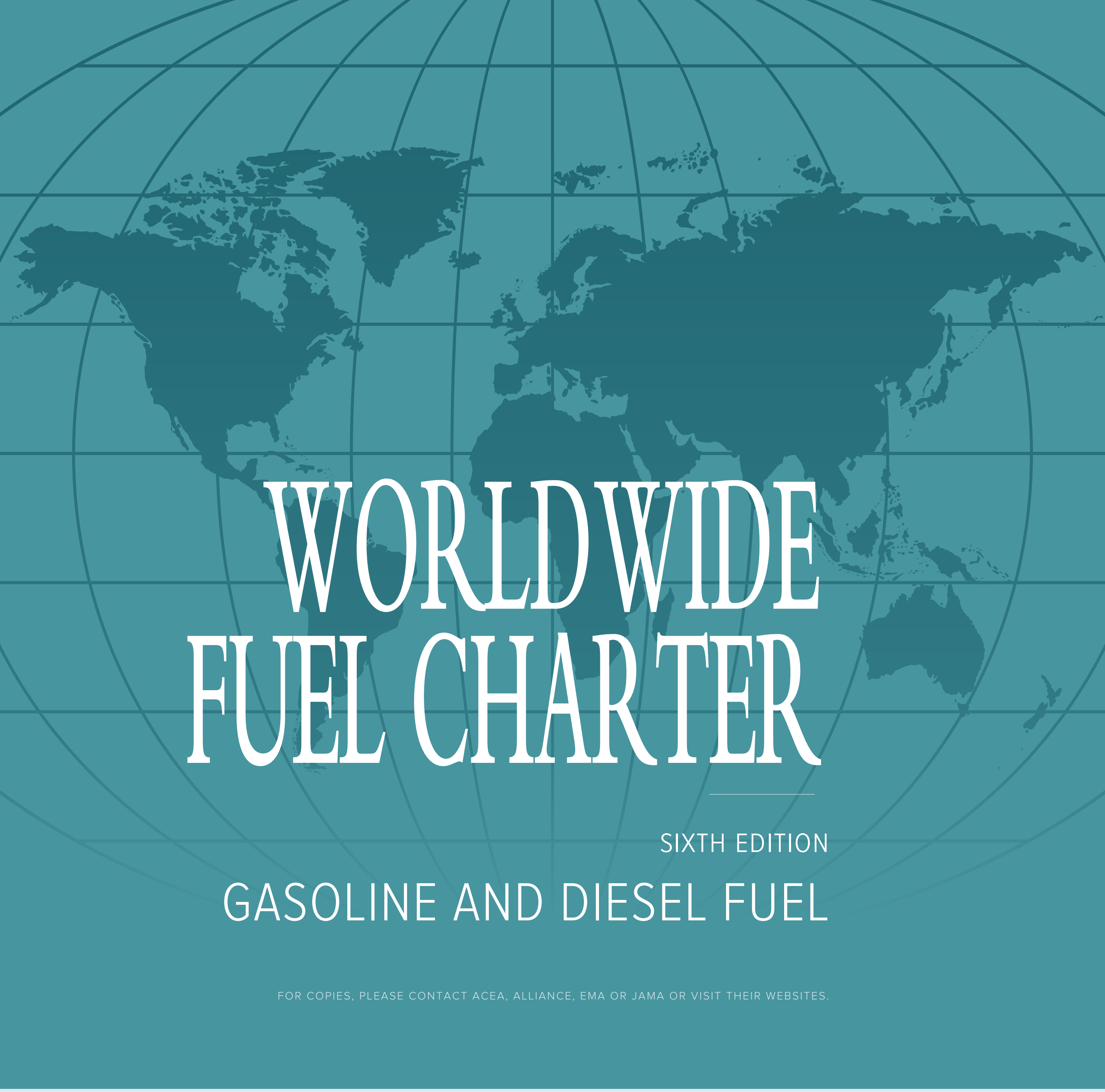

WORLDWIDE FUEL CHARTER

SIXTH EDITION

GASOLINE AND DIESEL FUEL

FOR COPIES, PLEASE CONTACT ACEA, ALLIANCE, EMA OR JAMA OR VISIT THEIR WEBSITES.

28 OCTOBER 2019

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ACEA European Automobile Manufacturers Association
AUTO ALLIANCE DRIVING INNOVATION
ema
JAMA

European Automobile Manufacturers Association
Alliance of Automobile Manufacturers
Truck and Engine Manufacturers Association
Japan Automobile Manufacturers Association

28 October 2019

Subject: Worldwide Harmonisation of Gasoline and Diesel Fuel

Dear Recipient:

On behalf of vehicle and engine manufacturers from around the world, the Worldwide Fuel Charter (WWFC) Committee is pleased to present the Sixth Edition of the Worldwide Fuel Charter for Gasoline and Diesel Fuel, 21 years after publishing the First Edition. In addition to this Charter, the Committee recently published the First Edition of the WWFC for Methane-Based Transportation Fuels and previously published guidelines for ethanol and biodiesel blendstocks.

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 edition updates the previous edition in several ways and presents each fuel in its own chapter for easier reading. The gasoline chapter 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 Category 1 diesel fuel, but only as guidance to a transitional quality fuel. The Committee is serving notice, however, that it intends to retire Category 1 diesel fuel 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 appreciate the many comments submitted on this new Sixth Edition; they have helped make it a better document. We look forward to working with you to support these harmonised fuel quality specifications for the benefit of consumers and the environment around the world.

Eric Mark Huitema
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David Schwietert
Interim President & CEO
Auto Alliance

Jed R. Mandel
President
EMA

Seiichi Nagatsuka
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- Thai Automotive Industry Association (TAIA)
- Vietnam Automobile Manufacturers Association (VAMA)

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
ACEA	Association des Constructeurs Européens d'Automobiles (European Automobile Manufacturers' Association)
AIAM	Association of International Automobile Manufacturers, now named Association of Global Automakers
Alliance	Alliance of Automobile Manufacturers
AMA	Accelerated Mileage Accumulation
AQIRP	Air Quality Improvement Research Programme (part of the US Auto Oil programme, 1989-1992)
ASTM	ASTM International (formerly American Society for Testing and Materials)
BHT	Butylated hydroxytoluene
Biofuel	Liquid transport fuel produced from biomass
Biomass	Biodegradable fraction of products, waste and residues from biological origin
BTL	Liquid fuel made from biomass ('Biomass to Liquid')
CCD	Combustion Chamber Deposits
CDPF	Catalysed Diesel Particulate Filter
CEC	Coordinating European Council for the Development of Performance Tests for Transportation Fuels, Lubricants and Other Fluids
CFPP	Cold Filter Plugging Point
CFR	Cooperative Fuel Research (RON/MON testing)
CN	Cetane Number
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CP	Cloud Point
CRC	Coordinating Research Council (US)
CR-DPF	Continuously Regenerating Diesel Particulate Filter
DBE	Double bond equivalence
DECSE	Diesel Emission Control – Sulfur Effects, research program of the US Department of Energy
DEF	Diesel Exhaust Fluid (for SCR systems)
DI	Distillation Index
DIN	Deutsches Institut für Normung (German Institute of Standardisation)
DISI	Direct Injection Spark Ignition
DOC	Diesel Oxidation Catalyst
DPF	Diesel Particulate Filter
DVPE	Dry Vapour Pressure Equivalence
EMA	Truck and Engine Manufacturers Association
EN	European Norm
EPA	Environmental Protection Agency (US)
EPEFE	European Programme on Emissions, Fuels and Engine Technology (part of the European Auto-Oil 1 programme, 1993-1995)
EtBE	Ethyl tertiary-Butyl Ether
EUDC	Extra-urban driving cycle (a European test)
FAEE	Fatty Acid Ethyl Esters
FAME	Fatty Acid Methyl Esters
FBP	Final Boiling Point
FTP	(US) Federal Test Procedure
FLTM	Ford Laboratory Test Method
FVV	Forschungsvereinigung Verbrennungskraft maschinen (German research organization)
GHG	Greenhouse Gas
GPF	Gasoline particulate filter
GTDI	Gasoline Turbo Direct Injection
GTL	Liquid fuel typically made from methane gas using a gas-to-liquid/Fischer-Tropsch-type process
HC	Hydrocarbons
HFRR	High Frequency Reciprocating Rig
HVO	Hydrotreated Vegetable Oil
IDID	Internal Diesel Injector Deposits
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry
IP	Energy Institute (formerly Institute of Petroleum)
ISO	International Organisation for Standardization
IVD	Intake Valve Deposits
JAMA	Japan Automobile Manufacturers Association
JARI	Japan Automobile Research Institute
JATOP	Japan Auto - Oil Program
JCAP	Japan Clean Air Program
JIS	Japanese Industrial Standards
LEV	Low Emission Vehicle
LTFT	Low Temperature Flow Test
MECA	Manufacturers of Emission Controls Association
METI	Ministry of Economy, Trade and Industry (Japan)
MMT	Methylcyclopentadienyl Manganese Tricarbonyl
MON	Motor Octane Number
MtBE	Methyl tertiary Butyl Ether
MTZ	MotorTechnische Zeitschrift (German technical journal)
NF M	Norme Française - Industrie du Pétrole
NF T	Norme Française - Industrie Chimique (French Norm - Petroleum Industry)
NMHC	Non-Methane Hydrocarbon
NOx	Oxides of Nitrogen
NVH	Noise, vibration, harshness
OBD	On-Board Diagnostics
OFP	Ozone Forming Potential
OICA	Organisation Internationale des Constructeurs d'Automobiles
Oxy	Oxygen
PAH	Polycyclic Aromatic Hydrocarbons
PAJ	The Petroleum Association of Japan
pHe	Acidity of ethanol
PM	Particulate Matter
PMI	Particulate matter index
ppm	Parts per million
PZEV	Partial Zero Emission Vehicle
RDE	Real driving emissions
RON	Research Octane Number
SBA	Sec-Butyl Acetate
SCR	Selective Catalytic Reduction
SULEV	Super-Ultra-Low Emission Vehicle
TAN	Total Acid Number
TDC	Top Dead Center
TGA	Thermal Gravimetric Analysis
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: www.sgs.com/en/news/2018/10/sgs-inspire-delivers-in-depth-analysis-and-reporting-on-global-fuel-quality-trends

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

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GASOLINE BACKGROUND FIGURES, TABLES AND EQUATIONS

DIESEL FUEL BACKGROUND FIGURES AND EQUATIONS

INTRODUCTION

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

- Minimising 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

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, Euro 3 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 (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, Euro 5, Euro 6/6b, 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 light-duty vehicle fuel economy, California LEV III and as amended, Euro 6c, Euro 6dTEMP, Euro 6d, current EU CO_2 target, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category aims to minimise 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 future or anticipated US light-duty vehicle GHG and fuel economy standards and future EU targets for CO_2. This category aims to minimise 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. Vehicle/engine 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 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-typical refinery stream 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 required under local standards and 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 minimise contamination from dust, water, incompatible fuels and other 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 (which refers to anhydrous ethanol) 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, Euro 3 or equivalent emission standards, or other market demands.

PROPERTIES		UNITS	LIMITS	
			MIN	MAX
91 RON [1]	Research Octane Number		91.0	
	Motor Octane Number		82.5	
95 RON [1]	Research Octane Number		95.0	
	Motor Octane Number		85.0	
98 RON [1]	Research Octane Number		98.0	
	Motor Octane Number		88.0	
Oxidation stability		minutes	480	
Sulphur [2]		mg/kg		150
Trace metal [3]		mg/kg	No intentional addition	
Chlorine		mg/kg	No intentional addition	
Organic contaminants [4]			No intentional addition	
Oxygen [5]		% m/m		2.7 [6]
Olefins		% v/v		18.0
Aromatics		% v/v		40.0
Benzene		% v/v		2.5
Volatility			See Tables, page 10-11	
Sediment (total particulate)		mg/l		1
Unwashed gums [7]		mg/100 ml		70
Washed gums		mg/100 ml		5
Density		kg/m^3	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-05-93), or		avg. mg/valve		30
Method 2 (ASTM D6201)		avg. mg/valve		50
Combustion chamber deposits [7]				
Method 1 (ASTM D6201), or		% of base fuel		140
Method 2 (TGA - FLTM BZ154-01)		% mass.@ 450°C		20

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[1] Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

[2] The unit 'mg/kg' is often expressed as ppm.

[3] 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.

[4] Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

[5] Ethers are acceptable. The use of methanol is only acceptable if: (i) specified by applicable standards (e.g., maximum 3% v/v methanol in standard EN 228); (ii) consumed in vehicles compatible with its use; and (iii) stated in the owner's manual.

[6] 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.

[7] To provide flexibility (for example, to enable the use of deposit control 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 (except lean burn gasoline engines), JP 2005 or equivalent emission standards, or other market demands.

PROPERTIES		UNITS	LIMITS	
			MIN	MAX
91 RON [1]	Research Octane Number		91.0	
	Motor Octane Number		82.5	
95 RON [1]	Research Octane Number		95.0	
	Motor Octane Number		85.0	
98 RON [1]	Research Octane Number		98.0	
	Motor Octane Number		88.0	
Oxidation stability		minutes	480	
Sulphur [2]		mg/kg		30
Trace metal [3]		mg/kg	No intentional addition	
Chlorine		mg/kg	No intentional addition	
Organic contaminants [4]			No intentional addition	
Oxygen [5]		% m/m		2.7 [6]
Olefins		% v/v		10.0
Aromatics		% v/v		35.0
Benzene		% v/v		1.0
Volatility			See Tables, page 10-11	
Sediment (total particulate)		mg/l		1
Unwashed gums [7]		mg/100 ml		30
Washed gums		mg/100 ml		5
Density		kg/m^3	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-05-93), or		avg. mg/valve		30
Method 2 (ASTM D6201)		avg. mg/valve		50
Combustion chamber deposits [7]				
Method 1 (ASTM D6201), or		% of base fuel		140
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[7] To provide flexibility (for example, to enable the use of deposit control 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 advanced requirements for emission control, such as US Tier 2, US Tier 3, California LEV II, Euro 4, Euro 5, Euro 6/6b, JP 2009 or equivalent emission standards, or other market demands; enables sophisticated NOx and particulate matter after-treatment technologies.

PROPERTIES		UNITS	LIMITS	
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Benzene		% v/v		1.0
Volatility			See Tables, page 10-11	
Sediment (total particulate)		mg/l		1
Unwashed gums [7]		mg/100 ml		30
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Copper corrosion		rating		Class 1
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Appearance			Clear and bright; no free water or particulates	
Fuel injector cleanliness, Method 1, or		% flow loss		5
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Particulate contamination, size distribution		Code rating		18/16/13 per ISO 4406
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[6] 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.

[7] To provide flexibility (for example, to enable the use of deposit control 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 light-duty vehicle fuel economy, California LEV III and as amended, Euro 6c, Euro 6dTEMP, Euro 6d, current EU CO_2 target, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category aims to minimise 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 [1]		mg/kg		10
Trace metal [2]		mg/kg	No intentional addition	
Chlorine		mg/kg	No intentional addition	
Organic contaminants [3]			No intentional addition	
Oxygen [4]		% m/m		3.7 [5]
Olefins		% v/v		10.0
Aromatics		% v/v		35.0
Benzene		% v/v		1.0
Volatility			See Tables, page 10-11	
E130 [6]		% v/v	See Tables, page 10	
E170 [6]		% 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^3	720	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-05-93), 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 (TGA - FLTM BZ154-01)		% mass.@ 450°C		20
PMI [6]				

[1] The unit 'mg/kg' is often expressed as ppm.

[2] 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.

[3] Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

[4] Ethers are acceptable. The use of methanol is only acceptable if: (i) specified by applicable standards (e.g., maximum 3% v/v methanol in standard EN 228); (ii) consumed in vehicles compatible with its use; and (iii) stated in the owner's manual.

[5] 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.

[6] 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) are needed in the interim. See the Technical Background discussions on pages 39 and 42.

CATEGORY 6 GASOLINE SPECIFICATIONS

Category 6: Markets with potential emission control and fuel efficiency targets more stringent than those in Category 5, such as future or anticipated US light-duty vehicle GHG and fuel economy standards and future EU targets for CO_2. This category aims to minimise 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 [1]		mg/kg		10
Trace metal [2]		mg/kg	No intentional addition	
Chlorine		mg/kg	No intentional addition	
Organic contaminants [3]			No intentional addition	
Oxygen [4]		% m/m		3.7 [5]
Olefins		% v/v		10.0
Aromatics		% v/v		35.0
Benzene		% v/v		1.0
Volatility			See Tables, page 10-11	
E130 [6]		% v/v	See Tables, page 10	
E170 [6]		% 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^3	720	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-05-93), 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 (TGA - FLTM BZ154-01)		% mass.@ 450°C		20
Method 3 (DISI) [7]				
PMI [6]				

[1] The unit 'mg/kg' is often expressed as ppm.

[2] 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.

[3] Organic contaminants include, for example, methylal, aniline and aniline derivatives, and secondary butyl acetate (SBA).

[4] Ethers are acceptable. The use of methanol is only acceptable if: (i) specified by applicable standards (e.g., maximum 3% v/v methanol in standard EN 228); (ii) consumed in vehicles compatible with its use; and (iii) stated in the owner's manual.

[5] 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.

[6] 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.

[7] 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	65-80	75-90	85-105
T10, °C, max	65	60	55	50	45
T50, °C [1]	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) [2]	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

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

[2] 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 [3]	77-100	77-100	75-100	70-100	65-100
T70, °C [4]	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) [5]	20-45	20-45	25-47	25-50	25-50
E100, % (V/V) [6]	50-65	50-65	50-65	55-70	55-70
E130, % (V/V) min [7]	70	70	70	70	70
E150, % (V/V) min [7]	83	83	83	86	86
E170, % (V/V) min [7]	90	90	90	95	95
D.I., max	570	565	560	555	550

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

[4] 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.

[5] 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.

[6] 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.

[7] 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.), also known as the oxygen-corrected Driveability Index

$$\mathbf{D.I. = (1.5 * T10) + (3 * T50) + T90 + (11 * mass\ \%\ of\ oxygen)}$$

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 90th 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 [1]	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, D8110
Manganese	mg/l		D3831	K 2255	EN 237
Potassium	mg/l		D8110		NF M 07065, EN 14538
Trace metal	mg/kg		D7111 mod. & D8110		
Phosphorus	mg/l		D 3231		D8110
Silicon	mg/kg		D7111		ICP-AES (Reference in-house methods with detection limit = 1 mg/kg)
Chlorine	mg/kg	15597	D7359 or D7536		EN ISO 22854
Oxygen	% m/m	EN 22854	D4815 D5599	K 2536-2 K 2536-4	EN 13132; ASTM D5622; JIS K 2536-6, K 2536-5
Olefin [2]	% v/v	3837	D1319	K 2536-1	EN 22854; ASTM D6550; JIS K 2536-2
Aromatic [2]	% v/v	3837	D1319	K 2536-1	EN 14517, 22854; ASTM D5580, D5769; JIS K 2536-2, K 2536-3, K 2536-4
Benzene	% v/v	EN 22854	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		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^3	3675	D4052	K 2249-2	JIS K 2249-3
		12185		K 2249-1	

[1] Updated procedures are needed to better measure oxygenated blends.

[2] 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 (3 hrs, 50°C)	rating	2160	D130	K 2513	
Silver corrosion (3 hrs, 50°C)	rating		D7671		
Appearance			D4176		Visual inspection
Fuel injector cleanliness, Method 1	% flow loss		D5598		
Fuel injector cleanliness, Method 2	% flow loss	[3]	D6421		
Particulate contamination, size distribution	code rating no. of particles/ml			B9933	4406 4407 & 11500
Intake-valve sticking	pass/fail				CEC F-16-96
Intake valve cleanliness II					
Method 1, 4 valve avg.	avg. mg/valve				CEC F-05-93
Method 2, Ford 2.3L	avg. mg/valve		D6201		
Combustion chamber deposits					
Method 1	% of base fuel		D6201		
Method 2	% mass @ 450°C				FLTM-BZ154 [4]
Method 3 (DISI) [5]					
PMI					SAE 2010-01-2115 & ASTM D6729 [6]

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[3] In development.

[4] This method is available at http://global.ihs.com.

[5] A CEC work group, TDG F 113, is developing a new method for DISI engines.

[6] 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 hybridisation. As discussed below, octane rating has become the most important limiting factor in achieving new efficiency and environmental objectives for gasoline-powered vehicles.

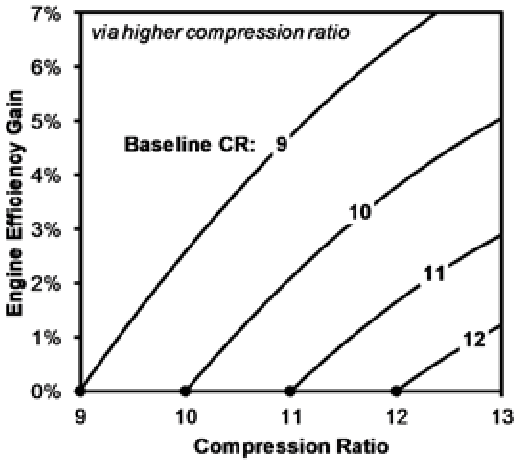
Octane Rating and Performance, Fuel Efficiency and Emissions

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, summarises seven of the most relevant and credible data sets, based on an analysis by Smith et al. (see SAE 2014-01-2599).

