

Effects of Natural Gas Composition Variations on the Operation, Performance and Exhaust Emissions of Natural Gas - Powered Vehicles

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ABSTRACT

This paper examines the variations of natural gas composition, as supplied in the distribution systems of natural gas utilities, and their effects on the operation, performance and exhaust emissions of natural gas-powered vehicles.

A survey of the gas composition in many countries over time has revealed significant variations in the parameters affecting engine performance, durability and emissions.

The actual composition of natural gas depends primarily on the production field from which it is extracted. At the local gas distribution level, seasonal adjustments by the local gas distributor may cause significant variations in the hydrocarbon composition.

The extent and effects of the various contaminants in the natural gas fuel arriving at the vehicle engine are discussed, together with suggested ways of mitigating them.

With appropriate modern engine control hardware and software, variations in the composition of commercially available natural gases have little effect on emissions from light- and heavy-duty vehicles using modern engine control technology.

With the increasingly widespread regulatory requirements of more and more complex on-board diagnostic systems for vehicles, variability in natural gas fuel composition will pose special technical challenges for both OEM NGVs and aftermarket converted NGVs.

There needs to be a review and harmonization of certification fuel specifications, commercial fuel specifications, and engine manufacturers' specifications to ensure that they are compatible for successful in-service operation of natural gas vehicle engines.

1. INTRODUCTION

This paper is a condensed version of a study of the same name prepared by the author for the International Association for Natural Gas Vehicles. The full report is presented on the IANGV website, www.iangv.org

The performance and emissions of gas engines depend on good ignition, optimum combustion rate, high knock resistance, and a sufficient energy content of the fuel mixture. When using natural gas as a fuel the following fuel properties are important in relation to engine performance:

- Density
- Heating value, i.e. the Wobbe Index
- The stoichiometric air-fuel ratio
- Knock resistance.

These gas properties are closely linked to the composition of the gas. Thus variations in gas composition can have an effect on the performance and exhaust emissions of natural gas powered vehicles.

The composition of natural gas is not universally constant, as it is normally drawn from several production fields. The composition from a particular source or at a particular end-use location can also vary over time. Gas composition surveys have been reported in the literature. Liss and Thrasher (1992) found from a nationwide survey that variations in composition across the U.S. at that time could produce variations of 14% in heating value, 14% in density, 20% in Wobbe Index and 25% in stoichiometric air-fuel ratio. Similarly, natural gas in Europe comes from several sources within and outside the continent, and the gas quality is characterised in ranges, i.e. as group L (low heating value) and group H (high heating value) gases.

Such large gas composition variations can have important effects on engine performance and emissions, especially if the engine is optimised for maximum performance and efficiency on a fixed gas composition and is not equipped with means of adjusting to other compositions. This is because the engine-out emissions of a spark-ignited engine are dependent upon the air-fuel ratio (see Figure 1). This is compounded by the influence of composition on the knock resistance of the fuel.

The fuel composition can also affect the amount and the composition of the unburnt hydrocarbon emissions. Composition of the hydrocarbons is important because of the question of catalyst efficiency and atmospheric reactivity.

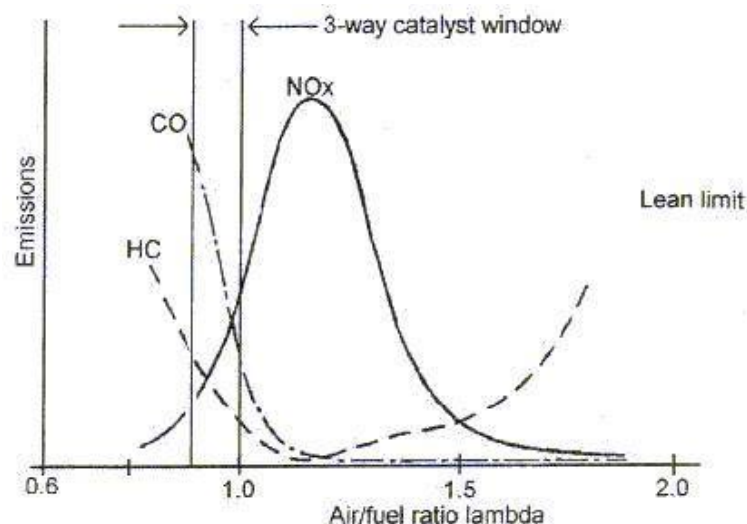


Figure 1 - Variations of emissions with change in lambda (air/fuel) ratio in spark-ignited engines.

As gas composition affects the gas density and stoichiometric air-fuel ratio, it has an important influence on the performance of the exhaust emission system.

There exists in the literature a substantial body of work on the effects of natural gas composition variations on the performance and emissions of natural gas engines and vehicles. Some of the more often cited works are:

- Liss and Thrasher (1992) produced the first comprehensive survey of the variation of natural gas composition in the U.S.
- Dubel et al (1983) examined the effects of composition on methane number (MN) and engine performance optimisation and found that MN provided a good indication of the fuel's ability to achieve acceptable efficiency within the knock limit spark advance.
- Klimstra (1978) examined the relationships between gas composition and mixture properties and reported on the effect on stoichiometric air-fuel ratio, heating value and the Wobbe Index and knock sensitivity.
- Jones et al (1983) found that an engine optimised on one gas composition demonstrated significant performance penalties when run on a gas of different composition.
- Bosch et al (1989) found that the compositional effects on NO_x emissions due to variations in the methane number are compounded by the effects on the stoichiometric air-fuel ratio. The total hydrocarbon emissions were found to decrease with increasing Wobbe Index, perhaps due to the higher reactivities of the higher hydrocarbons that are present in higher Wobbe Index fuels.
- More recent studies by Ryan and Callahan (1991), King (1992), Bevilacqua (1997), and Schollmeyer and Wegener (2001), which will be described in more detail later in the present report.

