INTERNATIONAL JOURNAL OF ENERGY RESEARCH
Int. J. Energy Res. 2003; **27**:467–480 (DOI: 10.1002/er.889)

Viability of LPG use in low-power outboard engines for reduction in consumption and pollutant emissions

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SUMMARY

This study presents the viability of the use of liquified petroleum gases (LPG) dosage systems in order to solve the fuel supply in four-stroke outboard engines in compliance with regulations concerning emissions of immediate application pollutants. Results obtained show an important decrease in specific fuel consumption (nearly 20%) provoking a small power loss (about 5%), with an extra saving when making use of bottled fuel, which does not suffer spills in the bunkers and maintenance operations. Laboratory tests have been carried out on 8 and 15 HP Yamaha outboard engines, obtaining reductions in pollutants (CO, HC and NO_x) of 60% and of 95% for each power, respectively. These trials have been contrasted with tests carried out in the Vigo estuary and the river Miño waterways, both located in the South of Galicia (Spain). Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS: LPG; outboard engines; pollutant emissions; fuel consumption

1. INTRODUCTION

Motorboats, particularly those involved in coastal fishing and pleasure boats, are responsible for high emissions of hydrocarbons to atmosphere and water, such as unburned or partially burnt fuel, carbon monoxide and nitrogen oxides.

Emissions of nitrogen oxides lead to acidification and contribute, together with organic compounds, to ozone formation in low layers of the atmosphere, causing local problems in air quality.

The US Environment Protect Agency (EPA) considers that carbon monoxide emissions tend to be concentrated in specific areas (ports, coastal areas and riversides) making pollutant levels excessive at those local points. Another aim concerns the reduction of emission levels for

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Contract/grant sponsor: Entity Portos of Galicia (Consellería of Territorial Politics Xunta of Galicia).
Contract/grant sponsor: The collaboration of the Companies Cepsa-Elf Gas,Yamaha, Zona, Franca de Vigo.

Received 2 October 2001
Accepted 13 February 2002

carcinogenic substances by 2005. This group includes aromatic polycyclic hydrocarbons, some of which are in outboard engine exhaust gases.

There are proven technologies for emissions reduction in the automobile world. At least three of them can be used in marine engines: electronic fuel injection systems, exhaust gas recirculation and 2- and 3-way catalysts (1). Electronic injection allows a more precise control of the mixture in each cylinder giving greater flexibility and accuracy to engine management. As an example, it can be said that Honda-marine works with multipoint injection while Yamaha uses carburetion systems in each cylinder in their mid-power range and electronic multipoint injection systems for higher powers (Sling, 1995; Yamaha, 1996). Nevertheless, the costs of these systems make them only applicable to higher power engines than those tested in this work.

Exhaust Gas Recirculation (EGR) is used to reduce NO_x significantly (EPA, 2000). Gas recirculation acts as a diluter in the mixture reducing combustion temperature. The lower temperature reduces NO_x formation with some increase in HC formation. Depending on engine load and the quantity of recycled gas, EGR can even reduce fuel consumption (EPA, 2000; McDonald and Gamulski, 1999). Although EGR is a widely used technique in automotive engines, and outboard engines generally stem from these engines, the EGR valve is usually eliminated.

The use of 3-way catalysts can provide great reductions in emissions, although there is the problem of seawater reaching the catalyst (EPA, 2000). In order to avoid this contact, the catalyst needs to be placed far from where exhaust gas mixes with cooling seawater. This will lead to very small catalysts losing a lot of the active surface needed. On the other hand, 3-way catalysts require a strict mixture control which can only be guaranteed by means of fuel injection systems which are not available in small engines such as those tested. The 2-way catalysts can be used with less mixture control although they can be damaged by thermal shock when the engine is immersed in water (McDonald and Gamulski, 1999; Sun et al., xxxx).

As all these alternatives are too expensive to be used in small engines, some other systems need to be developed in order to fulfil modern gaseous emission standards. The one chosen in this work is the use of a gaseous fuel.

LPG has been commonly used for more than 40 years as a fuel in ground-vehicles but never in outboard engines. The present viability study bears in mind the above context and it is conditioned by many factors such as: the environmental benefits, the distance that a craft can travel without refueling, the spread of existing distribution networks in certain areas, etc.

With this in mind, and considering specific problems of small craft on the Galician coast (Spain) the conversion of four-stroke gasoline engines to LPG has been considered, because these are becoming common among new craft and, as will be shown, are simple to adapt to LPG use.

