

# WORLDWIDE FUEL CHARTER

SIXTH EDITION

## GASOLINE AND DIESEL FUEL

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MARCH 2019



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Japan Automobile  
Manufacturers Association

March 2019

## Subject: Worldwide Harmonisation of Gasoline and Diesel Fuel

Dear Recipient:

On behalf of automobile and engine manufacturers from around the world, the Worldwide Fuel Charter (WWFC) Committee is pleased to present the latest proposed update of the Worldwide Fuel Charter for Gasoline and Diesel Fuel on the twentieth anniversary of the original charter for gasoline and diesel fuel that was published in 1998. This proposed draft updates the Fifth Edition published in 2013 and will become the sixth edition when finalised. In addition to this charter, the Committee has previously published guidelines for ethanol and biodiesel blending stock for use in gasoline and diesel fuel, respectively. The charter and guidelines have two purposes: to inform policymakers and other interested parties how fuel quality can significantly affect engine and vehicle operation, durability and emissions performance throughout the year; and to promote harmonised fuel quality worldwide in accordance with vehicle, engine and emission control system needs, for the benefit of consumers and the general environment.

This proposal updates the previous edition in several ways and presents each fuel in its own section of the document for easier reading. The gasoline section introduces a new Category 6 to address anticipated vehicle and engine regulations for emission control and fuel efficiency in certain major markets. Also, it introduces new metrics to help reduce particle emissions. Notably, in light of global progress on gasoline quality since the WWFC was first published more than two decades ago, we are pleased to announce the retirement of Category 1 gasoline as obsolete.

We have also seen great progress in diesel fuel quality around the world, but some regions, unfortunately, still have unacceptably high sulphur levels, even exceeding 10,000 ppm in some markets. To encourage these regions to bring their fuel quality to cleaner and more modern specifications, we decided to retain diesel Category 1, but only as guidance to a transitional quality fuel. The Committee is serving notice, however, that we do intend to retire this diesel Category 1 in a future edition. The second change to the diesel fuel specifications appears in Category 5, which has been modified to encourage greater use of alternative and synthetic diesel fuel blends.

As countries move toward ever more stringent engine and vehicle emission and efficiency requirements, fuel quality becomes an ever more important factor in engine and vehicle performance and cleanliness. Sulphur-free and metal-free fuels remain critical prerequisites for ultraclean, efficient and durable technology, and the best fuel quality, as represented in the highest numbered categories, will enable the most advanced vehicles, engines and emission control systems to meet their design potential for high performance, clean operation, maximum efficiency and optimum environmental performance.

We welcome your comments on this proposed Sixth Edition of the gasoline and diesel fuel charter and look forward to working with you to support these harmonised fuel quality specifications.

Worldwide Fuel Charter Committee

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**Supporting organisations:**

- › Organisation Internationale des Constructeurs d'Automobiles (OICA)

## ACRONYMS

AAMA	American Automobile Manufacturers Association, the U.S. trade association for Chrysler, Ford and GM from 1992 until 1998	HC	Hydrocarbons
ACEA	Association des Constructeurs Européens d'Automobiles (European Automobile Manufacturers' Association)	HFRR	High Frequency Reciprocating Rig
AIAM	Association of International Automobile Manufacturers, now named Association of Global Automakers	HVO	Hydrotreated Vegetable Oil
Alliance	Alliance of Automobile Manufacturers	IDID	Internal Diesel Injector Deposits
AMA	Accelerated Mileage Accumulation	ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry
AQIRP	Air Quality Improvement Research Programme (part of the US Auto Oil programme, 1989-1992)	IP	Energy Institute (formerly Institute of Petroleum)
ASTM	ASTM International (formerly American Society for Testing and Materials)	ISO	International Organisation for Standardization
BHT	Butylated hydroxytoluene	IVD	Intake Valve Deposits
Biofuel	Liquid transport fuel produced from biomass	JAMA	Japan Automobile Manufacturers Association
Biomass	Biodegradable fraction of products, waste and residues from biological origin	JARI	Japan Automobile Research Institute
BTL	Liquid fuel made from biomass ('Biomass to Liquid')	JATOP	Japan Auto-Oil Program
CCD	Combustion Chamber Deposits	JCAP	Japan Clean Air Program
CDPF	Catalysed Diesel Particulate Filter	JIS	Japanese Industrial Standards
CEC	Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids	LEV	Low Emission Vehicle
CFPP	Cold Filter Plugging Point	LTFT	Low Temperature Flow Test
CFR	Cooperative Fuel Research (RON/MON testing)	MECA	Manufacturers of Emission Controls Association
CN	Cetane Number	METI	Ministry of Economy, Trade and Industry (Japan)
CO	Carbon Monoxide	MMT	Methylcyclopentadienyl Manganese Tricarbonyl
CO <sub>2</sub>	Carbon Dioxide	MON	Motor Octane Number
CP	Cloud Point	MtBE	Methyl tertiary Butyl Ether
CRC	Coordinating Research Council (US)	MTZ	MotorTechnische Zeitschrift (German technical journal)
CR-DPF	Continuously Regenerating Diesel Particulate Filter	NF M	Norme Française - Industrie du Pétrole
DBE	Double bond equivalence	NF T	Norme Française - Industrie Chimique (French Norm - Petroleum Industry)
DECSE	Diesel Emission Control – Sulfur Effects, research program of the US Department of Energy	NMHC	Non-Methane Hydrocarbon
DEF	Diesel Exhaust Fluid (for SCR systems)	NOx	Oxides of Nitrogen
DI	Distillation Index	NVH	Noise, vibration, harshness
DIN	Deutsches Institut für Normung (German Institute of Standardisation)	OBD	On-Board Diagnostics
DOC	Diesel Oxidation Catalyst	OFP	Ozone Forming Potential
DPF	Diesel Particulate Filter	Oxy	Oxygen
DVPE	Dry Vapour Pressure Equivalence	PAH	Polycyclic Aromatic Hydrocarbons
EMA	Truck and Engine Manufacturers Association	PAJ	The Petroleum Association of Japan
EN	European Norm	pHe	Acidity of ethanol
EPA	Environmental Protection Agency (US)	PM	Particulate Matter
EPEFE	European Programme on Emissions, Fuels and Engine Technology (part of the European Auto-Oil 1 programme, 1993-1995)	PMI	Particulate matter index
EtBE	Ethyl tertiary-Butyl Ether	ppm	Parts per million
FAEE	Fatty Acid Ethyl Esters	PZEV	Partial Zero Emission Vehicle
FAME	Fatty Acid Methyl Esters	RDE	Real driving emissions
FBP	Final Boiling Point	RON	Research Octane Number
FTP	(US) Federal Test Procedure	SBA	Sec-Butyl Acetate
FLTM	Ford Laboratory Test Method	SCR	Selective Catalytic Reduction
FVV	Forschungsvereinigung Verbrennungskraft maschinen (German research organization)	SULEV	Super-Ultra-Low Emission Vehicle
GHG	Greenhouse Gas	TAN	Total Acid Number
GPF	Gasoline particulate filter	TDC	Top Dead Center
GTDI	Gasoline Turbo Direct Injection	TGA	Thermal Gravimetric Analysis
GTL	Liquid fuel typically made from methane gas using a gas-to-liquid/Fischer-Tropsch-type process	THC	Total Hydrocarbons
		TLEV	Transitional Low Emission Vehicle
		TWD	Total Weighted Demerits
		ULEV	Ultra-Low Emission Vehicle
		VDE	Vegetable Derived Esters
		WWFS	Worldwide Fuel Survey, produced by SGS. See: <a href="http://www.sgs.com/en/news/2018/10/sgs-inspire-delivers-in-depth-analysis-and-reporting-on-global-fuel-quality-trends">www.sgs.com/en/news/2018/10/sgs-inspire-delivers-in-depth-analysis-and-reporting-on-global-fuel-quality-trends</a>

N.B.: "Gasoline" and "petrol" are used interchangeably in this document. Both terms refer to unleaded petroleum-based fuel intended for use in spark ignition engines and vehicles.

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The Worldwide Fuel Charters and Guidelines are part of a global effort by vehicle and engine manufacturers to increase awareness of the many significant ways that fuel quality affects vehicle and engine operation, durability and emissions. These documents provide consistent fuel quality advice to anyone –policymakers, fuel producers, fuel suppliers, standard-setting technical organizations, public interest organizations, educators and citizens— who is interested in helping consumers and improving the environment.

Ultimately, harmonizing fuel quality worldwide in accordance with vehicle and engine requirements and providing consumer access to the recommended fuels will help society by:

- Minimizing vehicle and engine emissions;
- Enabling vehicle and engine designs and maintaining good performance longer, which, in turn, can lower purchase and operation costs and increase consumer satisfaction; and
- Improving the functioning of transportation markets, both locally and worldwide.

These fuel quality recommendations represent the manufacturers' best collective judgment about a range of fuel factors considered to be the most important in terms of affecting vehicle and engine performance, durability and emissions. The recommended specifications are arranged in categories that correspond to different levels of vehicle and engine technologies. The most sophisticated technologies require and will perform best when using the highest category of fuel quality, but all levels of technology typically achieve improved performance, greater longevity and lower emissions when using higher category fuels on a regular basis. Importantly, the fuels specified in the highest categories enable the introduction of technologies having the greatest fuel efficiency and lowest greenhouse gas emissions. To improve understanding of the rationale behind the recommendations, the Charters and Guidelines explain the underlying science in the technical backgrounds of these documents.

# CHAPTER 1

## UNLEADED GASOLINE

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## ABOUT THIS EDITION

This edition makes two important category changes to the gasoline charter. First, Category 1 is being retired as obsolete, given the significant fuel quality progress since the Worldwide Fuel Charter was first published in 1998 particularly regarding lead and sulphur content. For historical reference only, this category's specifications are included as an appendix.

The second major change is the addition of a new Category 6, to reflect the emergence of a new generation of emission control limits and fuel efficiency requirements in several major markets. The specifications in Category 6 will inform interested parties about the fuel quality needs of the next generation of vehicles and engines.

## GASOLINE CATEGORIES

### Category 2

Markets with requirements for emission control, such as US Tier 1, EURO 2/II, EURO 3/III or equivalent emission standards, or other market demands.

### Category 3

Markets with more stringent requirements for emission control, such as, US LEV, California LEV or ULEV, EURO 4/IV (except lean burn gasoline engines), JP 2005 or equivalent emission standards, or other market demands.

### Category 4

Markets with advanced requirements for emission control, such as US Tier 2, US Tier 3, California LEV II, EURO 4/IV, EURO 5/V, EURO 6/6b, EURO VI, JP 2009 or equivalent emission standards, or other market demands. Category 4 fuels enable sophisticated NOx and particulate matter after-treatment technologies.

### Category 5

Markets with highly advanced requirements for emission control (including GHG) and fuel efficiency, such as US Tier 3 Bin 5, US 2017-2021 light duty fuel economy, California LEV III and as amended, Euro 6c, Euro 6dTEMP, Euro 6d, EU CO<sub>2</sub> target 120 g/km, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category aims to minimize real driving emissions (RDE) required for Euro 6dTEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023).

### Category 6

Markets with potential emission control and fuel efficiency targets more stringent than those in Category 5, such as US 2022-2025 light-duty GHG limits, anticipated US 2022-2025 fuel economy standards, EU 95g/km CO<sub>2</sub> fleet average for 2021, and post-2020 EU targets for CO<sub>2</sub>. This category aims to minimize real driving emissions (RDE) required for Euro 6dTEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023). This category is intended to enable the introduction of engines and vehicles with higher fuel efficiency and lower exhaust emissions and to specify a gasoline with lower carbon intensity, thereby enabling greater efficiency and GHG benefits than possible with lower category fuels.

## CHARTER SCOPE AND THE DEFINITION OF GASOLINE

This Charter covers finished unleaded gasoline and gasoline-based blends that qualify as conventional fuel for spark-ignition engines and vehicles. Engine/vehicle manufacturers test and certify their products to known fuel specifications, so it is important for the market to provide fuel that falls within the product's design boundaries.

Gasoline is commonly described as the lighter fractions of crude oil, which are separated from the heavier fractions during the refining process. Chemically, the liquid is composed of organic molecules (straight-chain and aromatic) within a certain boiling range; these molecules consist primarily of carbon and hydrogen atoms. If sulphur is present in crude oil molecules (as it may be naturally), it will need to be reduced or removed during the refining process to yield gasoline that will not damage engine or vehicle technologies, especially emission control equipment.

Gasoline may include certain non-hydrocarbon-only blending components (i.e., used at levels greater than 0.25% m/m) or additives to improve its quality or increase the use of renewable fuel, as discussed in the Technical Background; these should be used within the limits and using the advice in this document. All other compounds increase the risk of material incompatibility or engine damage and are not recommended. Compounds such as metallics, acids, solvents or sediment, for example, should not be present in any amount. New types of additives and blendstocks proposed for this market should be fully tested for potential adverse effects before introduction.

This Charter does not intend to cover fuels considered alternatives to gasoline, such as a high ethanol-content gasoline blend. The Charter provides flexibility to increase the ethanol level to 20-22% by volume, however, if needed to achieve the 98-102 RON specifications of Category 6, but only for vehicles designed for such fuel. Fuel dispenser labelling (for ethanol content and advising consumers to check their owner's manual) is recommended to enable consumers to determine if their vehicles can use a particular gasoline-ethanol blend.

Importantly, the European voluntary specification for gasoline (EN228) states: "Unleaded petrol shall be free from any adulterant or contaminant that may render the fuel unacceptable for use in petrol engine vehicles designed to run on unleaded petrol." The Committee concurs with this statement.

#### RECOMMENDATIONS FOR ALL MARKETS

Maintaining good fuel quality at the dispenser requires attention to the quality of the fuel upstream, including monitoring of other fuels and blend components that may be added during distribution. Good housekeeping practices should be applied throughout, from production and processing through distribution to fuel dispensing. The following recommendations apply broadly in all markets:

- Using additives that are compatible with engine oils, to prevent any increase in engine sludge or deposits of varnish.
- Not adding ash-forming components.
- Using good housekeeping practices throughout distribution to minimize contamination from dust, water, incompatible fuels and other sources of foreign matter.
- Using pipeline corrosion inhibitors that do not interfere with fuel quality, whether through formulation or reaction with sodium.
- Labelling dispenser pumps adequately to help consumers identify the appropriate fuels for their vehicles. Pump labels should advise consumers to consult their vehicle's owner manual for specific guidance on fuel selection.
- Dispensing fuel through nozzles meeting SAE J285, 'Dispenser Nozzle Spouts for Liquid Fuels Intended for Use with Spark Ignition and Compression Ignition Engines.'
- When blending with ethanol, using ethanol that adheres to the E100 Guidelines published by the WWFC Committee.

The gasoline quality recommendations that begin on page 5 apply to the finished fuel as provided to the consumer. 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 must be met.

To meet ongoing environmental, energy and consumer challenges, vehicle and engine manufacturers will continue to develop and introduce advanced and innovative propulsion technologies that may require changes in fuel quality. Category revisions will occur as needed to reflect such changes in technology, as well as in fuel production, test methods and global market conditions.

**UNLEADED GASOLINE SPECIFICATIONS**

**Category 2:** Markets with requirements for emission control, such as US Tier 1, EURO 2/II, EURO 3/III or equivalent emission standards, or other market demands.

PROPERTIES	UNITS	LIMITS	
		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	
Sulphur	mg/kg <sup>2</sup>		150
Trace metal <sup>3</sup>	mg/kg	No intentional addition	
Chlorine	mg/kg	No intentional addition	
Organic contaminants <sup>4</sup>		No intentional addition	
Oxygen <sup>5</sup>	% m/m		2.7 <sup>6</sup>
Olefins	% v/v		18.0
Aromatics	% v/v		40.0
Benzene	% v/v		2.5
Volatility		See Tables, page 10	
Sediment (total particulate)	mg/l		1
Unwashed gums <sup>7</sup>	mg/100 ml		70
Washed gums	mg/100 ml		5
Density	kg/m <sup>3</sup>	715	770
Copper corrosion	rating		Class 1
Appearance		Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or	% flow loss		5
Fuel injector cleanliness, Method 2	% flow loss		10
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 D6201)	avg. mg/valve		50
Combustion chamber deposits <sup>7</sup>			
Method 1 (ASTM D6201), 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

<sup>1</sup> Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

<sup>2</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>3</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No trace metal should exceed 1 mg/kg.

<sup>4</sup> Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

<sup>5</sup> Methanol is not permitted.

<sup>6</sup> By exception to the limit shown in the table, up to 3.7% oxygen by mass (10% ethanol content by volume) is allowed if permitted by existing regulation. Some countries allow, and some vehicles/engines can use, gasoline with a higher ethanol content. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee. Fuel dispenser labelling is recommended for gasoline-ethanol blends to enable consumers to determine if their vehicles can use the fuel, consistent with their owner manuals.

<sup>7</sup> To provide flexibility (for example, to enable the use of detergency additives that increase unwashed gum levels), the fuel may comply with either the Unwashed Gum limit or the Combustion Chamber Deposits limit.

**Category 3:** Markets with more stringent requirements for emission control, such as US LEV, California LEV or ULEV, EURO 4/IV (except lean burn gasoline engines), JP 2005 or equivalent emission standards, or other market demands.

PROPERTIES	UNITS	LIMITS	
		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	
Sulphur	mg/kg <sup>2</sup>		30
Trace metal <sup>3</sup>	mg/kg	No intentional addition	
Chlorine	mg/kg	No intentional addition	
Organic contaminants <sup>4</sup>		No intentional addition	
Oxygen <sup>5</sup>	% m/m		2.7 <sup>6</sup>
Olefins	% v/v		10.0
Aromatics	% v/v		35.0
Benzene	% v/v		1.0
Volatility		See Tables, page 10	
Sediment (total particulate)	mg/l		1
Unwashed gums <sup>7</sup>	mg/100 ml		30
Washed gums	mg/100 ml		5
Density	kg/m <sup>3</sup>	715	770
Copper corrosion	rating		Class 1
Appearance		Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or	% flow loss		5
Fuel injector cleanliness, Method 2	% flow loss		10
Particulate contamination, size distribution	Code rating		18/16/13 per ISO 4406
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 D6201)	avg. mg/valve		50
Combustion chamber deposits <sup>7</sup>			
Method 1 (ASTM D6201), 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

<sup>1</sup> Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

<sup>2</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>3</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No trace metal should exceed 1 mg/kg.

<sup>4</sup> Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

<sup>5</sup> Methanol is not permitted.

<sup>6</sup> By exception to the limit shown in the table, up to 3.7% oxygen by mass (10% ethanol content by volume) is allowed if permitted by existing regulation. Some countries allow, and some vehicles/engines can use, gasoline with a higher ethanol content. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee. Fuel pump labelling is recommended for gasoline-ethanol blends to enable consumers to determine if their vehicles can use the fuel, consistent with their owner manuals.

<sup>7</sup> To provide flexibility (for example, to enable the use of detergency additives that increase unwashed gum levels), the fuel may comply with either the Unwashed Gum limit or the Combustion Chamber Deposits limit.

**Category 4:** Markets with highly advanced requirements for emission control, such as US Tier 2, US Tier 3, California LEV II, EURO 4/IV, EURO 5/V, EURO 6/6b, EURO VI, JP 2009 or equivalent emission standards, or other market demands; enables sophisticated NO<sub>x</sub> and particulate matter after-treatment technologies.

PROPERTIES	UNITS	LIMITS	
		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	
Sulphur	mg/kg <sup>2</sup>		10
Trace metal <sup>3</sup>	mg/kg	No intentional addition	
Chlorine	mg/kg	No intentional addition	
Organic contaminants <sup>4</sup>		No intentional addition	
Oxygen <sup>5</sup>	% m/m		2.7 <sup>6</sup>
Olefins	% v/v		10.0
Aromatics	% v/v		35.0
Benzene	% v/v		1.0
Volatility		See Tables, page 10	
Sediment (total particulate)	mg/l		1
Unwashed gums <sup>7</sup>	mg/100 ml		30
Washed gums	mg/100 ml		5
Density	kg/m <sup>3</sup>	715	770
Copper corrosion rating			Class 1
Silver corrosion rating			Class 1
Appearance		Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or	% flow loss		5
Fuel injector cleanliness, Method 2	% flow loss		10
Particulate contamination, size distribution	Code rating		18/16/13 per ISO 4406
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 D6201)	avg. mg/valve		50
Combustion chamber deposits <sup>7</sup>			
Method 1 (ASTM D6201), 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

<sup>1</sup> Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

<sup>2</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>3</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No trace metal should exceed 1 mg/kg.

<sup>4</sup> Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

<sup>5</sup> Methanol is not permitted.

<sup>6</sup> By exception to the limit shown in the table, up to 3.7% oxygen by mass (10% ethanol content by volume) is allowed if permitted by existing regulation. Some countries allow, and some vehicles/engines can use, gasoline with a higher ethanol content. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee. Fuel dispenser labelling is recommended for gasoline-ethanol blends to enable consumers to determine if their vehicles can use the fuel, consistent with their owner manuals.

<sup>7</sup> To provide flexibility (for example, to enable the use of detergency additives that increase unwashed gum levels), the fuel may comply with either the Unwashed Gum limit or the Combustion Chamber Deposits limit.

**Category 5:** Markets with highly advanced requirements for emission control (including GHG) and fuel efficiency, such as US Tier 3 Bin 5, US 2017-2021 light duty fuel economy, California LEV III and as amended, Euro 6c, Euro 6dTEMP, Euro 6d, EU CO<sub>2</sub> target 120 g/km, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category aims to minimize real driving emissions (RDE) required for Euro 6dTEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023).

PROPERTIES		UNITS	LIMITS	
			MIN	MAX
95 RON	Research Octane Number		95.0	
	Motor Octane Number		85.0	
98 RON	Research Octane Number		98.0	
	Motor Octane Number		88.0	
Oxidation stability		minutes	480	
Sulphur		mg/kg <sup>1</sup>		10
Trace metal <sup>2</sup>		mg/kg	No intentional addition	
Chlorine		mg/kg	No intentional addition	
Organic contaminants <sup>3</sup>			No intentional addition	
Oxygen <sup>4</sup>		% m/m		3.7 <sup>5</sup>
Olefins		% v/v		10.0
Aromatics		% v/v		35.0
Benzene		% v/v		1.0
Volatility			See Tables, page 10	
E130 <sup>6</sup>		% v/v	See Tables, page 10	
E170 <sup>6</sup>		% v/v	See Tables, page 10	
Sediment (total particulate)		mg/l		1
Unwashed gums		mg/100 ml		30
Washed gums		mg/100 ml		5
Density		kg/m <sup>3</sup>	715	775
Copper corrosion rating				Class 1
Silver corrosion rating				Class 1
Appearance			Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or		% flow loss		5
Fuel injector cleanliness, Method 2		% flow loss		10
Particulate contamination, size distribution		Code rating		18/16/13 per ISO 4406
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 D6201)		avg. mg/valve		50
Combustion chamber deposits				
Method 1 (ASTM D6201), 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
PM Index <sup>6</sup>				

<sup>1</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>2</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No trace metal should exceed 1 mg/kg.

<sup>3</sup> Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

<sup>4</sup> Methanol is not permitted.

<sup>5</sup> Some countries allow, and some vehicles/engines can use, gasoline with a higher ethanol content. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee. Fuel pump labelling is recommended for gasoline-ethanol blends to enable consumers to determine if their vehicles can use the fuel, consistent with their owner manuals.

<sup>6</sup> A limit will be adopted when improved methodology is available; using current methodology, the Committee believes the maximum PMI should be in the range of 1.5-1.8. Volatility limits (E130/E170 or, optionally, E150/E180) are needed in the interim. See the Technical Background discussions on pages 39 and 42.



**Category 6:** Markets with potential emission control and fuel efficiency targets more stringent than those in Category 5, such as US 2022-2025 light-duty GHG limits, anticipated US 2022-2025 fuel economy standards, EU 95g/km CO<sub>2</sub> fleet average for 2021, and post-2020 EU targets for CO<sub>2</sub>. This category aims to minimize real driving emissions (RDE) required for Euro 6dTEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023). This category is intended to enable the introduction of engines and vehicles with higher fuel efficiency and lower exhaust emissions and specify a gasoline with lower carbon intensity, thereby enabling greater efficiency and GHG benefits than possible with lower category fuels.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
98 RON	Research Octane Number	98.0	
	Motor Octane Number	88.0	
102 RON	Research Octane Number	102.0	
	Motor Octane Number	88.0	
Oxidation stability	minutes	480	
Sulphur	mg/kg <sup>1</sup>		10
Trace metal <sup>2</sup>	mg/kg	No intentional addition	
Chlorine	mg/kg	No intentional addition	
Organic contaminants <sup>3</sup>		No intentional addition	
Oxygen <sup>4</sup>	% m/m		3.7 <sup>5</sup>
Olefins	% v/v		10.0
Aromatics	% v/v		35.0
Benzene	% v/v		1.0
Volatility		See Tables, page 10	
E130 <sup>6</sup>	% v/v	See Tables, page 10	
E170 <sup>6</sup>	% v/v	See Tables, page 10	
Sediment	mg/l		1
Unwashed gums	mg/100 ml		30
Washed gums	mg/100 ml		5
Density	kg/m <sup>3</sup>	720	775
Copper corrosion			Class 1
Sulphur corrosion			Class 1
Appearance		Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or	% flow loss		5
Fuel injector cleanliness, Method 2	% flow loss		10
Particulate contamination, size distribution	Code rating		18/16/13 per ISO 4406
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 D6201)	avg. mg/valve		50
Combustion chamber deposits			
Method 1 (ASTM D6201), 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
Method 4 (DISI) <sup>7</sup>			
PM Index <sup>6</sup>			

<sup>1</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>2</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No trace metal should exceed 1 mg/kg.

<sup>3</sup> Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

<sup>4</sup> Methanol is not permitted.

<sup>5</sup> To achieve this category's 98-102 RON specifications, the oxygen limit has flexibility to reach up to 8% m/m (equivalent to about 20-22% v/v ethanol), but only for vehicles designed for such fuel. Fuel dispenser labelling for ethanol content and advising consumers to check their owner's manual is recommended; this will enable consumers to determine if their vehicles can use a particular gasoline-ethanol blend, consistent with their owner manuals. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee.

<sup>6</sup> A PMI limit will be adopted when improved methodology is available. Using current methodology, the Committee believes the maximum PMI should be in the range of 1.5-1.8. Volatility limits (E130/E170 or, optionally, E150/E180) are needed in the interim. See the Technical Background discussions on pages 39 and 42.

<sup>7</sup> Method and limit are in development.

## Categories 2-4

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	100	100	85-105
T10, °C, max	65	60	100	100	45
T50, °C <sup>1</sup>	77-100	77-100	75-100	70-100	65-100
T90, °C	130-175	130-175	130-175	130-175	130-175
EP, °C max.	205	205	205	205	205
E70, % (V/V) <sup>2</sup>	20-45	20-45	25-47	25-50	25-50
E100, % (V/V)	50-65	50-65	50-65	55-70	55-70
E150, % (V/V) min	75	75	75	75	75
E180, % (V/V) min	90	90	90	90	90
D.I., max	570	565	560	555	550

<sup>1</sup> For gasoline containing between 2.7% – 3.7% m/m oxygen, T50 should be between 65-100°C for all classes.

<sup>2</sup> For gasoline containing between 2.7%-3.7% m/m oxygen, E70 should be between 20 – 50% (V/V) for classes A and B and between 24 – 52% (V/V) for classes C, D and E.

## Categories 5-6

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 <sup>3</sup>	77-100	77-100	75-100	70-100	65-100
T70, °C <sup>4</sup>	106-130	106-130	106-130	100-124	100-124
T90, °C max.	170	170	170	160	160
EP, °C max.	205	205	205	205	205
E70, % (V/V) <sup>5</sup>	20-45	20-45	25-47	25-50	25-50
E100, % (V/V) <sup>6</sup>	50-65	50-65	50-65	55-70	55-70
E130, % (V/V) min <sup>7</sup>	70	70	70	70	70
E150, % (V/V) min <sup>7</sup>	83	83	83	86	86
E170, % (V/V) <sup>7</sup>	90-100	90-100	90-100	95-100	90-100
D.I., max	570	565	560	555	550

<sup>3</sup> For gasoline containing more than 2.7% m/m oxygen, T50 should be between 65-100°C for all classes.

<sup>4</sup> For gasoline containing more than 3.7% m/m oxygen, T70 should be between 75-130°C for classes A, B and C, and between 74-124°C for classes D and E.

<sup>5</sup> For gasoline containing between 2.7% - 3.7% m/m oxygen, E70 should be between 22 - 50% (V/V) for classes A and B and between 24 - 52% (V/V) for classes C, D and E. For gasoline containing more than 3.7% m/m oxygen, E70 should be between 30 - 58% (V/V) for classes A and B and between 32 - 60% (V/V) for classes C, D and E.

<sup>6</sup> For gasoline containing more than 2.7% m/m oxygen, E100 should be between 50 - 75% (V/V) for all volatility classes, based on field experience in Brazil.

<sup>7</sup> E150 can be used optionally as an alternative to E130 & E170 for particle control.

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

**Notes:**

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.

Equation G-1: Calculation of Distillation Index (D.I.)

$$\text{D.I.} = (1.5 * T_{10}) + (3 * T_{50}) + T_{90} + (11 * \text{mass \% of oxygen})$$

where temperatures are in degrees Celsius.

The D.I. oxygenate correction does not apply to ethers, but limited data on LEV/ULEV vehicles suggest that ethers may require a similar oxygenate correction. The need for and the magnitude of the correction will be determined as more data become available. Preliminary data indicate that vehicles may need further volatility controls beyond what is currently specified.

#### Vapour / Liquid Ratio (V/L), T V/L=20

#### ALL CATEGORIES

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 based on the 90<sup>th</sup> percentile maximum (applicable) daily temperature. The minimum test temperature of the gasoline for V/L=20 is provided for each vapour lock class. Limits to TV/L=20 are needed to prevent hot fuel handling problems such as vapour lock, as discussed in the gasoline technical background under 'Volatility.' Additional information is provided in ASTM D4814.

The latest test methods should be used unless otherwise indicated by specific method year. 'Non-detectable' means the lowest possible levels are expected with no intentional additions of the additive or contaminant. Multiple methods indicate the manufacturer should assure the product conforms to the most precise method available.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Research Octane Number		EN 5164	D2699	K 2280-1	
Motor Octane Number		EN 5163	D2700	K 2280-2	
Oxidation stability <sup>1</sup>	minutes	7536	D525	K 2287	
Sulphur	mg/kg	20846	D2622	K 2541-7	JIS K 2541-1, K 2541-2
		20884	D5453	K 2541-6	ASTM D7039
Lead	mg/l		D3237	K 2255	EN 237
Potassium (K)	mg/l				NF M 07065, EN 14538
Trace metal	mg/kg				ICP; ASTM D7111 modified
Phosphorus	mg/l		D 3231		
Silicon	mg/kg				ICP-AES (Reference in-house methods with detection limit = 1 mg/kg)
Chlorine	mg/kg		D7359 or D7536		
Oxygen	% m/m		D4815 D5599	K 2536-2 K 2536-4	EN 13132; ASTM D5622; JIS K 2536-6, K 2536-5
Olefin <sup>2</sup>	% v/v	3837	D1319	K 2536-1	ASTM D6550; JIS K 2536-2
Aromatic <sup>2</sup>	% v/v	3837	D1319	K 2536-1	EN 14517; ASTM D5580, D5769; JIS K 2536-2, K 2536-3, K 2536-4
Benzene	% v/v		D5580	K 2536-3	EN 238, 14517
			D3606	K 2536-2	JIS K2536-4
Vapour Pressure	kPa		D5191	K 2258-1	EN 13016/1 DVPE; JIS K 2258-2
Distillation: T10/T50/T90, E70/E100/E180, End Point, residue		3405	D86	K 2254	
Vapour/liquid ratio (V/L)	°C		D5188		
Sediment (total particulate)	mg/l		D5452		
Unwashed gums	mg/100 ml	6246	D381	K 2261	May be replaced with CCD test
Washed gums	mg/100 ml	6246	D381	K 2261	
Density	kg/m <sup>3</sup>	3675	D4052	K 2249-2	JIS K 2249-3
		12185		K 2249-1	

<sup>1</sup> Updated procedures are needed to better measure oxygenated blends.

