

WORLDWIDE FUEL CHARTER

FIRST EDITION
METHANE-BASED
TRANSPORTATION FUELS

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OCTOBER 2019



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European Automobile
Manufacturers Association



Alliance of Automobile
Manufacturers



Truck and Engine
Manufacturers Association



Japan Automobile
Manufacturers Association

October 2019

Subject: Methane-Based Transportation Fuels

Dear Recipient:

On behalf of vehicle and engine manufacturers from around the world, the Worldwide Fuel Charter (WWFC) Committee is pleased to present the First Edition of the Worldwide Fuel Charter for Methane-Based Transportation Fuels. The WWFC Committee published its first Charter, for gasoline and diesel fuel, in 1998; that Charter is now in its sixth edition. In addition to these Charters, the Committee has published Guidelines for ethanol and biodiesel blendstocks. These documents are available through the associations shown above.

The purpose of these Charters and Guidelines is twofold: to inform policymakers and other interested parties about the key role of fuel quality in engine and vehicle operation, durability and emissions, 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.

The use of methane-based fuels for transportation has grown rapidly in recent years, and the quality of these fuels varies widely around the world. As a result, the Committee saw a need to provide information about these fuels and how to match their quality with the needs and capabilities of modern vehicle and engine technologies. This document presents recommended fuel quality specifications for markets with the most advanced motor vehicles and engines as well as for markets with less advanced vehicles and engines. Vehicles and engines work with fuels as a system, so matching fuel quality to vehicle and engine technology will provide the best vehicle and engine performance and minimise emissions and fuel consumption for the various categories of technologies. Matching fuel quality to vehicle/engine capabilities also provides a path to fuel quality harmonisation worldwide and to improved functioning of transportation markets.

As an alternative fuel, methane-based fuels have the potential to help reduce greenhouse gas emissions and enhance the sustainability of hydrocarbon-based fuels. The key to achieving the best available performance with the least environmental impact is to produce high quality methane-based fuels in a sustainable way and to preserve their quality throughout the distribution system until the fuel reaches the consumer.

This document represents our best collective judgment based on experience with these fuels. Technical information and field data will continue to evolve, however, so we will strive to update this document periodically as we learn more.

We appreciate the many comments submitted on this new fuel Charter; they helped make it a better document. We look forward to working with you to support harmonised high quality fuel specifications for the benefit of consumers and the environment around the world.

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ACRONYMS

A/F	Air-Fuel Ratio
AVL	Company (AVL List GmbH) that developed a proprietary method for calculating Methane Number
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
COS	Carbonyl Sulphide
CRC	Coordinating Research Council
DNV GL	Company based in Norway
EPDM	Ethylene Propylene Diene Monomer Rubber
GHG	Greenhouse gases
GHV	Gross Heating Value (also referred to as Higher Heating Value)
H ₂ S	Hydrogen Sulphide
HC	Hydrocarbon
HEPA	High Efficiency Particulate Air (a type of air filter)
HHV	Higher Heating Value
HNBR	Hydrogenated Nitrile Butadiene Rubber
JGA	The Japan Gas Association
LEV	Low Emission Vehicle
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
MN	Methane Number, also known as MNc (calculated Methane Number) or MI (Methane Index)
MWM	Company (originally Mechanische Werkstätte Mannheim) that developed a non-proprietary method for calculating Methane Number
N ₂	Nitrogen
NBR	Nitrile Butadiene Rubber
NGV	Natural Gas Vehicle
NGVA	Natural Gas Vehicle Association
NMHC	Non-Methane Hydrocarbon
NO _x	Oxides of Nitrogen
OBD	On-Board Diagnostics
PM	Particulate Matter
ULEV	Ultra-Low Emission Vehicle
RISE	Research Institute of Sweden
WI	Gross Wobbe Index (also referred to in this document as Wobbe Index). In this Charter, WI is based on HHV and calculated at 15°C reference temperature and 1 atmosphere reference pressure.

The Worldwide Fuel Charters 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 technologies that maintain 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 explain the underlying science in the technical backgrounds of these documents.

This Charter recommends quality specifications for methane-based fuels used for transportation purposes, including fuels identified as compressed natural gas (CNG), liquefied natural gas (LNG) and biogas. Methane-based fuel is an important alternative that has the potential to improve a region's energy security and lower greenhouse gas emissions, especially when it contains advanced, sustainable biogas. Its use in transportation has been limited due to lack of infrastructure, relatively short driving range and the need for vehicle and engine adaptation. Wide variations in fuel quality around the world also have limited the size of this market. The recent rapid rise in methane production through unconventional techniques, however, has rekindled and strengthened interest in this fuel, and better, harmonised fuel quality is a key pathway to help this market grow.

Like the Worldwide Fuel Charter for Gasoline and Diesel Fuel, the Worldwide Fuel Charter for Methane-Based Transportation Fuels (referred to here as the Methane-Based Fuels Charter) divides the vehicle and engine markets into categories of increasing performance and emissions regulations. Moving from the lowest category (least stringent performance and emission controls) to the highest (the most stringent requirements) will typically achieve improved performance and lower emissions from the vehicles and engines using the fuel specified for the category.

The Methane-Based Fuels Charter provides recommendations for Categories 3, 4, and 5 to closely match the emission controls for each category with their gasoline and diesel fuel equivalents in the Worldwide Fuel Charter for those fuels. In the Gasoline and Diesel Fuel Charter, Category 1 and 2 fuels were intended for markets with no emission controls or first generation emission controls such as US Tier 1, Euro 2/II, or Euro 3/III. Methane-based fuels are inherently cleaner, however, so engines/vehicles that are able to use methane generally meet the more stringent emission control requirements aligned with the Gasoline and Diesel Fuel Charter's Category 3 and above; therefore, Categories 1 and 2 are not listed in the Methane-Based Fuels Charter.

Category 3

Basic quality for methane-based fuels, recommended for use in natural gas vehicles/engines with either no emission controls or stoichiometric positive-ignition engines and 3-way emission control catalysts.

Category 4

Higher methane-based fuel quality, recommended for use in natural gas vehicles/engines with advanced exhaust after-treatment and/or enhanced performance (e.g., positive-ignition engines with a high compression ratio), or having other market demands.

Category 5

Highest methane-based fuel quality, recommended for use in natural gas vehicles/engines with highly advanced exhaust after-treatment and/or enhanced performance (e.g., positive-ignition engines with a high compression ratio), or having other market demands. Category 5 markets require the highest Methane Number (MN) and energy content fuel that simultaneously enables a longer driving range and higher fuel efficiency.

A significant portion of the global methane market can provide fuel that meets the Category 5 specifications for high MN and high Gross Wobbe Index (WI). Several countries and regions, however, cannot. For example, some areas of Southeast Asia can only provide fuel meeting Category 3 or Category 4 specifications. Of the two, Category 4 fuel is preferred because it has the lower sulphur level critical to emission control technologies.