As with most vehicles converted to LPG, the engines will be conditioned for operation with both fuels (dual operation). The adaptation of gaseous fuel dosage systems to two-stroke engines presents the difficulty of requiring the existence of a lubrication system separated from the fuel supply in the engine. Two-stroke engines without separate lubrication cannot be transformed by these means because of their need for a pulverized mixture of fuel and oil as their lubricating agent, the transformation of a two-stroke engine with a self-lubricating system would be very similar to that in a four-stroke.

For the selection of the engines models from which prototypes were made, the most common manufacturers in the fishing sector (in the Spanish area) were assessed. These were Evinrude, Honda, Suzuki and Yamaha. Yamaha has been the one chosen because of their complete range of powers up to 50 HP, and because of their 70% share in the current fleet. Thus their presence is guaranteed in the whole Autonomous Community of Galicia.

2. LIMITS OF APPLICATION

2.1. *European union requirements*

The work of the European Commission (EC) in the emissions field has been centered, so far, on limitations for different types of road vehicles and off-road diesel engines. The EU work on small craft exhaust gas requirements has not been declared high priority by the Commission.

However, some European countries have had such requirements for several years. The regulation dispositions of the Lago Constanza (Verordnung uber die Abgasemissionen von Schiffsmotoren au Schweizerischen gewassern, 1993) (also known as Bodensee) cover emissions from motorboat engines navigating on Lago Constanza and have been published jointly by Austria, two German federal States and a Swiss canton.

The Bodensee statements are considered some of the strictest emission regulations in the world, aimed at preserving the lake as a source of drinking water. This regulation limits the emission of gases (CO, NO_x, HC) from craft engines to very low levels. In fact the regulations are so rigorous that they are considered to be difficult to fulfil.

Furthermore, in recent years, Scandinavian countries have applied environment respect criteria to motorboat engines, by means of the SVAN mark system. This certification is voluntary and only one four-stroke engine maker fulfils it. There is no evidence that two-stroke or diesel engines use the SVAN trademark. The requirements concerning exhaust gas fit those based on the first stage of the Bodensee required regulations.

On the other hand International Council of Marine Industry Associations (ICOMIA) and the International Marine Engine Manufacturers' Committee (IMEC), present a proposal of required regulation referring to the requirements concerning noise exhaust gas in two stages, known as 'IMEC 1 and 2'. The marine industry, on its own, presented these required regulations to the Commission at the beginning of the nineties (DG III and XI). With this, new outboard engines should meet the limits of Directive 94/25/EC starting from January 1 1998 (COD, 2000). As regards ICOMIA, most two- or four-stroke outboard engines fail to fulfill this measure.

2.2. *United States requirements*

As for the United States, in November 1991 the EPA published the NEVES study (EPA, 1991) (EPAs Nonroad Engine and Vehicle Emission Study). Later, at the end of 1996, it proposed (EPA, 1996) the introduction of increasingly stringent requirements for application between 1998 and 2006 in both gasoline and diesel boat engines. The required regulations that will have to be applied in the US starting from the year 2006 largely correspond to the levels in the IMEC stage two, suggesting the same test method used for the IMEC requirements.

2.3. *Emission limitations for motorboat engines*

Carbon monoxide, hydrocarbon and nitrogen oxide emissions, according to Bodensee, should not exceed the limitations obtained by means of Table I, in which A, B and n are constant

Table I. Emission limits according to Bodensee.

	$g\,kWh^{-1}$			$g\,kWh^{-1}$			$g\,kWh^{-1}$		
Engine type	A	B	n	A	B	n	A	B	n
Two-stroke gasoline	150	600	1	39	100	0.75	10	0	0
Four-stroke gasoline	150	600	1	6	50	0.75	15	0	0
Diesel	10	0	0	1.5	2	0.5	10	0	0

Table II. Emission limits. European proposal based on EPA ($g\,kWh^{-1}$).

Motor type	NO_x	PM	HC	CO
Gasoline	15	—	6.4	145
Diesel	9.8	1.4	1.5	5.0

Table III. Emission limits. Four-stroke Outboard (M4 Tech Type) ($g\,kWh^{-1}$).

Power (HP)	HC	No_x	CO
0–3	121.2	4.93	585.0
3–11	29.71	5.20	585.0
11–25	18.36	7.98	454.7
25–50	20.0	10.0	454.7
50 –100	11.0	12.0	346.0
100 –175	10.0	12.0	346.0
> 175	10.0	12.0	346.0

according to the table and P is the engine output power in kW.

$$X = A + \frac{B}{P_N^n}$$

$$\text{where } X = \text{CO} \quad \text{or} \quad \text{HC} \quad \text{or} \quad \text{NO}x$$

The European Commission, in an attempt to harmonize its criteria with those established by the EPA, has proposed, in the latest Directive 94/25/EC, the emission limits for pleasure boat engines (diesel and gasoline) that are shown in Table II.