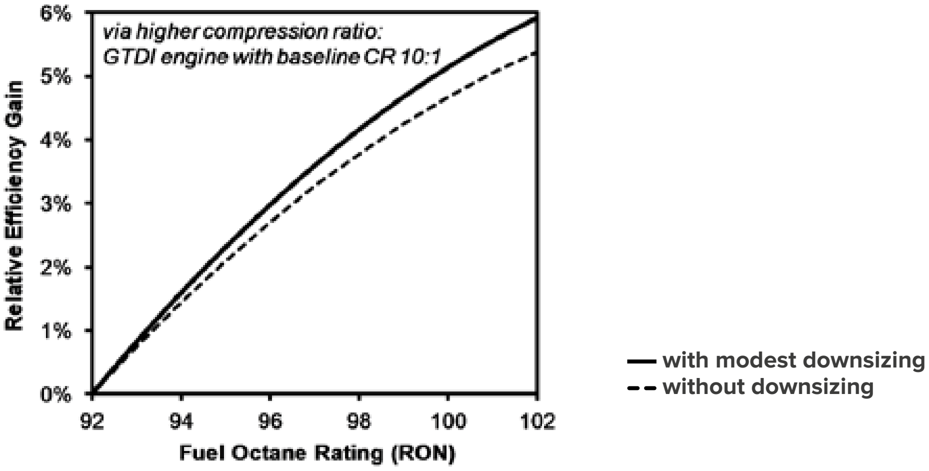
Figure G-1: Relationship Between Compression Ratio and Engine Efficiency Gain



Source: Leone et al. (Ford, GM, Fiat Chrysler), Environ Sci. Technol. 49 (18), 2015, using data from 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, summarises possible efficiency improvements derived from a recent review of the literature.

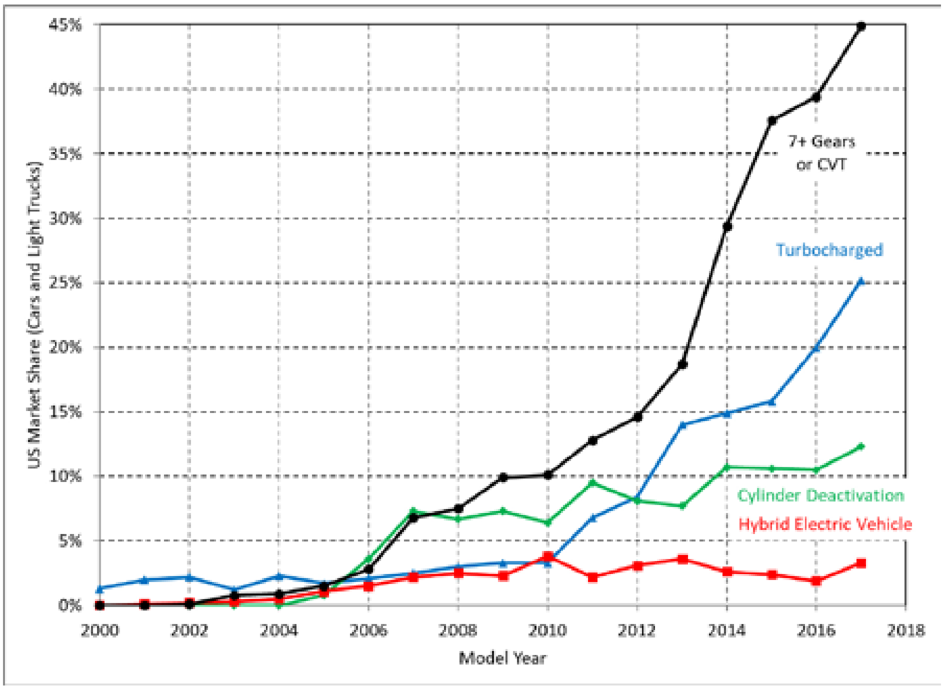
Figure G-2: Efficiency Gains Enabled by Higher RON



Source: Ford 2018, based on equations in Leone et al. (Ford, GM, Fiat Chrysler), Environ. Sci. Technol. 49 (18), 2015, and using data in SAE 2014-01-2599.

Furthermore, powertrain technology is constantly evolving to achieve better fuel economy and lower CO_2 emissions. The most common improvements in fuel economy and CO_2 emissions in recent years have been due to downsizing, downspeeding, cylinder deactivation and hybridisation. 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_2) 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

$$\mathbf{OI = RON - K * (RON - MON)}$$

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 (CPI) number. 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':

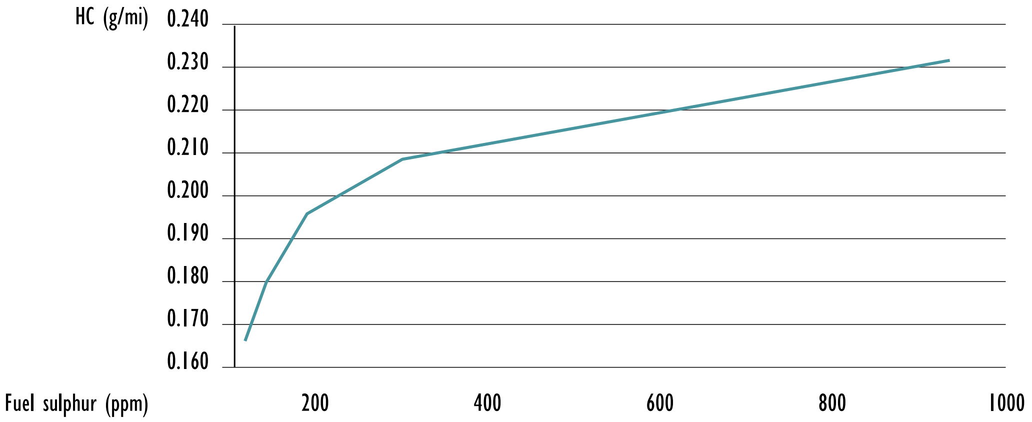
Table G-1: Impact of Sulphur on Emissions

STUDY	VEHICLE TECHNOLOGY	SULPHUR RANGE (PPM)		EMISSION REDUCTION,% (HIGH TO LOW SULPHUR)		
		high	low	HC	CO	NOx
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/NOx cat.	25	2			37

* Reduction achieved during European hot extra-urban driving cycle (EUDC) 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

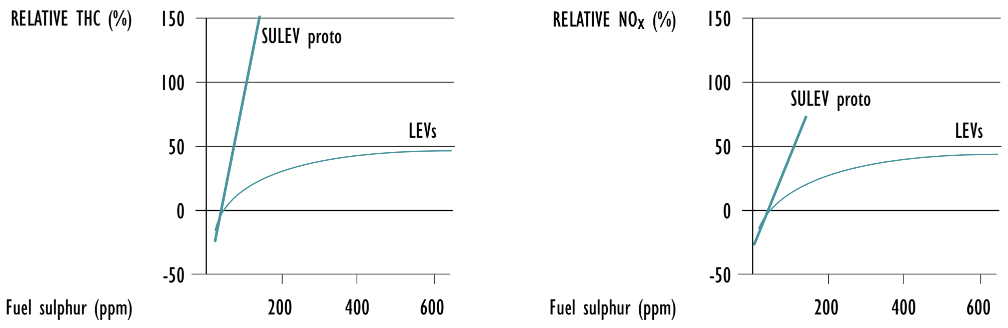
In addition, laboratory research of catalysts has demonstrated delays in light-off time, increases in light-off temperature and reductions in efficiency resulting from higher sulphur fuels across a full range of air/fuel ratios. Studies have also demonstrated that sulphur slows the rich to lean transition, 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, exhaust aftertreatment 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 NOx 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)

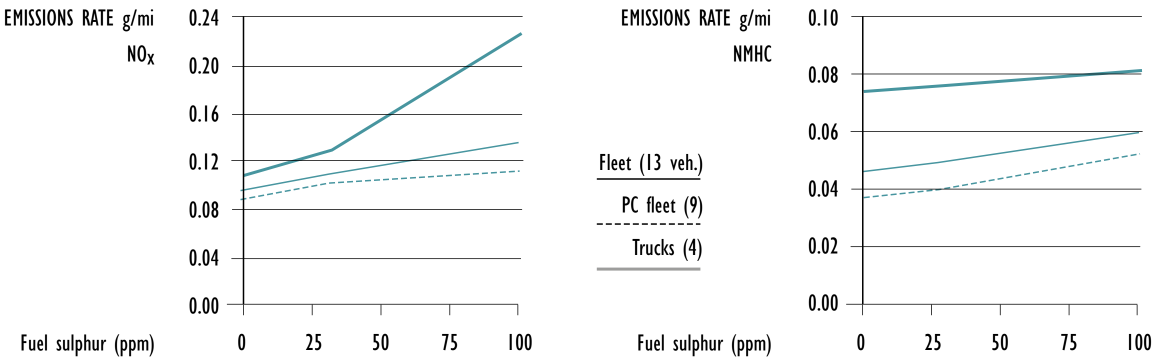


Source: Toyota, 1999

In 2001, the Auto 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 NOx 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 NOx and NMHC



Source: Auto 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

NOx 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 NOx 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.

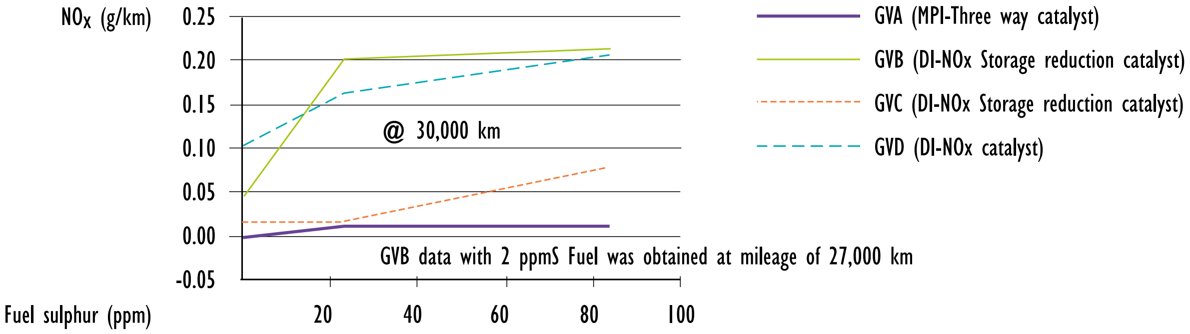
One study published in 2011 documented the effect of sulphur on a 2009 Model Year mid-sized sedan with three-way catalyst technology meeting California's PZEV standards (see SAE 2011-01-0300). The study compared the effects of a 3 ppm sulphur gasoline with those of a 33 ppm sulphur gasoline. One of the objectives was to determine whether 3 ppm fuel would cause NOx emission control to deteriorate during repeated testing, similar to the test-to-test deterioration seen with 33 ppm fuel ('NOx 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 NOx 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 NOx 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-NOx adsorbers or traps) is required for lean-burn engines to meet emission standards for NOx that are associated with Category 4 and 5 fuels. Manufacturers are working toward ambitious goals for improved fuel consumption/reduced CO_2 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 NOx only during stoichiometric or rich operation. Lean-NOx traps can operate in a lean exhaust environment, but they are highly sensitive to sulphur.

Lean NOx adsorber catalysts function by trapping NOx chemically during lean engine operation. NOx 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 NOx, they reduce the NOx capacity of the adsorber. Sulphur removal requires prolonged rich operating conditions, but the original NOx 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.

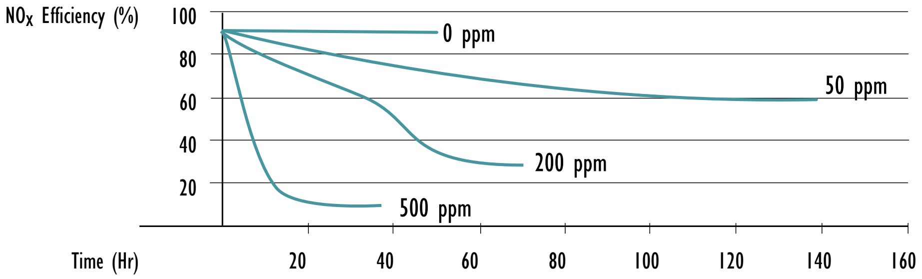
Figure G-7 and Figure G-8 provide examples of the adverse effect of sulphur on storage-type NOx reduction catalysts. With increased exposure time, the lower sulphur gasolines allow the catalysts to retain a higher NOx conversion efficiency. Further tests in vehicles (Figure G-9 and Figure G-10) confirm the critical need for very low sulphur gasolines. Maintaining a high level of NOx 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 NOx conversion efficiencies over time compared with higher sulphur levels. Thus, ultra-low or sulphur-free gasoline is required to achieve and maintain high NOx conversion efficiencies over years of vehicle use.

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



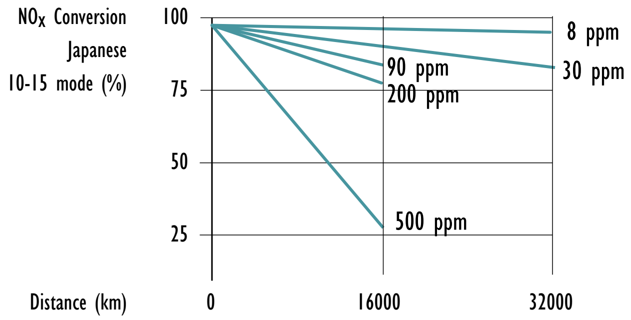
Source: Japan Clean Air Program

Figure G-8: Effect of Fuel Sulphur on Lean NOx Traps, Flow Reactor Study



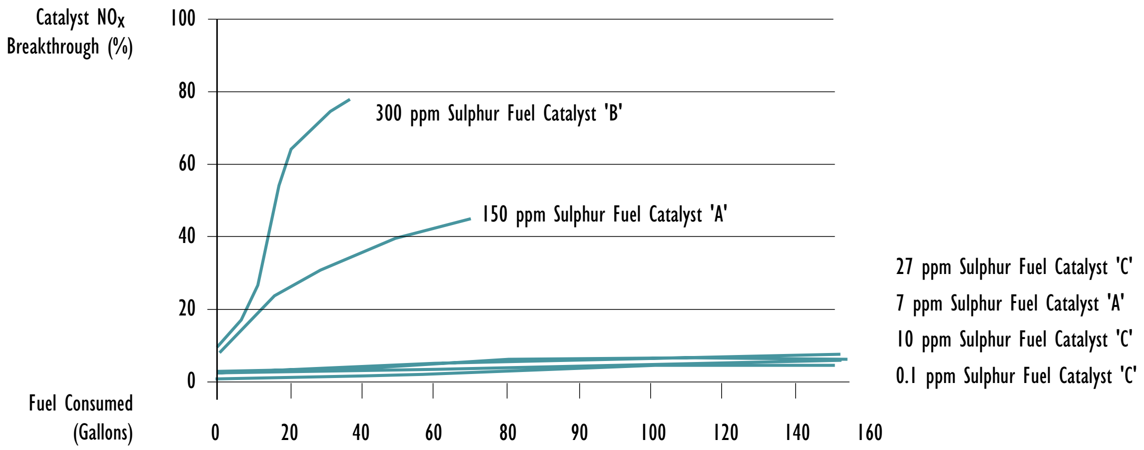
Source: SAE 962051

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



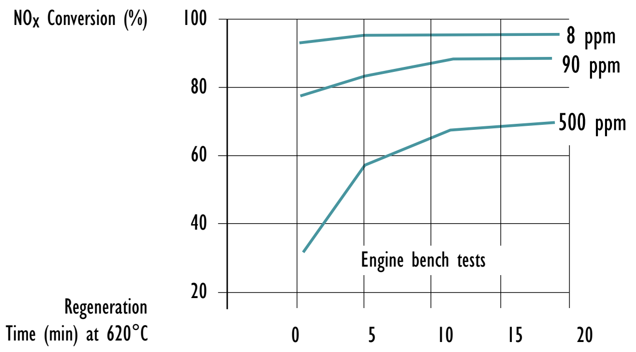
Source: Toyota 1999

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 computerised 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 NOx 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.

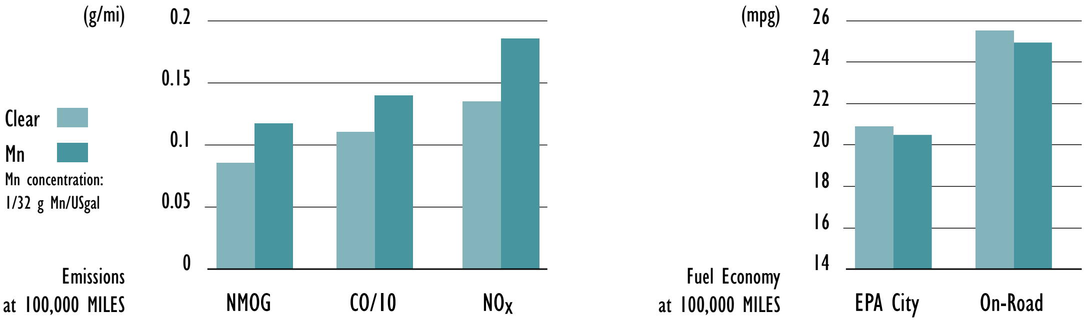
Powertrain and Emission Control System Impacts

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.

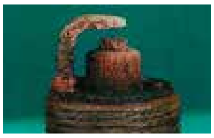
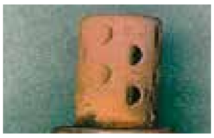
In 2002, automobile manufacturers jointly completed a multi-year study of the real-world impact of MMT on Low Emission Vehicles (LEVs). After 100,000 miles of driving with fuel containing 1/32 g Mn/gal, the test fleet showed significantly increased non-methane organic gases (NMOG), CO and NOx emissions. 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 oxidised 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

	SPARK PLUG	OXYGEN SENSOR	CATALYTIC CONVERTER
MMT TEST FUEL			
MMT-FREE FUEL			

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 computerised 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). 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.

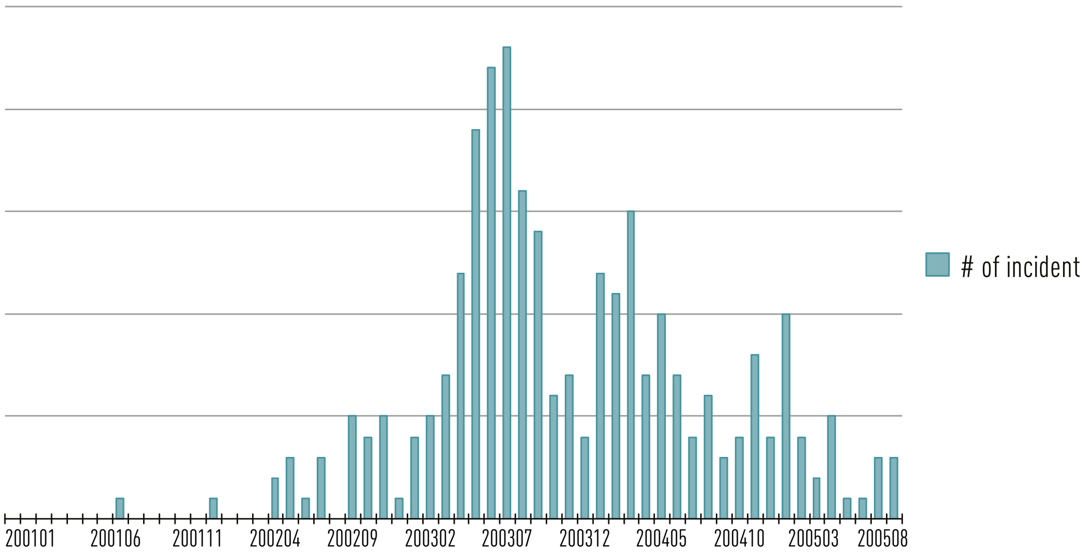
Table G-2: Source of Evidence of Adverse MMT Impacts on Exhaust Emissions, Operation and Performance of In-Use Canadian Vehicles with Advanced Emission Control Technologies and Systems

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 NOx 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's Manual 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

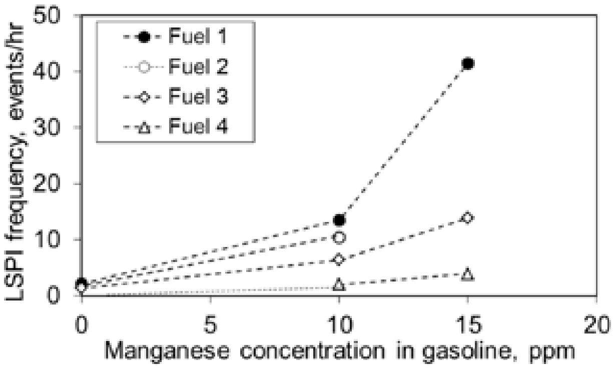
B: South Africa

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.

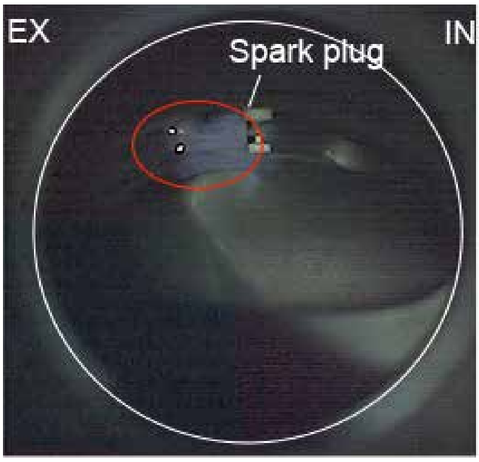
Figure G-16: Low-Speed Pre-ignition Caused by Manganese



	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: Toyota, Soken, 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 Union adopted strict limits on the metallic additive methylcyclopentadienyl manganese tricarbonyl (MMT) that were upheld in 2011 against a legal challenge. The European MMT limit is now 2mg/l, effectively making its use redundant as an octane booster. Also, EU fuels using metallic additives must be specifically labelled 'contains metallic additives' at point of sale.

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 www.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

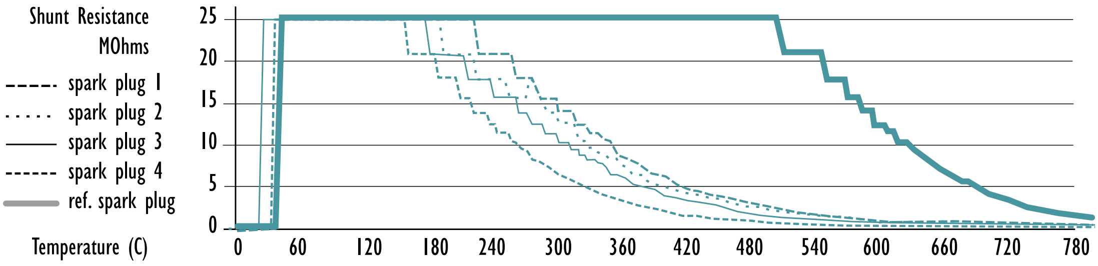
Source: SAE 2006-01-3448, JARI

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.