The fuel quality recommendations that begin on page 4 apply to the finished fuel as provided to the consumer at refuelling stations. 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.

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

- Using good housekeeping practices throughout distribution to minimise contamination from dust, water, different fuels and other sources of foreign matter.
- Using materials to protect distribution equipment that do not interfere with fuel quality.
- Labelling dispenser pumps adequately to help consumers identify the appropriate fuels for their vehicles/engines.
- Dispensing fuel through nozzles meeting ISO 14469-2017 or the CSA/ANSI NGV 4.1 standard for CNG dispensers.

To meet ongoing environmental, energy and consumer 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.

The quality of methane-based fuels can vary considerably based on many factors. Historically, methane-based fuel comes primarily from natural gas extracted from the earth and is distributed as Compressed Natural Gas (CNG) or Liquefied Natural Gas (LNG). Fuel properties, such as sulphur content, may vary significantly across regions due to naturally occurring variations in natural gas sources. Regulations also can affect quality; some countries, for example, require odoriferous sulphur-containing compounds to be added to the fuel to help alert consumers to gas leaks. More recently, methane-based fuel has become available through biomass fermentation (often called biogas) or gasification of wood biomass. Biomass feedstock impurities like silica compounds must be considered when specifying methane-based fuel quality for transportation purposes.

Beyond these factors, regional processing differences can further affect fuel quality. In most markets, fuel intended for use in transportation represents a very small portion of the overall methane-based fuel available in a given region. As a result, local fuel quality is largely determined by non-transportation uses, which have very different requirements and capabilities than vehicles and mobile engines. Burners and stationary engines, for example, require a relatively consistent Wobbe Index over time but may be readily adjusted at the installation site to accommodate the locally available gas quality. By contrast, vehicles and mobile engines cannot be tuned after the product is in the consumer's hands. As a result, when vehicles and other mobile engine products use different quality fuels due to refuelling in different locations, they may exhibit different levels of performance and emissions.

In markets where the recommended fuel quality is not yet available or feasible, manufacturers need to determine if engines or vehicles could be adapted to the fuel available before the product reaches the consumer. Adaptation allows some flexibility to provide vehicles and mobile engines to these markets, but it also may compromise the vehicles/engines in various ways. For example, the need for adaptation may constrain product availability, so that some methane-powered vehicles and mobile engines may be unavailable in those markets. Also, the vehicles and mobile engines that are available in or adapted for markets with lower fuel quality may exhibit significantly poorer performance, higher emissions, higher rates of fuel consumption and/or reduced power. As the use of gaseous methane as a transportation fuel increases in a given region, better alignment of the region's fuel properties with the Charter's recommended category specifications will encourage greater availability of methane-powered vehicles/engines and generally will improve their performance and emission profile.

The methane-based fuel properties described by this Charter are intended to enable the broadest use of vehicles and mobile engines regardless of the market context into which they are sold. The WWFC Committee recognizes, however, that significant factors outside the vehicle/engine manufacturer's control may affect fuel quality, and these, in turn, may affect the vehicle and mobile engine market. Importantly, care must be taken to assure that whatever fuel is delivered to vehicles and mobile engines in a given market is appropriate for that market's level of vehicle/engine technology. More information about how quality issues affect vehicle and engine technology is provided in the Technical Background, beginning on page 8.

Basic quality for methane-based fuels, recommended for use in natural gas vehicles/engines with either no emission controls or stoichiometric positive-ignition engines and 3-way emission control catalysts.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Wobbe Index ¹	MJ/m ³	40	
Methane Number ¹		65	
Sulphur (total)	mg/kg		30
H ₂ S + COS	mg/kg (as sulphur)		5
Hydrogen	mol% (dry gas)		2
Carbon monoxide ²	mol%		0.1
CO ₂	mol%		5
Oxygen	mol%		1
Liquid Hydrocarbon	dew point (°C)		2°C below lowest expected ambient temperature ³ at any pressure in the vehicle's gas system
Water	dew point (°C)		5°C below lowest expected ambient temperature ³ at maximum fuel tank pressure
Particulate ⁴			Not detected
Silicon, total	mg/m ³		0.1 ⁵
Lubricating oil	mg/m ³		15 ⁶

¹ WI, as used in this document, is based on Higher Heating Value (HHV). WI and MN should be considered together. Also note that Lower Heating Value (LHV) is closely associated with WI and, therefore, is not separately specified. Please see discussion on methane markets and regional variations, above at page 3.

² CO measurement is needed only when the methane-based fuel is produced from synthesis gas, such as by gasification of biomass or coal.

³ Depending on region and time of year.

⁴ Particulate matter may include dust, metal, biological material or other solid contaminants.

⁵ A standardised test method needs to be developed for this range.

⁶ Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor minus recovered lubricant oil weight)/(Compressed natural gas volume), as measured over the timeframe between oil additions.

Higher methane-based fuel quality, recommended for use in natural gas vehicles/engines with advanced exhaust after-treatment and/or enhanced performance (e.g., positive-ignition engines with a high compression ratio) or having other market demands.

This category includes two subcategories to accommodate regional differences and provide guidance for vehicles/engines designed for regional market fuels. These subcategories should be considered as having comparable fuel quality, and the WWFC Committee has no preference for one over the other. Refuelling pumps should be clearly and precisely labelled for quality and should advise consumers to consult their owners' manuals. Fuel providers should take note of the types of vehicle and engine designs in their regional markets and provide the fuel that is compatible with those designs.

PROPERTIES	UNITS	LIMITS	
		SUBCATEGORY A	SUBCATEGORY B
		MIN	MIN
WI ¹	MJ/m ³	40	46
MN ¹		75	65

PROPERTIES	UNITS	MAX
Sulphur (total)	mg/kg	10
H ₂ S + COS	mg/kg (as sulphur)	5
Hydrogen	mol% (dry gas)	2
Carbon monoxide ²	mol%	0.1
CO ₂	mol%	5
Oxygen	mol%	1
Liquid Hydrocarbon	dew point (°C)	2°C below lowest expected ambient temperature ³ at any pressure in the vehicle gas system
Water	dew point (°C)	5°C below lowest expected ambient temperature ³ at maximum fuel tank pressure
Particulate matter ⁴		Not detected
Silicon, total	mg/m ³	0.1 ⁵
Lubricating oil	mg/m ³	15 ⁶

¹ WI, as used in this document, is based on HHV. WI and MN should be considered together. Also note that LHV is closely associated with WI and, therefore, is not separately specified. Please see discussion on methane markets and regional variations, above at page 3.

² CO measurement is needed only when the methane-based fuel is produced from synthesis gas, such as by gasification of biomass or coal.

³ Depending on region and time of year.

