WORLDWIDE FUEL CHARTER

FIRST EDITION

GASEOUS METHANE TRANSPORTATION FUEL

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MARCH 2019

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ACEA

European Automobile Manufacturers Association

AUTO ALLIANCE
DRIVING INNOVATION

Alliance of Automobile Manufacturers

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Truck and Engine Manufacturers Association

JAMA

Japan Automobile Manufacturers Association

March 2019

Subject: Gaseous Methane Transportation Fuel

Dear Recipient:

On behalf of vehicle and engine manufacturers from around the world, the Worldwide Fuel Charter (WWFC) Committee is pleased to present its proposed First Edition of a Worldwide Fuel Charter for Gaseous Methane Transportation Fuel. The WWFC Committee published its first charter, for gasoline and diesel fuel, in 1998; this charter is now in its fifth 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 and engine needs, for the benefit of consumers and the environment.

The use of methane as a transportation fuel has grown rapidly in recent years, and its quality varies widely around the world. As a result, the Committee saw a need to provide information about this fuel and how to match its quality with the needs and capabilities of modern vehicle and engine technologies. This document presents recommended methane quality specifications for markets with the most advanced motor vehicles and engines; it also recommends specifications for 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 minimize emissions and fuel consumption for the various categories of technologies. Matching fuel quality to vehicle/engine capabilities also provides a path to fuel quality harmonization and improved functioning of transportation markets.

As an alternative fuel, gaseous methane has 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 good quality methane in a sustainable way and to preserve its quality throughout the distribution system until it reaches the consumer.

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

We welcome your comments on this proposed new fuel charter and look forward to working with you to support harmonised fuel quality specifications for the benefit of consumers and the environment around the world.

Worldwide Fuel Charter Committee

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Supporting organisations:
- Organisation Internationale des Constructeurs d'Automobiles (OICA)

CONTENTS

ACRONYMS

A/F	Air-Fuel Ratio
AVL	A proprietary method for measuring Methane Number from AVL List GmbH.
CNG	Compressed Natural Gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
COS	Carbonyl Sulphide
CRC	Coordinating Research Council
DNG VL	is a global 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_2S	Hydrogen Sulphide
HC	Hydrocarbon
HEPA	High Efficiency Particulate Air (a type of air filter)
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
MWM	A method for determining Methane Number
N2	Nitrogen
NBR	Nitrile Butadiene Rubber
NGV	Natural Gas Vehicle
NGVA	Natural Gas Vehicle Association
NMHC	Non-Methane Hydrocarbon
NOx	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 calculated at 15°C reference temperature and 1 atmosphere reference pressure.

INTRODUCTION

The Worldwide Charters and Guidelines have two purposes: to inform policy makers and other interested parties how fuel quality can significantly affect engine and vehicle operation, durability and emission 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.

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

- Minimizing vehicle and engine emissions;
- Enabling vehicle and engine 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 and guidelines explain the underlying science in the technical backgrounds of these documents.

This Charter recommends quality specifications for gaseous methane used for transportation purposes, including fuels identified as compressed natural gas (CNG), liquefied natural gas (LNG) and biogas. Methane is an important alternative fuel that has the potential to improve a region's energy security and lower greenhouse gas emissions, especially when mixed with 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 methane 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 Gasoline and Diesel Fuel Charter, the Methane 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 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 is an inherently clean fuel, however, so engines/vehicles designed for methane fuel 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 Charter.

Category 3
Basic methane fuel quality, 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 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 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.

A significant portion of the global methane market can provide methane fuel quality that meets the Category 5 specifications for high MN and high WI . Several countries and regions, however, cannot. For example, some areas of South East Asia can only provide methane 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 6 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 minimize 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 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.

Methane fuel quality can vary considerably based on many factors. Historically, methane fuel comes primarily from natural gas extracted from the earth and is distributed as Compressed Natural Gas (CNG) or Liquified Natural Gas (LNG). Methane 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 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 quality for transportation purposes.

Beyond these factors, regional methane processing differences can further affect fuel quality. In most markets, methane intended for use as transportation fuel represents a very small portion of the overall methane available in a given region. As a result, local methane 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's 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 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 engine/vehicle technology. More information about how quality issues affect vehicle and engine technology is provided in the Technical Background, beginning on page 9.