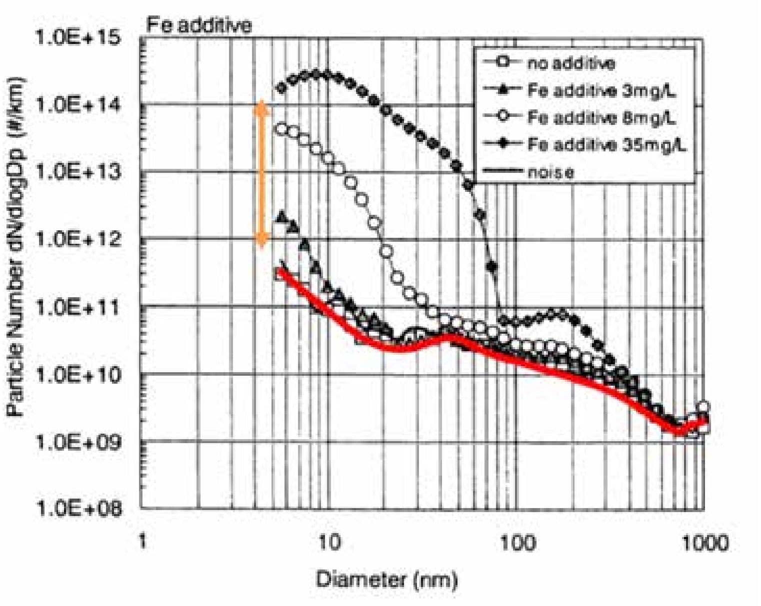
Figure G-20: Insulator Resistance at Temperature Test Results for Spark Plugs Taken from Test Engine after 32 Hours



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 minimise 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 fertilised 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 (zero ethanol content) 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 in 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 or component 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_2 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 NOx 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.

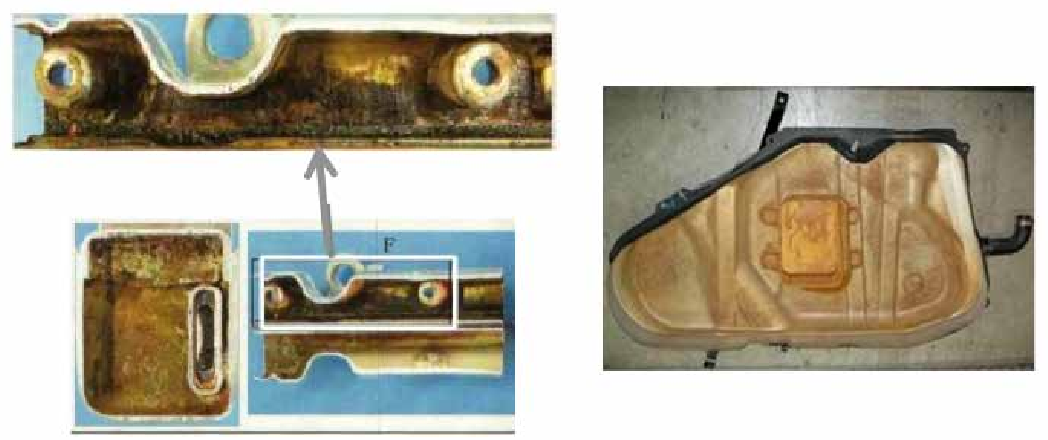
Based on experience with impurities in ethanol that have led to degradation of fuel systems, fuel ethanol must have a specification to control pHe and its blending properties (ASTM D 4806). Also, the limits and restriction on the oxygenates permitted in each Category were developed on the basis of emission 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, coal, captured CO_2 or renewable sources, 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. The use of methanol is only acceptable if: (i) specified by applicable standards (e.g., maximum 3% v/v methanol in standard EN 228); (ii) consumed in vehicles compatible with its use; and (iii) stated in the owner's manual.

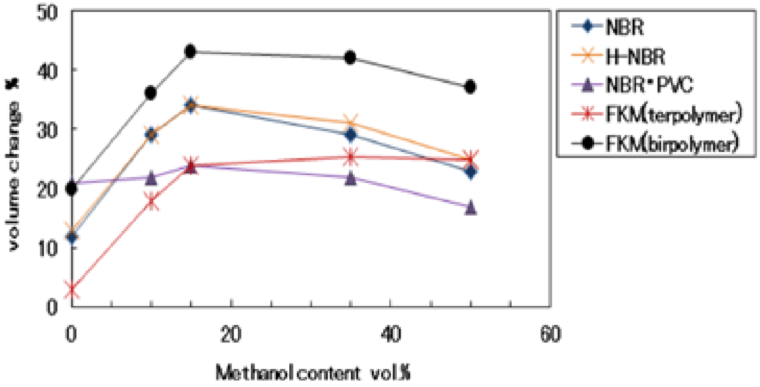
One example of the potential damage is due to corrosion of metallic fuel system components (see Figure G-22). Methanol also can degrade plastics and elastomers or may cause them to swell (see Figure G-23). These impacts can lead to fuel system leaks.

Figure G-22: Fuel System Components Corroded by Methanol



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

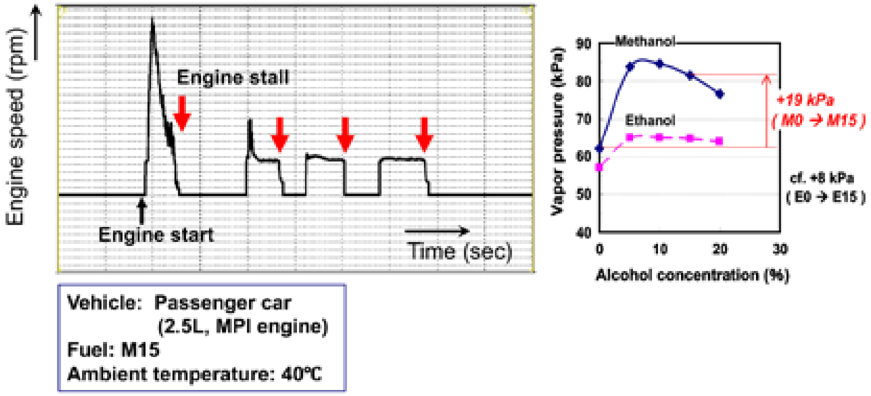
Figure G - 23: Methanol Causes Materials to Swell



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

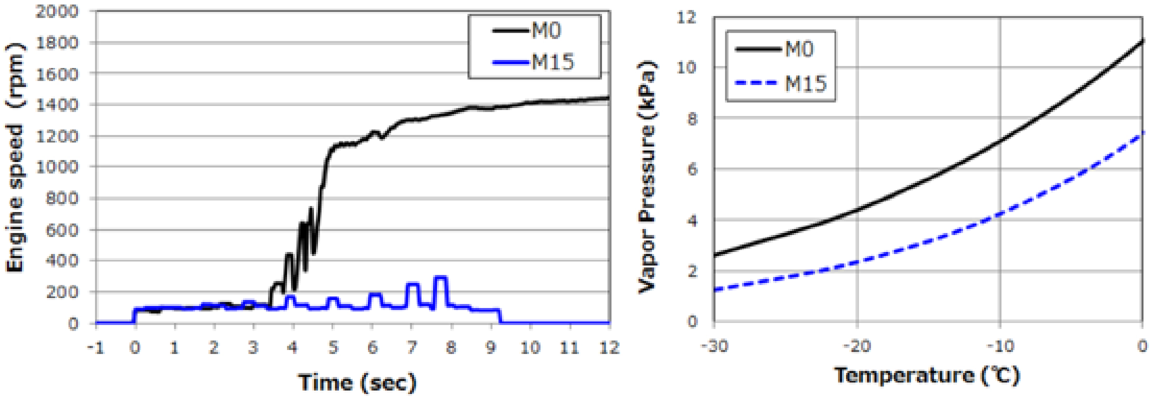
Methanol in gasoline can cause a variety of operational problems. By increasing the vapor pressure at normal temperatures, the fuel mixture can cause hot re-start failure. See Figure G - 24. Cold -start can be a problem, too, since the vapour pressure decreases significantly when the temperature is below 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, 2013

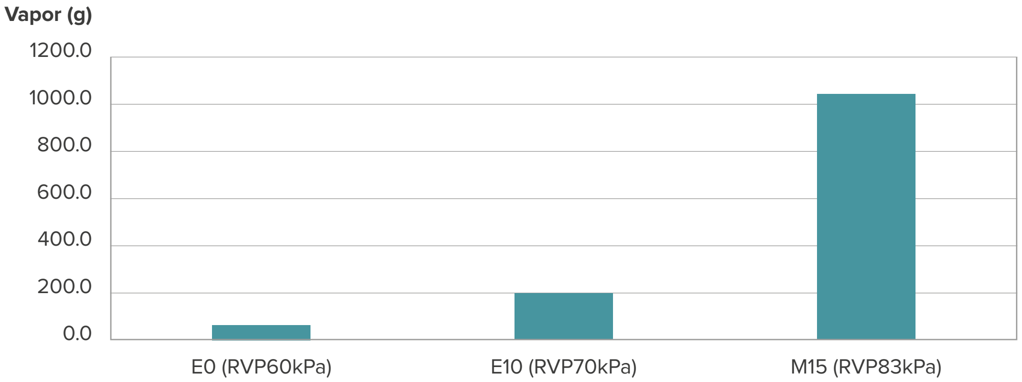
Figure G - 25: Cold-Start Behaviour of M0 vs M15



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

Emissions are also a concern. The fuel's higher vapour pressure at ambient temperatures and pressures may 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. Mitigating these concerns would require vehicles/engines designed for this fuel.

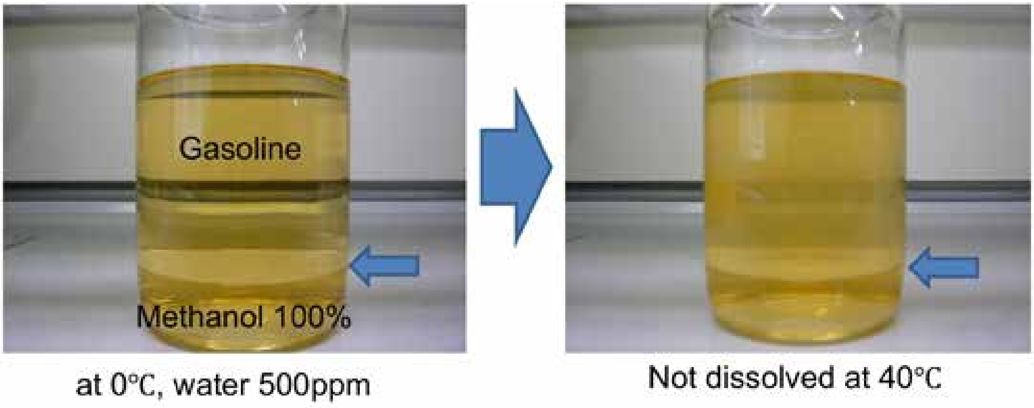
Figure G-26: Vapour Amounts from E0, E10 and M15 on CARB Running Loss Test (start fuel T = 35°C)



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

Another potential 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

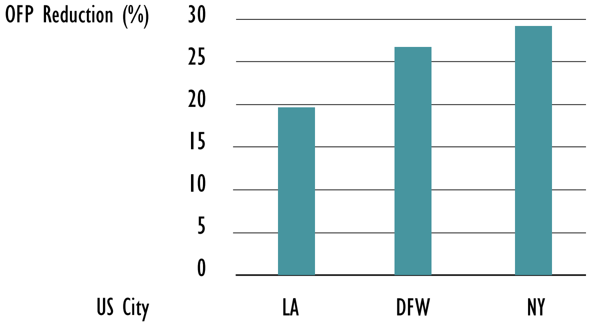
Olefins

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.

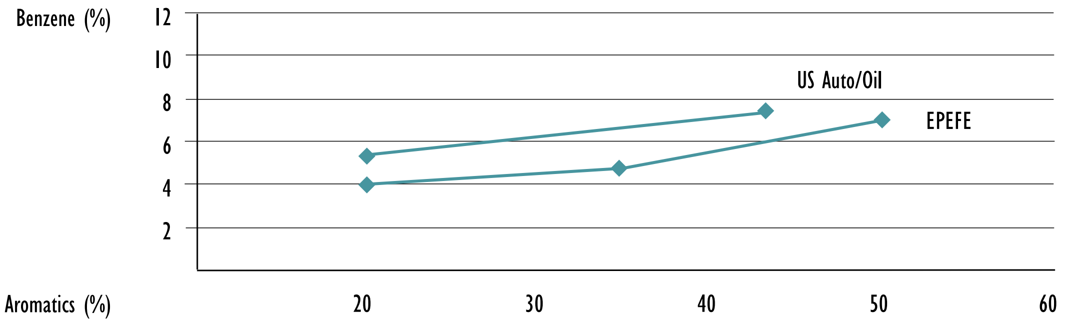
Aromatics

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_2, 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 NOx. Since it is not feasible to specify limits for individual hydrocarbon compounds in the fuel, the total aromatic limit of Categories 3-6 and the final boiling point (EP) limit for Categories 2-4 provide a good means to limit heavy aromatics (see also the section on PMI on page 39).

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_2 emissions. The European EPEFE programme demonstrated a linear relationship between CO_2 emissions and aromatic content. The reduction of aromatics from 50 to 20% was found to decrease CO_2 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, refuelling 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 increased volatility of gasoline components. It can also influence particulate emissions, as explained below on page 39.

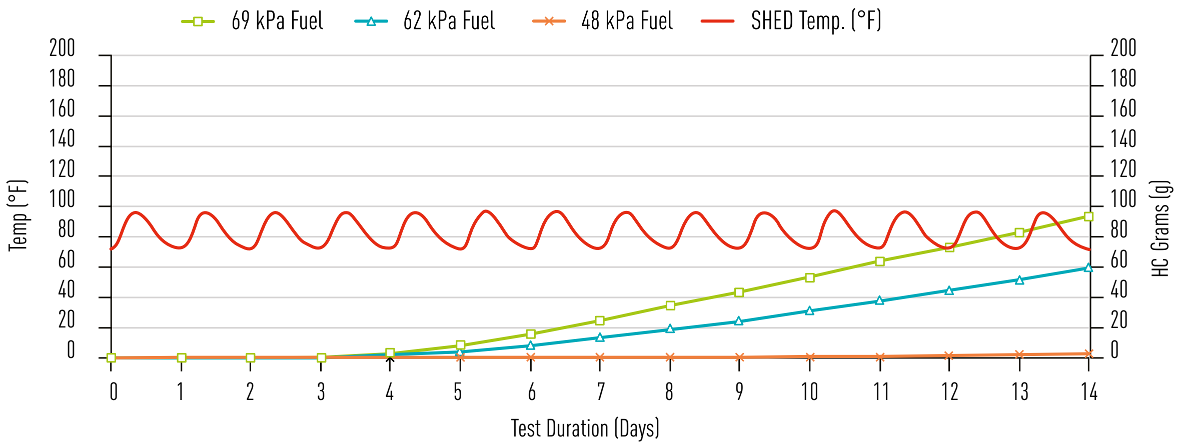
Volatility may be characterised by various measurements, the most common of which are vapour pressure, distillation and the vapour/liquid ratio. The presence of ethanol or other oxygenates may affect these properties and, as a result, performance and emissions as well.

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.

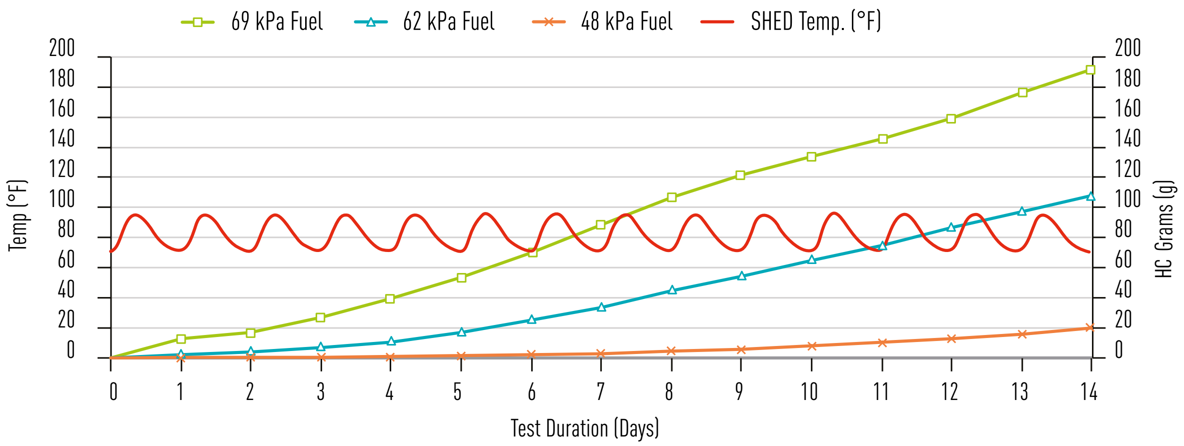
New data have become available on the effects of vapour pressure. Figure G-30 and Figure G-31 provide the hydrocarbon slip from canisters for two sample vehicles tested during study of the effects of 48 (0% ethanol), 62 (0% ethanol) and 69 kPa E10 (10% ethanol gasoline blend) fuels on canister breakthrough 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

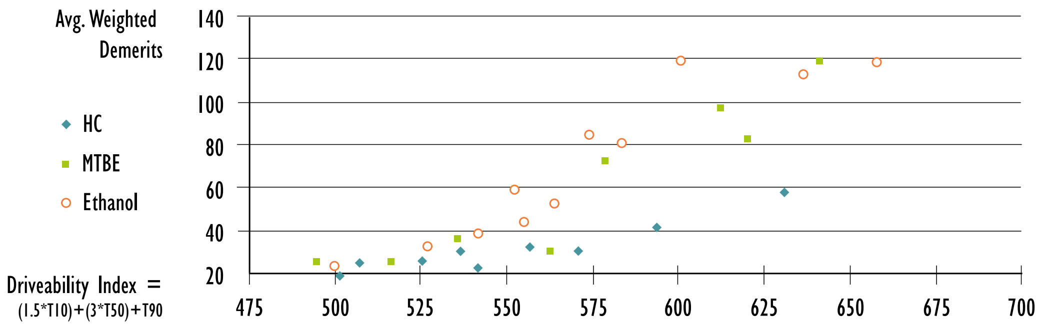


Source: SAE 2013-01-1057

Distillation
Distillation of gasoline yields either a set of ‘T’ points (T50 is the temperature at which 50% of the gasoline distils) 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.

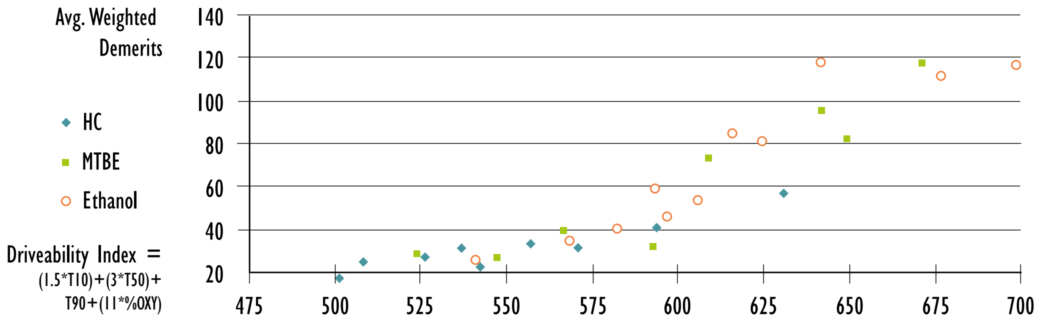
Figure G-32: Effect of Driveability Index on Driveability



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 smoothes the data presented in Figure G-32.

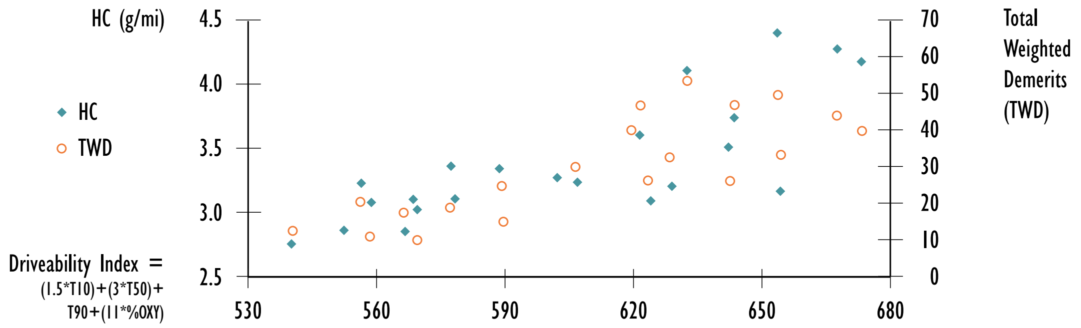
Figure G-33: Effect of Driveability Index (Oxygen Corrected) on Driveability



Source: CRC Report No. 605

Driveability Index 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.