2. EXISTING CNG GAS QUALITY STANDARDS

The general purpose pipeline gas quality standards do not necessarily serve the needs of engines and vehicles, which operate within much wider ranges of pressure and temperature than conventional gas burning appliances. To accommodate the requirements of NGV engine and vehicle application, a number of international standards have been established, i.e. SAE J1616 and ISO 15403.

2.1 SAE J1616

Water content: The local dewpoint temperature of the fuel should be 5.6° C below the monthly lowest dry-bulb temperature at the maximum operating cylinder pressure. The margin of 5.6° C is intended to prevent hydrate blockage due to pressure reduction at various stages in the vehicle fuel system.

Carbon dioxide: Given that the corrosive environment is controlled via the limited water concentration, no limits are required on the concentration of CO₂ for this purpose. Rather, a limit of 3.0% CO₂ by volume is recommended to help maintain stoichiometry.

Sulphur compounds: The total content of sulphur compounds, including odorants, should be limited to 8-30 ppm by mass to avoid excessive exhaust catalyst poisoning.

Methanol: No methanol shall be added to natural gas at the CNG refuelling station. Methanol can cause corrosion of natural gas cylinders and deterioration of fuel system components.

Oxygen: Given that the corrosive environment is controlled by the limited water concentration, no limits are required on the concentration of oxygen for the control of corrosion. On the other hand, the oxygen level must not produce a mixture within the flammability limits of natural gas.

Particulate and foreign matter concentration should be minimized to avoid contamination, clogging and erosion of fuel system components. CNG fuel delivered to the vehicle should have particulate matter content equal to or less than 5 µm (micron) in size.

Oil content: Additional data are required to determine acceptable lubricating oil levels as well as standardized test procedures for quantifying lubricating oil content. Lubricated compressor oil levels should be monitored and coalescing filters may be installed downstream of the compressor discharge to control oil.

Hydrocarbon dewpoint temperature: The composition of natural gas should be such that the original gaseous storage volume will form less than 1% of a liquid condensate at the lowest ambient temperatures and gas storage pressure between 5.5 and 8.3 MPa, at which maximum condensation occurs, depending on gas composition.

Natural gas odorant: Natural gas introduced into any CNG refuelling station or vehicle shall have a distinctive odour strong enough for its presence to be detected down to a concentration in air of not over 1/5 of the lower flammability limit. This is approximately 1% gas-in-air volume.

Wobbe Index: Variability in the Wobbe Index affects most significantly engines that are not equipped with closed loop controls. A Wobbe Index range of 48.5-52.9 MJ/m³ is recommended, although a range of 44.7-46.6 MJ/m³ has also been found acceptable for use on current equipment in high altitude areas. The recommended range, typical of most U.S. natural gas, would allow maximum variation from nominal air-fuel ratio of about ±3.7%, which is comparable to the range in variation in petrol density.

Knock rating: No specific recommendations are given on the MON rating of natural gas. It is noted that work by King (1992) and Kubesh (1992) shows a close correlation between the reactive hydrogen-carbon ratio and MON antiknock performance.

2.2 ISO 15403

Water content: The water dewpoint of the fuel at the refuelling station outlet shall be sufficiently below the lowest ambient temperature in which refuelling stations and vehicles will operate.

Hydrocarbon content: The composition of natural gas shall be such that at any pressure, less than 1% of a liquid condensate is formed at the lowest ambient temperature and under the worst gas storage pressure conditions. Maximum condensation occurs at between 2.5 MPa and 4.5 MPa.

Sulphur compounds: The total sulphur content may have an adverse impact on exhaust aftertreatment equipment and should be taken into account. Given that the corrosive environment is controlled by the lack of liquid water, no special limitation is required on the concentration of hydrogen sulphide.

Carbon dioxide and oxygen: Given that the corrosive environment is controlled by the lack of liquid water, no special limits are required on the concentration of carbon dioxide and oxygen.

Methanol: No methanol shall be added at the CNG refuelling station.

Particulate material: The CNG fuel delivered shall be technically free from dust. The possible oil content of natural gas shall have no effect on the safe operation of the vehicle.

Odour: Natural gas delivered to any natural gas vehicle should be odorized similar to a level found in the local gas distribution system.

Wobbe Index: Although it is acknowledged that variations in the Wobbe Index can significantly affect engines without closed loop, adaptive fuelling controls, no limits or ranges are specified.

Knock rating: No generally accepted standard test procedure is available. No knock rating values are specified.

2.3 Engine Manufacturers' Recommended Gas Quality

Table 1 - Recommended Gas Composition Ranges by Some Natural Gas Engine Manufacturers (SAE, 2001 and Detroit Diesel Corporation, 1998)

Component	Tolerance	CAT Dual-Fuel	Cummins	Deere	Detroit	Mack
Hydrocarbons						
Methane	Minimum	88.0%	90%		88%	85%
Ethane	Maximum	6.0%	4%		6%	11%
C ₃ +	Maximum	3.0%				
Propane	Maximum		1.7%	5%	1.7%	9%
C ₄ +	Maximum		0.7%		0.3%	
C ₆ +	Maximum	0.2%				
Butane	Maximum			1%		5%
C ₂ + C ₃ +C ₄						11%
Inerts (N ₂ , CO ₂)	Range/ Max	1.5-4.5%	3.0% total			2% N ₂ 3%CO ₂
Oxygen	Maximum	1.0%	0.5%			
Hydrogen	Maximum	0.1%	0.1%		0.1%	
CO	Maximum	0.1%	0.1%			
Sulfur	Maximum		0.001% by mass		22 ppm by mass	
Methanol	Maximum				0%	
CO ₂ + N ₂ + O ₂	Maximum				4.5%	

To ensure that their engines will work satisfactorily and durably in the end-use application, normally engine manufacturers require information on the composition of the natural gas in the location of use. They also issue recommended fuel specifications to guide intending users (see Tables 1 and 2).