<sup>2</sup> Some methods for olefin and aromatic content are used in legal documents; more precise methods are available and may be used.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Copper corrosion	rating	2160	D130	K 2513	
Silver corrosion	rating		D7671		
Appearance			D4176		Visual inspection
Carburettor cleanliness	merit				CEC F-03-T
Fuel injector cleanliness, Method 1	% flow loss		D5598		
Fuel injector cleanliness, Method 2	% flow loss	<sup>3</sup>	D6421		
Particulate contamination, size distribution	code rating no. of particles/ml			B9933	4406 4407 & 11500
Intake-valve sticking	pass/fail				CEC F-16-T
Intake valve cleanliness I	merit				CEC F-04-A
Intake valve cleanliness II					
Method 1, 4 valve avg.	avg. mg/ valve				CEC F-05-A
Method 2, Ford 2.3L	avg. mg/ valve		D6201		
Combustion chamber deposits					
Method 1	% of base fuel		D6201		
Method 2	mg/engine				CEC F-20-A
Method 3	% mass @ 450°C				FLTM-BZ154 <sup>4</sup>
Method 4 (DISI) <sup>5</sup>					
PMI					SAE 2010-01-2115 & ASTM D6729 <sup>6</sup>

<sup>3</sup> In development.

<sup>4</sup> This method is available at <http://global.ihs.com>.

<sup>5</sup> A CEC work group, TDG F 113, is developing a new method for DISI engines.

<sup>6</sup> ASTM D6729 results are inputs to the PMI equation in SAE 2010-01-2115.

## GASOLINE TECHNICAL BACKGROUND

### Octane rating

A gasoline's octane rating or grade is a measure of the fuel's ability to resist auto-ignition, which can cause objectionable engine noise (i.e., knock) and, in severe cases, engine damage. Importantly, octane rating also affects engine efficiency and emissions and constrains engine design. These issues make octane rating among the most important properties of gasoline. Achieving proper engine operation, good fuel efficiency and reduced emissions requires the use of fuel with the octane rating recommended in the vehicle owner's manual.

Each vehicle is designed and calibrated for a certain octane rating. When a customer uses gasoline with an octane rating lower than required, knocking may result. Engines equipped with knock sensors can handle lower octane ratings by retarding the spark timing, but this will increase fuel consumption, impair driveability and reduce power, and knock may still occur. Using gasoline with an octane rating higher than recommended will not cause problems. The Charter specifies different octane number ratings for market flexibility, but not all grades are needed in all markets; fuel providers should make available the grades needed by the local market and should not provide fuel with an octane rating below the specified minimum in each market category.

Gasoline sold at higher altitudes should have the same octane ratings as gasoline sold at lower altitudes. Historically, vehicles equipped with older model engines had the same anti-knock performance at high altitudes using lower octane grades as with higher octane grades at sea level. Since 1984, however, most vehicles have been equipped with electronic control systems that adjust to changes in air temperature and barometric pressure. These vehicles require the same octane rating at all altitudes. See, e.g., SAE 2017-01-0801 and CRC Report No. 669 (2015).

Octane rating of gasoline is typically increased during the refining process, and certain compounds may be added to increase the fuel's octane level. Some oxygenates, for example, can safely increase octane when used as specified by the engine or vehicle manufacturer. (see Oxygenates, page 29, below, for a list of octane enhancers believed most compatible with vehicle and engine technologies.) Metallic additives should not be used (see Metallic Additives, below, at page 22).

Higher octane gasoline enables improved engine efficiency, fuel consumption and greenhouse gas (GHG) emissions by allowing higher compression ratios (CR) and other efficient powertrain designs, such as downsizing, downspeeding, cylinder deactivation and hybridization. As discussed below, octane rating has become the most important limiting factor in achieving new efficiency and environmental objectives for gasoline-powered vehicles.

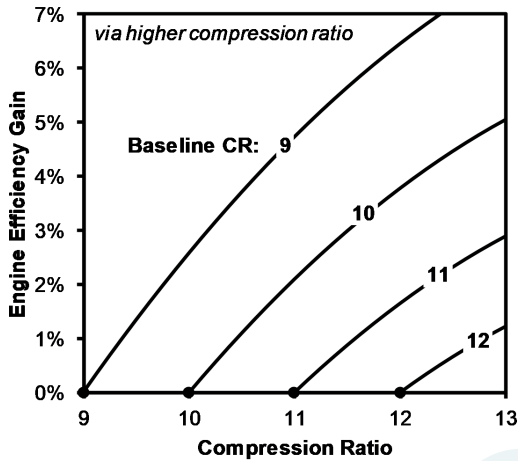
#### **Octane Rating and Performance, Fuel Efficiency and Emissions**

Octane rating has both direct and indirect impacts on engine performance, fuel efficiency and emissions. The direct effect occurs when the engine is operating at high load and the vehicle's knock sensors and feedback control systems engage to avoid knock by retarding the ignition timing away from optimum settings. See, e.g., SAE 2001-01-3584 and SAE 2016-01-0834. Lower octane fuel requires more spark retardation at high loads; this additional spark retardation decreases engine efficiency, degrades torque and power output, and increases exhaust temperature. In some cases, fuel enrichment is required to avoid engine or catalyst damage from the higher exhaust temperature, and this enrichment causes increased emissions of carbon monoxide. See, e.g., Heywood (MIT), "Internal Combustion Engine Fundamentals," MIT (1988); Caris and Nelson (GM), SAE Technical Paper 590015; and SAE 2017-01-0801

The octane rating also indirectly affects performance, efficiency and emissions because it is a key factor in engine design and calibration. That is, higher octane fuel enables the production of higher CR engines while maintaining acceptable levels of spark retard at high loads. Adding these vehicles to the fleet yields corresponding cumulative benefits. This indirect impact is larger than the direct effects of octane rating because higher CR improves engine efficiency at a wide range of operating conditions, not just during high load operation.

The efficiency benefits of higher CR have been well studied. Figure G-1, below, summarizes seven of the most relevant and credible data sets, based on an analysis by Smith et al. (see SAE 2014-01-2599).

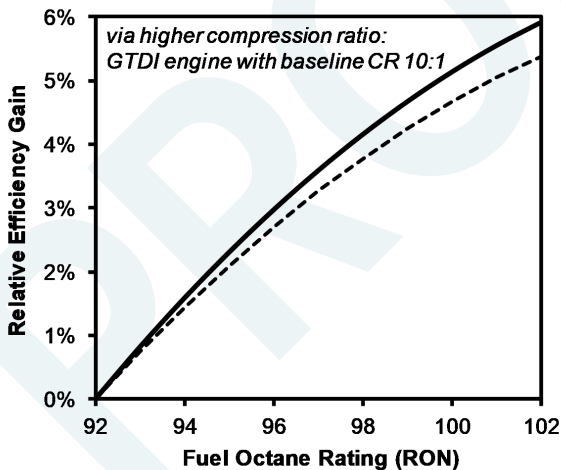
**Figure G-1: Relationship Between Compression Ratio and Engine Efficiency Gain**



Source: Ford, 2018, based on SAE 2014-01-2599

The efficiency benefits of optimizing an engine for higher octane fuel will vary depending on the baseline fuel octane number, engine compression ratio, degree of downsizing and other factors. Figure G-2, below, summarizes possible efficiency improvements derived from a recent review of the literature.

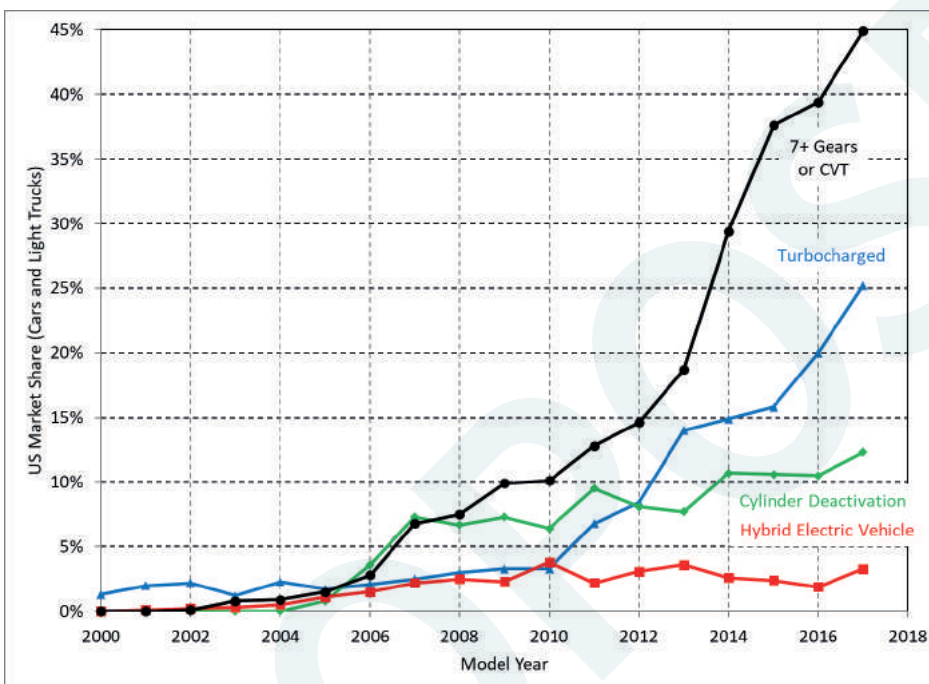
**Figure G-2: Efficiency Gains Enabled by Higher RON**



Source: Leone et al. (Ford, GM, Fiat Chrysler), Environ. Sci. Technol. 49 (18), 2015.

Furthermore, powertrain technology is constantly evolving to achieve better fuel economy and lower CO<sub>2</sub> emissions. The most common improvements in fuel economy and CO<sub>2</sub> emissions in recent years have been due to downsizing, downspeeding, cylinder deactivation and hybridization. These technologies shift engine operation to higher loads where the fuel's octane rating is the primary constraint. Figure G-3, below, shows the penetration of these technologies into the US market since the year 2000. See EPA-420-R-18-001 "Light-Duty Automotive Technology, Carbon Dioxide Emissions, and Fuel Economy Trends: 1975 Through 2017," 2018. As their use continues to grow, especially in markets with advanced requirements for emission control (including CO<sub>2</sub>) or increased fuel efficiency, the need for higher fuel octane rating also increases. In other words, this evolution in powertrain technology in markets with advanced standards requires the availability of gasoline with higher octane ratings than in markets with less stringent standards, if the stated environmental and efficiency goals are to be met.

Figure G-3: US Market Shares of Fuel Efficient Technologies Since 2000



Source: EPA-420-R-18-001, 2018.

### Measuring Octane

The predominant measures of octane rating used globally since 1929 are the Research Octane Number (RON) and the Motor Octane Number (MON). RON is the most widely used octane measure globally, while in North America, the octane rating is specified as  $(RON + MON)/2$ , also known as the Anti-Knock Index or AKI. Another important octane measure is Sensitivity, calculated as RON minus MON.

Many studies have pointed to RON as the most important parameter for representing the octane requirements of modern engines. New octane measures have been emerging in recent years, however, as the understanding has improved regarding how fuel properties, engine design, operating conditions and environmental factors affect knock tendency. For example, it has been shown that the knock performance of modern, downsized boosted gasoline engines operating at low speed and high load conditions correlates poorly to MON, better to RON and best to a combination of RON and MON. This research has produced a measure called the Octane Index (OI), shown below:

Equation G-2: Octane Index

$$OI = RON - K * (RON - MON)$$

where K is a factor that depends on engine design and operating conditions. See, e.g.: SAE 2001-01-3584; SAE 2005-01-0239; and Remmert et. al., 23rd Aachen Colloquium Automobile and Engine Technology 2014.



Since (RON-MON) equals sensitivity, OI also may be calculated using the fuel's sensitivity. Thus, OI incorporates the three most critical factors of engine design, operating conditions and fuel properties.

The K factor is an important element of OI that can be positive or negative depending on the system variables. The value of K is negative in modern boosted engines at the highest-load, most knock-limited conditions, and higher sensitivity fuels provide greater knock resistance in such circumstances. The value of K can be positive at other operating conditions, however, particularly at high engine speed and high intake air temperature (and possibly at medium loads where the engine is only moderately knock-limited). Further research is needed to quantify the overall benefits of higher sensitivity fuels, and to determine whether a minimum MON constraint is still needed for modern engines.

### Low-Speed Pre-Ignition

The trend toward smaller, turbocharged spark ignited engines may increase the risk of pre-ignition events, especially at low engine speed. Importantly, low speed pre-ignition (LSPI) could become the most critical limiting factor for further improving engines for greater fuel efficiency. Various engine conditions (for example, the presence of oil droplets, hot engine parts and glowing deposits) are known to contribute to pre-ignition phenomena. As suggested above, RON and MON may be unsuitable for assessing a gasoline's pre-ignition behavior. A promising new method to predict pre-ignition resistance of gasoline, based on a modified CFR-Engine, recently emerged. It measures the fuel-related gaseous phase pre-ignition behavior by varying the compression ratio in the modified CFR-engine as Compression Pre-ignition Number (CPI). Proponents intend to include the CPI test in a future standard See MTZ, May 2018, and FVV Report No. 1158/2018.

## Sulphur

Sulphur naturally occurs in crude oil. If the sulphur is not removed during the refining process, it will remain in the finished gasoline. Cross-contamination also can occur in the fuel distribution system. Sulphur has a significant impact on vehicle emissions by reducing the efficiency of catalysts. Sulphur also adversely affects heated exhaust gas oxygen sensors. Reductions in sulphur will provide immediate reductions of emissions from all catalyst-equipped vehicles on the road.

There has been extensive testing done on the impact of sulphur on vehicle emissions. The following studies (see Table G-1, below) indicate the emission reductions that occur with different vehicle technologies as sulphur is reduced from the 'high' sulphur gasoline to the 'low':

**Table G-1: Impact of Sulphur on Emissions**

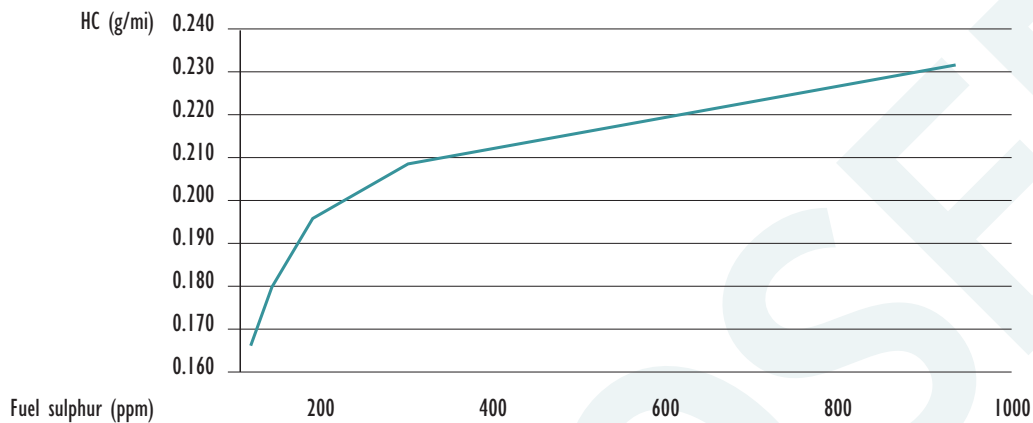
STUDY	VEHICLE TECHNOLOGY	SULPHUR RANGE (PPM)		EMISSION REDUCTION,% (HIGH TO LOW SULPHUR)		
		high	low	HC	CO	NO <sub>x</sub>
AQIRP	Tier 0	450	50	18	19	8
EPEFE	EURO 2+	380	18	9 (43*)	9 (52*)	10 (20*)
AAMA/AIAM	LEV & ULEV	600	30	32	55	48
CRC	LEV	630	30	32	46	61
JARI	1978 Regulations	197	21	55	51	77
Alliance/AIAM	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.

Source: US AQIRP, EPEFE, AAMA/AIAM, SAE 982726, JSAE 9838985

Figure G-4, which depicts the HC reductions from the US AQIRP study, indicates the typical emission reduction for the different studies as the sulphur level changes, including the significant reduction when sulphur is reduced from about 100 ppm to 'low' sulphur fuel. The data illustrate the importance of a very low sulphur limit even for vehicles with early generation three-way emission control systems.

**Figure G-4: Sulphur Effects on Tier 0 Technology**



Source: US AQIRP

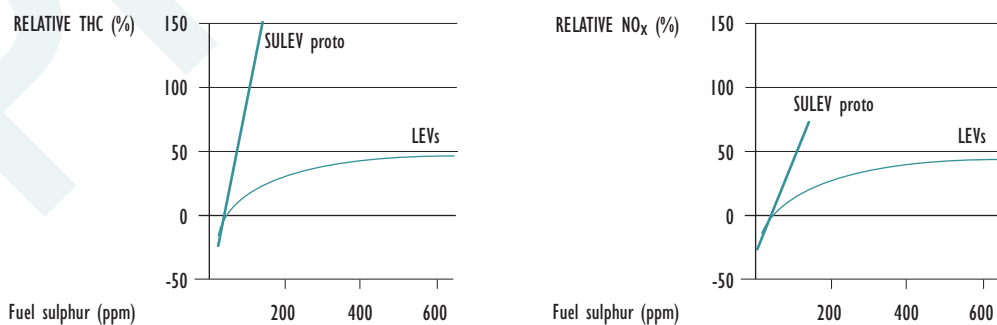
In addition, laboratory research of catalysts has demonstrated delays in light-off time, increases in light-off temperature and reductions in efficiency resulting from higher sulphur fuels across a full range of air/fuel ratios. Studies have also demonstrated that sulphur slows the rich to lean transition, 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 (i.e., 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 good quality (Category 3) gasoline. As standards further tighten, e.g., to Tier 3 in the U.S. with its 150,000 mile durability requirement, they become even more challenging; see discussion on page 19, below, regarding advanced and future technology, for additional perspective.

Figure G-5 indicates the significant HC and NO<sub>x</sub> sensitivity of LEV and prototype SULEV emission control technologies to sulphur content. Progressively more advanced technologies indicate an even higher response to sulphur.

**Figure G-5: Effects of Fuel Sulphur on Emissions (relative to 30 ppm Sulphur Fuels)**

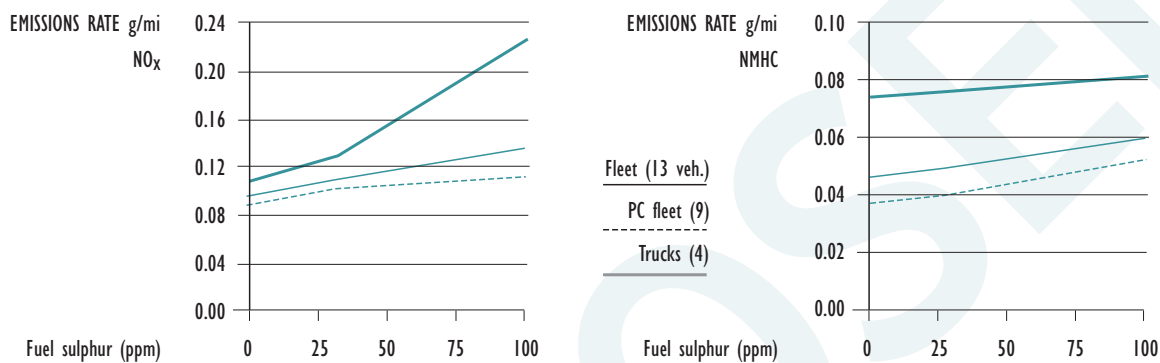


Source: Toyota, 1999

In 2001, the Alliance and AIAM completed a joint test program to evaluate the emission effects of decreasing fuel sulphur 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 sulphur contribution from the engine lubricant.

Figure G-6 shows how the emissions of NO<sub>x</sub> and non-methane hydrocarbons (NMHC) continue to decline significantly at ultra-low sulphur levels for advanced technology vehicles.

**Figure G-6: Effects of Ultra-Low Sulphur Levels on Emissions of NO<sub>x</sub> and NMHC**



Source: Alliance/AIAM Low Sulfur Emissions Study, 2001

Sulphur also will affect the feasibility of advanced on-board diagnostic (OBD) system requirements. Existing California on-board diagnostic (OBD II) regulations require vehicles to be equipped with catalyst monitors that determine when catalyst efficiency changes and tailpipe emissions increase by 1.5 times the standard. The loss of catalyst efficiency resulting from high sulphur fuels could cause some catalyst monitors to indicate a problem code resulting in the illumination of a malfunction indicator light to signal the driver. Similarly, some LEV data demonstrate that the catalysts monitor could fail to identify when a catalyst operated on high sulphur fuel is no longer able to function.

#### Advanced and Future Technology

NO<sub>x</sub> emission control to the limits required by emission standards associated with Category 4, 5 and 6 fuels — considering the concurrent needs of maintaining the control for the life of the vehicle and operating under very lean conditions — is among the biggest challenges for emerging emission control technologies, especially when sulphur is present in the fuel. Three way catalysts and lean NO<sub>x</sub> adsorbers are both highly sensitive to sulphur, albeit to different degrees, and the reversibility of the impact remains a concern for both types of emission control systems.

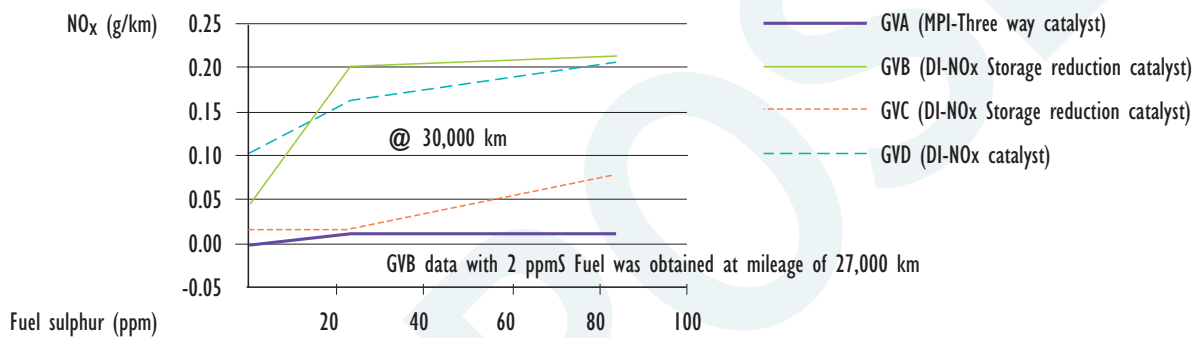
One study published in 2011 documented the effect of sulphur on a 2009 Model Year mid-sized sedan with three-way catalyst technology meeting California's PZEV standards (see SAE 2011-01-0300). The study compared the effects of a 3 ppm sulphur gasoline with those of a 33 ppm sulphur gasoline. One of the objectives was to determine whether 3 ppm fuel would cause NO<sub>x</sub> emission control to deteriorate during repeated testing, similar to the test-to-test deterioration seen with 33 ppm fuel ('NO<sub>x</sub> creep'). The study first confirmed that, at the low level of emissions being measured from PZEV technology, sulphur levels as low as 33 ppm can indeed contaminate the emission control system and affect test-to-test NO<sub>x</sub> stability during compliance (FTP) testing. Special procedures not typically found during real world driving can be applied prior to testing to nearly recover the original emission system efficiency, but the contamination and emission system degradation do not occur when 3 ppm sulphur fuel is used. The study also found that using a 3 ppm sulphur fuel can reduce tailpipe NO<sub>x</sub> emissions by 40% over the emissions produced when the vehicle is operated using a 33 ppm sulphur fuel.

A different type of emission control technology (lean-NO<sub>x</sub> adsorbers or traps) is required for lean-burn engines to meet emission standards for NO<sub>x</sub> that are associated with Category 4 and 5 fuels. Manufacturers are working toward ambitious goals for improved fuel consumption/reduced CO<sub>2</sub> emissions, and operation at lean air-fuel ratio is one of the most promising means to achieve these reductions in gasoline-powered vehicles. Manufacturers estimate lean-burn engines have the potential to reduce fuel consumption by up to 10 to 15%, but lean operation introduces a new challenge: while three-way catalysts effectively remove unburned HC and CO during lean operation, they can remove NO<sub>x</sub> only during stoichiometric or rich operation. Lean-NO<sub>x</sub> traps can operate in a lean exhaust environment, but they are highly sensitive to sulphur.

Lean NO<sub>x</sub> adsorber catalysts function by trapping NO<sub>x</sub> chemically during lean engine operation. NO<sub>x</sub> can then be released and destroyed over a catalyst by a few seconds of rich operation. However, sulphur 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. Sulphur removal requires prolonged rich operating conditions, but the original NO<sub>x</sub> reduction efficiency level can never be fully recovered. Also, allowing any rich engine operation significantly negates the fuel efficiency benefits of the lean burn engine technologies used with these catalysts. Sulphur-free gasoline is therefore necessary to maximise the benefits of lean-burn, fuel-efficient technology.

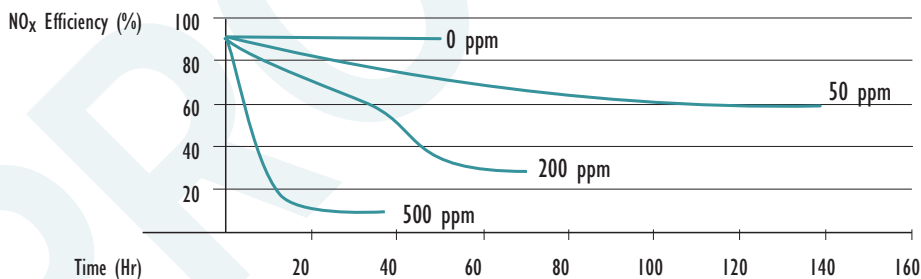
Figure G-7 and Figure G-8 provide examples of the adverse effect of sulphur on storage-type NO<sub>x</sub> reduction catalysts. With increased exposure time, the lower sulphur gasolines allow the catalysts to retain a higher NO<sub>x</sub> conversion efficiency. Further tests in vehicles (Figure G-9 and Figure G-10) confirm the critical need for very low sulphur gasolines. Maintaining a high level of NO<sub>x</sub> conversion efficiency over a long period of time — e.g., for the life of the vehicle — is another major concern due to sulphur's cumulative impact in the field. Figure G-11 shows how ultra-low sulphur gasoline can maintain much higher NO<sub>x</sub> conversion efficiencies over time compared with higher sulphur levels. Thus, ultra-low or sulphur-free gasoline is required to achieve and maintain high NO<sub>x</sub> conversion efficiencies over years of vehicle use.

**Figure G-7: Sulphur Effect on Low Emission Vehicles - Direct Fuel Injection Engines**



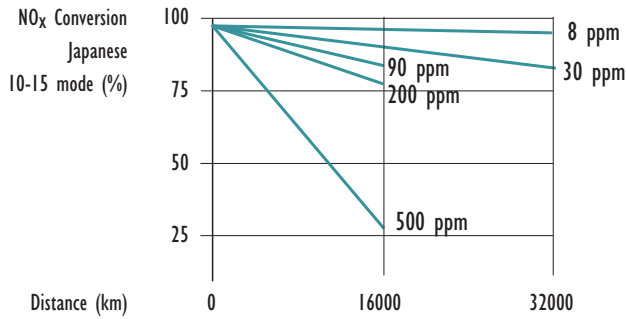
Source: Japan Clean Air Program

**Figure G-8: Effect of Fuel Sulphur on Lean NO<sub>x</sub> Traps, Flow Reactor Study**



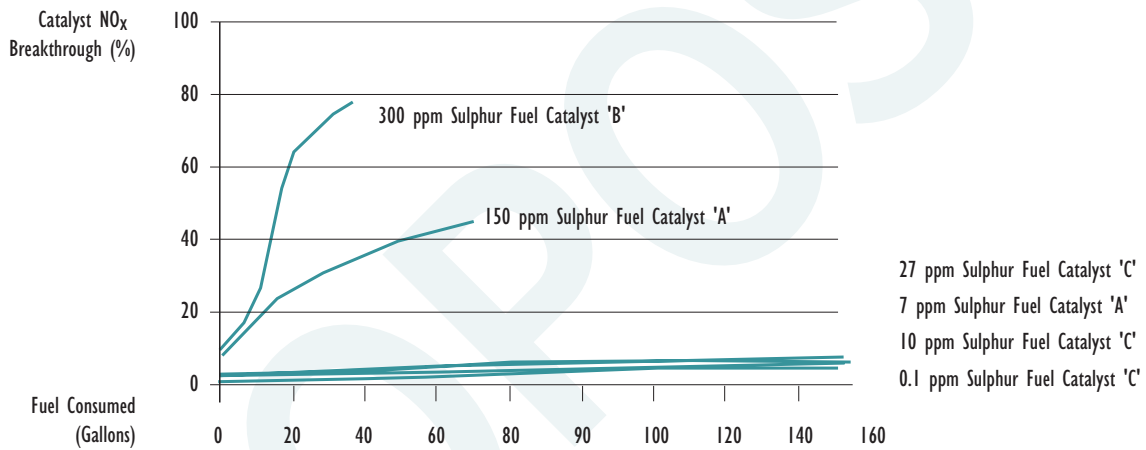
Source: SAE 962051

Figure G-9: Influence of Sulphur Concentration in Gasoline on Vehicle Aftertreatment System Durability



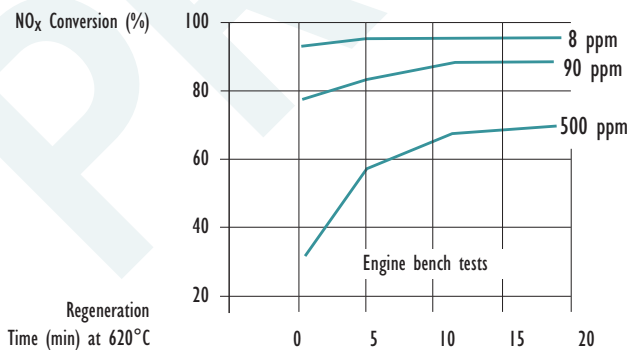
Source: Toyota 1999

Figure G-10: Lean NOx Adsorber Catalyst Data — Catalyst NOx Breakthrough vs Fuel Consumed & Fuel Sulphur Content



Source: General Motors, 1999

Figure G-11: Regeneration of Sulphur Poisoning



Source: Toyota, 1999

## Metallic Additives

Today's vehicles employ sophisticated exhaust emission control equipment and strategies, such as close-coupled high cell density three-way catalysts, ceramic oxygen sensors and computerized engine control modules that provide precise closed-loop control. These systems must be kept in optimal condition to maintain the vehicle's low emissions capability. Fuel additives that form ash include metallic compounds and contaminants, such as those containing calcium, copper, phosphorous, sodium and zinc, can irreversibly impair the operation of these systems and thereby increase emissions. Thus, ash-forming additives and contaminants must be avoided, and gasoline that contains these additives or contaminants cannot be considered good quality fuel.

### Lead

Tetra-ethyl lead has been used historically as an inexpensive octane enhancer for gasoline, but it will poison vehicle emission control systems. The lead binds to active sites within the catalyst and oxygen sensor, greatly reducing their effectiveness. The tolerance to lead contamination has steadily declined as catalyst efficiencies and sensors have improved, so even a slight amount of lead in the fuel will irreversibly disable the emission control system. As a result, vehicle hydrocarbon and NO<sub>x</sub> emissions will increase even when the vehicle returns to using lead-free gasoline. Unleaded gasoline must be available wherever catalyst-equipped vehicles refuel, which today means every market around the world. A global lead-free market also is essential for public health, given lead's well-known adverse health effects. These concerns have led most countries to require lead-free gasoline. Automakers recommend no intentional addition of lead to gasoline.

### Manganese (MMT)

Manganese is a key component of methylcyclopentadienyl manganese tricarbonyl (MMT), which also is marketed as an octane-enhancing fuel additive for gasoline. Like lead, manganese in the fuel will irreversibly reduce the efficiency of exhaust emission control systems. It is also reported to increase the frequency of knock at low engine speeds (called Low-Speed Pre-ignition, or LSPI) in turbocharged engines.

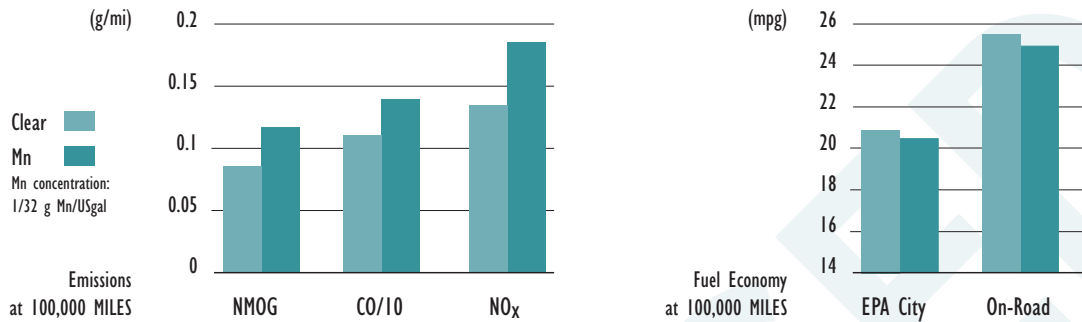
### Powertrain and Emission Control System Impacts

Studies have shown that most of the MMT-derived manganese in the fuel remains within the engine, catalyst and exhaust system. The oxidized manganese coats exposed surfaces throughout the system, including spark plugs, oxygen sensors and inside the cells of the catalytic converter. These effects result in higher emissions and lower fuel economy. The effect is irreversible and cumulative.