At the same time, in the United States gasoline pleasure boat engines can be included in the non-road limits with EPA regulation (EPA, 1995), seen in the pre-proposal of November, 2000 (EPA, 2000). These emissions, Table III, are generally higher than those admitted by Bodensee and the new European and EPA proposals.

On the 19th of September 2000, the '2000 Workshop, California Air Resources Board' (EPA, 2000) proposed standards of 9,4 $g\,kW\,h^{-1}$ for $HC + NO_x$ and 134 $g\,kW\,h^{-1}$ of CO for the year

2003, and of 4 g kW h^{-1} for HC + NO$_x$ and 50 g/ kW h^{-1} of CO for the year 2007. These can be shown to be very restrictive.

As for proposals on LPG use in four-stroke engines, the NEVES study proposes emissions that surpass the requirements established by the European and American directive boards. These emission limits proposed by NEVES for internal combustion engines can be reached with the non-dual use of fuels and they are those shown in Table IV.

3. EXPERIMENTAL INSTALLATION

3.1. Equipment

A series of outboard engines, those usually used in fishing operations by small craft or by pleasure boats, have been tested in this work.

The engines have been placed on a test bench composed of a hydraulic brake and equipped with the appropriate instruments to monitor and measure the variables of interest. The standards applied in these tests are ISO 3046 and ISO 8178 (ISO, 1996), which describe the measurement and declaration methods for performance and exhaust gas emissions for non-road engines. The main characteristic of the tested engines are shown in Table V.

The test type has the aim of obtaining comparative behaviour curves, for power, torque, consumption and emissions from the different engines when they work with gasoline or with commercial LPG (butane with a $< 12\%$ propane content)—The measurement instruments used in the study are those given in Table VI.

3.2. Test conditions

For the proper execution of this study, it has been necessary to design a device that allowed the use of commercial gas dosimeters in outboard engines. These membrane dosimeters provide a

Table IV. NEVES emission limits.

Engine type		NO$_x$(g HP h^{-1})	PM(g HP h^{-1})	HC(g HP h^{-1})	CO(g HP h^{-1})
Pleasure	LPG	5.25	0.06	3.19	84.27
(<25 HP)	Gasoline	3.50	0.06	5.2	409
Great SI	LPG	11.99	0.06	1.68	28.23
(> 25 HP)	Gasoline	7.13	0.06	6.22	203.4

Table V. Characteristics of the tested engines.

Engine type	Outboard 4 stroke	Outboard 4 stroke
Manufacturing	Yamaha	Yamaha
Model	F 15 AMHL	F 8 BMHL
Diameter/stroke (mm)	59/59	59/42
No. of cylinders	2	
Cylinder capacity (cm^3)	323	232
Denomination	15HP xx (gasoline or butane)	8 HP xx (gasoline or butane)

Table VI. Instruments used.

Gas Analysers	
	Horiba Mexa 574GE NDIR
	Horiba FIA-510 CLD
	Horiba CLA-510SS FID
	Gases preparation equipment
Apparatus	
	Load control—extensiometric band
	Hydraulic brake—Marine 2000
	Electronic load regulator
	Data acquisition cards: National Instruments
	Measure indicators and transducers

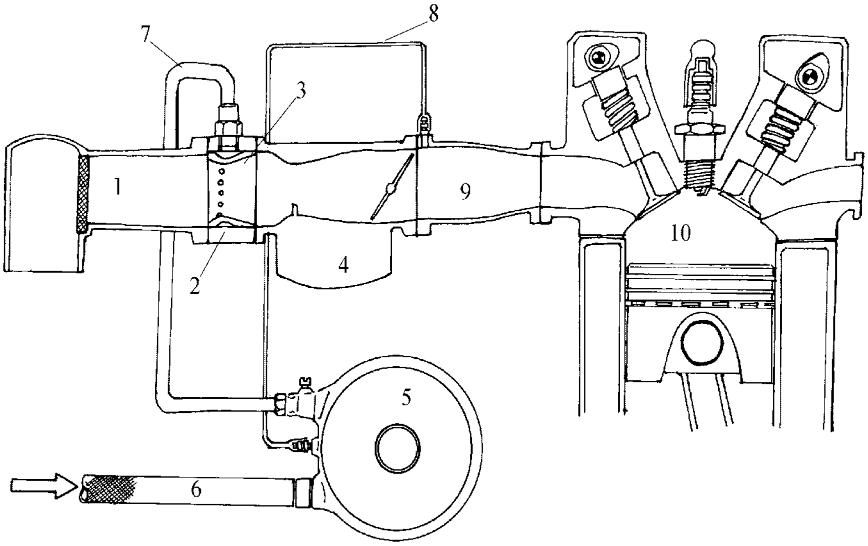


Figure 1. LPG system. 1—intake manifold (original); 2—diffuser support; 3—diffuser; 4—carburetor (original); 5—dosing device; 6—gas intake; 7—supply line to the engine; 8—idling gas line; 9—manifold (original) and 10—engine.