Table 2 - Recommended Gas Combustion Properties by Some Natural Gas Engine Manufacturers (SAE, 2001, Cummins, 2001 and Detroit Diesel Corporation, 1998)

Property	Tolerance	CAT Dual-Fuel	Cummins	Deere	Detroit	Mack
Wobbe Index. (MJ/m ³)	Range		48.46 – 51.33		47.7-51.06	
Octane Rating (MON)	Minimum			118	115	
Methane Number (MN)	Minimum		80 (std. engines) 65 for Plus Technology			
Lower heating value	Minimum		43.7 MJ/kg for Plus Technology engines	33.74 MJ/m ³		
Higher heating value			36.3 MJ/m ³ (standard engines)			

2.4 Commercial CNG Quality Standard in California

Starting January 1, 1993, the composition of CNG fuel sold for motor vehicle use in California has been controlled by the California Code of Regulations, which sets limits on the hydrocarbon components, hydrogen, oxygen, carbon dioxide and monoxide, sulphur, water content, particulate content, and odorants.

Industry sources indicate however, that the commercially available CNG fuel in California may not meet the California specification, and the issue may have to be reviewed in future.

3. NORMALLY OCCURRING QUALITY OF COMMERCIAL NATURAL GAS

3.1 Contaminant Levels

The contractual limits specified by commercial contracts and the limits specified by standards are just that – limits. In reality the normally occurring levels of non-hydrocarbon levels tend to be quite well below the limits. Table 3 gives a comparison in the case of sulphur compounds in natural gas in New South Wales, Australia (AGL, 1995).

Similarly, the contract limit for water content in pipelines in many countries are specified at some 112 mg/m³ while the normally occurring water content can be much lower, at some 65 mg/m³ or lower.

Based on an example of natural gas density of 0.755 kg/m³, the typical total sulphur concentration of 7 mg/m³ is equivalent to 9.24 ppm. This is still lower than the sulphur content of diesel fuel. For example, the sulphur content of “low sulphur” diesel is 500 ppm and “ultralow sulphur” diesel, 10 - 50 ppm.

Table 3 - Sulphur Concentration Levels in NSW Natural Gas (AGL, 1995 and Tas, 2002)

Sulphur Compound	Contract Limit at Source (mg/m ³)	Typical Level at Odorant Injection Location (mg/m ³)	Typical Level in Downstream Distribution System (mg/m ³)
Mercaptan sulphur	4.6	1.5	1.5
Hydrogen sulphide	5.7	2.5	2.5
Odorants *	-	6.0	3
Total	35.0	10.0	7

*The odorants (TBM and THT) are added only at the gas utility custody transfer point, not during transmission.

As the commercial contracts and specifications do not normally specify the individual hydrocarbon constituent limits, to predict potential performance characteristics of natural gas engines one has to examine the actual variations in the hydrocarbon composition.

3.2 Composition Variations

In the early 1990s, with the need to specify an acceptable gas quality standard for the safe operation of on-board CNG storage systems and the acceptable operation of CNG engines and vehicles, a major survey of the variation of the quality of natural gas was carried out in a study funded by the then Gas Research Institute. The results of this study (Liss and Thrasher, 1992) were summarised in the SAE CNG fuel quality standard J1616, and showed a degree of gas composition variation across the geographic spread of the US.

Later surveys also established the degree of variations between supply sources within large geographic areas such as Europe and Australia. Variations in the composition of gas delivered by pipelines can be caused by:

- (a) Variations in the proportion of the contribution from various sources at a given supply location; and
- (b) Time variations within a given supply source.

These variations involve mainly the composition of the hydrocarbon mix and are not regulated by the general purpose pipeline gas standards beyond keeping within the limits of the heating value and the Wobbe Index.

Spot surveys of natural gas composition at an Australian location taken at 30-minute intervals for two 16-day periods in the (Southern) summer and winter of 2000 have shown the following variations:

- Methane: 86.91-92.05%
- Ethane: 4.61-9.80%
- Propane: 0.075-0.997%
- n-butane: 0.001-0.020%
- i-butane: 0.001-0.012%
- Wobbe Index: 48.73 – 49.96 MJ/m³.

The variations in the average daily Wobbe Index and Motor Octane Number (MON) were calculated from composition data for Argentina and Malaysia in 2001 and 2002 and are given in Table 4. The MON calculation method is given by Kubesh (1992).

Table 4 - Wobbe Index (MJ/m³) and MON variations, and their range as a percentage of the average, in Argentinean and Malaysian natural gas.