- The coating of internal engine components, such as spark plugs, can cause in-cylinder combustion misfire, which leads to increased HC and CO emissions, increased fuel consumption, poor vehicle driveability and possible physical damage to the catalyst. These conditions result in increased owner dissatisfaction and expensive repairs for consumers and vehicle manufacturers.
- MMT's combustion products also accumulate on the catalyst. In some cases, the front face of the catalyst can become plugged with deposits, causing increased back pressure on the engine, poor vehicle operation, increased emissions and increased fuel consumption.

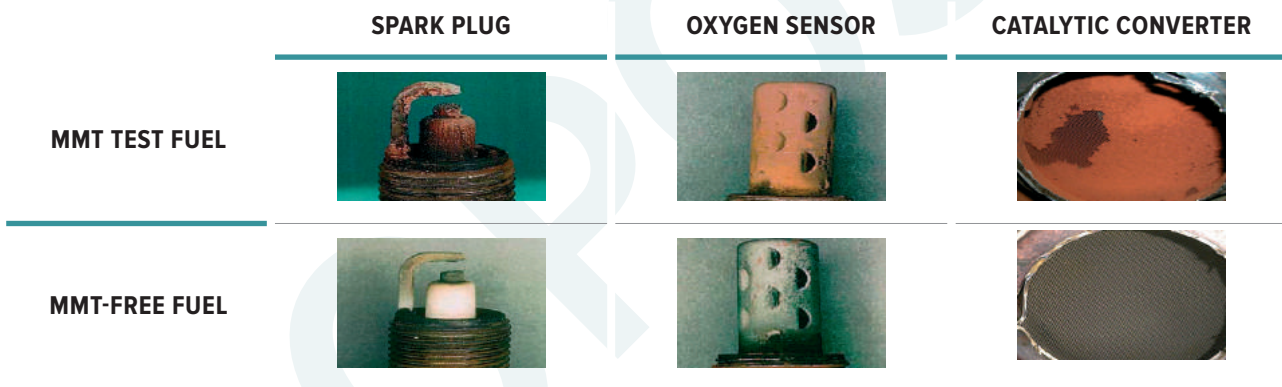
In 2002, automobile manufacturers jointly completed a multi-year study of the real-world impact of MMT on Low Emission Vehicles (LEVs). After 100,000 miles of driving with fuel containing 1/32 g Mn/gal, the test fleet showed significantly increased non-methane organic gases (NMOG), CO and NO<sub>x</sub> emissions. MMT also significantly decreased fuel economy; on average, on-road (highway) fuel economy was about 0.5 miles per gallon (mpg) lower than with a clear test gasoline (Figure G-12). Similar results were found in another part of the study with earlier model vehicles equipped with Tier 1 emission control technology, where HC emissions increased after 50,000 miles of driving. Figure G-13 provides visual evidence of MMT's impact on parts used in some Tier 1 and LEV vehicles. The spark plug and oxygen sensor came from vehicles used in the 2002 joint automaker study, and the catalytic converters came from market vehicles, one driven in Canada when MMT was in widespread use and the other driven in California where MMT is not allowed. The reddish-brown deposits were identified as oxidized manganese.

Figure G-12: Emission and Fuel Economy Effect of MMT - 1998-99 LEVs



Source: SAE 2002-01-2894

Figure G-13: Impact of MMT on Tier 1/LEV Parts at 50,000 Miles



Source: Alliance, AIAM and CVMA, 2002

Around the time when this study was released (2002), North American automakers began to notice increased warranty claims in Canada, where MMT was in widespread use, compared to claims in the U.S., where MMT was not in widespread use. The growth in claims was occurring just as new emission control technologies were being introduced. Beginning in the late 1990s, automakers had been introducing vehicles with high cell density catalysts, close-coupled catalysts, catalysts with new washcoats, more sophisticated computerized engine-control systems and engine design modifications, in anticipation of more stringent emission standards. By the early 2000s, the newer technologies were penetrating the Canadian fleet at increasing rates, varying by manufacturer and model. Today, in the EU, Japan, North America and many other developed markets, these highly advanced technologies now dominate the fleets because they are needed to meet stringent emission standards.

Sierra Research, Inc., compiled and analysed these observations in Sierra Report SR2008-08-01, Impacts of MMT Use in Unleaded Gasoline on Engines, Emission Control Systems and Emissions (available at [www.autoalliance.org](http://www.autoalliance.org)). The report revealed cases of severe catalyst plugging, driveability problems, illumination of the dashboard engine malfunction indicator light (MIL) and increased tailpipe emissions, among other adverse effects (Table G-2). The automakers conducted laboratory tests to confirm the in-use findings, investigated causative factors and measured the emission impacts. The data confirmed their suspicions: MMT had adversely affected at least 25 different models, including both advanced and older technologies of 1999-2003 model year vintage produced by nine different manufacturers and accounting for about 85% of Canadian light-duty vehicle sales in 2006.

The magnitude of this statistic fails to reflect the full potential impact, however, due to unknowns and varying conditions such as changing vehicle technologies, fuel quality, vehicle mileage, MMT concentrations and actual use of MMT-containing gasoline. The report's Executive Summary includes the following statement:

There is no demonstrated method, other than eliminating MMT® from the fuel, to ensure that an emission control system that allows a vehicle to comply with the requirements of the Tier 2/LEV II and more stringent regulations will not experience catalyst plugging caused by manganese oxides as well as one or more of the observed problems of degraded driveability, MIL illumination, and increased emissions.

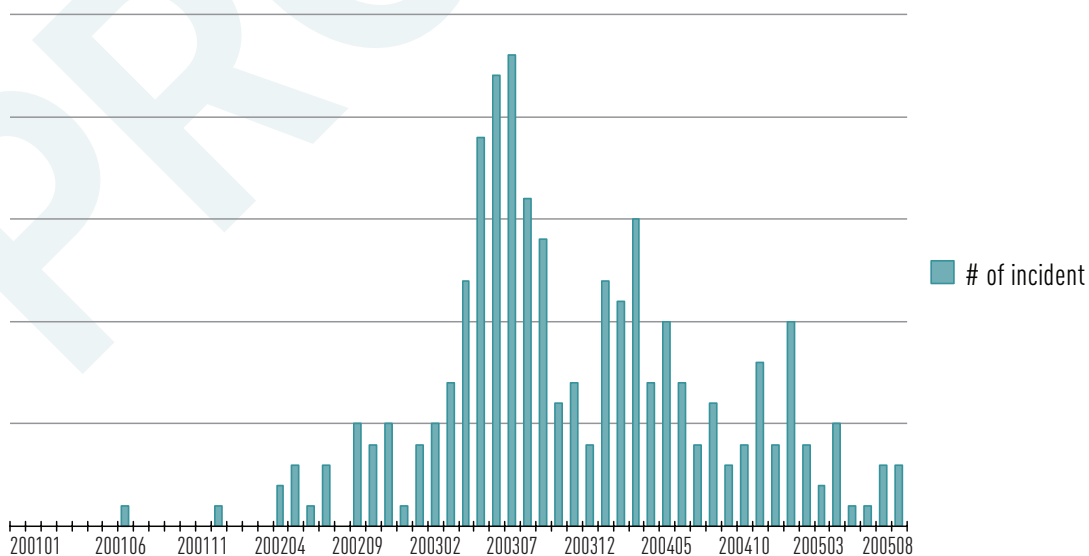
**Table G-2: Source of Evidence of Adverse MMT(R) Impacts on Exhaust Emissions, Operation and Performance of In-Use Canadian Vehicles with Advanced Emission Control Technologies and Systems**

MFR	WARRANTY CLAIMS	IN-USE VEHICLE INSPECTION	LABORATORY TESTING	EMISSIONS TESTING	NUMBER OF MODELS	MODEL YEARS
A	YES	YES	NO	NO	1	1999
C	YES	YES	YES	YES	4	2000-2002
D	YES	YES	YES	YES	2	2003
I	NO	YES	NO	NO	1	2002
J	YES	YES	YES	YES	7	2002-2003
K	YES	YES	YES	YES	1	2003
L	NO	YES	YES	YES	3	2001
M	YES	YES	YES	YES	5	2001-2003
O	NO	NO	YES	NO	1	2001

Source: Sierra Report SR2008-08-01

After Canadian refiners voluntarily halted MMT use between 2003 and 2005 (most use had ended by the summer of 2004), automakers then observed a rapid decline in the incidence of catalyst plugging. Figure G-14 shows one manufacturer's month-by-month warranty analysis for the period between 2001 and 2005. Other manufacturers found similar impacts, including the reversal of the monitored effect as MMT was phased out in most of Canada

**Figure G-14: Warranty Analysis: Number of Catalyst Replacement Incidences per Month due to MMT Plugging (Manufacturer C)**



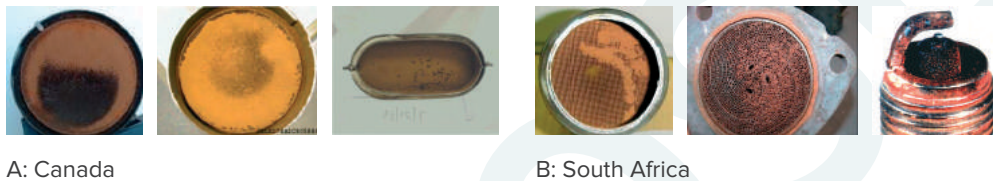
Source: Sierra Report SR2008-08-01



Automakers consider the above statistics to be very conservative and believe the true vehicle impact was greater than recorded. Since the vehicle impairment also meant the emission control systems were functioning poorly, automakers conservatively estimate that VOC, CO and NO<sub>x</sub> emissions would have increased by 77%, 51% and 12%, respectively, by 2020, if MMT had been reintroduced into Canada in 2008. The reader is referred to the Sierra Report for more detail concerning this analysis.

The real-world evidence of adverse impacts continues to grow. In addition to the above studies and experience in North America, several major companies have reported failed emission components in China, South Africa, parts of Eastern Europe, parts of Asia, and/or Argentina. South African vehicles, which have less advanced control systems than in Canada but use fuel with higher levels of MMT, also have been adversely affected (Figure G-15). Given this overwhelming body of information, automobile manufacturers remain extremely concerned about MMT's impact, especially on the highly sensitive technologies that are being or will be used in markets around the world. Most major auto manufacturers state in their Owner Guides that they recommend against the use of MMT, advising further that any damage caused by MMT may not be covered by the warranty.

**Figure G-15: Evidence of MMT's Impact on Canadian and South African Vehicles**



A: Canada

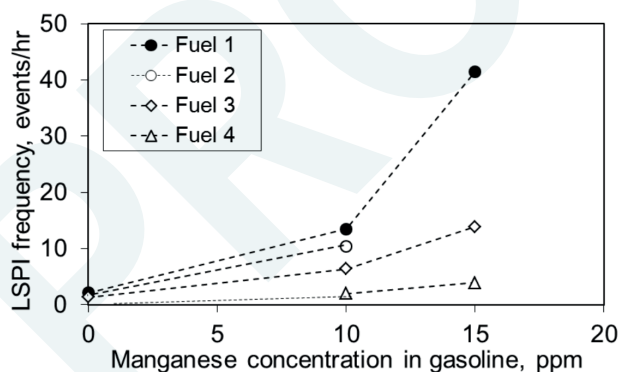
B: South Africa

Source: Honda, BMW and Ford.

#### Impact on Low Speed Pre-Ignition (LSPI)

In addition to the harm described above, new research confirms that manganese in gasoline increases the possibility of LSPI in turbocharged spark ignition engines. (See Octane LSPI discussion, above, at page 17.) Less volatile gasoline containing heavy aromatic components tends to show higher sensitivity to manganese concentration in these engines. The research also shows that the amount of deposits containing manganese increases in the combustion chamber. These deposits reduce ignition temperature, thereby becoming a starting point of LSPI. Figure G-16, below, shows the correlation between manganese level and the frequency of LSPI events in four different test fuels. Figure G-17 shows starting points for LSPI events not caused by spark plug ignition.

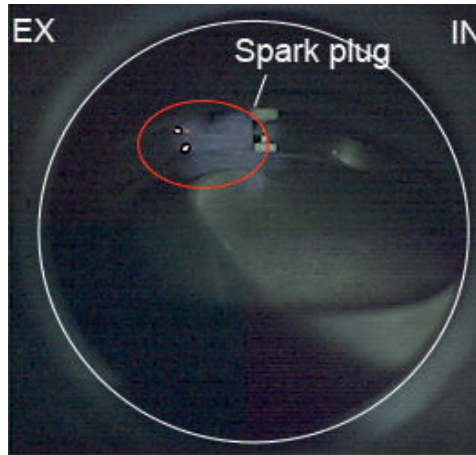
**Figure G-16: Low-Speed Pre-ignition Caused by Manganese**



	FUEL 1	FUEL 2	FUEL 3	FUEL 4
E170, %v	92.0	91.0	93.8	98.7
E130, %v	60.0	65.0	70.0	83.4
Simplified PMI	2.03	1.93	1.59	0.84

Source: SAE 2018-01-0936

Figure G-17: Starting Point of Low Speed Pre-Ignition



Source: SAE 2018-01-0936

#### Global Use of Manganese Additives

Information on the amount of MMT consumed worldwide is not publicly available, although fuel surveys suggest declining use around the globe. In Europe, Japan and North America, for example, manganese is virtually absent from market gasoline, either as a result of regulation or voluntary action by fuel providers. U.S. law, for example, prohibits MMT use in federal reformulated gasoline (RFG), which constitutes more than one third of the U.S. gasoline pool, and the State of California also bans use in that state. Even outside RFG and regulated areas, the fuel is believed to be virtually MMT-free through voluntary action. Fuel providers in Canada, India, Indonesia and Japan also are voluntarily providing MMT-free gasoline. In 2009, the European Parliament adopted market restrictions on MMT that were upheld in 2011 against a legal challenge.

Elsewhere, progress also is being made. South Africa adopted a dual fuel approach where gasoline with MMT may legally be sold for use in older vehicles (as Lead Replacement Petrol), but that market has been declining. China had been among the regions where MMT use was growing in the last decade. In 2011, however, the government imposed tight limits nationwide beginning in 2015 with no intentional addition, and the most recent fuel survey has shown only a residual amount of MMT in that market.

For markets where at least some gasoline contains MMT, appropriate pump labelling is imperative to inform the consumer. One approach is through a fuel pump labelling program called TOP TIER™. Fuel that complies with program's quality standards, including the absence of metallic additives, can be licensed to use the TOP TIER™ label at the pump (see <https://toptiergas.com/>). Several fuel marketers in Central America adopted TOP TIER™ standards in 2017, and a much lower usage of MMT in that region has already been seen in 2018.

**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, and this may cause thermal damage to the exhaust catalyst. Photographs of deposits on a spark plug and the resulting damage to a catalyst are shown below in Figure G-18 and Figure G-19.

**Figure G-18: Iron Deposits on a Spark Plug**



Source: SAE 2006-01-3448, JARI

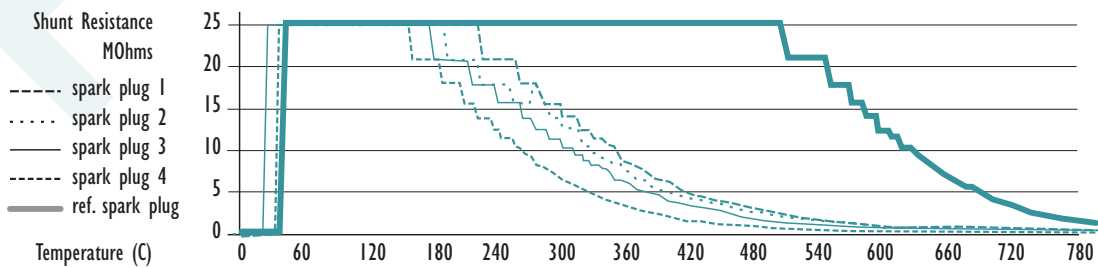
**Figure G-19: Catalyst Thermal Damage by Misfiring of Spark Plugs Coated in Iron (UAE market, mileage 50,000km)**



Source: Non-confidential image used with permission by Toyota.

Figure G-20 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.

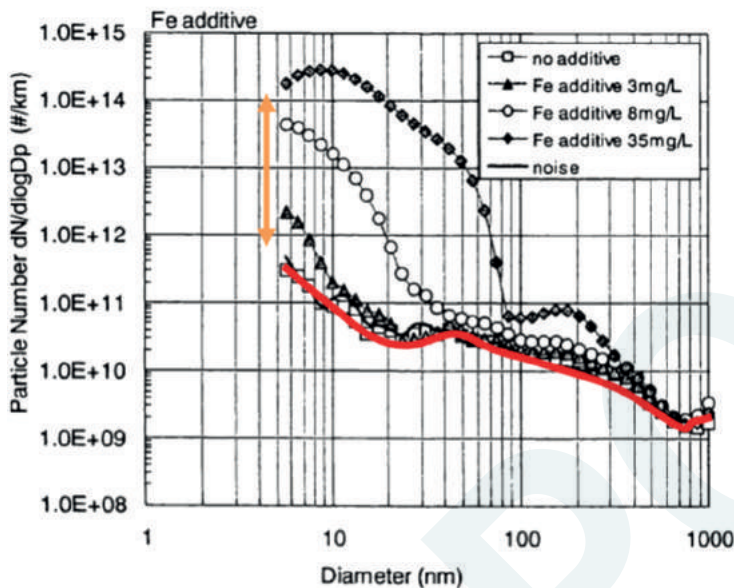
**Figure G-20: Insulator Resistance at Temperature Test Results for Spark Plugs Taken from Test Engine after 32 Hours**



Source: Ford, 2000.

In addition to spark plug failure and thermal damage to the catalyst, iron oxide creates a physical barrier between the catalyst/oxygen sensor and the exhaust gases and causes erosion and plugging of the catalyst. It may have the same impact on gasoline particulate filters (GPF) and, ultimately, disable them. As a result, the emission control system is not able to function as designed, causing emissions to increase. As the amount of iron additive in the fuel increases, so will the number of ultra-fine (5 to 50 nm diameter) particles in the exhaust emissions, measured as PN, as shown below in Figure G-21. Premature wear of critical engine components, such as pistons and rings, also can occur due to the presence of iron oxide in the vehicle lubrication system.

Figure G-21: Effect of Fe Additive Concentration in Fuel on Exhaust Particle Number Size Distribution



Source: JSAE 20104612, JARI.

Note: Red line added to highlight the baseline results (i.e., test fuel without Fe additive).

## Contaminants

Contaminants may enter the fuel in many ways, both intentionally and unintentionally. Fuel additives may introduce some undesirable contaminants, as may fuel production or distribution. Many of these compounds can cause significant harm to the powertrain, fuel, exhaust or emission control systems. Good housekeeping practices can help minimize or prevent inadvertent contamination. The elements and compounds listed below should not be added to gasoline and should be strictly controlled from fuel production and throughout distribution; it may prove necessary to check and control the fuel quality at the pump. Test methods will be added to this Charter as they become available.

### Phosphorus

Phosphorus is sometimes used as a valve recession fuel additive, or it may enter the fuel from blendstocks produced from agricultural products fertilized with phosphorus-containing compounds. Like many other contaminants, phosphorus can foul spark plugs and will deactivate catalytic converters.

### Silicon

Silicon has been found in commercial gasoline in several instances, usually as a result of silicon-containing waste solvents being added to the gasoline after the fuel has left the refinery. A vehicle affected by silicon in the fuel will exhibit a noticeable decline in power. Even at low concentrations, silicon can cause high levels of white-coloured deposits in engines, oxygen sensors, gasoline particulate filters (GPF) and catalytic converters. These impacts can lead to catastrophic engine failures in less than one tankful of contaminated fuel. Automobile manufacturers are increasingly concerned about the potential for silicon deposits, especially on the most advanced and highly sensitive technologies that are present in increasing numbers in the global market.

### Chlorine

This element is not naturally contained in petroleum, but it has been found in gasoline in both inorganic and organic forms. Inorganic chlorine is believed to enter the fuel as a result of contamination by sea water ballast during shipping or from salt water intrusion during storage. Such contamination occurs more readily in gasoline-ethanol blends than in E0 due to the blends' ability to dissolve more water. Some organic chlorine is believed to enter the fuel during the reforming process at refineries, since the catalysts used to convert low RON naphtha to higher octane aromatics often contain chloride. Organic chlorine also may enter the fuel as a result of adulteration with chemical or waste solvents. Chlorine forms highly corrosive acids during combustion, which can reduce significantly the durability of the engine, fuel system and emission control system. In the worst case, the presence of chlorine may lead to catastrophic engine failure as injectors fail to operate or operate improperly after various periods and levels of exposure. See, e.g., Clark and Studzinski, Flex Fuel Vehicle Performance and Corrosion Study of E85 Fuel with Chloride Addition, SAE 2010-01-2088.

### Aniline and Aniline Derivatives

N-methyl-aniline (NMA) is a commonly used solvent that has been used as an octane-enhancing additive for gasoline; other aniline derivatives, such as N-ethyl aniline, also are a concern. Besides being toxic, this class of compounds can have serious adverse effects on engine parts and the emission control system. NMA's high boiling point (184°C) can cause an increase in exhaust VOC emissions. Aniline-containing fuel additives may include benzene, which itself is toxic and will increase toxic tailpipe emissions. In addition, the use of these additives can increase gum formation inside the engine. High gum levels will cause increased carbon deposits on engine parts such as fuel injectors.

### Secondary Butyl Acetate (SBA)

Sec-Butyl Acetate is another additive that has been used to increase the octane number of gasoline in some parts of the world. SBA reacts strongly with acids and oxidants, dissolves readily and may cause engine operational problems. It shares some similarity with NMA in that it may cause rubber components to swell. SBA also may cause increased fouling of the internal engine parts and reduce the durability of lubricating oils.

### Methylal (Dimethoxymethane)

Methylal is an organic solvent that might be used to extend the total fuel output or to bypass stringent requirements for methanol blending. From the perspective of the engine, methylal has no benefits (octane enhancing or otherwise) and can introduce disadvantages such as lower fuel efficiency, higher CO<sub>2</sub> emissions and a higher swelling rate for commonly used elastomer materials. There are also concerns regarding a higher pre-ignition tendency of methylal blended gasoline.

## Oxygenates

Oxygenated organic compounds, such as MtBE and ethanol, often are added to gasoline to increase octane or extend gasoline supplies. Oxygenating the fuel, however, may change the fuel's characteristics and affect vehicle emissions (tailpipe, evaporative or both), performance and/or durability. Adding ethanol, for example, changes the distillation profile of the gasoline blend. See Volatility, below, at page 34. The oxygenates most compatible with vehicle/engine technologies are shown in Table G-3.

**Table G-3: Compatible Oxygenates**

	MAX (%v/v)
Ethanol*	10
Iso-propyl-alcohol	12
Iso-butyl-alcohol	15
Tert-butyl-alcohol	15
Ethers (5 or more C atoms)	22
Other mono-alcohols and mono-ethers	15

Source: Adapted from EN 228.

\*To achieve 98-102 RON, the Charter provides flexibility for oxygen to reach up to 8% m/m (equivalent to about 20-22% v/v ethanol), but only for vehicles designed for such fuel and where dispensers are labelled to enable consumers to determine if their vehicles can use a particular gasoline-ethanol blend.

Adding oxygenates to gasoline will induce a lean shift in engine stoichiometry, which, in turn, will reduce carbon monoxide (CO) emissions, especially from carburetted vehicles without electronic feedback-controlled fuel systems. These emission benefits are smaller in modern electronic feedback-controlled vehicles, however, because the leaning effect only occurs during cold operation or during rapid accelerations. In fact, fuel-leaning caused by oxygenates can cause tailpipe emissions to increase, depending on the leanness of the engine's base calibration with non-oxygenated gasoline. The California Air Resources Board (CARB) found in emission tests on 14 1990-1995 model year vehicles that a gasoline containing 10% ethanol by volume decreased toxic emissions by 2% and CO by 10% but increased NO<sub>x</sub> by 14%, total HC by 10% and ozone-forming potential by 9%, relative to a gasoline containing 11% MtBE by volume. Testing by the Coordinating Research Council (CRC) on LEV, ULEV and SULEV vehicles produced similar results (CRC E-67, 2006).

This over-leaning also can degrade driveability, and it is well documented that ethanol-blended gasoline, in particular, can cause an offset in driveability performance. Increased exhaust hydrocarbon emissions are likely to accompany this offset in driveability performance. Because ethanol has a higher heat of vaporisation than ethers, some of the driveability and emissions degradation of gasoline-ethanol blends can be attributed to the additional heat needed to vaporise the gasoline.

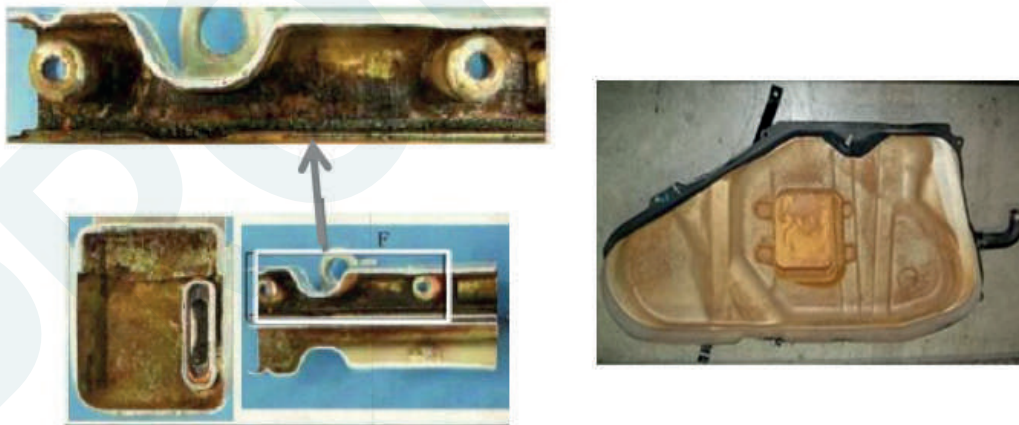
Based on experience with impurities in ethanol that have led to degradation of fuel systems, fuel ethanol must have a specification to control pH and its blending properties (ASTM D 4806). Also, the limits and restriction on the oxygenates permitted in each Category were developed on the basis of emission benefits, vehicle performance and existing regulations. Based on these criteria, when oxygenates are used, ethers are preferred. Also, the use of ethanol-blended gasoline may require other fuel changes to mitigate evaporative and exhaust emission impacts. Maintaining the availability of protection-grade fuel (up to E5) may be necessary in some markets to protect older vehicles designed for ethanol-free gasoline.

### Methanol

Methanol, which can be produced relatively easily from natural gas or coal, can help boost octane and has been investigated for use as an alternative fuel, but it is an aggressive material that can damage vehicles not designed for its use. In addition, it can cause performance problems and increase emissions. Methanol should not be used in vehicles and engines designed to use gasoline; consumers should consult their owner's manual for more guidance.

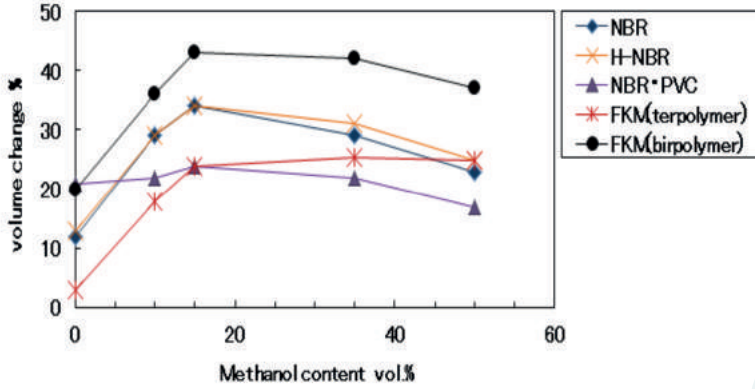
One example of the potential damage is due to corrosion of metallic fuel system components (see Figure G-22). Methanol also degrades plastics and elastomers or may cause them to swell (see Figure G-23). These impacts can lead to fuel system leaks.

**Figure G-22: Fuel System Components Corroded by Methanol**



Source: Non-confidential images used with Toyota's permission

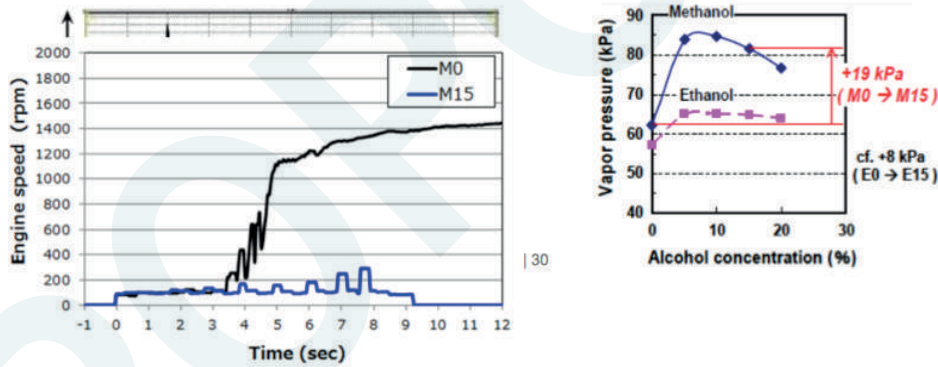
Figure G-23: Methanol Causes Materials to Swell



Source: Non-confidential data used with Toyota's permission

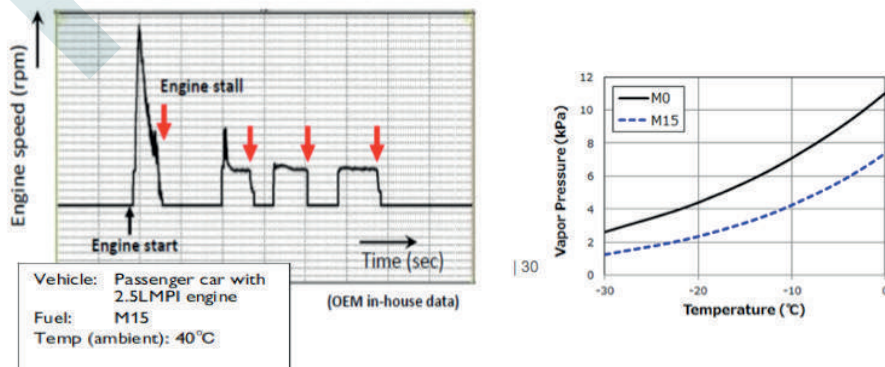
Methanol in gasoline can cause a variety of operational problems. By increasing the vapor pressure at normal temperatures, the fuel mixture can cause hot re-start failure. See Figure G-24. Cold-start can be a problem, too, since the vapour pressure decreases significantly when the temperature is below freezing. See Figure G-25.