gaseous mixture that will enable a decrease in consumption and a higher stability of the fuel–air ratio against the temperature variations during engine operations. Furthermore, it guarantees easier operation during engine starting and running at idle speed. These devices require the use of a diffuser with several orifices in order to guarantee the homogeneity of the mixture.

The standard solutions found are only suitable for automobile engines. That is the reason why a new system had to be developed. This system is composed of a new intake manifold that incorporates the diffuser and different gas-lines that will be used to carry out the regulation of the mixture. These devices are represented in a schematic way in Figure 1.

The Lovato dosimeter used, serves a double function: the reduction of the supply pressure and the gas dosage to the air. Thus, it has two pressure measuring points, one located in a diffuser before the carburetor and the other after the throttle gas that allows better regulation of starting and idling.

Table VII. ISO E-4 performance and weighting factors.

Mode number	1	2	3	4	5
Speed %	100	80	60	40	Ticking over
Torque%	100	71.6	46.5	25.3	0
Weighting factor	0.06	0.14	0.15	0.25	0.4

During the engine tests LPG is extracted in gaseous phase so that, unlike gasoline, LPG should evaporate inside its tank before being supplied to the engine. Thus, the LPG in liquid phase demands heat to undergo its evaporation, so tending to reduce the tank's global temperature. If this heat is not given from the outside, the cooling effect of the evaporation process would be able to reduce the pressure available inside the tank below that needed in the dosimeter. Several tests have been carried out to determine the capacity of commercial LPG gas tanks to supply the characteristic demand from engines chosen, obtaining satisfactory results.

3.3. Emissions tests according to ISO

For the declaration of pollutant emissions, norm ISO 8178 will be applied (ISO, 1996), where the trial procedures and pollutant emissions declarations for marine engines are specified (among others).

In the case of the spark-ignition engines for pleasure boats under 24 m long, the E4 test cycle will be applied whose performance and weighting factors are shown in Table VII:

Each performance corresponds to a point of operation of an engine moving a legal propeller:

$$T = kN^{1,5}$$

where T is the torque, N is the engine speed and k is a constant characteristic of each propeller.

The ISO standard demands, in the case of marine engines (cycles E), that the text is also developed in the upward order of the mode number.

With the concentration data for each component in the exhaust gas for each performance mode and with the value for specific fuel consumption, the mass flow rate of each component is obtained. This mass flow rate is weighted for each performance mode and measured power according to the expression

$$M_{\mathrm{GASi}}\left(\mathrm{g\ kWh}^{-1}\right) = \frac{\sum_{7=1}^{n} M_{\mathrm{GASi}}\left(\mathrm{g\ h}^{-1}\right) W_{Fi}}{\sum_{7=1}^{n} P_i(\mathrm{kW}) W_{Fi}}$$

where the W_{Fi} weighting factors will grant more or less importance to the emissions in each performance mode giving rise to a typical cycle used in marine applications. Thus, a unique value is obtained for specific emissions that will be the value subjected to various limitations that exist.

4. RESULTS

4.1. Engine performance

As it was initially supposed, outboard engines shown full capacity to work with LPG. This was deduced from the experimental data given below.

For the comparison of the engine characteristics, tests were carried out in the typical range of engine speed. A representative mode for comparison is engine's maximum power, where the differences obtained in the different motorizations can be clearly noticed. These differences are shown in Table VIII.

Once these tuning-up tests were carried out at different loads, specific tests for the determination of emissions according to ISO 8178 (ISO, 1996) were also done.

In Table VIII, it can be seen that with the use of commercial butane small decreases of power and torque took place in the 15 HP engine, while in that of 8 HP power remained almost the same. This reduction is quite in agreement with the references consulted (Lovato, 1999). The consumption decreases dramatically by between 15 and 25% in both cases, as shown in Figure 2.

Table VIII. Engine performance.