⁴ Particulate matter may include dust, metal, biological material or other solid contaminants.

⁵ A standardised test method needs to be developed for this range.

⁶ Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor minus recovered lubricant oil weight)/(Compressed natural gas volume), as measured over the timeframe between oil additions.

Highest methane-based fuel quality, recommended for use in natural gas vehicles/engines with highly advanced exhaust after-treatment and/or enhanced performance (e.g., positive-ignition engines with a high compression ratio) or having other market demands. Category 5 markets require the highest MN and energy content fuel that simultaneously enables a longer driving range and higher fuel efficiency.

PROPERTIES	UNITS	LIMITS	
		MIN	MAX
Wobbe Index ¹	MJ/m ³	46	
Methane Number ¹		75	
Sulphur (total)	mg/kg		10
H ₂ S + COS	mg/kg (as sulphur)		5
Hydrogen	mol% (dry gas)		2
Carbon monoxide ²	mol%		0.1
Inert gases (CO ₂ +N ₂)	mol%		4.5
Oxygen	mol%		1
Liquid Hydrocarbon	dew point (°C)		2°C below lowest expected ambient temperature ³ at any pressure in the vehicle gas system
Water	dew point (°C)		5°C below lowest expected ambient temperature ³ at maximum fuel tank pressure
Particulate matter ⁴			Not detected
Silicon, total	mg/m ³		0.1 ⁵
Lubricating oil	mg/m ³		15 ⁶

¹ WI as used in this document is based on HHV. WI and MN should be considered together. Also note that LHV is closely associated with WI and, therefore, is not separately specified. Please see discussion on methane markets and regional variations, above at page 3.

² CO measurement is needed only when the methane-based fuel is produced from synthesis gas, such as by gasification of biomass or coal.

³ Depending on region and time of year.

⁴ Particulate matter may include dust, metal, biological material or other solid contaminants.

⁵ A standardised test method needs to be developed for this range.

⁶ Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor minus recovered lubricant oil weight)/(Compressed natural gas volume), as measured over the timeframe between oil additions.

All gas properties are to be determined at standard temperature and pressure conditions to reflect ASTM practice: P = 14.696 psia (101.325 kPa) and T = 60°F (15.55°C) (ref: D3588-98).

PROPERTIES		UNITS	ISO	ASTM	JIS	Other
Wobbe Index		MJ/m ³	6976	D3588-98		
Methane Number				D8221		EN16726 ¹
Lower Heating Value		MJ/m ³	6976	D3588	K2301	
Sulphur ²	Category 3	mg/kg	6326-5			
	Category 4/5	mg/kg	19739			
H ₂ S + COS ²		mg/kg (as sulphur)	6326-1,3 19739	D4084-07		
Hydrogen	Dry gas	mol%	6974	D1945-14	K2301	
	Wet gas		6975	D2504-88		
Carbon monoxide		mol%	6975	D2504-88	K2301	
Inert gases (CO ₂ +N ₂)		mol%		D1945		
CO ₂		mol%	6974-6	D1945	K2301	
Oxygen		mol%	6974 6975	D1945 D2504-88	K2301	
Liquid HC dew point			23874 TR11150 TR12148	D1945		
Water (dew point)		°C	6327	D1142-95		
Particulate matter ³						
Silicon, total ⁴		mg/m ³	16017- 1:2000			RISE SP4846
Lubricating oil ⁵		mg/m ³				RISE SP5184

¹ Not an ISO standard. Annex A contains the MWM method.

² A typical value of 0.74 kg/Sm³ can be used for conversion (Swedish standard SS 155438:2015).

A sulphur level of 10 mg/Sm³ is then equivalent to 13 mg/kg.

³ A standardised test method needs to be developed.

⁴ A standardised test method with sufficiently low detection limits needs to be developed/verified.

⁵ Additional methods are in development.

Gross Wobbe Index (Wobbe Index)

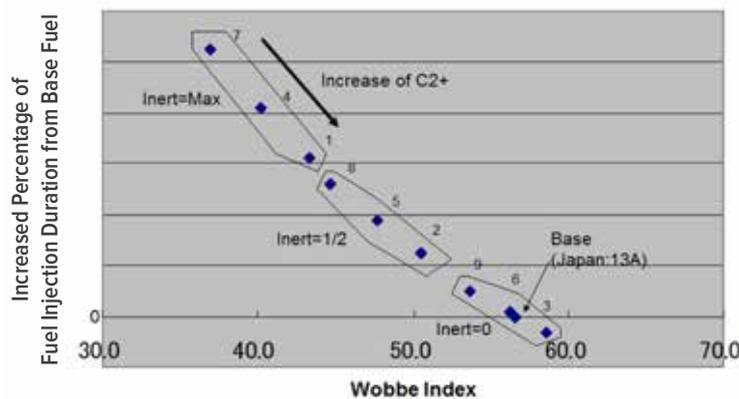
The Wobbe Index (WI), which is a measure of the energy content of methane-based fuels, is derived from the fuel energy flow rate through a fixed orifice under given conditions. Mathematically, it is calculated using the heating value of the fuel and the square root of the fuel's specific gravity. When calculated using the gross (higher) heating value of the fuel, it is called the Gross Wobbe Index.

WI is important for vehicle/engine operation because it correlates directly with the indicated power output available from an engine (limited by the potential for knock and the water content). In general, vehicles and engines can function with fuel having a WI lower than the specified range, but they will have a correspondingly lower power output.

WI variations will cause variations in the air-fuel ratio, which, in turn, affect engine power, performance, durability and emissions. The impact of WI variability on power output and performance is significantly greater in engines lacking closed-loop air-fuel ratio controls than in those equipped with such controls. It is important to limit WI variability within a narrow range to enable proper vehicle/engine calibration for performance and emissions. Considering the limits of controllability in current closed-loop controlled engines, the WI should vary less than $\pm 3 \text{ MJ/m}^3$ within each category to maintain desired vehicle/engine performance and minimise exhaust emissions.

It is instructive to look at the relationship between WI and the duration of fuel injection in closed-loop controlled engines. Figure 1, below, shows the necessity of increasing the fuel injection duration as the WI declines to properly maintain the air-fuel ratio. The impact of WI on a closed-loop controlled engine can become dramatically worse, however, when the WI exceeds the engine's limit of controllability. This will significantly increase exhaust emissions and reduce engine performance.

Figure 1: Relation Between Wobbe Index and Fuel Injection Duration at Constant A/F Ratio



Source: Calculations by Toyota from in-house data

While all fuel properties are important, the most critical for determining a vehicle/engine's design for a given market are WI, methane number (MN) and Lower Heating Value (LHV). These properties are interrelated to some extent; thus, the Charter can specify limits for just two of them.