Figure G-24: Hot M15 Restart Failure (with Alcohol VP Curves)



Source: Non-confidential data used with Toyota's permission

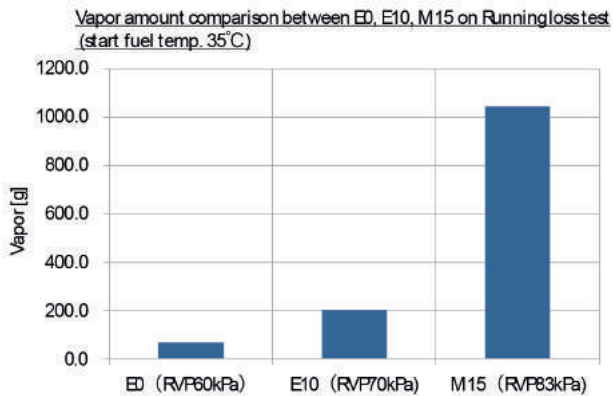
Figure G-25: Cold-Start Differences between M0 and M15



Source: Non-confidential data used with Toyota's permission

Emissions are a concern, as well. The fuel's higher vapour pressure at ambient temperatures and pressures will cause a significant increase in evaporative emissions, including emissions of formaldehyde. Also, while emissions of NMHC may decrease, as with other oxygenates, emissions of formaldehyde and NMOG are likely to increase. See Figure G-26

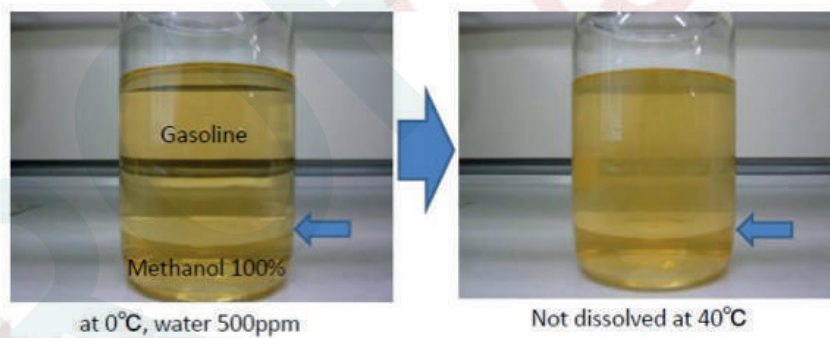
**Figure G-26: Vapour Amounts from E0, E10 and M15 on CARB Running Loss Test (start fuel T = 35°C)**



Source: Non-confidential data used with Toyota's permission

Another important problem with methanol is phase separation, which even the smallest amount of water may trigger. Once the fuel components separate, they are unlikely to recombine quickly, even when the temperature increases. See Figure G-27. While separated, the methanol portion sinks to the bottom of the fuel tank where it may corrode or otherwise harm tank materials. Phase separation also causes the air/fuel ratio to become too lean, which reduces startability and driveability performance.

**Figure G-27: Methanol-Gasoline Phase Separation Continues after Warm-up**



Source: Non-confidential image used with Toyota's permission



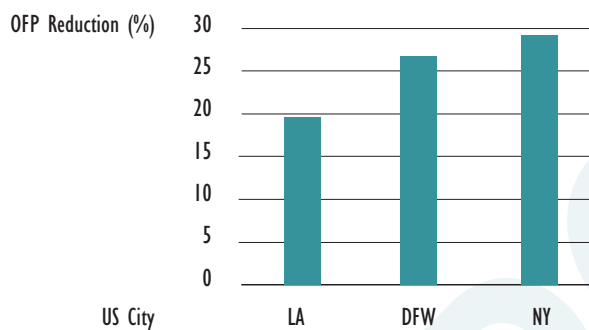
## Olefins

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.

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 City (Figure G-28).

**Figure G-28: Reduction in Ozone-Forming Potential with Reduction in Fuel Olefins (20%-5%)**



Source: US AQIRP

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 G-28. About 70% of this effect was due to reducing low molecular weight olefins.

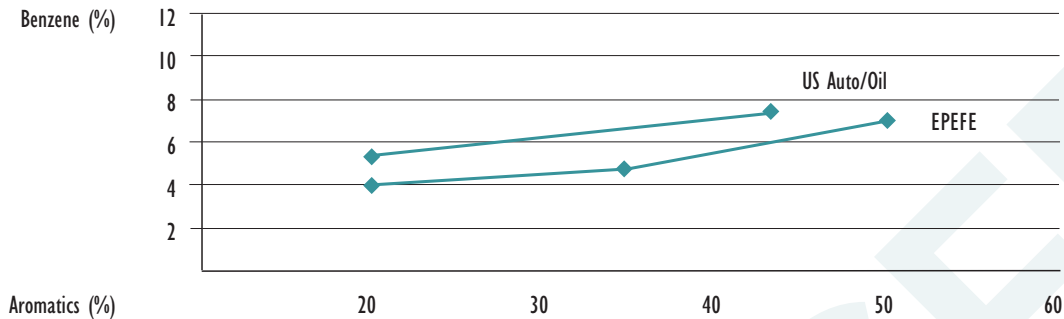
## Aromatics

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, however, also can increase engine deposits, engine wear, particle formation, tailpipe emissions including CO<sub>2</sub>, and the risk of pre-ignition.

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.

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 G-29).

Figure G-29: Fuel Aromatics Effect on Benzene Exhaust Emissions



Source: US AQIRP, EPEFE Report

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).

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%.

One mechanism for these effects is the higher level of fuel impingement inside the engine which leads to higher diffusion flame and particulate emissions; oil dilution and pre-ignition; and greater engine wear. Heavier fuel also means higher particulate formation, which increases combustion chamber deposits, EGR cooler deposits, timing chain wear, and risk of pre-ignition. See, e.g.: SAE 2018-01-0634, Daimler-Development of a LIF-Imaging System for Simultaneous High-Speed Visualization of Liquid Fuel and Oil Films in an Optically Accessible DISI Engine; and SAE 2017-01-0806, DENSO - Accumulation Mechanism of Gasoline EGR Deposit.

Importantly for the newest, high efficiency vehicles and engines subject to the strictest emission and fuel economy standards are especially vulnerable to these effects. Gasoline particulate filters can help reduce the higher Particulate Matter (PM)/Particulate Number (PN) emissions but only insofar as the filters remain functional and are not overloaded and at the cost of better fuel efficiency. Increased particulate deposits mean more frequent filter regeneration events, which uses more fuel and reduces fuel economy. Also, no technologies exist to mitigate the increased risk of pre-ignition. Thus, this property must be controlled before the fuel enters the vehicle or engine.

## Benzene

Benzene is a naturally occurring constituent of crude oil and 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 may directly influence emissions through the volatilization of gasoline components. It can also influence particulate emissions, as explained below on page 39.

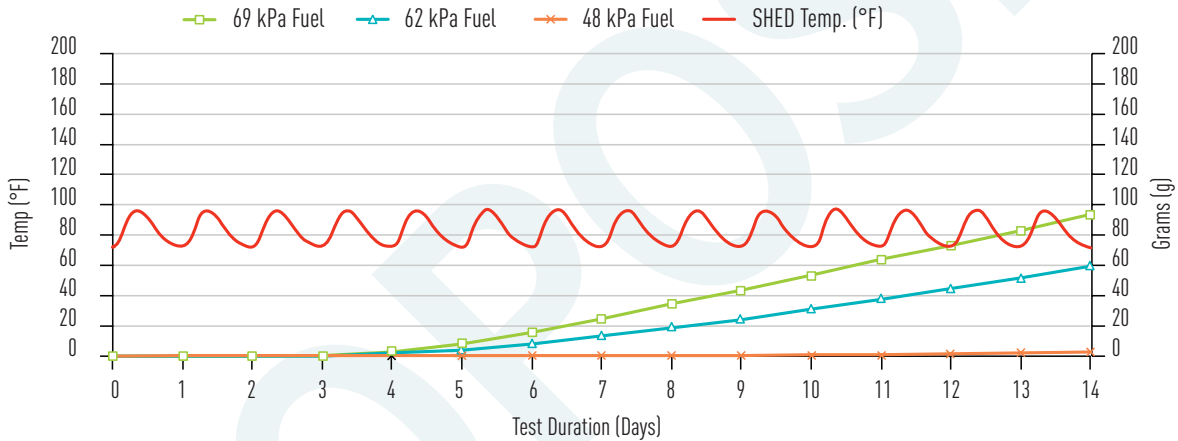
Volatility may be characterised by various measurements, the most common of which are vapour pressure, distillation and the vapour/liquid ratio. The presence of ethanol or other oxygenates may affect these properties and, as a result, performance and emissions as well.

**Vapour Pressure**

The vapour pressure of gasoline should be controlled seasonally to allow for the differing volatility needs of vehicles at different ambient 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 excessive evaporative emissions due to carbon canister overloading, especially at higher temperatures. At lower temperatures, a sufficiently high vapour pressure is needed to allow ease of starting and good warm-up performance. Therefore, both minimum and maximum vapour pressures are specified.

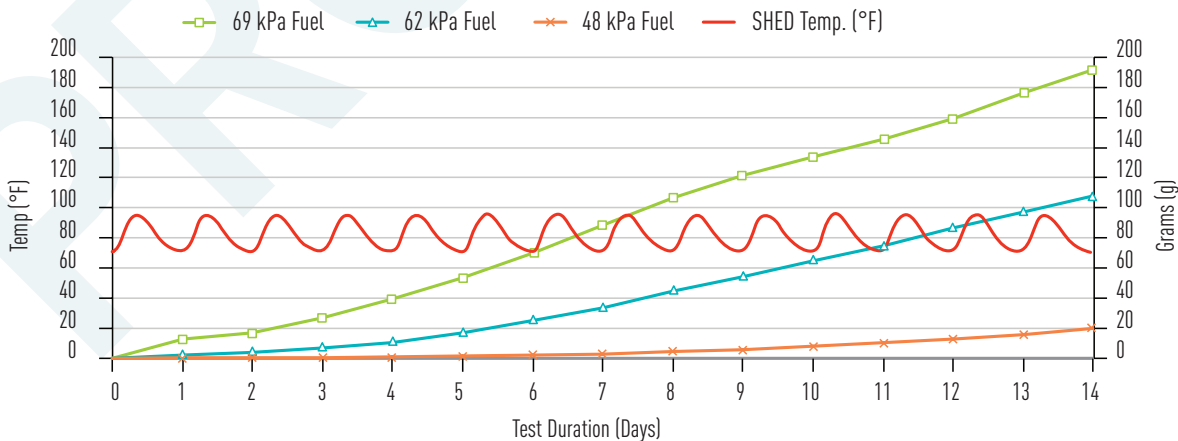
New data have become available on the effects of vapour pressure. Figure G-30 and Figure G-31 provide the hydro-carbon slip from canisters for two sample vehicles tested during study of the effects of 48 (0% ethanol), 62 (0% ethanol) and 69 kPa E10 (10% ethanol gasoline blend) fuels on canister breakthrough emissions over 14 days of SHED testing using the temperature profile from the U.S. Federal Diurnal Cycle. The data collected throughout the testing provides a correlation between the hydrocarbon slip from the vehicle canister and the fuel vapour pressure. The data indicate that the lower vapour pressure fuels, such as 48 kPa, are imperative during warm ambient temperatures for achieving very low evaporative emissions. The full report, with additional data, can be found at SAE 2013-01-1057. The study provided additional empirical evidence to a previous SAE study (Clontz, SAE Technical Paper No. 2007-01-1929) that showed the most important property of the fuel blend for canister performance is the vapour pressure. More importantly, the vapour pressure, not ethanol concentration, is the determining factor for vapour generation in the fuel tank.

**Figure G-30: Effect of Vapour Pressure on LEVII PZEV Vehicle Canister During 14-day Diurnal**



Source: SAE 2013-01-1057

**Figure G-31: Effect of Vapour Pressure on Tier 2 Vehicle Canister During 14-day Diurnal**



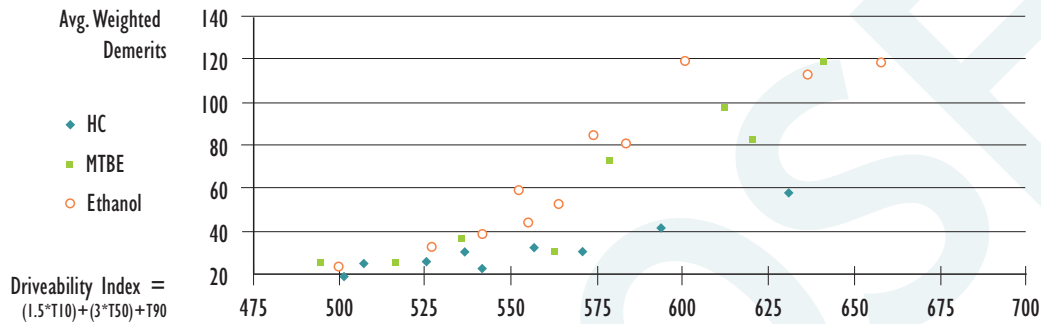
Source: SAE 2013-01-1057

### 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, also can be used to assure good cold start and warm-up performance.

Driveability concerns are measured as demerits. Figure G-32 provides the test results from one CRC study of the impact of the Driveability Index on driveability. This study tested 29 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 the Driveability Index increases. At Driveability Index levels higher than those specified in this Charter, driveability concerns increase dramatically.

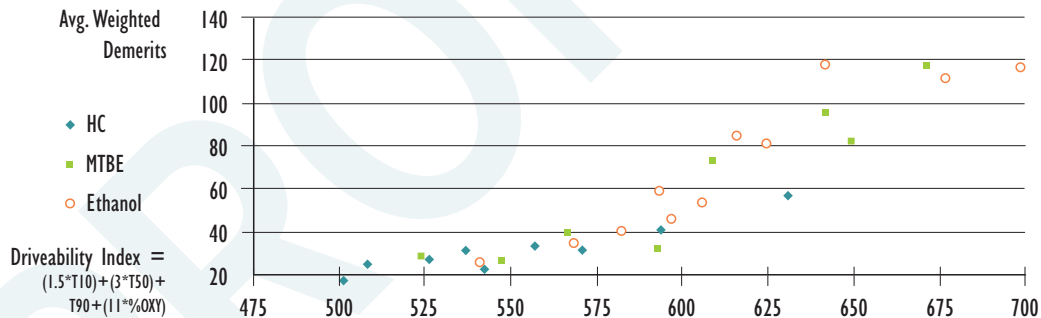
**Figure G-32: Effect of Driveability Index on Driveability**



Source: CRC Report No. 605

An oxygen correction factor is required to correct for higher driveability demerits for oxygenated fuels as compared to all-HC gasoline. Figure G-33 indicates how the correction factor smooths the data presented in Figure G-32.

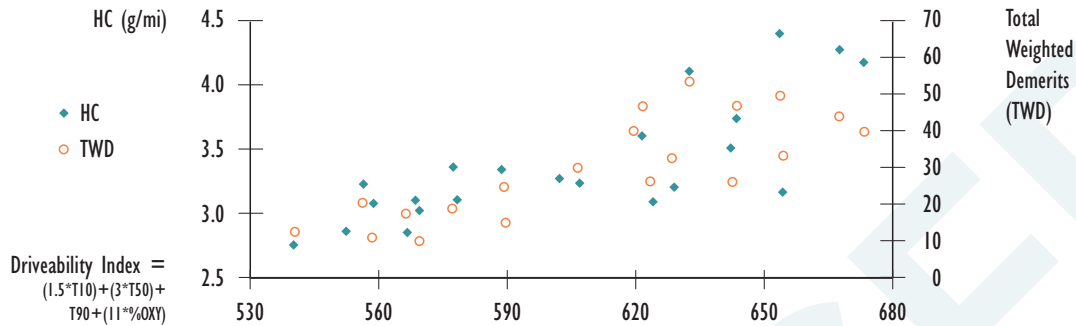
**Figure G-33: Effect of DI on Driveability (Oxygen Corrected)**



Source: CRC Report No. 605

DI also is directly related to tailpipe HC emissions, as shown in Figure G-34. As with driveability demerits, HC emissions increase significantly at DI levels higher than those specified in this Charter.

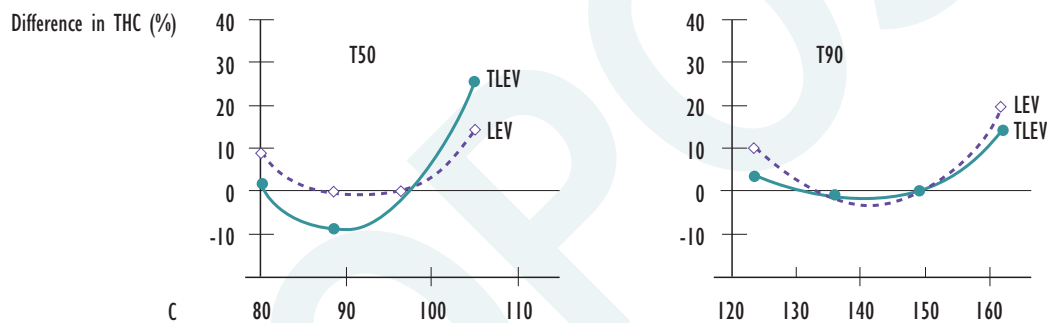
Figure G-34: Effect of DI on Driveability and Exhaust Emissions



Source: GM/SAE 962023

Figure G-35 indicates that optimum values for T50 and T90 exist to achieve lower exhaust THC emissions.

Figure G-35: Effect of T50/T90 on Exhaust Emissions, Comparison of LEV and TLEV



Source: Toyota/SAE 972851

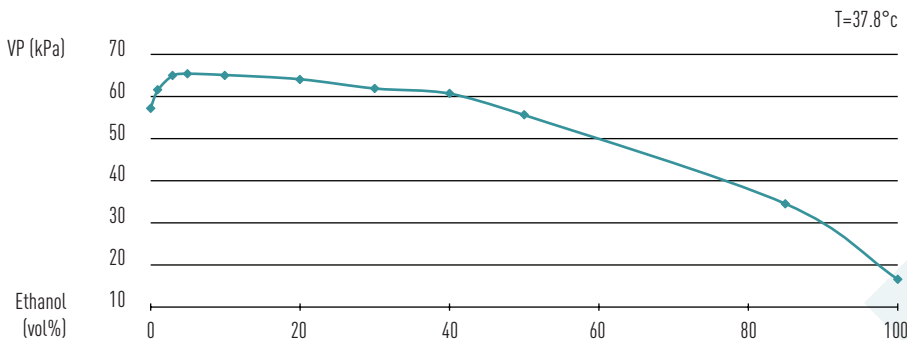
### Vapour/Liquid Ratio

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 decreases or blocks fuel flow to the engine. This can result in loss of power, rough engine operation or engine stalls. Since controls on vapour pressure and distillation properties are insufficient to prevent this problem, a Vapour/Liquid Ratio specification is necessary.

### Ethanol's Impact on Volatility

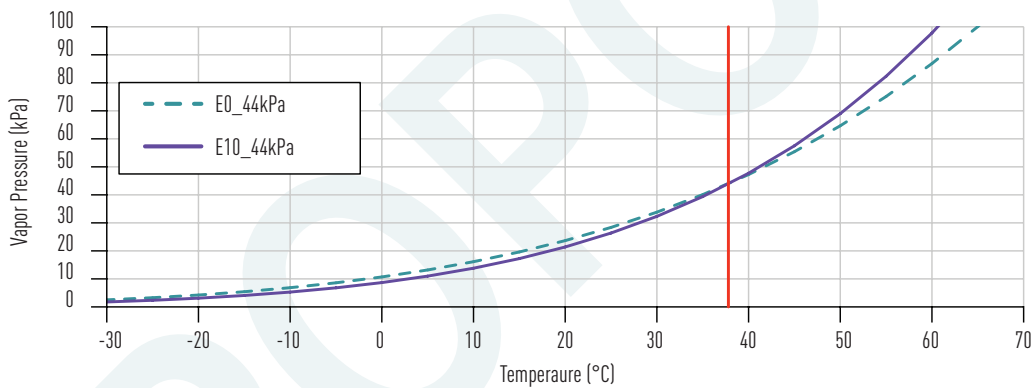
As a pure compound, ethanol exhibits straightforward behaviour regarding vapour pressure and distillation. When added to a base gasoline, however, the behaviour of the mixture is anything but straightforward. As a result, the vapour pressure and distillation of ethanol-gasoline blends, at a minimum, must be carefully regulated to ensure proper vehicle operation and emissions control. Ethanol also will make vapour lock more likely, so controlling the vapour-liquid ratio is even more important when ethanol is present.

Ethanol by itself has a very low vapour pressure, but adding it to gasoline has a non-linear and synergistic effect. Importantly, the final vapour pressure of the blend could be either higher or lower than the base gasoline, depending on temperature and ethanol concentration. At lower ethanol concentrations (below about 10% by volume) and typical temperatures, ethanol will cause the blend's vapour pressure to exceed that of the base gasoline. To prevent excess evaporative emissions, the vapour pressure of the finished blend, not just the base gasoline, must be controlled. Figure G-36 illustrates this effect.

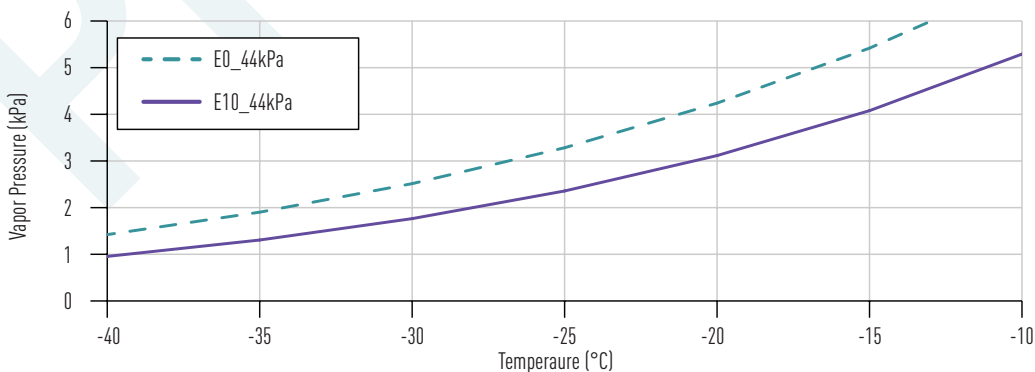
**Figure G-36: Impact of Ethanol Level on Vapour Pressure at 37.8°C**

Source: Honda 2010

Figure G-37, below, looks more closely at the variation for an E10 and its base gasoline (E0), showing the impact for a wider range of temperatures. Importantly, at temperatures above 37.8°C, the E10 has a higher vapour pressure relative to E0, but at lower temperatures, the vapour pressure goes below that of E0. The effect could be significant and prevent an engine from starting at very cold temperatures. Therefore, a higher minimum vapour pressure is required for ethanol-gasoline blends than would be needed for the base gasoline alone at these very low temperatures.

**Figure G-37: Comparison of E0 and E10 Vapour Pressures at Various Temperatures**

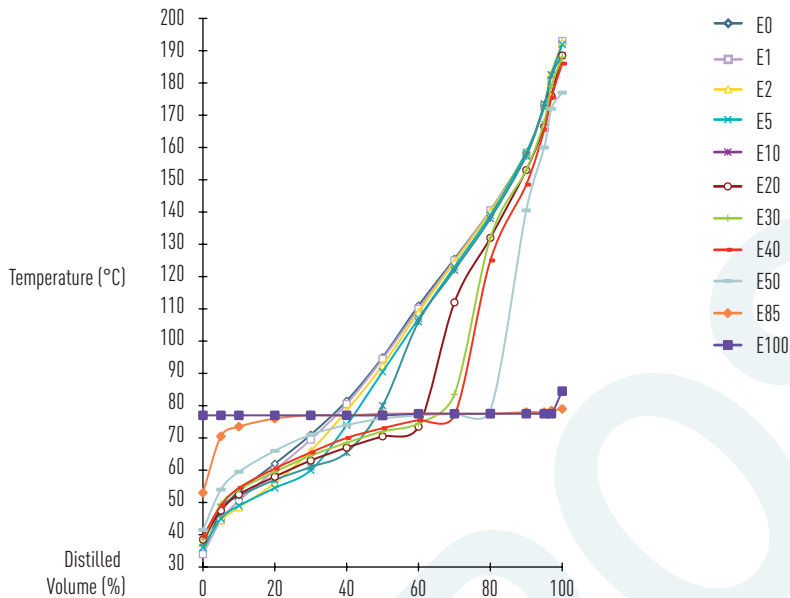
Source: Honda 2010

**Figure G-38: Magnification of Figure G-37 at Temperatures Below Freezing**

Source: Honda 2010

Ethanol's impact on the distillation curve is just as complex, if not more so. Figure G-39 shows how different ethanol levels in gasoline can cause dramatic changes in distillation, especially as the ethanol concentration goes above 10% by volume and near the middle of the distillation curve. The distillation measurement must be adjusted to account for the impact, and the blend's distillation must be well-controlled.

Figure G-39: Influence of Ethanol on Gasoline Distillation



Source: Toyota 2005

## Particulate Matter Index (PMI)

To address the potentially serious adverse health and environmental effects of particulate matter emissions, regulators have focused almost exclusively on setting stringent vehicle emissions requirements such as Euro 6d and US Tier 3. Fuel quality, however, also plays an important role and should be considered as part of society's control strategy for particulate emissions. Important progress has been made in developing methods for predicting the propensity of fuels for generating particulate emissions; one of the most studied is the Particulate Matter Index (PMI) (see K. Aikawa, T. Sakurai and J. Jetter, "Development of a Predictive Model for Gasoline Vehicle Particulate Matter Emissions," SAE 2010-01-2115).

PMI is an analytically derived value based on several inputs: the double bond equivalence (DBE), vapor pressure at 443°K and the weight fraction of each component in the fuel, as shown below in Equation G-3.

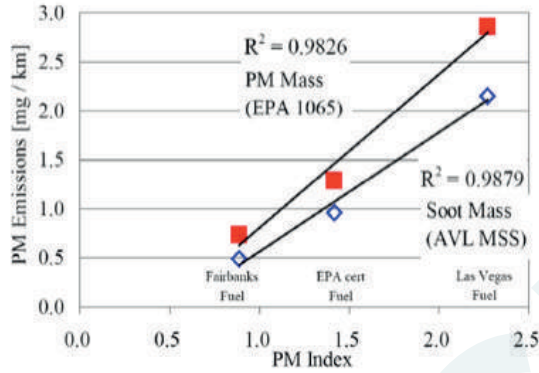
Equation G-3: Particulate Matter Index

$$PMI = \sum_{i=1}^n \left( \left( \frac{DBE_i + 1}{VP(443K)} \right) \times Wt_i \right)$$

Source: Aikawa et al, SAE 2010-01-2215.

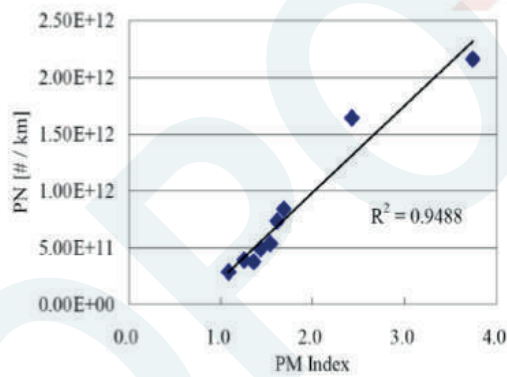
As Figure G-40 and Figure G-41 show, PMI correlates well with both particulate number (PN) and particulate matter mass (PM) emissions, in the same direction, i.e., the higher the PMI value, the higher the observed PN and PM emissions.

Figure G-40: PMI Compared to Measured PM And Soot Mass Emissions



Source: Aikawa et al, SAE 2010-01-2215.

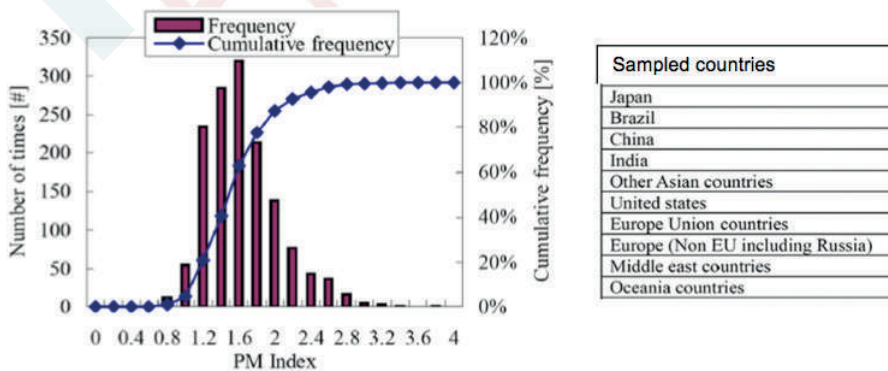
Figure G-41: Relationship Between PMI and Particulate Number Emissions on the New European Driving Cycle



Source: Aikawa et al, SAE 2010-01-2215.

Figure G-42 below, show the PMI results of a global fuel survey reported in 2010. The distribution of frequency reflects the number of samples calculated at each PMI level. These data show the widespread occurrence of gasoline with tendencies to produce higher PN and PM emissions and emphasize the need to do more to control the particulate formation tendencies of market fuel.

Figure G-42: PMI Distribution of Worldwide Commercially Available Gasoline

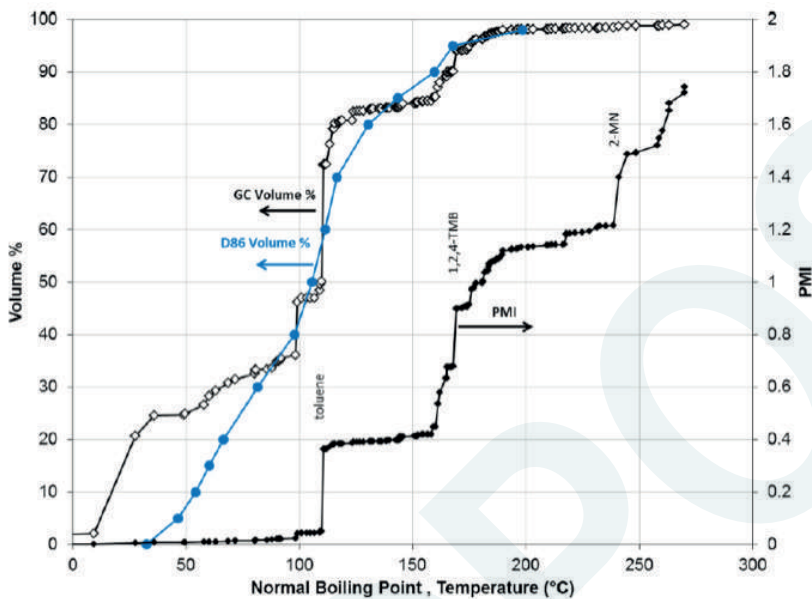


Source: Aikawa et al, SAE 2010-01-2215.



The nature of the PMI equation suggests several ways a fuel's PMI may be controlled. For example, fuel components with high DBE and low vapor pressure can contribute to the overall PMI of a fuel, even in very small quantities. See E. Barrientos, J. Anderson, M. Maricq and A. Boehman, "Particulate Matter Indices Using Fuel Smoke Point for Vehicle Emissions with Gasoline, Ethanol Blends, and Butanol Blends," *Combustion and Flame*, vol. 167, pp. 308-319, 2016. Figure G-43, below, shows that roughly half of a fuel's PMI value can be caused by only 10% of the fuel's volume (volume measured both by gas chromatography (GC) and by ASTM D86). Minimizing the quantity of very high PMI hydrocarbons, such as naphthalenes, can significantly decrease the PMI value for a given fuel.

**Figure G-43: Cumulative Distribution of Speciated Hydrocarbon Volume Percentage and PMI Contributions of Hydrocarbons in a U.S. Tier 2 Certification Gasoline**



Source: E. Barrientos et al, *Combustion and Flame*, vol. 167, 2016.

Introducing a maximum PMI specification into the marketplace will help decrease vehicle particulate emissions from all on-road vehicles by a significant amount, thereby reducing the associated health and environmental impacts. Similar benefits also would likely accrue from off-road gasoline-powered vehicles and engines, which also contribute to PM emissions. Various fuel-sampling efforts have shown that many areas of the developed world have achieved a PMI value of 1.5 in their commercially available gasoline without actively trying to minimize PMI. Setting a maximum PMI value of 1.5 for all grades of commercially available gasoline will reduce and help control the particulate emissions from legacy, current, and future vehicles.

#### Using Volatility Limits to Control Particulate Emissions

While PMI offers one approach to controlling the tendency of gasoline to produce particulate matter emissions, the search continues for the best way to measure this fuel property. As this search continues, a pragmatic approach is to limit gasoline's volatility. It can be shown that higher aromatics in gasoline (e.g., those having eight or more carbon atoms ('C8+')) contribute disproportionately to PM formation in the exhaust gas. See Figure G-43, above. Since C8+ aromatics have a boiling point greater than 150°C (with a few exceptions), limiting this fraction is a simple way to control PM precursors in the fuel. The WWFC Committee recommends setting the E150 distillation cut point at the limits shown in the volatility table on page 10 in Section 1 (Specifications) of this chapter. For a Category 6 Class A gasoline, then, the minimum E150 cut point should be set at 83% V/V.