Basic methane quality, 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	mg/kg		30
H_2S + COS	mg/kg (as sulphur)		5
Hydrogen	mol% (dry gas)		2
Carbon monoxide	mol%		0.1
CO_2	mol%		5
Oxygen	mol%		1
Liquid Hydrocarbon	dew point (°C)		2°C below lowest expected ambient temperature[2] at any pressure in the vehicle's gas system
Water	dew point (°C)		5°C below lowest expected ambient temperature[2] at maximum fuel tank pressure.
Particulate[3]			Not detected
Silicon, total	mg/m^3		0.1[4]
Lubricating oil	mg/m^3		15[5]

[1] 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] Depending on region and time of year.
[3] Particulate matter may include dust, metal, biological material or other solid contaminants.
[4] A standardized test method needs to be developed for this range.
[5] Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor)/(Compressed natural gas volume), as measured over the timeframe between oil additions.

Higher methane 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. Methane 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	SUBCATEGORY A MIN	SUBCATEGORY B MIN
WI[1]	MJ/m^3	40	46
MN[1]		75	65

PROPERTIES	UNITS	LIMITS MIN	LIMITS MAX
Sulphur	mg/kg		10
H_2S + COS	mg/kg (as sulphur)		5
Hydrogen	mol% (dry gas)		2
Carbon monoxide	mol%		0.1
CO_2	mol%		5
Oxygen	mol%		1
Liquid Hydrocarbon	dew point (°C)		2°C below lowest expected ambient temperature[2] at any pressure in the vehicle gas system
Water	dew point (°C)		5°C below lowest expected ambient temperature[2] at maximum fuel tank pressure
Particulate matter[3]			Not detected
Silicon, total	mg/m^3		0.1[4]
Lubricating oil	mg/m^3		15[5]

1 WI and MN should be considered together. Lower Heating Value 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 Depending on region and time of year.
3 Particulate matter may include dust, metal, biological material or other solid contaminants.
4 A standardized test method needs to be developed for this range.
5 Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor)/(Compressed natural gas volume), as measured over the timeframe between oil additions.

Highest methane 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	mg/kg		10
H_2S + COS	mg/kg (as sulphur)		5
Hydrogen	mol% (dry gas)		2
Carbon monoxide	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[2] at any pressure in the vehicle gas system
Water	dew point (°C)		5°C below lowest expected ambient temperature[2] at maximum fuel tank pressure
Particulate matter[3]			Not detected
Silicon, total	mg/m^3		0.1[4]
Lubricating oil	mg/m^3		15[5]

[1] WI and MN should be considered together. Lower Heating Value 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] Depending on region and time of year.
[3] Particulate matter may include dust, metal, biological material or other solid contaminants.
[4] A standardized test method needs to be developed for this range.
[5] Pending the development of an adequate measurement procedure, this limit can be calculated as: (Weight of lubricant oil added to compressor)/(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			EN16726	D8211		MWM
Lower Heating Value		MJ/m^3	6976	D3588	K2301	
Sulphur	Category 3	mg/kg[1]	6326-5			
	Category 4/5	mg/kg[1]	19739			
H_2S + COS		mg/kg[1] (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[2]						
Silicon, total[3]		mg/m^3				
Lubricating oil[4]		mg/m^3				RISE SP5184

1 A typical value of 0.74 kg/Sm^3 can be used for conversion (Swedish standard SS 155438:2015). A sulphur level of 10 mg/Sm^3 is then equivalent to 13 mg/kg.
2 A standardized test method needs to be developed.
3 A standardized test method for low levels needs to be developed.
4 Additional methods are in development.