The fuel's Gross WI increases with an increasing fraction of heavier gas components (ethane, propane, etc.), and at the same time, MN decreases when methane content decreases. If the amount of inert gases (CO_2 and N_2) is low, Gross WI and MN will have a linear inverse relationship. Thus, limiting inert gases to low levels enables a specified minimum MN limit to act like an upper limit on WI, eliminating the need to specify a max WI.

LHV is another fuel energy content parameter that is sometimes used for engine performance calibration because it correlates well with indicated engine power output. Even at the same LHV, however, WI may vary depending on gas density. The difference between WI and LHV is very small at the low water content limits specified in this Charter, so a separate limit for LHV has not been specified.

Equation 1: Gross Wobbe Index

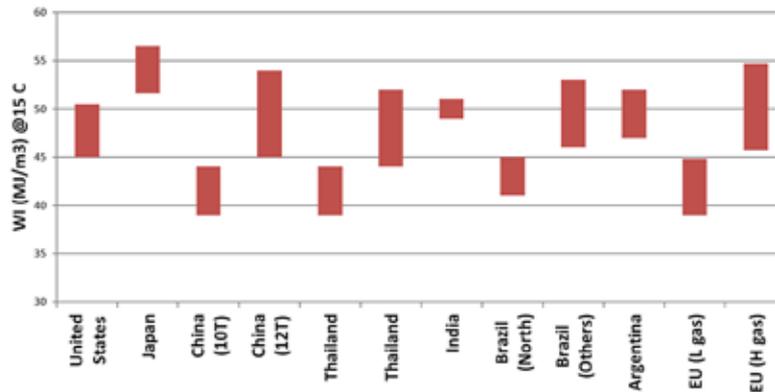
$$WI = \frac{H}{\sqrt{S}}$$

where H = Gross Heating Value (MJ/m^3) and S = Specific Gravity (Air=1).

WI can be calculated at any temperature; for consistency in this Charter, we use 15.55°C as the reference temperature and 1 atmosphere (14.696 psia) as the reference pressure.

Methane-based fuel properties in various countries around the world, and even within some countries, show wide variation in WI ranges (see Figure 2, below). Some countries further subdivide the fuel into different classifications by region or some other basis. This Charter recognizes these variations by assigning the classifications to levels of vehicle/engine technology list in the Categories.

Figure 2: Wobbe Index Ranges in Several Countries, Based on Local Specifications and Survey Data



Source: Data compiled by JAMA and ACEA; US data derived from CRC Project No. PC-2-12.

Methane Number

MN is the anti-knocking indicator for methane-based fuel; it is generally related to the percent of methane by volume in a gaseous hydrocarbon mixture. In that sense, MN is like the octane rating of gasoline. As with gasoline engines, knock events can be serious and cause catastrophic damage to engines. Figure 3 shows pictures of the type of damage that can occur.

Figure 3: Examples of Piston Damage from Knock



Courtesy of Cummins Wesport, Inc.

The importance of MN on vehicle/engine operation varies with engine configuration. Diesel-based turbocharged engines designed for heavy-duty trucks have high compression ratios and are very sensitive to detonation (knocking); their high combustion pressure can lead to catastrophic engine failure when operating on a fuel with inadequate MN. Gasoline-based naturally aspirated engines designed for passenger cars and other light-duty vehicles/engines, on the other hand, are less sensitive to knock because the combustion pressure is lower.

The discussion on regional variability (see page 3, above) describes how widely market fuel MN can vary. Some or all of this variability is due to the fuel source. For example, natural gas extracted in one region may differ naturally from natural gas extracted in a different region. Also, methane-based fuel containing LNG may have a beneficially higher MN relative to unprocessed natural gas if heavier hydrocarbons were removed from the LNG during the liquefaction process.

Importantly, it is impossible to build a vehicle/engine that will operate properly and efficiently at all MN levels. At the same time, catastrophic engine failure must be prevented. From the perspective of vehicle operation, engine architecture dictates the necessary MN level and the need to control MN within certain limits. Many of the latest vehicles/engines, with either type of engine configuration, now have sophisticated systems that control knock, and this helps maintain proper engine operation in an efficient manner. Even with these control systems in place to protect engines from knock, however, other adverse impacts may occur when a vehicle/engine uses a fuel with a MN below the preferred level for that engine, such as:

- Significant decline in engine power (down to 65% load);
- Reduced engine efficiency;
- Decreased engine durability; and
- Consumer dissatisfaction.

Determining Methane Number

MN is determined from the gas composition; pure methane gas will have a high MN. In general, higher hydrocarbons contained in the natural gas – such as ethane, propane and butane – reduce the MN, while inert gases – such as nitrogen, carbon dioxide and noble gases – increase the MN. Several methods exist for calculating MN. Historically, the “AVL” method has been the most popular among those in engine manufacturing, but the algorithm it uses is proprietary. The newer “MWM” method, which made improvements to the AVL method, was recently standardised by ASTM and CEN (thus, it is publicly available) and is the method recommended here.

Table 1: Examples of Wobbe Index and Methane Number Calculations

Fuel ID	1	2	3	4	5	6	7	8	9	10	11
Methane (%)	100	95	90	85	76	95	90.6	98	90	94	88.4
Ethane (%)		5	10	15	24				5	5	5.6
Propane (%)						5	9.4		5		4.5
Butane (%)								2		1	1.5
Wobbe Index (Mj/m ³ @ 0°C)	53.6	54.5	55.3	56.2	57.7	55.4	56.9	54.7	56.2	55.0	57.0
Wobbe Index (Mj/m ³ @ 15°C)	50.8	51.7	52.4	53.3	54.7	52.5	53.9	51.9	53.3	52.1	54.0
Methane Number ¹	99.0	88.0	80.0	74.0	66.0	80.0	68.0	85.0	73.0	81.0	66.0

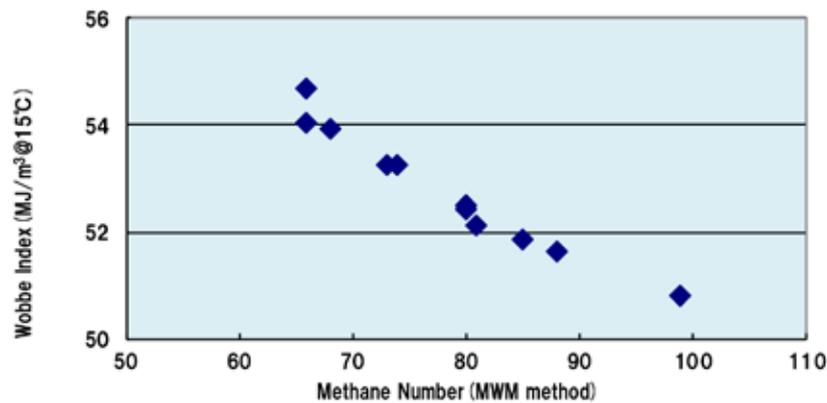
Source: Non-confidential Data Used with Honda’s Permission

¹ Calculated using D8221/EN16726 (“MWM” Method).