Property	Argentina		Malaysia		
	Daily average		Daily average		Monthly average
	June 2001	January 2002	June 2001	December 2001	June-Dec. 2001
Wobbe Index					
• Minimum	49.58	49.43	45.23	42.08	42.08
• Average	49.73	49.82	48.00	48.49	48.35
• Maximum	49.95	50.29	50.42	49.77	50.42
• Range	0.7%	1.7%	10.8%	15.8%	17.3%
MON					
• Minimum	127.3	132.7	124.0	127.3	123.8
• Average	127.7	135.2	129.6	129.8	129.3
• Maximum	128.3	136.9	135.4	132.0	135.4
• Range	0.8%	3.1%	8.8%	3.6%	9.0%

Adding to the normal composition variations is the practice in many countries of adding propane/butane/air mixtures into normal natural gas for peak shaving, thus lowering the Motor Octane rating of the fuel during those periods.

The results of the surveys indicate that significant gas composition variations can occur at the local end-use level and are not predictable. Such variations in the Wobbe Index and MON should be provided to engine suppliers to ensure suitably designed engines are supplied to the location.

4. EFFECTS OF NATURAL GAS QUALITY ON ENGINE AND VEHICLES

4.1 Water Content

The use of natural gas with high water content can result in the formation of liquid water, ice particles or hydrates at low operating temperatures and high pressure. Such formations can

interfere with consistently smooth flow of fuel into the engine and cause problems such as poor drivability or even engine stoppage.

A range of gas dryer products is available on the market. There are no major technical issues beyond the correct selection and operation of the dryer systems. It should be noted that certain drying media have an affinity for compressor oil and gas odorants, and they should be suitably selected so that the required oil and odorant contents of the natural gas fuels are maintained.

As water is removed from gas during the liquefaction process, water is not an issue in LNG vehicle operation.

4.2 Heavier Hydrocarbons

Some gas utilities may add propane/air mixtures to natural gas during peak demand periods. Propane has a low vapour pressure and if present in significant quantities it will form a liquid phase at elevated pressures and low temperatures. Fuel variability due to revaporisation of this liquid condensate at reduced storage cylinder pressure can lead to difficulty in controlling the air-fuel ratio.

In addition, the significant presence of the heavier hydrocarbons in the gas mixture lowers its knock rating and can lead to potential engine damage.

4.3 Compressor Carryover Oil

Substantial amounts of oil can be added to the gas during compression, which can subsequently condense and interfere with the operation of CNG engine components such as gas pressure regulators. On the other hand, a minimum level of carryover oil is required for durable gas injector operation. Various injector manufacturers recommend different minimum oil levels.

Oil in the gas at the compressor outlet is commonly removed by coalescing filters, however, they are insufficient in many cases, as up to 50% of the carryover oil exists in vapour form in the warm (or hot) compressor outlet gas. Additional measures will need to be considered, for example, by additional cooling of the discharge gas or by using synthetic oil or mineral oil or a combination of mineral oil and a suitable adsorption filter downstream of the coalescing filter (Czachorski et al, 1995).

At this time there is no established, generally accepted carryover oil level as well as consistent, standardized methods of determining the oil level in gas.

LNG has an opposite problem as lubricants are removed in the liquefaction process.

4.4 Sulphur Compounds

Sulphur compounds in natural gas are in the form of mercaptans, hydrogen sulphide, and odorants. The first two are naturally occurring at source (gas fields) and have already been reduced by treatment at the gas processing plant.

The sulphur-based odorants (tetrahydrothiophene, THT, and tertiary butylmercaptan, TBM), at concentrations as low as 10-15 mg sulphur/m³ of natural gas, can have a very detrimental

effect on the conversion efficiency of oxidation catalysts used on lean burn natural gas engines (Nylund and Lawson, 2000).

In the US, typical contract terms and industry practice limit total sulphur to 8 – 30 ppm on a mass basis, although extensive surveys have indicated that the average sulphur content of all samples is around 10 ppm. Typically, 80% of the sulphur, i.e. 8ppm is from the odorant (Liss and Thrasher, 1992).

In Europe, the natural gas coming from the Siberian gas fields Urengoi and Jamburg contains less than 1.5 ppm S. In Finland it is 9 ppm (Riikonen, 1993, as reported by Nylund et al, 2002). This corresponds well to the US example.

At these levels, natural gas sulphur content is well below that of low sulphur (500 ppm) and ultralow sulphur (10 – 50 ppm) diesel. However, as will be seen in the following, it may be necessary to lower it further to ensure oxidation catalyst durability.

Some of the most detailed reported work on the effect of sulphur on oxidation catalysts for methane in lean burn natural gas engine exhaust is that of Lampert et al (1996), McCormick et al (1996) and Lampert and Farrauto (1997). They have found that:

- NGV exhaust contains sulphur derived from the gas and engine lubricating oil (see Table 5 for typical values).
- Sulphur in NGV exhaust strongly inhibits methane oxidation over palladium catalysts- at as little as 1 ppm (by mass) of sulphur in sulphur oxides present in the exhaust of a lean burn natural gas engine.
- Sulphur poisoning deactivates methane activity to a greater extent than the alkanes (ethane and propane), which comprise the non-methane hydrocarbon (NMHC) components of NGV exhaust. Thus, as the catalyst ages, total hydrocarbon (THC) emissions may increase above THC regulation levels even if the NMHC emissions remain below the regulatory NMHC limits.
- Currently, emission standards for NMHC, CO, and engine oil-derived particulates in lean burn NGV exhaust can be met with palladium or platinum containing catalysts supported on monoliths.

Table 5 - Estimates of sulphur (S) in lean burn NGV exhaust (Lampert and Farrauto, 1997). Sulphur concentration in the oil is 0.4% by mass.