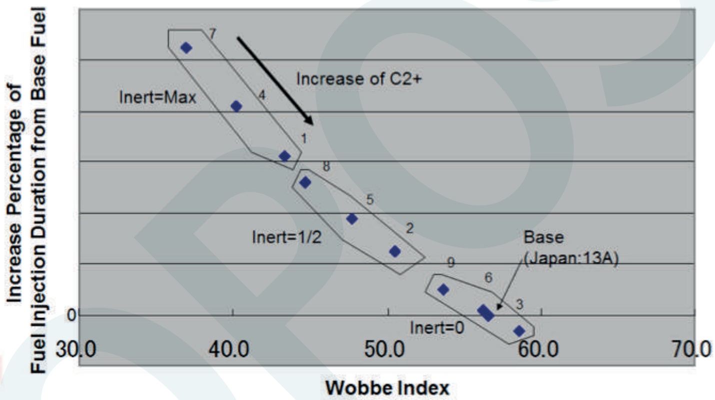
Gross Wobbe Index (Wobbe Index)

The Wobbe Index (WI), which is a measure of the energy content of methane fuel, 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 calibration for performance and emissions. Considering the limits of controllability in current closed-loop controlled engines, the WI should vary less than ± 3 MJ/m^3 within each category to maintain desired vehicle/engine performance and minimize 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



While all fuel properties are important, the most critical for determining a vehicle/engine's design for a given market are Gross Wobbe Index (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.

Another fuel energy content parameter, Lower Heating Value (LHV), 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.

The WI 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.

Equation 1: Gross Wobbe Index

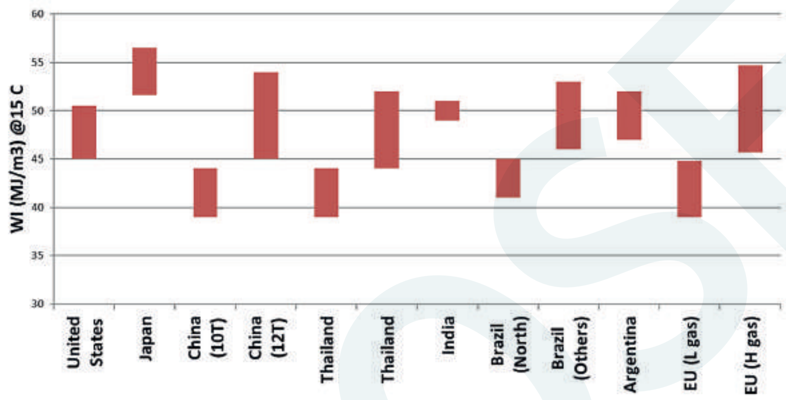
$$\mathbf{WI} = \frac{\mathbf{H}}{\sqrt{\mathbf{S}}}$$

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 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

The Methane Number (MN) is the anti-knocking indicator for methane 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 Westport, Inc.

The importance of MN on engine/vehicle 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, methane extracted in one region may differ naturally from methane extracted in a different region. Also, methane 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[1] has been the most popular among those in engine manufacturing. A newer method—the “MWM” method—is publicly available and the one recommended here. Table 1 shows examples of MN calculations using the MWM method.

Table 1: Examples of MN Calculations by the MWM Method

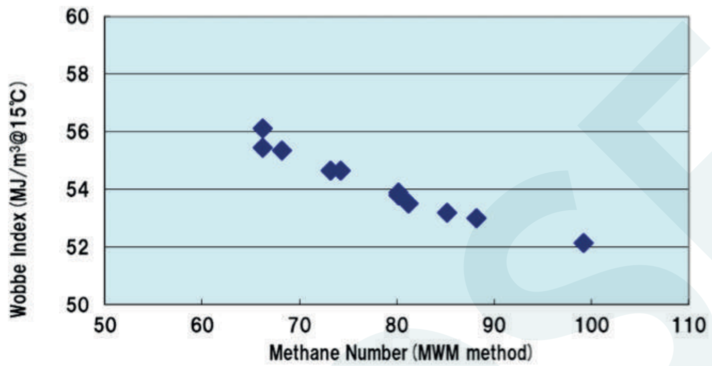
Methane Fuel ID	1	2	3	4	5	6	7	8	9	10	11
Methane (%)	100	95	90	85	76	95	90.6	98	90	94	88.4
Ethane (%)		5	10	15	24				5	5	5.6
Propane (%)						5	9.4		5		4.5
Butane (%)								2		1	1.5
Wobbe Index (Mj/m³ @ 0°C)	53.6	54.5	55.3	56.2	57.7	55.4	56.9	54.7	56.2	55	57
Wobbe Index (Mj/m³ @ 15°C)	52.2	53.1	53.8	54.7	56.2	53.9	55.4	53.3	54.7	53.5	55.5
Methane Number (MWM)	99	88	80	74	66	80	68	85	73	81	66

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

[1] This proprietary method is named for the company that developed it.

