catalysts.

We thank those who submitted comments on these fuel specifications, which we have carefully reviewed. We look forward to working with you to implement these harmonised specifications for the benefit of consumers and the environment.

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- National Association of Automobile Manufacturers of South Africa (NAAMSA)
- Thai Automotive Industry Association (TAIA)

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- Organisation Internationale des Constructeurs d'Automobiles (OICA)

ACRONYM LIST	4
INTRODUCTION	5
CATEGORY 1 <b>UNLEADED GASOLINE</b>	7
CATEGORY 2 <b>UNLEADED GASOLINE</b>	8
CATEGORY 3 <b>UNLEADED GASOLINE</b>	9
CATEGORY 4 <b>UNLEADED GASOLINE</b>	10
VOLATILITY CLASSES FOR HARMONISED <b>GASOLINE SPECIFICATIONS</b>	11
VAPOUR/LIQUID RATIO	11
TEST METHODS <b>GASOLINE</b>	12
CATEGORY 1 <b>DIESEL FUEL</b>	13
CATEGORY 2 <b>DIESEL FUEL</b>	14
CATEGORY 3 <b>DIESEL FUEL</b>	15
CATEGORY 4 <b>DIESEL FUEL</b>	16
TEST METHODS <b>DIESEL FUEL</b>	17
TECHNICAL BACKGROUND FOR HARMONISED FUEL RECOMMENDATIONS <b>GASOLINE</b>	19
TECHNICAL BACKGROUND FOR HARMONISED FUEL RECOMMENDATIONS <b>DIESEL FUEL</b>	35
SOURCES OF THE GRAPHS	49

<b>AAMA</b>	American Automobile Manufacturers Association ceased to exist after 31 December 1998 (whose members were formerly Chrysler, Ford and GM)
<b>ACEA</b>	Association des Constructeurs Européens d'Automobiles (European automotive manufacturers association)
<b>AIAM</b>	Association of International Automobile Manufacturers
<b>Alliance</b>	Alliance of Automobile Manufacturers
<b>AMA</b>	Accelerated Mileage Accumulation
<b>AQIRP</b>	Air Quality Improvement Research Programme (part of the US Auto Oil programme, 1989-1992)
<b>ASTM</b>	(ASTM International) American Society for Testing and Materials
<b>CCD</b>	Combustion Chamber Deposits
<b>CEC</b>	Coordinating European Council For The Development Of Performance Tests For Transportation Fuels, Lubricants And Other Fluids
<b>CFPP</b>	Cold Filter Plugging Point
<b>CI</b>	Cetane Index
<b>CN</b>	Cetane Number
<b>CO</b>	Carbon Monoxide
<b>CO<sub>2</sub></b>	Carbon Dioxide
<b>CP</b>	Cloud Point
<b>CRC</b>	Coordinating Research Council (US)
<b>DECSE</b>	Diesel Emission Control – Sulfur Effects, research program of the US Department of Energy
<b>DI</b>	Distillation Index
<b>DIN</b>	Deutsches Institut für Normung (German Institute of Standardisation)
<b>DVPE</b>	Dry Vapour Pressure Equivalence
<b>EMA</b>	Engine Manufacturers Association
<b>EN</b>	European Norm
<b>EPA</b>	Environmental Protection Agency (US)
<b>EPEFE</b>	European Programme on Emissions, Fuels and Engine Technology (part of the European Auto Oil I programme, 1993-1995)
<b>FAME</b>	Fatty Acid Methyl Esters
<b>FBP</b>	Final Boiling Point
<b>FLTM</b>	Ford Laboratory Test Method
<b>HC</b>	Hydrocarbons
<b>HFRR</b>	High Frequency Reciprocating Rig
<b>ICP-AES</b>	Inductively Coupled Plasma - Atomic Emission Spectrometry
<b>IP</b>	The Institute of Petroleum
<b>ISO</b>	International Organisation for Standardisation
<b>IVD</b>	Intake Valve Deposits
<b>JAMA</b>	Japan Automobile Manufacturers Association
<b>JARI</b>	Japan Automobile Research Institute
<b>JIS</b>	Japanese Industrial Standards
<b>LEV</b>	Low Emission Vehicle
<b>LTFT</b>	Low Temperature Flow Test
<b>MECA</b>	Manufacturers of Emission Controls Association
<b>MMT</b>	Methylcyclopentadienyl Manganese Tricarbonyl
<b>MtBE</b>	Methyl tertiary Butyl Ether
<b>MON</b>	Motor Octane Number
<b>NF M</b>	Norme Française - Industrie du Pétrole (French Norm - Petroleum Industry)
<b>NFT</b>	Norme Française - Industrie Chimique (French Norm - Chemical Industry)
<b>NO<sub>x</sub></b>	Oxides of Nitrogen
<b>OBD</b>	On-Board Diagnostics
<b>OFF</b>	Ozone Forming Potential
<b>Oxy</b>	Oxygen
<b>PAH</b>	Polyaromatic Hydrocarbons
<b>pH<sub>e</sub></b>	Acidity of ethanol
<b>PM</b>	Particulate Matter
<b>ppm</b>	parts per million
<b>RON</b>	Research Octane Number
<b>SULEV</b>	Super-Ultra-Low Emission Vehicle
<b>TGA</b>	Thermal Gravimetric Analysis
<b>THC</b>	Total Hydrocarbons
<b>TLEV</b>	Transitional Low Emission Vehicle
<b>TWD</b>	Total Weighted Demerits
<b>ULEV</b>	Ultra-Low Emission Vehicle
<b>VDE</b>	Vegetable Derived Esters

The objective of the global fuels harmonisation effort is to develop common, world-wide recommendations for 'quality fuels', taking into consideration customer requirements and vehicle emission technologies, which will in turn benefit our customers and all other affected parties.

**Development** of these common recommendations will ensure that automotive and engine manufacturers provide consistent fuel quality advice, world-wide.

**Implementation** of the recommendations will:

- Reduce the impact of motor vehicles on environment through reduced vehicle fleet emissions;
- Consistently satisfy customer performance expectations; and
- Minimise vehicle equipment complexities with optimised fuels for each emission control category, which will reduce customer costs (purchase and operation) and increase satisfaction.

Four different categories of fuel quality have been established for both unleaded gasoline and diesel fuel. These are described below.

**Category 1:**

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

**Category 2:**

Markets with stringent requirements for emission control or other market demands.

*For example, markets requiring US Tier 0 or Tier 1, EURO 1 and 2 or equivalent emission standards.*

**Category 3:**

Markets with advanced requirements for emission control or other market demands.

*For example, markets requiring US California LEV, ULEV and EURO 3 and 4, or equivalent emission standards.*

**Category 4:**

Markets with further advanced requirements for emission control, to enable sophisticated NO<sub>x</sub> and particulate matter after-treatment technologies.

*For example, markets requiring US California LEV-II, US EPA Tier 2, EURO 4 in conjunction with increased fuel efficiency constraints or equivalent emission standards.*

These fuel quality recommendations are for the properties of the finished fuel as provided to the end user. Internal quality control methods are not dictated or restricted, as long as the fuel meets these specifications. Where national requirements are more severe than these recommendations, those national limits have to be met.

To meet future customer, environmental and energy challenges, the automotive and engine industries are exploring advanced propulsion technologies world-wide. While Category 3 has been defined as those requirements needed by advanced technologies, as they exist today, Category 4 has been defined as a sulfur-free fuel to meet the needs of advanced and future vehicle technologies.

All the Categories will be reviewed and revised as appropriate to reflect changes in vehicle technologies, petroleum refining, and test methods.



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	-	91.0	--
	Motor Octane Number	-	82.0	--
'95 RON' <sup>(1)</sup>	Research Octane Number	-	95.0	--
	Motor Octane Number	-	85.0	--
'98 RON' <sup>(1)</sup>	Research Octane Number	-	98.0	--
	Motor Octane Number	-	88.0	--
Oxidation stability	minutes	360	--	
Sulfur content	mg/kg	--	1000 <sup>(2)</sup>	
Metal content (Fe, Mn, Pb <sup>(3)</sup> , other)	g/l	--	Non detectable <sup>(4)</sup>	
Oxygen content	% m/m	--	2.7 <sup>(5)</sup>	
Aromatics content	% v/v	--	50.0	
Benzene content	% v/v	--	5.0	
Volatility		See Following Tables, page 11		
Unwashed gums	mg/100 ml	--	70	
Washed gums	mg/100 ml	--	5	
Density	kg/m <sup>3</sup>	715	780	
Copper corrosion	merit	Class I		
Appearance		Clear and Bright		
Carburettor cleanliness	merit	8.0 <sup>(6)</sup>	--	
Fuel injector cleanliness	% flow loss	--	10 <sup>(6)</sup>	
Intake valve cleanliness I	merit	9.0 <sup>(6)</sup>	--	

**General Notes:**

N.B. # 1: Additives must be compatible with engine oils (no increase in engine sludge/varnish deposits).  
Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

**Footnotes:**

- (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. Lower sulfur content preferred for catalyst-equipped vehicles.
- (3) No intentional lead addition. Maximum level of 0.005 g/l is acceptable during the transitional period.
- (4) Metal-containing additives are accepted for valve seat protection in non-catalyst cars only. In this case, potassium-based additives are recommended.
- (5) Where oxygenates are used, ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and a pH<sub>e</sub> of 6.5-9) is permitted, by pre-existing regulation, the blended fuel must meet all other Category I requirements and fuelling pump labelling is recommended. Higher (C > 2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.
- (6) Compliance with this requirement can be demonstrated by the use of proper detergent additives in comparable-base gasolines.



Markets with stringent requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT		
		Min.	Max.	
'91 RON' <sup>(1)</sup>	Research Octane Number	-	91.0	--
	Motor Octane Number	-	82.5	--
'95 RON' <sup>(1)</sup>	Research Octane Number	-	95.0	--
	Motor Octane Number	-	85.0	--
'98 RON' <sup>(1)</sup>	Research Octane Number	-	98.0	--
	Motor Octane Number	-	88.0	--
Oxidation stability	minutes	480	--	
Sulfur content	mg/kg	--	200 <sup>(2)</sup>	
Metal content (Fe, Mn,Pb,Others)	g/l	Non-detectable <sup>(3)</sup>		
Phosphorus content	mg/l	Non-detectable <sup>(3)</sup>		
Silicon content	mg/kg	Non-detectable <sup>(3)</sup>		
Oxygen content	% m/m	--	2.7 <sup>(4)</sup>	
Olefins content	% v/v	--	20.0	
Aromatics content	% v/v	--	40.0	
Benzene content	% v/v	--	2.5	
Volatility		See Following Tables, page 11		
Sediment	mg/l	--	1	
Unwashed gums <sup>(5)</sup>	mg/100 ml	--	70	
Washed gums	mg/100 ml	--	5	
Density	kg/m <sup>3</sup>	715	770	
Copper corrosion	merit	Class I		
Appearance		Clear and Bright		
Fuel injector cleanliness	% flow loss	--	5	
Intake-valve sticking	pass/fail	Pass		
Intake valve cleanliness II				
Method 1 (CEC F-05-A-93), or	avg. mg/valve	--	50	
Method 2 (ASTM D 5500), or	avg. mg/valve	--	100	
Method 3 (ASTM D 6201)	avg. mg/valve	--	90	
Combustion chamber deposits <sup>(5)</sup>				
Method 1 (ASTM D 6201), or	% of base fuel		140	
Method 2 (CEC-F-20-A-98), or	mg/engine		3500	
Method 3 (TGA - FLTM BZ154-01)	% mass.@ 450° C		20	

**General Notes:**

N.B. # 1: Additives must be compatible with engine oils (no increase in engine sludge/varnish deposits). Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

**Footnotes:**

(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): Where oxygenates are used, ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and a p<sub>H</sub><sub>e</sub> of 6.5-9) is permitted by pre-existing regulations, the blended fuel must meet all other Category 2 requirements and fuelling pump labelling is recommended. Higher (C > 2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.

(5): Compliance with either the Unwashed Gum limit or the Combustion Chamber Deposits limit is permitted.

Markets with advanced requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT		
		Min.	Max.	
'91 RON' <sup>(1)</sup>	Research Octane Number	-	91.0	--
	Motor Octane Number	-	82.5	--
'95 RON' <sup>(1)</sup>	Research Octane Number	-	95.0	--
	Motor Octane Number	-	85.0	--
'98 RON' <sup>(1)</sup>	Research Octane Number	-	98.0	--
	Motor Octane Number	-	88.0	--
Oxidation stability	minutes	480	--	
Sulfur content	mg/kg	--		30 <sup>(2)</sup>
Metal content (Fe,Mn,Pb,Other)	g/l			Non-detectable <sup>(3)</sup>
Phosphorus content	mg/l			Non-detectable <sup>(3)</sup>
Silicon content	mg/kg			Non-detectable <sup>(3)</sup>
Oxygen content	% m/m	--		2.7 <sup>(4)</sup>
Olefins content	% v/v	--		10.0
Aromatics content	% v/v	--		35.0
Benzene content	% v/v	--		1.0
Volatility				See Following Tables, page 11
Sediment	mg/l	--		1
Unwashed gums <sup>(5)</sup>	mg/100 ml	--		30
Washed gums	mg/100 ml	--		5
Density	kg/m <sup>3</sup>	715		770
Copper corrosion	merit			Class I
Appearance				Clear and Bright
Fuel injector cleanliness	% flow loss	--		5
Intake-valve sticking	pass/fail			Pass
Intake valve cleanliness II				
Method 1 (CEC F-05-A-93), or	avg. mg/valve	--		30
Method 2 (ASTM D 5500), or	avg. mg/valve	--		50
Method 3 (ASTM D 6201)	avg. mg/valve	--		50
Combustion chamber deposits <sup>(5)</sup>				
Method 1 (ASTM D 6201), or	% of base fuel			140
Method 2 (CEC-F-20-A-98), or	mg/engine	--		2500
Method 3 (TGA FLTM BZ154-01)	% mass. @ 450° C			20

### General Notes:

N.B. # 1: Additives must be compatible with engine oils (no increase in engine sludge/varnish deposits).  
Addition of ash forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

### Footnotes:

(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): Where oxygenates are used, ethers are preferred. Where up to 10% by volume ethanol (meeting ASTM D 4806 and a pH<sub>e</sub> of 6.5-9) is permitted by pre-existing regulations, the blended fuel must meet all other Category 3 requirements and fuelling pump labelling is recommended. Higher (C > 2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.

(5): Compliance with either the Unwashed Gum limit or the Combustion Chamber Deposits limit is permitted.

Markets with further advanced requirements for emission control, to enable sophisticated NO<sub>x</sub> after-treatment technologies.

PROPERTIES	UNITS	LIMIT		
		Min.	Max.	
'91 RON' <sup>(1)</sup>	Research Octane Number	-	91.0	--
	Motor Octane Number	-	82.5	--
'95 RON' <sup>(1)</sup>	Research Octane Number	-	95.0	--
	Motor Octane Number	-	85.0	--
'98 RON' <sup>(1)</sup>	Research Octane Number	-	98.0	--
	Motor Octane Number	-	88.0	--
Oxidation stability	minutes	480	--	
Sulfur content	mg/kg	--		Sulfur-free <sup>(2)</sup>
Metal content (Fe,Mn,Pb,other)	g/l			Non-detectable <sup>(3)</sup>
Phosphorus content	mg/l			Non-detectable <sup>(3)</sup>
Silicon content	mg/kg			Non-detectable <sup>(3)</sup>
Oxygen content	% m/m	--		2.7 <sup>(4)</sup>
Olefins content	% v/v	--		10.0
Aromatics content	% v/v	--		35.0
Benzene content	% v/v	--		1.0
Volatility				See Following Tables, page 11
Sediment	mg/l	--		1
Unwashed gums <sup>(5)</sup>	mg/100 ml	--		30
Washed gums	mg/100 ml	--		5
Density	kg/m <sup>3</sup>	715		770
Copper corrosion	merit			Class I
Appearance				Clear and Bright
Fuel injector cleanliness	% flow loss	--		5
Intake-valve sticking	pass/fail			Pass
Intake valve cleanliness II				
Method 1 (CEC F-05-A-93), or	avg. mg/valve	--		30
Method 2 (ASTM D 5500), or	avg. mg/valve	--		50
Method 3 (ASTM D 6201)	avg. mg/valve	--		50
Combustion chamber deposits <sup>(5)</sup>				
Method 1 (ASTM D 6201), or	% of base fuel			140
Method 2 (CEC-F-20-A-98), or	mg/engine	--		2500
Method 3 (TGA FLTM BZ154-01)	% mass. @ 450° C			20

**General Notes:**

N.B. # 1: Additives must be compatible with engine oils (no increase in engine sludge/varnish deposits). Addition of ash forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

**Footnotes:**

(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): 5-10 mg/kg maximum, depending on the applicable emission standard. 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 a pH<sub>e</sub> of 6.5-9) is permitted by pre-existing regulations, the blended fuel must meet all other Category 4 requirements and fuelling pump labelling is recommended. Higher (C > 2) alcohols are limited to 0.1 % maximum by volume. Methanol is not permitted.