	Maximum S Level (ppm)	Average S Level (ppm)
In input CNG	30 (or 22.65 mg S/m ³ gas) *	12 (or 9.06 mg S/m ³ gas) *
In exhaust at idle:	2.6	1.6
* CNG contribution	1.7	0.7
* Engine oil contribution	0.9	0.9
In exhaust at cruise:	1.3	0.6
* CNG contribution	1.2	0.5
* Engine oil contribution	0.1	0.1

* Based on an example of natural gas density of 0.755 kg/m³, i.e. each mass ppm of sulphur is equivalent to 0.755 mg S/m³ gas.

In the example of Table 5, the sulphur level in the lean burn NGV exhaust exceeds 1 ppm at idle, but is well below 1 ppm at cruise condition, with the natural gas-derived sulphur contributions in the exhaust at 0.7 and 0.5 ppm at idle and cruise respectively. The contribution of engine oil is larger than that of CNG during idling, i.e. the more critical phase of operation.

Sulphur content in gas can be minimized by more accurate injection of odorants (just sufficient for leak detection), and further reducing hydrogen sulphide and mercaptans at the gas fields.

As even very low levels of sulphur can still cause catalyst deterioration over time, it is essential that methods and hardware be developed to minimize the effects of exhaust sulphur on the exhaust catalyst system. In fact, this very issue is currently under investigation by the diesel engine and diesel exhaust aftertreatment industry (EPA, 2002), using approaches such as:

- Developing more sulphur- tolerant aftertreatment materials and systems
- Reducing the sulphur level of engine oils (by changing oil formulations).

As sulphur compounds – including odorants - are removed by the gas liquefaction process, sulphur poisoning of the exhaust catalyst will not be an issue for LNG vehicles. On the other hand, the lack of odorant in liquefied natural gas means that some cost-effective means of leakage detection would have to be added to the LNG for use on vehicles.

4.5 Fuel Composition and Air-fuel Ratio Control

Typical emissions trends as a function of the air-fuel ratio are shown in Figure 1. It is essential to maintain the desired equivalence ratio of the engine under all operating conditions in order to minimize emissions and maximize efficiency. Changes in the gas composition which affect the equivalence ratio will affect engine performance and emissions, whether it be stoichiometric or lean-burn combustion.

The composition variations are the result of adjustments carried out either at the producer level (gas fields) or local level (at peak demand times) in an effort to maintain key parameters such as the Wobbe Index. As NGV usage continues to form a minor portion of the total gas usage, it is doubtful that producer and utility operation will be amenable to change in response to the requirements of the NGV market only.

Attempting to remove the heavier hydrocarbons at NGV compression and refuelling stations is impractical as it would:

- Require additional equipment, operation and cost;
- Further upset the essential fuel parameters such as the Wobbe Index; and
- Lose valuable heating value, which is the reason the heavier hydrocarbon adjustments are made in the first place.

The more practical solution at this time appears to be further development/deployment of vehicle fuel control systems that can tolerate changes in the heavier hydrocarbon contents in the intended vehicle market.

4.6 Fuel Composition and Knock Resistance of the Fuel

The most comprehensive work in recent times on the knock resistance rating of natural gas fuel appears to be that of Kubesh (1992).

Of all hydrocarbon compounds used as motor fuel, methane has the highest knock resistance. The higher the carbon content of the compound, the lower is its knock rating. Thus, gas composition has a definite effect on the knock rating of the natural gas.

In Kubesh's work it was established that the MON for available natural gases in the USA ranged between 115 and 130+. The MON ranges of Argentina and Malaysia are respectively 127-137 and 124-135 (see Table 4).

To ensure that gas engines will operate without knock in service, engine manufacturers specify minimum knock resistance properties of the fuel. For heavy-duty gas engines (see Table 2) the manufacturers specify minimum fuel MON or methane number (MN). For example, Deere and Detroit require minimum MON of 118 and 115 respectively. Very encouragingly, Cummins has been able, through improved control systems, to reduce the minimum MN from 80 for its standard engines to 65 for its Plus Technology engines.

4.7 On-board Diagnostic (OBD) Systems

A discussion on OBD systems is given in the 2000 IANGV report on Exhaust Emissions from Natural Gas Vehicles (Nylund and Lawson, 2000).

It would appear that the OBD systems would become so complex that only a close working relationship with the vehicle OEMs would allow suppliers of natural gas conversion systems to achieve full OEM OBD compatibility and capability. This poses a great problem for the majority of the aftermarket conversion market due to their generally small scale operation, with limited technical and financial resources.

There are several difficulties faced by bi-fuel petrol/natural gas conversion systems due to the differences between petrol and natural gas fuels, however, this report will note only those due to the variations of the natural gas composition. According to Nylund and Lawson, some of the challenges caused by natural gas composition variations are:

- For catalyst monitors, natural gas fuel variability will likely cause additional variability in exhaust oxygen sensor switching ratios.
- For fuel system monitors, stoichiometric differences resulting from natural gas fuel composition changes will add to the fuel system variability making it difficult to set thresholds for good monitoring process efficiency.

5. STUDIES ON THE EFFECTS OF GAS COMPOSITION VARIATIONS

5.1 U.S. Study for Heavy-duty Vehicles (1991)

This Gas Research Institute study (Ryan and Callahan, 1991) had as one of its objectives the determination of the effects of natural gas composition on engine performance and emissions.

The single cylinder test engine used had a similar configuration to the cylinders of a Cummins L10 engine.