The Relationship Between MN and WI
As discussed above on page 13, it is important to recognize that the MN and Wobbe Index, which are key characteristics of gaseous methane 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 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 affects engines and vehicles inside the engine, in the exhaust aftertreatment system and sensors used for the on-board diagnostic (OBD) systems. These adverse effects on vehicles/engines require it to be reduced or limited in methane fuel used for transportation.

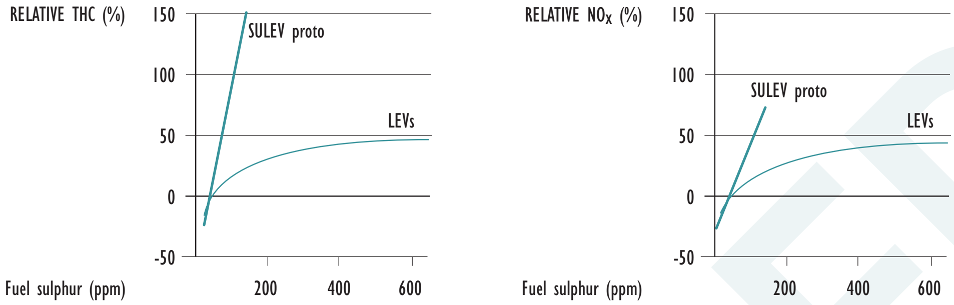
Sulphur can significantly increase smog-forming emissions by reducing the efficiency of three-way exhaust system catalysts;[2] if the sulphur level is high enough, it may render the catalyst ineffective through sulphur poisoning of the catalyst's active sites. In addition, in powertrains with Otto-cycle, 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 emissions and emission control systems also used on methane-powered vehicles/engines. Figure 5 shows the relationships between sulphur and emissions of NOx 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/Nm^3. When using ethyl mercaptan (C_2H_6S), the resulting sulfur level is 3.1 mg/kg. The amount of added odorizing 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 NOx.

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.

Methane-fuelled vehicles/engines use similar emission control systems as those used in Otto-cycle (gasoline) engines, so the sulphur standard applicable to gasoline engines should also be applied to methane transportation fuel. Dual fuel vehicles/engines using compression ignition use similar emission control systems as Diesel-cycle engines, and sulphur standards applicable to diesel engines should also be applied for methane fuel in these applications.

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 odorisation that increases the sulphur level locally. The following Table 2 provides the sulphur content of methane in various markets based on survey and other data.

Table 2: Methane 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)
Germany	1.5	5	(a)
Netherlands	1.5	6	(a)
UK	3.3		(a)
Italy	25	35	(a)
Spain	11	25.7	(a)
Denmark	2.6		(a)
France	<5	14	(a)
Japan		2	(b)
US	3.4	23	(c)

[1] A typical value of 0.74 kg/m^3 can be used for conversion (Swedish standard SS 155438:2015). A sulphur level of 10 mg/m^3 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 (H_2S) plus carbonyl sulphide (COS) in the fuel. H_2S is present naturally in raw gas, including biogas. It is best to limit H_2S in the purification-desulphurization process to 2 ppm or less. COS, which is an environmental precursor to H_2S, is emitted by oceans and naturally abundant in the atmosphere; human activity also contributes to ambient levels. The total content of these sulphur compounds in the fuel should be limited to 30 mg/kg max in Category 3 and to 10 mg/kg max in Categories 4 and 5 to avoid excessive exhaust catalyst poisoning.

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 NOx 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 fuel transportation infrastructure, so this practice is not recommended. In addition, if the hydrogen content in the methane 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 natural gas transportation fuel.

Hydrogen can be specified either as a dry gas or a wet gas. The ECE R110 natural gas specification requires a maximum hydrogen limit of 2 mol% in dry gas (which normally limits water vapor to less than 32 mg/m^3 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.)[1] The wet gas specification is usually intended to help prevent corrosion in the methane fuel transportation systems and in the steel fuel tanks used in natural gas vehicles/engines.