## Deposit Control Additives

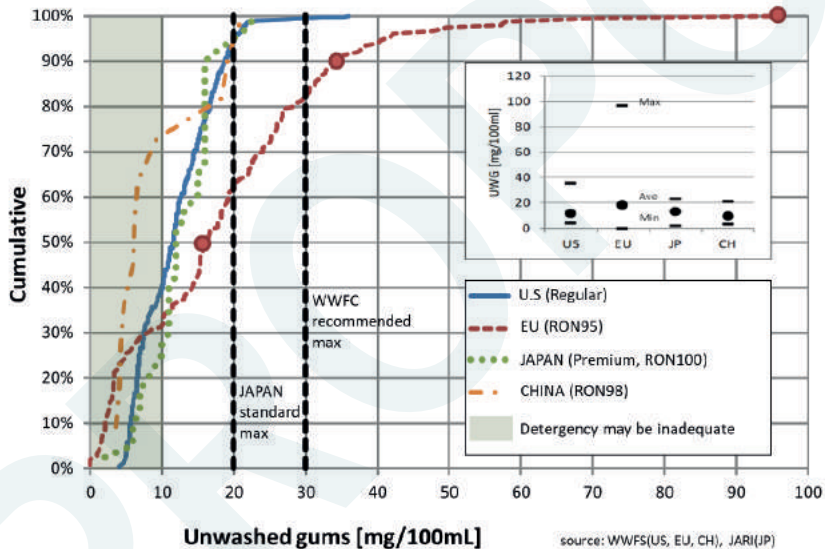
Combustion of even good quality gasoline can lead to deposit formation that will increase engine-out emissions and affect vehicle performance. Deposit control additives (also called detergents) can help reduce or minimize these deposits as long as they are used properly. High quality fuel contains a sufficient amount of deposit control additives to reduce deposit formation to acceptable rates. A series of engine tests for performance and absence of harm determines the appropriate chemistry and treat rate, and each specific detergent package may have a unique acceptable treat rate.

Automotive companies support proper usage through performance standards proven to keep engines clean. Proper additive chemistry and dosage are key to keeping engines clean and running optimally. Undertreated gasoline will fail to keep the engine clean, and overtreated gasoline can lead to valve sticking or build-up of combustion chamber deposits (discussed below on page 45), which also lead to adverse impacts. Care must be taken to avoid undertreating or overtreating the fuel, either of which can lead to higher emissions. See discussion and data below.

Unwashed gum, which is a laboratory measurement of the residue of a sample of evaporated fuel, can indicate the amount of detergency. Care must be taken in interpreting the results, however, because the residue may also indicate contamination of the gasoline by other substances, such as diesel fuel. Japan enforces a maximum unwashed gums limit of 20 mg/100 mL as a control measure for cross contamination of diesel fuel into gasoline.

Detergency treat rates vary widely around the world; Figure G-44 shows the results of a recent survey of unwashed gum levels in four major markets. Two aspects are of concern: the volume of fuel treated, and the levels of unwashed gum. The shaded area on the left side of the graph indicates samples that may be inadequately treated. The samples to the right of the WWFC recommended maximum unwashed gum level may have excessive levels of detergency. One finding is that European gasoline tends to have very high treat rates of detergency compared to fuel from the US, Japan and China.

Figure G-44: Unwashed Gum Levels in Several Major Markets (2016)



Source: The SGS Worldwide Fuel Survey and JARI.

### Carburettors

First generation additives based on amine chemistry were developed in the early 1950's and are 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.

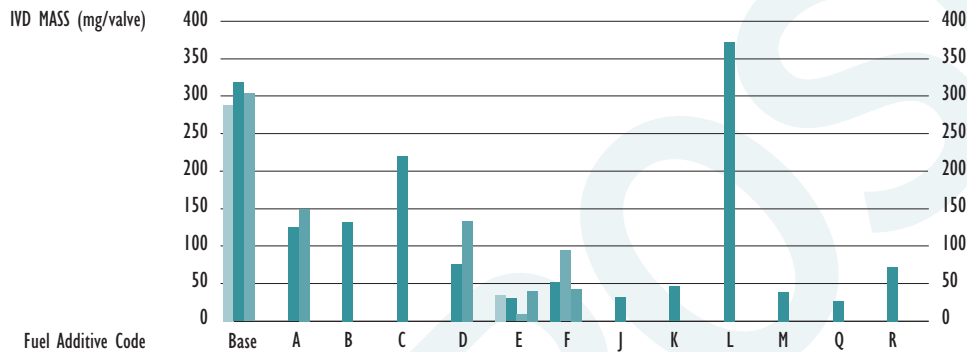
### Port Fuel Injectors

US gasoline marketers introduced port fuel injector deposit control additives 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. Detergent technology and test procedures are being developed to protect the more advanced injectors being introduced in direct injection engines.

### Intake Valves

Various tests are available to evaluate the gasoline's capability of maintaining acceptable intake valve cleanliness. Figure G-45 compares the intake valve "keep clean" performance results of base fuel without detergent additives with fuels having various detergent additive chemistries in the Ford 2.3L IVD test (ASTM D6201). Proper 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 G-45: IVD Performance of Gasolines With and Without Detergents, Using the Ford 2.3L Dynamometer Test**

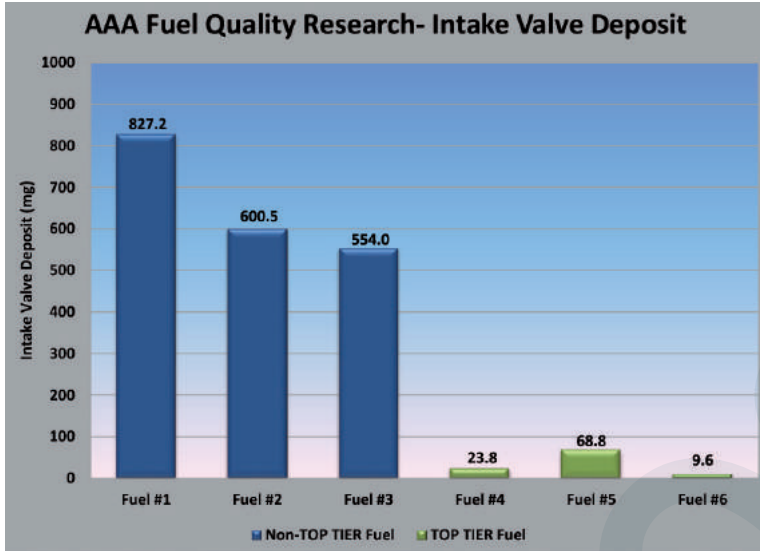


Source: Ford, 1996

The impact of intake valve deposits on driveability in both North America and Europe has been severe enough in recent years to prompt vehicle manufacturers to steer customers to gasoline known to contain adequate detergency for minimizing and reducing intake valve deposits. Figure G-48 shows the results of a Ford study of US market gasoline performance regarding intake valve deposits conducted in 1999-2000 and presented to ASTM in 2003. One third of the fuel samples caused unacceptable IVD rates ranging from 392 mg/valve to 1157 mg/valve. This problem continues to cause concern.

The American Automobile Association (AAA) conducted a study in 2016 comparing US fuels treated at the EPA-mandated detergency treat rates compared to fuel formulated to the TOP TIER™ Detergent Gasoline performance standard. See AAA.com at [www.aaa.com/AAA/common/AAR/files/Fuel-Quality-Full-Report.pdf](http://www.aaa.com/AAA/common/AAR/files/Fuel-Quality-Full-Report.pdf). Using the ASTM D6201 100 hour engine dynamometer test to compare six market fuels, the study found gasoline treated at the TOP TIER™ treat rates had 19 times fewer intake valve deposits than fuel treated at the federally required levels. See Figure G-46 and Figure G-47 from the study, below, showing the impacts of different fuel detergency.

Figure G-46: Results of AAA Study of US Gasoline Detergency



Source: American Automobile Association, 2016.

Figure G-47: Impact of Different Gasoline Detergency on Two Intake Valves

AAA Fuel Quality Research: Intake Valve Comparison

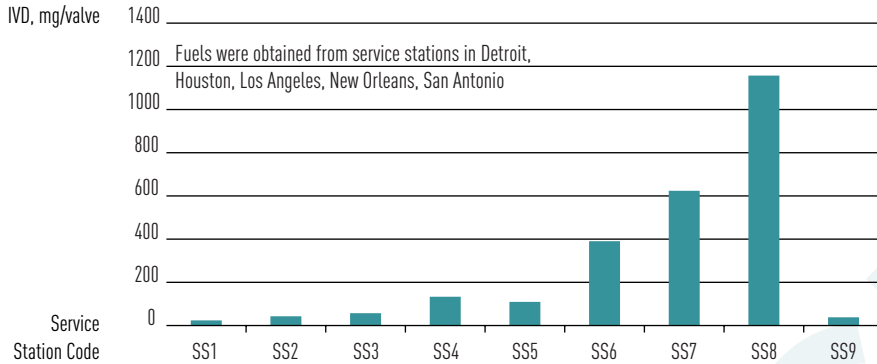


\*Among gasoline brands tested.  
Full report available at [NewsRoom.AAA.com](http://NewsRoom.AAA.com)



Source: American Automobile Association, 2016.

Figure G-48: IVD Performance of Service Station Gasolines, using the Ford 2.3L Dynamometer Test



Source: Ford, ASTM 2003

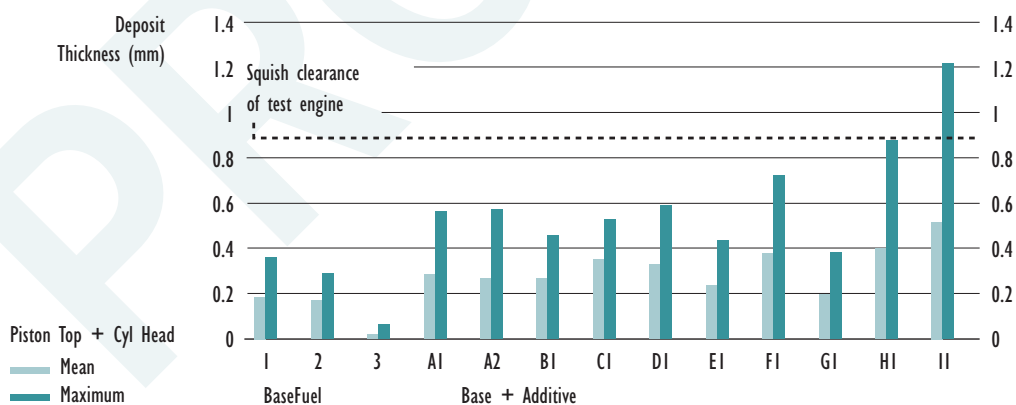
### Combustion Chambers

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'.

Methods for measuring CCD could be improved. CEC F-20-A (Method 2), for example, produces technically relevant results when the engine operator has detailed knowledge about the measurement precision of the particular test stand, but in general, the method lacks precision data and cannot produce statistically valid CEC results for chamber deposits.

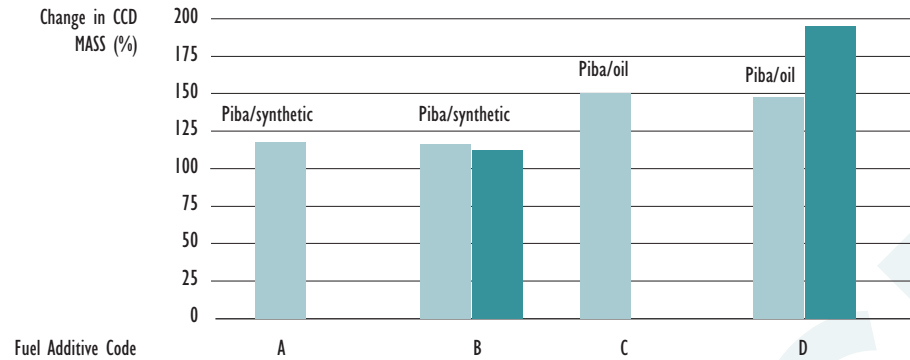
Certain detergent additives can increase the level of CCDs relative to base fuel, as shown in Figure G-49 and Figure G-50. Detergent packages with higher ratios of mineral oil carriers tend to increase CCDs, while detergent packages with optimised high-quality synthetic carrier fluids and compounds like polyether amines (PEA) minimise CCD build-up. Additive packages and concentrations should be optimised to minimise CCDs, which will allow engine designers to improve combustion chamber designs further for lower emissions and fuel consumption.

Figure G-49: Engine Dynamometer Results



Source: Ford, SAE 962012

Figure G-50: CCD Performance of Gasolines Using the Ford 2.3L Dynamometer Test (ASTM D6201)

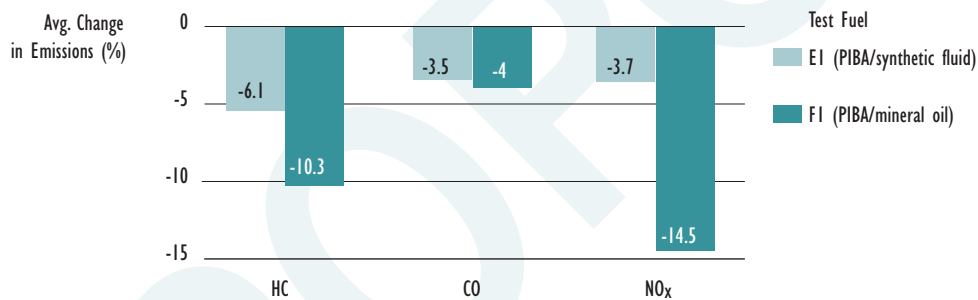


Source: Ford, 1996

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

The removal of CCDs can reduce engine out HC emissions by up to 10%, CO by 4%, and NO<sub>x</sub> by 15% in some engines, as shown in Figure G-51 for fleet vehicles after accumulating 50,000 miles.

Figure G-51: Effect of CCD Removal on Engine-Out Emissions

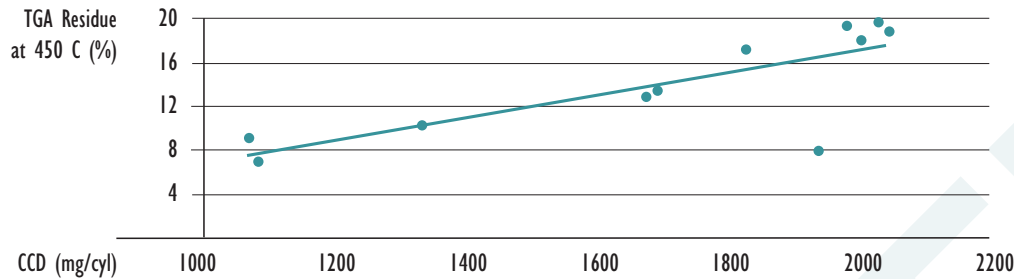


Source: Ford, SAE 962012

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.

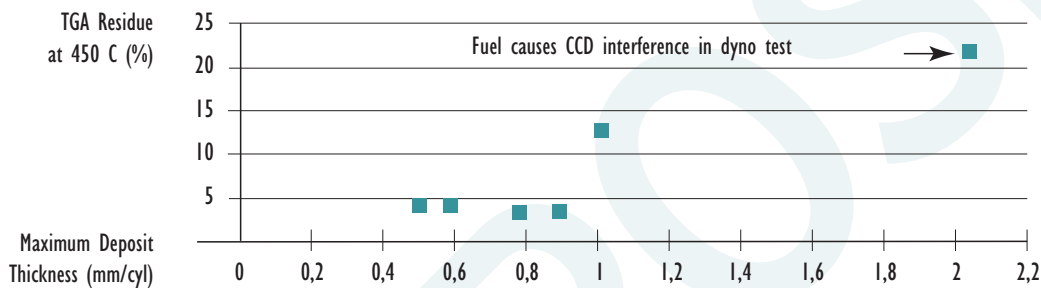
A thermogravimetric analysis (TGA) bench test method has been developed that provides a good correlation with CCDs in a dynamometer-based multi-cylinder engine test as shown in Figure G-52 and Figure G-53.

Figure G-52: Correlation of CCD and TGA Results of Commercial Fuels in Ford 2.3L IVD Test (ASTM D6201)



Source: Ford, ASTM 2003

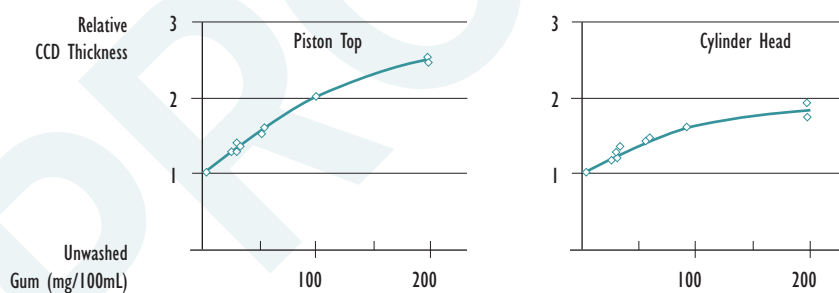
Figure G-53: TGA Proposed Pass/Fail Limit - 4.0L Dynamometer Test Results



Source: Ford, SAE 962012

Figure G-54 indicates the correlation between unwashed gums and CCD formation as compared to base gasoline without detergent. Thus, the Charter allows compliance to either an unwashed gum or a CCD specification.

Figure G-54: Relationship Between Unwashed Gum and CCD Thickness



Source: Toyota, SAE 941893

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. While deposit control additives can greatly improve the fuel quality, one must be careful not to overtreat the fuel because it can lead to other problems.

## Fuel Stability

Gasoline can undergo quality changes during distribution and storage that highlight the need for fuel stability as a fuel quality measure. This quality is an emerging concern for gasoline used in hybrid vehicles, where the fuel is consumed more slowly and spends a longer time in the vehicle's tank, therefore having a greater likelihood of aging compared with fuel used in conventional vehicles.

Fuel aging can increase the oxidation of fuel components, leading to the formation of harmful new compounds such as peroxides and acids. Peroxides can aggressively attack fuel system materials, especially elastomers and plastics. They also can crosslink with other chemicals to form insoluble coatings on the interior surfaces of system components, a process called varnishing. Similarly, acids will aggressively attack fuel system materials, including metallic components such as fuel lines and connectors.

Aging also can change the gasoline's RVP and other measures of the fuel's volatility. These changes can affect run/cold-start calibration.

## Corrosive (Active) Sulphur

Certain fuel sulphur compounds, including elemental sulphur, hydrogen sulphide (H<sub>2</sub>S), mercaptans and other sulphur-containing molecules, can tarnish silver- and copper-containing metals that are widely used in fuel system parts such as fuel level sender units and fuel pump bearings. Active sulphur compounds may be present in the fuel due to problems during gasoline production, such as improper operation of a refinery's desulphurization process or through accidental events. These compounds are highly reactive, and their presence even at very small levels (a few ppm) can cause harm. The sulphur compounds react with the metal parts to form silver or copper sulphides. In the case of fuel level sender units, which measure the amount of fuel in a fuel tank, the formation of silver sulphide on the electrical contacts interrupts the flow of current to the fuel gauge and causes the gauge to display erratic readings. In the case of fuel pump bearings, which enable the pump to operate smoothly, the formation of copper sulphide on the bearing surface causes the pump shaft to stick, interrupting the pump's smooth operation and potentially causing pump failure and vehicle stalling. To prevent the presence of these compounds in fuel, strict and continuous quality control is required.

## Good Housekeeping Practices

It is important that vehicles and engines receive the same high quality fuel at the service station dispenser as measured upstream at the refinery gate. Many problems encountered by vehicles/engines, if not most, are caused by contamination that occurs after the fuel has left the refinery gate. Inadequate pipeline and storage facilities and failure to properly maintain equipment, for example, can lead to volatility losses, and contamination by particulates and water. At the service station, infrequent replacement of fuel dispenser filters or auditing (such as 'dipping') of tanks to check for water can magnify this contamination. Harmful elements such as copper, zinc and sodium also can enter the fuel through poor fuel handling practices.

Post-refining degradation of fuel quality is preventable through good housekeeping practices, regular equipment maintenance, adequate investment in facilities and protection from adulteration, all along the distribution system and at the service station. Filtering the fuel at every transfer point will further help by removing damaging contaminants such as particulate and water. Helpful guidance to good housekeeping practices for gasoline may be found in CEN/TR 15367-2, "Petroleum Products - Guide for Good Housekeeping - Part 2: Automotive Petrol Fuels."

Cross-contamination between gasoline and diesel fuel, which may occur anywhere in the distribution and storage system, raises serious concerns for engines and vehicles. Gasoline contaminated with diesel fuel has a higher potential for pre-ignition (damaging engine knock), which is a critical issue for newer, high efficiency turbocharged engines with their strong need for preignition resistance. Contaminated gasoline also greatly increases the possibility of diluted engine oil, which increases the risk of catastrophic engine damage. Even just 1% of low volatility diesel fuel in gasoline can lead very quickly to unexpected lubricant degradation (low viscosity, loss of dispersant/detergent performance).

One way to minimize cross-contamination is to clean out tanker trucks between fuel batches. To fully prevent it, however, the most effective approach is to use dedicated and segregated systems for gasoline and diesel fuel and to prohibit "switch loading" at the filling station. CEN/TR 15367-3, "Petroleum Products - Guide for Good Housekeeping - Part 3: Prevention of Cross Contamination," provides additional guidance. The Charter recommends using gas chromatography test methods to test for cross contamination, to supplement the annex A "quality parameters" of CEN/TR 15367-3. Suggested test methods include EN 16270 (high boilers in petrol) and VDA\* 265 (diesel fuel contamination).



## Appendix – Unleaded Gasoline

### Category 1: Retired as obsolete; for historical reference only.

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

PROPERTIES	UNITS	LIMITS	
		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	
Sulphur	mg/kg <sup>2</sup>		1000
Trace metal <sup>3</sup>	mg/kg	1 or non-detectable, whichever is lower	
Oxygen <sup>4</sup>	% m/m		2.7 <sup>5</sup>
Aromatics	% v/v		50.0
Benzene	% v/v		5.0
Volatility		See 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	rating		Class 1
Appearance		Clear and bright; no free water or particulates	
Carburettor cleanliness	merit	8.0 <sup>6</sup>	
Fuel injector cleanliness, Method 1, or	% flow loss		10 <sup>6</sup>
Fuel injector cleanliness, Method 2	% flow loss		10 <sup>6</sup>
Intake valve cleanliness	merit	9.0 <sup>6</sup>	

<sup>1</sup> Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

<sup>2</sup> The unit mg/kg is often expressed as ppm. Lower sulphur content preferred for catalyst-equipped vehicles.

<sup>3</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. Another undesirable element is Cl. Metal-containing additives are acceptable only for valve seat protection in non-catalyst cars; in this case, potassium-based additives are recommended. No intentional addition of metal-based additives is allowed.

<sup>4</sup> Where oxygenates are used, ethers are preferred. Methanol is not permitted.

<sup>5</sup> By exception, up to 10% by volume ethanol content is allowed if permitted by existing regulation. Blendstock ethanol should meet the E100 Guidelines published by the WWFC Committee. Fuel pump labelling is recommended for gasoline-ethanol blends to enable customers to determine if their vehicles can use the fuel.

<sup>6</sup> Compliance with this requirement can be demonstrated by the use of proper detergent additives in comparable-base gasolines.

# CHAPTER 2

## DIESEL FUEL

### **ABOUT THIS EDITION** 51

Diesel Fuel Categories  
Charter Scope and the Definition of Diesel Fuel  
Recommendations for all Markets

### **DIESEL FUEL SPECIFICATION** 53

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Cetane | Density And Viscosity | Sulphur | Ash | Aromatics | Distillation Characteristics  
Cold Flow | Foam | Biofuels And Alternative Synthetic Fuel Components | Fuel Stability  
Injector Cleanliness | Lubricity | Particulate Contamination  
Contaminants | Good Housekeeping Practices

### ABOUT THIS EDITION

These fuel quality recommendations represent the manufacturers' best collective judgment about a range of fuel factors considered to be the most important in terms of affecting vehicle and engine performance, durability and emissions. The recommended specifications are arranged in categories that correspond to different levels of vehicle and engine technologies. The most sophisticated technologies require and will perform best when using the highest category of fuel quality, but all levels of technology typically achieve improved performance, greater longevity and lower emissions when using higher category fuels on a regular basis. Importantly, the fuels specified in the highest categories enable the introduction of technologies having the greatest fuel efficiency and lowest greenhouse gas emissions. To improve understanding of the rationale behind the recommendations, the Charters and Guidelines explain the underlying science in the technical backgrounds of these documents.

### DIESEL FUEL CATEGORIES

This Charter for diesel fuel establishes five categories of fuel quality, reflecting different levels of regulatory standards and performance needs. More than twenty years after the adoption of the first Worldwide Fuel Charter, some regions continue to have unacceptably high sulphur levels, even exceeding 10,000 ppm in some markets. To encourage these regions to bring their fuel quality in line with cleaner and more modern specifications, the Committee is retaining Category 1 as guidance for transitional diesel fuel quality. The Committee is also serving notice, however, that it intends to retire this category in a future edition.

#### Category 1

Markets with no or first level requirements for emission control; based primarily on fundamental vehicle/ engine performance and protection of emission control systems. This category will be retired in a future edition.

#### Category 2

Markets with requirements for emission control, such as US Tier 1, US 1998 and 2004 Heavy-Duty On-Highway, EURO 2/II, EURO 3/III or equivalent emission standards, or other market demands.

#### Category 3

Markets with more stringent requirements for emission control, such as US LEV, California LEV or ULEV, US 1998 and 2004 Heavy-Duty On-Highway, EURO 4/IV, JP 2005 or equivalent emission standards, or other market demands.

#### Category 4

Markets with advanced requirements for emission control, such as US Tier 2, US Tier 3, California LEV II, US 2007/2010 Heavy-duty On-Highway, US Non-Road Tier 4, EURO 4/IV, EURO 5/V, EURO 6/6b, EURO VI, JP 2009 or equivalent emission standards, or other market demands. Category 4 fuels enable sophisticated NOx and particulate matter after-treatment technologies.

#### Category 5

Markets with highly advanced requirements for emission control (including GHG) and fuel efficiency, such as US Tier 3 Bin 5, US 2017-2021 light duty fuel economy, US Heavy Duty Fuel Efficiency/GHG Emission, California LEV III and as amended, US 2007/2010 Heavy-duty On-Highway, US Non-Road Tier 4, Euro 6c, Euro 6dTEMP, Euro 6d, EU CO<sub>2</sub> target 120 g/km, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category is intended to minimize real driving emissions (RDE) to levels required for Euro 6dTEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023). Category 5 fuels enable sophisticated NOx and particulate matter after-treatment technologies.

### CHARTER SCOPE AND THE DEFINITION OF DIESEL FUEL

This Charter covers finished diesel fuel and diesel-based blends that qualify as conventional fuel for compression-ignition engines and vehicles. Engine/vehicle manufacturers test and certify their products to known fuel specifications, so it is important for the market to provide fuel that falls within the product's design boundaries.

Diesel fuel is commonly described as the middle distillate fractions of crude oil, which are separated from the lighter and heavier fractions during the refining process. Chemically, the liquid is composed of organic molecules (straight-chain and aromatic) within a certain boiling range; these molecules consist primarily of carbon and hydrogen atoms. Certain straight chain molecules may require modification to provide the specified cold flow properties. If sulphur is present in crude oil molecules (as it may be naturally), it will need to be reduced or removed during the refining process to yield diesel fuel that will not damage engine or vehicle technologies, especially emission control equipment.

Diesel fuel may include certain non-hydrocarbon-only blending components (i.e., used at levels greater than 0.25% m/m) or additives to improve its quality or increase the use of renewable fuel, as discussed in the Technical Background under Biofuels and Alternative Synthetic Fuel Compounds (see page 81); all other compounds — such as glycerides (mono, di or tri), lubricating oils, solvents or sediment — should not be present in any amount due to the risks of material incompatibility or engine damage. New types of proposed blendstocks should be fully tested for potential adverse effects before introduction.

This Charter does not intend to cover fuels considered alternatives to diesel fuel, such as high FAME-(biodiesel) content diesel fuel blends.

Importantly, the European voluntary specification for diesel fuel (EN590) states: “Diesel fuel shall be free of any adulterant or contaminant that may render the fuel unacceptable for the use in diesel fuel engine vehicles.” The Committee concurs with this statement.

### RECOMMENDATIONS FOR ALL MARKETS

Maintaining good fuel quality at the dispenser requires attention to the quality of the fuel upstream, including monitoring of other fuels and blend components that may be added during distribution. Good management practices should be applied throughout, from production and processing through distribution to fuel dispensing. The following recommendations apply broadly in all markets:

- Using additives that are compatible with engine oils, to prevent any increase in engine sludge or deposits of varnish.
- Not adding ash-forming components.
- Using good housekeeping practices throughout distribution to minimize contamination from dust, water, incompatible fuels and other sources of foreign matter.
- Using pipeline corrosion inhibitors that do not interfere with fuel quality, whether through formulation or reaction with sodium.
- Labelling dispenser pumps adequately to help consumers identify the appropriate fuels for their vehicles. Pump labels should advise consumers to consult their vehicle owner’s manual for specific guidance on fuel selection.
- Dispensing fuel through nozzles meeting SAE J285, ‘Dispenser Nozzle Spouts for Liquid Fuels Intended for Use with Spark Ignition and Compression Ignition Engines.’
- When blending with FAME (biodiesel), using FAME that adheres to the B100 Guidelines published by the WWFC Committee.
- Where ‘non-detectable’ is shown for a given parameter, the lowest possible levels are expected with no intentional additions of the additive or contaminant.

The diesel fuel quality recommendations that begin on page 53, below, apply to the finished fuel as provided to the consumer. 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 must be met.

To meet ongoing environmental, energy and customer challenges, vehicle and engine manufacturers will continue to develop and introduce advanced and innovative technologies that may require changes in fuel quality. Category revisions will occur as needed to reflect such changes in technology, as well as in fuel production, test methods and global market conditions.

**DIESEL FUEL SPECIFICATIONS**

**Category 1:** Markets with no or first level requirements for emission control; based primarily on fundamental vehicle/engine performance and protection of emission control systems, for example, markets requiring US Tier 0, EURO 1 or equivalent emission standards. This category is being retained only as a transitional fuel quality and will be retired in a future edition.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Cetane Number		48.0	
Cetane Index <sup>1</sup>		48.0 (45.0) <sup>1</sup>	
Density @ 15°C	kg/m <sup>3</sup>	820 <sup>2</sup>	860
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>3</sup>	4.5
Sulphur	mg/kg <sup>4</sup>		2000 <sup>5</sup>
T95	°C		370
Flash point	°C	55 <sup>6</sup>	
Carbon residue	% m/m		0.30
CFPP or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature <sup>7</sup>
Water	mg/kg		500
Oxidation stability			
Method 1	g/m <sup>3</sup>		25
Method 2a (Rancimat, modified) <sup>8</sup>	hours	30	
Method 2b (Delta TAN) <sup>8</sup> , or	mg KOH/g		0.12
Method 2c (PetroOxy) <sup>8</sup>	minutes	60	
FAME <sup>9</sup>	% v/v		5%
Other biofuels <sup>10</sup>	% v/v		10
Copper corrosion	rating		Class 1
Ethanol/Methanol	% v/v		Non-detectable <sup>11</sup>
Ash	% m/m		0.01
Particulate contamination, total	see test method		10
Appearance		Clear and bright; no free water or particulates	
Lubricity (HFRR wear scar dia. @ 60°C)	micron		460

<sup>1</sup> Cetane Index is acceptable instead of Cetane Number if cetane improvers are not used. When cetane improvers are used, the estimated Cetane Number must meet the the specified value and the Cetane Index must meet the number in parenthesis.

<sup>2</sup> May relax the minimum limit to 800 kg/m<sup>3</sup> for fuels used in low temperature conditions (cloud point below -10°C).

<sup>3</sup> May relax the minimum limit to 1.5 mm<sup>2</sup>/s when ambient temperatures are below -30°C or to 1.3 mm<sup>2</sup>/s when ambient temperatures are below -40°C.

<sup>4</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>5</sup> Sulphur levels at or above 2000 ppm are considered extremely high. Countries with diesel fuel containing such high sulphur levels are urged to transition to a market fuel containing no greater than 500 ppm sulphur for a cleaner and more modern transportation system.

<sup>6</sup> The minimum limit can be relaxed to 38°C when ambient temperatures are below -30°C.

<sup>7</sup> If compliance is demonstrated by meeting CFPP, then the maximum must be no more than 10°C less than cloud point.

<sup>8</sup> Fuels containing FAME must be tested using either Method 2a, Method 2b or Method 2c. Method 2c may be used for FAME-free diesel fuel.

<sup>9</sup> For FAME, both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used, the blendstock should meet the B100 Guidelines published by the WWFC Committee, and fuel pumps should be labelled accordingly.

<sup>10</sup> Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

<sup>11</sup> At or below detection limit of the test method used.