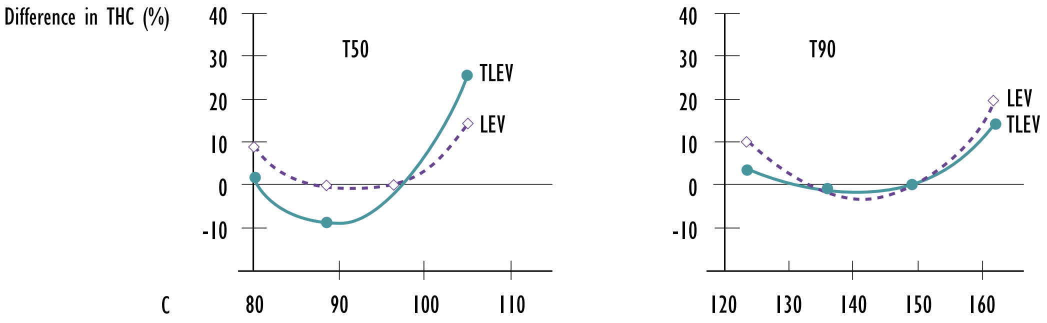
Figure G-34: Effect of Oxygen-Corrected Driveability Index on Driveability and Exhaust Emissions



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

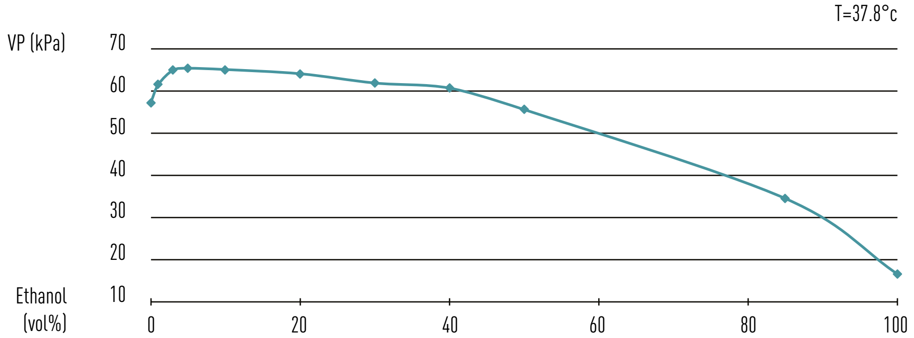
Excessively high gasoline volatility can cause hot fuel handling problems such as vapour lock, canister overloading, and higher emissions. Vapour lock occurs when too much vapour forms in the fuel system and decreases or blocks fuel flow to the engine. This can result in loss of power, rough engine operation 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.

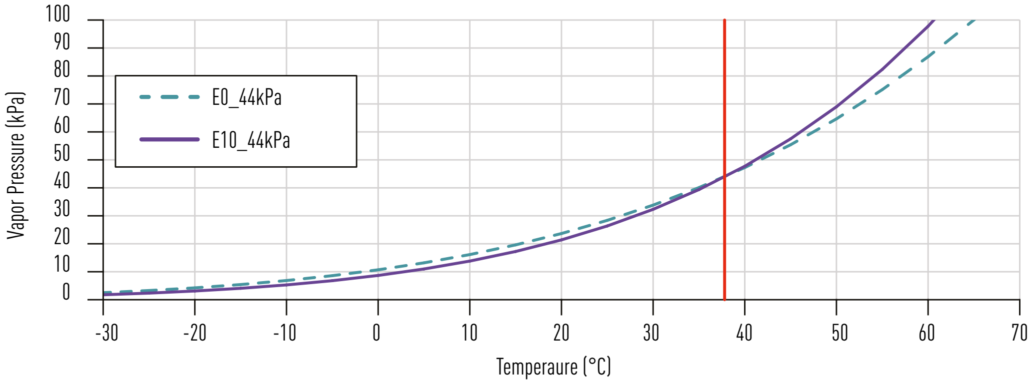
Figure G-36: Impact of Ethanol Level on Vapour Pressure at 37.8°C



Source: Toyota, 2005

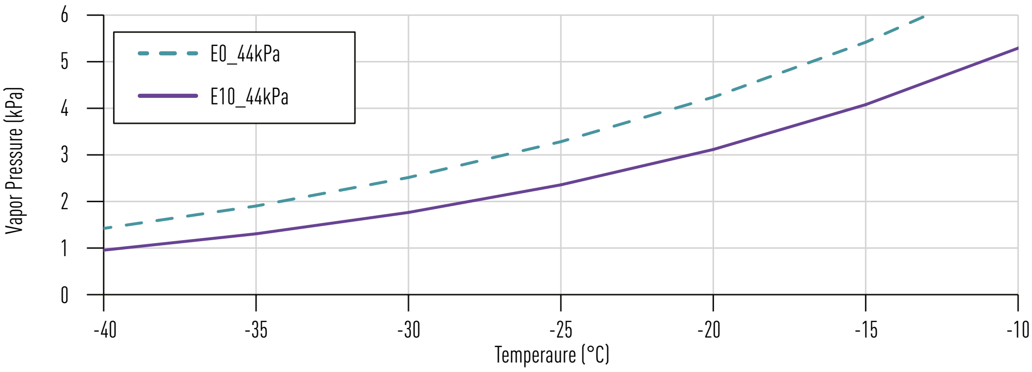
Figure G-37, below, looks more closely at the variation for an E10 and its base gasoline (E0), showing the impact for a wider range of temperatures. Importantly, at temperatures above 37.8°C, the E10 has a higher vapour pressure relative to E0, but at lower temperatures, the vapour pressure goes below 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

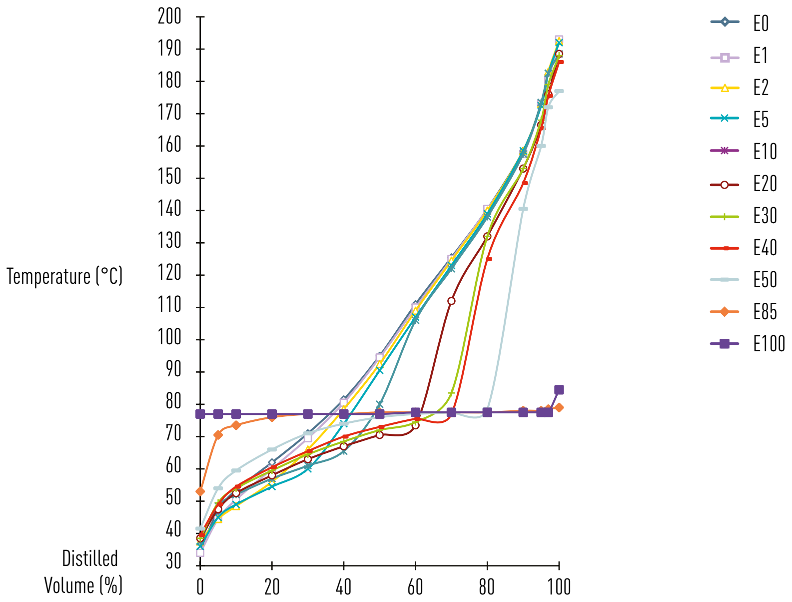
Figure G-38: Magnification of Figure G-37 at Temperatures Below Freezing



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).

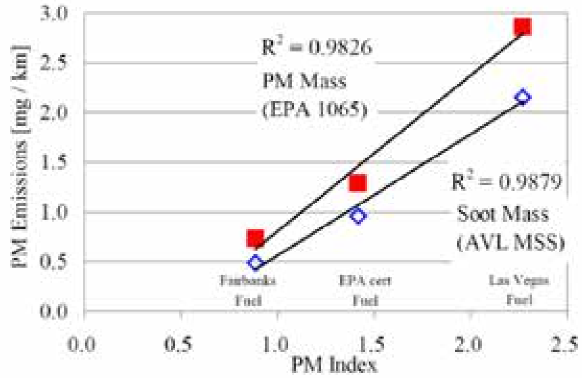
PMI is an analytically derived value based on several inputs: the double bond equivalence (DBE), vapor pressure at 443°K and the weight fraction of each component in the fuel, as shown below in Equation G-3.
Equation G-3: Particulate Matter Index

$$\mathbf{PMI} = \sum_{i=1}^{n}\left(\left(\frac{\mathbf{DBE}_i + \mathbf{1}}{\mathbf{VP\ (443K)}}\right) \mathbf{x\ Wt}_i\right)$$

Source: Aikawa et al, SAE 2010-01-2115.

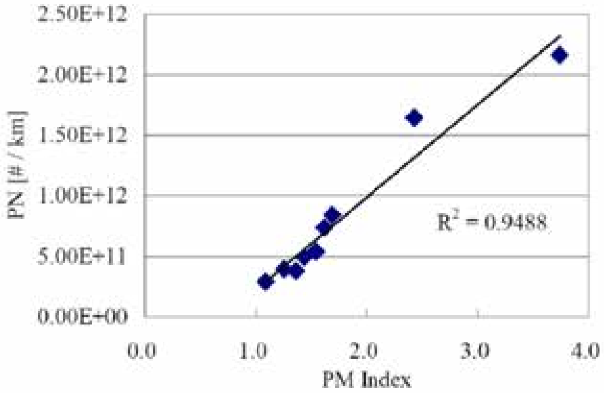
As Figure G-40 and Figure G-41 show, PMI correlates well with both particulate number (PN) and particulate matter mass (PM) emissions, in the same direction, i.e., the higher the PMI value, the higher the observed PN and PM emissions.

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



Source: Aikawa et al, SAE 2010-01-2115.

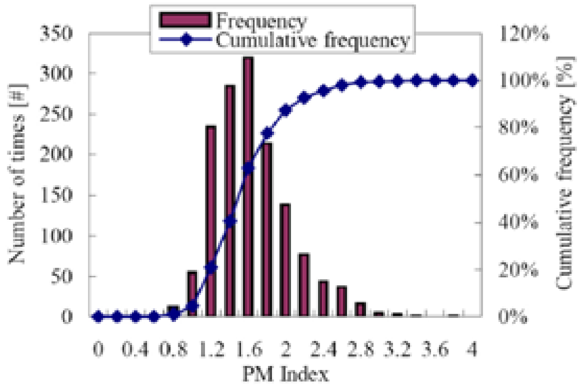
Figure G-41: Relationship Between PMI and Particulate Number Emissions on the New European Driving Cycle



Source: Aikawa et al, SAE 2010-01-2115.

Figure G-42 below, shows 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

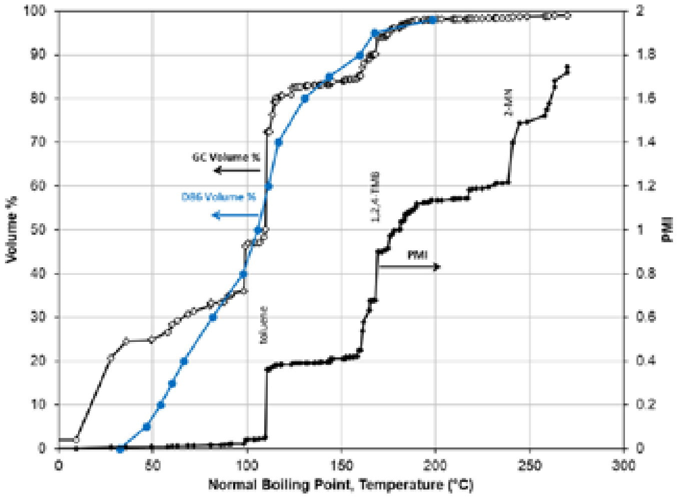


Sampled Countries
Japan
Brazil
China
India
Other Asian countries
United States
European Union countries
Europe (non-EU including Russia)
Middle East countries
Oceania countries

Source: Aikawa et al, SAE 2010-01-2115.

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). Minimising 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 minimise 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 nine or more carbon atoms contribute disproportionately to PM formation in the exhaust gas. See Figure G-43, above. Since C9 and higher 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

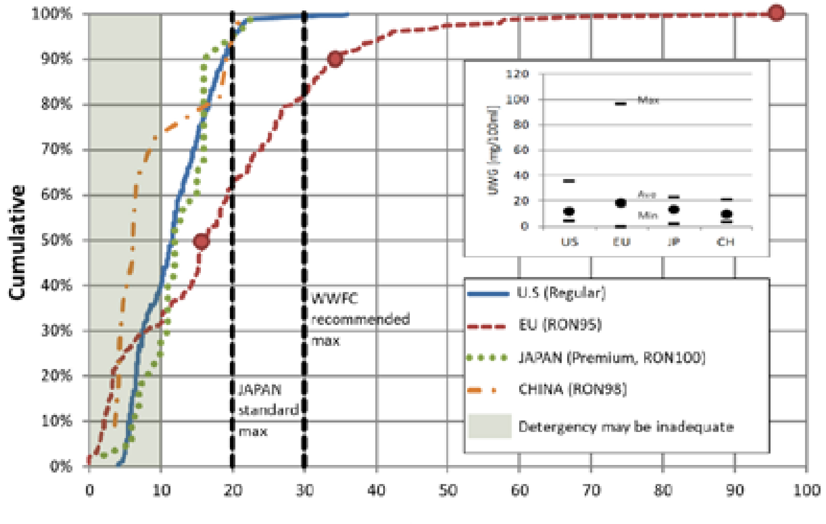
Combustion of even good quality gasoline can lead to deposit formation that will increase engine-out emissions and affect vehicle performance. Deposit control additives can help reduce or minimise these deposits as long as they are used properly. High quality fuel contains a sufficient amount of deposit 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 additive 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 deposit control additive. 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.

Additive 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 deposit control additive. One finding is that European gasoline tends to have very high treat rates compared to fuel from the US, Japan and China.

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



source: WWFS(US, EU, CH), JARI(JP)

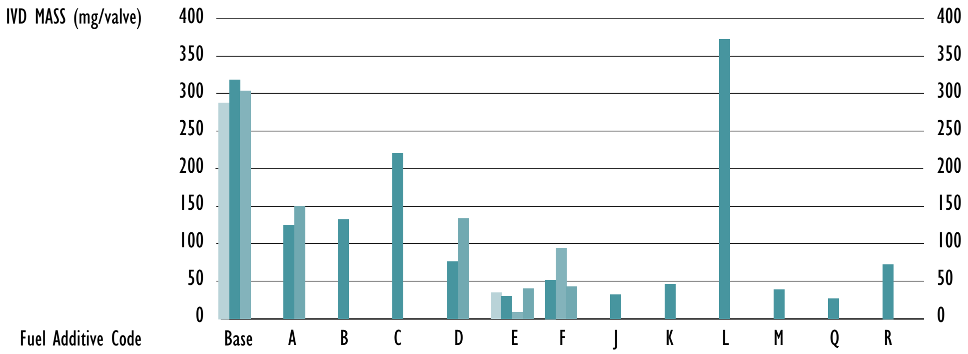
Source: The SGS Worldwide Fuel Survey and JARI.

Deposit Control Additive Development
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 deposit control. 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 deposit control additives, resulting in increased intake valve deposits in many cases. Deposit control additive technology and test procedures are being developed to protect the more advanced injectors being introduced in direct injection engines. New test methods also are needed for engines with modern port fuel injectors.

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 deposit control additives with fuels having various 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 Deposit Control Additives, Using the Ford 2.3L Dynamometer Test

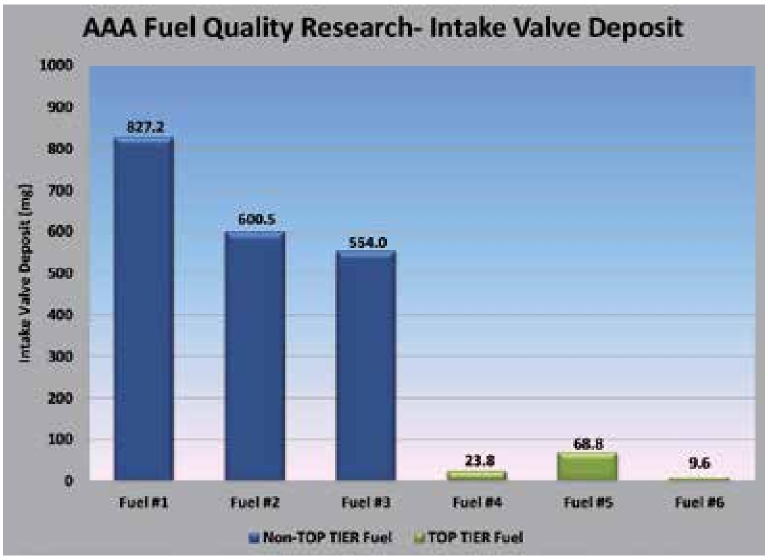


Source: Ford, 1996

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 deposit control for minimising 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 treat rates compared to fuel formulated to the TOP TIER™ gasoline performance standard. See AAA.com at 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 levels of deposit control.

Figure G - 46: Results of AAA Study of US Gasoline Deposit Control


AAA Fuel Quality Research- Intake Valve Deposit

Source: American Automobile Association, 2016.

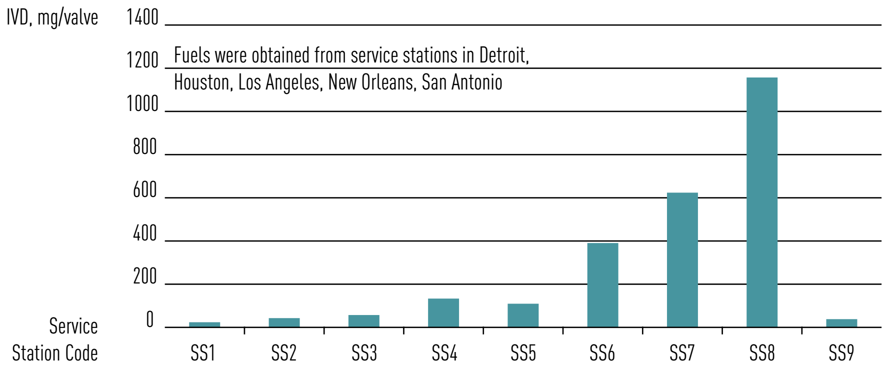
Figure G - 47: Impact of Different Levels of Gasoline Deposit Control on Two Intake Valves


AAA Fuel Quality Research: Intake Valve Comparison

*Among gasoline brands tested.
Full report available at 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

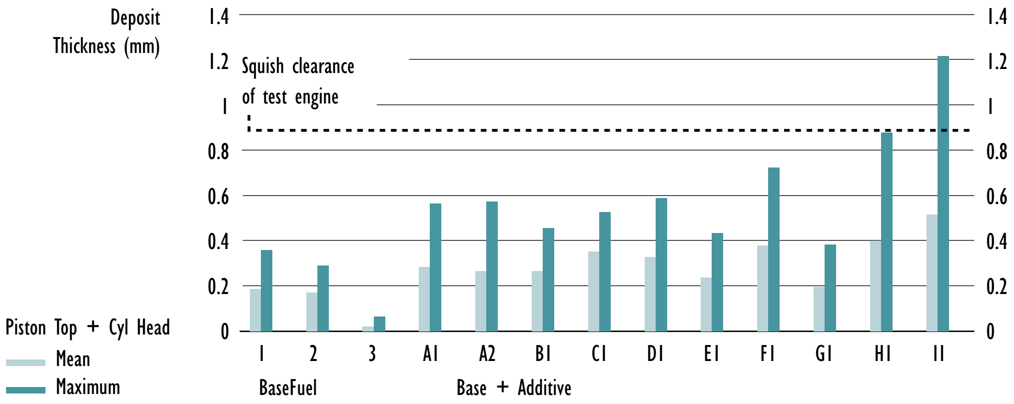
Combustion Chambers

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-20-98, for example, which is no longer supported, produced technically relevant results when the engine operator had detailed knowledge about the measurement precision of the particular test stand, but in general, the method lacked precision data and could not produce statistically valid CEC results for chamber deposits.

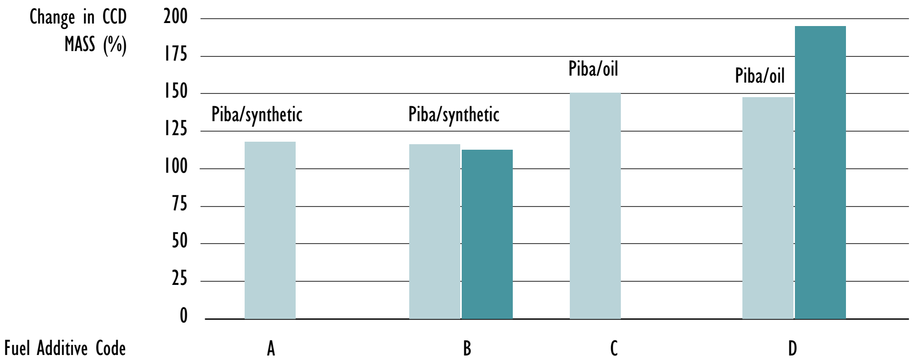
Certain deposit control additives can increase the level of CCDs relative to base fuel, as shown in Figure G-49 and Figure G-50. Additive packages with higher ratios of mineral oil carriers tend to increase CCDs, while packages with optimised high-quality synthetic carrier fluids and compounds like polyether 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)

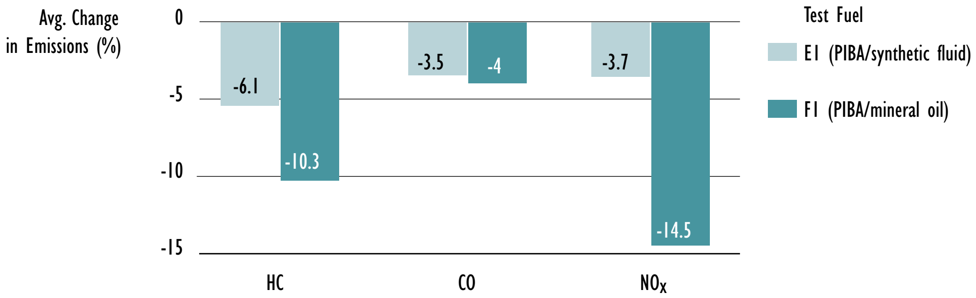


Source: Ford, 1996

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 NOx 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

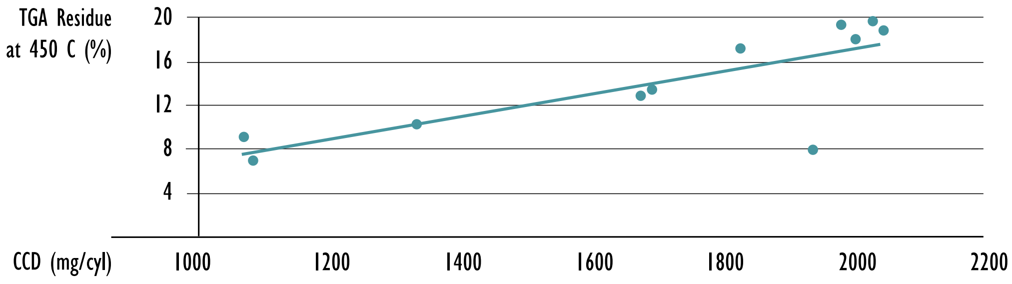


Source: Ford, SAE 962012

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.