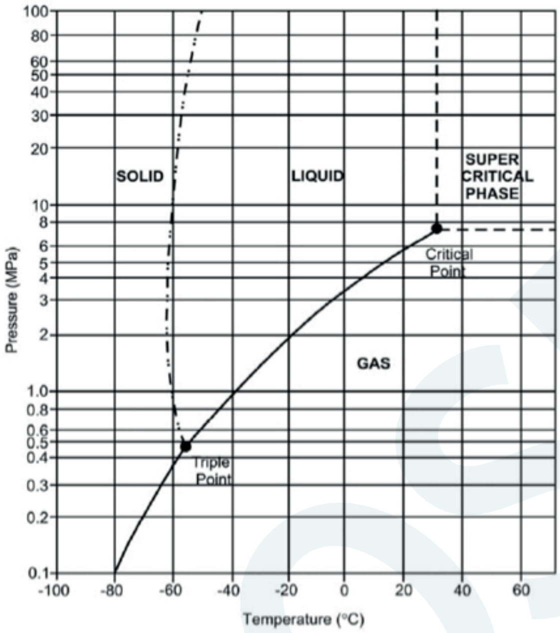
Carbon Dioxide

Carbon dioxide (CO_2) 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, since the CO_2 molecule is smaller than rubber molecules, 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, NBR, HNBR, and 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, CO_2 may condense at elevated pressures and low temperatures. When the condensate revaporizes 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 minimize the risk of this situation, the CO_2 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 CO_2: 2 MPa at -20°C, and 1 MPa at -40°C (see phase diagram in Figure 6).

[1] "Wet gas" and "dry gas" are defined in UN R110.

Figure 6: Vapor-Liquid Equilibrium Curve of Carbon Dioxide



Source: APEC Energy Working Group, "Building Capacity for CO_2 Capture and Storage in the APEC Region," June 2012, available at www.canadiancleanpowercoalition.com/files/1513/8601/5389/CCS21_-_building-capacity-co2-capture-and-storage-apec-region.pdf.

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% CO_2 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.

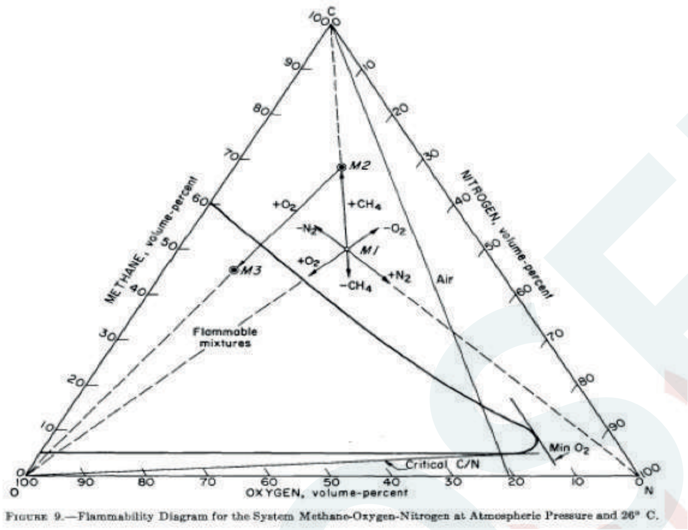
Oxygen

The oxygen concentration in methane 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%, 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 vehicles/engines), the minimum oxygen requirement for flame propagation is about eight percent (by extrapolation). Based on this analysis, this Charter recommends a maximum oxygen limit of 1 mol%, which is far less than 8 vol%[25] and therefore provides a comfortable margin of safety.

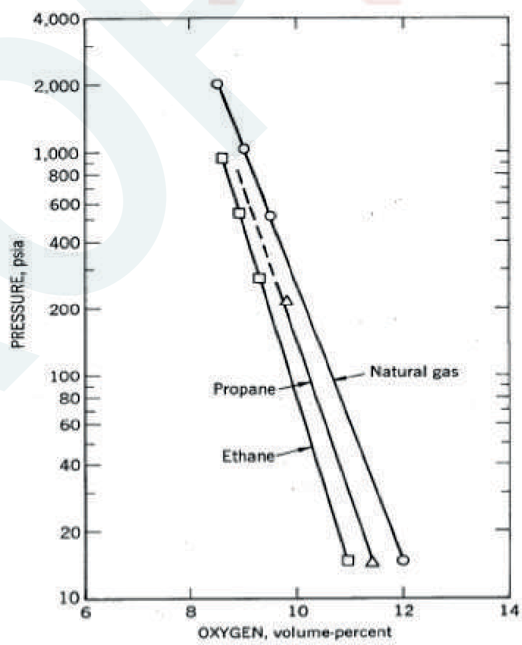
[25] For ideal gases, mol% and vol% are equivalent.