Engine 8 HP			
	Gasoline	Commercial butane	Variation (%)
100% load (5250 rpm)			
Max. power kW (HP)	6.02 (8.2)	6.06 (8.25)	0.6
Consumption (g kWh^{-1})	432	362	−16.3
Torque (N m)	10.49	10.58	0.86
Engine 15 HP			
100% load (5500 rpm)			
Max. power kW (HP)	11.15 (15.16)	10.55 (14.34)	−5.04
Consumption (g kW h^{-1})	427	311	−27.2
Torque (N m)	19.31	19.11	−1.03

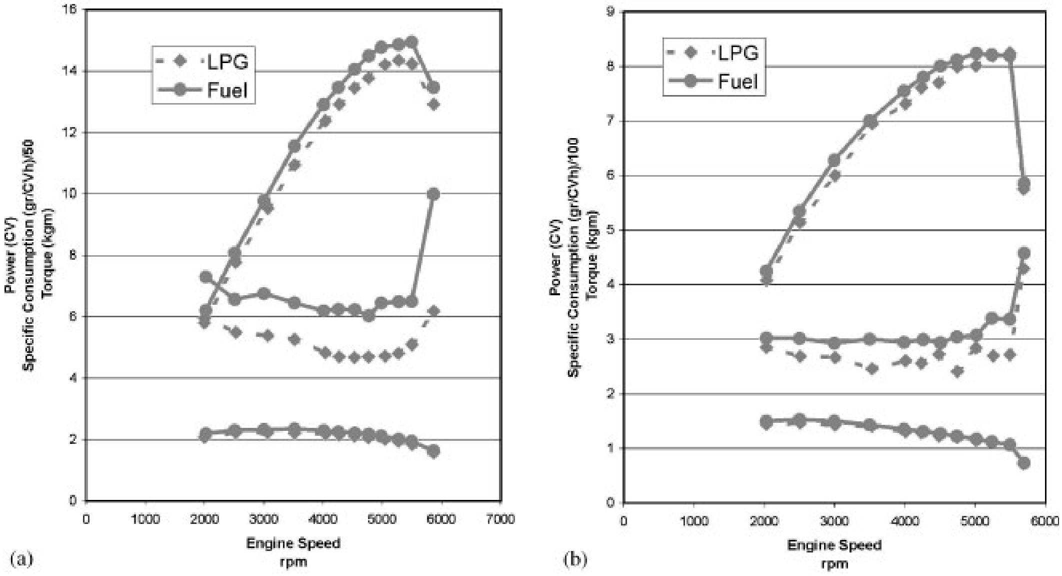


Figure 2. Engine performance at WOT. (a) Yamaha 15 CV and (b) Yamaha 8 CV.

An important operation mode for the manual fishing sector is the idling consumption, because in fishing tasks the engine usually remains at idle speed for hours instead of being stopped. Eventually the engine is accelerated abruptly to reach the areas where manual fishing operations continue. Thus several tests to check and optimize this aspect were carried out with very satisfactory results (Table IX).

It was observed that the loss of power was accentuated in the areas at medium and low speed with high throttle angles. The imperfect adaptation of the system chosen to all the load and speed combinations seemed to be the explanation of this effect. Nevertheless, in marine applications the engine find a direct relationship between its speed and load. This relationship is imposed by the propeller law. For this reason, the operation with high throttle angles at low speed should not be considered. Thus the system's overall behaviour does not represent a reduction in engines performance in its marine application.

The specific consumption maps, Figure 3, shown that at medium and high throttle angles, the consumption remains stable with both fuels. The maximum power-specific consumption peak

Table IX. Consumption and idling cost (15 HP engine).

Mean consumption	
LPG	0.391 Kg h^{-1}
Gasoline	0.511 Kg h^{-1}
Fuel cost ('2000 average)	
LPG	0.577 kg
Gasoline	1.149 kg
Expense	
LPG	0.225 h^{-1}
Gasoline	0.587 h^{-1}

