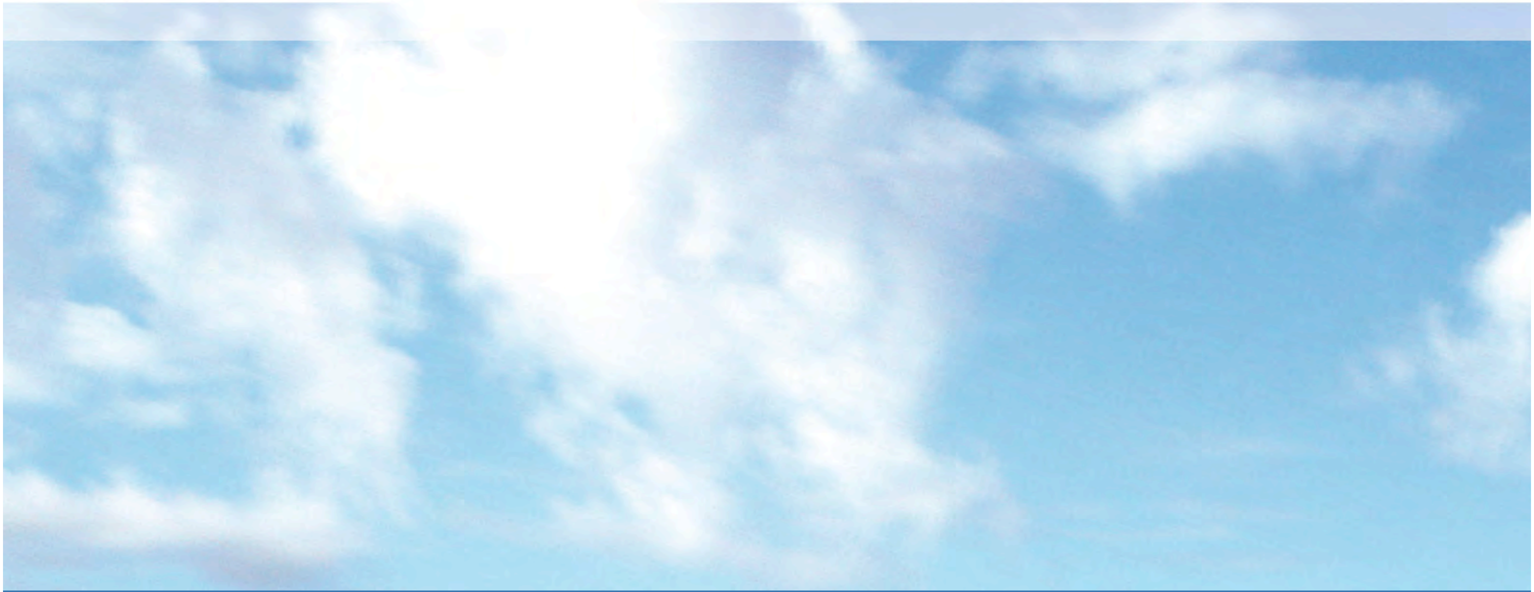

Biogas Composition and Engine Performance, Including Database and Biogas Property Model

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Summary

In order to enable this evaluation of the current biogas quality situation in the EU; results are presented in a biogas database. Furthermore the key gas parameter Sonic Bievo Index (influence on open loop A/F-ratio) is defined and other key gas parameters like the Methane Number (knock resistance) are made available in a biogas calculation tool. Finally the results of the study of the influence of biogas quality on the engine performance of Natural Gas Vehicles (NGV), efficiency and emission are presented.

1. Introduction

This BiogasMax report describes TNO's' activities in subtask 5.2.1 of task 5.2 "Use in Vehicles". TNO studied various biogas qualities, based on information received through BiogasMax partners as well as based on information from the WP 3 report D3.1 [5].
Both raw biogas data as upgraded biogas (biomethane) data is presented in a biogas database. This biogas data is collected to get an overall idea of the biogas quality range, in relation to the use of biogas in light-duty and heavy-duty vehicles. Based on this information, the biogas calculation tool is developed [8].

From an engine point of view a number of key gas parameters, such as LHV, stoichiometric Air-to-fuel ratio (A/F-ratio), Sonic Bievo index and Methane Number (the MN is the index for knock resistance) are listed and subsequently these key parameters are calculated in the biogas calculation tool.

Finally this report discusses the influence of biogas gas quality on engine performance, efficiency and exhaust gas emissions of both heavy-duty and light-duty NGV's.

2. Raw biogas and upgrading to biomethane

In the following sections an overview of raw biogas composition, a brief summary of upgrading techniques as well as an overview of upgraded biogas (biomethane) is presented. This information was required in order to be able to develop the BiogasMax biogas calculation tool [8].

2.1. Overview of raw biogas

Biogas is produced by digestion of organic waste in a digester or in a landfill site. Both the biogas composition and the contaminants are strongly dependent on the type of feedstock. Typical feedstocks are sewage, landfill waste or waste from the food industry. Based on TNO's experience, the CH_4 content of sewage derived biogas normally is approx. 70%. When dealing with waste from the food industry the maximum CH_4 content can be as high as 85% and on the other hand the CH_4 content of landfill gas can be as low as 30%.

From partners and from WP3 deliverable D3.1 [5] the following raw biogas data was derived:

Raw Biogas		Gothenburg Sweden	Stockholm Sweden	Lille France	Rome Italy	Berne Switzerland
In production		since 2000	since 1996	since 1969 (19'75,	< 1994	
Analysis date		-	2001	-	1998	
Feedstock		sewage	sewage	sewage	landfill	sewage
CH_4	% vol	average 65	average 65	63,5	50 - 60	
CO_2	% vol	average 34,4	average 35	35,5	37 - 47	
H_2	% vol				rest	
O_2	% vol	< 0,1		0,2	rest	
N_2	% vol	< 0,5	1	0,7	rest	
H_2O	mg/m_n^3					
H_2S	ppm	< 10 ppm (?)		3000	5000 - 10000	
CL, Fl	mg/m_n^3				5 - 10 ppm	

Figure 1: Examples of raw Biogas data

2.2. Upgrading

Raw biogas can not be used directly in e.g. engines or heaters because of corrosion problems; the biogas needs to be cleaned. This cleaning incorporates H_2S removal and removal of dust, water, halogenated hydrocarbons and siloxanes etc. This cleaned biogas can be used in engines for co-generation or in heaters.

However, for use in vehicles it is generally accepted to upgrade the biogas, to natural gas like composition, also called biomethane, by means of CO_2 removal (among others). In this way the upgraded biogas (biomethane) can be used for grid injection or can be used in standard light-duty or heavy-duty natural gas vehicles (NGV's). As a result the maximum driving range of the NGV is not reduced, compared to its natural gas fueled counterpart.

The following upgrading techniques are commonly used:

- Physical absorption (scrubbing with liquid)
- Chemical absorption (chemical reaction with a liquid)
- Pressure swing adsorption (adsorption on adsorption material like activated carbon)
- Membrane separation
- Cryogenic separation (cooling at elevated pressure)
- In-situ enrichment (sludge treatment)

Since both production and upgrading are studied in WP2 and WP3 no further detailed information on upgrading techniques will be reported here.