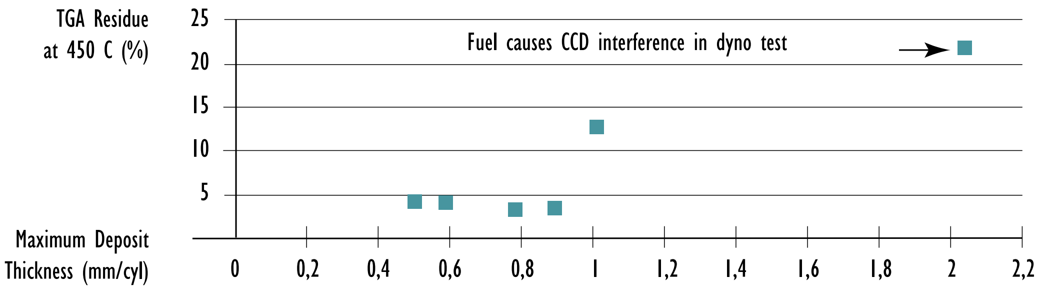
A thermogravimetric analysis (TGA) bench test method has been developed that provides a good correlation with CCDs in a dynamometer-based multi-cylinder engine test as shown in Figure G - 52 and Figure G - 53.

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



Source: Ford, ASTM 2003

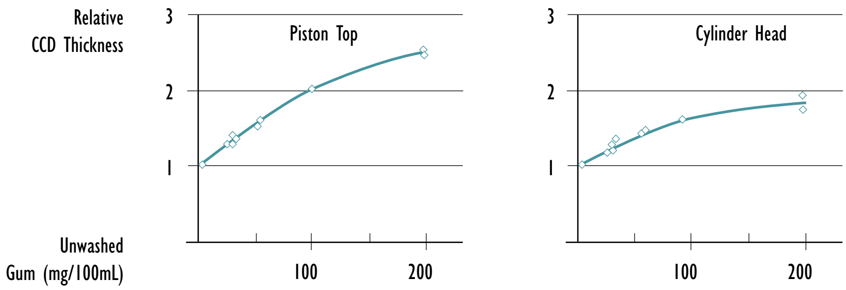
Figure G-53: TGA Proposed Pass/Fail Limit-4.0L Dynamometer Test Results



Source: Ford, SAE 962012

Figure G-54 indicates the correlation between unwashed gums and CCD formation as compared to base gasoline without deposit control additive. 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. Deposit control 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_2S), 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/additive performance).

One way to minimise 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 – Retired Category 1

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' [1]	Research Octane Number		91.0	
	Motor Octane Number		82.0	
95 RON' [1]	Research Octane Number		95.0	
	Motor Octane Number		85.0	
98 RON' [1]	Research Octane Number		98.0	
	Motor Octane Number		88.0	
Oxidation stability		minutes	360	
Sulphur		mg/kg [2]		1000
Trace metal [3]		mg/kg	1 or non-detectable, whichever is lower	
Oxygen [4]		% m/m		2.7 [5]
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^3	715	780
Copper corrosion		rating		Class 1
Appearance			Clear and bright; no free water or particulates	
Carburettor cleanliness		merit	8.0 [6]	
Fuel injector cleanliness, Method 1, or		% flow loss		10 [6]
Fuel injector cleanliness, Method 2		% flow loss		10 [6]
Intake valve cleanliness		merit	9.0 [6]	

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[1] Three octane grades are defined for maximum market flexibility; availability of all three is not needed.

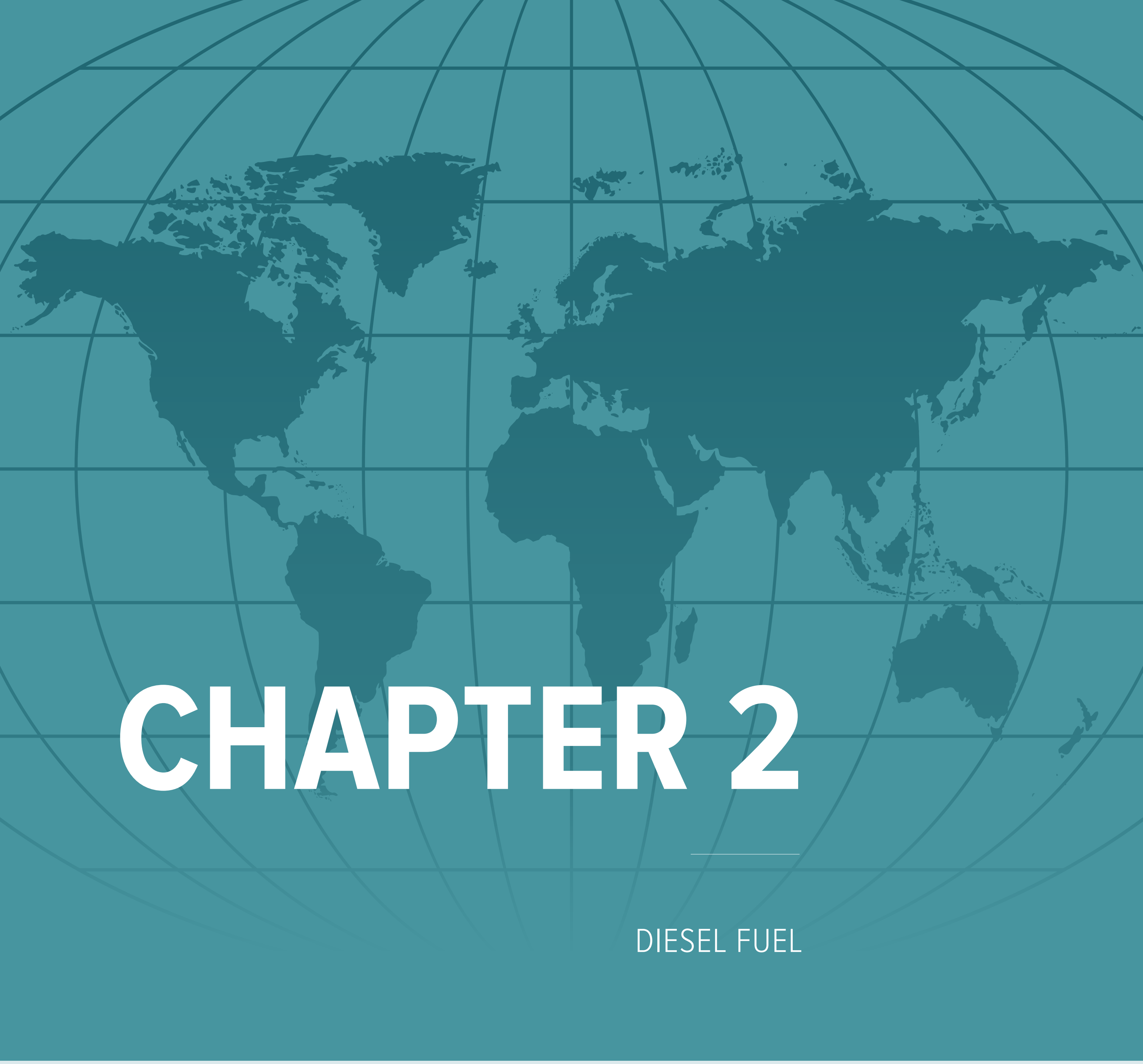
[2] The unit mg/kg is often expressed as ppm. Lower sulphur content preferred for catalyst-equipped vehicles.

[3] 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.

[4] Where oxygenates are used, ethers are preferred. Methanol is not permitted.

[5] 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.

[6] 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

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 light-duty vehicle 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, current EU CO_2 targets, China 6a, China 6b or equivalent emission control and fuel efficiency standards, or other market demands. This category is intended to minimise real driving emissions (RDE) to levels required for Euro 6dTEMP (from 2017), Euro 6d (from 2020), Euro VI 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. Vehicle/engine 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 Fatty Acid Methyl Esters (FAME, also known as 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 required under local standards and 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 minimise contamination from dust, water, incompatible fuels and other 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 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.

		LIMITS	
PROPERTIES	**UNITS**	**MIN**	**MAX**
Cetane Number		48.0	
Cetane Index [1]		48.0 (45.0) [1]	
Density @ 15°C	kg/m^3	820 [2]	860
Viscosity @ 40°C	mm^2/s	2.0 [3]	4.5
Sulphur [4]	mg/kg		2000 [5]
T95	°C		370
Flash point	°C	55 [6]	
Carbon residue	% m/m		0.30
CFPP or LTFT or CP	°C		Equal to or lower than the lowest expected ambient temperature [7]
Water	mg/kg		500
Oxidation stability [8]			
Method 1	g/m^3		25
Method 2a (Rancimat, modified), or	hours	30	
Method 2b (Delta TAN), or	mg KOH/g		0.12
Method 2c (PetroOxy)	minutes	60	
FAME [9]	% v/v		5%
Other biofuels [10]	% v/v		
Copper corrosion	rating		Class 1
Ethanol/Methanol	% v/v		Non-detectable [11]
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

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[1] 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.

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

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

[4] The unit 'mg/kg' is often expressed as ppm.

[5] 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.

[6] The minimum limit can be relaxed to 38°C when ambient temperatures are below -30°C.

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

[8] 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. Some cetane improvers may interfere with Method 2c due to its high temperature test condition.

[9] 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.

[10] Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

[11] 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 [1]		51.0 (48.0) [1]	
Density @ 15°C	kg/m^3	815 [2]	850
Viscosity @ 40°C	mm^2/s	2.0 [3]	4.0
Sulphur [4]	mg/kg		300
Trace metal [5]	mg/kg		Non-detectable
Total aromatics	% m/m		25
PAH (di+, tri+)	% m/m		5
T90 [6]	°C		340
T95 [6]	°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 [7]
Water	mg/kg		200 [8]

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[1] 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.

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

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

[4] The unit 'mg/kg' is often expressed as ppm.

[5] 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.

[6] Compliance with either T90 or T95 is required.

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

[8] May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability [9]			
Method 1	g/m^3		25
Method 2a (Rancimat, modified), or	hours	35	
Method 2b (Delta TAN), or	mg KOH/g	0.12	
Method 2c (PetroOxy)	minutes	65	
Biological growth [10]			Zero content
FAME [11]	% v/v		5
Other biofuels [12]	% v/v		
Ethanol/Methanol	% v/v		Non-detectable [13]
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

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[9] 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. Some cetane improvers may interfere with Method 2c due to its high temperature test condition.

[10] Alternative test methods, with appropriate limits for no biological growth, can be used.

[11] 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.

[12] Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

[13] 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.

		LIMITS	
PROPERTIES	UNITS	MIN	MAX
Cetane Number		53.0	
Cetane Index [1]		53.0 (50.0) [1]	
Density @ 15°C	kg/m^3	815 [2]	840
Viscosity @ 40°C	mm^2/s	2.0 [3]	4.0
Sulphur [4]	mg/kg		50
Trace metal [5]	mg/kg		Non-detectable
Total aromatics	% m/m		20
PAH (di+, tri+)	% m/m		3.0
T90 [6]	°C		320
T95 [6]	°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 [7]
Water	mg/kg		200 [8]

[1] 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.
[2] May relax minimum limit to 800 kg/m^3 for fuels used in low temperature conditions (cloud point below -10°C).
[3] May relax minimum limit to 1.5 mm^2/s when ambient temperatures are below -30°C or to 1.3 mm^2/s when ambient temperatures are below -40°C.
[4] The unit 'mg/kg' is often expressed as ppm.
[5] 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.
[6] Compliance with either T90 or T95 is required.
[7] If compliance is demonstrated by meeting CFPP, then it must be no more than 10°C less than cloud point
[8] May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability [9]			
Method 1	g/m^3		25
Method 2a (Rancimat, modified), or	hours	35	
Method 2b (Delta TAN), or	mg KOH/g		0.12
Method 2c (PetroOxy)	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth [10]			Zero content
FAME [11]	% v/v		5
Other biofuels [12]	% v/v		
Ethanol/Methanol	% v/v		Non-detectable [13]
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

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[9] 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. Some cetane improvers may interfere with Method 2c due to its high temperature test condition.

[10] Alternative test methods, with appropriate limits for “no biological growth,” can be used.

[11] 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.

[12] Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

[13] 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 NOx and PM after-treatment technologies.

		LIMITS	
PROPERTIES	**UNITS**	**MIN**	**MAX**
Cetane Number		55.0	
Cetane Index [1]		55.0 (52.0) [1]	
Density @ 15°C	kg/m^3	815 [2]	840
Viscosity @ 40°C	mm^2/s	2.0 [3]	4.0
Sulphur [4]	mg/kg		10
Trace metal [5]	mg/kg		Non-detectable
Chlorine	mg/kg		Non-detectable
Total aromatics	% m/m		15
PAH (di+, tri+)	% m/m		2.0
T90 [6]	°C		320
T95 [6]	°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 [7]
Water	mg/kg		200 [8]

[1] 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.

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

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

[4] The unit ‘mg/kg’ is often expressed as ppm.

[5] 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.

[6] Compliance with either T90 or T95 is required.

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

[8] May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability [9]			
Method 2a (Rancimat, modified), or	hours	35	
Method 2b (Delta TAN), or	mg KOH/g		0.12
Method 2c (PetroOxy)	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth [10]			Zero content
FAME [11]	% v/v		5
Other biofuels [12]	% v/v		
Ethanol/Methanol	% v/v		Non-detectable [13]
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) and	% 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

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[9] 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. Some cetane improvers may interfere with Method 2c due to its high temperature test condition.

[10] Alternative test methods with appropriate limits for "no biological growth" can be used.

[11] 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.

[12] Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

[13] 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 vehicle 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_2 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 minimise real driving emissions (RDE) required for Euro 6d TEMP (from 2017), Euro 6d (from 2020) and China 6b (from 2023). Enables sophisticated NOx and PM after-treatment technologies.

		LIMITS	
PROPERTIES	**UNITS**	**MIN**	**MAX**
Cetane Number		55.0	
Cetane Index [1]		55.0 (52.0) [1]	
Density @ 15°C	kg/m^3	815 [2]	840
Viscosity @ 40°C	mm^2/s	2.0 [3]	4.0
Sulphur [4]	mg/kg		10
Trace metal [5]	mg/kg		Non-detectable
Chlorine	mg/kg		Non-detectable
Total aromatics	% m/m		15
PAH (di+, tri+)	% m/m		2.0
T90 [6]	°C		320
T95 [6]	°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 [7]
Water	mg/kg		200 [8]

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[1] 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.

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

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

[4] The unit mg/kg is often expressed as ppm.

[5] 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.

[6] Compliance with either T90 or T95 is required.

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

[8] May use a Haze Clarity Index (HCI) of 90 minimum as an alternative.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Oxidation stability [9]			
Method 2c (PetroOxy)	minutes	65	
Foam volume	ml		100
Foam vanishing time	sec.		15
Biological growth [10]			Zero content
FAME			Non-detectable
Other biofuels [11]			
Ethanol/Methanol	% v/v		Non-detectable [12]
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) and	% 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

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[9] Some cetane improvers may interfere with Method 2c due to its high temperature test condition.

[10] Alternative test methods with appropriate limits for "no biological growth" can be used.

[11] Other biofuels include HVO and BTL. Blending level must allow the finished fuel to meet all the required specifications.

[12] 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, EN 16906 [1]
Cetane Index		4264	D4737	K 2280	
Density @ 15°C	kg/m^3	3675	D4052	K 2249	
		12185			
Viscosity @ 40°C	mm^2/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^3	12205	D2274 D7462 [2]		
Method 2a (Rancimat, modified)	induction time (hours)				EN 15751
Method 2b (Delta TAN) [3]	mg KOH/g		D664		
Method 2c (PetroOxy) [4]	minutes		D7545		EN 16091
Foam volume	ml				NF M 07-075
Foam vanishing time	sec.				NF M 07-075

[1] ASTM D6890 and D7170 and EN 16906 measure Derived Cetane Number (DCN) and are being widely used as alternatives to D613.

[2] D2274 can be used with B0; D7462 is good for blends with up to 7% v/v FAME.

[3] Measure Acid Number using D664 before and after aging fuel per D2274 (modified – 115°C).

[4] Method 2c correlation data are based on fuels containing FAME, but the method may be used for FAME-free diesel fuel. Some cetane improvers may interfere with the method due to its high temperature test condition.

PROPERTIES	UNITS	ISO	ASTM	JIS	Other
Biological growth					NF M 07-070, IP385 [4]
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 (3 hrs, 50°C)	merit	2160	D130	K 2513	
Appearance			D4176		Visual inspection
Ash [5]	% m/m	6245	D482 [6]	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 F-23-01
Injector cleanliness, Method 2	% power loss				CEC F-98-08
Injector cleanliness, Method 3	Rank (demerits scale)				CEC F-110-16 [7]
Filter Blocking Tendency			D2068 Procedure B		
Lubricity (HFRR wear scar diameter @ 60°C)	micron	12156-1.3	D6079		
Trace metal	mg/kg		D7111 mod. & D8110		
Chlorine	mg/kg		D7359 or D7536		

[4] Alternative test methods, with appropriate limits for “no biological growth,” can be used.
[5] Limit and test method are under review to assure diesel particulate filter (DPF) endurance.
[6] Minimum 100 g sample size.
[7] Also known as DW10C. Method is under review.

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). Higher cetane provides 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 additised 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.

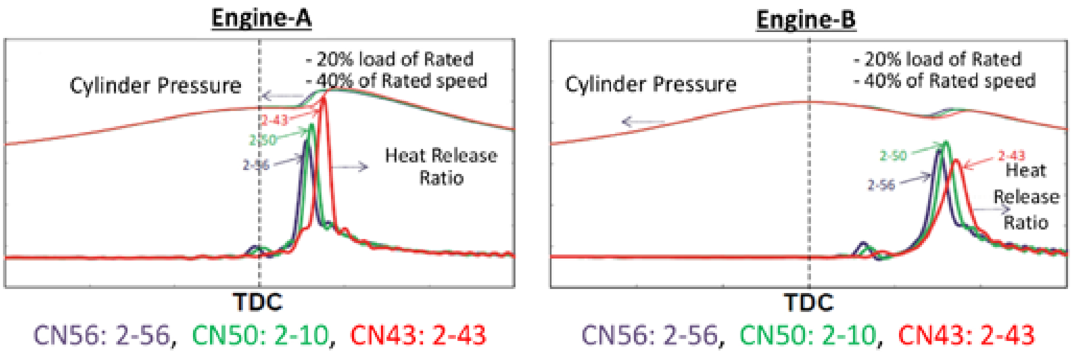
Influence of Cetane on Cold Startability

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 NOx 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 NOx 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.

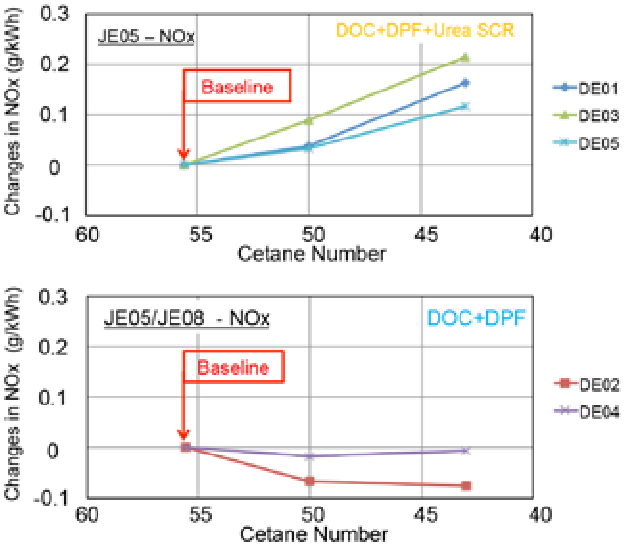
Figure DF-1: Cetane Number's Impact on Combustion in Two Engines



Source: JATOP II, 2015

The same JATOP-II study examined the influence of cetane on engine-out NOx, verifying the effect in JE05 mode using 2009 JP-compliant engines. It found that, when the cetane number was decreased, engine-out NOx increased in vehicles equipped with emission control equipment (DOC, DPF and SCR) whereas engines without such equipment 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 NOx to cetane.

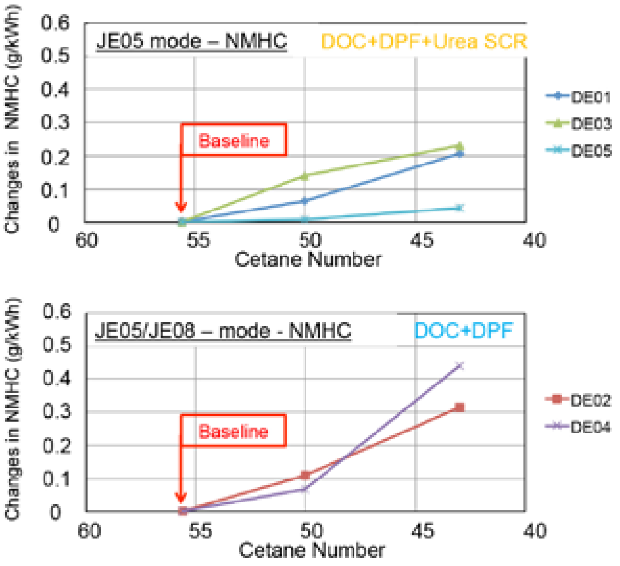
Figure DF-2: Influence of Cetane Number on Engine Out NOx (2009 JP compliant engines/vehicles)



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 showed 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)

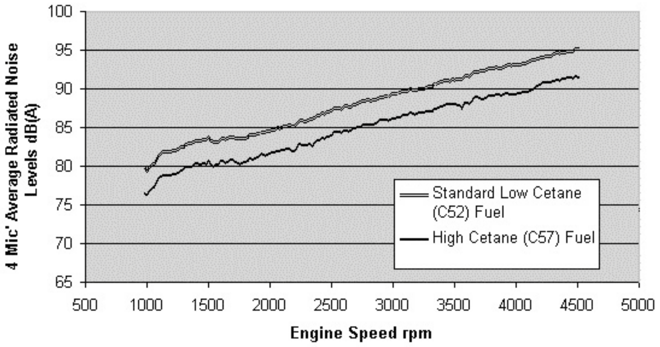


Source: Produced by JAMA using published data from JATOP II

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

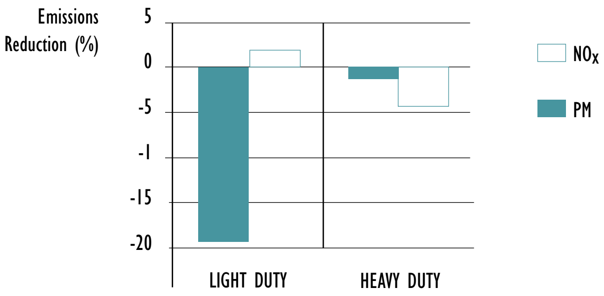
Density And Viscosity

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 NOx emissions from heavy-duty vehicles (Figure DF-5).