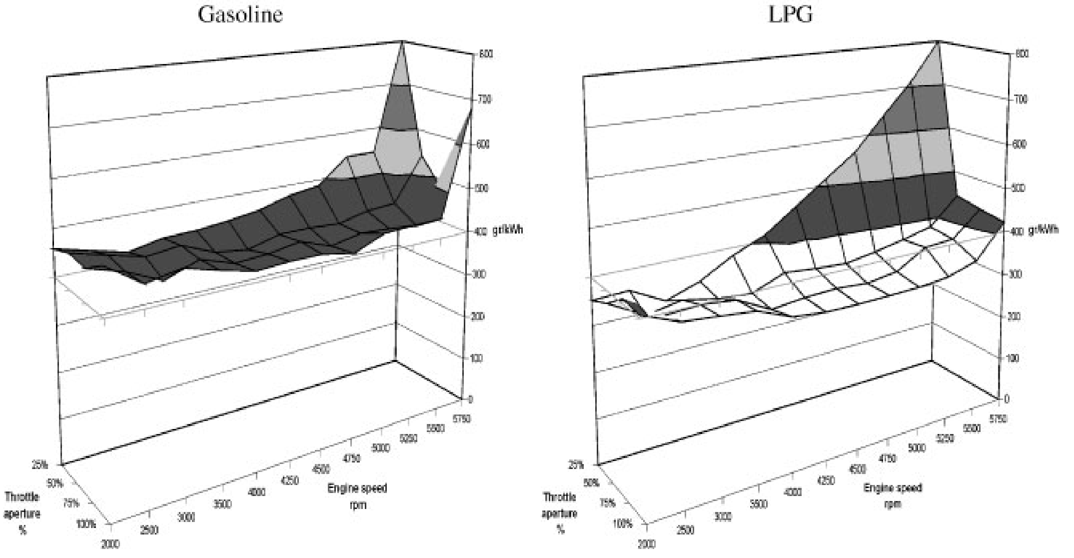


Figure 3. Specific fuel consumption map (Yamaha 15 CV).

experimented in the gasoline version is not present in LPG models. Therefore, it can be said that in this range, LPG-specific consumption is between 15 and 25% less than gasoline-specific consumption.

On the other hand, high LPG-specific consumption at low throttle angles can be explained with the arguments exposed before. The imperfect adaptation of the system developed to every combination of load and speed.

4.2. *Gaseous emissions*

The tests carried out on outboard engines and the bibliography consulted (Brown, 1999; Anon, 1971; BIA, 1975; Butcher, 1982; English *et al.*, 1963; Juettner *et al.*, 1995; Shuster, 1971) coincide with the difficulty of gasoline carburetor engines to fulfil recent strict standards. Usually the problem is the non-fulfillment of the CO specific emission.

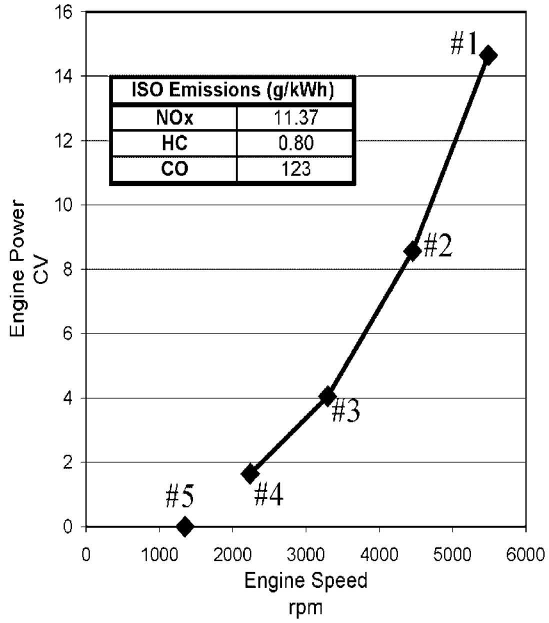
It can be seen from Tables X and XI that the use of LPG fulfils the requirements thanks to an 80% reduction in carbon monoxide emission by the use of commercial butane. At the same time, the almost total oxidation of CO into CO_2 leads to better thermal performance which helps with the 16.2% specific fuel consumption. A remarkable increase in the NO_x emissions took place.

Table X. 8 HP benefits and emissions.

ISO 8178 Cycle E4	Gasoline	Commercial butane	Variation (%)	
Max. power kW (HP)	6.02 (8.2)	6.05 (8.25)	0.6	
Consumption ($g\,kWh^{-1}$)	432	362	−16.2	
CO ($g\,kWh^{-1}$)	442.8	85.8	−80.6	
HC ($g\,kWh^{-1}$)	0.87	1.54	77	
NO_x ($g\,kWh^{-1}$)	4.12	7.41	+180	
	Limit (g kWh−1)		Bodensee	EPA
CO	NO	YES	252	145
HC	YES	YES	19.04	6.4
NO_x	YES	YES	15	15

Table XI. 15 HP benefits and emissions.