2.3. Upgraded biogas (Biomethane)

As a result of one or more upgrading and cleaning steps, a high quality biogas is produced, often referred to as "biomethane". The quality of the biomethane can be compared with natural gas quality, and subsequently this biomethane can be used in both heavy-duty and light-duty NGV's, see next sections.

Below an overview of the various biomethane qualities within the BiogasMax project is presented:

Biomethane		Gothenburg Sweden	Stockholm Sweden	Lille France	Rome Italy	Berne Switzerland
In production		Expected Feb 2007	Yes, since 1996	1969		
Analysis date		-	2001			
CH_4	% vol	av. 97 (96 – 98)	> 97	97,5 - 99	97 - 99	> 96
CO_2	% vol	av. 2 (< 4)	< 2	1,6 av. (< 2.5)	1 – 3	< 6
H_2	% vol	< 0.5		< 6		
O_2	% vol	< 1	0.2	< 0.01		
N_2	% vol	av. 1	< 0.8			
H_2O	mg/m_n^3	< 32				
H_2S	mg/m_n^3	< 23	< 0.5	2 av. (< 5 ppm)	1 – 10 (ppm)	< 5
CL, Fl	mg/m_n^3			< 0.1	< 1 ppm	
THT	mg/m_n^3		< 4 - 23	15 – 40		
Particles	mg/m_n^3			< 5		
LHV	MJ/m_n^3		35	37.8		
Density	kg/m_n^3		0.7075	0.555(?) – 0.7		
Wobbe (upper)	MJ/m_n^3					
Wobbe (lower)	MJ/m_n^3	45.5 – 48.2	> 44.7			

Figure 2: Examples of biomethane data

2.4. Biomethane national regulations

The regulations presented as an example in table 1 below generally don't have any specific limits for dust, moisture or siloxane. Dust and moisture could interfere with the NGV fuel system equipment, and components like siloxane can have a negative influence on engine durability.

The international ISO 15403 fuel standard for NGV's can be used to address this issue.

Table 1: Example of national biomethane regulations

Country	Switzerland[1]	Germany	Sweden	France
Regulation		G262	SS 15 54 38	2004
CH_4 %	≥96		> 97	
CO_2 %	≤ 6	< 6	< 3	< 2
H_2 %	≤ 5		< 0.5	
O_2 %	≤ 0.5	< 3	<1	
H_2O [mg/mn^3]				
H_2S [mg/m_n^3][2]	≤ 5		< 23	
HHV [MJ/m_n^3]				H: 38.5 - 46.1 L: 34.2 - 37.8
Wobbe (upper) [MJ/m_n^3]		H: 46.1 - 56.5 L: 37.8 - 46.8		H: 48.2 - 56.5 L: 42.5 - 46.8
Wobbe (lower) [MJ/m_n^3]			43.9 – 47.3	

[1] Switzerland regulations for unlimited grid injection

[2] 1 ppm H_2S equals 1.52 mg/m_n^3 H_2S.

3. Key gas parameters

A number of key gas parameters are used to compare the performance of NGV's on different natural gas or biogas (biomethane) qualities. Apart from obvious parameters such as LHV, density, stoichiometric A/F-ratio, some parameters are used to predict the "open loop" A/F-ratio error, or the required authority range of the (closed loop) fuel system. The parameters often used are: Wobbe index, TNO's (subsonic) Bievo index, the new Sonic Bievo index, and the lambda-shift factor from R49. All these key gas parameters are extensively described in the sections below.

Please note that it depends on the NGV's type of fuel system, which key gas parameter should be used. The Sonic Bievo index as presented in section 3.4 should be used when comparing fuels for modern NGV's that are using gaseous fuel injection equipment, with sonic flow conditions at the injector. The Wobbe index (section 3.1) can only be used in combination with venturi based fuel systems, and the (subsonic) Bievo index [6] of section 3.3 should be used if the specific NGV is equipped with a subsonic over pressure gaseous fuel system.

There is one other key gas parameter, the so called "methane number" (MN), an index representing the knock sensitivity of the fuel, that is important as well when using natural gas or biomethane as fuel for NGV's.
For more information see section 3.5.

3.1. <u>Wobbe index:</u>

The Wobbe index is a measure of heat input to gas appliances derived from the orifice flow equation. Heat input for different natural gas compositions is the same if they have the same Wobbe index, and operate under the same gas pressure.

From a historic perspective the Wobbe index is presented in this section, although the Wobbe index can only be used for venturi-based gas burners or venturi-based NGV fuel systems. Only one HD-NGV manufacturer still uses a venturi-based fuel system. All others HD-NGV's and all LD-NGV's are using over-pressure (sonic) fuel injection equipment. In the table 2 on page 12, the relative Wobbe index (Wobbe gas / Wobbe pure methane) is used.

The Wobbe index can be based on the lower caloric heat value (LHV) (Wobbe **l**ower of Wobbe **i**nferior) or based on the higher caloric heat value (HHV) (Wobbe **h**igher or Wobbe **s**uperior); see formula's below:

$$Wobbe_{l,i} = LHV / \sqrt{\frac{density_{gas}}{density_{air}}}$$

$$Wobbe_{h,s} = HHV / \sqrt{\frac{density_{gas}}{density_{air}}}$$

The Wobbe index was defined to ensure constant A/F-ratio in fuel systems using *venturi based, zero pressure type, mixture formation* as used in gas burners or venturi type engine carburetor systems.

The use of the Wobbe index is becoming slightly old-fashioned in automotive applications, because all light-duty NGV's and almost all heavy-duty NGV's use fuel injection equipment working with over pressure. In that case the Wobbe index can not be used to achieve a constant A/F-ratio. For over pressure fuel systems the (subsonic) Bievo index and the Sonic Bievo index was developed at TNO; see sections 3.3 and 3.4.

3.2. Lambda shift factor S_λ as defined in R49 [2, 3]

In R49 [2, 3] a number of reference gases i.e. G20, G23, G25 and GR are defined, as well as the so called "lambda shift factor" or "S_λ". This factor should indicate how much the A/F-ratio (lambda) will shift when any NGV is operated not on pure methane, but on a specific natural gas composition. The calculation of the "lambda shift factor" is quite complex, and still not very accurate or correct. The calculation of the "S_λ" will be explained by means or the original "R49 rev3 ammend1" text below.

Notes: Conform R49/03 ammend-2 paragraph 4.1.2 [3] (type approval) the L-range natural gas has a lambda shift factor $1.08 < S_\lambda < 1.19$ and natural gas within the H-range has a lambda shift factor $0.89 < S_\lambda < 1.08$. However in the same document, paragraph 8.3.2.4, related to COP testing, the L-range is defined by $1.00 < S_\lambda < 1.19$ and the H-range by $0.89 < S_\lambda < 1.00$.

In figure 3 below the actual R49/03 ammend-1 text [2] is presented:

> 2.26. "λ-shift factor (S_λ)" means an expression that describes the required flexibility of the engine management system regarding a change of the excess-air ratio λ if the engine is fuelled with a gas composition different from pure methane (see annex 8 for the calculation of S_λ).