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: Flame Propagation Pressure Dependence 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/.

Liquid Hydrocarbon

Methane 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.

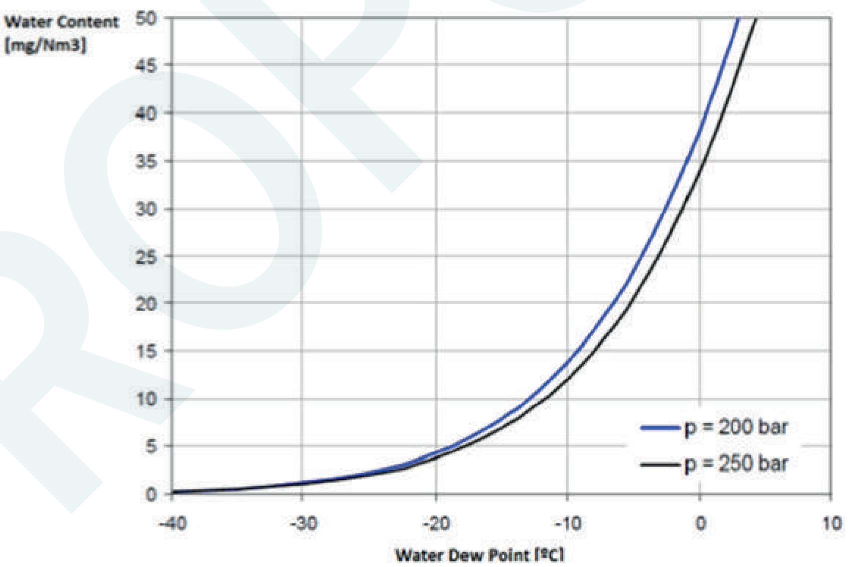
This Charter adopted the hydrocarbon (HC) dew point as the property to monitor for minimizing HC liquids in the fuel; other parameters also may be used, for example, percent liquid volume/total gas volume. The maximum allowable HC dew point depends on the lowest ambient temperature to which the vehicle 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 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 minimizing 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

Fuel methane 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 less than 1 micron 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 methane, 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. A HEPA (High Efficiency Particulate Air Filter)-type filter 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 methane, 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 fuel through the addition of biogas and can cause serious damage to the engine/vehicle system. Some raw biogas, especially that generated from landfills, sewage or municipal biowaste, contains significant amounts of siloxanes that are volatilized 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/m^3 can severely harm the oxygen sensors of some vehicles/engines.[1] Higher silicon levels reduce oxygen sensor durability. Engine/vehicle manufacturers recommend as little silicon in the fuel as possible as well as continued review and monitoring of this issue.

Currently, a standardized 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, engine and vehicle manufacturers consider the maximum silicon limit in the category tables to be an important step toward protecting vehicles/engines from silicon contaminated methane gas.

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 fuel by lubricant oil used in gas compression equipment can cause injector fouling and lead to the disabling of the vehicle's pressure regulator. These problems have occurred in many countries, but published fuel limits are rare; the Japan Gas Association (JGA) is one organization that has published such a specification.[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

Lubricating oil mg/m^3 = (Added lubricant oil weight to compressor)/(Compressed natural gas volume)

Measurements are taken for the time period between oil additions at the compressor.
It has been discovered in the Japanese market that ester-type synthetic oils have caused damage to certain types of rubber materials. Thus, lubricant oil for compressors should be chosen carefully.

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. Based on field data, a limit of 20 mg/Nm^3 is desirable. These limits will be revisited when oil-less compressors become more widely used. Indeed, many refuelling stations in Japan are now equipped with oil-less compressors.

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