(5): Compliance with either the Unwashed Gum limit or the Combustion Chamber Deposits limit is permitted.

**CATEGORY I**

Class *	A	B	C	D	E
Ambient Temp. Range, °C	> 15	5 to 15	-5 to +5	-5 to -15	< -15
Vapour Pressure, kPa	45 - 60	55 - 70	65 - 80	75 - 90	85 - 105
T10, °C, max	70	70	65	60	55
T50, °C	77 - 110	77 - 110	77 - 110	77 - 110	77 - 110
T90, °C	130 - 190	130 - 190	130 - 190	130 - 190	130 - 190
EP, °C max.	215	215	215	215	215
E70, %	15 - 45	15 - 45	25 - 45	25 - 47	25 - 47
E100, %	50 - 60	50 - 65	50 - 65	55 - 70	55 - 70
E180, % min	85	85	85	85	85

\* Where 'Class' is based on the minimum expected ambient temperatures of the market. Class will vary by season.

**CATEGORY 2, 3 and 4**

Class *	A	B	C	D	E
Ambient Temp. Range, °C	> 15	5 to 15	-5 to +5	-5 to -15	< -15
Vapour Pressure, kPa	45 - 60	55 - 70	65 - 80	75 - 90	85 - 105
T10, °C, max	65	60	55	50	45
T50, °C	77 - 100	77 - 100	77 - 100	77 - 100	77 - 100
T90, °C	130 - 175	130 - 175	130 - 175	130 - 175	130 - 175
EP, °C max.	195	195	195	195	195
E70, %	20 - 45	20 - 45	25 - 45	25 - 47	25 - 47
E100, %	50 - 65	50 - 65	50 - 65	55 - 70	55 - 70
E180, % min	90	90	90	90	90
D.I., max	570	565	560	555	550

\* Where 'Class' is based on the minimum expected ambient temperatures of the market. Class will vary by season.

**Note:**

Ambient temperature ranges listed represent the condition the vehicle operator will encounter. Local regulations/standards may define classes based on expected temperatures from varying historical or statistical information sources applicable to their locale.

D.I. (Distillation Index) =  $(1.5 * T10) + (3 * T50) + T90 + (11 * \text{mass \% of oxygen})$ ; Temperatures in degrees Celcius.

Oxygenate correction does not apply to ethers. Limited data on LEV/ULEV vehicles suggest that a similar oxygenate correction may be needed for ethers. The need for and the magnitude of the correction will be determined as more data become available.

Preliminary data indicate that there may be a need for further volatility controls beyond what is currently specified.

**VAPOUR/LIQUID RATIO (V/L), T V/L=20****CATEGORY 1, 2, 3 and 4**

Class	Test Temperature, °C, min.	Applicable Temperature, °C
1	60	≥ 43
2	56	< 43
3	51	< 36
4	47	< 29
5	41	< 21
6	35	< 14

Vapour lock class is determined based on the 90th percentile maximum (applicable) daily temperature. The minimum test temperature of the gasoline for V/L=20 is provided for each vapour lock class. Additional information is provided in ASTM D 4814.

The latest test methods should be used unless otherwise indicated by specific method year.

On those parameters where "no detectable" is listed, the lowest possible levels are expected with no intentional additions of this additive or contaminant. Where multiple methods are indicated, the manufacturer should assure the product conforms to the most precise method listed.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Research Octane Number	-	5164	D 2699	K 2280	
Motor Octane Number	-	5163-90	D 2700-86	K 2280-96	
Oxidation stability	minutes	7536	D 525	K 2287	
Sulfur content	mg/kg	4260	D 2622	K 2541	ASTM D5453 pr EN ISO/DIS 20846 pr EN ISO/DIS 20884
Lead content	g/l		D 3237	K 2255	EN 237
Potassium (K) content	g/l				NF M 07065
Iron (Fe) content	g/l				
Metal content	g/l				
Phosphorus content	mg/l		D 3231		
Manganese content	mg/l		D 3831		
Silicon content	mg/kg				ICP-AES (Reference in-house methods with detection limit = 1 mg/kg)
Oxygen content	% m/m		D 4815		EN 13132
Olefins content <sup>(1)</sup>	% v/v	3837	D 1319	K 2536	
Aromatics content <sup>(1)</sup>	% v/v	3837	D 1319	K 2536	pr EN 14517
Benzene content	% v/v		D 4420	K 2536	EN 238 pr EN 14517
Vapour Pressure	kPa		D 5191	K 2258	EN 13016/1 DVPE
Distillation: T10/T50/T90, E70/E100/E180, End Point, residue		3405	D 86	K 2254	
Vapour/liquid ratio (V/L)	°C		D 5188		
Sediment	mg/l		D 5452		
Unwashed gums	mg/100 ml	6246	D 381	K 2261	May be replaced with CCD test
Washed gums	mg/100 ml	6246	D 381	K 2261	
Density	kg/m <sup>3</sup>	3675 12185	D 4052	K 2249	
Copper corrosion	merit	2160	D 130	K 2513	
Appearance			D 4176		Visual inspection
Carburettor cleanliness	merit				CEC F-03-T
Fuel injector cleanliness	% flow loss		D 5598		
Intake-valve sticking	pass/fail				CEC F-16-T
Intake valve cleanliness I	merit				CEC F-04-A
Intake valve cleanliness II	avg. mg/valve				
Method 1, 4 valve avg.					CEC F-05-A
Method 2, BMW test			D 5500		
Method 3, Ford 2.3L			D 6201		
Combustion chamber deposits					
Method 1	% of base fuel		D 6201		
Method 2	mg/engine				CEC F-20-A
Method 3	% mass @ 450 °C				FLTM-BZ154 <sup>(2)</sup>

(1) Some methods for olefin and aromatic content are used in legal documents; more precise methods are available and may be used.

(2) This method is available at [www.autoalliance.org](http://www.autoalliance.org)

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 Index <sup>(1)</sup>	-	45.0 <sup>(3)</sup>	--
Density @ 15°C	kg/m <sup>3</sup>	820 <sup>(4)</sup>	860
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>(5)</sup>	4.5
Sulfur content	mg/kg	--	3000 <sup>(6)</sup>
T95	°C	--	370
Flash point	°C	55 <sup>(7)</sup>	--
Carbon residue	% m/m	--	0.30
CFPP <sup>(8)</sup> or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	500
Oxidation stability	g/m <sup>3</sup>	--	25
FAME content	% v/v	--	5% <sup>(9)</sup>
Copper corrosion	merit	--	Class I
Ethanol/Methanol content	% v/v	--	Non detectable <sup>(10)</sup>
Ash content	% m/m	--	0.01
Particulate	mg/l	--	10 <sup>(11)</sup>
Appearance		--	Clear and bright
Lubricity (HFRR wear scar dia. @ 60°C)	micron	--	400

#### General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

#### Footnotes:

(1): Compliance with either cetane index or cetane 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<sup>3</sup> when ambient temperatures are below -30°C.

(5): 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.

(6): The unit mg/kg is often expressed as ppm.

(7): The minimum limit can be relaxed to 38°C when ambient temperatures are below -30°C.

(8): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

(9): For FAME (Fatty Acid Methyl Esters), both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used it is recommended that fueling pumps are marked accordingly.

(10): At or below detection limit of the test method used.

(11): Limit and test method under further review.

Markets with stringent requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	53.0 <sup>(1)</sup>	--
Cetane Index	-	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	mg/kg	--	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	--
Carbon residue	% m/m	--	0.30
CFPP <sup>(7)</sup> or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature.
Water content	mg/kg	--	200
Oxidation stability	g/m <sup>3</sup>	--	25
Biological growth	-	'Zero' content	
FAME content	% v/v	--	5 <sup>(8)</sup>
Ethanol/Methanol content	% v/v	Non detectable <sup>(9)</sup>	
Total acid number	mg KOH/g	--	0.08
Ferrous corrosion	-	--	Light rusting or less
Copper corrosion	merit	Class I	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	10 <sup>(10)</sup>
Appearance		Clear and bright	
Injector cleanliness	% air flow loss	--	85
Lubricity (HFRR wear scar dia. @ 60°C)	micron	--	400

**General Notes:**

- N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.
- N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc...).
- N.B. # 3: Adequate labeling of pumps must be defined and used.

**Footnotes:**

- (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<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.
- (4): 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.
- (5): The unit mg/kg is often expressed as ppm.
- (6): Compliance either with T90 or T95 is required, not both.
- (7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.
- (8): For FAME (Fatty Acid Methyl Esters), both ENI 4214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used it is recommended that fueling pumps are marked accordingly.
- (9): At or below detection limit of the test method used.
- (10): Limit and test method under further review.

Markets with advanced requirements for emission controls or other market demands.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	55.0 <sup>(1)</sup>	--
Cetane Index	-	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	mg/kg	--	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	--
Carbon residue	% m/m	--	0.20
CFPP <sup>(7)</sup> or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg	--	200
Oxidation stability	g/m <sup>3</sup>	--	25
Foam volume	ml	--	100
Foam vanishing time	sec.	--	15
Biological growth	-	'Zero' content	
FAME content	% v/v	--	5 <sup>(8)</sup>
Ethanol/Methanol content	% v/v	Non detectable <sup>(9)</sup>	
Total acid number	mg KOH/g	--	0.08
Ferrous corrosion	-	--	Light rusting or less
Copper corrosion	merit	Class I	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	10 <sup>(10)</sup>
Appearance		Clear and bright	
Injector cleanliness	% air flow loss	--	85
Lubricity ( HFRR wear scar dia. @ 60°C )	micron	--	400

### General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

### Footnotes:

(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<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.

(4): 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.

(5): The unit mg/kg is often expressed as ppm.

(6): Compliance either with T90 or T95 is required, not both.

(7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

(8): For FAME (Fatty Acid Methyl Esters), both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used it is recommended that fueling pumps are marked accordingly.

(9): At or below detection limit of the test method used.

(10): Limit and test method under further review.



Markets with further advanced requirements for emission control, to enable sophisticated NO<sub>x</sub> and PM after-treatment technologies.

PROPERTIES	UNITS	LIMIT	
		Min.	Max.
Cetane Number	-	55.0 <sup>(1)</sup>	--
Cetane Index	-	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	mg/kg	--	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	--
Carbon residue	% m/m	--	0.20
CFPP <sup>(7)</sup> or LTFT or CP	°C	--	Maximum must be equal to or lower than the lowest expected ambient temperature
Water content	mg/kg	--	200
Oxidation stability	g/m <sup>3</sup>	--	25
Foam volume	ml	--	100
Foam vanishing time	sec.	--	15
Biological growth	-	'Zero' content	
FAME content	% v/v	Non-detectable <sup>(8)</sup>	
Ethanol/Methanol content	% v/v	Non detectable <sup>(8)</sup>	
Total acid number	mg KOH/g	--	0.08
Ferrous corrosion	-	--	Light rusting or less
Copper corrosion	merit	Class I	
Ash content	% m/m	--	0.01
Particulates	mg/l	--	10 <sup>(9)</sup>
Appearance		Clear and bright	
Injector cleanliness	% air flow loss	--	85
Lubricity ( HFRR wear scar dia. @ 60°C )	micron	--	400

### General Notes:

N.B. # 1: Additives must be compatible with engine oils. Addition of ash-forming components is not allowed.

N.B. # 2: Good housekeeping practices to reduce contamination (dust, water, other fuels, etc.).

N.B. # 3: Adequate labeling of pumps must be defined and used.

### Footnotes:

(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<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.

(4): 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.

(5): 5-10 ppm maximum, depending on the applicable emission standard. The unit mg/kg is often expressed as ppm.

(6): Compliance either with T90 or T95 is required, not both.

(7): If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

(8): At or below detection limit of the test method used.

(9): Limit and test method under further review.

The latest test methods should be used unless otherwise indicated by specific method year.

On those parameters where "no detectable" is listed, the lowest possible levels are expected with no intentional additions of this additive or contaminant. Where multiple methods are indicated, the manufacturer should assure the product conforms to the most precise method listed.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Cetane Number	-	5165	D 613	K 2280	
Cetane Index	-	4264	D 4737	K 2280	
Density @ 15°C	kg/m <sup>3</sup>	3675	D 4052	K 2249	ISO 12185
Viscosity @ 40°C	mm <sup>2</sup> /s	3104	D 445	K 2283	
Sulfur content	mg/kg	4260	D 2622	K 2541	ASTM D 5453 pr EN ISO/DIS 20846 pr EN ISO/DIS 20884
Total aromatics content	% m/m		D 5186		EN 12916
Polyaromatics content (di+tri+)	% m/m		D 2425		EN 12916
T90, T95, FBP	°C	3405	D 86	K 2254	
Flash point	°C	2719	D 93	K 2265	
Carbon residue	% m/m	10370	D 4530	K 2270	
Cold Filter Plugging Point (CFPP)	°C			K 2288	EN 116, IP 309
Low Temperature Flow Test (LTFT)	°C		D 4539		
Cloud Point (CP)	°C	3015	D 2500	K 2269	
Water content	mg/kg	DIS 12937	E 203	K 2275	
Oxidation stability	g/m <sup>3</sup>	12205	D 2274		
Foam volume	ml				NF M 07-075
Foam vanishing time	sec.				NF M 07-075
Biological growth	-				NF M 07 070
FAME content	% v/v				EN 14078
Ethanol/Methanol content	% v/v		D 4815 (modified)		
Total acid number	mg KOH/g	6618	D 974		
Ferrous corrosion	-		D 665		
Copper corrosion	merit	2160	D 130	K 2513	
Appearance			D 4176		Visual inspection
Ash content	% m/m	6245	D 482	K 2272	
Particulates	mg/l		D 2276		DIN 51419 / EN 12662 (1)
Injector cleanliness	% air flow loss				CEC (PF-023) TBA
Lubricity (HFRR wear scar diameter @ 60°C )	micron	12156-1.3	D 6079		CEC F-06-A
Lubricity - pump test					Pump test under development

(1): Method under review



TECHNICAL BACKGROUND  
FOR HARMONISED  
FUEL RECOMMENDATIONS **GASOLINE**

## OCTANE

Octane is a measure of a gasoline’s ability to resist auto-ignition; auto-ignition can cause engine knock. There are two laboratory test methods to measure gasoline octane numbers: one determines the Research octane number (RON) and the other the Motor octane number (MON). RON correlates best with low speed, mild-knocking conditions and MON correlates with high-temperature knocking conditions and with part-throttle operation. RON values are typically higher than MON and the difference between these values is the sensitivity, which should not exceed 10.

Vehicles are designed and calibrated for a certain octane value. When a customer uses gasoline with an octane level lower than that required, knocking may result which could lead to severe engine damage. Engines equipped with knock sensors can handle lower octane levels by retarding the spark timing; however, fuel consumption, driveability and power will suffer and at low octane levels, knock may still occur. Using gasoline with an octane rating higher than that recommended may not improve the vehicle’s performance.