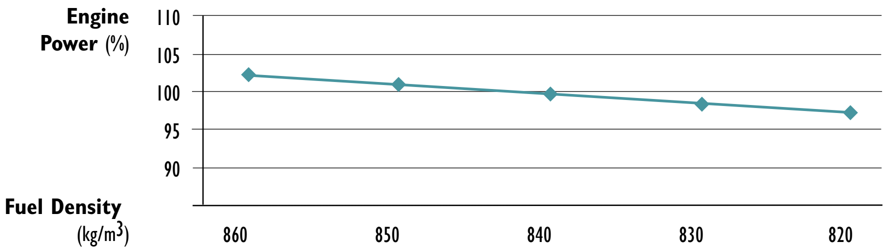
Figure DF-5: Effect of Density on Exhaust Emissions 855 to 828 kg/m^3



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



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.

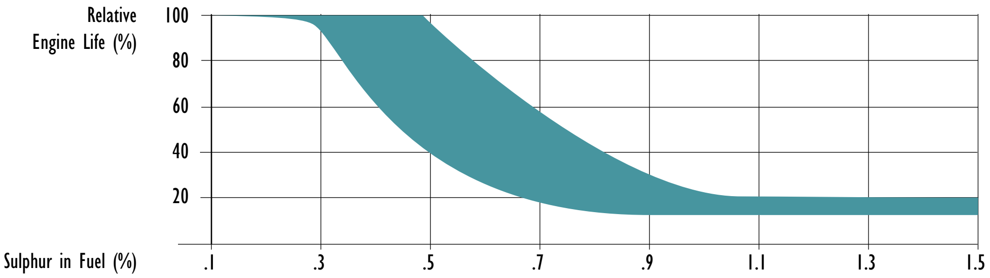
Sulphur

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 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 NOx 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 Vehicle/Engine 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



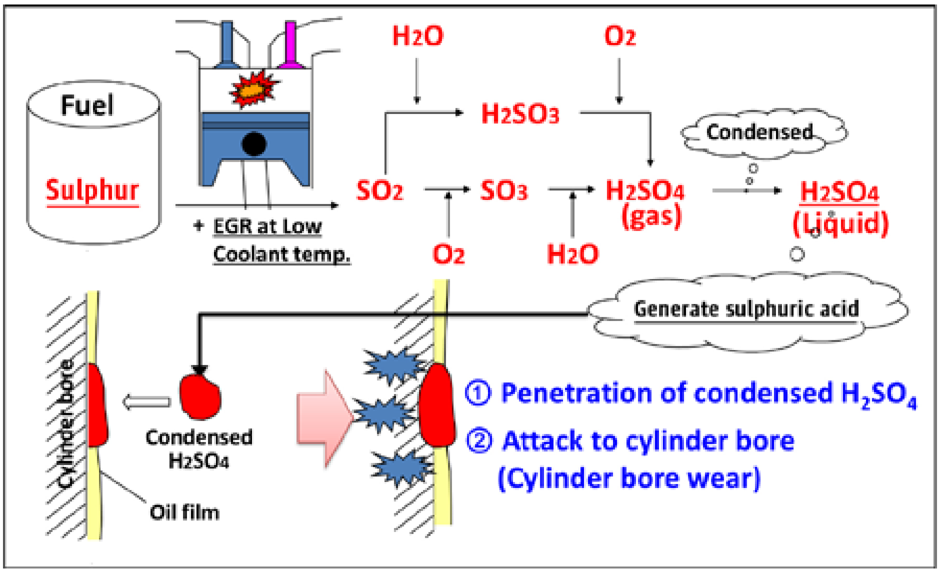
Source: Detroit Diesel

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 NOx emission standards. These technologies require diesel fuel with a low enough sulphur level to maintain proper vehicle operation. Fuel sulphur oxidises to sulphates during combustion, and some portion of that oxidised 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

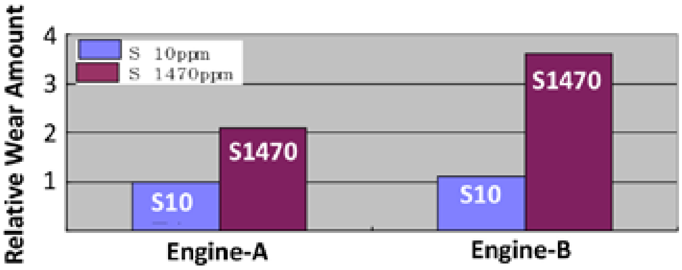
Figure DF-9: Mechanism of Sulphuric Acid Attack



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

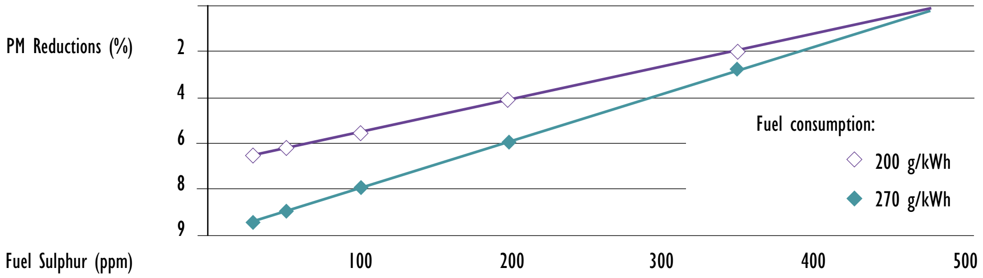


Source: Hino

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 in 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 SO_2, which is the primary sulphur compound emitted from the engine. Some of the SO_2 is further oxidised — in the engine, exhaust, catalyst or atmosphere — to sulphate (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 SO_2 will be oxidized to 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 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

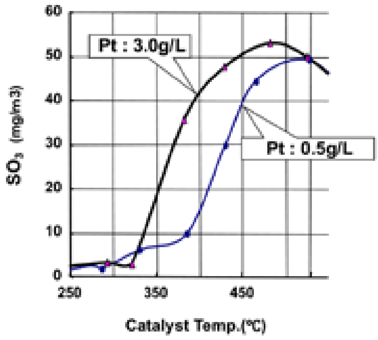
$BSSO_4 = BSFC * FSC/100 * PCSC/100 * 7$

Where:
$BSSO_4$ = Brake specific sulphate (mass/brake power-hour)
BSFC = Brake specific fuel consumption (g/kWh)
FSC = Fuel sulphur content (% mass)
PCSC = Percent sulphur conversion (to SO_4)
7 = Weight increase factor for S to (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 oxidising exhaust gases, such as CO and HC. To the extent the fuel also contains sulphur, some of it is oxidised 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 oxidise any sulphur and sulphates in the exhaust stream. Oxidised sulphur in the form of sulphate is then emitted to the atmosphere as very fine particulate matter.

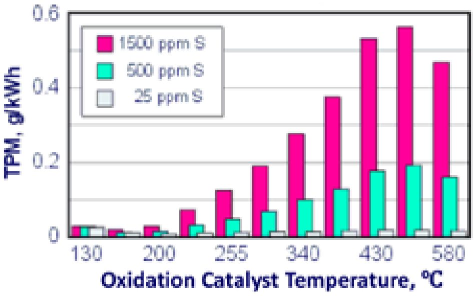
The DOC also serves an additional critical role in highly advanced emission control systems where it is used to generate heat for other after-treatment components, such as the diesel particulate filter (DPF) and selective catalytic reduction (SCR) devices which remove particulate and NOx, respectively, 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 NOx (its conversion efficiency) is greatly decreased. Catalyst composition and exhaust gas temperatures play a significant role in the formation of sulphur oxides (SOx), 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_3 Amount after DOC, by Catalyst Temperature



Source: Toyota

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



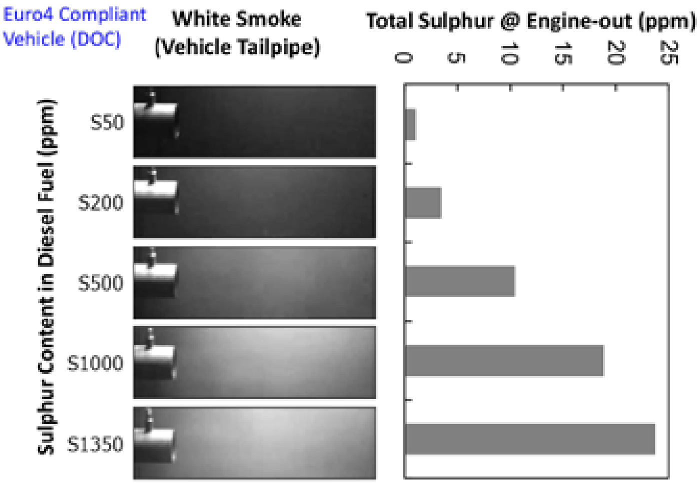
Source: SAE 950750

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 oxidises to SO_2 and SO_3 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

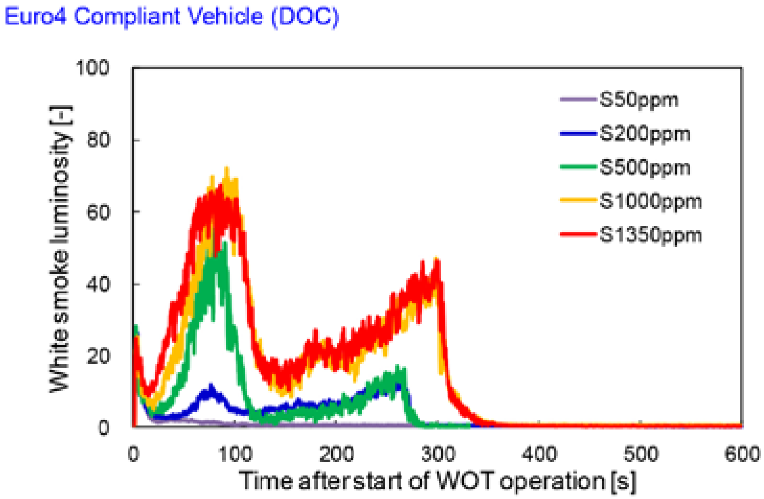
Source: 2017 JAMA Research Project

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



Source: 2017 JAMA Research Project

Sulphur's Impact on Highly Advanced Diesel Emission Control Systems
No single device can simultaneously reduce NOx, 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 after-treatment devices. Sulphur has a particularly strong impact on these NOx 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-NOx catalyst systems, such as Lean NOx traps (LNT) (also known as NOx adsorbers) and SCR devices, which can remove a greater amount of NOx 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 minimise impacts on fuel efficiency. DOCs, which reduce HC and CO emissions, and EGR systems, which reduce NOx, 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.

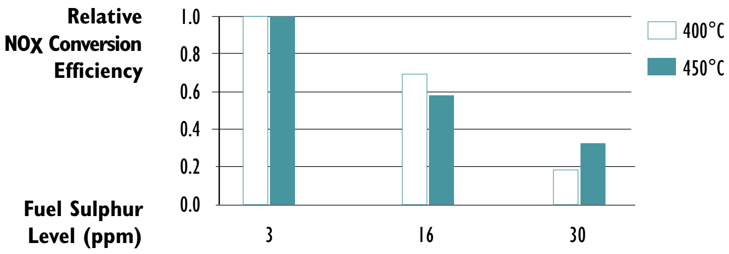
The Advanced Petroleum Based Fuels - Diesel Emission Control (APBF-DEC) Program, another collaborative effort, identified optimal combinations of low-sulphur diesel fuels, lubricants, diesel engines and emission control systems to meet projected emission standards for the 2001 to 2010 time period. Reference: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

NOx Adsorber (Lean NOx Trap)

NOx adsorbers are poisoned and rendered ineffective by the presence of sulphur. These devices can be up to 90% efficient in NOx removal if operated on sulphur-free fuel. The SO_2 formed during combustion and released in the exhaust undergoes reactions in these devices that are similar to those of NOx, but the oxidised sulphur compounds adsorb more strongly to the catalyst surface than the NOx, thereby poisoning the catalyst.

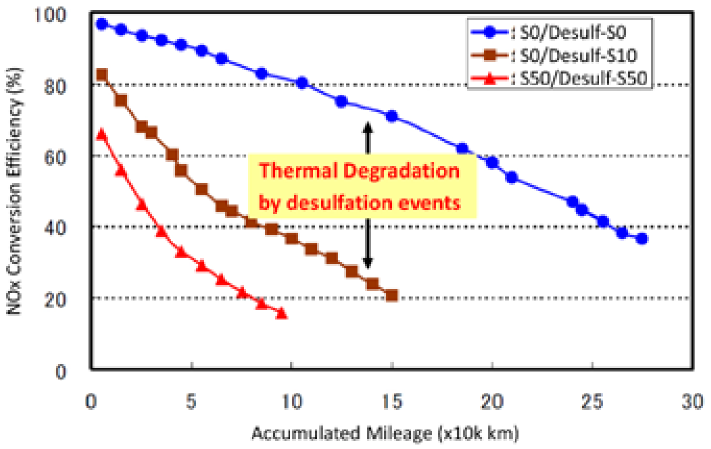
The effect of fuel sulphur content on NOx adsorber conversion efficiency is shown in Figure DF - 17 below. The figure illustrates the effect of fuel sulphur on relative NOx conversion efficiencies. Compared to 3 ppm sulphur fuel, both 16 and 30 ppm sulphur fuels resulted in a significant decline in performance. Importantly, the need to desulphurise 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 NOx 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



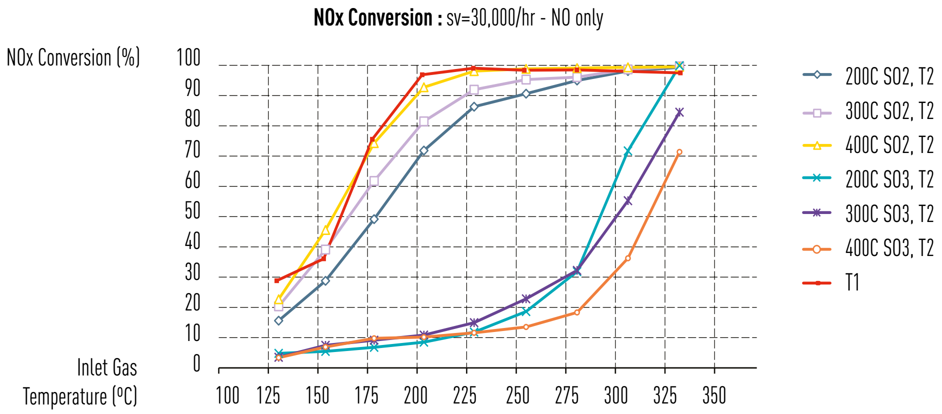
Source: JCAP

Selective Catalytic Reduction

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. or commonly AdBlue® in the EU) to convert NOx 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 DOC in front of the SCR because DOCs convert much of the exhaust SO_2 to SO_3. While both SO_2 and SO_3 poison the SCR, research has shown SO_3 to have a stronger impact on SCR conversion efficiency. Figure DF-19 shows how SO_2 and SO_3 affect NOx conversion in SCRs at different temperatures (also see SAE 2009-01-0898).

Figure DF-19: Impact of SOx 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.

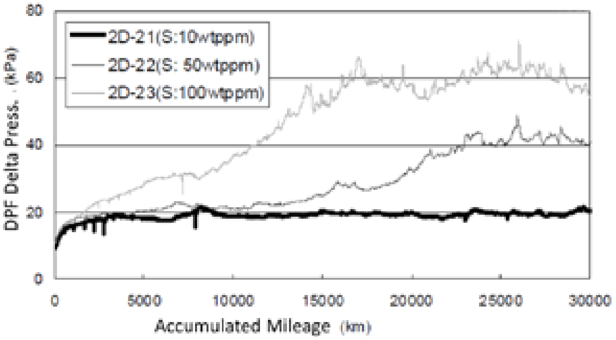
The latest generation of common rail engines with their electronic injection strategies, however, enabled the possibility of increasing exhaust gas temperatures, which then enabled the possibility of combusting the particulate trapped on the DPF. A different strategy for regenerating filters uses a combination 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 103 -104 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 oxidised 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 vehicle/engine performance and lowers fuel economy. See Figure DF-20.

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



Source: JCAP Report

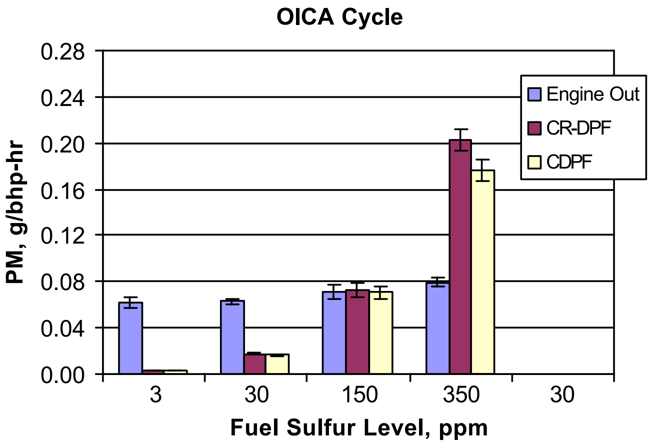
Continuously Regenerating and Catalysed Diesel Particulate Filters
The Continuously Regenerating Diesel Particulate Filter (CR-DPF) and Catalysed Diesel Particulate Filter (CDPF) represent two different approaches to DPF regeneration.

The CR-DPF regenerates by continuously generating NO_2 from engine-emitted NO over a diesel oxidation catalyst placed upstream of the DPF. Proper vehicle calibration is necessary to generate sufficient NO_2 for this purpose. NO_2 has been established as a more effective low-temperature oxidising 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 NO and 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).

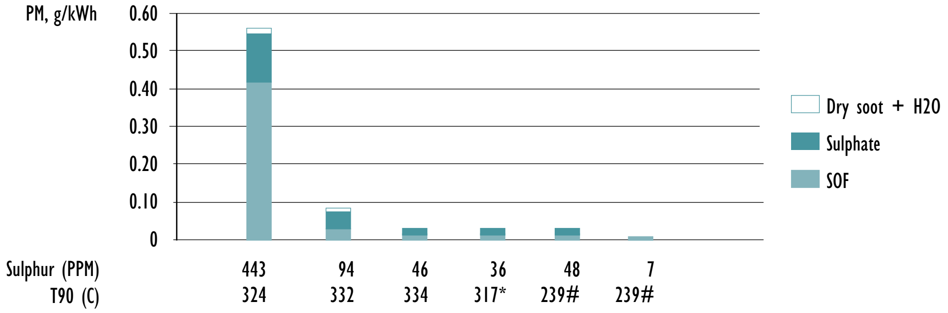
Fuel sulphur has a significant effect on PM emissions from these emission control devices. Both types of DPF effectively reduce PM emissions when fuel sulphur is very low, but when fuel sulphur increases, so do sulphate levels, which affects the amount of PM emitted. In one study, PM was reduced by 95% using the European Stationary Cycle (initially known as 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



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

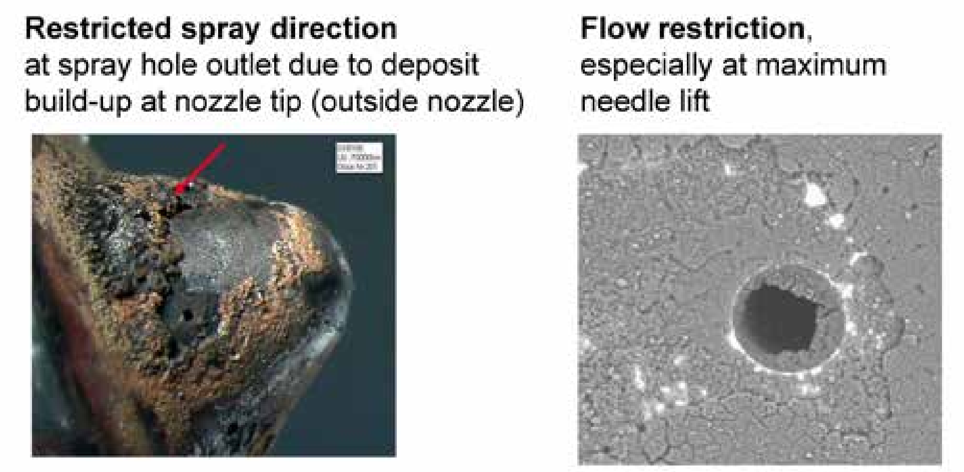


Source: JCAP Report

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



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 of 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

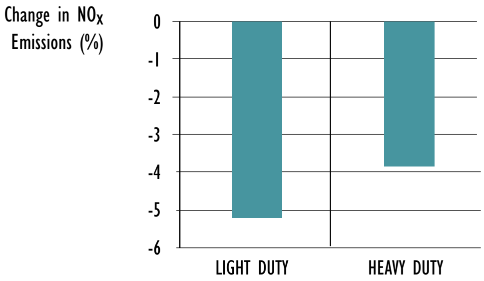
Aromatics are molecules that contain at least one benzene ring. The fuel aromatic content will affect combustion and the formation of particulate and polycyclic aromatic hydrocarbons (PAH) emissions.