A test matrix of six typical (commercially available) natural gas mixtures was used to study the performance and emissions characteristics at both lean and stoichiometric conditions in the heavy-duty engine. The ranges of hydrocarbon gas constituents were: methane, 83.3-99.7%; ethane, 0.28-7.8%; propane, 0.5-11.9%; butane, 0.3-0.6%; and pentane, 0-0.2%.

To study the effects of high concentrations of propane that can be found in natural gas during peak shaving periods, an additional test matrix was used, with the level of propane ranging between 0 and 40%.

The performance and emissions data were obtained over a range of air-fuel ratios from stoichiometric to lean using the six gas mixtures. The results indicated air-fuel ratio was the dominant parameter controlling the emissions and performance, followed by spark timing, boost pressure and then the chemical effect of the fuel on combustion.

The knock sensitivity of a gas fuel was confirmed to be primarily dependent on the composition, i.e. its methane number, but found to be also affected by the engine operating condition.

At the naturally aspirated condition, both lean and stoichiometric, there appeared to be no significant effect for the range of six typical gases tested, although there seemed to be a fuel effect related to the methane number at the lean, turbocharged condition. Very high levels of ethane and propane concentrations resulted in higher levels of NO_x emissions.

In the case of the six typical natural gases, it was found that:

- There were no apparent differences in the NO_x emissions between the test gas mixtures and methane at the naturally aspirated lean burn test condition.
- There were statistically significant differences in the NO_x emissions between the test gases and methane under turbocharged lean burn test condition.
- The NO_x emissions of the test gas mixtures were not significantly different from those from methane at the stoichiometric test condition, although they appeared to be higher and the trend appeared to be a result of the higher temperatures and combustion rates for gas mixtures compared to methane.
- The composition of the exhaust HC appeared to be directly related to the fuel composition.

In the case of the test mixtures of high levels of ethane and propane, it was found that:

- The NO_x emissions were directly related to the concentrations of both ethane and propane at all test conditions, being more strongly affected at the higher concentrations of propane and ethane and the more severe stoichiometric test conditions.

The fuel composition controls the stoichiometric air-fuel ratio and the flame speed so that composition does have significant effects on the emissions and performance. In other words,

from the combustion point of view, variations in gas composition would have minimal effect (with the exception of engine knocking) if the engine was controlled to a constant air-fuel ratio. This pointed to the need for adaptive electronic controls on gas engines which are required to maintain the low emission levels of factory-developed engine operating specifications. On both stoichiometric and lean burn engines, this would require closed loop adaptive control systems that can maintain calibration over the broad range of commercially available CNG fuels.

5.2 U.S. Study on the Effects on Engine Operational Characteristics (1992)

In a study on the impact of natural gas composition on fuel metering and engine operational characteristics, King (1992) found that:

- The effect of gas composition on engine power, efficiency and emissions is small at a constant air-fuel ratio;
- From a survey of gas composition in the U.S. at the time, the largest lean deviation in equivalence ratio from the median (50 percentile blend) gas was 12.4% and the largest rich deviation was 6.3%. For a stoichiometric engine fitted with a three-way catalyst this would be very serious, as a 0.5% variation in the equivalence ratio, rich or lean, would result in significantly reduced catalyst efficiency and high catalyst-out exhaust emissions. For a lean burn engine even this small metering variation could result in high unburnt hydrocarbon emissions due to a lean mixture, or an increase in NO_x emissions due to a rich mixture.
- Rich mixtures are more prone to detonate than lean mixtures. Unfortunately, the fuel compositions that cause rich fuel metering conditions also have higher amounts of heavy hydrocarbons which lower the octane (or knock resistance) rating of the fuel making detonation even more likely to occur.
- Stoichiometric engines do not experience the same detonation problems as lean burn engines.
- Fuel composition affects the lean-flammability limit of the fuel-air mixture.

The test gases used included 5 gases representative of the spread of gases in the U.S.; a high energy gas with high propane (3.7%) and butane (2.1%) content; two propane/air peak shaving gases (propane up to 28.7%); and a high ethane gas (11%) representative of some LNG.

5.3 U.S. Study for Light-duty Vehicles (1997)

In this study ((Bevilacqua, 1997), the test fuels used represented commercially available fuels in the U.S. as well as gases of fringe conditions representing the extreme variations found in the country. These gas compositions were determined by the earlier-mentioned gas composition survey by Liss and Thrasher.

The hydrocarbon constituent ranges were: methane, 82.38-91.44%; ethane, 1.75-8.44%; propane, 0-6.00%; and butane and heavier, 0-4.07%.

A total of eight light-duty NGVs were selected as test vehicles as they:

- Had potential for wider use;
- Incorporated emergent NGV design or configuration concepts;
- Contributed to establishing a diverse vehicle sample set; and
- Were at the time available or could be obtained during the test period.

Testing focused on original equipment manufacture (OEM) vehicles, although one was an aftermarket conversion.

Overall, even dramatic variations in fuel composition would not significantly impact the emissions or drivability of a well designed and engineered NGV. Although a vehicle operator might experience a problem in operating an NGV that is a result of a widely fluctuating fuel, the likelihood of this happening was considered to be small, and any such problems would also be transient.

Other research findings are:

- The best, most sophisticated vehicle technologies generally showed only modest sensitivity to the broad fuel composition changes. The emission changes were small, while drivability remained consistent.
- While the emission levels for the bi-fuel vehicles were significantly higher than those for the dedicated NGVs (which was probably a function of the vehicle design/performance targets), these vehicles did not exhibit large changes in emissions as the gas composition varied. Drivability with the varying fuels was also not a problem with these vehicles.