**Category 2:** Markets with requirements for emission controls, such as US Tier 1, US 1998 and 2004 Heavy-Duty On-Highway, EURO 2/II, EURO 3/III or equivalent emission standards, or other market demands.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Cetane Number		51.0	
Cetane Index <sup>1</sup>		51.0 (48.0) <sup>1</sup>	
Density @ 15°C	kg/m <sup>3</sup>	815 <sup>2</sup>	850
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>3</sup>	4.0
Sulphur	mg/kg <sup>4</sup>		300
Trace metal <sup>5</sup>	mg/kg		Non-detectable
Total aromatics	% m/m		25
PAH (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 or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature <sup>7</sup>
Water	mg/kg		200 <sup>8</sup>

<sup>1</sup> Cetane Index is acceptable instead of Cetane Number if cetane improvers are not used. When cetane improvers are used, the estimated Cetane Number must meet the specified value and the Cetane Index must meet the number in parentheses.

<sup>2</sup> May relax the minimum limit to 800 kg/m<sup>3</sup> for fuels used in low temperature conditions (cloud point below -10°C).

<sup>3</sup> May relax the minimum limit to 1.5 mm<sup>2</sup>/s when ambient temperatures are below -30°C or to 1.3 mm<sup>2</sup>/s when ambient temperatures are below -40°C.

<sup>4</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>5</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No intentional addition of metal-based additives is allowed.

<sup>6</sup> Compliance with either T90 or T95 is required.

<sup>7</sup> If compliance is demonstrated by meeting CFPP, then the maximum must be no more than 10°C less than cloud point.

<sup>8</sup> May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability			
Method 1	g/m <sup>3</sup>		25
Method 2a (Rancimat, modified) <sup>9</sup>	hours	35	
Method 2b (Delta TAN) <sup>9</sup> , or	mg KOH/g	0.12	
Method 2c (PetroOxy) <sup>9</sup>	minutes	65	
Biological growth <sup>10</sup>			Zero content
FAME <sup>11</sup>	% v/v		5
Other biofuels <sup>12</sup>	% v/v		<sup>12</sup>
Ethanol/Methanol	% v/v		Non-detectable <sup>13</sup>
Total acid number	mg KOH/g		0.08
Ferrous corrosion			Light rusting
Copper corrosion	rating		Class 1
Ash	% m/m		0.01
Particulate contamination, total	see test method		10
Particulate contamination, size distribution	code rating		18/16/13 per ISO 4406
Appearance		Clear and bright; no free water or particulates	
Injector cleanliness (Method 1)	% air flow loss		85
Lubricity (HFRR wear scar dia. @ 60°C)	micron		460

<sup>9</sup> Fuels containing FAME must be tested with either Method 2a, Method 2b or Method 2c. Method 2c may be used for FAME-free diesel fuel.

<sup>10</sup> Alternative test methods, with appropriate limits for no biological growth, can be used.

<sup>11</sup> For FAME, both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used, the blendstock should meet the B100 Guidelines published by the WWFC Committee, and fuel pumps should be labelled accordingly.

<sup>12</sup> Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

<sup>13</sup> At or below detection limit of the test method used.

**Category 3:** Markets with more stringent requirements for emission control, such as US LEV, California LEV or ULEV, US 1998 and 2004 Heavy-Duty On-Highway, EURO 4/IV, JP 2005 or equivalent emission standards, or other market demands.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Cetane Number		53.0	
Cetane Index <sup>1</sup>		53.0 (50.0) <sup>1</sup>	
Density @ 15°C	kg/m <sup>3</sup>	815 <sup>2</sup>	840
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>3</sup>	4.0
Sulphur	mg/kg <sup>4</sup>		50
Trace metal <sup>5</sup>	mg/kg		Non-detectable
Total aromatics	% m/m		2.0
PAH (di+, tri+)	% m/m		3.0
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 or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature <sup>7</sup>
Water	mg/kg		200 <sup>8</sup>

<sup>1</sup> Cetane Index is acceptable instead of Cetane Number if cetane improvers are not used. When cetane improvers are used, the estimated Cetane Number must meet the specified value and the Cetane Index must meet the number in parenthesis.

<sup>2</sup> May relax minimum limit to 800 kg/m<sup>3</sup> for fuels used in low temperature conditions (cloud point below -10°C).

<sup>3</sup> May relax minimum limit to 1.5 mm<sup>2</sup>/s when ambient temperatures are below -30°C or to 1.3 mm<sup>2</sup>/s when ambient temperatures are below -40°C.

<sup>4</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>5</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No intentional addition of metal-based additives is allowed.

<sup>6</sup> Compliance with either T90 or T95 is required.

<sup>7</sup> If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point

<sup>8</sup> May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.



PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability			
Method 1	g/m <sup>3</sup>		25
Method 2a (Rancimat, modified) <sup>9</sup>	hours	35	
Method 2b (Delta TAN) <sup>9</sup> , or	mg KOH/g		0.12
Method 2c (PetroOxy) <sup>9</sup>	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth <sup>10</sup>			Zero content
FAME <sup>11</sup>	% v/v		5
Other biofuels <sup>12</sup>	% v/v		<sup>12</sup>
Ethanol/Methanol	% v/v		Non-detectable <sup>13</sup>
Total acid number	mg KOH/g		0.08
Ferrous corrosion			Light rusting
Copper corrosion	rating		Class 1
Ash	% m/m		0.01
Particulate contamination, total	see test method		10
Particulate contamination, size distribution	code rating		18/16/13 per ISO 4406
Appearance		Clear and bright; no free water or particulates	
Injector cleanliness (Method 1)	% air flow loss		85
Filter blocking tendency			1.6
Lubricity (HFRR wear scar dia. @ 60°C)	micron		460

<sup>9</sup> Fuels containing FAME must be tested using either Method 2a, Method 2b or Method 2c. Method 2c may be used for FAME-free diesel fuel.

<sup>10</sup> Alternative test methods, with appropriate limits for "no biological growth," can be used.

<sup>11</sup> For FAME, both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used, the blendstock should meet the B100 Guidelines published by the WWFC Committee, and fuel pumps should be labelled accordingly.

<sup>12</sup> Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

<sup>13</sup> At or below detection limit of the test method used.

**Category 4:** Markets with advanced requirements for emission control, such as US Tier 2, US Tier 3, California LEV II, US 2007/2010 Heavy-duty On-Highway, US Non-Road Tier 4, EURO 4/IV, EURO 5/V, EURO 6/6b, EURO VI, JP 2009 or equivalent emission standards, or other market demands. Enables sophisticated NO<sub>x</sub> and PM after-treatment technologies.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Cetane Number		55.0	
Cetane Index <sup>1</sup>		55.0 (52.0) <sup>1</sup>	
Density @ 15°C	kg/m <sup>3</sup>	815 <sup>2</sup>	840
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>3</sup>	4.0
Sulphur	mg/kg <sup>4</sup>		10
Trace metal <sup>5</sup>	mg/kg		Non-detectable
Chlorine	mg/kg		Non-detectable
Total aromatics	% m/m		15
PAH (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 or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature <sup>7</sup>
Water	mg/kg		200 <sup>8</sup>

<sup>1</sup> Cetane Index is acceptable instead of Cetane Number if Cetane improvers are not used. When Cetane improvers are used, the estimated Cetane Number must meet the specified value and the Cetane Index must meet the number in parenthesis.

<sup>2</sup> May relax the minimum limit to 800 kg/m<sup>3</sup> for fuels used in low temperature conditions (cloud point below -10°C).

<sup>3</sup> May relax the minimum limit to 1.5 mm<sup>2</sup>/s when ambient temperatures are below -30°C or to 1.3 mm<sup>2</sup>/s when ambient temperatures are below -40°C.

<sup>4</sup> The unit 'mg/kg' is often expressed as ppm.

<sup>5</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No intentional addition of metal-based additives is allowed.

<sup>6</sup> Compliance with either T90 or T95 is required.

<sup>7</sup> If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

<sup>8</sup> May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability			
Method 2a (Rancimat, modified) <sup>9</sup>	hours	35	
Method 2b (Delta TAN) <sup>9</sup> , or	mg KOH/g		0.12
Method 2c (PetroOxy) <sup>9</sup>	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth			Zero content
FAME <sup>10</sup>	% v/v		5
Other biofuels <sup>11</sup>	% v/v		<sup>11</sup>
Ethanol/Methanol	% v/v		Non-detectable <sup>12</sup>
Total acid number	mg KOH/g		0.08
Ferrous corrosion			Light rusting
Copper corrosion	rating		Class 1
Ash	% m/m		0.001
Particulate contamination, total	see test method		10
Particulate contamination, size distribution	code rating		18/16/13 per ISO 4406
Appearance		Clear and bright; no free water or particulates	
Injector cleanliness (Method 2) or	% power loss		2
Injector cleanliness (Method 3)	Rank (demerits scale)	9	
Filter blocking tendency			1.6
Lubricity (HFRR wear scar dia. @ 60°C)	micron		400

<sup>9</sup> Fuels containing FAME must be tested using either Method 2a, Method 2b or Method 2c. Method 2c may be used for FAME-free diesel fuel.

<sup>10</sup> For FAME, both EN14214 and ASTM D6751, or equivalent standards, should be considered. Where FAME is used, the blendstock should meet the B100 Guidelines published by the WWFC Committee, and fuel pumps should be labelled accordingly.

<sup>11</sup> Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

<sup>12</sup> At or below detection limit of the test method used.

**Category 5:** Markets with highly advanced requirements for emission control (including GHG) and fuel efficiency, such as US Tier 3 Bin 5, US 2017-2021 light duty fuel economy, US Heavy Duty Fuel Efficiency/GHG Emission, California LEV III and as amended, US 2007/2010 Heavy-duty On-Highway, US Non-Road Tier 4, Euro 6c, Euro 6dTEMP, Euro 6d, EU CO<sub>2</sub> target 120 g/km, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category is intended to minimize real driving emissions (RDE) required for Euro 6d TEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023). Enables sophisticated NO<sub>x</sub> and PM after-treatment technologies.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Cetane Number		55.0	
Cetane Index <sup>1</sup>		55.0 (52.0) <sup>1</sup>	
Density @ 15°C	kg/m <sup>3</sup>	815 <sup>2</sup>	840
Viscosity @ 40°C	mm <sup>2</sup> /s	2.0 <sup>3</sup>	4.0
Sulphur	mg/kg <sup>4</sup>		10
Trace metal <sup>5</sup>	mg/kg		Non-detectable
Chlorine	mg/kg		Non-detectable
Total aromatics	% m/m		15
PAH (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 or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature <sup>7</sup>
Water	mg/kg		200 <sup>8</sup>

<sup>1</sup> Cetane Index is acceptable instead of Cetane Number if cetane improvers are not used. When cetane improvers are used, the estimated Cetane Number must meet the specified value and the Cetane Index must meet the number in parenthesis.

<sup>2</sup> May relax the minimum limit to 800 kg/m<sup>3</sup> for fuel used in low temperature conditions (cloud point below -10°C).

<sup>3</sup> May relax the minimum to 1.5 mm<sup>2</sup>/s when ambient temperatures are below -30°C or to 1.3 mm<sup>2</sup>/s when ambient temperatures are below -40°C.

<sup>4</sup> The unit mg/kg is often expressed as ppm.

<sup>5</sup> Examples of trace metals include, but are not limited to, Cu, Fe, Mn, Na, P, Pb, Si and Zn. No intentional addition of metal-based additives is allowed.

<sup>6</sup> Compliance with either T90 or T95 is required.

<sup>7</sup> If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point.

<sup>8</sup> May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability			
Method 2c (PetroOxy)	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth			Zero content
FAME			Non-detectable
Other biofuels <sup>9</sup>			
Ethanol/Methanol	% v/v		Non-detectable <sup>10</sup>
Total acid number (TAN)	mg KOH/g		0.08
Ferrous corrosion			Light rusting
Copper corrosion	rating		Class 1
Ash	% m/m		0.001
Particulate contamination, total	see test method		10
Particulate contamination, size distribution	code rating		18/16/13 per ISO 4406
Appearance		Clear and bright; no free water or particulates	
Injector cleanliness (Method 2) or	% power loss		2
Injector cleanliness (Method 3)	Rank (demerits scale)	9	
Filter blocking tendency			1.6
Lubricity (HFRR wear scar dia. @ 60°C)	micron		400

<sup>9</sup> Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

<sup>10</sup> At or below detection limit of the test method used.

The latest test methods should be used unless otherwise indicated by specific method year. 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	D613	K 2280	D6890, D7170 <sup>1</sup> EN 16906 <sup>1</sup>
Cetane Index		4264	D4737	K 2280	
Density @ 15°C	kg/m <sup>3</sup>	3675	D4052	K 2249	
		12185			
Viscosity @ 40°C	mm <sup>2</sup> /s	3104	D445	K 2283	
Sulphur	mg/kg	20846	D5453	K 2541	
		20884	D2622		
Total aromatic	% m/m		D5186		EN 12916
PAH (di+, tri+)	% m/m		D5186		EN 12916, D2425
T90, T95, FBP	°C	3405, 3924	D86	K 2254	D2887
Flash point	°C	2719	D93	K 2265	D56
Carbon residue	% m/m	10370	D4530	K 2270	
Cold Filter Plugging Point (CFPP)	°C		D6371	K 2288	EN 116, IP 309
Low Temperature Flow Test (LTFT)	°C		D4539		
Cloud Point (CP)	°C	3015	D2500	K 2269	D5771, D5772, D5773
Water	mg/kg	12937	D6304	K 2275	
Haze clarity index (HCI)			D8148		
Oxidation stability					
Method 1	g/m <sup>3</sup>		D6468		
Method 2a (Rancimat, modified)	induction time (hours)				EN 15751
Method 2b (Delta TAN) <sup>2</sup>	mg KOH/g		D664 & D2274 (modified)		
Method 2c (PetroOxy) <sup>3</sup>	minutes		D7545		EN 16091
Foam volume	ml				NF M 07-075
Foam vanishing time	sec.				NF M 07-075

<sup>1</sup> ASTM D6890 and D7170 and EN 16906 measure Derived Cetane Number (DCN) and are being widely used as alternatives to D613.

<sup>2</sup> Measure Acid Number using D664 before and after aging fuel per D2274 (modified – 115°C).

<sup>3</sup> Method 2c correlation data are based on fuels containing FAME, but the method may be used for FAME-free diesel fuel.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Biological growth					NF M 07-070, IP385 <sup>4</sup>
FAME	% v/v		D7371		EN 14078
Ethanol/Methanol	% v/v		D4815 (modified)		
Total acid number (TAN)	mg KOH/g	6618	D664	K 2501	
Ferrous corrosion			D665 Procedure A		
Copper corrosion	merit	2160	D130	K 2513	
Appearance			D4176		Visual inspection
Ash <sup>5</sup>	% m/m	6245	D482 <sup>6</sup>	K 2272	
Particulate contamination, total	see test method		D6217 FAME-free (mg/l)		EN 12662 (mg/kg)
			D7321 with FAME (mg/l)		
Particulate contamination, size distribution	code rating	4406	D7619		
	no. of particles/ml	4407 & 11500			
Injector cleanliness, Method 1	% air flow loss				CEC (PF-023) TBA
Injector cleanliness, Method 2	% power loss				CEC-F-098
Injector cleanliness, Method 3	Rank (demerits scale)				CEC-F-110-16 <sup>7</sup>
Filter Blocking Tendency			D2068 Procedure B		
Lubricity (HFRR wear scar diameter @ 60°C)	micron	12156-1.3	D6079		CEC F-06-A, D7688
Trace metal					ICP, D7111 modified
Chlorine	mg/kg		D7359 or D7536		

<sup>4</sup> Alternative test methods, with appropriate limits for "no biological growth," can be used.

<sup>5</sup> Limit and test method are under review to assure DPF endurance.

<sup>6</sup> Minimum 100 g sample size.

<sup>7</sup> Also known as DW10C.

## DIESEL FUEL TECHNICAL BACKGROUND

### Cetane

Cetane is a measure of the compression ignition behaviour of a diesel fuel; higher cetane levels enable quicker ignition. Cetane influences cold startability, exhaust emissions and combustion noise, with the magnitude of the impact depending on the overall combustion and emission control strategies and their application. In general, higher cetane enables improved control of ignition delay and combustion stability, especially with modern diesels which use high amounts of exhaust gas recirculation (EGR). It does this by providing room for engine calibrators to tailor combustion for the best calibration compromise among combustion noise, emissions and fuel consumption goals across the engine operating range. Additives can enhance a fuel's cetane level; natural cetane refers to the cetane level when the fuel contains no additives, and artificial cetane refers to the cetane level in an additized fuel. Cetane levels achieved through additives affect vehicle performance differently than natural cetane levels, and sometimes they produce inconsistent results.

Cetane is measured or derived in various ways. The cetane number is produced by testing the fuel in a test engine (ASTM D613). When the fuel does not contain any cetane improver, the cetane number is the same as the fuel's natural cetane. The derived cetane number, which is produced using a combustion tester (see ASTM D6890 and D7170), is an indirect measure of combustion ignition behaviour that is equated to the cetane number. The cetane index (ASTM D4737) is calculated from certain measured fuel properties (fuel density and distillation temperatures); it is designed to approximate the natural cetane. Since the cetane number and the derived cetane number are measured by combusting the fuel, both may reflect the effects of cetane improver additives; by contrast, the cetane index does not. To avoid excessive additive dosage, the maximum difference between the cetane index and the cetane number must be maintained as specified in the various category tables. Use of cetane improver additives to increase cetane more than 10 numbers over the natural cetane is not recommended. Concern exists regarding potential emission or other impacts of fuel containing an excessive amount of cetane additive; more research is needed. Blending with high cetane fuels, such as renewable hydrocarbon diesel, is the preferred approach for increasing cetane.

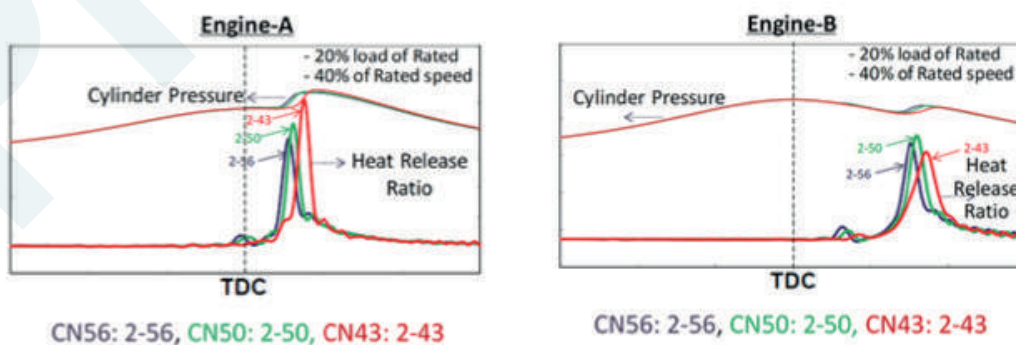
#### Influence of Cetane on Cold Startability

Increasing the 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. A shorter cranking cycle means fewer cycles with incomplete or partial combustion during 'crank to run' operation, and this leads to improved combustion stability and lower noise, vibration and harshness (NVH).

#### Cetane Influence on Combustion and Exhaust Emissions

A recent JATOP-II program studied the impact of cetane number on combustion using the same medium duty base engines with different applications and found differences in cylinder pressure and calculated heat release ratio. The study also examined the fuel impact on exhaust emissions (using the JE05 HD emission cycle) and found differences in NO<sub>x</sub> emission trends. In the case of engine A, for example, the crank angle at peak of heat release was relatively close to top dead center (TDC), resulting in a significant impact on peak of heat release. This effect, in turn, caused NO<sub>x</sub> to significantly increase. In the case of engine B, by contrast, the crank angle at peak of heat release ratio was comparatively later than in engine A, causing a very small cetane impact on the peak of heat release. See Figure DF-1.

Figure DF-1: Cetane Number's Impact on Combustion in Two Engines

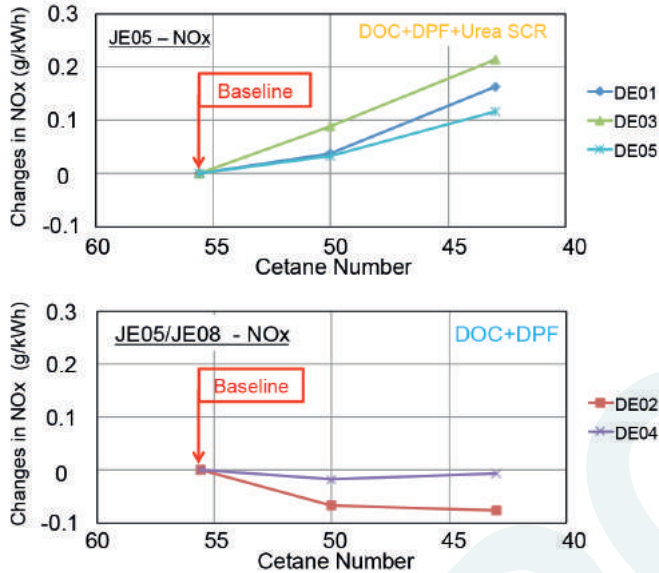


Source: JATOP II, 2015



The same JATOP-II study examined the influence of cetane on engine-out NO<sub>x</sub>, verifying the effect in JE05 mode using 2009 JP compliant engines. It found that, when the cetane number was decreased, engine-out NO<sub>x</sub> increased in vehicles equipped with emission control equipment (DOC, DPF and SCR) whereas engines without SCR did not. See Figure DF-2. This can be explained by the fact that the injection timing of each engine group differed because of the impact of the after-treatment system on the combustion design, and injection timing affects the sensitivity of engine-out NO<sub>x</sub> to cetane.

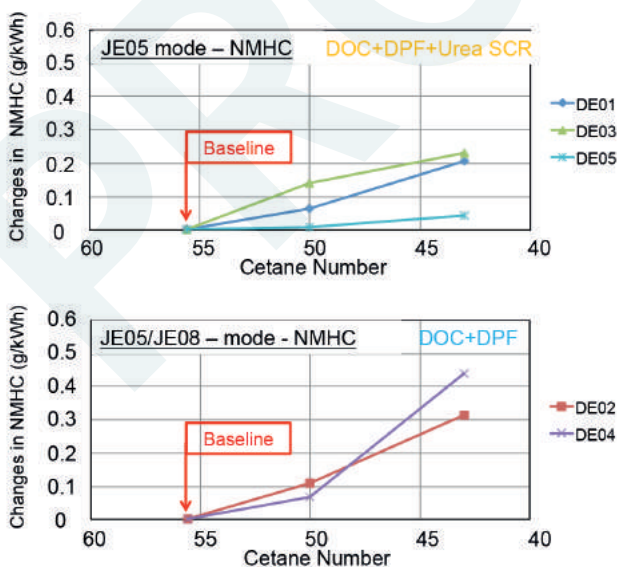
Figure DF - 2: Influence of Cetane Number on Engine Out NO<sub>x</sub> (2009 JP compliant engines/vehicles)



Source: Produced by JAMA using published data from JATOP II

Similarly, cetane was found to influence engine-out non-methane hydrocarbon (NMHC) emissions, again verifying the effect in JE05 mode using 2009 JP compliant engines. See Figure DF-3. It found all the tested engines showing a tendency to have higher engine-out NMHC when the cetane number was decreased. This can be explained by the longer ignition delay and delay in the start of combustion with lower cetane diesel fuel. As a result, the actual combustion with lower cetane fuel occurs later than combustion with higher cetane fuel, and the combustion misses the “hot spot” timing for better combustion. The delayed combustion means that some of the injected fuel is not burned and exits the engine as NMHC.

Figure DF - 3: Influence of Cetane Number on Engine-Out NMHC (2009 JP compliant engines/vehicles)

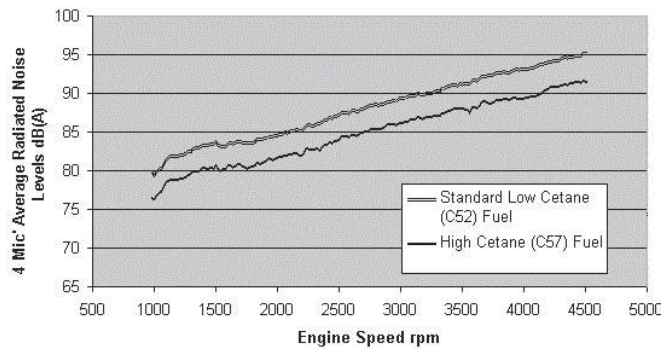


Source: Produced by JAMA using published data from JATOP II

### Cetane Influence on Combustion Noise

Increased cetane will also reduce noise, as demonstrated by the results shown here (Figure DF-4). In this case, natural and artificial cetane have similar effects.

Figure DF-4: Effect of Cetane on Engine Noise, 52 to 57 CN



Source: Ford, 2004

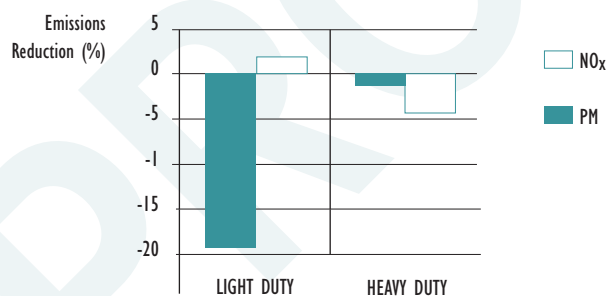
## Density And Viscosity

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 found that fuel density also influences injection timing of mechanically controlled injection equipment, which also affects 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 Engine Power

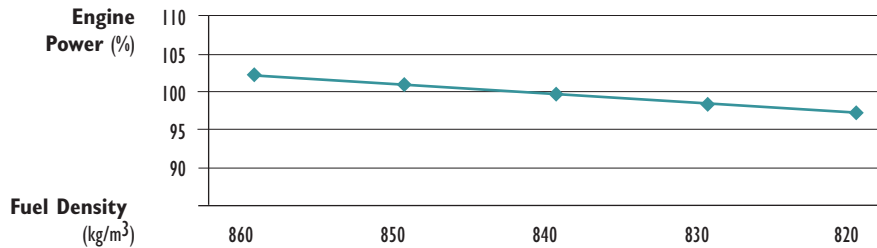
Emission testing has demonstrated that reduced density will reduce PM emissions from all diesel vehicles, and NO<sub>x</sub> emissions from heavy-duty vehicles (Figure DF-5).

Figure DF-5: Effect of Density on Exhaust Emissions 855 to 828 kg/m<sup>3</sup>



Source: EPEFE Report

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 lowering fuel density decreases engine power output (Figure DF-6) 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 DF - 6: Effect of Density on Engine Power 855 to 828 kg/m<sup>3</sup>

Source: EPEFE Report

#### 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 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

Fuelling and injection timing are also dependent on fuel viscosity. High viscosity can reduce fuel flow rates, resulting in inadequate fuelling. 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.

## Sulphur

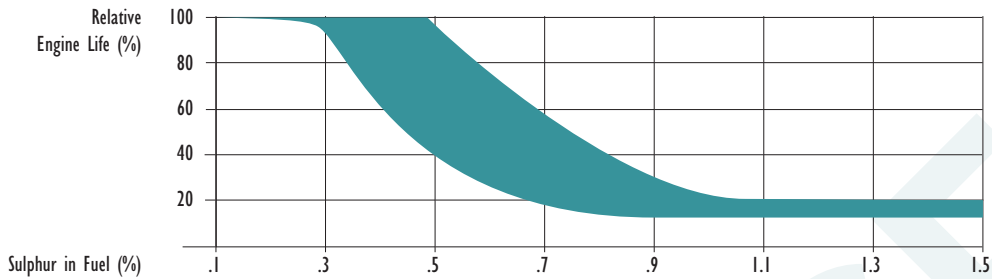
Sulphur naturally occurs in crude oil. If the sulphur is not removed during the refining process, it will remain in the vehicle fuel. Cross-contamination also can occur in the fuel distribution system. Fuel sulphur has a variety of adverse impacts, however, and should be reduced to levels that are compatible with engine and vehicle technology and designs. For example, sulphur can significantly reduce engine life by increasing corrosion and wear of engine systems. Diesel fuel sulphur also contributes significantly to fine particulate matter (PM) emissions, through the formation of sulphates both in the exhaust stream and later in the atmosphere. Furthermore, the efficiency of exhaust after-treatment systems designed to reduce both NO<sub>x</sub> and PM emissions is reduced or rendered permanently ineffective through sulphur poisoning as the fuel sulphur content increases.

As sulphur levels are reduced, fuel stability requires special attention. The industry has developed 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 by oxidised products (sludge). 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.

#### Impact on Engine/Vehicle Durability

At the most basic level, fuel sulphur can be converted into sulphuric acid inside the powertrain. Sulphuric acid is a very powerful and corrosive acid that will attack any metal components with which it comes into contact. Figure DF-7 shows how relative engine life decreases as the fuel sulphur level increases.

Figure DF-7: Effect of Sulphur on Engine Life



Source: Detroit Diesel

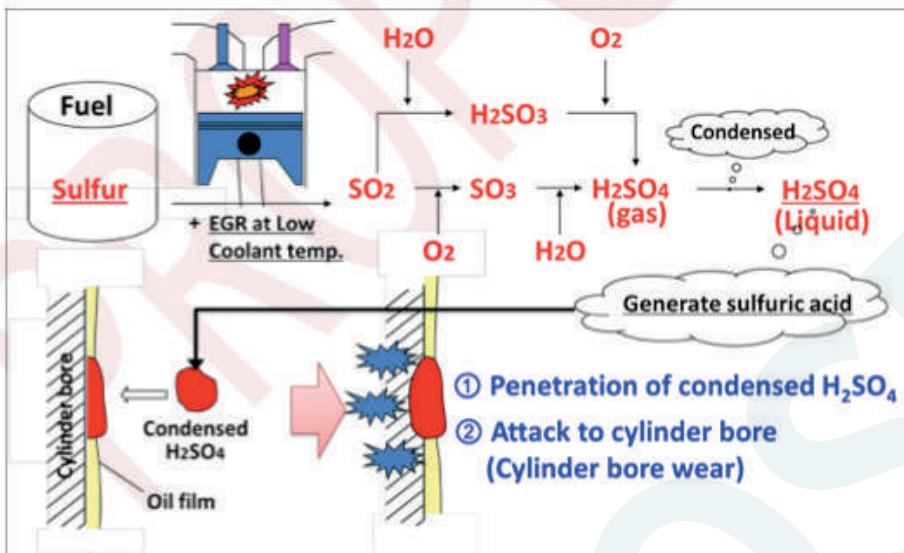
Moving beyond the engine, vehicles and engines meeting Euro 4, U.S. 1998 Heavy Duty On-Highway and more stringent emission standards have EGR and EGR cooler technology to meet NO<sub>x</sub> emission standards. These technologies require diesel fuel with a low enough sulphur level to maintain proper vehicle operation. Fuel sulphur oxidizes to sulphates during combustion, and some portion of that oxidized sulphur will react with water and be converted to sulphuric acid. Exhaust gas that contains sulphuric acid will move through the EGR system; when it reaches the EGR cooler, the gas temperature drops rapidly, causing acidic condensate to form. This acid will flow back into the engine as well as move through the exhaust system. When the engine shuts down, some acid will remain in the engine, causing rust and corrosion on the interior surfaces. Very little time is needed—even a short overnight period—for corrosion to begin. At this point, the cylinder bore surface is already damaged, and repeating this cycle will significantly shorten engine life. Figure DF-8 shows beads of acidic water condensate on the internal surface of an engine. The overall mechanism is described below in Figure DF-9.

Figure DF-8: Acidic Condensate Beads on a Cylinder Bore



Source: Hino

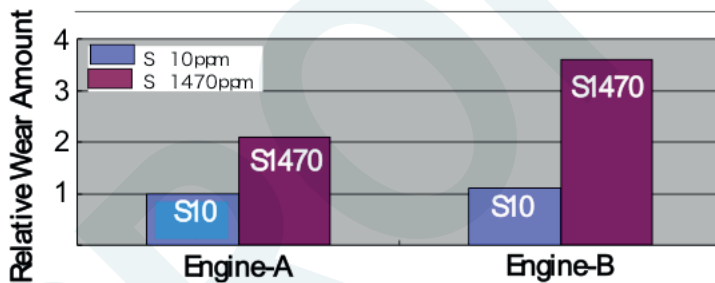
Figure DF-9: Mechanism of Sulphuric Acid Attack



Source: Toyota

One study of engine endurance testing with diesel fuels containing either 10 ppm or 1470 ppm sulphur found much greater engine wear with the high sulphur fuel compared to the 10 ppm sulphur fuel. After 1000 hours of testing with two different displacement engines, engine A showed twice the relative wear on the high sulphur fuel as on the low sulphur fuel, while engine B showed more than three times as much wear. The results of this study are shown in Figure DF-10.