The diesel fuel aromatics content influences flame temperature, and therefore, NOx emissions during combustion. PAH in the fuel affect the formation of particulates and PAH emissions from a diesel engine.

Influence of Total Aromatics Content on NOx Emissions

A higher aromatic content in the fuel will increase the flame temperature during combustion, which results in increased NOx 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 NOx emissions as shown in Figure DF-24.

Figure DF-24: Effect of Total Aromatics on NOx Emissions (30 to 10% Aromatics)



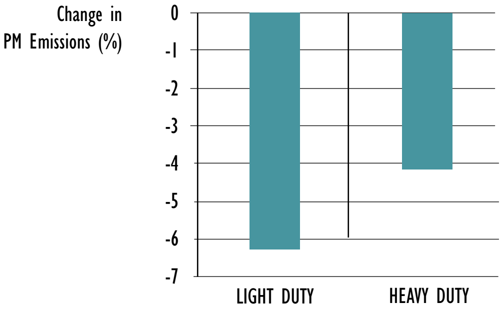
Source: ACEA Report: Influence of Diesel Fuel Quality on Heavy Duty Diesel Engine Emissions, March 1997

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%.

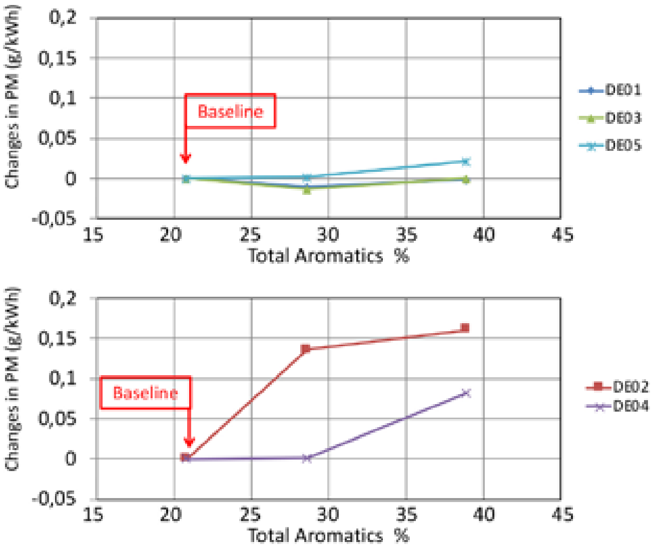
Figure DF-25: Effect of Polyaromatics on PM Emissions (from 9 to 1% di+ Polyaromatics)



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)

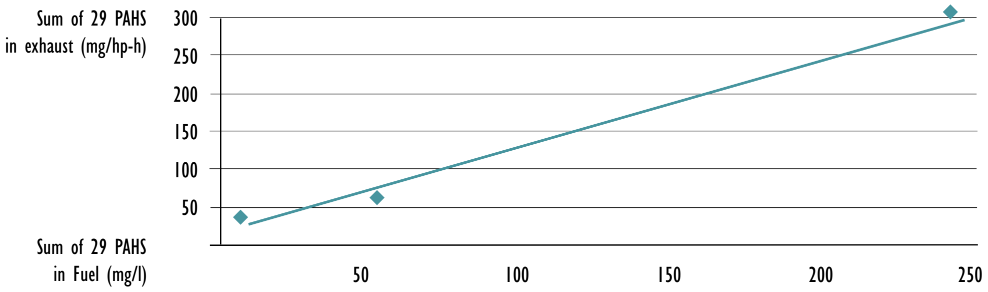


Source: Produced by JAMA using published data from JATOP II

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.

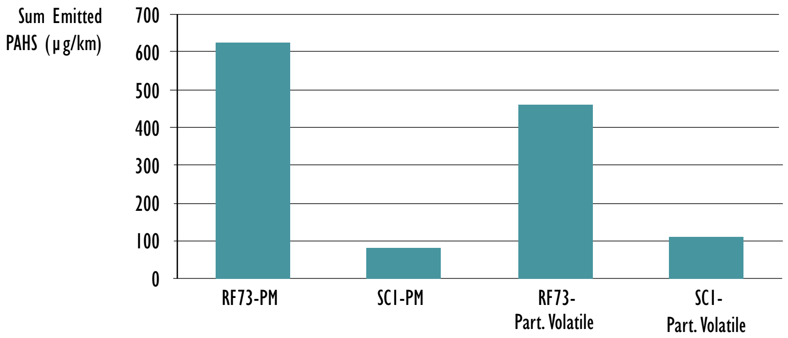
Figure DF-27: Effect of Fuel PAH on Emissions of PAH



Source: Karlsson (Scanraff Refinery) and Röj (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

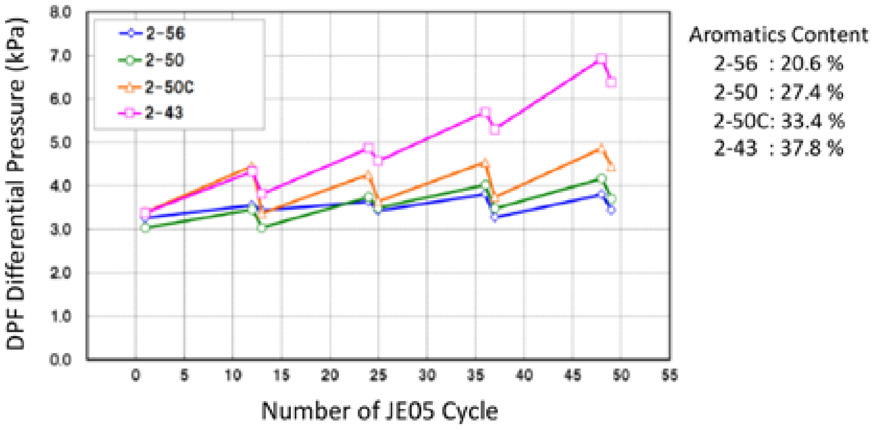
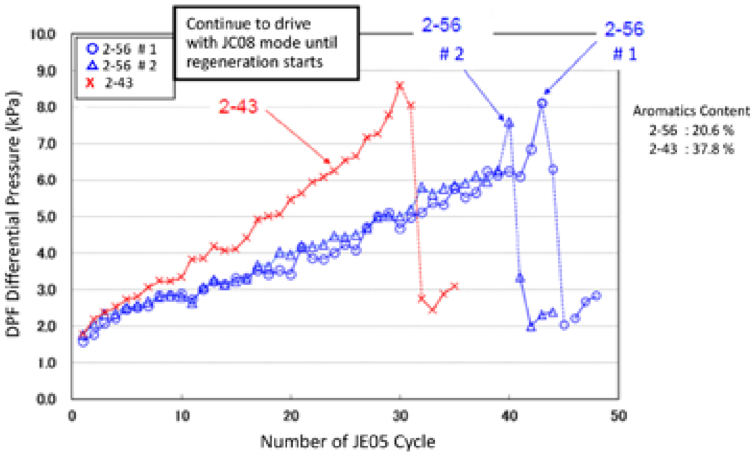


Figure DF-30: Influence of Total Aromatics Content on DPF Regeneration Interval



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 NOx 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 NOx 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): The temperature at which the heaviest paraffins start to precipitate and form wax crystals; the fuel becomes ‘cloudy’.

Cold Filter Plugging Point (CFPP): The lowest temperature at which the fuel can pass through the filter in a standardised filtration test. The CFPP test was developed for passenger cars from vehicle operability data and demonstrates an acceptable correlation for fuels and vehicles in the market (including heavy-duty trucks) as long as the delta between CFPP and CP is below 10°C max. Thus, the CFPP should be used only in conjunction with the CP, with the maximum delta below the CP maintained at 10°C and with its maximum cold point temperature set equal to or lower than the lowest expected ambient temperature.

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

Low Temperature Flow Test (LTFT): The LTFT was developed to assess 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.

It is important to avoid over-additising the fuel. Both CFPP and LTFT can be influenced by cold flow additives. Also, too much additive can cause precipitation onto the fuel filter and result in fuel filter plugging.

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, and if the CFPP is used, it should be with the CP under the stated constraints, as noted above.

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 additive eventually 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 deposit control 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 NOx 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.

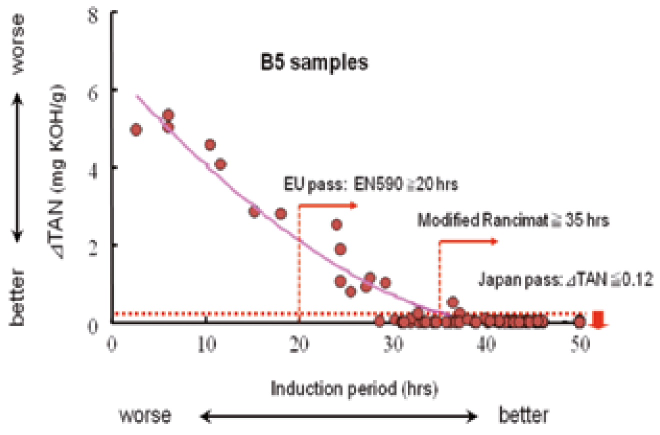
In view of the high level of interest in this fuel, including amongst vehicle and engine manufacturers, biodiesel and alternative diesel specifications and test methods will continue to be investigated and evaluated.

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 oxidised 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 butylated hydroxytoluene (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 Total Acid Number (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.

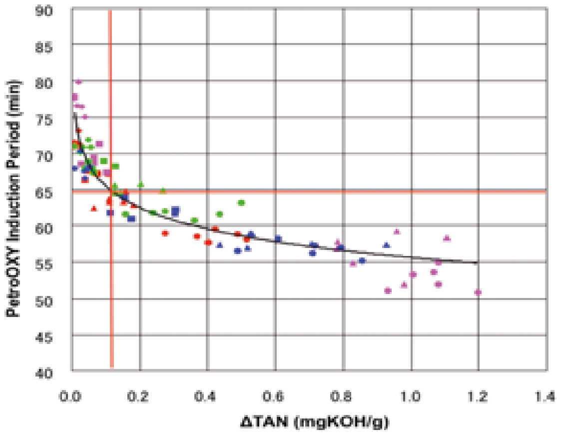
The current European limit is believed to be inadequate to prevent corrosion in metal parts such as vehicle fuel tanks, however. Figure DF-31 shows that a 35-hour minimum induction period by the modified Rancimat method is comparable to a delta TAN maximum of 0.12 mg KOH/g. Figure DF-32 shows the correlation 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



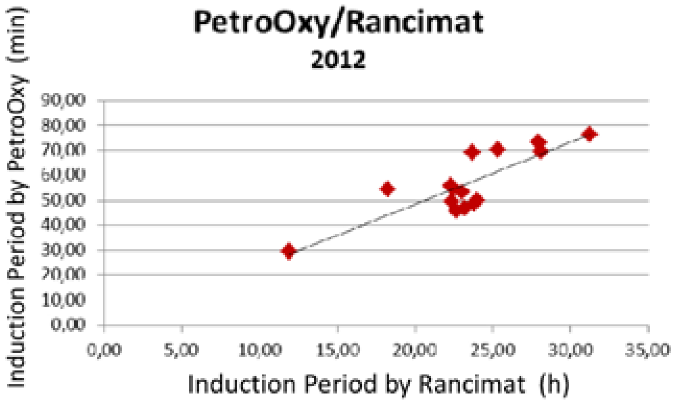
Source: JAMA, 2007

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-based fuels (such as natural gas), power (multiple renewable sources exist) or coal into paraffinic diesel fuels, commonly referred to as BTL (‘biomass-to-liquid’), GTL (‘gas-to-liquid’), PTL ('power-to-liquid') or CTL (‘coal-to-liquid’). 'XTL' is a common name for BTL, GTL, PTL and CTL. Renewable XTL feedstocks provide more sustainable pathways than fossil fuel feedstocks. 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. In addition to their potential GHG and other advantages, XTL fuels 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; these factors may reduce fuel economy, compared to an equivalent volume of conventional 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, such as meeting lubricity requirements.

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.

XTL and HVO are very clean-burning themselves and can help improve conventional diesel fuel because they have virtually no sulphur or aromatics. They generally have poor lubricity, however, so both types of these alternative fuels will likely need appropriate additives in the finished fuels to enable them to meet or exceed requirements. EN 15940 may be used as a production guideline for XTL and HVO when used as blending components. Additional engine validation may be needed to ensure the fuel ultimately works well in vehicles and engines. Subject to such validation and care using additives, these fuels are usable in any diesel engine either in pure form or when blended with conventional diesel fuel, assuming the finished fuels also meet finished fuel quality requirements.

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. Certain diesel fuel chemistries may react synergistically with biodiesel. These potential interactions should be studied further.

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 sodium (Na) and zinc (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 Deposit Control Additives

Deposit control 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 standardised 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 standardised 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 to the vehicle/engine 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 spectroscopy.

Lubricity

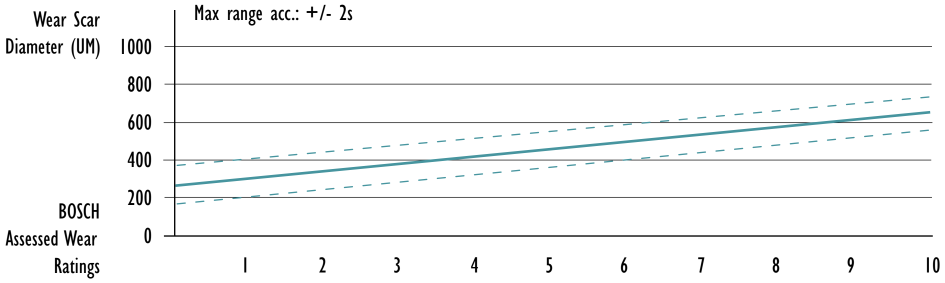
Lubrication at component boundaries is critical for protecting engines and fuel handling systems. The components of the diesel fuel that provide boundary lubrication are believed to be the heavier hydrocarbons and polar fuel compounds. Diesel fuel pumps without an external lubrication system rely on 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 mm). 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

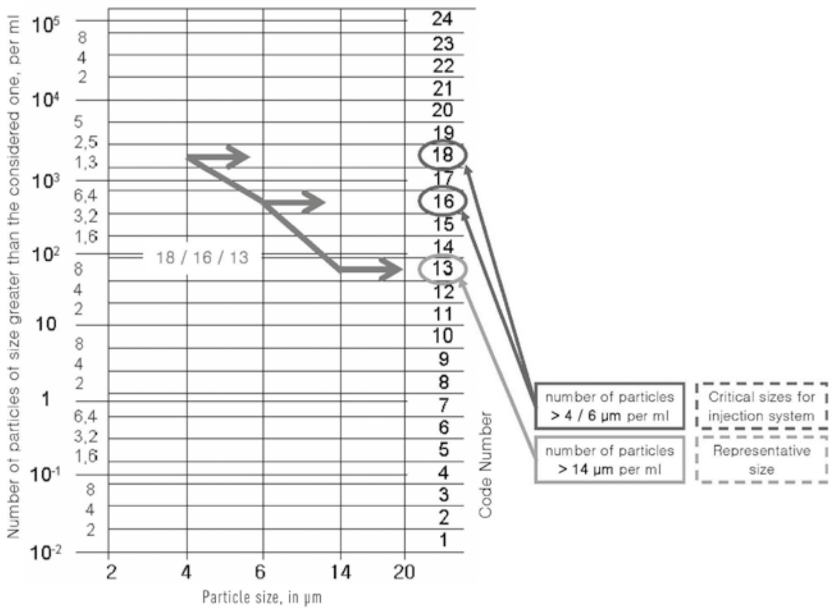
Fuel injection equipment manufacturers continue to develop fuel injection systems to reduce emissions and fuel consumption and to improve performance. Injection pressures have been increasing; currently, they have reached more than 2000 bars. Such levels of injection pressure demand reduced orifice sizes and component clearances, typically from 2 to 5 µm 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 µm 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 minimise 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

Heavy corrosion:

Distributor head:

Customer complaint:

No restart

Root cause:

Sticking plunger

Sticking governor ring

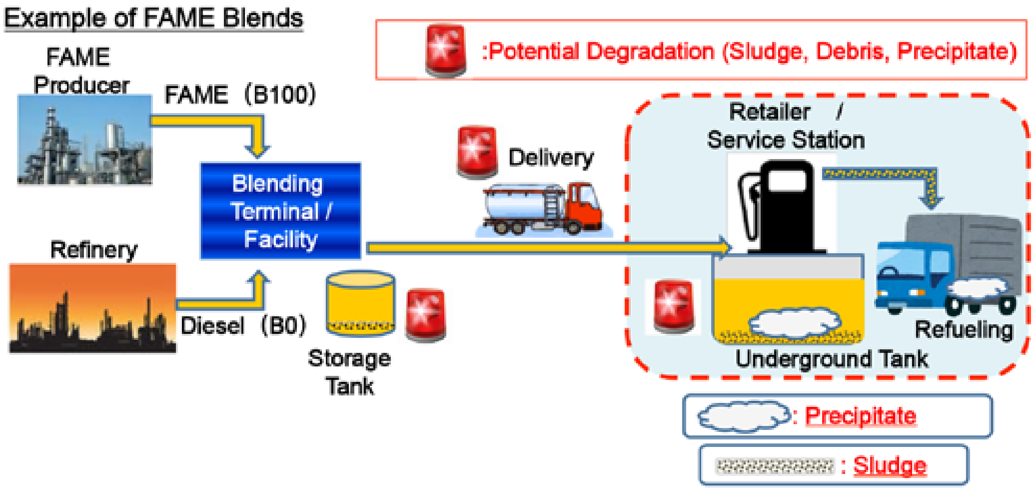
Source: Bosch, 2002

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, oxidises 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, 2017

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



Source: JAMA, 2019

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 minimise 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.

The WWFC Committee recommends that countries adopt specifications to promote good housekeeping practices, as described in CEN/TR 15367-3, for example. Where such specifications do not yet exist, retailers may choose to participate in voluntary programs such as the new TOP TIER™ Diesel program, which helps assure acceptable quality diesel fuel at the refuelling pump for deposit control additive usage, oxidative stability, lubricity and water and particulate contamination controls. Like its sister program for gasoline, this program provides a trademarked, licensed, fuel performance standard enforced by its sponsoring automakers and engine manufacturers. For more information, see www.toptiergas.com.

RESPONSE TO COMMENTS

The WWFC Committee appreciates the many comments received on the proposed Sixth Edition of the Worldwide Fuel Charter for Gasoline and Diesel Fuel. The Committee carefully reviewed each comment and provides its responses below, which, in many cases, are also reflected in changes to the document. For brevity, the Committee consolidated and condensed similar comments, and for confidentiality, has not identified commenters.

General Comments or Relating to Both Gasoline and Diesel Fuel Chapters

Ⓒ **Changes from the previous version should be highlighted.**
Ⓡ The Committee considered this possibility but concluded it was not feasible.

Ⓒ **The comment period should be 90 days.**
Ⓡ The Committee welcomes comments at any time for consideration in a future edition.

Ⓒ **Quality control should be based on commonly available test methods with reasonable costs. Some engine tests are limited geographically or otherwise. Please list testing facilities that can provide the needed tests.**
Ⓡ Other resources and forums are better positioned to provide this information. The Committee provides multiple test method options where possible.

Ⓒ **The WWFC's future-looking and technical-needs-based approach is welcomed. Modern oil refineries should be able to produce at least some volumes of the highest WWFC grades. FAME-free diesel fuel meeting the highest WWFC category has been successfully produced in Finland since 2012 with availability widened since then to include Baltic countries.**
Ⓡ The Committee appreciates the comment and information.

Ⓒ **Proposed limit values should consider the repeatability and reproducibility of the methods.**
Ⓡ The Committee considers all aspects of test methods and always welcomes additional information.

Ⓒ **We support the call for sulphur-free and metal-free fuels.**
Ⓡ The Committee appreciates the comment.

Ⓒ **The WWFC should explicitly mention the need to develop no-harm, engine-based test methods that can be adopted by standard-setting groups, to test new types of additives and blendstocks before market introduction.**
Ⓡ The Committee welcomes new methods and additional information.

Ⓒ **The copper and silver corrosion tests should specify operating conditions.**
Ⓡ The Committee appreciates the comment and has clarified the methods.

Ⓒ **Several referenced test methods have incorrect designations.**
Ⓡ The Committee appreciates this information and has edited the methods accordingly.

Ⓒ **We recommend replacing "detergent" and "detergency additives" with "deposit control additives" because EU regulation does not consider the terms to be interchangeable.**
Ⓡ The Committee has accepted this recommendation.

Ⓒ **The document includes very old data which is not very relevant for modern vehicles.**
Ⓡ Older research remains relevant for many regions with significant fleets of older vehicle/engine technologies. As fuel quality improves globally, it will enable newer technologies in these markets. The Committee welcomes efforts to upgrade the research.

Comments Relating Specifically to Gasoline

Ⓒ **We welcome the introduction of RON 102 within Category 6 of the gasoline specification, but much evidence suggests MON is not important for modern vehicles.**
Ⓡ The Committee appreciates the comment and is continuing to monitor the importance of MON.

Ⓒ **Locally sourced ethanol is key for fuel sustainability and for lower CO_2/air pollutant emissions from gasoline.**
Ⓡ The Committee appreciates the comment.

Ⓒ **Increasing the maximum oxygen level to 8% by mass is good progress, but even higher levels of renewable components might be needed during the next decade to meet greenhouse gas reduction targets. We suggest increasing the maximum oxygen to 12% m/m, with ethanol allowed to reach 30% v/v as one component among others.**
Ⓡ The Committee appreciates the comment and suggestion.

Ⓒ **I commend the authors for eliminating Category 1, which allows recognition of higher oxygen levels in the other categories, especially up to 3.7% by weight oxygen in Categories 5 and 6, with higher amounts of ethanol allowed in Category 6 to achieve higher octane fuel.**
Ⓡ The Committee appreciates the comment.