Historically, lower octanes at high altitude have provided the same anti-knock performance as higher octanes at sea level in older-model engines. Since 1984, however, most vehicles have been equipped with sophisticated electronic control systems that adjust to changes in air temperature and barometric pressure. These vehicles require the same octane levels at all altitudes. Thus, gasoline octane levels should not be lower at higher altitudes.

This Fuel Charter specifies three octane grades in each gasoline Category. It is not intended to require all three grades in all markets. One or more of the octane grades should be made available consistent with market requirements. In North America, (RON + MON)/2 is typically used to specify the octane rating.

Ash-forming (metal-containing) additives sometimes used for boosting octane are not recommended (see Ash-Forming Additives discussion, page 24).

## SULFUR

Sulfur naturally occurs in crude oil. If the sulfur is not removed during the refining process it will contaminate vehicle fuel. Sulfur has a significant impact on vehicle emissions by reducing the efficiency of catalysts. Sulfur also adversely affects heated exhaust gas oxygen sensors. Reductions in sulfur will provide immediate reductions of emissions from all catalyst-equipped vehicles on the road.

There has been extensive testing done on the impact of sulfur on vehicle emissions. The following studies (see table) indicate the emission reductions that occur with different vehicle technologies as sulfur is reduced from the ‘high’ sulfur gasoline to the ‘low’:

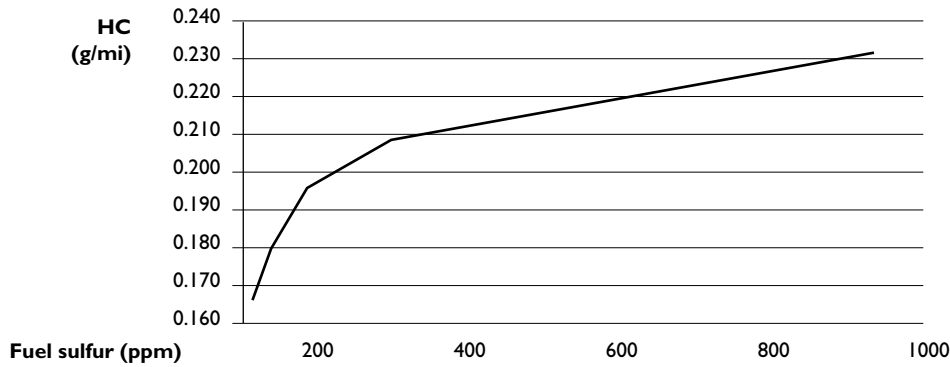
Table 1: Impact of sulfur on emissions

Study	Vehicle Technology	Sulfur Range (ppm)		Emission Reduction, % (high to low sulfur)		
		high	low	HC	CO	NO <sub>x</sub>
AQIRP	Tier 0	450	50	18	19	8
EPEFE	EURO 2+	382	18	9 (43*)	9 (52*)	10 (20*)
AAMA/AIAM	LEV & ULEV	600	30	32	55	48
CRC	LEV	630	30	32	46	61
JARI	1978 Regulations	197	21	55	51	77
Alliance/AIAM	LEV/ULEV	100	30	21	34	27
	LEV/ULEV	30	1	7	12	16
JCAP	DI/NO <sub>x</sub> cat.	25	2			37

\* Reduction achieved during hot EUDC (extra-urban) portion of test.

This Figure (Figure 1) depicting the HC reductions from the US AQIRP study indicates the typical emission reduction for the different studies as the sulfur level changes, including the significant reduction when sulfur is reduced from about 100 ppm to the 'Low' sulfur fuel. This suggests the importance of a very low sulfur limit for advanced technology vehicles.

Figure 1: Sulfur Effects on Tier 0 Technology



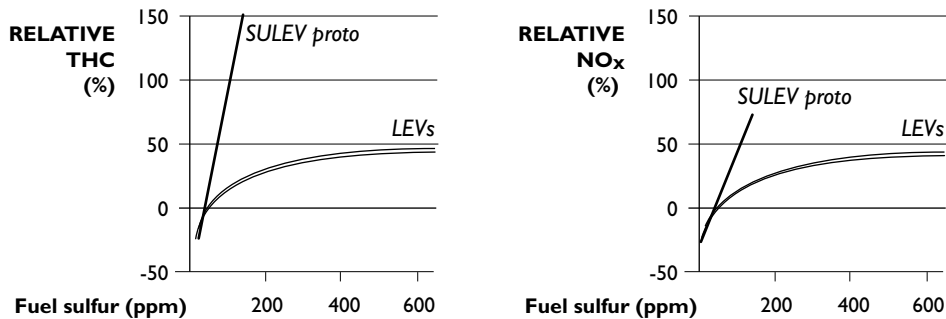
In addition, laboratory research of catalysts has demonstrated delays in light-off time, increases in light-off temperature and reductions in efficiency resulting from higher sulfur fuels across a full range of air/fuel ratios. Studies have also demonstrated that sulfur slows the rich to lean transition, thereby introducing an unintended rich bias into the emission calibration.

**Stringent Emission Standard Challenges**

Stringent emission requirements, combined with long-life compliance, demand extremely efficient, and durable, after-treatment systems. For example, it is generally recognised that catalyst hydrocarbon efficiency at 100,000 miles must be at least 93% for a vehicle meeting Low Emission Vehicle (LEV)/EURO 3 standards, and about 97% for a vehicle meeting Ultra-LEV/EURO 4 standards. Studies on LEVs indicate that warmed-up catalyst HC efficiency (ie., excluding the start-up portion) must be 98% or better for 120,000 miles to ensure that new US Tier 2 emission limits are met. These standards represent significant technological hurdles, even in markets with high quality (Category 3) gasoline.

Figure 2 indicates the significant HC and NO<sub>x</sub> sensitivity to sulfur content. Advanced technologies indicate an even higher response to sulfur.

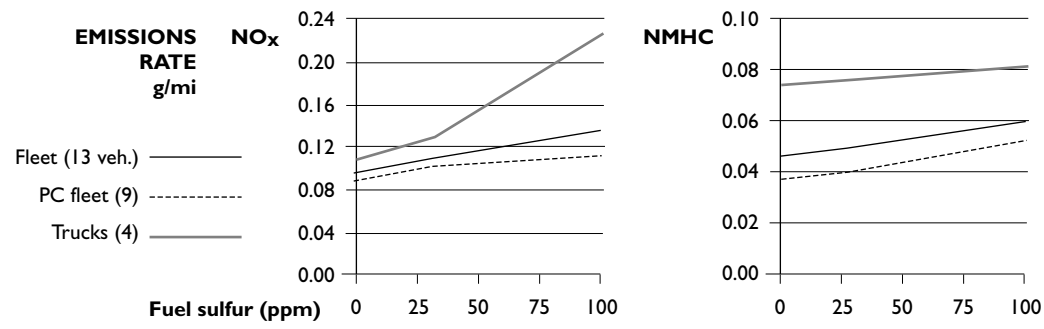
Figure 2: Effects of Fuel Sulfur on Emissions (relative to 30 ppm sulfur fuels)



In 2001, the Alliance and AIAM completed a joint test program to evaluate the emission effects of decreasing fuel sulfur levels ranging from 100 to 30 to 1 ppm S in a California Phase 2 reformulated gasoline containing 11% MTBE. The test fleet consisted of 13 vehicles with LEV and ULEV technology, including nine passenger cars and four light trucks. Vehicles were tested using the U.S. EPA Federal Test Procedure (FTP). The relative rate of emissions reduction in the 30 to 1 ppm S range may have been due to a sulfur contribution from the engine lubricant.

Figure 3 shows how the emissions of NO<sub>x</sub> and non-methane hydrocarbon (NMHC) continue to decline significantly at ultra-low sulfur levels for advanced technology vehicles.

Figure 3: Effects of ultra-low sulfur levels on emissions of NO<sub>x</sub> and NMHC



Sulfur will also affect the feasibility of advanced on-board diagnostic system requirements. Existing California on-board diagnostic (OBD II) regulations require vehicles to be equipped with catalyst monitors to determine when catalyst efficiency changes and tailpipe emissions increase by 1.5 times the standard. There is concern that the loss of catalyst efficiency resulting from high sulfur fuels will cause some catalyst monitors to indicate a problem code resulting in the illumination of a malfunction indicator light to signal the driver. Data on other LEVs demonstrate that the impact on the system is such that the catalyst monitor fails to properly identify a failed catalyst when operated on high sulfur fuel.

**Advanced and Future Technology**

Manufacturers are working toward ambitious goals for improved fuel consumption/reduced CO<sub>2</sub> emissions. Operation at lean air-fuel ratio is the most promising means to achieve these reductions in gasoline-powered vehicles. However, lean operation introduces a new challenge for exhaust emission control. While unburned HC and CO are effectively removed by existing catalysts during lean operation, NO<sub>x</sub> is removed only during stoichiometric or rich operation.

Many manufacturers are developing and introducing lean-burn technology. These technologies have the potential to reduce fuel consumption by up to 15 to 20%, but require NO<sub>x</sub> control technologies which can function under lean conditions. These technologies are very sensitive to fuel sulfur.

Figures 4 and 5 provide examples of the adverse effect of sulfur on storage type NO<sub>x</sub> reduction catalyst needed in lean burn vehicles. With increased exposure time, the lower sulfur gasolines allow the catalysts to retain a higher NO<sub>x</sub> conversion efficiency. Further tests in vehicles (Figures 6 and 7) confirm the critical need for very low sulfur gasolines. Sulfur-free gasolines are required to achieve and maintain high NO<sub>x</sub> conversion efficiencies.

Figure 4: Sulfur effect on Low emission vehicles – Direct Fuel injection engines (Japan Clean Air Program)

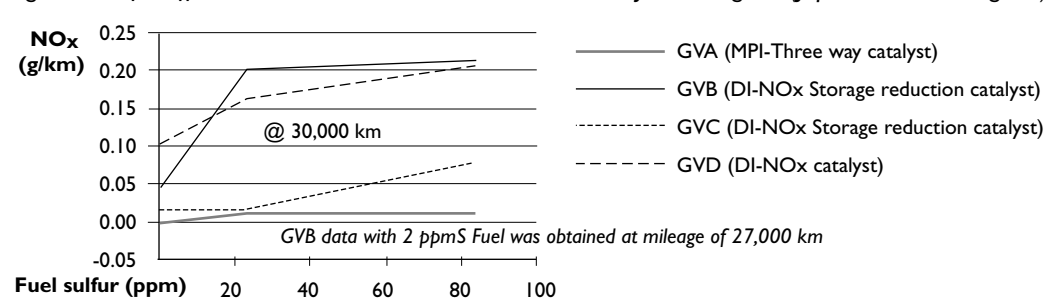


Figure 5: Effect of Fuel Sulfur on Lean NO<sub>x</sub> Traps Flow Reactor Study

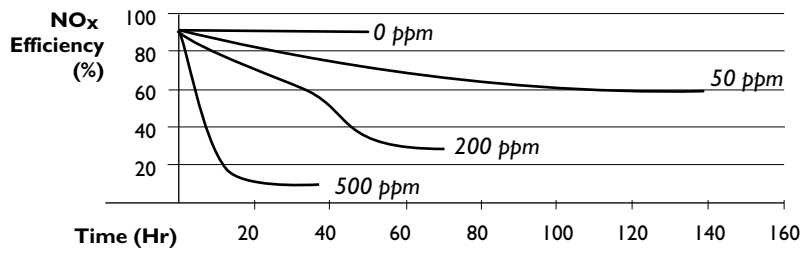


Figure 6: Influence of Sulfur Concentration in Gasoline on Vehicle Aftertreatment System Durability

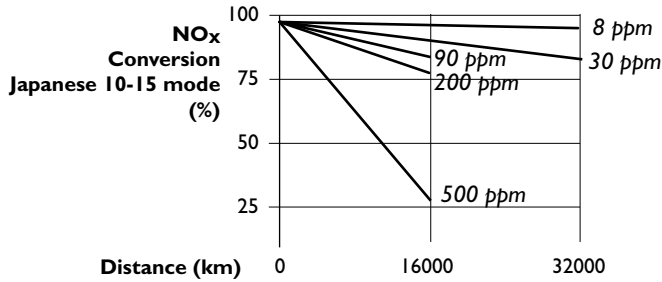
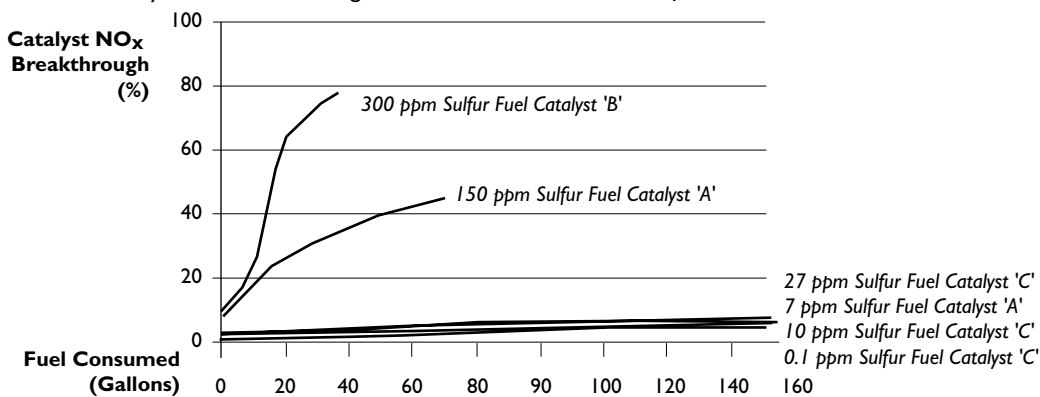
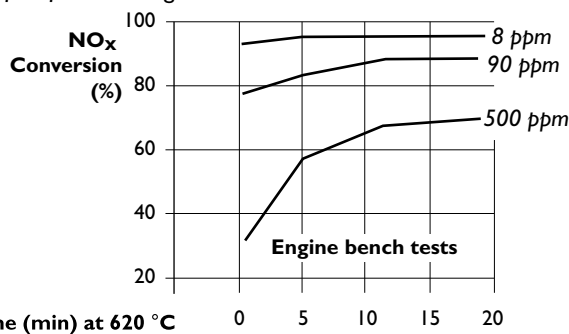


Figure 7: Lean NO<sub>x</sub> Adsorber Catalyst Data – Catalyst NO<sub>x</sub> Breakthrough vs Fuel Consumed & Fuel Sulfur Content



Lean NO<sub>x</sub> adsorber catalysts function by trapping NO<sub>x</sub> chemically during lean burning conditions. NO<sub>x</sub> can then be released and destroyed over a catalyst by a few seconds of rich operation. However, sulfur oxides are more strongly trapped, and as a competitor to NO<sub>x</sub>, they reduce the NO<sub>x</sub> capacity of the adsorber. Sulfur removal requires a more prolonged rich operating condition, but the original efficiency level can never be fully recovered. Also, allowing any rich operation significantly negates the fuel efficiency benefits of the lean burn engine technologies used with these catalysts. Sulfur-free gasolines, however, will maintain the necessary NO<sub>x</sub> conversion efficiency (Figure 8). Sulfur-free gasoline is therefore necessary to maximise the benefits of lean-burn, fuel-efficient technology.

Figure 8: Regeneration of Sulfur Poisoning





## ASH-FORMING (METAL-CONTAINING) ADDITIVES

Today's vehicles employ sophisticated emission control equipment such as three-way catalysts and exhaust gas oxygen sensors to provide precise closed-loop control. These systems must be kept in optimal condition to maintain low emissions for the lifetime of the vehicle. Ash-forming additives can adversely affect the operation of catalysts and other components, such as oxygen sensors, in an irreversible way that increases emissions. Thus, high-quality gasoline should be used and ash-forming additives must be avoided.

### Lead

Lead alkyl additives have been used historically as inexpensive octane enhancers for gasoline. Concerns over health effects associated with the use of these additives, and the need for unleaded gasoline to support vehicle emission control technologies such as catalytic converters and oxygen sensors, have resulted in the elimination of leaded gasoline from many markets. As vehicle catalyst efficiencies have improved, tolerance to lead contamination is very low, so that even slight lead contamination can poison a catalyst. As catalyst-equipped vehicles are introduced into developing areas, unleaded gasoline must be available. Removal of lead compounds from gasoline reduces vehicle hydrocarbon emissions, even from vehicles without catalytic converters. A lead-free market worldwide is therefore essential, not only for emission control compatibility, but also because of the well-known adverse health effects of lead. Leaded gasoline should be eliminated as soon as possible.