The Relationship Between MN and WI

As discussed above on page 8, it is important to recognize that the MN and WI, which are key characteristics of gaseous methane-based fuels, are directly related (as long as the inert content is low) and vary inversely as the gas composition changes. For example, high MN fuel has good anti-knocking characteristics but with lower WI (i.e., lower energy content). This inverse relationship is shown in Figure 4 using the fuels listed in Table 1.

Figure 4: Inverse Quality Relationship of MN to WI in Several Fuel Samples (see Table 1)



Source: Non-confidential Data Used with Honda's Permission

Sulphur

Sulphur can enter methane-based fuel through several routes: natural gas extracted from the earth naturally contains sulphur; gas derived from other sources may contain it if those sources contain it; and sulphur-containing odorants may be added to the gas during processing or distribution to aid in leak detection for safety reasons.¹ Sulphur has impacts inside the engine, in the exhaust after-treatment system and on sensors used for the on-board diagnostic (OBD) systems. These adverse effects on vehicles/engines require it to be reduced or limited in methane-based fuel used for transportation.

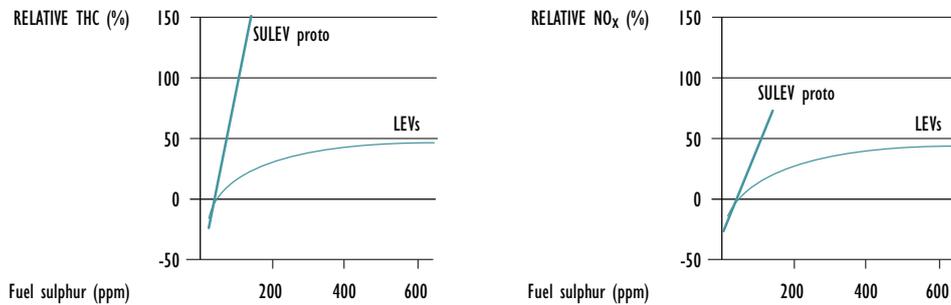
Sulphur can significantly increase smog-forming emissions by reducing the efficiency of three-way exhaust system catalysts.² If the sulphur level is high enough, it may render the catalyst ineffective through sulphur poisoning of the catalyst's active sites. In addition, in powertrains with Otto-cycle, spark ignition-type engines, sulphur adversely affects heated oxygen sensors in the exhaust after-treatment system, which also reduces the system's ability to control emissions. In both diesel and Otto-cycle spark ignition-type engines, sulphur further contributes significantly to emissions of fine particulate matter (PM), through the formation of sulphates both in the exhaust stream and, later, in the atmosphere. Fortunately, these effects may be reversible, depending on the starting and ending sulphur levels. Controlling sulphur to the levels recommended in this Charter can reduce smog-forming emissions from catalyst-equipped vehicles/engines on the road and fine PM emissions from all vehicles/engines while protecting engine and emission control system components.

Extensive testing has been done to determine the impact of sulphur in gasoline and diesel fuel on vehicle/engine emissions and emission control systems also used on methane-powered vehicles/engines. Figure 5 shows the relationships between sulphur and emissions of NO_x and non-methane hydrocarbons (NMHC) in systems with three-way catalysts.

¹ SAE1616 states: "Natural gas delivered to any CNG fueling station or vehicle shall have a distinctive odor potent enough for its presence to be detected down to a concentration in air of not over 1/5 of the lower limit of flammability. This is approximately 1.0% methane in air by volume." In Japan, the typical dosage of odorising agent is 5 mg/Nm³. When using ethyl mercaptan (C₂H₆S), the resulting sulphur level is 3.1 mg/kg. The amount of added odorising compound should be carefully limited to keep the total sulphur level below Charter limits while maintaining compliance with applicable safety regulations.

² Three-way catalysts control emissions of HC, CO and NO_x.

Figure 5: Effect of Ultra-low Sulphur Levels on Emissions of NOx and NMHC



Source: Alliance/AIAM Low Sulphur Emissions Study (2001)

Fuel sulphur affects the feasibility of implementing advanced OBD systems on vehicles/engines. Existing California OBD II regulations require vehicles/engines to be equipped with catalyst monitors that determine when catalyst efficiency declines to the point of increasing tailpipe emissions by 1.5 times the standard. OBD systems, however, can malfunction if exposed to excess sulphur from the fuel.

Most methane-powered vehicles/engines use emission control systems similar to those used in gasoline engines, so methane-based transportation fuel intended for single-fuel powertrains should meet the same sulphur limits needed for gasoline-powered vehicles/engines. Dual-fuel vehicles/engines with compression ignition use emission control systems similar to those used in Diesel-cycle engines, so methane-based transportation fuel intended for dual-fuel powertrains should meet the same sulphur limits needed for diesel fuel-powered vehicles/engines.

Sulphur content, which has the most impact on emissions, is generally very low in both natural gas and biogas. Typically, it is lower than 10 mg/kg. Some regions, however, have a higher natural sulphur content and/or require odourisation that increases the sulphur level locally. The following Table 2 provides the sulphur content of methane-based fuels in various markets, based on survey and other data.

Table 2: Methane-Based Fuel Sulphur Levels Found in Some Countries

COUNTRY/REGION	Sulphur, Average (mg/m ³) ¹	Sulphur, Max (mg/m ³)	Source
Belgium	2.7	8	(a)
Denmark	2.6		(a)
France	<5	14	(a)
Germany	1.5	5	(a)
Italy	25	35	(a)
Japan		2	(b)
Netherlands	1.5	6	(a)
Spain	11	25.7	(a)
UK	3.3		(a)
US	3.4	23	(c)

¹ A typical value of 0.74 kg/m³ can be used for conversion (Swedish standard SS 155438:2015). A sulphur level of 10 mg/m³ is then equivalent to 13 mg/kg.

Sources:

- (a) Assessment on Sulphur Limitation in NG/ biomethane as Automotive Fuels; Input for CEN/TC 408; NGVA Europe, 2013.
- (b) The Japan Gas Association.
- (c) CRC Project No. PC-2-12, Natural Gas Vehicle Fuel Survey, June 2014; Table 2.1 in this report shows the range of pipeline tariff limits posted to the US Federal Energy Regulatory Commission in March 2008.

Hydrogen Sulphide + Carbonyl Sulphide

As an additional check on sulphur content, this Charter also recommends separately controlling the level of hydrogen sulphide (H₂S) plus carbonyl sulphide (COS) in the fuel. H₂S is corrosive to internal vehicle/engine parts and fuel storage systems. It is present naturally in raw gas, including biogas. It is best to limit H₂S in the purification-desulphurisation process to 2 ppm or less. COS, which is an environmental precursor to H₂S, is emitted by oceans and naturally abundant in the atmosphere; human activity also contributes to ambient levels.