C **We recommend restoring the statement: “where oxygenates are used, ethers are preferred. Ethers have many benefits, e.g.: helping to reduce cold start emissions; helping ethanol achieve higher-octane blends more cost-effectively by reducing ethanol’s impact on emissions; reducing ethanol’s impact on metallic and elastomeric components; allowing more butane blending; and providing flexibility to refiners.**

R The Committee appreciates the comments and agrees ethers are acceptable blending components.

C **The Committee should reconsider its continued recommendation for ethers. Ethers perform acceptably as a gasoline component but have contaminated groundwater. Metallic additives also perform acceptably but are not recommended due to negative environmental and health effects.**

R The Committee appreciates the comment, but its position on metallic additives is specifically related to their adverse impacts on vehicles and engines.

C **The 6th Edition of the Charter should recommend fuel pump warning labels for low octane grades (e.g., below minimum 91 RON and minimum 82.5 MON).**

R The Committee agrees pump labelling is important.

C **The “PM Index” entries in the tables don’t match its name in the footnote.**

R The Committee has edited the document to be more consistent.

C **The use of “Distillation Index” along with “Driveability Index” is confusing.**

R The Committee has clarified the terminology.

C **The octane discussion is fulsome and very educational.**

R The Committee appreciates the comment.

C **The Charter should mention that no chlorine-based components are used to produce ethanol, and any concerns that exist arise from potential contamination in storage or transport.**

R The Committee appreciates the comment.

C **Ethanol should be included in each of the categories based on the wealth of data that exists on its emission and performance benefits.**

R The Committee appreciates the comment and literature references.

C **The Charter’s exclusion of methanol-blended gasoline is inconsistent with the current EN228 limit which allows up to 3% v/v. Some countries allow even higher levels of methanol in gasoline.**

R The Committee understands its recommendations may differ from local regulations.

C **Several countries, such as India, China and Israel, are allowing or increasing methanol-gasoline blends to help address climate change, air pollution or other reasons. M15 is providing a less-polluting alternative to diesel fuel and heavy fuel oil without much problem. Legacy vehicles only require changing certain gaskets, and the existing infrastructure can handle the blends with very little added cost.**

R Countries have a range of options to address climate change and air pollution, including upgrading the local fleet and its fuel quality to modern standards. The Charter does not interfere with local policy choices.

C **Methanol blends produce lower particulate (soot), NOx and formaldehyde emissions than gasoline and diesel fuels.**

R The Committee appreciates this information.

C **The Charter should not seek to ban methanol because it would be seen as anti-competitive.**

R The Charter imposes no obligation on any fuel users or producers, nor does it prohibit use of any engine or vehicle technology or design or any fuel or fuel quality specification.

C **Methanol-containing fuels, especially from renewable sources, can help address global climate change in a sustainable and cost-effective manner. It is the only carbon-based fuel product that can be produced from carbon capture and recycling. It can supplement ethanol supplies, which are inadequate in some regions. It will help decarbonize the transportation system.**

R We recognise the importance of these goals, but they are beyond the Charter’s scope.

C **A key advantage of biomethanol as an advanced fuel is that it is readily available.**

R The Committee appreciates the comment.

C **Claims that methanol is “aggressive” are unsubstantiated. Most studies showing incompatibility are quite old and refer to experience in China, where fuel quality is quite poor and no countermeasures were used. Modern vehicles use polymeric parts that are compatible with methanol-based fuels. A proper fuel formulation with appropriate additives can prevent metallic corrosion.**

R The Committee disagrees and has not relied on old studies to inform its position. Not all vehicles use polymeric parts. Anti-corrosion additive use may be unreliable at the retail level.

C **Claims of operational problems with gasoline-methanol blends are unsubstantiated. Hot-restart problems should not occur if the fuel meets the vapor pressure limit. Data showing M0-M15 cold start differences are incomplete and lack details. M15 data on vapor pressures at sub-zero temp are probably derived from off-spec fuel.**

R The Committee agrees vehicles will behave similarly at similar vapor pressures, other properties being equal. Some properties, however – such as oxygen content – will not be

equal, and the fuel quality differences can result in different vehicle responses. Also, splash blending can significantly affect vapor pressure in the finished fuel.
N.B.: The Committee regrets that the proposed Charter inadvertently switched Figure G-24 (left-side, showing M15 hot restart failure) with Figure G-25 (left-side, showing cold-start behaviour of M0 and M15). This error has been corrected.

C **The data used to justify keeping methanol out of gasoline are inaccurate or obsolete. Other data show methanol blends can be used very successfully. We recommend delaying publication of the final edition until a collaborative research effort can be conducted.**
R The Committee appreciates the review and submission of studies and welcomes all research efforts.

C **Methanol-water phase separation should not occur because co-solvent use is an easy remedy; EPA waiver standards require co-solvents as well as corrosion inhibitors as an extra precaution.**
R The use of co-solvents and anti-corrosion additives may be unreliable at the retail level in all markets.

C **The California M85 fleet trials of the1980s/1990s successfully demonstrated the fuel's viability in terms of infrastructure, vehicle compatibility and vehicle exhaust emissions, among other measures.**
R This demonstration project used vehicles designed to be compatible with M85. Its results are not applicable to vehicles not so designed or to modern vehicles with very different technologies and very different regulatory requirements. Furthermore, M85 is outside the scope of this Charter.

C **Methanol can help provide the additional octane sought for Category 6.**
R The Committee considered all of methanol's properties.

C **Methanol is the best liquid carrier to produce hydrogen for fuel cell-powered vehicles.**
R Hydrogen production is outside the scope of this Charter.

C **We support the limit "no intentional addition" for trace metals, chlorine and organic contaminants (methylal, aniline and aniline derivatives) because it draws attention to post-refining behaviour. The auto industry should conduct additional research on the harm caused by such chemicals, to help policymakers address the potential impacts of post-refining operations.**
R The Committee appreciates the comment and always welcomes additional research.

C **The Charter lacks test methods for organic contaminants, so it should call upon standardization bodies to develop such methods.**
R The Charter calls for no intentional addition of these compounds and welcomes the development of test methods.

C **The Charter should provide references for how NMA might affect VOC emissions. Also, it should incorporate the conclusion of the CEN Harmful Chemicals Task Force (see draft technical report CEN/TC 19/WG 21 N371, section 5) that, in Europe, very few field problems have been associated with NMA at the reported concentrations and those that were reported were associated with the use of inadequate, obsolete engine oils.**
R The Committee appreciates the comment and will review this report.

C **The Category 5 minimum density limit of 720 kg/m^3 seems inconsistent with the other property limits.**
R The Committee appreciates the comment. The change in Category 5 from 720 to 715 kg/m^3 was a publishing error; both Category 5 and 6 are intended to enable better fuel efficiency.

C **We suggest adding a ferrous corrosion limit to the gasoline specifications, as with the diesel fuel specifications; the test method (ASTM D665) would need a temperature correction.**
R The Committee appreciates the comment and will consider this change for a future edition.

C **We suggest removing fuel injector cleanliness limits because the test methods (ASTM D5598 and ASTM D6421) are not commonly available in Europe. Also, based on experience, sufficient deposit control for intake valve cleanliness also will be sufficient for fuel injector cleanliness.**
R The Committee recognises effective test methods wherever they exist and welcomes the development of improved and alternative methods.

C **Two intake valve cleanliness test methods are provided, but they have different performance targets. Are there any correlation studies that demonstrate the equivalence of the IVD limits in both tests?**
R The Charter lists two tests for flexibility and welcomes any data correlating the methods.

C **We support the intake valve cleanliness limits and note that fuel ethers perform much better than metal-based additives or additives that contain aniline-derivatives, olefins or aromatics.**
R The Committee appreciates the comment and submitted references.

Ⓒ **We suggest including CEC-F-20 (CCD Method 2) for intake valve cleanliness.**
The CCD limit of 2500mg/engine is unrealistic; was 2500mg/combustion chamber intended?
The absolute mass limits associated with CEC F-20-98 are technically unsupportable and should be replaced by a relative value, as per the Ford ASTM D6201 test.

Ⓡ The Committee deleted this method because it is no longer supported and appreciated the comments that mentioned the test's revised status.

Ⓒ **We recommend removing the CCD limits or converting them to guidance because the listed test methods for Categories 5 and 6 are not commonly available in Europe or at oil companies. Also, the methods are inaccurate. Additives can help reduce CCD problems.**

Ⓡ The Committee recognises effective test methods wherever they exist and welcomes the development of improved and alternative methods.

Ⓒ **Unwashed gum increases when deposit control additives are used in high quality fuels, but the repeatability and reproducibility of the test method is challenging. The Charter should consider increasing the maximum gum limit to 40 mg/100 ml in Categories 3-6.**

Ⓡ The Committee appreciates the comment but disagrees with the recommendation. A higher unwashed gum limit may not improve deposit control and could increase the risk of heavier fuel components contaminating the fuel.

Ⓒ **Unwashed gum should not be encouraged as an alternative to CCD limits because correlation between unwashed gum and CCD formation exists only for some deposit control additives.**

Ⓡ The Committee disagrees with this comment.

Ⓒ **Engine performance tests are preferred to physical/chemical limits for CCD because cited performance correlations are not relevant to the current vehicle market.**

Ⓡ The Committee appreciates the comment and welcomes additional information.

Ⓒ **There should be flexibility in Categories 5 and 6 to follow either the unwashed gum limit or the combustion chamber deposit limit. Requiring both limits will severely constrain the use of deposit control additives in these categories and implies an unsubstantiated belief that deposit control additives could contribute to PM/PN emissions.**

Ⓡ This change was intended to improve the quality of Category 5 and Category 6 fuels.

Ⓒ **The proposed CCD Method 4 test is more appropriate for measuring fuel injector cleanliness because it addresses injector deposits in direct injection spark ignited engines (DISI).**

Ⓡ The Committee will consider this suggestion when the method is fully developed/finalised.

Ⓒ **The Charter should mention the need to prevent injector coking in DISI engines and suggests no interim methods. Consider removing the DISI method until fully developed. Which industry group is working on the DISI test method?**

Ⓡ Various groups are working on a DISI test method. The Committee seeks to encourage its development and will consider it when final.

Ⓒ **We support the inclusion of a Particulate Matter Index in Categories 5 & 6. The tables should include a limit of 1.5-1.8, notwithstanding the lack of a satisfactory test method.**

Ⓡ The Committee appreciates the comment.

Ⓒ **The WWFC should discuss DISI injector cleanliness/deposits which are much more important than PMI for reducing PM/PN emission from modern vehicles.**

Ⓡ The Committee appreciates the comment, believes a fuel property control is useful for limiting particulate formation and welcomes further research on this issue.

Ⓒ **The volatility limits proposed for helping control PMI are unclear.**

Ⓡ The Committee has clarified the limits and text.

Ⓒ **Is the "sulphur corrosion" appearing in Category 6 intended to be "silver-corrosion"?**

Ⓡ Yes; the Committee appreciates the careful review and has edited the table.

Ⓒ **The vapor limit tables should be checked for errors.**

Ⓡ The Committee appreciates the careful reviews and has corrected the tables.

Ⓒ **The evaporation class of Category 4 fuel should be classified as Category 5-6 because the Category 4 fuel meets the requirement of EURO6/6b market, where turbocharged direct injection engines are widely used. If T90 exceeds 170°C, these engines may have an increased risk of LSPI.**

Ⓡ The Committee appreciates the comment and welcomes data to improve its understanding.

Ⓒ **Modern PFI engines (VVT, turbocharged) also need intake valve deposit control but no standard tests are available.**

Ⓡ The Committee appreciates the comment and welcomes any advancement on this issue.

Ⓒ **Please consider adding ASTM D7111 modified as a test method for lead, potassium, phosphorus and silicon.**

Ⓡ The Committee appreciates the comment and has added the method.

Ⓒ **Please consider adding EN ISO 22854 as a method for oxygen, olefin, benzene and aromatic contents and ISO 15597 as a method for chlorine.**

Ⓡ The Committee appreciates the comment and has added these methods.

C **The carburettor cleanliness test method (CEC F-03-T-81) is obsolete and unavailable, so it should be removed.**
R The Committee appreciates the comment and has deleted this test method.

C **The intake valve cleanliness I test method (CEC F-04-A-87) is obsolete and unavailable.**
R The Committee appreciates the comment and has deleted the method.

C **Several test methods have been incorrectly identified.**
R The Committee appreciates the comment and has made corrections.

C **We recommend including the Intake Valve Sticking method used in the US Top Tier Gasoline program and commenting on its correlation with CEC F-16-96.**
R The Committee appreciates the comment and welcomes any correlation data.

C **The WWFC provides no evidence that any current fuel test can predict Low-Speed Pre-Ignition tendency. Certain lubricant oil components are more problematic in this regard than fuel quality.**
R The Committee agrees lubricants can contribute to LSPI but cannot ignore the fuel contribution. We welcome any data.

C **Aniline/Aniline Derivatives and Secondary Butyl Acetate are not fuel additives but fuel components, since they are used at higher levels than additives (as per definition in ATC document 113).**
R The Committee appreciates the comment and has edited the text accordingly.

C **Evidence to support the limits on olefins and aromatics in gasoline (AQIRP, EPEFE) is not relevant for modern vehicles.**
R Older technology remains in the marketplace, so the data remain relevant. The Committee also welcomes new data applying to old or modern technologies.

C **The source of the PMI formula should be "SAE 2010-01-2115."**
R The Committee appreciates the careful reviews and has corrected the error.

C **The WWFC should provide more background on deposit control for direct injection engines.**
R The Committee agrees and will consider doing this in the next edition.

C **Fuel #5 in Figure G-46 does not comply with the Top Tier IVD limit (max. 50 mg/V).**
R The Committee appreciates the comment.

Comments Relating Specifically to Diesel Fuel

C **Why doesn't the WWFC treat cetane like octane, i.e., reporting different grades in each category for maximum flexibility?**
R Cetane relates to compression ignition engines differently than octane relates to spark ignition engines. The Committee sees little/no benefit in specifying cetane grades for each category.

C **Please explain the rationale for limiting the maximum delta between Cetane Index and Cetane Number when using cetane improvers and for calling for more research, since it is well-known higher levels of additive can cause problems.**
R The Committee appreciates the support for the CI/CN delta and believes the background discussion adequately explains both the rationale and call for more research.

C **While cetane improvers have a long history of use without harm and help make diesel fuel economically viable, the WWFC should explain that improvers may interfere with Oxidation Stability Method 2c ("PetroOxy") due to the method's high temperatures.**
R The Committee agrees and has modified the relevant footnote.

C **The Charter should note that CEN is currently reviewing the PetroOxy method to establish its suitability and may modify the method.**
R The Committee looks forward to the outcome of CEN's review.

C **For oxidation stability in Category 5, which does not allow FAME, we recommend restoring Method 1 (EN ISO 12205) with a limit of 25 g/m^3 and removing Method 2c (PetroOxy), which is based on correlation with the Rancimat test for FAME-containing fuels.**
R The Committee is unaware of any evidence that the PetroOxy method will be affected by any FAME content, including zero FAME.

C **We recommend changing oxidation stability test method 1, D6468, to D2274/EN ISO 12205. Also, the listed units of D6468 are incorrect; they should be % reflectance.**
R The Committee agrees and has changed the listed tests.

Ⓒ **Commonly used corrosion inhibitors and lubricity additives, which Category 5 fuels are especially likely to need, may affect the Total Acid Number. We suggest adding a footnote that trouble-free additives should be separately considered when evaluating TAN results.**

Ⓡ The Committee appreciates the comment and notes the Technical Backgound addresses this issue.

Ⓒ **Are the separate limits on ash and total trace metal unnecessary duplication?**

Ⓡ The Committee believes both limits are necessary.

Ⓒ **Please include references to justify the tighter ash limit in Categories 4 and 5, which is beyond the test method's detectability. Further, we question the feasibility of developing a test method that goes down to these very low levels.**

Ⓡ The Committee believes the EN590 limit of 0.01% m/m ash is insufficient to protect vehicles/engines in these categories.

Ⓒ **Zero biological growth is difficult to interpret and unrealistic. A limit of 400 ufc/l (according to IP385), for example, is often considered low enough to avoid microbiological contamination issues.**

Ⓡ The Committee appreciates the comment.

Ⓒ **Calling for the use of antifoam agents where needed is inconsistent with the call for non-detectable trace metals because silicon is a common ingredient of anti-foaming agents.**

Ⓡ The Committee recommends using antifoam agents that do not contain silicon.

Ⓒ **We suggest using numerical limits instead of "non-detectable" for trace metals, chlorine, FAME and ethanol/methanol because detection limits depend on the method used for analysis.**

Ⓡ The Committee believes non-detectable limits based on the method used is a reasonable approach.

Ⓒ **Injector Cleanliness Method 2 and Method 3 cover different issues and are complementary rather than interchangeable. Method 2 (CEC F-98-08, DW10B) addresses injector tip coking, and Method 3 CEC F-110-16, DW10C) addresses IDID formation. Also, CEC F-98-08 now covers the impact of metals polluting the fuel when zinc is added to the test fuel. This should be referenced, and the comment for measuring metals might be suppressed.**

Ⓡ The Committee agrees, appreciates the comments and has edited the tables and text accordingly.

Ⓒ **Injector Cleanliness Method 3 (CEC F-110-16) is under review.**

Ⓡ The Committee is aware of the concern about the method and has edited the document accordingly.

Ⓒ **We recommend including Injector Cleanliness Method 1 (CEC-F-23) in Categories 4 and 5 because these fuels also may be used in Euro III and pre-Euro III engines in some markets. The test's availability and cost also may be an advantage.**

Ⓡ The application of Methods 2 and 3 (pending completion of its review) should lead to the use of deposit control additives sufficient to help maintain the cleanliness of older engine technologies.

Ⓒ **The density and aromatic limits are incompatible and could impact fuel supply in some fuel categories. Category 2 min density should be lowered to 810 kg/m^3 to enable production of CARB ULSD and Tx LED based on actual aromatics content. FAME can help Category 4, but making B5 having 815 density and 15% aromatics will be difficult. For 15% aromatics content, we recommend reducing density to 800-830 g/l for Category 4 and to 800-825 g/l for Category 5.**

Ⓡ The Committee believes the specifications are achievable but will continue to monitor this issue.

Ⓒ **Please explain the rationale for moving the density range downward by 5 units (from 0.820-0.845 to 0.815-0.840). Changing the lower density limit for certain fuel grades will be part of a future revision of the EN590, to increase flexibility for blending renewable components; perhaps this initiative should be explained for readers unfamiliar with CEN discussions.**

Ⓡ The Committee lowered the minimum density to increase flexibility to include more low-density renewable fuel blending components.

Ⓒ **The aromatics limit in Category 3 appears incorrect.**

Ⓡ The Committee appreciates the careful reviews that found this error, which has been corrected.

Ⓒ **We suggest removing the filter blocking tendency limit because filterability is a challenge, especially with fuels containing FAME. If kept, the Charter should justify the limit better.**

Ⓡ Filter blocking tendency tests more than the effects of FAME.

Ⓒ **We recommend adding a new Category 6, with density in the range of 765–800, as a Low Carbon Diesel Fuel, but note that aromatics content may affect producibility. See EN15940.**

Ⓡ The Committee appreciates this comment and will consider it for a future edition.

Ⓒ **ASTM has published a new ICP-MS method for trace metals in diesel fuel, D8110, which is more convenient than D7111.**
Ⓡ The Committee appreciates this information and has added this method; together, these two tests cover a broad range of trace metals.

Ⓒ **One of the listed lubricity tests, CEC F-06-96 (shown in the proposal as CEC F-06-A), is now obsolete.**
Ⓡ The Committee appreciates the information and has removed the method.

Ⓒ **We recommend certain changes to the Cold Flow discussion. Also, please explain the 10°C limit on the difference between Cloud Point and Cold Filter Plugging Point; is it because excess cold flow additive can come out on fuel filters or because the correlation with vehicle operability breaks down at larger deltas?**
Ⓡ CFPP alone is not fully adequate to provide acceptable correlation with operability, so it must be used with the CP. The reason for limiting the delta relates both to filter impacts and operability. The Committee has modified the text appropriately.

Ⓒ **The FAME limits require additional explanation, are not supported by references and are not in line with the general trends towards increasing FAME use.**
Ⓡ The Committee selected the limits to better protect vehicles/engines, based on data shown in Figure DF-31. The Charter's scope includes diesel fuels containing up to 5% FAME.

Ⓒ **Hydrotreated vegetable oils generally have poor lubricity, which may require specific attention and the use of appropriate additives to enable the finished blends to meet the specification.**
Ⓡ The Committee agrees and has modified the text to reflect this aspect. The Charter's lubricity specifications apply to all diesel fuel within its scope.

Ⓒ **We suggest changing the text for synthetic fuels and HVO to say finished blends should meet the quality standards. Unfinished XTL and HVO used as blendstocks can be asked to meet production guidelines (e.g., EN 15940).**
Ⓡ The Committee agrees and has modified the text accordingly.

Ⓒ **Please provide references for various statements relating to biofuel stability: D6468 (Oxidation Stability Method 1) has "very good scores;" preferences for modified Rancimat (for FAME-containing fuels) and PetroOxy (for FAME-Free Category 5); certain fuel chemistries may react synergistically with biodiesel even if the biodiesel has good oxidation stability; and investigations are ongoing.**
Ⓡ The Committee always welcomes additional information and has modified the text for clarity. Also, the Committee replaced D6468 (proposed Oxidation Stability Method 1) due to an improved understanding about the test methods.

Ⓒ **Sodium, not zinc, contributes to soap deposits. FAME itself has not been shown to contribute to IDID more the sodium-based impurities therein.**
Ⓡ The Committee disagrees. Biodiesel is not pure FAME and brings with it many impurities, so the concerns extend beyond the formation of soaps.

Ⓒ **The lubricity limit is based only on Bosch pump test ratings without evidence from the field.**
Ⓡ Bosch has significant expertise on lubricity; the Committee welcomes additional data.