### Manganese (MMT)

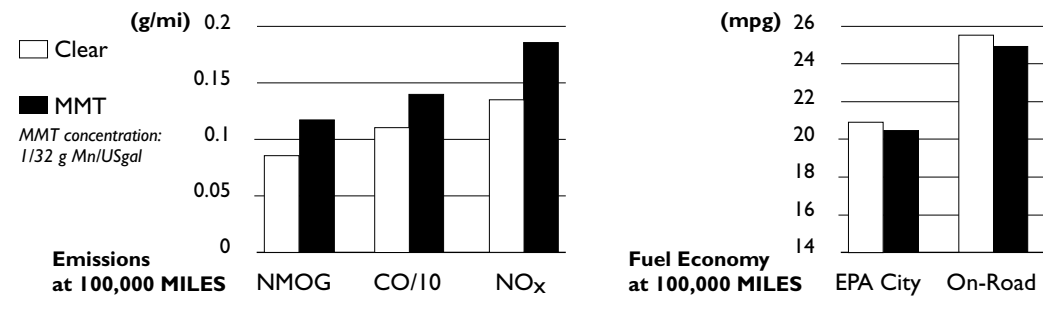
MMT (methylcyclopentadienyl manganese tricarbonyl) is a manganese-based compound marketed as an octane-enhancing fuel additive for gasoline. It has also been suggested for use in diesel fuel as a smoke reducing additive.

Studies have shown that only a small percentage of the MMT-derived manganese from the fuel is emitted from the tailpipe – the majority remains within the engine, catalyst and exhaust system.

- The combustion products of MMT coat internal engine components such as spark plugs, potentially causing misfire which leads to increased emissions, increased fuel consumption and poor engine performance. These conditions result in increased owner dissatisfaction and expense for consumers and vehicle manufacturers.
- The combustion products of MMT also accumulate on the catalyst. In some cases, the front face of the catalyst can become plugged with deposits, causing poor vehicle operation and increased fuel consumption in addition to reduced emission control.

In 2002, automobile manufacturers jointly completed a multi-year study of the impact of MMT on Low Emission Vehicles (LEVs). At 100,000 miles (Figure 9), MMT significantly increased non-methane organic gases (NMOG), CO and NO<sub>x</sub> emissions from the fleet. MMT also significantly decreased EPA City fuel economy, and on-road fuel economy through 100,000 miles was, on average, about 0.5 miles per gallon (mpg) lower. In another part of the study with earlier model vehicles equipped with Tier 1 emission control technology, HC emissions also increased through 50,000 miles.

Figure 9: Emission and Fuel Economy Effect of MMT – 1998-99 LEVs



Given this body of information, automobile manufacturers are extremely concerned with MMT's impact on the highly sensitive technologies that will be required to meet Tier-2 emission standards in the U.S. and Canada.

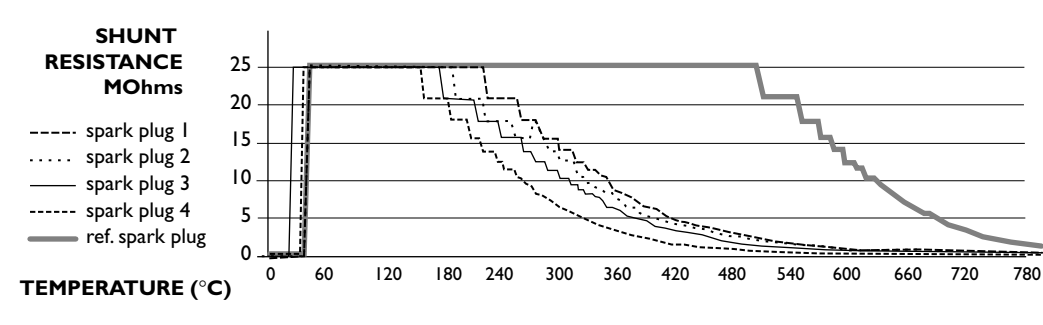
The use of this gasoline additive has been debated in many countries. PSA and VW have raised concerns about MMT in China and Argentina, where failed emissions components have been reported. Emission component failures, including catalyst plugging on advanced low emission vehicles, are also being reported in Canada where MMT is used in most of the gasoline. In spite of its approval for use in non-reformulated gasoline in the U.S. since 1995, it is used in very few gasolines sold in the U.S. Several auto manufacturers state in their Owner Guides that the use of fuels containing MMT is not recommended, and any damage caused by MMT may not be covered by the warranty.

**Iron (Ferrocene)**

Ferrocene has been used to replace lead as an octane enhancer for unleaded fuels in some markets. It contains iron, which deposits on spark plugs, catalysts and other exhaust system parts as iron oxide, and may also affect other engine components. The deposits will cause premature failure of the spark plugs, with plug life being reduced by up to 90% compared to normal service expectations. Failing spark plugs will short-circuit and cause misfiring when hot, such as under high load condition. This may cause thermal damage to the exhaust catalyst.

Figure 10 shows the reduction in spark plug insulator resistance as a function of temperature. The results compare plugs using fuel with a ferrocene additive after only 32 hours of testing, with a reference plug using conventional gasoline after 300 hours of testing.

Figure 10: Insulator resistance at temperature test results for spark plugs taken from test engine after 32 hours



Iron oxide also acts as a physical barrier between the catalyst/oxygen sensor and the exhaust gases, and also leads to erosion and plugging of the catalyst. As a result the emission control system is not able to function as designed, causing emissions to increase. Additionally, premature wear of critical engine components such as the pistons and rings can occur due to the presence of iron oxide in the vehicle lubrication system.

## SILICON

Silicon is not a natural component of gasoline. However, in several instances silicon has appeared in commercial gasolines, usually as a result of waste solvents containing silicon compounds being used as a gasoline-blending component after the fuel has left the refinery. Such contamination has significant adverse effects on emission control systems.

Silicon, even in low concentrations, can cause failure of oxygen sensors and high levels of deposits in engines and catalytic converters. This can lead to catastrophic engine failures in less than one tankful of contaminated fuel. Therefore, no detectable level of silicon should exist in gasoline nor should it be used as a component of any fuel additive package to improve gasoline and engine performance.

## OXYGENATES

Oxygenated organic compounds, such as MTBE and 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 vehicles without electronic feedback controlled fuel systems.

These emission benefits are not realised as much in modern electronic feedback controlled vehicles because the leaning effect only occurs during cold operation or during rapid accelerations. In fact, fuel leaning caused by oxygenates can degrade driveability depending on the leanness of the engine's base calibration with all-HC (ie., non-oxygenated) gasoline. This over-leaning can also cause emissions to increase. Because ethanol has a higher heat of vaporisation than ethers, some of the driveability degradation of gasoline oxygenated with ethanol can be attributed to the additional heat needed to vaporise the gasoline.

The California Air Resources Board (CARB) conducted emission tests on 14 1990-1995 vehicles using 2 gasolines with 10% ethanol and 11% MTBE. When the ethanol fuel was compared to the MTBE fuel, it decreased toxic emissions by 2% and CO by 10%, but it increased NO<sub>x</sub> by 14%, total HC by 10% and Ozone Forming Potential by 9%.

The use of ethanol-blended gasoline may require strategies to mitigate potential evaporative and exhaust emission impacts. General Motors has shown that LEV vehicles emit approximately 12 percent more evaporative emissions when using 10% ethanol-blended gasoline than when using a hydrocarbon-only fuel (see table). In a report to the California Air Resources Board dated September 20, 2000,

Table 2: *Evaporative Emissions Impact of E10 on LEVs*

Fuel	Odometer	Test Date	Diurnal	Hot Soak	Total
E10	3976	5-1	0.719	0.147	0.866
Gasoline	5019	5-11	0.645	0.137	0.782
E10	8655	5-2	0.619	0.140	0.759
Gasoline	8534	5-16	0.582	0.112	0.694
E10	2561	5-9	0.724	0.109	0.833
Gasoline	2216	5-15	0.672	0.126	0.798
E10	6797	7-21	0.576	0.093	0.669
Gasoline	6951	7-21	0.440	0.091	0.531
E10	8740	7-27	0.441	0.097	0.538
Gasoline	9557	8-21	0.396	0.053	0.449
Mean E10			0.616	0.117	0.733
Mean Gas			0.547	0.104	0.651
% Diff			+12.6%	+12.5%	+12.6%

entitled “Emission Effects (Permeation) of Ethanol in Gasoline,” Harold Haskew and Associates estimates a substantial increase in evaporative emissions due to fuel system permeation with ethanol-blends. The report also proposes a test program designed to evaluate the resulting evaporative emission impacts.

In addition to evaporative impacts, it is well documented that ethanol-blended gasoline also causes an offset in driveability performance. It is expected that this offset in driveability performance would be reflected in exhaust hydrocarbon emissions.

Based on past experience with impurities in ethanol that have led to degradation of fuel systems, fuel ethanol must have a specification to control pH<sub>e</sub> and its blending properties (ASTM D 4806). The limits and restriction on the oxygenates permitted in each Category were developed on the basis of emission benefits, vehicle performance and pre-existing regulations. Thus, when oxygenates are used, ethers are preferred.

Methanol is not permitted. Methanol is an aggressive material which can cause corrosion of metallic components of fuel systems and the degradation of plastics and elastomers.

## OLEFINS

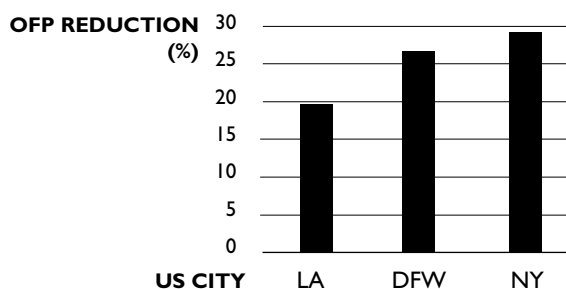
Olefins are unsaturated hydrocarbons and, in many cases, are also good octane components of gasoline. However, olefins in gasoline can lead to deposit formation and increased emissions of reactive (i.e., ozone-forming) hydrocarbons and toxic compounds.

### Effect of Olefins on Emissions

Olefins are thermally unstable and may lead to gum formation and deposits in an engine's intake system. Furthermore, their evaporation into the atmosphere as chemically reactive species contributes to ozone formation and their combustion products form toxic dienes.

The effect on ozone-forming potential was clearly demonstrated by the US Auto/Oil programme. The programme concluded that reducing total olefins from 20% to 5% would significantly decrease ozone-forming potential in three critical cities: Los Angeles, Dallas-Fort Worth, and New York (Figure 11).

Figure 11: Reduction in Ozone-Forming Potential with Reduction in Fuel Olefins (20%-5%)



The model also showed that the same reduction in gasoline olefin level would reduce the light-duty vehicle contribution to peak ozone by 13% to 25% in future years for the cities shown in figure 11. About 70% of this effect was due to reducing low molecular weight olefins.

## AROMATICS

Aromatics are fuel molecules that contain at least one benzene ring. In general, aromatics are good octane components of gasoline and high-energy density fuel molecules. Fuel aromatic content can increase engine deposits and increase tailpipe emissions, including CO<sub>2</sub>.

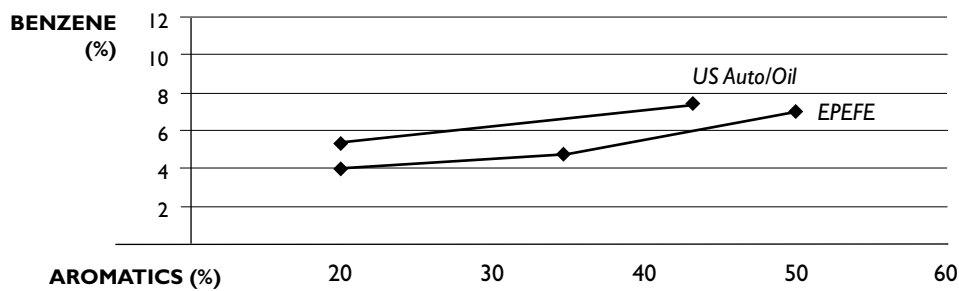
### Influence of Aromatics on Engine Deposits

Heavy aromatics, and other high molecular weight compounds, have been linked to engine deposit formation, particularly combustion chamber deposits. As discussed below ('Deposit Control Additives'), these deposits increase tailpipe emissions, including HC and NO<sub>x</sub>. Since it is not feasible to specify limits for individual hydrocarbon compounds in the fuel, the total aromatic limit in Category 1 and the final boiling point limits in Categories 2 and 3 provide the best means to limit heavy aromatics.

### Influence of Aromatics on Tailpipe Emissions

Combustion of aromatics can lead to the formation of carcinogenic benzene in exhaust gas and increased combustion chamber deposits which can increase tailpipe emissions. Lowering aromatic levels in gasoline significantly reduces toxic benzene emissions in exhaust from vehicles as shown in both the US AQIRP and the European EPEFE studies. (Figure 12)

Figure 12: Fuel Aromatics Effect on Benzene Exhaust Emissions



Findings from the US AQIRP programme showed that of all the fuel properties tested, aromatic level had the largest effect on total toxics, largely due to its effect on exhaust benzene emissions as shown in the above figure. Reducing total aromatics from 45% to 20% caused a reduction in total exhaust air toxics of 28% (74% of the total toxic emissions was benzene).

### Influence of Aromatics on CO<sub>2</sub> Emissions

Gasoline aromatic content also has a direct effect on tailpipe CO<sub>2</sub> emissions. The European EPEFE programme demonstrated a linear relationship between CO<sub>2</sub> emissions and aromatic content. The reduction of aromatics from 50 to 20% was found to decrease CO<sub>2</sub> emissions by 5%.

## BENZENE

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 automobiles. The control of benzene in gasoline has been recognised by regulators in many countries as an effective way to reduce human exposure to benzene. These gasoline recommendations recognise the increasing need for benzene control as emission standards become more stringent.

## VOLATILITY

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

### Vapour Pressure

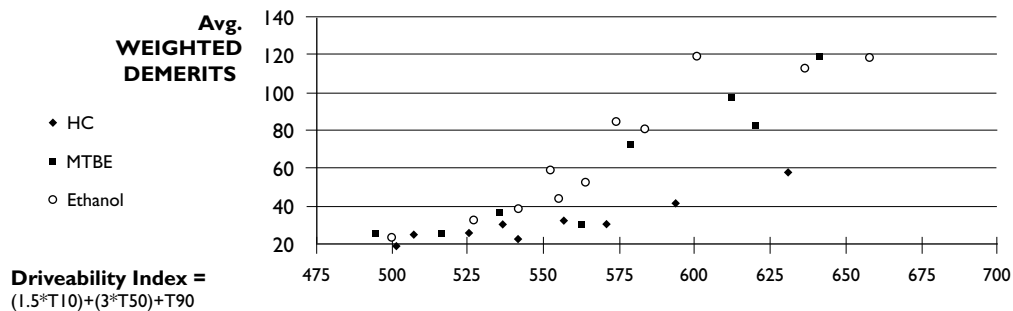
The vapour pressure of gasoline should be controlled seasonally to allow for the differing volatility needs of vehicles at different temperatures. The vapour pressure must be tightly controlled at high temperatures to reduce the possibility of hot fuel handling problems, such as vapour lock or carbon canister overloading. Control of vapour pressure at high temperatures is also important in the reduction of evaporative emissions. At lower temperatures higher vapour pressure is needed to allow ease of starting and good warm-up performance.

### Distillation

Distillation of gasoline yields either a set of 'T' points (T50 is the temperature at which 50% of the gasoline distills) or 'E' points (E100 is the percentage of a gasoline distilled at 100 degrees). Excessively high T50 (low E100) can lead to poor starting and warm-up performance at moderate ambient temperatures. Control of the Distillation Index (DI), derived from T10, T50, T90, and oxygen content can also be used to assure good cold start and warm-up performance.