Hydrogen

If hydrogen is present in the fuel, it is usually because it was added. For example, some have suggested adding the excess hydrogen produced by renewable power production, such as wind turbines, to natural gas on the theory that this will help reduce NO_x and/or greenhouse gas emissions. Hydrogen, however, can cause embrittlement of the high tension steel used widely in CNG vehicle fuel tanks and the methane-based fuel transportation infrastructure, so this practice is not recommended. In addition, if the hydrogen content in the methane-based fuel reaches a high enough level, a special vehicle/engine calibration would be needed to accommodate hydrogen's different burning velocity. For these reasons, hydrogen-methane mixtures should be managed separately from the usual methane-based transportation fuel.

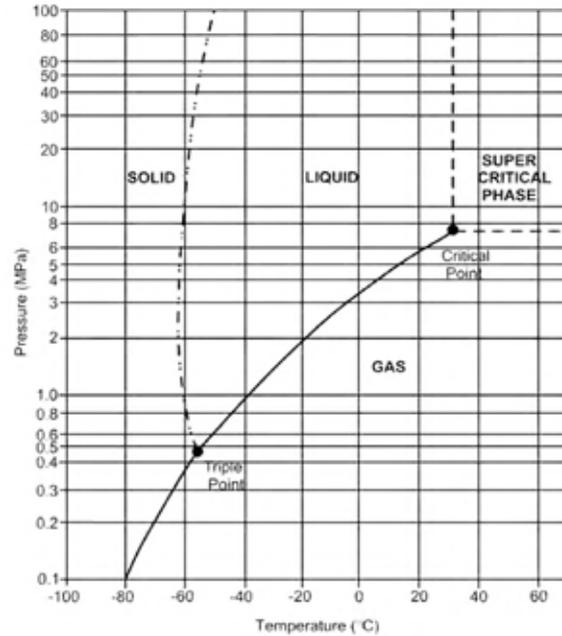
Hydrogen can be specified either as a dry gas or a wet gas. The ECE R110 technical regulation defines "wet gas" and "dry gas" and requires a maximum hydrogen limit of 2 mol% in dry gas (which normally limits water vapor to less than 32 mg/m³ at a pressure dew-point of -9°C at 20 MPa). Other specifications used in many countries limit the maximum hydrogen concentration to 0.1 mol% in wet gas (which means a water content higher than the dry gas limit). The wet gas specification is usually intended to help prevent corrosion in the methane-based fuel transportation systems and in the steel fuel tanks used in natural gas vehicles/engines.

Carbon Dioxide

Carbon dioxide (CO₂) in the fuel gas may affect vehicles and engines in different ways. As an inert gas, it reduces the engine's power output, so the goal is to keep the concentration at the lowest possible level. Also, the gas easily penetrates rubber components, thereby leading to such damage as causing the rubber to swell, crack or blister. Different rubber materials react differently; for example, nitrile butadiene rubber (NBR), hydrogenated nitrile butadiene rubber (HNBR), and ethylene propylene diene monomer rubber (EPDM) may experience greater swelling, and foaming also is possible.

A particular problem that affects emissions is the possibility that, if present at high enough levels, CO₂ may condense at elevated pressures and low temperatures. When the condensate reevaporises at reduced tank pressures, the gas mixture may then have a different or variable composition. This can lead to a reduced ability to control the air-fuel ratio and, consequently, vehicle/engine exhaust emissions. To minimise the risk of this situation, the CO₂ concentration should be low enough to avoid condensation at the lowest expected ambient temperature (e.g., -30°C) and the highest expected gas storage pressure (e.g., 30 MPa in the US market). Fuel providers should make note of the dew-point pressure of CO₂: 2 MPa at -20°C, and 1 MPa at -40°C (see phase diagram in Figure 6).

Figure 6: Vapor-Liquid Equilibrium Curve of Carbon Dioxide



Source: APEC Energy Working Group, “Building Capacity for CO₂ Capture and Storage in the APEC Region: A training manual for policy makers and practitioners”, Publication No. APEC#209-RE-04.5, Module 4-59, October 2009, available at www.apec.org.

Carbon dioxide cannot be liquefied when the partial pressure is below the curve shown in Figure 6. Assuming the lowest CNG temperature is -30°C, the dew-point pressure is 1.5 MPa, as shown above (Figure 6). When the highest CNG pressure is 30 MPa, the partial pressure of carbon dioxide needs to be less than 1.5 MPa (less than 5% CO₂ by volume in the fuel mixture) to keep the fuel in the gas phase. Some countries allow more than 5% of carbon dioxide in market gas; in this case, however, the minimum ambient temperature should be considered so that the carbon dioxide does not condense.

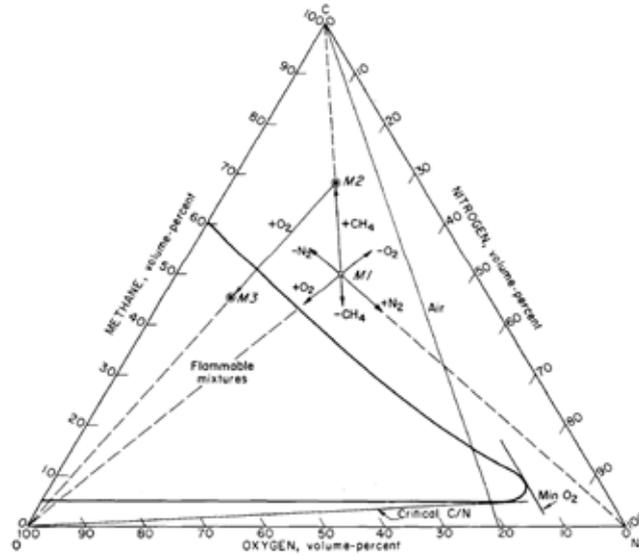
Oxygen

The oxygen concentration in methane-based fuel must be limited to prevent explosion in high pressure CNG tanks. An investigation into the flammability of methane-oxygen-nitrogen mixtures informs the decision about an appropriate oxygen limit.

Figure 7 shows the flammability range for a nitrogen-oxygen-methane mixture. When the oxygen concentration falls below 12 vol%, a flame will not propagate regardless of the methane and nitrogen levels. This point is called the minimum oxygen requirement for flame propagation. For this analysis, pressure also is a factor. Figure 8 shows how the minimum oxygen requirements for flame propagation for three types of hydrocarbons also depends on pressure. For methane at 3600 psia (the maximum filling pressure for methane-powered vehicles/engines), the minimum oxygen requirement for flame propagation is about 8 vol% (by extrapolation). Based on this analysis, this Charter recommends a maximum oxygen limit of 1 mol%, which is far less than 8 vol%¹ and therefore provides a comfortable margin of safety.