As a result of these very positive findings, the author thought it possible that the existing fuel specifications could be modified without degrading vehicle emissions or performance, especially in closed-loop control systems.

5.4 European Study for Light-duty Vehicles (2001)

Recently, a joint research program was conducted by Volkswagen, DaimlerChrysler, Ruhrgas and Thyssengas (Schollmeyer and Wegener, 2001) to collect information on the operating behaviour of natural gas vehicles available on the market with changing gas properties.

The test gases used were selected to reflect the properties of natural gases distributed within Europe, due to the various supply sources as well as the gas utility practice of adding propane/air or butane/air mixtures for short periods for peak shaving purposes. The test gases were 5 existing gas compositions, one natural gas with an LPG/air mixture added and 2 blended mixtures in accordance with the German standard DIN EN 437. The hydrocarbon constituent ranges in volume percent were: methane, 69.49-97.09%; ethane, 0.63-8.44%; propane, 0.21-11.77%; and butane, 0.07-11.84%. Thus, they covered the entire range of gas properties allowed by the German gas and water code of practice, ensuring that the main gas properties relevant in Germany and Europe were taken into account.

The test engine was a petrol engine supplied by Volkswagen and converted to bi-fuel natural gas/petrol. The conversion system was a stoichiometric NECAM-MEGA system, adjusted for group H (high heating value) and group L (low heating value) gases.

The results indicated that the light-duty natural gas vehicles available on the German market were highly flexible with regard to changes in gas properties provided they were properly

adjusted. If suitable ignition maps were used, satisfactory fuel economy and performance could be maintained even with changing gas properties. Two ignition maps (for group L and group H gases) would already be sufficient for operation with all the natural gases available in Europe.

The study also found that, in general, the control system was able to keep the air-fuel ratio within the required window and emissions remained low even when gas properties changed. Under the conditions of the tests, acceptable starting and running behaviour for the bi-fuel vehicles could be ensured with all natural gases in Europe.

The authors considered that it would only be necessary to indicate whether a gas was a group H- or a group L-gas to allow adaptation of the engine to the gas properties, by for example activating a switch on the dashboard. Alternatively, it would be more reliable to use an automatic detection and adaptation system, with appropriate on-board sensors.

6. CERTIFICATION REFERENCE FUEL ISSUES

To permit comparison of engine and vehicle performance and emissions that will not be influenced by variations in the composition of the test fuel, standard or reference gases have been specified for use during official homologation procedures and emission tests. The factors that have the most significant effect on engine performance and emissions are the lower heating value, the density, the stoichiometric air-fuel ratio, and the Wobbe Index. Limits on these parameters will help keep engine performance variations to within acceptable limits. In the reference fuel specifications, these factors are controlled by placing limits on the constituent hydrocarbons.

The cost of preparing a gas mixture for testing is directly proportional to the number of constituents. For this reason the reference gases do not contain the whole range of hydrocarbons that might be found in some commercially available natural gases.

6.1 US EPA and CARB reference fuels

In the US there are two (slightly) different CNG certification fuel standards: one for the Environmental Protection Agency (EPA) and the other, California Air Resources Board (CARB). The compositions of these reference fuels are listed in Table 6.

Table 6 - US Reference Fuel Composition Specification, in Volume Percent (NREL, 1998)

Constituent	EPA Reference Fuel	CARB	
		Reference Fuel	Commercial Fuel for mileage Accumulation
Methane	89.0 % minimum	90.0 ± 1.0%	88.0% minimum
Ethane	4.5% maximum	4.0 ± 0.5%	6.0% maximum
C ₃ and higher	2.3% maximum	2.0 ± 0.3%	3.0% maximum
Oxygen	0.6% maximum	0.5% maximum	1.0% maximum
Inert gases	4.0% maximum	3.5 ± 0.5%	1.5 to 4.5%
Odorant	See note	Not specified	not specified

Note: The natural gas at ambient condition must have a distinctive odour potent enough for its presence to be detected down to a concentration in air of not over one fifth of the lower flammability limit.

6.2 European reference fuels

According to the draft European regulation ECE R83, the amount of testing for exhaust emission approval of a CNG vehicle depends on whether it is a “parent” or a “member” of a vehicle family.

The “parent” vehicle should demonstrate its capability to adapt to any fuel composition that may occur across the market. In Europe there are generally two types of natural gas fuel: high calorific value (H-gas) and low calorific value (L-gas), but with a significant spread within both ranges. L-gas and H-gas differ significantly in the Wobbe Index. The limits of these variations are represented by the two reference fuels, G20 and G25 (Table 7). The vehicle is considered to conform if, with both reference fuels, its emissions are within the regulatory limits.

Table 7 - Draft European Natural Gas Reference Fuel Composition (ECE R83)

Constituent	G20			G25		
	Nominal	Minimum	Maximum	Nominal	Minimum	Maximum
Methane	100%	99%	100%	86%	84%	88%
Balance	n.s.	n.s.	1%	n.s.	n.s.	1%
Inerts +C ₂ and higher	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
Nitrogen	n.s.	n.s.	n.s.	14%	12%	16%
Sulphur	n.s.	n.s.	50mg/m ³	n.s.	n.s.	50mg/m ³

n.s.: not specified. Percentages are in terms of volume.

For a “family member” vehicle, the emission test shall be performed with one reference fuel, the results of which have to be corrected by a factor representing the ratio of results from tests on G25 over those from tests on G20. The vehicle is considered to conform if the corrected emission results are within the regulatory limits.