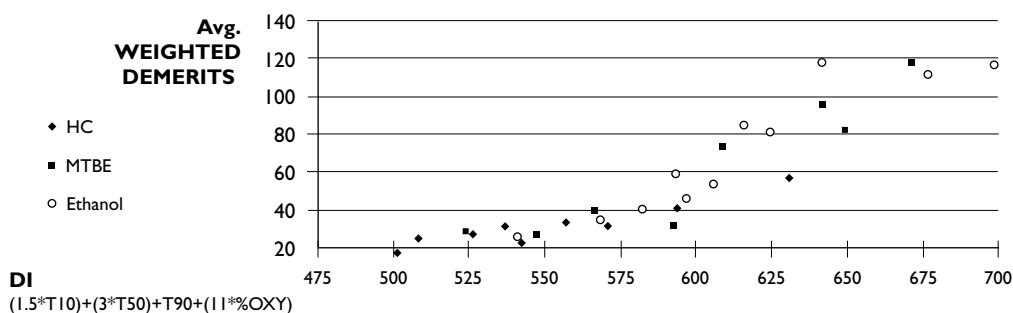
Driveability concerns are measured as demerits. Figure 13 provides the test results from a recent CRC study which tested 29 test fuels: 9 all hydrocarbon, 11 with 10% ethanol and 9 with 15% MTBE. The data indicate that driveability problems increase for all fuel types as Driveability Index increases. At Driveability Index levels higher than those specified in this Charter driveability concerns increase dramatically.

Figure 13: Effect of Driveability Index on Driveability



An oxygen correction factor is required to correct for higher driveability demerits for oxygenated fuels as compared to all-HC gasoline. Figure 14 indicates how the correction factor smooths the data presented in Figure 13.

Figure 14: Effect of DI on Driveability (Oxygen Corrected)



The DI is also directly related to tailpipe HC emissions, as shown in Figure 15. As with driveability demerits, HC emissions increase significantly at DI levels higher than those specified in this Charter.

Figure 15: Effect of DI on Driveability and Exhaust Emissions

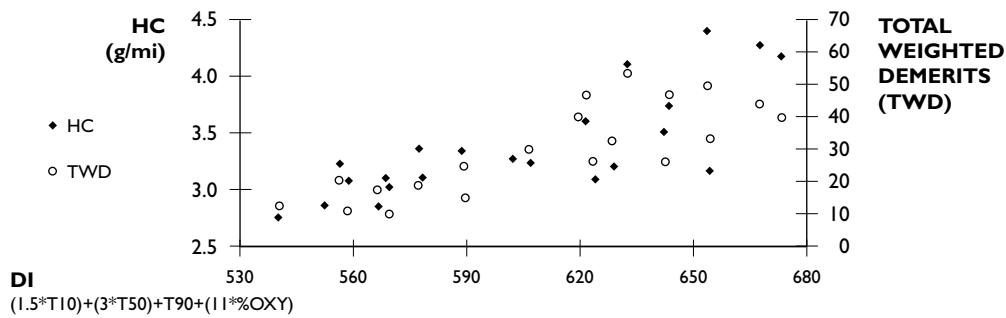
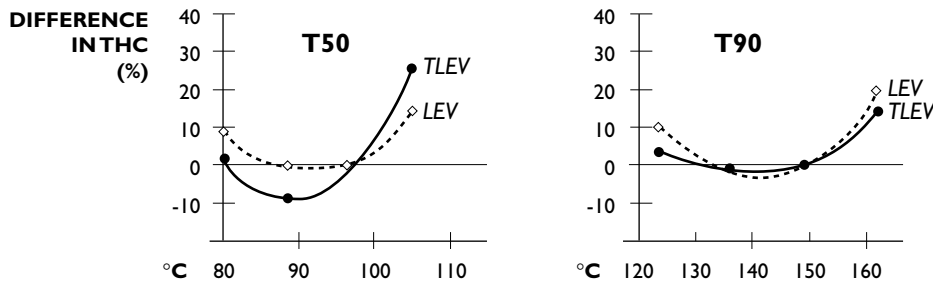


Figure 16 indicates that optimum values for T50 and T90 exist to achieve lower exhaust THC emissions.

Figure 16: Effect of T50/T90 on Exhaust Emissions Comparison of LEV and TLEV



In 1999, the US automakers petitioned the US-EPA to keep DI at 1200. This petition contains a compilation of available data on the impact of DI on emissions. This document is available at [www.autoalliance.org](http://www.autoalliance.org).

**Vapour Lock**

Excessively high gasoline volatility can cause hot fuel handling problems such as vapour lock, canister overloading, and higher emissions. Vapour lock occurs when too much vapour forms in the fuel system and fuel flow decreases to the engine. This can result in loss of power, rough engine operation or engine stalls. Since vapour pressure and distillation properties are not sufficient to assure good vehicle performance, a Vapour/Liquid Ratio specification is necessary.

## DEPOSIT CONTROL ADDITIVES

Combustion of even good quality gasoline can lead to deposit formation. Such deposits will increase engine-out emissions and affect vehicle performance. High quality fuel contains deposit control additives to significantly reduce deposit formation.

### Carburettors

First generation additives were developed in the early 1950's and are based on amine chemistry still used in some countries at levels of 50 parts per million treat rate. Many of these additives were multifunctional, providing anti-icing protection, corrosion inhibition and carburettor detergency performance.

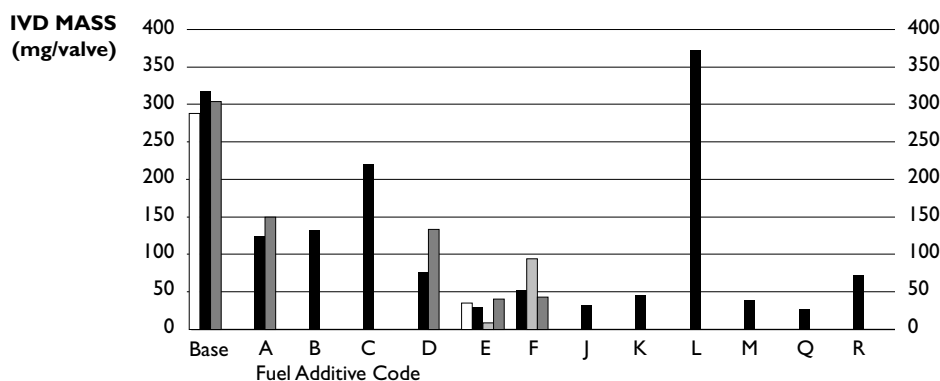
### Port Fuel Injectors

Port fuel injector deposit control additives were introduced by US gasoline marketers around 1985 to overcome problems with fuel injector fouling that led to driveability problems. However, treat rates were nearly double those for carburettor detergents resulting in increased intake valve deposits in many cases.

### Intake Valves

The impact of intake valve deposits on driveability in both North America and Europe was so severe that vehicle manufacturers required improved gasoline quality in terms of fuel detergents to keep valves clean and provide clean-up ability. Various tests are available to evaluate the gasoline's capability of maintaining acceptable intake valve cleanliness. Figure 17 shows the performance of base fuel without detergent additives and fuels with various detergent additive chemistries in the Ford 2.3L IVD test (ASTM D6201-97). Moderate additive treat rates combined with effective carrier fluids help avoid intake valve sticking. Passing the VW Wasserboxer Intake Valve Sticking Test minimises the likelihood of this problem occurring.

Figure 17: IVD Performance of Gasolines Ford 2.3L Dynamometer Test



### Combustion Chambers

As combustion chamber deposits (CCDs) form, they reduce the space available in the chamber for combustion while adding small crevices that increase the surface area of the chamber. This phenomenon has three undesirable effects: 1) higher compression ratios and end gas temperatures that increase the octane requirements higher than the engine was designed for, 2) increased exhaust emissions, and 3) mechanical interference between the piston top and cylinder head called 'Carbon Knock'.

### Engine Dynamometer Results

Detergent additives usually increase the level of CCDs relative to base fuel as shown in Figures 18 and 19. Detergent packages with higher ratios of mineral oil carriers tend to increase CCDs, while detergent packages with optimised high-quality synthetic carrier fluids and compounds like polyether amines (PEA) minimise CCD buildup. Additive packages should be optimised to minimise CCDs, which will



allow engine designers to further improve combustion chamber designs to provide lower emissions and fuel consumption.

Figure 18: Engine Dynamometer Results

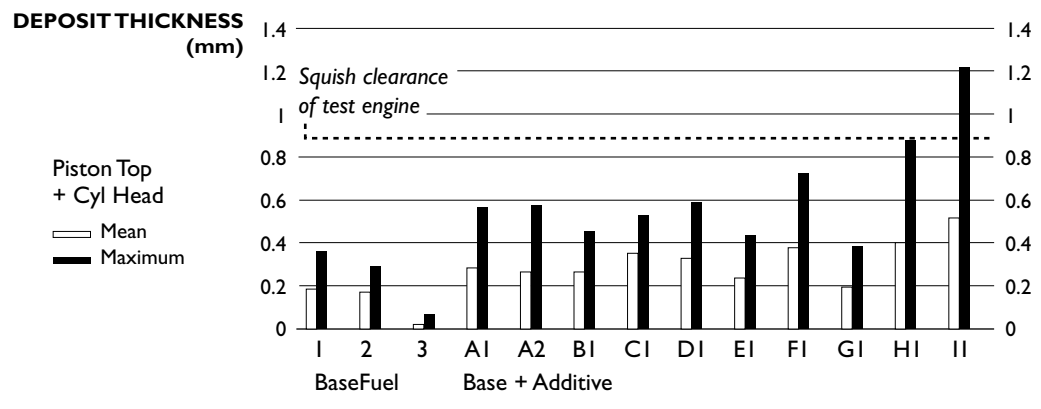
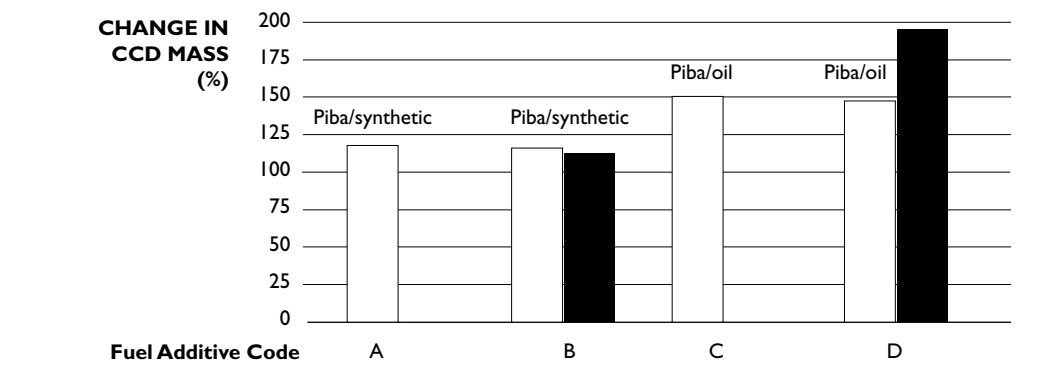


Figure 19: CCD Performance of Gasolines Ford 2.3L Dynamometer Test - Using ASTM D6201

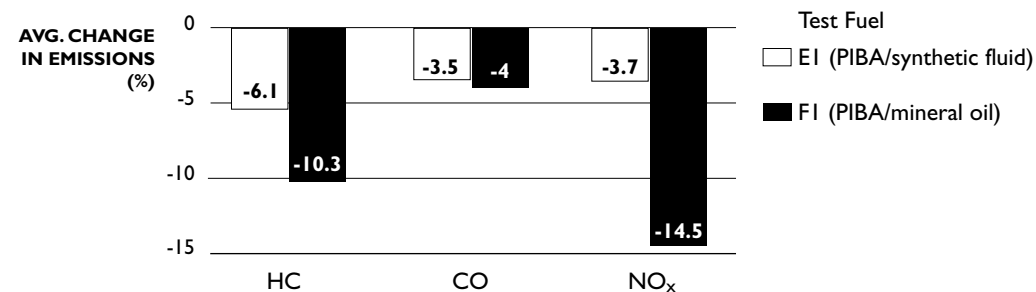


Note: Piba/Synthetic - polyisobutene amine/synthetic oil  
 Piba/Oil - polyisobutene amine/mineral oil

**Effect of CCD Removal on Engine-Out Emissions**

The removal of CCDs can reduce engine out HC emissions by up to 10%, CO by 4%, and NO<sub>x</sub> by 15% as shown in Figure 20 for fleet vehicles after accumulating 50,000 miles.

Figure 20: Effect on CCD Removal on Engine-Out Emissions

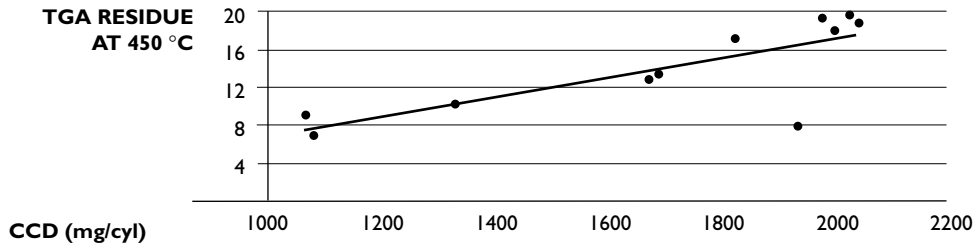


‘Carbon Knock’ in modern engines did not occur even at high mileages in Japan. When these same engines were sold in the US, customers began objecting to the engine noise after only a few thousand miles in some cases. Some customers required replacement of the cylinder heads because of the damage caused by the piston hitting the deposits. Other customers switched brands of gasoline or used after-market deposit control additives to help remove deposits causing carbon knock. The problem in the US was attributed to high-additive treat rates being used for IVD control.

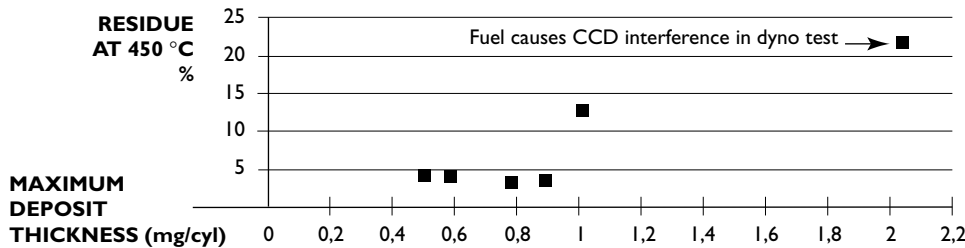
**Relationship of CCDs to TGA Test**

A test procedure with the Mercedes M111 E engine is being developed to evaluate the CCD-forming tendency of gasolines. A thermogravimetric analysis (TGA) bench test method has been developed that provides a good correlation with CCDs in a dynamometer-based multicylinder engine test as shown in Figure 21.

Figure 21: Correlation of CCD and TGA results of commercial fuels in Ford 2.3L IVD test (ASTM D 6201)



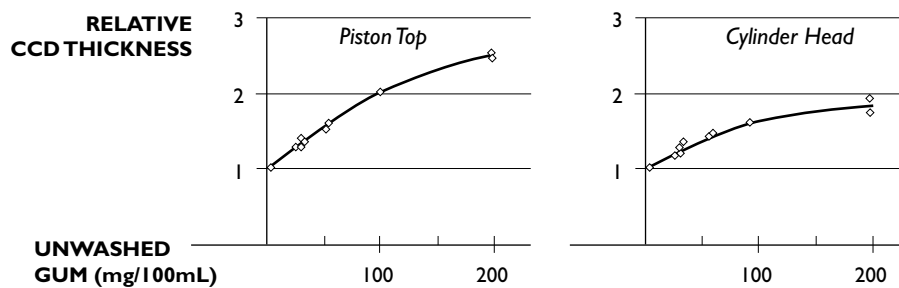
TGA proposed pass/fail limit - 4.0 L dynamometer test results



**Relationship Between Unwashed Gum and CCD Thickness**

Figure 22 indicates the correlation between unwashed gums and CCD formation. Thus, the Charter allows compliance to either an unwashed gum limit or a CCD requirement.