ISO 8178 Cycle E4	Gasoline	Commercial butane	Variation (%)	
Max. power kW (HP)	11.15 (15.16)	10.54 (14.34)	−5.8	
Consumption ($g\,kWh^{-1}$)	426.8	310.9	−27.2	
CO ($gwkWh^{-1}$)	484.12	122.99	−74,6	
HC ($g\,kWh^{-1}$)	0.87	0.80	−8	
NO_x ($g\,kWh^{-1}$)	3.36	11.37	+230.4	
	Limit (g kWh)		Bodensee	EPA
CO	NO	YES	204.5	145
HC	YES	YES	12.28	6.4
NO_x	YES	YES	15	15



	Yamaha 15 CV LPG				
Mode	**#1**	**#2**	**#3**	**#4**	**#5**
Power (CV)	14.65	8.56	4.05	1.64	0
Specific Fuel Consumption (g/CVh)	228.6	241.5	282.8	688.1	[391 g/h]
NOx (ppm)	2654	1650	516	254	74.4
HC (ppm)	248	201	157	293	522.5
CO (% vol)	0.53%	0.04%	0%	3.75%	9.10%
A/F	14.36	15.27	16.74	13.61	12.53

Figure 4. ISO E4 cycle emission data (Yamaha 15 CV LPG).

Figures 4 and 5 show ISO E4 cycle for LPG and gasoline.

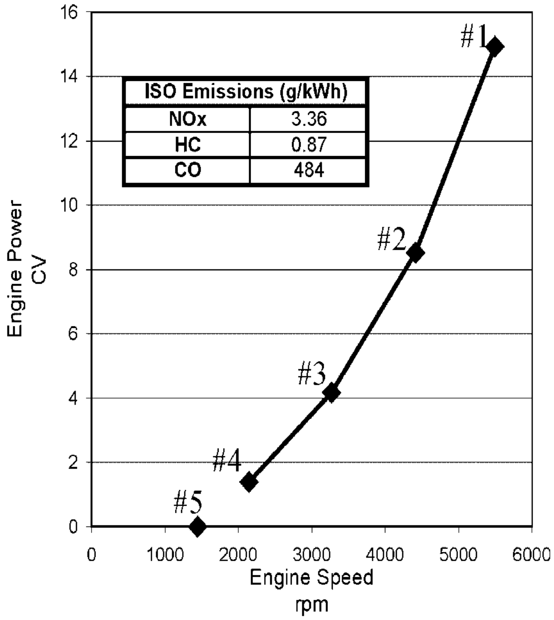
In both engines chosen in this work the same results were noticed. A great reduction in CO-specific emission with a controlled increase in NO_x emissions were found.

Although this remarkable increase in the NO_x emissions takes place as a consequence of the higher performance and expected temperature of the combustion process, the very low emission of carbon monoxides allows a wide range of variation of the fuel–air mixture in order to obtain a great CO reduction without exceeding NO_x limits.

Figure 6 shows CO vs NO_x emissions. Figure 7 shows CO vs engine speed at WOT

5. CONCLUSIONS

As a conclusion of the study the following points can be remarked: With the use of LPG fuel in small power outboard engines, fuel consumption decreased by about 20% and a reduction in emissions greater than 60% is obtained.



	Yamaha 15 CV Fuel				
Mode	**#1**	**#2**	**#3**	**#4**	**#5**
Power (CV)	14.92	8.52	4.17	1.39	0
Specific Fuel Consumption (g/CVh)	313.8	302.5	414.2	662.7	[511 g/h]
NOx (ppm)	346	509	177	175	147
HC (ppm)	309	252	249	224	318
CO (% vol)	8.41%	5.47%	9%	5.21%	9.90%
A/F	11.63	12.3	11.37	12.24	11.64

Figure 5. ISO E4 cycle emission data (Yamaha 15 CV Gasoline).

LPG engine emissions are located below the limits demanded by the studied standards, while the gasoline version doubles the value allowed for carbon monoxide emissions. It can also be observed that although nitrogen oxides increase, these stay reasonably below those authorized. The loss of power experienced by the gas engines is not significant and allows the engines to be used for the same applications as the gasoline version.

The increase in NO_x emissions can be controlled by mixture proportion in a certain way, leading to a small increase in CO emissions, where a certain operational margin exists.

The specific requirements of certain fishing techniques that demand stable idling performance and low fuel consumption seem to fit perfectly with the system developed in this work, where the special properties of gaseous fuels find their best use.

The disappearance of spills in bunker operations as a consequence of the nature of the gas itself and of the bottled system can also be taken into account, a fact that would be shown clearly in places with a concentration of craft. This would decrease pollutant flow into marine areas used for coastal operations (seafood catching, fishing, etc.) as well as in ports, pleasure marinas, and in reservoirs or internal waters used for reception and supply of drinking water.