Figure 3: Definition S_λ

In order to calculate the lambda shift factor, first the parameters "n" and "m" that refer to the average C_nH_m of the fuel. The "n" and "m" have to be calculated, using the following formula's, copied from in R49 Annex 8 as well, see figure 5 below:

$$n = \frac{1 * \left[\frac{CH_4\%}{100}\right] + 2 * \left[\frac{C_2\%}{100}\right] + 3 * \left[\frac{C_3\%}{100}\right] + 4 * \left[\frac{C_4\%}{100}\right] + 5 * \left[\frac{C_5\%}{100}\right] + ..}{1 - \frac{\text{diluent}\%}{100}}$$

$$m = \frac{4 * \left[\frac{CH_4\%}{100}\right] + 4 * \left[\frac{C_2H_4\%}{100}\right] + 6 * \left[\frac{C_2H_6\%}{100}\right] + 8 * \left[\frac{C_3H_8\%}{100}\right] + ..}{1 - \frac{\text{diluent}\%}{100}}$$

where:

CH_4 = % by volume of methane in the fuel;
C_2 = % by volume of all C_2 hydrocarbons (e.g.: C_2H_6, C_2H_4, etc.) in the fuel;
C_3 = % by volume of all C_3 hydrocarbons (e.g.: C_3H_8, C_3H_6, etc.) in the fuel;
C_4 = % by volume of all C_4 hydrocarbons (e.g.: C_4H_{10}, C_4H_8, etc.) in the fuel;
C_5 = % by volume of all C_5 hydrocarbons (e.g.: C_5H_{12}, C_5H_{10}, etc.) in the fuel;
diluent = % by volume of dilution gases in the fuel (i.e.: O_2*, N_2, CO_2, He, etc.).

Figure 4: Calculation "m" and "n" used in the Sλ calculation

In figure 5 below the "lambda shift" calculation as found in R49/03 ammend-1, Annex 8 [2] is presented:

$$S_\lambda = \frac{2}{\left(1 - \frac{\text{inert } \%}{100}\right)\left(n + \frac{m}{4}\right) - \frac{O_2 *}{100}}$$

Figure 5: R49/03 calculation S_λ

In the formula above "inert %" is defined as volume % of inert components like N_2, CO_2, and He etc.

Although the "lambda shift factor" does not represent the open loop A/F-ratio error of any gaseous fuel metering accurately, the"S_λ"can be calculated using the BiogasMax biogas calculation tool as well.

3.3. TNO's (subsonic) Bievo index [6]

To compare various natural gas compositions when used in NGV's *with subsonic over-pressure fuel metering* systems (like Volvo V70 bi-fuel, using Teleflex-GFI MEGA metering hardware) the Wobbe index from section 3.1, as well as using the lambda shift factor "S_λ" will give incorrect results, and an index was developed by TNO [6]. This (subsonic) Bievo index can be used to calculate the A/F-ratio error, in case the NGV with subsonic metering equipment is operated on a (natural) gas mixture like biomethane, in stead of on pure methane.

The absolute pressure ratio ($PR_{critical}$) across the metering device (e.g. injector) defines if the flow is subsonic or sonic (choked flow). For natural gas (kappa approx 1.3) the critical pressure ratio is calculated below:

$$PR_{critical} = \frac{p_{abs,downstream}}{p_{abs,upstream}} = \frac{p_2}{p_1} = \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa}{\kappa-1}} = 0.546$$

For pressure ratios 0.546 ≤ PR ≤ 1.00 the flow is subsonic, and the subsonic Bievo index can be used; for a PR ≤ 0.546 the flow is sonic (choked) and subsequently the "Sonic Bievo index" should be used; see section 3.4.

The (subsonic) Bievo index is defined as the required metering area, or injector opening duration for the same A/F-ratio, compared to the 100% methane situation. Validation measurements on engines with subsonic equipment proved that the Bievo index performs as expected [6].

By definition the Bievo index of pure methane is 100%. [6]. The Bievo index is calculated using the following formula:

$$Bievo\_index = \frac{14.231}{(1 + AF_{stoich})} * \sqrt{\frac{density}{kappa}} * 100\%$$

The "Sonic Bievo index" above is defined using the following data [6] for pure methane:

$\lambda_{stoich} = 9.55$ $\varkappa$ (kappa) = 1.301 ϱ (density) = 0.715

Notes:

- The AF_{stioch} in the formula above is the volumetric (or molar) A/F-ratio, not the mass A/F-ratio.
- Kappa is the polytrophic exponent c_p/c_v. For gaseous fuels values between 1.1 and 1.4 are expected.
- When using a mixture of gases, like biomethane or natural gas, the Bievo of the mixture can be calculated. Quantities like density, LHV, and AF_{stoich} can be calculated proportional to the individual components. However, for calculation of the kappa of the mixture it is required to calculate the proportional c_p of the mixture, and from this c_p the kappa of the mixture can be calculated.
- When calculating the (subsonic) Bievo index of "pure" methane, using the BiogasMax calculation tool, the result is not exactly 100.0% due to gas properties like kappa, AF_{stoich} and density used during Bievo definition.
- When dealing with gas analysis, one should note that such an analysis can be presented using $\%_{vol}$ units or $\%_{mol}$ units, which are often considered to be the same. However, due to non-ideal gas properties, in reality molar volume is not constant (~22.4 l/mol) but differs slightly per component.
- The (subsonic) Bievo index is based on the following formula for subsonic, un-choked flow: [6] [7]

$$\dot{m}_{gas} = C_d * A * \sqrt{\frac{2 * \kappa * p_1 * \rho}{\kappa - 1} * \left(PR^{\frac{2}{\kappa}} - PR^{\frac{\kappa+1}{\kappa}} \right)}$$

Where PR equals the pressure ratio (p2/p1) downstream and upstream of the metering device.

3.4. TNO's Sonic Bievo index

Most of today's OEM NGV's, both light-duty as well as heavy-duty, are some form of gaseous fuel injection with sonic flow conditions at the injector. This because the gas injectors are operated under a (relative) gas pressure of approx. 0.1 – 1 MPa and the manifold pressure varies between absolute pressures of 30 – 200 kPa depending on engine load and engine type, natural aspirated (NA) or turbo charged (TC).

In order to be able to compare different (bio)methane qualities for use in NGV's a new gas index, the "Sonic Bievo index" was developed within the BiogasMax project.

Definition: "Sonic Bievo index":

The "Sonic Bievo index" represents the required correction of the metering area (or nett injection duration) for sonic (choked) conditions like present with gaseous injectors. For pure methane the Sonic Bievo index is 100% by definition.