Figure DF-10: Relative Cylinder Bore Wear in Endurance Test with High and Low Sulphur Fuels

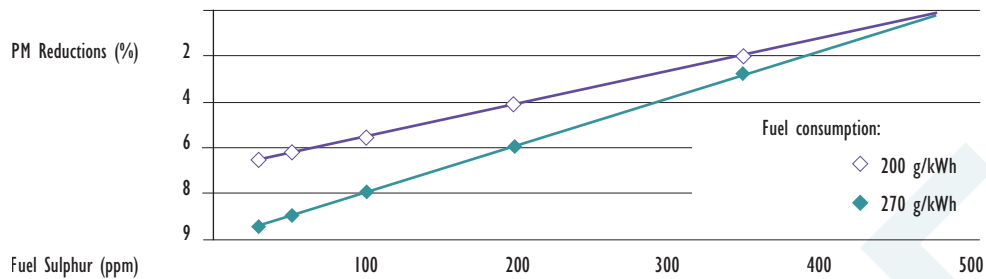


Source: Hino

#### How Sulphur Increases Particulate Emissions

The impact of sulphur on particulate emissions is widely understood and known to be significant. In the European Auto Oil programme, it was predicted that a reduction in sulphur from 500 ppm to 30 ppm would 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 sulphur levels. This correction suggests that the real benefit from sulphur reductions will be more significant, as shown here (Figure DF-11) for heavy-duty trucks. Reductions in fuel sulphur will also provide particulate emission reductions in all engines, regardless of emission calibration.

Figure DF - 11: Effect of Diesel Fuel Sulphur Level on PM Emissions Heavy-Duty Engines (PM = 0,10 g/kWh)



Source: ACEA Report: Influence of Diesel Fuel Quality on Heavy Duty Diesel Engine Emissions, March 1997

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 sulphur fuel were about double the emissions when operating on 2 ppm sulphur fuel. (JSAE 9831171)

When sulphur is oxidised during combustion, it forms  $\text{SO}_2$ , which is the primary sulphur compound emitted from the engine. Some of the  $\text{SO}_2$  is further oxidised — in the engine, exhaust, catalyst or atmosphere — to sulphate ( $\text{SO}_4$ ). The sulphate and nearby water molecules often coalesce to form aerosols or engulf nearby carbon to form heavier particulates that have a significant influence on both fine and total PM. Without oxidation catalyst systems, the conversion rate from sulphur to sulphate is very low, typically around 1%, so the historical sulphate contribution to engine-out PM has been negligible. However, oxidation catalysts dramatically increase the conversion rate to as much as 100%, depending on catalyst efficiency. Therefore, for modern vehicle systems, most of which include oxidation catalysts, a large proportion of the engine-out  $\text{SO}_2$  will be oxidized to  $\text{SO}_4$ , increasing the amount of PM emitted from the vehicle. Thus, fuel sulphur will have a significant impact on fine particulate emissions in direct proportion to the amount of sulphur in the fuel.

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

- The fuel consumption of the engine
- The fuel sulphur content
- The S to  $\text{SO}_4$  conversion rate

Both the fuel sulphur content and fuel consumption are measurable parameters; the conversion rate is predicted based on engine variability and the use of an oxidation catalyst. The following equation can provide an estimate of the impact:

Equation DF-1: Brake-Specific Sulphate

$$\text{BSSO}_4 = \text{BSFC} * \text{FSC}/100 * \text{PCSC}/100 * 7$$

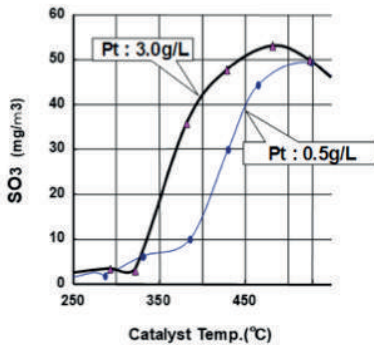
Where:

- $\text{BSSO}_4$  = Brake specific sulphate (mass/brake power-hour)
- $\text{BSFC}$  = Brake specific fuel consumption (g/kWh)
- $\text{FSC}$  = Fuel sulphur content (% mass)
- $\text{PCSC}$  = Percent sulphur conversion (to  $\text{SO}_4$ )
- 7 = Weight increase factor for S to ( $\text{SO}_4$  + water)

Diesel-powered vehicles commonly use highly advanced diesel oxidation catalyst (DOC) technology as part of their emission control system for meeting Euro 4, U.S. 1998 Heavy-Duty On-Highway and more stringent standard requirements. The DOC works by further oxidizing exhaust gases, such as CO and HC. To the extent the fuel also contains sulphur, some of it is oxidized inside the engine, sending both sulphur and sulphate to the emission control system. The sulphates can become absorbed by the DOC, which poisons its reactive surfaces. Poisoned DOCs have a reduced capability of controlling the CO and HC in the exhaust stream. Importantly, to the extent it is not poisoned, the DOC will also continue to oxidize any sulphur and sulphates in the exhaust stream. Oxidized sulphur in the form of sulphate is then emitted to the atmosphere as very fine particulate matter.

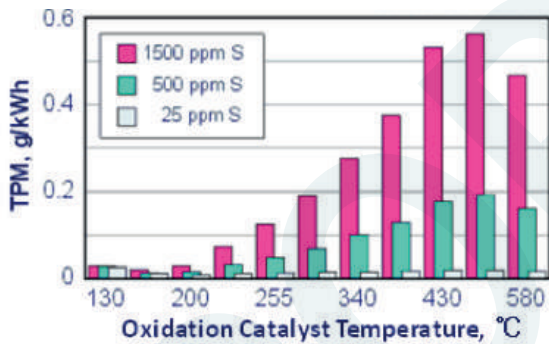
The DOC also serves an additional critical role in highly advanced emission control systems where it is used to generate heat for other aftertreatment components, such as the diesel particulate filter (DPF) and selective catalytic reduction (SCR) devices which remove particulate and NO<sub>x</sub>, respectively, to enable them to work properly and efficiently. If the DOC is poisoned by sulphur, however, it cannot fulfil this function. As a result, the DPF fails to burn off the PM deposited on its surface (in other words, it cannot regenerate itself) and the SCR ability to reduce NO<sub>x</sub> (its conversion efficiency) is greatly decreased. Catalyst composition and exhaust gas temperatures play a significant role in the formation of sulphur oxides (SO<sub>x</sub>), which make fine particulates, and in the interaction between fuel sulphur levels and particulate emissions, as shown in Figure DF-12 and Figure DF-13, below.

Figure DF-12: Example of SO<sub>3</sub> Amount after DOC, by Catalyst Temperature



Source: Toyota

Figure DF-13: Example of Total PM Emission by Catalyst Temperature



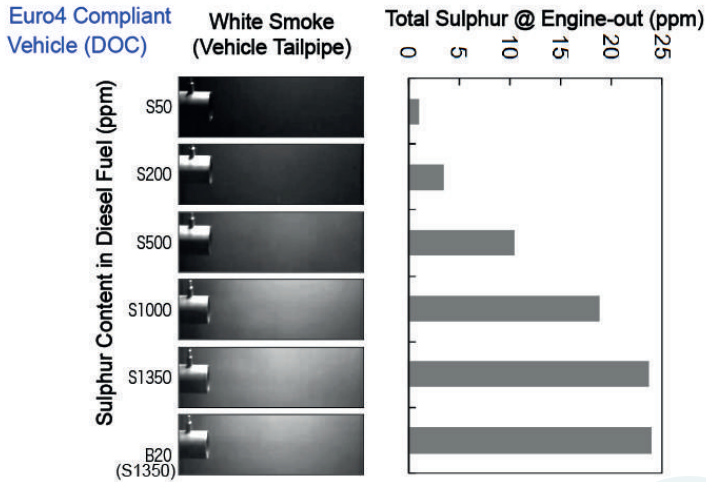
Another effect of fuel sulphur on the DOC is the increased production of white smoke. When high sulphur content diesel fuel is used in vehicles equipped with DOCs, white smoke can be seen at the tailpipe under normal driving conditions. As explained above, the sulphur oxidizes to SO<sub>2</sub> and SO<sub>3</sub> during combustion and at the DOC. These sulphates are absorbed onto the DOC at low temperatures, but when temperatures rise again, these particles desorb from the DOC, become entrained in the exhaust gas and are observed at the tailpipe as visible white smoke, as shown below in Figure DF-14 and Figure DF-15. Figure DF-16 further shows how the visibility changes with fuel sulphur level, using a device that measures luminosity.

Figure DF-14: Example of White Smoke from Tailpipe



Source: 2017 JAMA Research Project

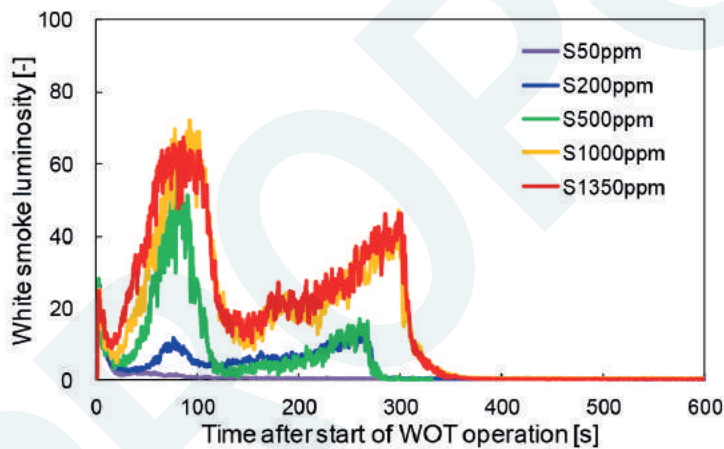
Figure DF - 15: White Smoke/Total Sulphur in Exhaust vs Sulphur Content in Diesel Fuel



Source: 2017 JAMA Research Project

Figure DF - 16: White Smoke Luminosity at Different Sulphur Levels

Euro4 Compliant Vehicle (DOC)



Source: 2017 JAMA Research Project

#### Sulphur's Impact on Highly Advanced Diesel Emission Control Systems

No single device can simultaneously reduce NO<sub>x</sub>, PM, HC and other emissions from diesel engines. Furthermore, tradeoffs historically have been required between and among emissions and fuel economy, especially for markets with higher sulphur diesel fuel. To meet the requirements of many regulations, highly advanced emission control systems have been developed around combinations of engine and aftertreatment devices. Sulphur has a particularly strong impact on these NO<sub>x</sub> controls, and many will stop working if the sulphur level becomes too high. Thus, these systems require low or ultra-low sulphur fuels to maintain their operational capability.

The most advanced of these technologies includes De-NO<sub>x</sub> catalyst systems, such as Lean NO<sub>x</sub> traps (LNT) (also known as NO<sub>x</sub> adsorbers,) and Selective Catalytic Reduction (SCR) devices, which can remove a greater amount of NO<sub>x</sub> emissions from the diesel's oxygen-rich exhaust than previously possible. Highly advanced particulate filters also have been developed to reduce PM emissions. Many of these devices are combined in various configurations to enable the vehicle to meet specific emission standards and to minimize impacts on fuel efficiency. Diesel oxidation catalysts (DOC), which reduce HC and CO emissions, and exhaust gas recirculation (EGR) systems, which reduce NO<sub>x</sub>, are among the proven technologies that may be used in conjunction with newer technologies. More importantly, all emission control systems perform better and last longer with sulphur-free fuel.



The Diesel Emission Control-Sulphur Effects (DECSE) project, a collaborative program conducted by the US Department of Energy (DOE), Truck and Engine Manufacturers Association (EMA) and Manufacturers of Emission Controls Association (MECA), studied the impact of diesel fuel sulphur levels of 3, 16, 30, 150 and 350 ppm on a number of these technologies on both heavy-duty and light-duty engines. Reference: [www.ott.doe.gov/decse](http://www.ott.doe.gov/decse).

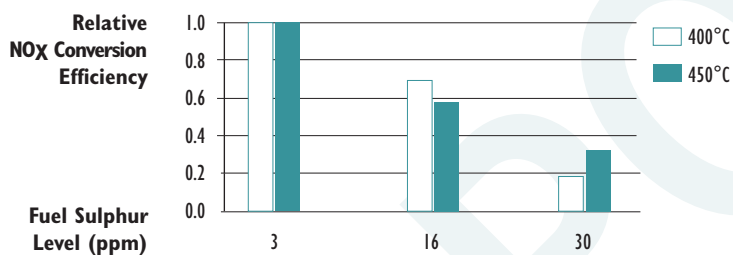
The Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC) Program, another collaborative effort, identified optimal combinations of low-sulphur diesel fuels, lubricants, diesel engines and emission control systems to meet projected emission standards for the 2001 to 2010 time period. Reference: <http://www.ott.doe.gov/apbf.shtml>.

### NO<sub>x</sub> Adsorber (Lean NO<sub>x</sub> Trap)

NO<sub>x</sub> adsorbers are poisoned and rendered ineffective by the presence of sulphur. These devices can be up to 90% efficient in NO<sub>x</sub> removal if operated on sulphur-free fuel. The SO<sub>2</sub> formed during combustion and released in the exhaust undergoes reactions in these devices that are similar to those of NO<sub>x</sub>, but the oxidized sulphur compounds adsorb more strongly to the catalyst surface than the NO<sub>x</sub>, thereby poisoning the catalyst.

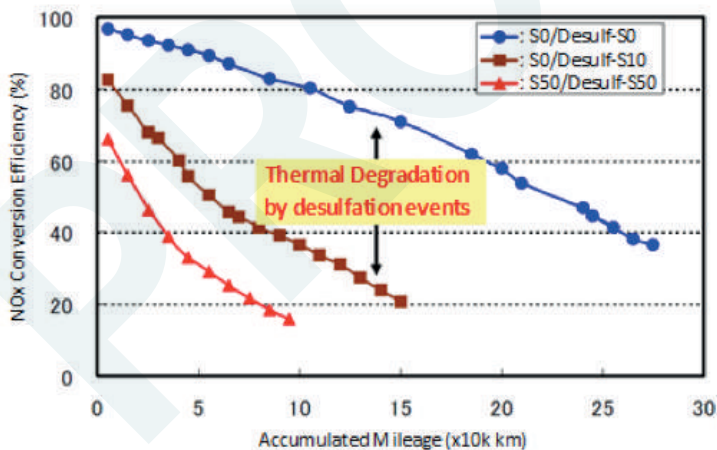
The effect of fuel sulphur content on NO<sub>x</sub> adsorber conversion efficiency is shown in Figure DF-17 below. The figure illustrates the effect of fuel sulphur on relative NO<sub>x</sub> conversion efficiencies. Compared to 3 ppm sulphur fuel, both 16 and 30 ppm sulphur fuels resulted in a significant decline in performance. Importantly, the need to desulphurize the adsorber occurs more frequently as the sulphur level in the fuel increases, with correspondingly quicker deterioration of LNT, as shown in Figure DF-18.

Figure DF-17: Effect of Fuel Sulphur Level on NO<sub>x</sub> Conversion Efficiency (150 Hours Aging)



Source: DECSE Program, Phase 1, Number 2, October 1999, US DOE/EMA

Figure DF-18: Desulphurization Frequency Increases LNT Deterioration



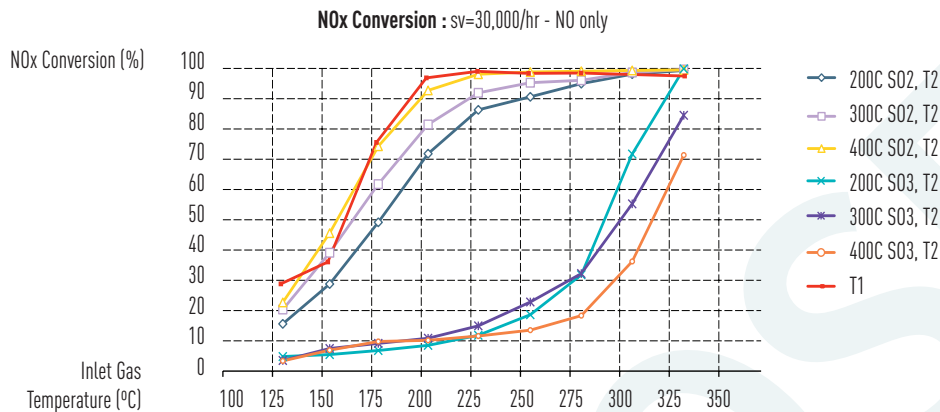
Source: JCAP

### Selective Catalytic Reduction

Selective Catalytic Reduction (SCR) emission control devices, which are being used on both light-duty and heavy-duty vehicles, are catalysts that work in conjunction with a specially formulated reactant (called Diesel Exhaust Fluid (DEF) in the U.S.) to convert NO<sub>x</sub> into nitrogen and water vapour. Like other catalysts, the effectiveness and durability of SCR systems can be adversely affected by fuel sulphur.

The impact is exacerbated by the use of a diesel oxidation catalyst (DOC) in front of the SCR because DOCs convert much of the exhaust  $\text{SO}_2$  to  $\text{SO}_3$ . While both  $\text{SO}_2$  and  $\text{SO}_3$  poison the SCR, research has shown  $\text{SO}_3$  to have a stronger impact on SCR conversion efficiency. Figure DF-19 shows how  $\text{SO}_2$  and  $\text{SO}_3$  affect  $\text{NO}_x$  conversion in SCRs at different temperatures (also see SAE 2009-01-0898).

Figure DF-19: Impact of  $\text{SO}_x$  on SCR Activity



Source: Ford & Pacific Northwest National Laboratory, 2009

### Diesel Particulate Filter

The Diesel Particulate Filter (DPF), which first appeared in the market on production vehicles in mid-2000, allows vehicles to achieve extremely low particulate emissions. The filtration of exhaust gas particulates has been possible for many years, but the disposal of the accumulated particulate has remained a difficult problem to solve. Apart from removing the filter frequently for cleaning (which is not allowed in the U.S.), a reliable and cost-effective system of on-board filter regeneration by combustion of the particulate was previously not available.

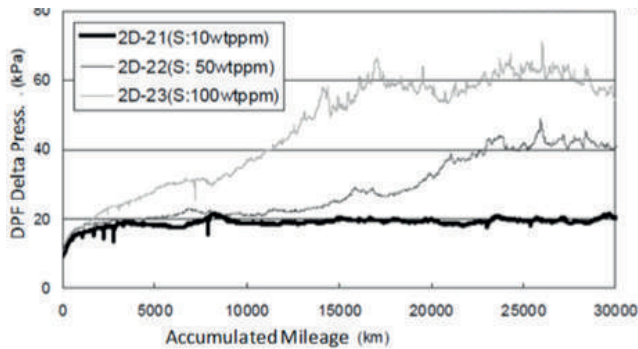
The latest generation of common rail engines with their electronic injection strategies, however, enabled the possibility of increasing exhaust gas temperatures, which then enabled the possibility of combusting the particulate trapped on the DPF. A different strategy for regenerating filters uses a combination of catalytic additive mixed on-board with the fuel, or post-combustion fuel injection into the exhaust and an oxidation catalyst pre-filter.

The latest generation of common rail direct injection diesel engines emits 60% less particulate matter than its immediate prechamber predecessors, and when combined with a DPF system, these engines can reduce the number of particulate in the exhaust gas to the level of ambient air, which completely eliminates black smoke. What is more, this  $10^3$  - $10^4$  magnitude of reduction in particulate emissions is constant over the whole range of particulate size. Thus, using DPF systems enhances the potential of the diesel engine as a low-emitting power unit.

The sulphur contained in diesel fuel undermines this potential because it is likely to be transformed into gaseous sulphur compounds in the diesel oxidation catalyst included with the emission control system. Secondary chemical reactions may transform these compounds into sulphate particulates in the atmosphere. Therefore, the use of sulphur-free fuels in vehicles with DPF systems is highly recommended to avoid this phenomenon.

Fuel sulphur also impairs the regeneration of the DPF, thereby affecting engine/vehicle performance and fuel efficiency. When oxidized sulphur poisons the DOC, it may cause the exhaust gas temperature to be lowered to the point where the DPF cannot regenerate. As a result, DPF regeneration events are incomplete and back-pressure upstream of the DPF continuously increases during the driving cycle. This back pressure reduces the efficiency of the powertrain, affects engine/vehicle performance and lowers fuel economy. See Figure DF-20.

Figure DF -20: Impact on DPF on Exhaust Back Pressure



### Continuously Regenerating and Catalysed Diesel Particulate Filters

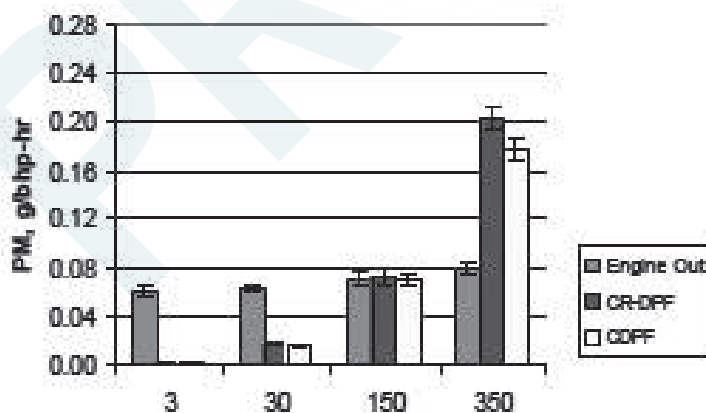
The Continuously Regenerating Diesel Particulate Filter (CR-DPF) and Catalysed Diesel Particulate Filter (CDPF) represent two different approaches to DPF regeneration.

The CR-DPF regenerates by continuously generating  $\text{NO}_2$  from engine-emitted  $\text{NO}$  over a diesel oxidation catalyst placed upstream of the DPF. Proper vehicle calibration is necessary to generate sufficient  $\text{NO}_2$  for this purpose.  $\text{NO}_2$  has been established as a more effective low-temperature oxidizing agent for diesel PM than oxygen. Sulphur in the exhaust is oxidised over the CR-DPF, however, forming sulphates that contribute to PM emissions. Sulphur oxides also compete for the critical  $\text{NO}$  and  $\text{NO}_2$  reaction sites on the DPF, making trap regeneration less effective.

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

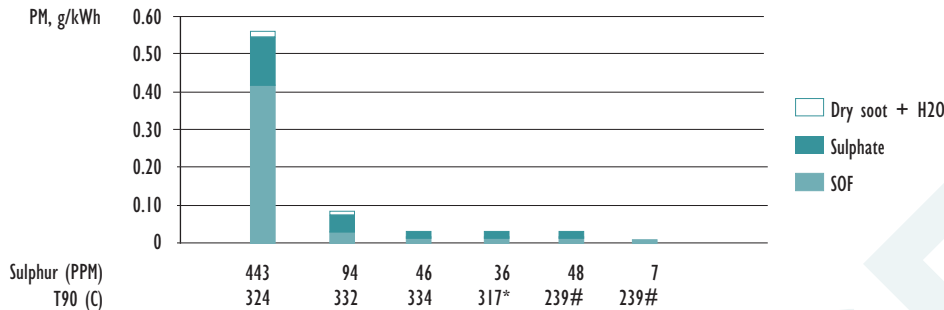
Fuel sulphur has a significant effect on PM emissions from these emission control devices. Both types of DPF effectively reduce PM emissions when fuel sulphur is very low, but when fuel sulphur increases, so do sulphate levels, which affects the amount of PM emitted. In one study, PM was reduced by 95% over the OICA cycle when the tested DPFs were used with 3-ppm sulphur fuel (Figure DF-21), but with 30-ppm sulphur fuel, the PM reduction efficiencies dropped to 72 and 74% for the CR-DPF and CDPF, respectively. At the 150-ppm sulphur test point, the sulphur content of the measured mass completely masked the reduction in carbonaceous particles, so that the measured total PM reductions were near zero. A similar outcome was seen in Japanese DPF testing (Figure DF-22).

Figure DF -21: Effect of Fuel Sulphur Level on PM Emissions - OICA Cycle



Source: DECSE Program, Phase 1, Number 3, November 1999, US DOE/EMA

Figure DF-22: Fuel Effect on Diesel Particulate-CR (Continuous Regeneration) - DPF Japan Diesel 13 Mode



Source: JCAP Report

## Ash

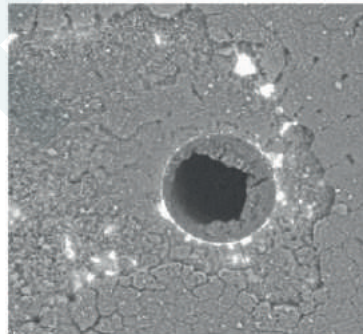
Fuel and lubricant derived ash can contribute to coking on injector nozzles (see Figure DF-23) and will have a significant effect on the life of diesel particulate filters. Ash-forming metals can be present in fuel additives, lubricant additives or as a byproduct of the refining process.

Figure DF-23: Examples of Increased Nozzle Coking Due to Metal Ion Impurities

**Restricted spray direction at spray hole outlet due to deposit build-up at nozzle tip (outside nozzle)**



**Flow restriction, especially at maximum needle lift**



Source: Bosch, 2004

Metallic ash constituents are incombustible, so when they are present in the fuel, they remain in the exhaust and become trapped within the DPF. Thus, the presence of ash-forming materials in the fuel will lead to a premature build-up of backpressure and other vehicle operability problems. Non-fuel solutions have been found unsatisfactory. Larger filters can reduce backpressure build-up but otherwise would be unnecessary and may be infeasible (for example, in smaller vehicles). Increased in-use maintenance or, in extreme cases, DPF replacement would help, but these steps may not be allowed in some markets. Therefore, keeping ash-forming compounds out of the fuel to the extent possible provides the best solution.

Ash-forming compounds may be present in fuel in four forms:

- Abrasive solids, such as suspended solids and organometallic compounds that contribute to injector, fuel pump, piston and ring wear and to the formation of engine deposits.
- Soluble metallic soaps, which have little effect on wear but may contribute to engine deposits.
- Soluble metals, which may be present in vegetable-derived fuels as a result of absorption by the plant source and inadequate removal during processing. Biodiesel fuel, for example, may contain metals that were left in the residue resulting from common catalytic production methods.
- Metals that originate in water entrained in the fuel.

Industry standards limiting ash to less than 0.01%, which were intended to protect close tolerance fuel injection equipment and reduce piston ring zone deposits, have addressed the first form of ash-forming compounds. Fuel surveys have confirmed that the ash content in most fuels has been near the detection limit of the currently available test procedure (0.001%). The remaining forms of metallic ash, however, may enter fuel during the distribution process and must be controlled before dispensing the fuel to the engine or vehicle.

Diesel fuel containing ash at the current detection limit (0.001%) may require the DPF to be serviced during the vehicle's useful life, but many jurisdictions do not allow this for Category 4 or Category 5 engines or vehicles. Therefore, ash-forming metals must be controlled to very low levels to enable these emission control devices to operate properly over the lifetime of the vehicle. To allow the appropriate level for these ash compounds, a new test procedure capable of measuring lower levels of ash in diesel fuel should be developed.

## Aromatics

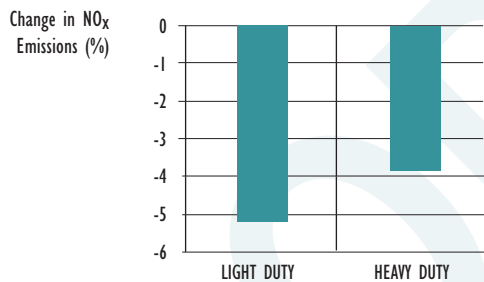
Aromatics are molecules that contain at least one benzene ring. The fuel aromatic content will affect combustion and the formation of particulate and polycyclic aromatic hydrocarbons (PAH) emissions.

The diesel fuel aromatics content influences flame temperature, and therefore, NO<sub>x</sub> emissions during the combustion. PAH in the fuel affect the formation of particulates and 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 lower NO<sub>x</sub> emissions as shown in Figure DF-24.

**Figure DF-24: Effect of Total Aromatics on NO<sub>x</sub> Emissions (30 to 10% Aromatics)**



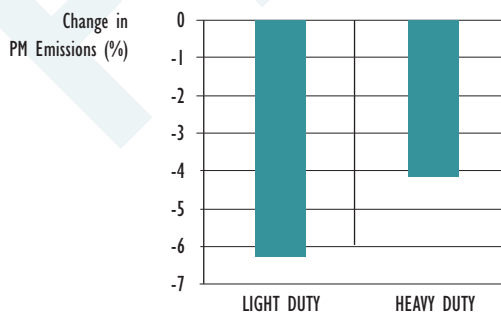
Source: ACEA Report: Influence of Diesel Fuel Quality on Heavy Duty Diesel Engine Emissions, March 1997

The light-duty data are 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 DF-25 shows the reductions of PM emissions that were measured when the polyaromatic content was reduced from 9 to 1%.

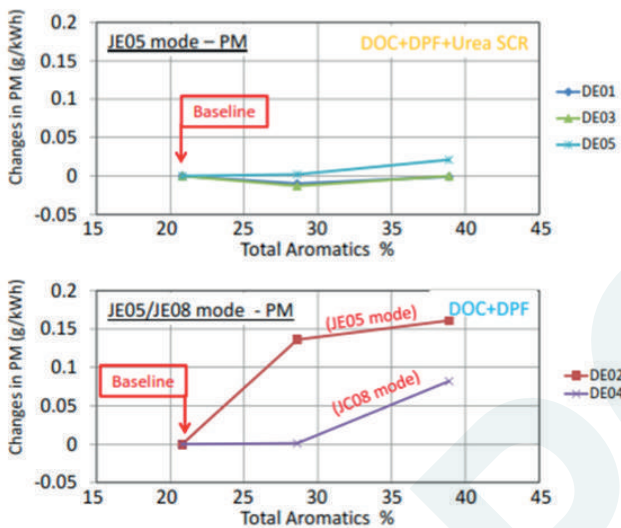
**Figure DF-25: Effect of Polyaromatics on PM Emissions (from 9 to 1% di+ Polyaromatics)**



Source: EPEFE Report

More recent studies have looked at the impact of diesel fuel total aromatics on PM emissions. The JATOP II research program examined the influence of total aromatics on engine-out PM, using the JE05 mode with 2009 JP compliant engines/vehicles. It found that increasing total aromatics did not affect engine-out PM in vehicles equipped with diesel oxidation catalysts, diesel particulate filters and selective catalytic reduction emission control technology (DOC/DPF/SCR), but it did increase engine-out PM in engines equipped only with DOC and DPF devices. See Figure DF-26. This effect can be explained by differences in injection timing for each engine group, since the combustion design is tailored to the emission control system, and the injection timing affects the sensitivity of the engine-out PM to the fuel's aromatics content. For vehicles equipped with DPF, the increase in engine-out PM would affect the DPF regeneration frequency. In other words, the higher the fuel's aromatics content, the more often the DPF will need to regenerate, and the regeneration also may be less than complete.

Figure DF-26: Influence of Total Aromatics on Engine-Out PM (2009 JP compliant engines/vehicles)

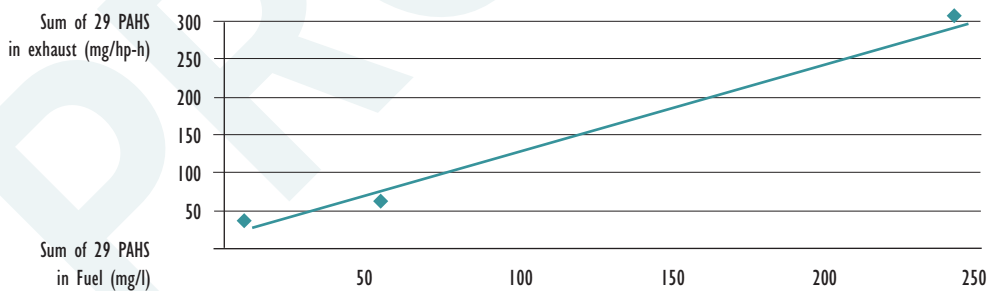


Source: Produced by JAMA using published data from JATOP II

#### Influence of PAH Content on Polyaromatic Emissions

PAH (tri+) content in diesel fuel has been shown to directly correlate to PAH emissions in diesel engine 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 DF-27 demonstrate this direct correlation.