Figure 22: Relationship Between Unwashed Gum and CCD Thickness



As emission standards become more stringent, it is critical for fuel quality to support improvements in emission control technology to meet these limits. Detergent additives that prevent the formation of CCDs have the benefit of helping meet environmental standards while improving vehicle performance.

**GOOD HOUSEKEEPING PRACTICES**

The problems encountered by vehicles from poor quality fuel often are caused by adulteration that occurs in the fuel distribution system, after the fuel has left the refinery gate. Failure to invest in adequate pipeline and storage facilities and failure to maintain the equipment can lead to volatility losses,

fuel leakage and contamination by particulates and water that, in turn, can lead to a host of vehicle problems. Poor operating practices at the service station, such as too infrequent replacement of fuel dispenser filters or "dipping" of tanks to check for water, can magnify these problems.

TECHNICAL BACKGROUND  
FOR HARMONISED  
FUEL RECOMMENDATIONS **DIESEL FUEL**

## CETANE NUMBER AND INDEX

Cetane number is a measure of the compression ignition behaviour of a fuel; it influences cold startability, exhaust emissions and combustion noise. Cetane index is the ‘natural’ cetane of the fuel which is calculated based on measured fuel properties. The cetane number is measured on a test engine and reflects the effects of cetane improver additives. As shown below, natural cetane levels affect vehicle performance differently than additivised cetane levels. Therefore, to avoid excessive additive dosage, a minimum difference between cetane index and cetane number must be maintained.

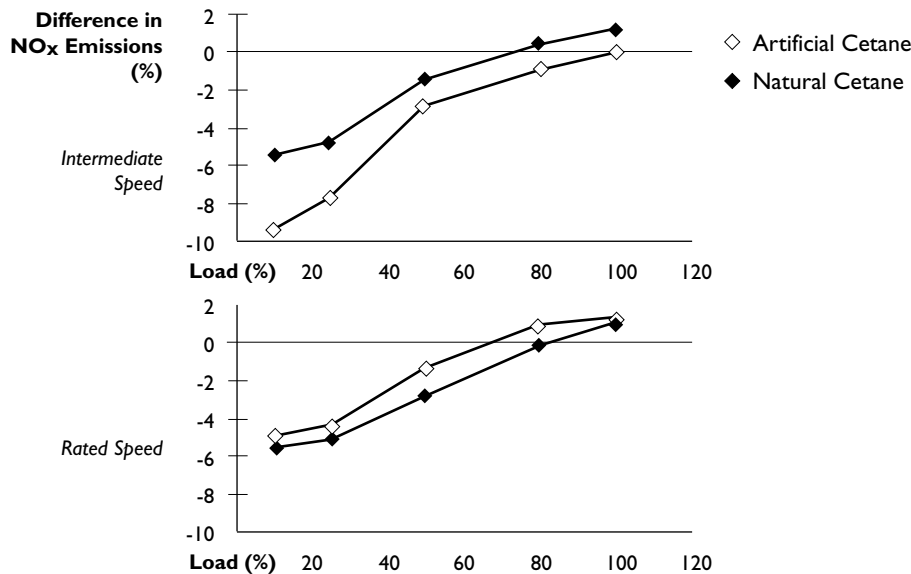
### Influence of Cetane on Cold Startability

Increasing cetane number will decrease engine crank time (the time before the engine reaches ‘starter off’) at a given engine speed. The ACEA EPEFE follow-up programme, which looked at the influence of diesel fuel quality on heavy duty diesel engine emissions, demonstrated a significant (up to 40%) reduction in crank time for an increase in cetane number from 50 to 58.

### Influence of Cetane on Exhaust Emissions and Fuel Consumption

The influence of cetane on NO<sub>x</sub> emissions and fuel consumption is shown as functions of engine load in the following figures (data on EPEFE heavy duty engines). Cetane is clearly shown to have a significant effect on NO<sub>x</sub> (Figure 1), particularly at low loads, where reductions of up to 9% are achieved. (Note that each point in the graph below shows the NO<sub>x</sub> reduction achieved for cetane increase at a given load.) The cetane increase also demonstrated a 30-40% reduction in HC emissions.

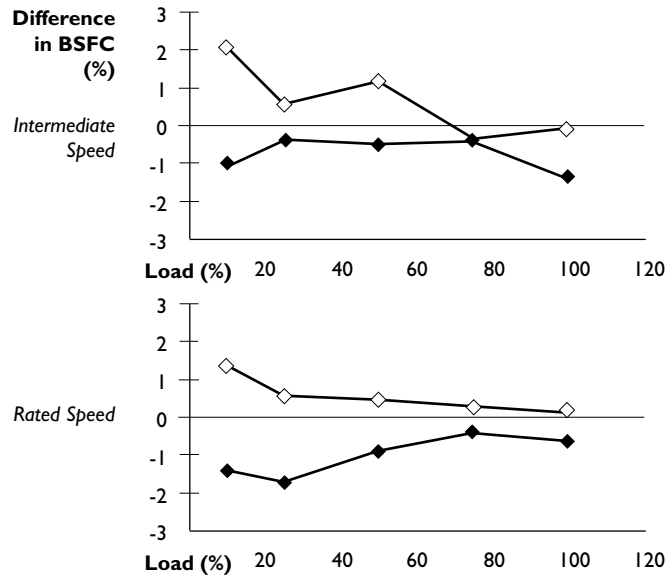
Figure 1: Effect of Cetane on NO<sub>x</sub> Emissions 50 to 58 CN



For light duty vehicles, EPEFE concluded that significant reductions in HC and CO would be achieved by increasing cetane number. The increase in cetane number from 50 to 58 resulted in a 26% reduction in both HC and CO emissions.

An increase in natural cetane has been shown to reduce fuel consumption. The data shown in Figure 2 demonstrates the importance of natural cetane (cetane index) compared to artificial cetane on heavy duty brake specific fuel consumption (BSFC). The increase in natural cetane (from 50 to 58) improved BSFC at every load level tested.

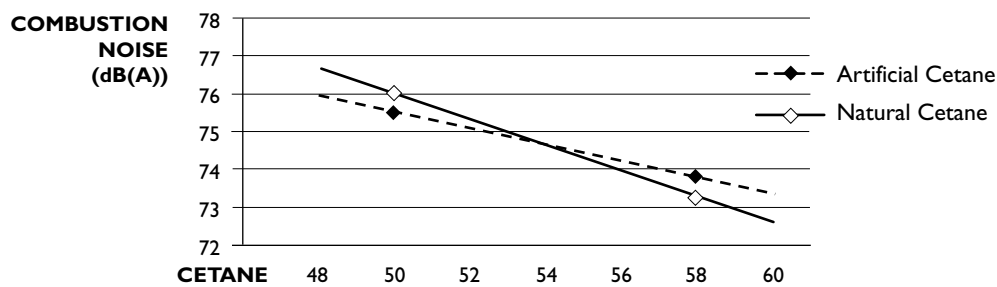
Figure 2: Effect of Cetane on Fuel Consumption 50 to 58 CN



**Cetane Influence on Combustion Noise**

Increased cetane will also reduce noise, as demonstrated by EPEFE results shown here (Figure 3). In this case, natural and artificial cetane have similar effects.

Figure 3: Effect of Cetane on Engine Noise 50 to 58 CN



**DENSITY and VISCOSITY**

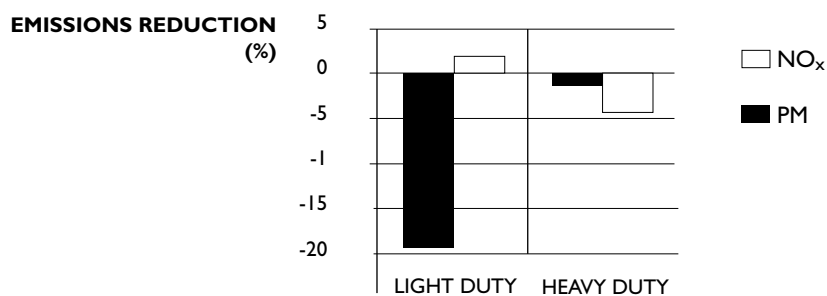
The diesel fuel injection is controlled volumetrically or by timing of the solenoid valve. Variations in fuel density (and viscosity) result in variations in engine power and, consequently, in engine emissions and fuel consumption. The European EPEFE programme further found that fuel density also influences injection timing of mechanically controlled injection equipment, which has further effects on emissions and fuel consumption. Therefore, in order to optimise engine performance and tailpipe emissions, both minimum and maximum density limits must be defined in a fairly narrow range.

**Effect of Density on Emissions and Fuel Consumption**

Emissions testing has demonstrated that reduced density will reduce PM emissions from all diesel vehi-

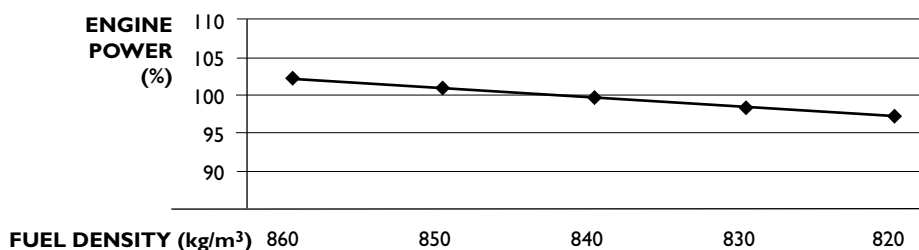
cles, and NO<sub>x</sub> emissions from heavy duty vehicles (Figure 4).

Figure 4: Effect of Density on Exhaust Emissions 855 to 828 kg/m<sup>3</sup>



However, due to the volumetric fuel injection of diesel engines, reduced density will also increase fuel consumption and reduce power output. EPEFE testing has shown that reductions in fuel density decreases engine power output (Figure 5) and increases volumetric fuel consumption. Variations in fuel viscosity (i.e., reduced density generally reduces viscosity) may accentuate the density effects on power (not necessarily fuel consumption), particularly in combination with distributor-type injection pumps.

Figure 5: Effect of Density on Engine Power 855 - 828 kg/m<sup>3</sup>



Despite the increase in fuel consumption, EPEFE found that reduced density actually decreased CO<sub>2</sub> emissions slightly (about 1%). This is explained by the higher hydrogen/carbon ratio in low density fuels when other fuel parameters (most importantly cetane number/index) are kept constant.

**Influence of Fuel Density on Emission Control Systems**

Production diesel engines are set to a standard density which determines the amount of fuel injected. The (volumetric) injection quantity is a control parameter for other emission control systems like the exhaust gas recirculation (EGR). Variations in fuel density therefore result in non-optimal EGR-rates for a given load and speed point in the engine map and, as a consequence, influence the exhaust emission characteristics.

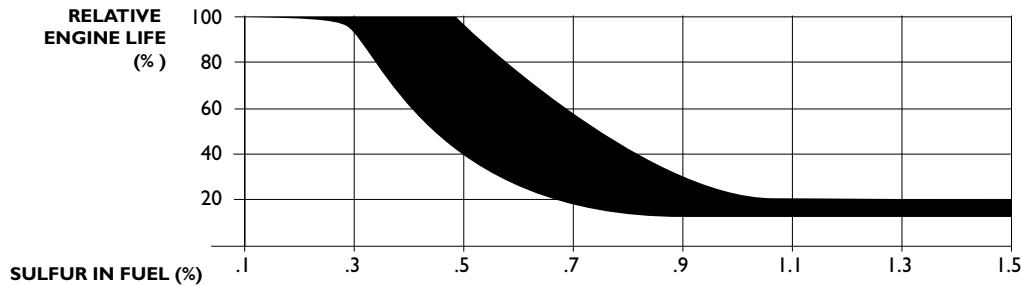
**Influence of Fuel Viscosity on Injection System Performance**

Fueling and injection timing are also dependent on fuel viscosity. High viscosity can reduce fuel flow rates, resulting in inadequate fueling. A very high viscosity may actually result in pump distortion. Low viscosity, on the other hand, will increase leakage from the pumping elements, and in worse cases (low viscosity, high temperature) can result in total leakage. As viscosity is impacted by ambient temperature, it is important to minimise the range between minimum and maximum viscosity limits to allow optimisation of engine performance.

## SULFUR

Sulfur naturally occurs in crude oil. If the sulfur is not removed during the refining process it will contaminate vehicle fuel. Sulfur can have a significant effect on engine life. As shown in Figure 6, as sulfur level increases, relative engine life decreases.

Figure 6: Effect of Sulfur on Engine Life



Diesel fuel sulfur also contributes significantly to fine particulate matter (PM) emissions, through the formation of sulfates both in the exhaust stream and, later in the atmosphere. Sulfur can lead to corrosion and wear of engine systems. Furthermore the efficiency of some exhaust after-treatment systems is reduced as fuel sulfur content increases, while others are rendered permanently ineffective through sulfur poisoning.

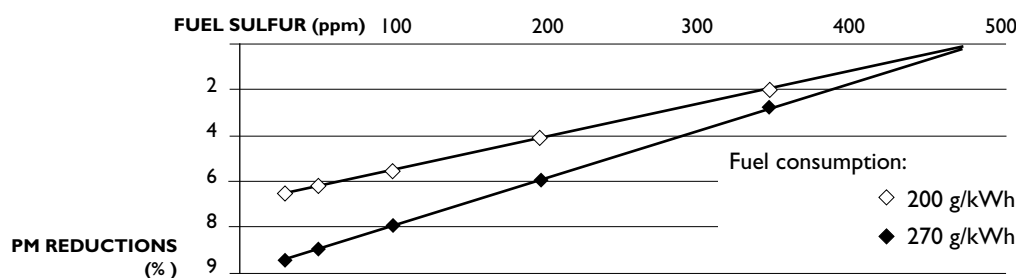
As sulfur levels are reduced, fuel stability requires special attention. The industry is currently in the process of developing a "Standard Test Method for High Temperature Stability of Distillate Fuels" (ASTM D 6468) for thermal oxidative stability. Inadequate thermal stability can result in fuel filter plugging. As fuel injection system pressures and temperatures increase, it may be more appropriate to measure the thermal oxidative stability of diesel fuel rather than only long-term storage stability.

### Effect of Sulfur on PM Emissions

The impact of sulfur on particulate emissions is widely understood and known to be significant. In the European Auto Oil programme it was predicted that a reduction from 500 ppm to 30 ppm will result in PM emission reductions of 7% from light duty vehicles and 4% from heavy duty trucks. However, the predictive equations do not take into account the absolute PM level or the fuel consumption.

A correction factor has been developed by European heavy duty manufacturers to better reflect the relationship between PM emissions and fuel sulfur levels. This correction suggests that the real benefit from sulfur reductions will be more significant, as shown here (Figure 7) for heavy duty trucks. Reductions in fuel sulfur will also provide particulate emission reductions in all engines, regardless of emission calibration.

Figure 7: Effect of Diesel Fuel Sulfur Level on PM Emissions Heavy Duty Engines (PM = 0,10 g/kWh)



Testing performed on heavy duty vehicles using the Japanese diesel 13 mode cycle have shown significant PM emission reductions can be achieved with both catalyst and non-catalyst equipped vehicles.



The testing showed that PM emissions from a non-catalyst equipped truck running on 400 ppm sulfur fuel were about double the emissions when operating on 2 ppm fuel. (JSAE 9831171)

**Fuel Sulfur Contribution to Particulate Matter**

The sulfur in fuel is oxidised during combustion to form SO<sub>2</sub>, which is the primary sulfur compound emitted from the engine. Some of the SO<sub>2</sub> is further oxidised to sulfate (SO<sub>4</sub>). The sulfate and associated water coalesce around the carbon core of the particulate. This increases the mass of the PM and thus fuel sulfur has a significant influence on the PM. Typically the conversion rate from sulfur to sulfate is around 1% and the sulfate contribution to engine out PM has been negligible. However, the use of an after-treatment containing an oxidation catalyst dramatically increases the conversion rate to up to 100% depending on the catalyst efficiency. Therefore, for vehicle systems with an oxidation catalyst, a large proportion of the engine out SO<sub>2</sub> will be oxidized to SO<sub>4</sub>, increasing the amount of PM emitted from the vehicle. This has a significant impact on the efficiency of the vehicle after-treatment system.