For choked (sonic) flow the mass flow is defined [7] as follows:

$$\dot{m}_{gas} = \frac{C_D * A * p_1}{\sqrt{R*T}} * \kappa^{1/2} * \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2*(\kappa-1)}} = C_D * A * \sqrt{p_1 * \rho * \kappa} * \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2*(\kappa-1)}}$$

Furthermore the gas flow of a given gas engine can be related to the mixture flow as follows, where λ_{stoich} equals the volumetric stoichiometric A/F-ratio.:

$$Q_{gas} = \frac{Q_{mix}}{1 + \lambda * \lambda_{stoich}} \quad \text{or} \quad \dot{m}_{gas} = \frac{Q_{mix} * \rho_{gas}}{1 + \lambda * \lambda_{stoich}}$$

For a given engine and operation point, the ratio of the mass flow of "gas x" and the mass flow "methane" can be represented as follows:

$$\frac{\dot{m}_{gas\_x}}{\dot{m}_{methane}} = \frac{\rho_{gas\_x} * (1 + \lambda_{stoich\_methane})}{\rho_{methane} * (1 + \lambda_{stoich\_gas\_x})}$$

Combining the above mass flow ratio with the sonic flow formula, the ratio of the required area (or injection time) can be calculated, see formula below:

$$\frac{A_x}{A_m} = \frac{\rho_x * (1 + \lambda_{stoich\_m}) * \sqrt{\rho_m * \kappa_m} * \left(\frac{2}{\kappa_m + 1}\right)^{\frac{\kappa_m + 1}{2*(\kappa_m - 1)}}}{\rho_m * (1 + \lambda_{stoich\_x}) * \sqrt{\rho_x * \kappa_x} * \left(\frac{2}{\kappa_x + 1}\right)^{\frac{\kappa_x + 1}{2*(\kappa_x - 1)}}}$$

In the formula above, indices "x" represent "gas_x" and indices "m" represents "methane".

The resulting formula for the "Sonic Bievo index" is as follows:

$$Sonic\_Bievo = \frac{\rho * 8.3359}{(1 + \lambda_{stoich}) * \sqrt{\rho * \kappa} * \left(\frac{2}{\kappa+1}\right)^{\frac{\kappa+1}{2*(\kappa-1)}}} * 100\%$$

The "Sonic Bievo index" above is defined using the following data [4] for methane:

$\lambda_{stoich} = 9.55$ κ (kappa) = 1.312 ϱ (density) = 0.717

By definition the Sonic Bievo index is, representing the correction of the metering area, or the injection duration for sonic (choked) conditions like present at most gaseous fuel injectors. With pure methane the Sonic Bievo should be 100% also by definition. The BiogasMax biogas calculation tool can be used to calculate the Sonic Bievo index for biogas, biomethane and natural gas.

3.5. Sonic Bievo validation measurements

To validate the Sonic Bievo index, engine testbed measurements were carried out.

The research engine used in this project is the same engine as used at the subtask 5.2.4 catalyst ageing program. The research engine is a Volvo B5234T engine, in natural aspirated version, with increased compression ratio from 8.5 : 1 to 11.5 : 1. Maximum torque approx. 170 Nm; maximum power approx. 95 kW. The engine was equipped with both MPFI sequential fuel injectors as well as equipped with a single point injection device, using 5 sequential injectors as well. By using a single point mixing device, high and constant mixture homogeneity can be achieved. Furthermore, in this way it is guaranteed that (varying) inaccuracies in fuel injectors will not be of any influence on the raw emission of the engine, and the subsequent conversion efficiency. The engine is controlled by means of TNO's rapid control prototyping system "MACS", using software generated in MatLab/Simulink the A/F-ratio can be controlled e.g. by a PID control or any other control algorithm.

In the fuel system used on the research engine, the fuel flow metered using sequential fuel injectors. The system layout is such that the fuel flow through these injectors is always choked. Therefore, the mass flow to the engine can be controlled by varying the injector actuation pulse width. Due to the injector design, the actual fuel delivery time of an injector will not be the same as the injector (electrical) pulse width. The electrical pulse width is called "Ti" and the fuel delivery time "BPW" from now on. Their relation is explained using the picture below. The top line represents the electrical actuation of the injector. The bottom line represents the fuel mass flow through the injector.

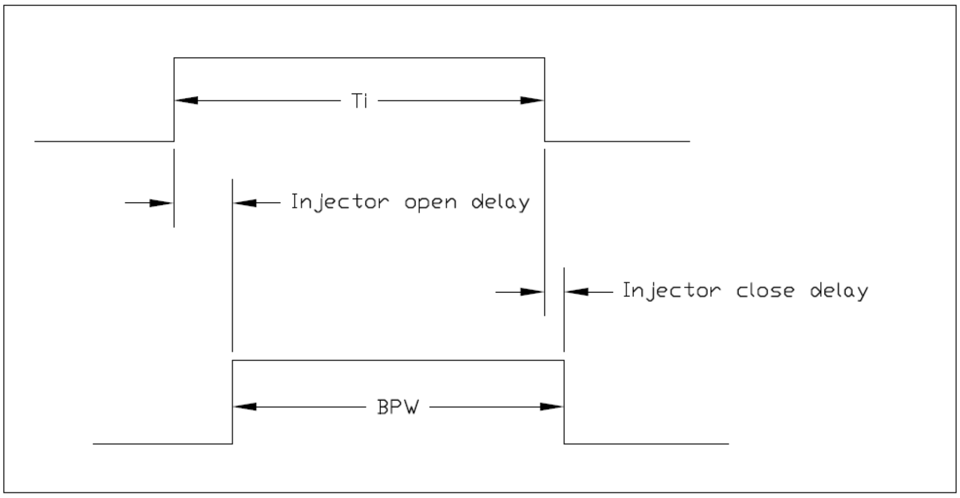

Figure 6 Ti and BPW of a fuel injector explained

As can be seen in the picture, there is a delay between the start of Ti and the start of BPW. This is called the injector open delay. There also is a delay between the end of Ti and the end of BPW. This is called the injector close delay. To describe the difference between Ti and BPW is commonly known as the "bias" time of the injector. An engine management calculates the BPW needed to fulfil the engines fuel demand, then adds the bias time to calculate Ti and finally energizes the fuel injector coils for the duration of Ti.

Because of the difference between Ti and BPW, Ti is not directly proportional to the fuel mass flow. Therefore, the injector pulse width ratio will not be suitable to validate the Sonic Bievo index. BPW however is directly proportional to the fuel mass flow (note: this only holds at a constant fuel pressure). This means that BPW can theoretically be used to validate the Sonic Bievo index. The internal "closed loop correction" parameter in the engine management system on the research engine is in fact a representation of BPW corrected for differences in lambda and fuel pressure. This is the parameter that is used to validate the Sonic Bievo index. It is comparable to the fuel trims used in commercial NGV's.

The validation was performed by running the engine on "GR" quality reference gasses at 2000RPM, 2Bar BMEP and then switching the fuel supply to "G25" quality reference gas. If the Sonic Bievo index is correctly defined, the "closed loop correction" should rise by a similar amount as the ratio of the Sonic Bievo indices of these two gasses. These indices are 0,976 and 1,200 respectively (see BiogasMax deliverable 5.5: "Report on biogas composition and engine performance, including database and biogas property model"). Therefore, the closed loop correction should rise by a factor of 1,200/0,976=1,230. The following graph shows the effect this changeover had on a number of engine parameters.