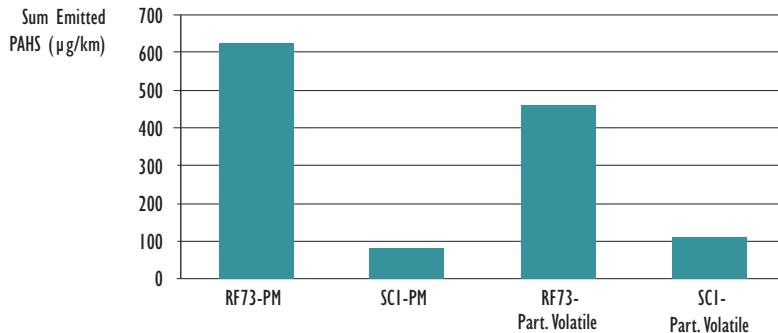
Figure DF-27: Effect of Fuel PAH on Emissions of PAH



Source: Karlsson (Scanraff Refinery) and Røj (Volvo): Diesel Fuel Quality for Reduced Emissions, World Fuels Conference, San Francisco, 1995

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 (SC1, PAH =24 mg/l) and European reference fuel (RF73; PAH=2100 mg/l). Figure DF-28 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 DF -28: Effect of Fuel PAH on Emissions of PAH



Source: Grägg, Ap Svensk Bilprovning/Motortestcenter, Report 9/1995 Bosch, 1997

#### Influence of Total Aromatics Content on the DPF and PM Emissions

The latest vehicles, regardless of vehicle categories, are required to have DPFs to meet stringent PM emission limits, but these devices are vulnerable to premature plugging and causing backpressure in the exhaust system that can increase PM emissions and harm engine performance. A collaboration between JAMA and PAJ produced an investigation into the influence of total aromatics content on DPF performance; the JATOPII program was conducted during 2013-2015. As expected, the study found engine-out PM emissions increasing as the total aromatics content in the test diesel fuels increased.

To reach this conclusion, the study monitored DPF differential pressure (i.e., pressure into and out of the DPF) as the amount of trapped PM increased during engine operation (multiple JE05 modes for medium duty (MD) vehicles and multiple JC08 modes for light duty (LD) vehicles). The DPF is designed to trap PM in the diesel exhaust, but maintaining performance depends on frequent regeneration to avoid a plugged filter. Vehicles use different types of DPF systems based on many factors, such as vehicle configuration, emission control strategy and system design. In the case of the MD test engine used in the study, the DPF was regenerating at a constant frequency and duration when using the higher aromatic-content fuel, reflecting significantly more accumulation on the filter, greater back pressure on the engine and higher PM emissions. A similar result was seen with the LD test vehicle, where the DPF criteria pressure — the pressure that triggers a regeneration event — occurred prematurely on the fuel with a higher total aromatics content. See Figure DF-29. In other words, the higher total aromatic fuel caused the DPF to reach criteria differential pressure earlier and the regeneration interval to become shorter than intended by design. See Figure DF-30. Both phenomena cause fuel consumption to increase; also, they may decrease DPF durability or reliability.

Figure DF -29: Influence of Total Aromatics Content on DPF Differential Pressure

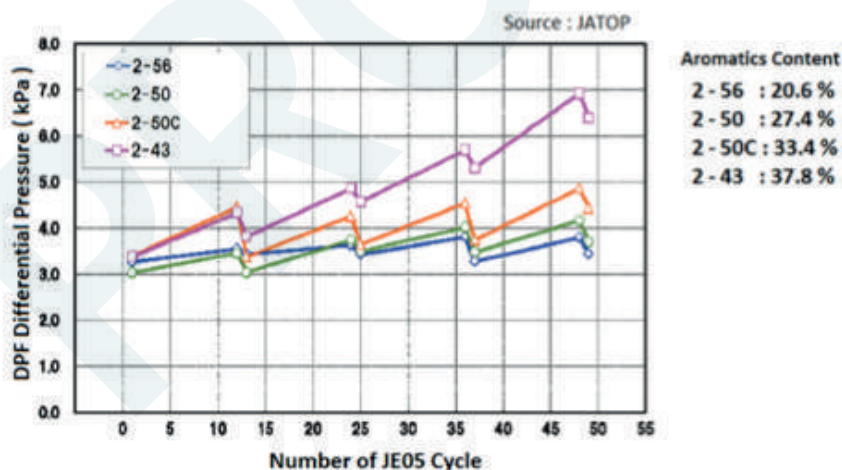
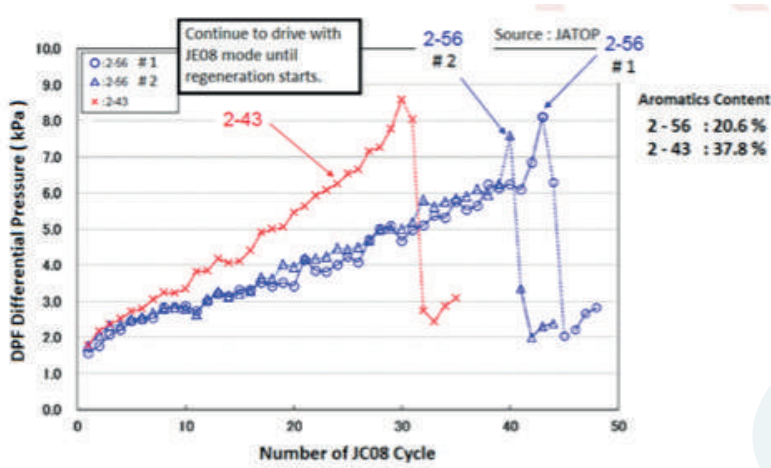


Figure DF – 30: Influence of Total Aromatics Content on DPF Regeneration Interval



## Distillation Characteristics

The distillation curve of diesel fuel indicates the amount of fuel that 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. Adequate cold flow performance, therefore, 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

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 (EN116):** 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.

**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.

Both CFPP and LTFT can be influenced by cold flow additives. Too much additive can cause precipitation onto the fuel filter, so it is important to avoid over-additizing the fuel.

#### 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 over-flow. Anti-foaming agents 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 control systems.

## Biofuels And Alternative Synthetic Fuel Components

#### Fatty Acid Methyl Esters

Fatty Acid Methyl Esters (FAME), also known as biodiesel, increasingly are being used to extend or replace diesel fuel. Such use has been driven largely by efforts in many nations to help reduce GHG emissions, exploit agricultural produce and/or to reduce dependency on petroleum-based products.

Several different oils may be used to make biodiesel, for example, rapeseed, sunflower, palm, soy, cooking oils, animal fats and others. These oils must be reacted with an alcohol to form ester compounds before they can be used as biodiesel fuel. Unprocessed vegetable oils, animal fats and non-esterified fatty acids are not acceptable as transportation fuels due to their very low cetane, inappropriate cold flow properties, high injector fouling tendency and high kinematics viscosity level. Historically, methanol has been the alcohol most used to esterify the fatty acids, and the resultant product is called fatty acid methyl ester (FAME). Using ethanol as the reactant alcohol produces a fuel called fatty acid ethyl ester (FAEE), but this fuel has not yet taken hold in the market. FAME predominates today, having achieved efficient production and much greater use globally.

The European standards organization, CEN, has published a FAME standard (EN 14214) that establishes specifications for biodiesel use as either: (i) a final fuel in engines designed or adapted for biodiesel use; or (ii) a blendstock for conventional diesel fuel. Similarly, ASTM International has established specifications for neat biodiesel (ASTM D 6751) but only for use as a blending component, not as a final fuel.

Generally, biodiesel is believed to enhance the lubricity of conventional diesel fuel and reduce exhaust gas particulate matter. Also, the production and use of biodiesel fuel is reported to lower carbon dioxide emissions on a source to wheel basis, compared to conventional diesel fuel.

At the same time, engine and vehicle manufacturers have concerns about introducing biodiesel into the marketplace, especially at higher levels. Specifically:

- Biodiesel may be less stable than conventional diesel fuel, so precautions are needed to avoid problems linked to the presence of oxidation products in the fuel. Some fuel injection equipment data suggest such problems may be exacerbated when biodiesel is blended with ultra-low sulphur diesel fuels.
- Biodiesel requires special care at low temperatures to avoid an excessive rise in viscosity and loss of fluidity. Additives may be required to alleviate these problems.
- Being hygroscopic, biodiesel fuels require special handling to prevent high water content and the consequent risk of corrosion and microbial growth.
- Deposit formation in the fuel injection system may be higher with biodiesel blends than with conventional diesel fuel, so detergent additive treatments are advised.
- At low ambient temperatures, FAME may produce precipitated solids above the cloud point, which can cause filterability problems.
- Biodiesel may negatively impact natural and nitrile rubber seals in fuel systems. Also, metals such as brass, bronze, copper, lead and zinc may oxidize from contact with biodiesel, thereby creating sediments. Transitioning from conventional diesel fuel to biodiesel blends may significantly increase tank sediments due to biodiesel's higher polarity, and these sediments may plug fuel filters. Thus, fuel system parts must be specially chosen for their compatibility with biodiesel.
- Neat (100%) biodiesel fuel and high concentration biodiesel blends have demonstrated an increase in NO<sub>x</sub> exhaust emission levels.
- Biodiesel fuel that comes into contact with the vehicle's shell may be able to dissolve the paint coatings used to protect external surfaces.

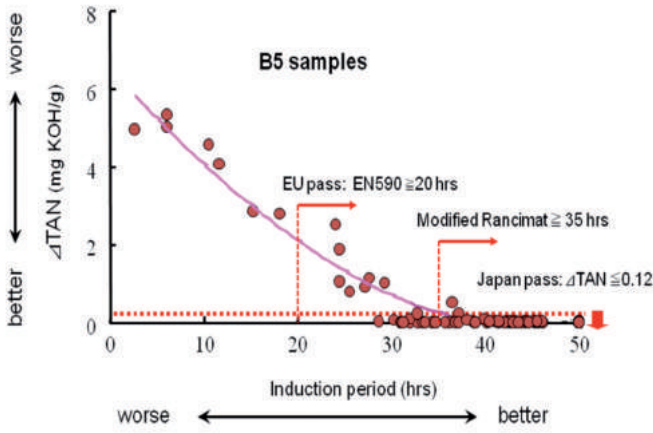
In view of the high level of interest in this fuel, including among vehicle and engine manufacturers, biodiesel specifications and test methods will continue to be investigated.

Biodiesel (FAME) inherently has poor oxidation stability due to the nature of its chemical composition. Most FAME contains carbon-to-carbon double bonds in its chemical construction that are easily oxidized after production and during the storage and use of the fuel. Such oxidation reactions are why precautions must be taken, such as the use of oxidation stability enhancing additives like BHT, when blending and distributing biodiesel fuels.

To secure the quality of biodiesel blended fuel, additional oxidation stability criteria are being introduced into finished fuel specifications in some regions. The European standard for B7 requires a 20 hour minimum induction period by the modified Rancimat method (See EN 590). As part of a compulsory standard for B5, Japan requires either a delta TAN maximum of 0.12 mg KOH/g or a minimum 65 minutes by the PetroOXY method. (The delta TAN method measures acid value before and after aging per ASTM D2274 (@ 115°C)); the growth in acid value is reported as delta TAN. This Charter includes a TAN limit to help prevent acidified diesel fuel (both with and without FAME) which can cause metal corrosion. Additives can affect TAN, so their presence should be considered when evaluating TAN results. The Committee will consider a lower TAN limit when data become available.

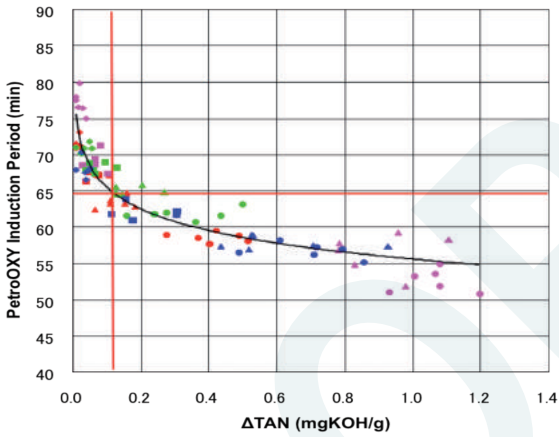
The current European limit is believed to be inadequate to prevent corrosion in metal parts such as vehicle fuel tanks, however. Figure DF-31 shows that a 35 hour minimum induction period by the modified Rancimat method is comparable to a delta TAN maximum of 0.12 mg KOH/g. Figure DF-32 shows the correlation between the PetroOxy and Delta TAN test methods for different FAME feedstocks and levels of antioxidant additive in B5 blends. Figure DF-33 shows the correlation between the PetroOxy and Rancimat methods for different diesel fuels, FAMEs and blend rates. It should be noted that the Rancimat and Delta TAN methods must be used with fuels containing FAME. All three of the correlations are based on fuels containing FAME.

Figure DF -31: Correlation between Modified Rancimat Method and Delta TAN Method



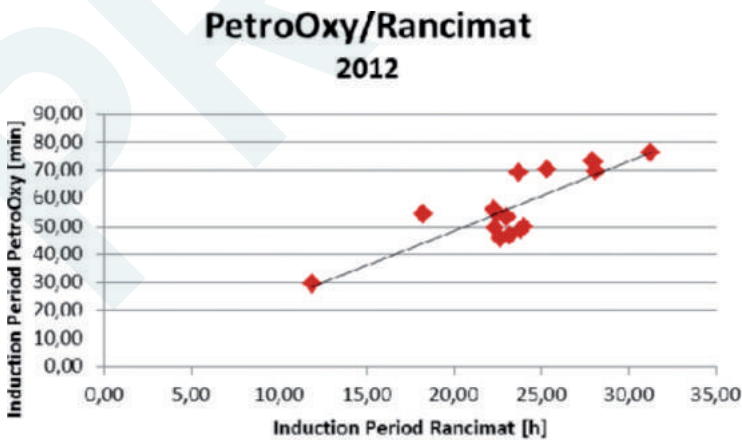
Source: JAMA, 2007

Figure DF -32: Correlation between PetroOxy and Delta TAN Methods



Source: METI, 2010

Figure DF -33: Correlation Between PetroOxy and Rancimat Methods



Source: CEN TC19/JWG1, 2012

### Synthetic Fuels

In recent years, various types of alternative and renewable diesel fuels have emerged that also can help extend or replace diesel fuel. The Fischer-Tropsch process, which was invented in the 1920s but today represents a variety of similar processes, converts feedstocks of biomass, methane (natural gas) or coal into paraffinic diesel fuels, commonly referred to as BTL ('biomass-to-liquid'), GTL ('gas-to-liquid') or CTL ('coal-to-liquid'), as the case may be. Regardless of feedstock, the process requires gasification and then synthesis to a liquid with the desired properties. BTL should not be confused with biodiesel (FAME), which is fundamentally a different fuel. Some of these blendstocks, particularly BTL, have relatively low well-to-wheel GHG emissions, and these are preferred over other synthetic fuels that are not considered to be low carbon fuels. CEN 15940 may be used as a production guideline for GTL and HVO quality; additional engine validation may be needed to ensure the fuel ultimately works well in vehicles and engines. XTL blending components (including BTL, GTL and CTL) should meet the EN 15940 fuel quality standard. Subject to additional engine validation, these fuels are usable in any diesel engine either in pure form or blended with conventional diesel fuel, although they generally have poor lubricity, which requires the addition of appropriate additives to enable the fuel to meet or exceed requirements. The fuels are very clean-burning because they have virtually no sulphur or aromatics. They also have very high cetane levels, which enable more efficient engine operation. Their distillation profile differs from petroleum diesel fuel, and they have a lower density than the Charter's diesel fuel specification, however, and these factors may reduce fuel economy, compared to an equivalent volume of diesel fuel meeting the Charter's specification.

### Hydrotreated Vegetable Oils

Renewable feedstocks such as vegetable oils may be processed by variations of conventional petroleum refining, including hydrotreatment. These refining methods produce saturated paraffinic hydrocarbon molecules with extremely low aromatic levels and a narrow distillation range, and properly processed, they can provide the required cold flow properties. Some HVO production processes may yield non-paraffinic hydrocarbons in addition to paraffins, however, so additional controls may be needed for acceptable quality fuel. When used as a blendstock, this fuel also should meet the EN15940 fuel quality standard.

Unlike FAME, the paraffinic middle distillate fuel oils produced by these methods are indistinguishable from conventional paraffinic fuel oils derived from petroleum and lack the residual process elements typical of biodiesel. Thus, they are highly suited as a blendstock for diesel fuel. Engine and vehicle manufacturers widely support the development of HVO fuels as a way to increase diesel fuel's renewable, low carbon content without the concerns associated with methyl ester fuels.

### E-Diesel

Adding ethanol to diesel fuel (E-diesel) has been 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 raise 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 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.

## Fuel Stability

Diesel fuel can undergo changes during distribution and storage that highlight the need for storage stability as a fuel quality measure. Category 1, 2 and 3 diesel fuels typically are tested for oxidation stability using Method 1. Category 4 and 5 diesel fuels have shown very good oxidation stability when evaluated using Method 1, but the testing may not reflect the fuel's actual stability. The refining processes used to reduce sulphur to the limits in these categories also tend to remove fuel components evaluated by Method 1. The result is a very good test outcome regardless of the fuel's actual stability.

Oxidation stability evaluations using Method 2a (modified Rancimat) or 2b (Delta TAN), for Category 4 fuels containing FAME, or Method 2c (PetroOxy), for any Category 4 or 5 diesel fuel, provide more reliable stability information. As discussed above, the absence of good oxidation stability can lead to significant fuel quality issues for biodiesel blends even at the 5% maximum blend level in this Charter. Some evidence suggests that certain diesel fuel chemistries may react synergistically with biodiesel even if the biodiesel has good oxidation stability. These interactions, as well as the stability of FAME-free diesel fuel, are the subjects of ongoing investigations that may lead to the addition of new information in a future edition of the Charter.

## Injector Cleanliness

The fuel injector, which is designed to meter fuel to a high degree of accuracy, is a component of very high precision. 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 result either in partial or complete hole blockage, with partial blockage the more common effect. Either effect will alter significantly the operation of the injector by reducing fuel flow and affecting power and emissions. 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, some 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.

### Internal Diesel Injector Deposits

Engine and vehicle manufacturers have detected an additional type of injector deposit that has been labelled Internal Diesel Injector Deposits (IDID). These deposits differ from injector nozzle (tip) coking deposits both in their location and their effects. The engine impacts range from increased noise and rough running to power loss and inability to start. Associated impacts include oil dilution, EGR line fouling, increased emissions and reductions in the efficiency and durability of emission control systems.

IDID have been found in several regions across a broad range of engine technologies, including both light and heavy duty vehicles, as well as non-road equipment. The rate of incidents has increased with the growth of common rail engines and their increasingly high fuel injection pressures, which are thought to be a contributing factor. Sub-ppm levels of metallic contaminants in the fuel, primarily Na and Zn, have been associated with IDID problems.

Two main types of IDID have been observed:

1. Lacquer or amide type deposits. Amine fuel constituents are thought to play a role, but the underlying mechanism, the types of constituents involved and the possibility of other co-contributors are open questions.
2. Carboxylate salt deposits. These deposits are thought to derive from reactions of sodium with organic acids present in FAME or in corrosion inhibitors used for pipeline protection.

Engineering solutions are unavailable to fully protect injectors from IDID risk. Some diesel fuel deposit control additives may mitigate the effects.

### Influence of Detergent Additives

Detergent additives can remedy many of the concerns associated with injector cleanliness. 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. Additive producers and fuel suppliers should check through field trials the extent to which their formulations may contribute to undesirable internal deposit formation at various treat rates. 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 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. It has been observed in service and by many laboratories, both in manufacturing facilities and independently, that small quantities of metals such as zinc, copper, lead, sodium and potassium in diesel fuel can lead to significant injector fouling with subsequent engine power loss and increased exhaust gas PM, as shown in Figure DF-23, above, page 76, which shows pictures of a nozzle with coking caused by metallic impurities.

Metals can contaminate the fuel during the distribution process, even if the fuel is clear when leaving the refinery. Ideally, a standardized engine test on a direct injection diesel engine would permit the setting of an acceptable limit value for injector fouling due either to metals being present in the fuel or to the fuel composition. At present, such a standardized test procedure has not been established, but candidate procedures are being considered. Until an engine performance test is established, therefore, it is prudent to require diesel fuel delivered at the filling station to respect the specific limits for each metal in the fuel, to reduce the risk of severe injector fouling in modern direct injection diesel engines. The technique for measuring the metals should be by inductively coupled plasma, such as with the ASTM D 5185 method (direct measurement improves the detection limit).

## Lubricity

Lubrication at component boundaries is critical for protecting engines and fuel handling systems. The components of the diesel fuel that provide boundary lubrication 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.

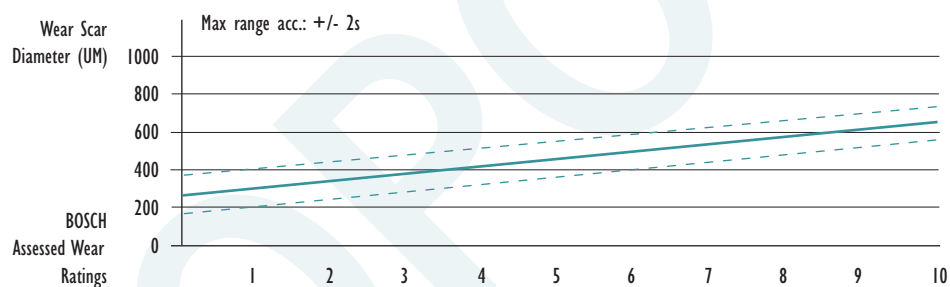
Refining processes to remove sulphur tend to simultaneously reduce diesel fuel components that provide natural lubricity. As diesel fuel sulphur levels decrease, the risk of inadequate lubricity also increases; however, poor lubricity has been observed even in diesel fuels with very high sulphur levels. Inexpensive additives can be used instead of changing the refining process to achieve the desired lubricity level.

### 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 among 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 that provides good correlation to measured pump effects.

Figure DF-34 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 a nominal HFRR Wear Scar Diameter of 400  $\mu\text{m}$ ). With a Bosch wear rating of 4, the pump will have decreased endurance, and ratings above 7 indicate potential fatal breakdown.

Figure DF-34: Assessed Pump Wear Rating vs. HFRR Results



Source: Bosch, 1997

## Particulate Contamination

Fuel injection equipment manufacturers continue to develop fuel injection systems to reduce emissions and fuel consumption and to improve performance. Injection pressures have been increasing; currently, they have reached more than 2000 bars. Such levels of injection pressure demand reduced orifice sizes and component clearances, typically from 2 to 5  $\mu\text{m}$  in injectors. Small, hard particles, which may be carried into these engine parts, are potential sources of engine failure.

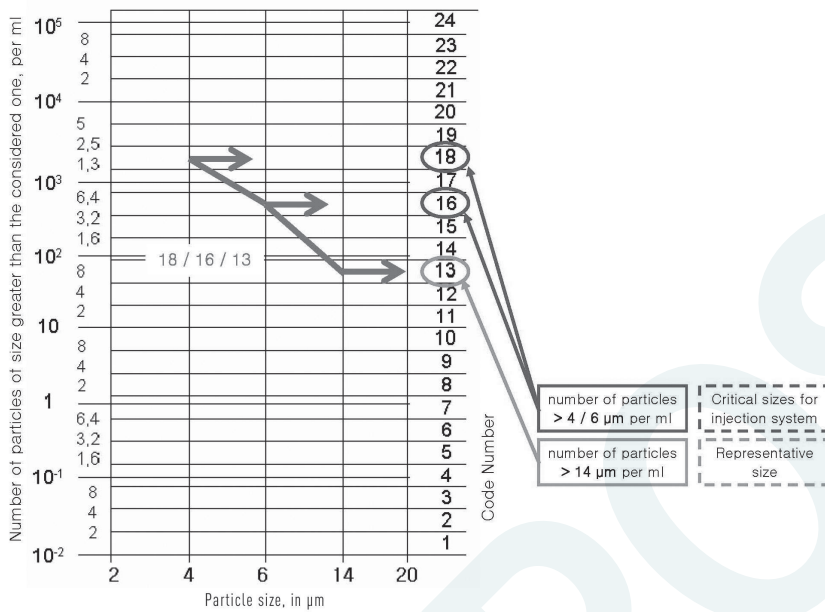
Excessive diesel fuel contamination can cause premature clogging of diesel fuel filters, depending on the level of both hard and organic particles, and premature wear of modern fuel injection system parts.

These impacts, depending on the size and the nature of the particles, will lead to:

- Reduced part lifetimes;
- Part malfunction;
- Engine failure; and
- Increased exhaust emissions.

Measuring fuel particle contamination necessarily considers both the size and number of particles per size class contained in the fuel, i.e. the particle size distribution. The ISO 4406 protocol provides a means of expressing the level of contamination by coding the size distribution. Three code numbers, corresponding to the numbers of particles of size greater than 4, 6 and 14  $\mu\text{m}$  per millilitre, respectively, are reported. Figure DF-35 shows how to use the ISO 4406 coding method.

Figure DF-35: ISO 4406 Particulate Size Distribution Coding Chart



Source: ISO 4406, 1999

Engine and vehicle manufacturers recommend applying the Worldwide Fuel Charter's particulate contamination specification at the fuel station nozzle to prevent particles originating from fuel transport, storage and logistics from reaching the engine.

## Contaminants

Contaminants, including some from additives, whether intentionally or inadvertently added during fuel production or distribution, also can cause significant harm to the powertrain, fuel, exhaust or emission control systems. Good housekeeping practices can help minimize or prevent inadvertent contamination. No detectable levels of the elements listed below should exist in diesel fuel, nor should they be used as components of any fuel additive package intended to improve diesel fuel and engine performance. These elements should be strictly controlled, and it may prove necessary to check and control the fuel quality at the pump.

Calcium, copper, sodium, manganese, potassium, phosphorus and zinc, even at levels as low as 0.1 ppm, can contribute to the formation of deposits in fuel injector internal surfaces and nozzles. Injector deposits reduce combustion efficiency and increase emissions. Concern about injector deposits is increasing as the latest nozzle technology with tighter clearances and higher pressures becomes more widely used in the marketplace.

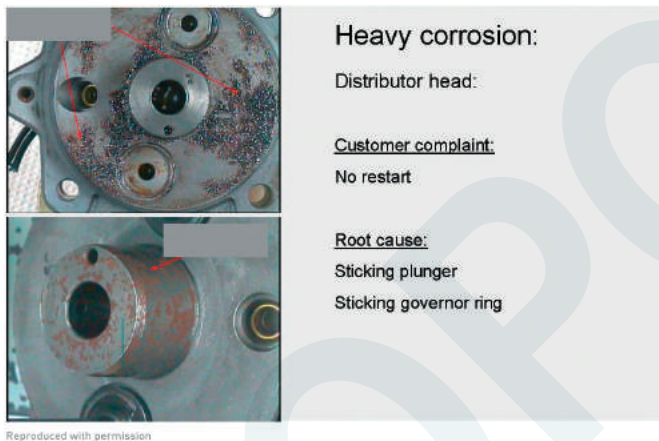
Chlorine, which is not naturally contained in petroleum, has been found in diesel fuel in both inorganic and organic forms. Inorganic chlorine usually enters the fuel as a result of contamination by sea water ballast during shipping or from the use of salt dryers during refining. Organic chlorine may enter the fuel through adulteration with chemical or waste solvents. Chlorine forms highly corrosive acids during combustion, which can reduce significantly the durability of the engine, fuel system and emission control system. In the worst case, the presence of chlorine may lead to catastrophic engine failure as injectors fail to operate or operate improperly after various periods and levels of exposure.

## Good Housekeeping Practices

It is important that vehicles and engines receive the same high quality fuel at the service station dispenser as measured upstream at the refinery gate. Many problems encountered by vehicles/engines, if not most, are caused by contamination that occurs after the fuel has left the refinery. Inadequate pipeline and storage facilities and failure to properly maintain equipment, for example, can lead to contamination by particulates and water. At the service station, infrequent replacement of fuel dispenser filters or auditing (such as ‘dipping’) of tanks to check for water can magnify this contamination. Excess levels of water will lead to corrosion, as shown in Figure DF-36, below. Adding used engine oil to fuel is unacceptable unless expressly allowed by the manufacturer. Harmful elements such as copper, zinc and sodium also can enter the fuel through poor fuel handling practices.

Post-refining degradation of fuel quality is preventable through good housekeeping practices, regular equipment maintenance, adequate investment in facilities and protection from adulteration, all along the distribution system and at the service station. Filtering the fuel at every transfer point will further help by removing damaging contaminants such as particulate and water. Helpful guidance to good housekeeping practices for diesel fuel may be found in CEN/TR 15367-1, “Petroleum Products - Guidelines for Good Housekeeping, Part 1: Diesel Fuel” and in CRC-667, “Diesel Fuel Storage and Handling Guideline.”

**Figure DF - 36: Example of Corrosion in Field Pump Caused by Free Water in Diesel Fuel**

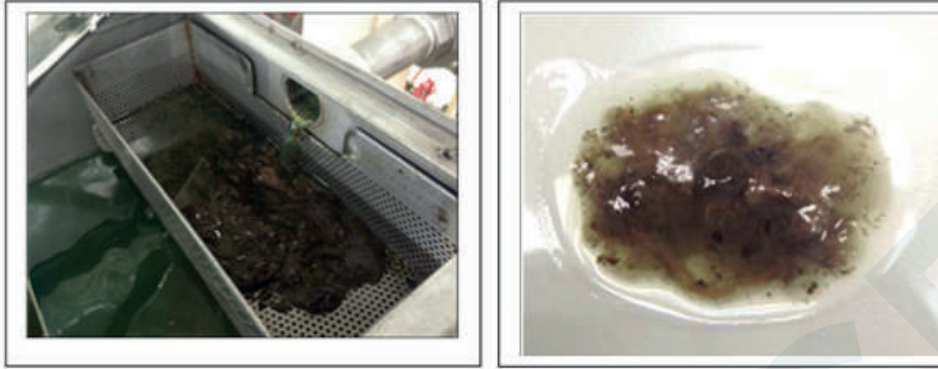


Source: Bosch, 2002

The recent expansion of FAME-blended diesel fuel around the world presents additional concerns about fuel quality at the dispenser because FAME is especially susceptible to quality deterioration. Compared to petroleum-based diesel fuel, it absorbs more water, oxidizes more readily and is prone to microbial growth, making FAME and fuel blends containing FAME less stable. See Figure DF-37. Importantly, these processes can create precipitate that contaminates the fuel while sitting for long periods in storage tanks, especially under hot conditions. As shown in Figure DF-38, the areas of greatest concern are the terminal storage tank, delivery tank truck and underground storage tank. Thus, while good housekeeping practices are important for all diesel fuels, they are especially important for FAME-diesel fuel blends.



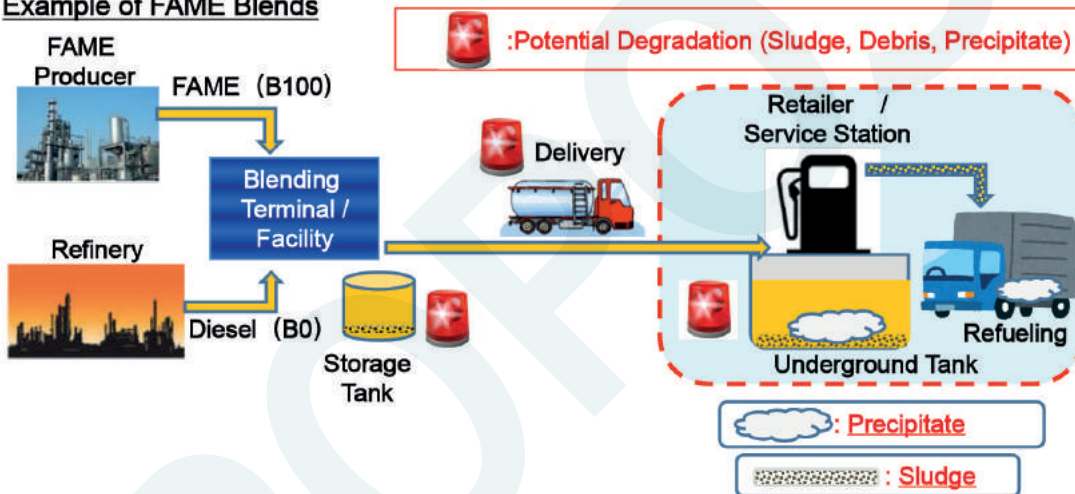
Figure DF-37: Examples of Microbial Growth in B5



Source: Toyota

Figure DF-38: Points of Concern for Quality Degradation for Diesel Fuel and FAME Blends

**Example of FAME Blends**



Source: JAMA

Cross-contamination between gasoline and diesel fuel, which may occur anywhere in the distribution and storage system, raises serious concerns for engines and vehicles. One way to minimize this problem is to clean out tanker trucks between fuel batches. To fully prevent it, however, the most effective approach is to use dedicated and segregated systems for gasoline and diesel fuel and to prohibit “switch loading” at the filling station. CEN/TR 15367-3, “Petroleum Products - Guide for Good Housekeeping - Part 3: Prevention of Cross Contamination,” provides additional guidance.