**Calculation of Sulfur Contribution to PM**

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

- The fuel consumption of the engine
- The fuel sulfur content
- The S to SO<sub>4</sub> conversion rate

Both the fuel sulfur content and fuel consumption are measurable parameters, whereas the conversion rate can only be predicted as it varies from engine to engine. The use of an after-treatment containing an oxidation catalyst dramatically increases the conversion rate to up to 100% depending on the catalyst efficiency.

The following formula clearly shows the impact of the fuel sulfur on PM:

$$BSSO_4 = BSFC * FSC / 100 * PCSC / 100 * 7$$

where BSSO<sub>4</sub> = Brake specific sulfate in mass/brake power-hour

BSFC = brake specific fuel consumption in g/kWh

FSC = fuel sulfur content in % mass

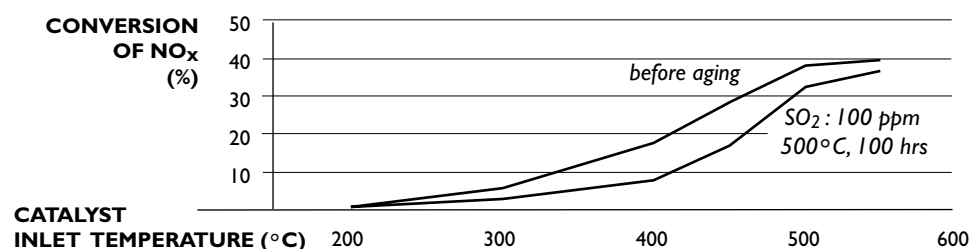
PCSC = Percent sulfur conversion (to SO<sub>4</sub>)

7 = S to (SO<sub>4</sub> + water) weight increase factor

**Effect of Sulfur on Diesel Aftertreatment**

Future regulations will require lower NO<sub>x</sub> and particulate emissions in combination with lower fuel consumption and CO<sub>2</sub> emissions. De-NO<sub>x</sub> catalyst systems, which can remove NO<sub>x</sub> emissions from the diesel's oxygen-rich exhaust, could be the solution to break the trade-off between NO<sub>x</sub>, PM and fuel consumption. However, as shown in Figure 8, these systems are very sensitive to fuel sulfur content. The level of sulfur in diesel fuel (and gasoline) is an important factor in the performance of De-NO<sub>x</sub> catalyst systems. The catalyst performance is always better with sulfur-free fuel.

Figure 8: Influence of Sulfur Dioxide Aging on NO<sub>x</sub> Conversion



Other technologies under development include NO<sub>x</sub> adsorber catalysts, Continuously Regenerating Diesel Particulate Filters (CR-DPF) and Catalysed Diesel Particulate Filters (CDPF). The Diesel Emission Control-Sulfur Effects (DCSE) project, a recent collaborative program between the US Department of Energy (DOE), Engine Manufacturers Association (EMA) and Manufacturers of Emission Controls Association (MECA) studied the impact of diesel fuel sulfur levels of 3, 16, 30, 150 and 350 ppm on a number of these technologies on both heavy and light duty engines.

Reference: <http://www.ott.doe.gov/decse>.

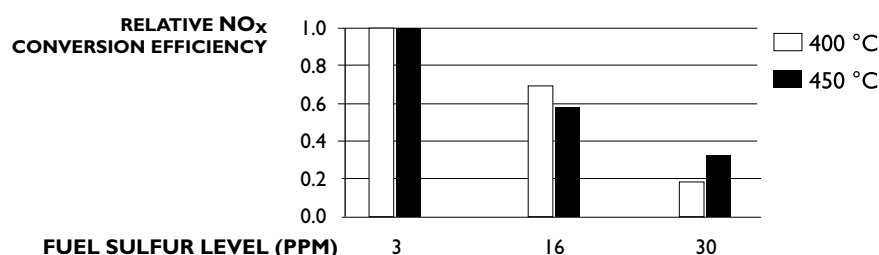
A successor to the DCSE project is the current Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC) Program. The mission of the APBF-DEC Program is to identify optimal combinations of low-sulfur diesel fuels, lubricants, diesel engines and emission control systems to meet projected emission standards for the 2001 to 2010 time period. Reference: <http://www.ott.doe.gov/apbf.shtml>.

### NO<sub>x</sub> Adsorber

NO<sub>x</sub> adsorbers, are poisoned and rendered ineffective by the presence of sulfur. These devices can be up to 90% efficient in NO<sub>x</sub> removal if operated on sulfur-free fuel. The concern with fuel sulfur is that SO<sub>2</sub> is formed during combustion and released in the exhaust. In a NO<sub>x</sub> adsorber catalyst, this SO<sub>2</sub> undergoes reactions that are similar to those of NO<sub>x</sub>. However, SO<sub>2</sub> generates a stronger adsorbate (SO<sub>3</sub>) when compared with NO<sub>2</sub>. As a result, SO<sub>2</sub> is a poison for the NO<sub>x</sub> adsorption sites.

The effect of fuel sulfur content on NO<sub>x</sub> adsorber conversion efficiency is shown in Figure 9 below. The figure illustrates the effect of fuel sulfur on relative NO<sub>x</sub> conversion efficiencies. Compared to 3 ppm sulfur fuel both 16 and 30 ppm sulfur fuels resulted in a significant decline in performance.

Figure 9: Effect of Fuel Sulfur Level on NO<sub>x</sub> Conversion Efficiency (150 hours aging)



Engine tested: 1.9 litre, High Speed Direct Injection, Common Rail, 81 kW

### Continuously Regenerating Diesel Particulate Filters

The Continuously Regenerating Diesel Particulate Filter (CR-DPF) and Catalysed Diesel Particulate Filter (CDPF) represent two approaches to regeneration of DPFs.

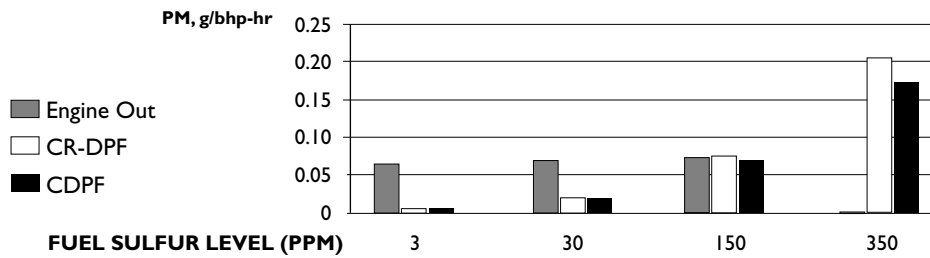
The CR-DPF accomplishes this filter regeneration by continuously generating NO<sub>2</sub> from engine-emitted NO over a diesel oxidation catalyst placed upstream of the CR-DPF. NO<sub>2</sub> has been established as a more effective low-temperature oxidizing agent for diesel PM than oxygen. Sulfur in the exhaust is oxidised over the CR-DPF, forming sulfates, which contribute to PM. Sulfur oxides also compete for the critical NO and NO<sub>2</sub> reaction, making the regeneration of the trap less effective.

The CDPF accomplishes the DPF regeneration by using a catalyst coating on the DPF element to promote oxidation of the collected PM using available oxygen in the diesel exhaust. Sulfur in the exhaust is oxidised over the CDPF to form sulfates. Exhaust-gas temperature and fuel-sulfur level are critical factors that affect the performance of both types of DPFs (CR-DPF and CDPF).

Fuel sulfur has a significant effect on PM emissions. Both DPF's were effective in reducing PM emissions (95% over the OICA cycle) when used with 3-ppm sulfur fuel (Figure 10a, 10b). With 30-ppm sulfur

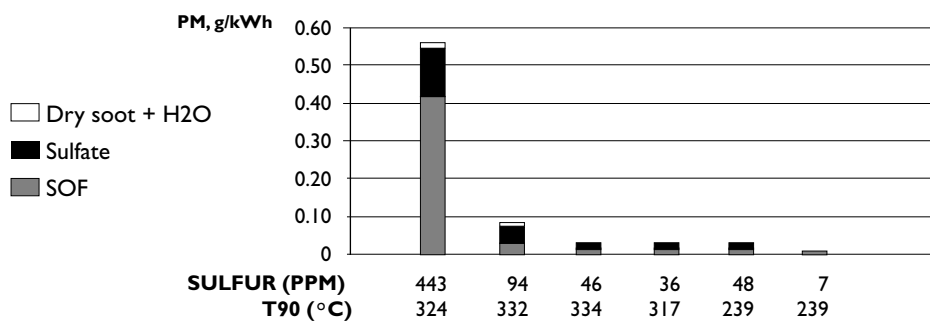
fuel, the PM reduction efficiencies dropped to 72 and 74% for the CR-DPF and CDPF, respectively. At the 150-ppm sulfur test point, PM reductions were near zero.

Figure 10a: Effect of Fuel Sulfur Level on PM Emissions – OICA Cycle



Engine tested: Caterpillar 3126, 7.2 litre, Inline 6 cylinder, 205 kW @2200 rpm

Figure 10b: Fuel effect on Diesel Particulate – CR (Continuous Regeneration) - DPF Japan diesel 13 mod



**Diesel Particulate Filter**

The Diesel Particulate Filter (DPF) for light-duty vehicles has appeared in the market on production vehicles in mid-2000, and allows these vehicles to achieve extremely low values of particulate emissions. The filtration of exhaust gas particulates has been possible for many years, but the disposal of the accumulated particulate has remained as a difficult problem to solve. Apart from removing the filter frequently for cleaning, a reliable and cost-effective system of on-board filter regeneration by combustion of the particulate was not available. The latest generation of common rail engines opened possibilities through electronic injection strategies for increasing exhaust gas temperatures, so combusting the trapped particulate. Through a combination of catalytic additive mixed on-board with the fuel, post-combustion fuel injection into the cylinder and a pre-filter HC combustion, reliable regeneration of the filter has become possible, so allowing DPFs to be used in service.

The latest generation of light-duty common rail direct injection diesel engines emits 60% less particulate matter than its immediate prechamber predecessors, and when combined with a DPF system, reduces the number of particulates in the exhaust gases to the level of ambient air, and completely eliminates black smoke. What is more, this 10<sup>3</sup> - 10<sup>4</sup> reduction magnitude in particulate emissions is constant over the whole range of particulate size. Thus using DPF systems further enhances the potential of the light-duty diesel engine as a low-polluting power unit.

The sulfur contained in diesel fuel is likely to be transformed into gaseous sulfur compounds in the oxidation catalyst contained in the DPF system, and may be transformed through secondary sulphate particulates in the atmosphere. Therefore the use of sulfur-free fuels in vehicles with DPS systems is highly recommended to avoid this phenomenon.

Fuel and lubricant derived ash will have a significant effect on the life of diesel particulate filters. The ash content of diesel fuel should be controlled to a low level to ensure that any effects are both minimal and

controlled. The limit for ash in diesel fuel should be reduced to provide this control. This will require an improved method for determination of the ash content.

## AROMATICS

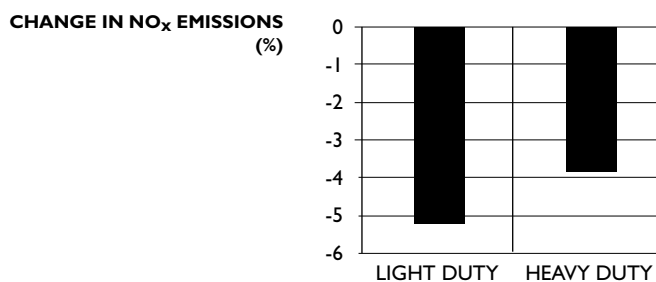
Aromatics are fuel molecules which contain at least one benzene ring. The fuel aromatic content will affect combustion and the formation of particulate and PAH emissions.

The diesel fuel aromatics content influences flame temperature, and therefore, NO<sub>x</sub> emissions during the combustion. Polyaromatics in the fuel affect the formation of particulates and the polyaromatic hydrocarbon (PAH) emissions from a diesel engine.

### Influence of Total Aromatics Content on NO<sub>x</sub> Emissions

A higher aromatic content in the fuel will increase the flame temperature during combustion which results in increased NO<sub>x</sub> emissions. Testing in Europe (ACEA follow-up programme to EPEFE) demonstrated that a reduction of the total aromatic content from 30 to 10% yields significantly lower NO<sub>x</sub> emissions as shown in Figure 11.

Figure 11: Effect of Total Aromatics on NO<sub>x</sub> Emissions 30 to 10% aromatics

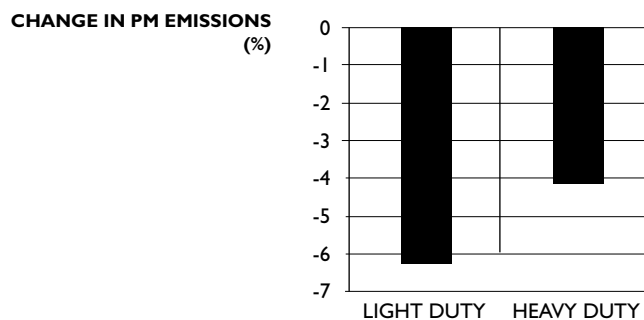


The light duty data is based on the combined ECE/EUDC cycle, the heavy duty on the 88/77/EEC 13-mode cycle.

### Influence of Polyaromatic Content on Particulate Emissions

The influence of polyaromatic (di+tri+) content on PM emissions was also investigated in the EPEFE programme. Figure 12 shows the reductions of PM emissions which were measured when the polyaromatic content was reduced from 9 to 1%.

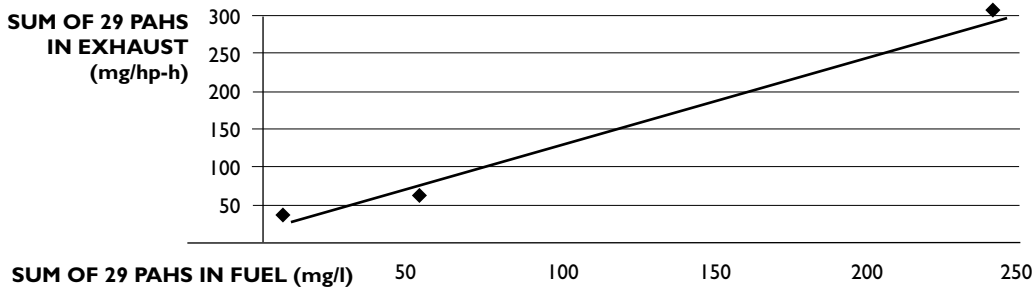
Figure 12: Effect of Polyaromatics on PM Emissions (from 9 to 1% di+ polyaromatics)



### Influence of Polyaromatic Content on PAH Emissions

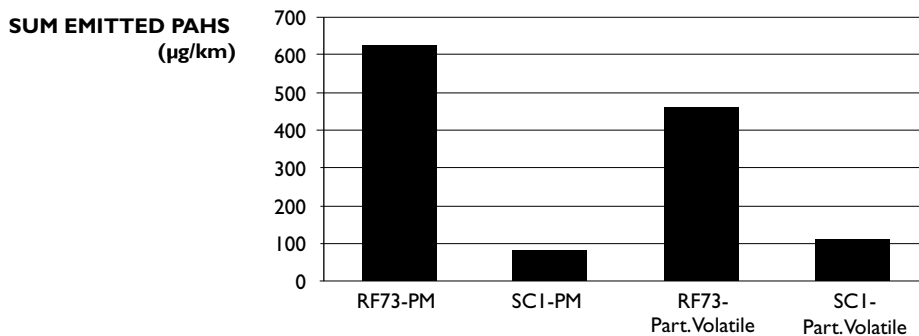
PAH (tri+) content in diesel fuel has been shown to directly correlate to PAH emissions in vehicle exhaust. The PAH emissions of a truck diesel engine on the US transient cycle using fuels with different PAH contents were measured in a Swedish study. The results shown in Figure 13 demonstrate this direct correlation.