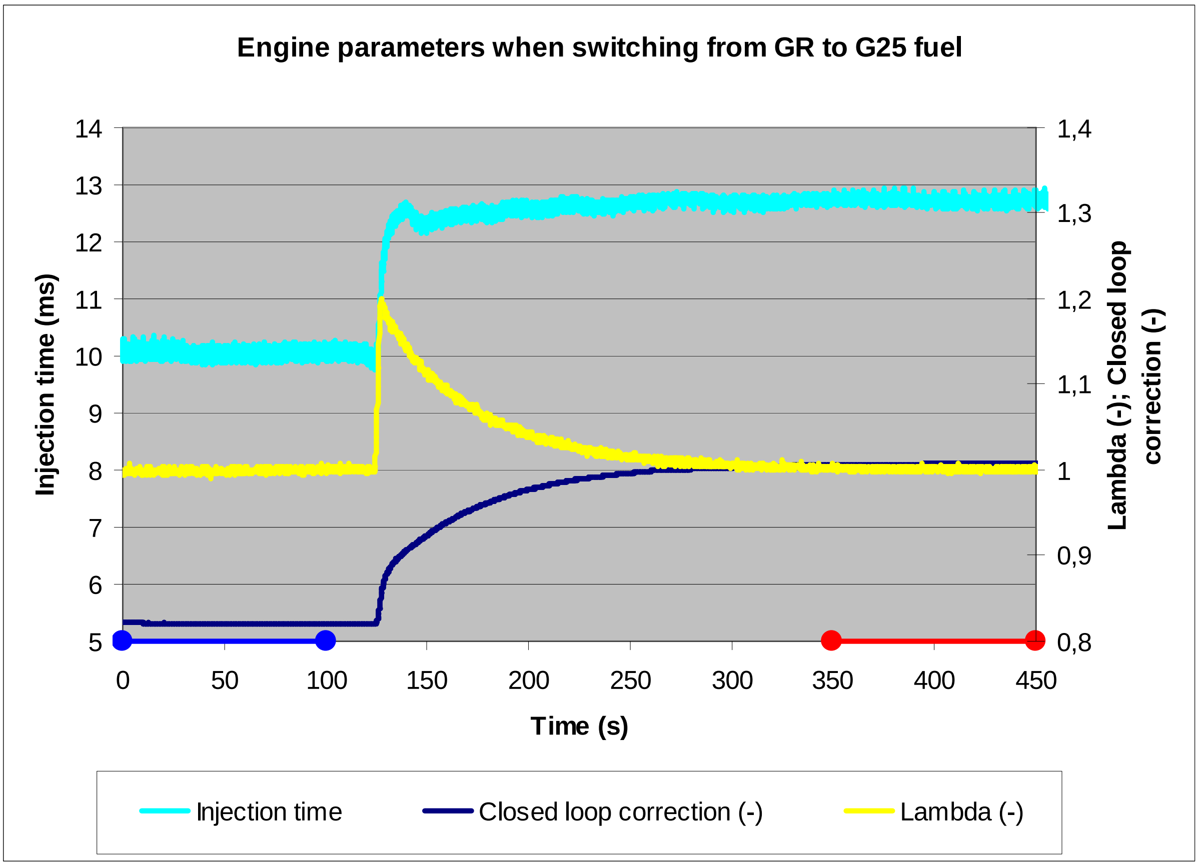

Figure 7 Engine parameters when switching from GR to G25 fuel

To cancel out cycle-to-cycle noise, a number of parameters were averaged over 100 seconds of stable engine operation. For operation on GR, this was done from 0 to 100 seconds (indicated by the blue bar at the bottom of the graph). For G25, this was done from 250 to 450 seconds (indicated by the red bar at the bottom of the graph). The averages thus obtained are summarized in the following table:

Table 2 Sonic bievo validation parameter overview

Parameter	GR fuel	G25 fuel
Lambda	0,999	1,001
Gas pressure	196,4	193,3
Ti	10,05	12,73
BPW	9,65	12,33
Closed loop correction	0,821	1,007
Closed loop correction ratio	1,228	

The closed loop ratio predicted by the Sonic Bievo index is 1,230. The measured value of 1,228 corresponds to within 0,16% with the predicted value. Therefore, the Sonic Bievo index correctly predicts the behaviour of different gas qualities in choked-flow gaseous fuel supply systems.

3.6. Overview (reference) gases and the different gas indices

The following table shows different heavy-duty R49/03 NGV [2, 3] reference fuels and Dutch natural gas:

"quality"	lowest	low	medium	high	highest
(reference) gas name	Dutch NG 05-01-2007	G25	G23	G20 (methane)	GR
relative Wobbe index	0.824	0.818	0.900	1.000	1.045
lambda shift factor R49/03	1.123	1.163	1.081	1.000	0.911
(subsonic) Bievo index	1.200	1.196	1.101	0.998	0.976
Sonic Bievo index	1.203	1.200	1.101	1.000	0.976

Table 3: Comparison of gas indices

Looking at the table above, the following three conclusions can be made:

- Using the "lambda shift factor" when characterizing fuel for modern fuel injected NGV's, does not give a correct indication of the required closed loop authority of the fuel system.
- Dutch natural gas is slightly lower in quality (using the Sonic Bievo Index) compared to the lowest quality reference fuel (G25). Together with day to day variation in Dutch natural gas composition, sufficient extra margin in the NGV's fuel system is required, for correct performance and emission. If no such extra margin is present, problems caused by a maximum fuel trim value (performance, emissions, durability) are shown by the CEL of the On Board Diagnosis (OBD) system.
- The Wobbe index as the "S_λ" does not show an alarming value with the Dutch natural gas composition.

3.7. Methane number

The methane number is an indication of the knock sensitivity of the natural gas or biomethane fuel. The definition of the "methane number" is similar to the definition of the "octane number" as used with gasoline fuel. The octane number is measured by comparing an unknown gasoline sample with a mixture of iso-octane and n-heptane on knock sensitivity. When e.g. the gasoline performs equal to a 90%/10% octane/heptane mixture, it will be characterised as RON or MON octane number 90.

Methane is much less sensitive to knock compared to gasoline, so natural gas or biomethane is not characterised using the RON or MON octane number; since it has a RON and MON number much higher then 100. As a result the methane number was defined, by using a similar procedure, however using mixture of methane and hydrogen. The methane number of natural gases depends strong on the composition, e.g. the amount of higher

hydrocarbons like ethane, propane and butane.
Normal MN values for natural gas from the grid will be between e.g. 75 and 100. Many natural gas engine manufacturers, both for stationary applications as used in HD or HD NGV's have a minimum methane number specification of e.g. 70. A mixture of methane and CO_2 can have a higher methane number the 100, due to thermodynamic effects of CO_2 during the combustion. As an example: the biogas calculator calculates a MN of approx 130 in case of a mixture of 70% methane and 30 % CO_2. However H_2S has a very strong negative influence on the methane number. Mixing 1% (10.000 ppm) H_2S with methane results in a MN of approx. 85.

Since biogas does not contain ethane, propane, butane or other higher hydrocarbons, the BiogasMax calculation tool does not take into account the effects of adding propane or butane/air mixtures on the Methane Number.

4. The BiogasMax biogas calculation tool [8]

In order to be able to predict the performance and the emission of NGV's operated on biomethane, it is necessary to calculate the key gas parameters for the specific biomethane quality. One of the deliverables of WP5.2 "Use in Vehicles" is the development of a "Biogas Calculator". This tool will be made available for the BiogasMax partners through the BiogasMax restricted website.