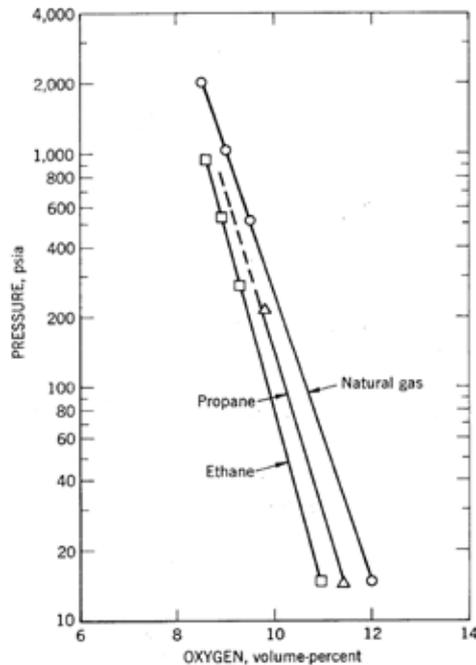
¹ For this discussion, mol% and vol% are considered equivalent.

Figure 7: Flammability Limits of Methane-Oxygen-Nitrogen Mixtures



Source: Zabetakis, Michael George, "Flammability Characteristics of Combustible Gases and Vapors," US Dept of Interior Bureau of Mines, 1965, available at www.osti.gov/scitech/servlets/purl/7328370/.

Figure 8: Effect of Pressure on Minimum Oxygen Requirements for Flame Propagation Through Natural Gas-Nitrogen-Air, Ethane-Nitrogen-Air and Propane-Nitrogen-Air Mixtures at 26°C



Source: Zabetakis, Michael George, "Flammability Characteristics of Combustible Gases and Vapors," US Dept of Interior Bureau of Mines, 1965, available at www.osti.gov/scitech/servlets/purl/7328370/.

Liquid Hydrocarbon

Methane-based vehicles/engines, including those using LNG, are designed to inject hydrocarbons in a gaseous state into the combustion chamber, making the presence of liquids undesirable.¹ The presence of liquid HC in the fuel may cause difficulty in controlling the amount of fuel injected into the engine. Also, if a liquid pool of higher hydrocarbons (with very low methane number) suddenly reaches the engine, severe knocking might result that can seriously damage the engine.

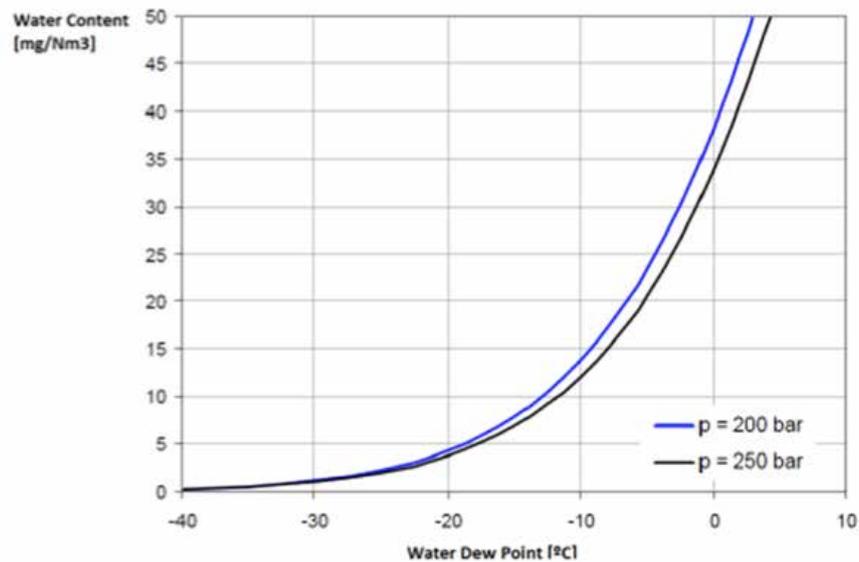
This Charter adopted the HC dew point as the property to monitor for minimising HC liquids in the fuel; other parameters also may be used, for example, percent liquid volume/total gas volume. The maximum allowable HC dew point depends on the lowest ambient temperature to which the vehicle might normally be exposed. HC dew point can be measured directly (e.g., using ISO/TR 12148) or calculated from a detailed composition, as in ISO 23874. See Test Methods, above, page 7.

Water

Methane-based vehicles/engines are designed to use hydrocarbons in a gaseous state, so the presence of water is undesirable. Excess water can cause fuel delivery problems, including fuel line plugging, due to the presence of the water itself, the formation of ice particles, or frost formation within the fuel system, especially at cold ambient temperatures. Condensed moisture also promotes corrosion in the fuel line and cylinder, which can have serious consequences.

This Charter has adopted the water dew point as the property to monitor for minimising water in the fuel; other parameters, such as percent liquid volume/total gas volume, also may be used. The correlation between water content and water dew point is given in EN ISO 18453:2005 (see Figure 9). The water dew point at a given fuel pressure should be compatible with the geographic location in which the vehicle/engine will operate and should be set to prevent water condensation in the fuel storage cylinder at the maximum operating container pressure.

Figure 9: Water Content vs. Water Dew Points



Source: EN ISO 18453:2005

¹ For LNG vehicles/engines, the need for gaseous fuel applies downstream of the fuel evaporator.

Particulate Matter

Methane-based fuel should not contain any dust, metal, biological, or other solid particles that can cause deposits in or blockage of the vehicle fuel system. To clean CNG-derived gas, a dedicated filter with a nominal mesh size of one micron or less should be placed as close as possible to the filling nozzle. In addition to removing dust and metal, the one micron or less filter size will also help capture biogenic material such as microorganisms.

With respect to biological particles, also relevant for CNG-derived fuel, the question of filter size presents trade-offs. A smaller mesh will be more effective at removing the biogenic material but may fill up faster; filling up the filter causes the pressure to drop across the filter, and faster filling means the filter will need to be changed more frequently. High Efficiency Particulate Air Filter (HEPA-type) will last longer with a lower pressure drop, relative to its capture efficiency. Generally speaking, filters with an efficiency of at least 99.95% (for particles between 0.2-10 μm) are efficient enough to reduce the risks of microbiological contamination of the gas as well as non-biological particles.

For LNG-derived fuel, a dedicated filter also should be placed as close as possible to the filling nozzle, to ensure the capture of max 10 mg/l solid particulates. Available filters range from 5 to 250 microns, and as fine a filter as possible is preferred. In addition, fuel providers should have in place a quality protocol to ensure fuel cleanliness. Such a protocol would include, for example, proper cleaning of tanks and pipes before commissioning the fuelling station.