Figure 13: Effect of Fuel PAH on Emissions of PAH



The Swedish EPA also tested a Euro 2 diesel engine on the 88/77/EEC and the transient ‘Braunschweig’-cycle on Sweden Class 1 fuel (SCI, PAH =24 mg/l) and European reference fuel (RF73; PAH=2100 mg/l). Figure 14 shows the sum of emitted PAH’s collected on the filter (PM) and the emissions of partly volatile PAH’s (average of four cycles).

Figure 14: Effect of Fuel PAH on Emissions of PAH



## DISTILLATION CHARACTERISTICS

The distillation curve of diesel fuel indicates the amount of fuel which will boil off at a given temperature. The curve can be divided into three parts:

- The light end, which affects startability,
- The region around the 50% evaporated point, which is linked to other fuel parameters such as viscosity and density; and,
- The heavy end, characterised by the T90, T95 and final boiling points.

The heavy end has been the most thoroughly studied with respect to its effect on tailpipe emissions.

### Influence of Heavy End on PM Emissions

In most new studies only the influence of the upper boiling range has been investigated with respect to exhaust gas emissions, whereas the lower boiling range varied widely. Conclusions concerning the whole boiling range and distillation influence are therefore not possible. However, it is clear that too much fuel in the heavy end will result in coking and increased tailpipe emissions of soot/smoke/particulate matter.

### Influence of T95 on Tailpipe Emissions

The effect of T95 on vehicle emissions was examined in the European EPEFE programme. The testing indicated that exhaust gas emissions from heavy duty diesel engines were not significantly influenced by T95-variations between 375°C and 320°C. However, a tendency for lower NO<sub>x</sub> and higher HC with lower T95 was observed.

In the case of light duty diesel engines the same reduction in T95 resulted in a 7% reduction in PM and 4.6% increase in NO<sub>x</sub> emissions.

## COLD FLOW

Diesel fuel can have a high content (up to 20%) of paraffinic hydrocarbons which have a limited solubility in the fuel and, if cooled sufficiently, will come out of solution as wax. Therefore, adequate cold flow performance is one of the most fundamental quality criteria for diesel fuels.

The cold flow characteristics are primarily dictated by:

- Fuel distillation range, mainly the back-end volatility;
- Hydrocarbon composition: content of paraffins, naphthenes, aromatics;
- Use of cold flow additives.

### Measures of Cold Flow Performance

Specifications for diesel cold flow properties must be specified according to the seasonal and climatic needs in the region where the fuel is to be used. Wax in vehicle fuel systems is a potential source of operating problems; the low-temperature properties of diesel fuels are therefore defined by wax-related tests:

- Cloud Point, CP (ISO 3015, ASTM D2500): The temperature at which the heaviest paraffins start to precipitate and form wax crystals; the fuel becomes 'cloudy'.
- Cold Filter Plugging Point, CFPP (ENI 116): The lowest temperature at which the fuel can pass through the filter in a standardised filtration test. The CFPP test was developed from vehicle operability data and demonstrates an acceptable correlation for fuels and vehicles in the market. For North American fuels however, CFPP is not a good predictor of cold flow operability. CFPP can be influenced by cold flow additives.
- Low Temperature Flow Test, LTFT (ASTM D4539): The LTFT was developed to predict how diesel fuels in the United States and Canada will perform at low temperatures, in the diesel vehicles present in these markets. LTFT is a slow cooling test and therefore more severe than CFPP. LTFT temperature can be influenced by cold flow additives.

### Cold Flow Limits

The diesel fuel cold flow performance can be specified by Cloud Point, by CFPP (with maximum delta between CFPP and Cloud Point), or by LTFT (in USA and Canada).

- If Cloud Point (only) or LTFT is used, the maximum allowed temperature should be set no higher than the lowest expected ambient temperature.
- If CFPP is used to predict cold flow, the maximum allowed CFPP temperature should be set equal to, or lower than, the lowest expected ambient temperature. In this case, the Cloud Point should be no more than 10°C above the CFPP specified.

Example:

- Lowest expected ambient temperature (statistical): -32°C
- Maximum allowed CFPP temperature: -32°C
- Maximum allowed Cloud Point: -22°C

## FOAM

Diesel fuel has a tendency to generate foam during tank filling which slows the process and risks an overflow. Anti-foamants are sometimes added to diesel fuel, often as a component of a multifunctional additive package, to help speed up or to allow more complete filling of vehicle tanks. Their use also minimises the likelihood of fuel splashing on the ground which in turn reduces the risk of spills polluting the ground, the atmosphere and the consumer.

### Foam Control

Silicon surfactant additives are effective in suppressing the foaming tendency of diesel fuels, the choice of silicon and co-solvent depending on the characteristics of the fuel to be treated. Selection of a diesel anti-foamant is generally decided by the speed at which the foam collapses after vigorous manual agitation to simulate the effect of air entrainment during tank filling. It is important that the eventual additive chosen should not pose any problems for the long-term durability of the emission post-treatment control systems.

## FATTY ACID METHYL ESTERS

Fatty Acid Methyl Esters (FAME) including vegetable derived esters (VDE) are increasingly being used as extenders to, or replacements of, diesel fuel. This has been driven largely by national efforts to exploit agricultural produce and/or to reduce the dependency on imported oil products. Some data suggests that environmental benefits can be achieved through the use of these esters. However, manufacturers do have concerns over the introduction of vegetable derived esters in high quality diesel fuel.

Many oils may be used for making methyl esters, eg., rapeseed, sunflower, palm, soya, cooking oils and animal fats, but to date, the rapeseed product comes closest to the behaviour of conventional diesel fuel. For example, typical characteristics for rapeseed methyl ester (RME) are as follows:

cetane number = 51

density = 0.880 kg/m<sup>3</sup>

viscosity at 40°C = 3.5 mm<sup>2</sup>/sec

The technical advantages of methyl ester are primarily that they ensure lubricity of injection equipment (lubricity can be diminished by the refining processes to remove diesel sulfur) and they reduce exhaust gas particulate matter. The disadvantages of methyl esters are as follows:

- They require special care at low temperatures to avoid excessive rise in viscosity and loss of fluidity. Additives may be required to alleviate the problems.
- Being hygroscopic, special care is needed to prevent high water content and the consequent risk of corrosion.
- Deposit formations tend to be higher than for diesel fuel, so detergent additive treatment is strongly advisable.
- Seals and composite materials in the fuel system are attacked by methyl esters unless they are specially chosen for their compatibility.

Based on the technical effects of FAME, it is strongly advised that FAME content be restricted to less than or at 5%. As a pure fuel, or at higher levels in diesel fuel, the vehicles need to be adapted to the fuel, and particular care is needed to avoid problems.

The European standards organisation CEN is finishing in 2002 the FAME specification EN 14214 to be used as diesel fuel in engines designed or adapted for this fuel. The group is also evaluating the diesel fuel specifications to determine if changes are needed to either the parameters or test methods to accommodate the introduction of FAME as a diesel extender at levels up to 5%. Until this work is completed and based on the technical concerns raised by the introduction of FAME in diesel fuel, it should not be introduced into a high quality fuel such as required in Category 4 markets. ASTM recently approved a standard specification (D6751) for biodiesel (B100) that is still under review by some automakers and engine manufacturers. Non-extended fatty acids are not acceptable for use as fuels.

## E-DIESEL

Adding ethanol to diesel fuel (E-diesel) increasingly is being considered as a way to extend the volume of diesel fuel, reduce dependency on imported oil products or exploit agricultural produce and waste. E-diesel fuel typically has an extremely low flashpoint of about 13°C (55°F), which is well below the minimum limit set by various organisations: ASTM D975 standard of 52°C (126°F), EN590 standard of 55°C min (131°F), JIS K2204 standard of 45°C (113°F). Such flashpoint levels are likely to generate risks to engines, vehicles and fuel distribution facilities, which raises serious safety concerns (such as explosions), for fuel handling, storage and use. Vehicle and engine manufacturers are concerned that e-diesel may damage vehicle parts, especially fuel injectors, and cause other types of vehicle failure due to low lubricity. The fuel's compatibility with the vehicle in other ways, its impact on vehicle emissions and its health effects remain unknown. Since ethanol has a lower energy content than diesel fuel, its presence in the fuel will reduce fuel economy. Therefore, until the many safety, performance and health concerns are resolved and sufficient peer-reviewed research is conducted in these important areas, manufacturers do not support adding ethanol to any category of diesel fuel.

## INJECTOR CLEANLINESS

The fuel injector is a component of very high-precision designed to meter fuel to a high degree of accuracy. The correct behaviour of the engine depends on the injector doing its job properly, otherwise there will be repercussions in terms of noise, smoke and emissions.

### Effect of Injector Fouling

The tip of the injector is subject to a very harsh environment as it is in direct contact with the combustion process, both in pre-chamber and in direct injection engines. The solid matter products of combustion are deposited on the tip, and can alter significantly the operation of the injector. For pre-chamber engines, the combustion products partially block the progressive delivery of the fuel at part load, and the combustion can become violent and disorganised. Likewise in direct injection engines, a partial or complete blockage of one of the fine spray holes will perturb the atomisation of the fuel jet, and the engine no longer functions as designed.

Where pre-chamber engines are concerned, coking is inevitable due to the type of injector used, and the choice of injector takes this into account. However, the coking level depends on the quality of the fuel, and excessive coking cannot be tolerated. The injectors of direct injection engines are initially more resistant to coking, but poor fuel quality can eventually block a spray hole.

### Influence of Detergent Additives

The solution to this difficulty is to be found in the use of detergent additives in the fuel. High doses of these additives can partially clean an already heavily coked injector, while smaller doses can maintain injectors at an acceptably clean state which ensures correct operation. Many fuel distributors include these additives in commercial diesel fuels as quality features to obtain a 'keep clean' effect.

Cleanliness of the injectors has become an even higher priority at present as high-pressure injection systems are increasingly used on both heavy-duty and light-duty direct injection engines. The conformity of modern engines with their specified performance in terms of power, fuel consumption and emissions over time will depend largely on the cleanliness of their injectors.



## LUBRICITY

The lubricating components of the diesel fuel are believed to be the heavier hydrocarbons and polar fuel compounds. Diesel fuel pumps, without an external lubrication system, rely on the lubricating properties of diesel fuel to ensure proper operation.

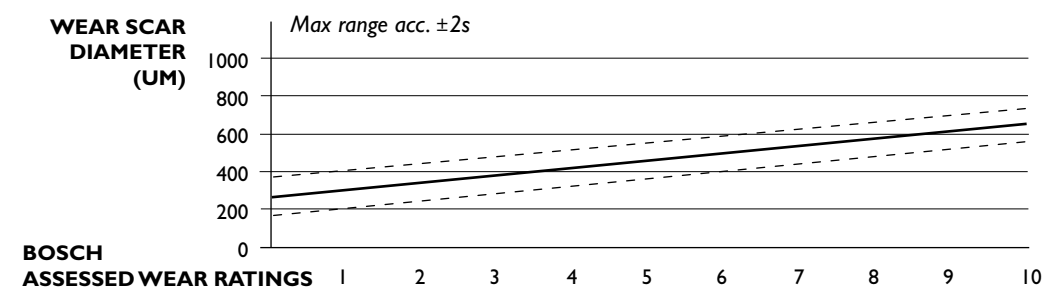
Refining processes to remove diesel fuel sulfur tend to simultaneously reduce the components of the fuel which provide natural lubricity. As diesel fuel sulfur levels decrease, the risk of inadequate lubricity also increases; however, poor lubricity has been observed even in diesel fuels with very high sulfur levels.

### Influence of Lubricity on Pump Wear

Inadequate lubricity can result in increased tailpipe emissions, excessive pump wear and, in some cases, catastrophic failure. Concerns over problems experienced with fuels with poor lubricity led to a significant international collaboration between oil companies, OEMs, additive companies and pump manufacturers to develop a test method and performance limit for fuel lubricity. The resultant method, the High Frequency Reciprocating Rig (HFRR) procedure, is a bench test which provides good correlation to measured pump effects.

Figure 15 shows the correlation between actual pump wear (measured by Bosch) and HFRR measured wear scar diameter. Bosch's rating scale describes 'normal wear' as less than 3.5 (which corresponds to an HFRR limit of 400  $\mu\text{m}$ ). At a wear rating of 4, the pump will have decreased endurance, and ratings above 7 indicate potential fatal breakdown.

Figure 15: Assessed Pump Wear Rating vs. HFRR Results



A pump rig test method is under development which will complement the HFRR. The new test will provide better correlation between test results and actual in-use observations of the protection provided by lubricity additives.

## GOOD HOUSEKEEPING PRACTICES

The problems encountered by vehicles from poor quality fuel often are caused by adulteration that occurs in the fuel distribution system, after the fuel has left the refinery gate. Failure to invest in adequate pipeline and storage facilities and failure to maintain the equipment can lead to volatility losses, fuel leakage and contamination by particulates and water that, in turn, can lead to a host of vehicle problems. Poor operating practices at the service station, such as too infrequent replacement of fuel dispenser filters or "dipping" of tanks to check for water, can magnify these problems.

**GASOLINE Sources**

Table	1	US AQIRP, EPEFE, AAMA/AIAM, SAE 982726, JSAE 9838985
Table	2	GENERAL MOTORS, 2000
Figure	1	US AQIRP
Figure	2	TOYOTA, 1999
Figure	3	AAM/AIAM LOW SULFUR EMISSIONS STUDY
Figure	4	JAPAN CLEAR AIR PROGRAM
Figure	5	SAE 962051
Figure	6	TOYOTA, 1999
Figure	7	GENERAL MOTORS, 1999
Figure	8	TOYOTA, 1999
Figure	9	SAE 2002-01-2894
Figure	10	FORD, 2000
Figure	11	US AQIRP
Figure	12	US AQIRP, EPEFE REPORT
Figure	13	CRC REPORT, No 605
Figure	14	CRC REPORT, No 605
Figure	15	GM/SAE 962023
Figure	16	TOYOTA/SAE 972851
Figure	17	FORD, 1996
Figure	18	FORD/SAE 962012
Figure	19	FORD, 1996
Figure	20	FORD/SAE 962012
Figure	21	FORD, 2001
Figure	22	TOYOTA/SAE 941893

**DIESEL**

Figure	1,2,3	ACEA REPORT: INFLUENCE OF DIESEL FUEL QUALITY ON HEAVY DUTY DIESEL ENGINE EMISSIONS, MARCH 1997
Figure	4,5	EPEFE REPORT
Figure	6	DETROIT DIESEL, EFFECT OF SULFUR ON ENGINE LIFE
Figure	7	ACEA REPORT: INFLUENCE OF DIESEL FUEL QUALITY ON HEAVY DUTY DIESEL ENGINE EMISSIONS, MARCH 1997
Figure	8	JAMA, PRESENTED AT 30TH ISATA, JUNE 1997
Figure	9	DECSE PROGRAM, PHASE I, NUMBER 2, OCTOBER 1999, US DOE/EMA
Figure	10a	DECSE PROGRAM, PHASE I, NUMBER 3, NOVEMBER 1999, US DOE/EMA
Figure	10b	JAPAN CLEAN AIR PROGRAM
Figure	11	ACEA REPORT: INFLUENCE OF DIESEL FUEL QUALITY ON HEAVY DUTY DIESEL ENGINE EMISSIONS, MARCH 1997
Figure	12	DATA FROM THE EPEFE REPORT
Figure	13	KARLSSON (SCANRAFF REFINERY) AND RÖJ (VOLVO): DIESEL FUEL QUALITY FOR REDUCED EMISSIONS, WORLD FUELS CONFERENCE SAN FRANCISCO, 1995
Figure	14	GRÄGG, AP SVENSK BILPROVNING/MOTORTESTCENTER, REPORT 9/1995
Figure	15	BOSCH, 1997