4.1. The Biogas calculator

Below, the Excel based biogas key parameter calculation tool is presented. In the small white input field on top left of your screen, the gas components methane CH_4, hydrogen H_2 hydrogen-sulfide H_2S, nitrogen N_2, carbon-dioxide CO_2, carbon-monoxide CO and oxygen O_2 should be filled out in volumetric (or molar) ratio's.

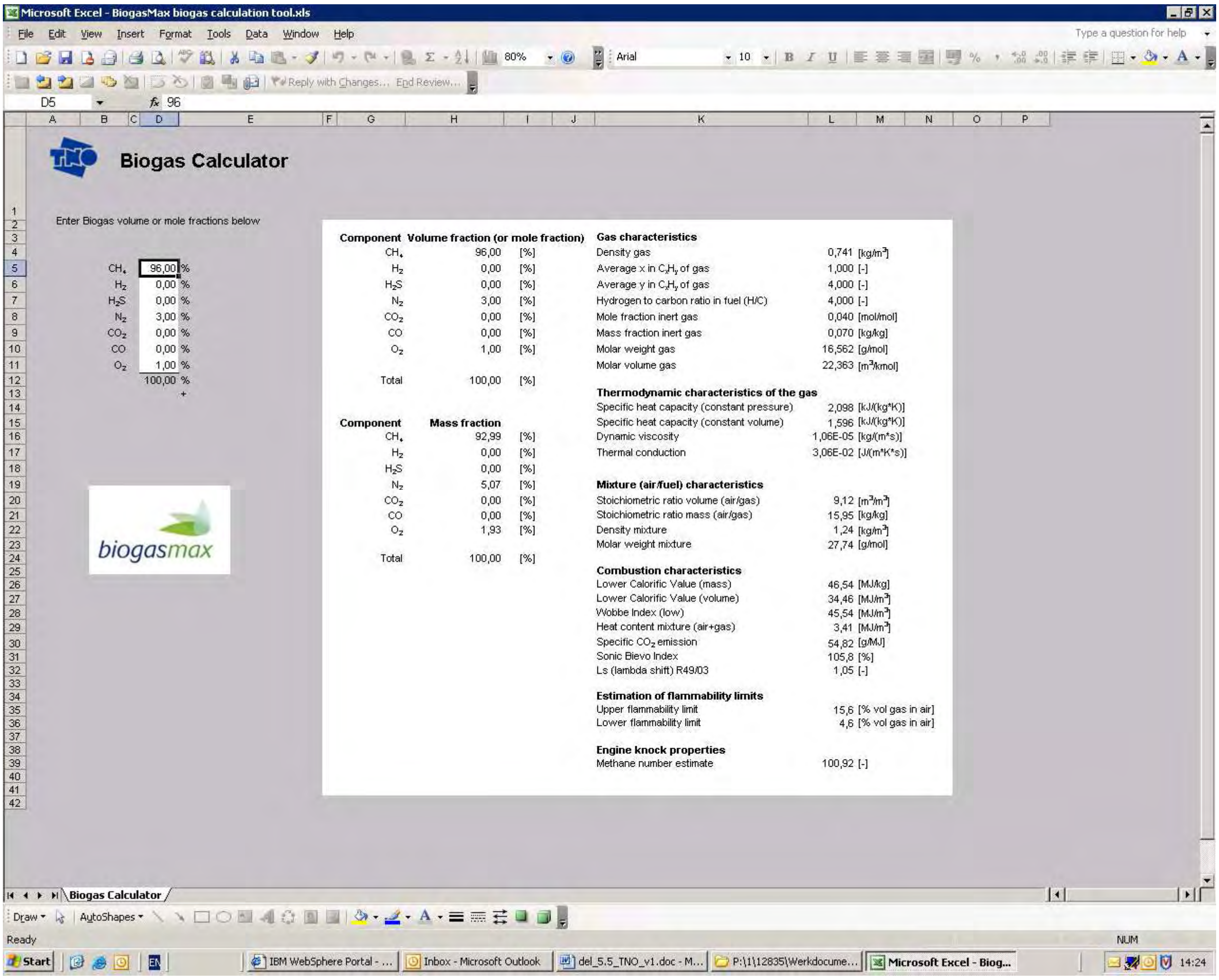

Figure 8: "BiogasMax Biogas calculation tool.xls"

In the big white field in the middle of the screen, all calculated results are presented. The .xls sheet is protected so no accidental deletion of formula's etc. can happen. A few key gas parameters are described in the next section.

5. NGV fuel specification

Both heavy-duty as light-duty NGV's have to comply to UN-ECE legislation, as can be found in ECE regulations. For light-duty R83 [1] applies; for heavy-duty vehicles R49 {2, 3] should be used. For light-duty and for heavy-duty NGV's there are different regulations and subsequently different NGV fuel specifications. The sections below describe the differences between light-duty and heavy duty NGV's.

Furthermore ISO 15403 NGV fuel specification will be discussed.

5.1. R83 light-duty NGV fuel specification [1]:

LD NGV's have to be able to cover the gas quality range from reference fuels **G20 to G25**, a relatively wide range; see data derived from R83 below. As a result it is possible to operate LD-NGV's in all countries, even when traveling from one country of the EU.

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Regulation No. 83
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Annex 10a

1.2. TECHNICAL DATA OF THE NG REFERENCE FUELS

Characteristics	Units	Basis	Limits		Test Method
			min.	max.	
Reference fuel G_{20}					
Composition:					
Methane	per cent mole	100	99	100	ISO 6974
Balance 1/	per cent mole	-	-	1	ISO 6974
N_2	per cent mole				ISO 6974
Sulphur content	mg/m^3 2/	-	-	10	ISO 6326-5
Wobbe Index (net)	MJ/m^3 3/	48.2	47.2	49.2	
Reference fuel G_{25}					
Composition:					
Methane	per cent mole	86	84	88	ISO 6974
Balance 1/	per cent mole	-	-	1	ISO 6974
N_2	per cent mole	14	12	16	ISO 6974
Sulphur content	mg/m^3 2/	-	-	10	ISO 6326-5
Wobbe Index (net)	MJ/m^3 3/	39.4	38.2	40.6	

1/ Inerts (different from N_2) + C_2 + C_{2+}

2/ Value to be determined at 293.2 K (20 °C) and 101.3 kPa

3/ Value to be determined at 273.2 K (0 °C) and 101.3 kPa

Figure 9: Light-duty reference fuels

5.2. R49 HD fuel specification [2, 3].

For heavy-duty NGV's the fuel specification situation is much more complex. Conform R49 HD-NGV's can be approved for a wide gas quality range (G20 to G25) like the light-duty range fuel specification range, see below. However, it is also allowed in R49 to specify a certain limited gas quality range, e.g. L-gas or H-gas or even only one specific (bio)methane fuel composition; see section 5.3 NGV classification.