Total Silicon

Silicon and silica are contaminants that may enter methane-based fuel through the addition of biogas and can cause serious damage to the vehicle/engine system. Some raw biogas, especially that generated from landfills, sewage or municipal biowaste, contains significant amounts of siloxanes that are volatilised during anaerobic digestion. Siloxanes also are used as de-foamers during biomass fermentation. When present during combustion, siloxanes and other organo-silicon compounds will form silica that deposits onto many internal vehicle parts, such as valves, lambda oxygen sensors and cylinder walls. These deposits can cause abrasion, exhaust gas misalignment and even blockage of pistons and cylinder heads. Figure 10 shows an engine that has been damaged by the presence of silicon in the fuel gas.

Silica also creates deposits on sensor elements, thereby impeding oxygen diffusion. Oxygen sensor manufacturers have shown that silicon levels above 0.1 mg/m³ can severely harm the oxygen sensors of some vehicles/engines.¹ Higher silicon levels reduce oxygen sensor durability. Vehicle/engine manufacturers recommend as little silicon in the fuel as possible as well as continued review and monitoring of this issue.

Currently, a standardised test method for measuring silicon at the recommended limit is not yet available. A method for measuring silicon in natural gas has been developed but is not yet fully validated, so the silicon limit in the category specification tables is preliminary. Nevertheless, vehicle and engine manufacturers consider the maximum silicon limit in the category tables to be an important step toward protecting vehicles/engines from silicon-contaminated fuel.

Figure 10: Picture of an Engine Damaged by Silicon



Source: Presentation about the Biogas Project in Kobe-City, by the City of Kobe, available at www.gcus.jp/report/wholeReport/conference/pdf/rep110314_06.pdf

¹ See CEN/TC 408 WI 00408005: 2013(E).

Lubricating Oil

The contamination of methane-based fuel by lubricant oil used in gas compression equipment can cause injector fouling and lead to the disabling of the vehicle's pressure regulator. Some oil types also can damage certain types of rubber materials. Thus, lubricant oil for compressors should be chosen carefully with those potential impacts in mind.

These problems have occurred in many countries, but published fuel limits are rare. The limit in this Charter (15 mg/m³) matches a CEN standard (EN 16723-2) for a dedicated high quality fuel grade. The CEN standard, in turn, was based on a pre-existing Swedish standard developed to enable most Swedish filling stations to comply while also meeting vehicle manufacturer needs for fuel filter service intervals. The Japan Gas Association (JGA) also has published a specification, and importantly, along with a measurement method.¹ In the absence of accurate and easily available measurement methodology, JGA estimated the potential oil contamination by using basic engineering principles to calculate the consumed oil, as shown in Equation 2, below. A JGA survey indicated that this calculation correlated well to the trapped oil found at the dispenser.² This equation may be used until an internationally-accepted test method is developed.

Equation 2: Amount of Lubricant in Methane-Based Fuel

$$\text{Lubricating oil mg/m}^3 = \frac{(A - B)}{C}$$

where

A = Added compressor lubricant oil weight

B = Oil weight recovered from compressor filter

C = Compressed natural gas volume

Measurements are taken for the time period between oil additions at the compressor.

Recovered oil lubricant weight means oil filtered as the fuel leaves the compressor and before it reaches the vehicle/engine.

The vehicle's fuel filter should be able to capture contaminating oil if the fuel is not too dirty. With one-year filter maintenance terms becoming increasingly common, the amount of oil trapped per year should not exceed the filter's capacity. The Charter's lubricating oil specification will be revisited when compressor technology advances, for example, when it becomes more durable and when reliable oil-less compressors become available.

¹ "Safety Technology Guidelines for Compressed Natural Gas Stations," JGA.

² Id.

The WWFC Committee appreciates the many comments received on the proposed First Edition of the Worldwide Fuel Charter for Methane-Based Transportation Fuels. 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

C The document should refer to the fuel as natural gas instead of methane because methane is a single compound that cannot have varying quality.

R The Committee relabeled the fuel as Methane-Based Transportation Fuels (short-version: Methane-Based Fuel), which also encompasses bio-based fuel.

C Please clarify whether WI as used in this Charter is based on HHV or LHV and explain why the more common heating value was not used.

R The Charter's WI is based on HHV. WI is used because it measures fuel energy entering the engine and is a standard in the gas industry.

C Please explain why a maximum WI is unnecessary.

R Limiting inert gas content enables a minimum MN specification to also limit the maximum WI.

C Carbon monoxide should be omitted because it is never measured.

R The Committee has accepted the suggestion except for fuel produced from synthesis gas.

C Having both sulphur and H₂S+CO_s limits while also accommodating sulphur-based odorants is confusing.

R The tables have been changed to show that "sulphur" means total sulphur from all sources.

C Some countries require odorization that can cause the sulphur level to approach or exceed 10 mg/kg.

R The Committee suggests fuel providers in markets with sulphur levels above 10 mg/kg use Category 3 for guidance.

C The maximum silicon limit should be increased to match the test method detection limit.

R The Committee appreciates the concern but is cautious about higher levels and notes the selected limit is also used by Bosch. The Committee seeks improved test methods.

C Why did the Committee set a limit for lubricating oil when a test method has not been developed?

R Lubricating oil is contaminating the fuel supply today, so it is an important concern for vehicles/engines. ASTM is currently working to develop a test method.

C Equation 2 is inaccurate because it fails to include recovered lubricant oil weight.

R The Committee agrees and has modified the equation accordingly.

C Regarding lubricant oils, the Japanese market uses glycol-type synthetic oil and mineral oil, not ester-type synthetic oils.

R The Committee has modified the document.

C Please confirm that the background reference to a 20 mg/Nm³ limit for lubricating oil considered a reasonable period of filter maintenance.

R The Committee has modified the document.

C The Committee should delete the sentence regarding oil-less compressors. While widely used in Japan, their reliability and long-term durability remain a concern.

R The Committee has modified the document.

C The Committee should consider including the Propane Knock Index Methane Number in the draft ISO standard for LNG as a marine fuel.

R The Committee acknowledges this effort and will consider including the property when fully developed.

C The Committee should note that a higher MN does not automatically mean a higher methane content. The correlation highly depends on the amount of other molecules, such as ethane & propane, in the gas.

R The Committee believes the relationship between MN and methane content is accurately described.

C The MWM method is open to interpretation and can produce different values.

R The Committee disagrees.

C A graph showing the relationship between MN and LHV would be more relevant than Figure 4.

R The Committee disagrees.

C The sentence explaining CO₂ permeation through rubber should be corrected because rubber is a polymer and not a molecule.

R The Committee agrees and has edited the document accordingly.

C Methane at 3600 psia is far from an ideal gas as implied in the text and a footnote.

R The Committee agrees and has edited the document accordingly.

C Certain corrections and improvements are needed to the MWM references.

R The Committee has edited the document accordingly.