Unlike the US standards, the European natural gas reference fuel specification does not contain details on hydrocarbons higher than methane (i.e. C₂ and above). By contrast, the same draft ECE Regulation 83 specifies for LPG the percentages of hydrocarbons lower than propane (C₃) and higher than butanes (C₄), the main constituents of LPG – as well as the lower limit of the fuel’s motor octane rating.

6.3 Discussion

(a) Sulphur/odorant limits

It appears that, if the purpose of reference fuel specifications is to ensure that the certified exhaust emission performance of a gas engine can be maintained in service, the test fuel limit values should be set at levels that adequately cover those that may occur in actual service.

For example, for engines whose exhaust aftertreatment system is susceptible to sulphur, the sulphur limit in the test fuel should be a lower limit (a minimum) so that in service any commercially available fuel that has sulphur levels below that of the test fuel will not adversely affect the engine. If this policy is accepted, the sulphur limits in several test fuel specifications will need to be changed from the present “maximum” to “minimum”. This change would affect the draft ECE R83 (see Table 7), where the sulphur limit is “maximum 50 mg/m³”. In the case of US EPA and CARB (see Table 13), where currently there is no limit on either the odorant or the total sulphur, a minimum limit might be considered for engines that are susceptible to sulphur.

(b) Heavier hydrocarbon limits

In jurisdictions where the hydrocarbon exhaust limit is specified in terms of non-methane hydrocarbons (NMHC), the NMHC content in the test fuel is important. Thus, the specification should call for minimum levels of C₂ and higher hydrocarbons. At present US EPA calls for maxima, while CARB specifies fixed levels (see Table 6).

(c) Inerts

As inerts do not directly affect the Wobbe Index and Octane Number of the fuel, nor the hydrocarbon composition, they are perhaps not needed in an exhaust emission test fuel specification. At present US EPA, CARB and the draft ECE R83 specify the inerts.

(d) Correlation between certification reference fuel specification, commercial fuel specification and vehicle/engine manufacturers’ end use fuel specifications

To ensure the engine operates successfully with respect to performance, emissions and durability, there should be correspondence between the certification fuel specification (Tables 6 and 7), commercial fuel specification (see Section 3.4, the specification for California) and engine manufacturers’ specifications (Tables 1 and 2). This requires that the three sets of specifications be harmonized, which at present does not appear to be the case. An example of correlation and harmonization is the setting of a minimum limit say for sulphur in the certification fuel and a maximum limit of the same value in the commercial fuel and the manufacturers’ end use specifications.

7. SUMMARY AND CONCLUSIONS

The survey carried out by this study indicates that, at any location and any particular time, significant gas composition variations can occur at the local end-use level and are not predictable.

The actual composition of natural gas depends primarily on the production field from which it is extracted and limited variations in composition must therefore be accepted. Worldwide there are major differences in natural gas quality specifications. These specifications are mainly intended to meet pipeline requirements and the needs of industrial and domestic consumers. The properties of natural gas relevant as an engine fuel have not been considered.

At the local gas distribution level, seasonal adjustments by the local gas distributor may cause significant variations in the hydrocarbon composition.

The existing water content in delivered natural gas can be sufficiently low to not cause an NGV operational problem, however, gas drying will be necessary in colder climates or in cases where an old, low pressure gas distribution system allows water into the gas, raising the water content to significantly higher levels.

Technology exists to reduce compressor carryover oil content, although there is not yet a generally agreed or standardised method for determining it, as well, there is no well defined oil level requirement among the automotive manufacturers.

Currently, emissions standards for non-methane hydrocarbons (NMHC), CO, and engine oil-derived particulates in the lean burn NGV exhaust can be met with palladium and platinum containing catalysts.

Natural gas sulphur content is well below that of low sulphur (500 ppm) and ultralow sulphur (10 –50 ppm) diesel. However, it may be necessary to lower it further to avoid oxidation catalyst poisoning. Alternatively, it will be necessary to develop more sulphur-tolerant exhaust aftertreatment systems and reducing sulphur in engine oil by reformulation.

As sulphur compounds – including odorants - are removed by the gas liquefaction process, sulphur poisoning of exhaust catalyst will not be an issue for LNG vehicles.

Variations in gaseous fuel composition can affect the level of pollutant emissions. The primary effect is due to variations in the Wobbe Index, which can directly affect the air-fuel ratio and thus exhaust emissions. Additionally, they can affect the species composition and reactivity of the HC emissions in the exhaust. This effect can be of considerable regulatory importance in countries where the emission standards specify NMHC.

Given appropriate engine control hardware and software, variations in the composition of commercially available natural gases have little effect on emissions from light- and heavy-duty vehicles using modern engine control technology.

For heavy-duty vehicles, there is the additional consideration of engine knock, which places restrictions on the allowable knock rating, i.e. the hydrocarbon composition of the fuel. This is reflected in the inclusion of knock rating in engine manufacturers' CNG fuel specifications. The fuel knock rating requirements for heavy-duty engines can be reduced through improved engine control, as is the case of Cummins.

With the increasingly widespread regulatory requirement of more and more complex on-board diagnostic systems for vehicles, variability in natural gas fuel composition will pose special technical challenges for both OEM NGVs and aftermarket converted NGVs.

As the purpose of reference fuel specifications is to ensure that the certified exhaust emission performance of a gas engine can be maintained in service, the test fuel limit values should be set at levels that adequately cover those that may occur in actual service.

Finally, to ensure that the engine operates successfully with respect to performance, emissions and durability, there should be correspondence between the certification fuel

specification, commercial fuel specification and engine manufacturers' specifications. This requires that the three sets of specifications be harmonized.

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