Earlier UN-ECE R49 specified G20 - G23 for the H-gas range and G23 - G25 for the L-range. However, in the latest UN-ECE R49 regulations ammend-1 the G20 is replaced by GR. Today's heavy-duty NGV reference gas specification (GR, G23 and G25) can be found in "Annex 6 of R49 ammend-1" see the relevant data in figure 6 below:

Reference fuel GR

Characteristics	Units	Basis	Limits		Test Method
			Min.	Max.	
Composition:					
Methane	% mole	87	84	89	
Ethane	% mole	13	11	15	
Balance (*)	% mole	-	-	1	ISO 6974
Sulphur content	mg/m^3 (**)	-	-	10	ISO 6326-5

(*) Inerts $+C_{2+}$
(**) Value to be determined at standard conditions (293.2 K (20°C) and 101.3 kPa)

Reference fuel G23

Characteristics	Units	Basis	Limits		Test Method
			Min.	Max.	
Composition:					
Methane	% mole	92.5	91.5	93.5	
Balance (*)	% mole	-	-	1	ISO 6974
N_2	% mole	7.5	6.5	8.5	
Sulphur content	mg/m^3 (**)	-	-	10	ISO 6326-5

(*) Inerts (different from N_2) $+C_2/C_{2+}$
(**) Value to be determined at standard conditions (293.2 K (20°C) and 101.3 kPa).

Reference fuel G25

Characteristics	Units	Basis	Limits		Test Method
			Min.	Max.	
Composition:					
Methane	% mole	86	84	88	
Balance (*)	% mole	-	-	1	ISO 6974
N_2	% mole	14	12	16	
Sulphur content	mg/m^3 (**)	-	-	10	ISO 6326-5

(*) Inerts (different from N_2) $+C_2/C_{2+}$
(**) Value to be determined at standard conditions (293.2 K (20°C) and 101.3 kPa).

Figure 10: R49/03 HD reference fuels [2, 3]

5.3. HD-NGV classification

As a result of flexibility of R49/03 [2,3] regarding fuel specifications for HD-NGV's, based on the mainly regional operation of heavy-duty NGV's, these vehicles are allowed to be designed for the "whole" natural gas quality range (GR – G25) or to a limited fuel quality range; see table 3 below:

HD-NGV "class" ↓	Reference fuel	Manufacturers' request and/or (COP) reference fuel*	Approval mark
universal	GR and G25	Market fuel with $0.89 < S_\lambda < 1.19$	HL
"universal" plus switch	both H: GR and G23 and L: 25 and G23	Market fuel with $0.89 < S_\lambda < 1.19$	HL
restricted: L- or H-gas	H: GR and G23 or L: 25 and G23	Market fuel with $0.89 < S_\lambda < 1.19$	H or L
restricted: one specific gas	GR and G25 fine tuning allowed	H: GR and G23 or L: 25 and G23	H_t or L_t or HL_t

Table 4: R49/03 HD vehicle classifications [2, 3]

* The gas quality parameter S_λ is described in section 3.2.

To what extend various biomethane (upgraded biogas) qualities fall within the vehicle specifications, and the type approval category (not necessarily the same!) requires detailed information regarding NGVs' type approval classification.

In section 6 the results regarding performance, efficiency and emissions will be discussed, of using biomethane fueled NGV's compared with its natural gas fueled counterparts.

5.4. ISO 15403 NGV fuel specification

Apart from the UN-ECE regulations R83 [1] and R49 [2,3] the NGV fuel specifications are also laid down in the ISO international standard 15403-2006, part 1 and 2. This standard can be used e.g. by the industry to specify the quality of the fuel to be used in e.g. NGV's, storage systems, filling stations etc.

In ISO 15403 natural gas is defined as a gas with more then $70\%_{vol,\ mol}$ methane, and a higher caloric value of 30-45 MJ/m^3. Furthermore Wobbe ranges from the German DVGW G 260/I and from the EN 437 are presented.

The ISO 15403 has recommended limits for moisture, dust, e.g. a recommend limit of $3\%_{vol}$ for both CO_2 and O_2 and a H_2S limit of $<5mg/m^3$.

In ISO 15403 the MN (methane number) is also presented, by means of a (simple) calculation as developed by the South West Research Institute. This calculation is quite accurate when validated using AVL data (ASTM D 2699-97) presented in the ISO 15403. However, when using a mixture of e.g. methane and 5% CO_2 and 5% N_2 the MN calculated by the SWRI method (90.7) seems incorrect, since both CO_2 and N_2 increase the knock resistance of pure methane. The value calculated by the TNO BiogasMax biogas calculation tool (106.3) seems more realistic. Further studies regarding MN calculation methods and tools fall outside the BiogasMax project.

The ISO 15403-2006 international standard, as NGV fuel specification, is of limited use when looking at NGV's performance, fuel economy and emissions.

6. Combination biomethane and NGV's

Since the objective of this BiogasMax task is to check how NGV's perform on biogas or biomethane (upgraded biogas) the combination biomethane and NGV's is studied for heavy-duty and light-duty NGV's separately.

6.1. Heavy-duty NGV fuel requirements

In this section the HD-NGV fuel requirements, expressed by both the lambda shift factor S_λ and the Sonic Bievo index, are presented; data is calculated using the BiogasMax biogas calculation tool.

	L-gas min	L-gas max	H-gas min	Methane	H-gas max
HD reference fuel	G25	G23	G23	G20	GR
Lambda shift factor (S_λ)	1.163	1.081	1.081	1.00	0.911
Sonic Bievo index	1.200	1.101	1.101	1.00	0.976

Table 5: HD-NGV's fuel requirements

Table 4 above again shows the difference between the lambda shift factor (S_λ) and the Sonic Bievo index, although both characterizing gas parameters are defined as 1.00 with pure methane. As explained in previous sections, for use in modern NGV's, equipped with engines with sonic (choked flow) metering devices (e.g. injectors) the Sonic Bievo index should be used.

From table 5 the following important conclusions can be made:

- HD-NGV's with "H" certification can use (bio)methane with 0.975 < Sonic Bievo < 1.101
- HD-NGV's with "L" certification can use (bio)methane with 1.101 < Sonic Bievo < 1.200
- HD-NGV's with "HL" certification can use (bio)methane with 0.975 < Sonic Bievo < 1.200

Note: in case the HD-NGV is using a venturi-based fuel system, the Wobbe index should be used.

6.2. Light-duty NGV fuel requirements

In this section the light-duty NGV requirements, are presented; key gas parameters are calculated using the BiogasMax biogas calculation tool.

	Minimum quality	Maximum quality (methane)
HD reference fuel	G25	G20
Lambda shift factor (S_λ)	1.163	1.00
Sonic Bievo index	1.200	1.00

Table 6: LD-NGV's fuel requirements

From table 5 the following important conclusion can be made: As long as the Sonic Bievo index of the (bio) methane is between 1.00 and 1.200 the can be used in all light-duty NGV's.

6.3. Examples of upgraded biogas

Below a number of estimated biomethane examples are compared regarding the Sonic Bievo index:

$\%_{vol,mol}$	Biomethane example 1	Biomethane example 2	Biomethane example 3	Biomethane example 4	100% Methane	Exceptionally low quality biomethane
CH_4	94	97	95.5	98	100	89.8
N_2	2	0.8	2	0_1	0	0
CO_2	2	2	2	2	0	10.2
H_2	1.5	0	0	0	0	0
O_2	0.5	0.2	0.5	0	0	0
Sonic Bievo	1.077	1.050	1.073	1.036	1.00	1.197

Table 7: Biomethane examples

First important conclusions:

- Table 6 shows, that if biogas will be upgraded to above presented estimated "normal" biomethane example qualities, all of these biomethane fuels can be used in HD-NGV's with "H" approval, as well as in HD-NGV's with the "HL" type approval. Exceptional low biomethane qualities, as presented in the last column, can be used in "L" approved, or "HL" approved HD-NGV's.
- Table 6 also shows that "normal" biomethane as well as the exceptional low quality of the last column, can be used in LD-NGV's since the Sonic Bievo index of all the biomethane examples falls between 1.00 and 1.200; which are the Sonic Bievo indices of G20 and G25.

6.4. Combination of biomethane and NGV's

In order to check the combination of various biomethane qualities with NGV (fuel) specifications, the Sonic Bievo index is developed by TNO. When applying this calculation methodology, together with nationally regulated biomethane qualities (see section 2.4) the following can be concluded:

Conclusion 1a (highest gas quality in combination with heavy-duty NGV's)

Because no other hydrocarbons like ethane, ethene, propane and butane are present in biomethane, the biomethane quality (expressed by the Sonic Bievo Index) will never be higher then that of pure methane. This actually means that the Sonic Bievo index of any biomethane will never be lower than 1.00

For this reason the highest possible biomethane quality will never exceed the (heavy-duty) maximum quality of the "H"- or "HL"-range, that equals Sonic Bievo index values from 0.975 - 1.101; see section 6.1.

Even in rare cases where a few percentages propane is added to the biomethane to boost the Wobbe index, the Sonic Bievo Index probably does not drop below 0.975, which means it can be used in HD-NGV's of the "H" or "HL" class as well. Please note that adding propane reduces the MN (knock resistance) significantly.

Conclusion 1b (highest gas quality in combination light-duty NGV's)

Because no other hydrocarbons like ethane, ethene, propane and butane are present in biomethane, the biomethane quality (expressed by the Sonic Bievo Index) will never be higher then that of pure methane. This actually means that the Sonic Bievo index of any biomethane will never be lower than 1.00

For this reason the highest possible biomethane quality will never exceed the (light-duty) G20 specification, which is pure methane, and which has a Sonic Bievo index of 1.00.

However, biomethane with a Sonic Bievo index below 1.00, e.g. in rare cases where a few percentages propane is added to the biomethane to boost the Wobbe index, this biomethane mixture will exceed the LD-NGV vehicle specification, see section 5.1. As a result performance, emissions and fuel economy will be outside the type approval values; even engine damage cannot be excluded!

Conclusion 2a (lowest gas quality in combination heavy-duty NGV's)

Assuming that the two main components of biomethane are methane (CH_4) and carbon dioxide (CO_2) an exceptional low biomethane quality is defined which has a Sonic Bievo index of 1.196, see table 6 in section 6.3 above.

Even this exceptional low biomethane quality, with a CO_2 content of approx. 10%, can be used in L or HL gas approved NGV's, since the L-range equals 1.101 < Sonic Bievo < 1.20

However, various national regulations limit the CO_2 content up to values like 2% up to 6% which means that the Sonic Bievo index of the specific biomethane qualities needs to calculated to see if this fuel requires a "L" of "HL" specified heavy-duty NGV, or a "H" or "HL" specified HD-NGV.

Conclusion 2b (lowest gas quality in combination light-duty NGV's)

Since both light-duty as heavy-duty NGV's use the same low limit regarding fuel quality (G25, with a Sonic Bievo index of 1.200) *biomethane qualities up to approx. 10% CO_2 can be used in all LD-NGV's as long as the Sonic Bievo is between 1.00 < Sonic Bievo < 1.20*

Conclusion 3:

The conclusions above indicate that expected biomethane qualities can be used in both heavy-duty as well as light-duty NGV's conform R49 [2,3] and R83 [1].

This means that using biogas (biomethane) will have no negative influence on NGV's performance, efficiency * and emissions.

* Note:

If the NGVs' fuel economy e.g. in the MVEG cycle is not represented in "energy" units like MJ/100 km, but in "mass" units like kg/100 km, the NGVs' fuel economy will off course vary in case fuels with different LHV (MJ/kg) will be used.

7. Conclusions and recommendations

7.1. Conclusions

Regarding the combination of biogas (biomethane) and light-duty and heavy-duty NGVs' fuel specifications, the following conclusions can be made:

- For modern NGV's with (sonic) fuel injection equipment, the "Sonic Bievo Index" has to be used, when comparing biomethane gas quality with the NGVs' fuel specification. All other key gas parameters like Wobbe index, R49/03 lambda shift factor (S_λ) and (subsonic) Bievo Index will lead to incorrect conclusions. Measurements were conducted that show the Sonic Bievo index correctly predicts the behaviour of different gas qualities in choked-flow gaseous fuel supply systems.
- Raw biogas will be upgraded to so called biomethane gas quality, following regional regulations. By doing so, this biomethane quality can be used in almost all NGV's without influence on the NGV's performance, fuel economy * and emissions:
    - "Regional regulated" biomethane qualities (with e.g. CH_4 content of approx. 95% or higher) can be used in all LD-NGV's as well as all HD-NGV's specified for the "HL" or "H" fuel range.
    - Even exceptional low biomethane quality (e.g. with a CO_2 content of approx. 10%) can be used in all LD-NGV's, but also in all HD-NGV's if designed for the L or HL fuel quality range.
    - Even the highest possible biomethane (upgraded biogas) gas quality will never exceed both light-duty as well as heavy-duty NGV fuel specifications. The exception is upgraded biogas with additional propane; in that case some LD-NGV's may run into problems. Exact calculation of the Sonic Bievo Index is required to check this combination.
- Using the new "Sonic Bievo index" it became clear that Dutch natural gas has approx. the same Sonic Bievo index as the lowest NGV reference fuel specification (G25). This means that in case the vehicle manufacturer has not designed sufficient extra margin in the fuel injection system, both in the hardware and the software, in combination with day to day variation of the (Dutch) natural gas quality, problems with NGV performance and/or emissions can occur.

* Note:

If the NGVs' fuel economy e.g. in the MVEG cycle is not represented in "energy" units like MJ/100 km, but in "mass" units like kg/100 km, the NGVs' fuel economy will off course vary in case fuels with different LHV (MJ/kg) will be used.

7.2. Recommendations

The following general recommendations are made:

- It is common practice to validate theoretical calculations by means of measurements in the "real world situation". In this case this would mean that it is recommended to validate the developed "Sonic Bievo Index" by means of NGV chassis dynamometer measurements using different fuels. The easiest way would be to use a LD-NGV and read the adaptive fuel trim value on different fuels using a universal OBD-tool.
- Following the theoretical "Sonic Bievo Index" calculations, it proves to be the case that Dutch natural gas is on the edge of the low limit of the fuel specification of both light-duty as heavy-duty NGV's. If this proves to be true (see remark above) a new low limit reference fuel needs to be defined, and introduced in both R49 and R83 type approval regulations.

8. References

[1] R83 from UN-ECE website: http://www.unece.org/trans/main/wp29/wp29regs81-100.html

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