Finally, from the above data for consumption, and in view of the current price of domestic butane, reductions of over 50% could be obtained in operating costs, meaning savings of

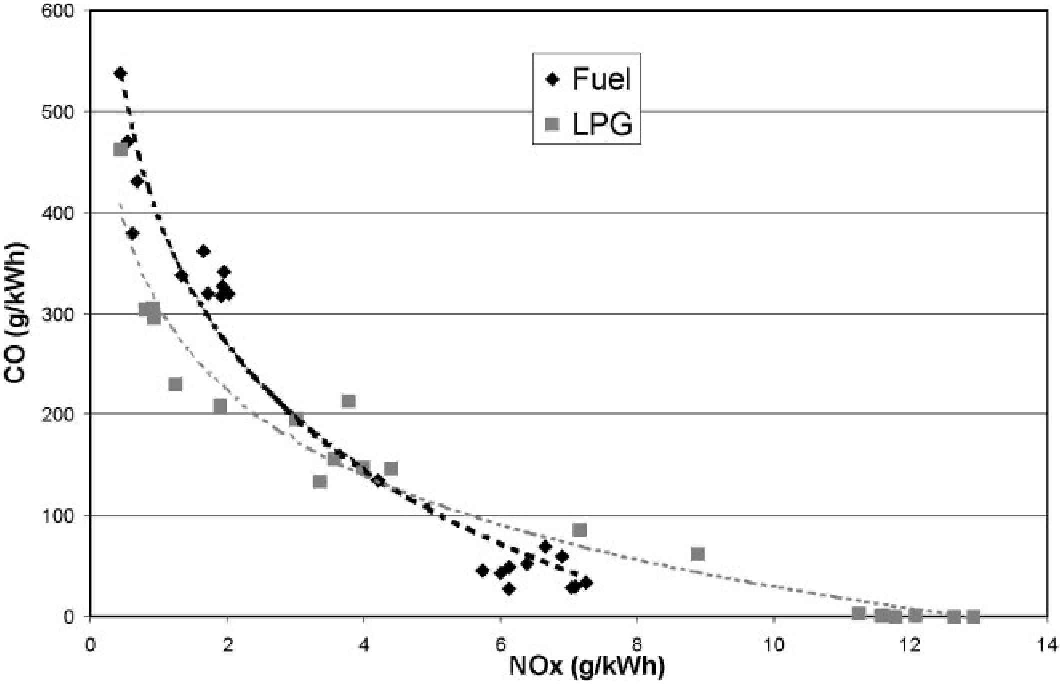


Figure 6. CO vs No_x emissions.

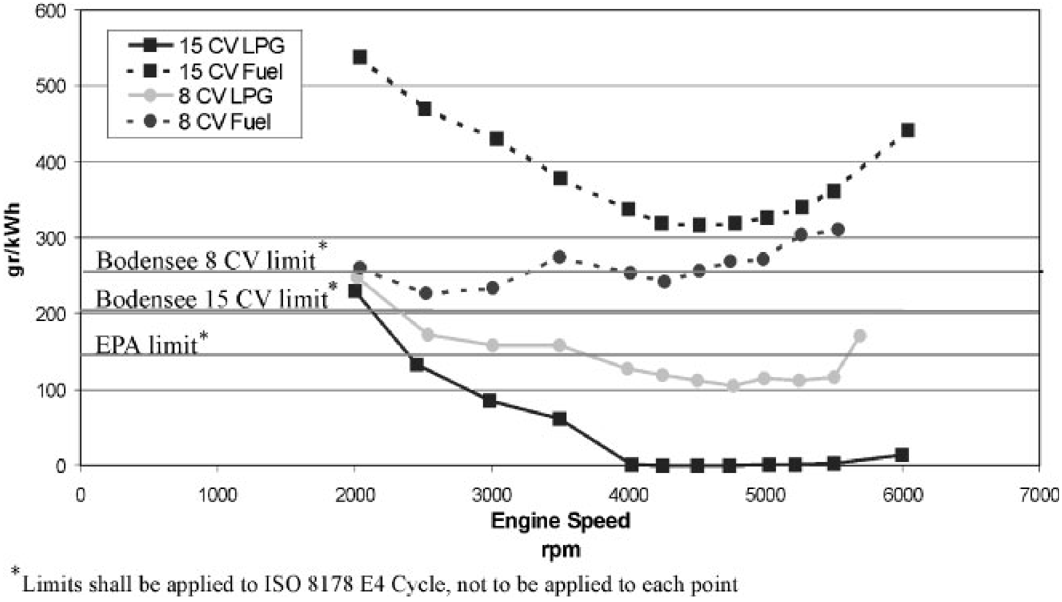


Figure 7. CO vs engine speed at WOT.

between 1.8 and 3 Euros per hour worked depending on engine type and use, which represents an important stimulus for the development and installation of this technology in craft with outboard engines.

ACKNOWLEDGEMENTS

We must thank the financing of the project by the Entity Portos of Galicia (Consellería of Territorial Politics Xunta of Galicia) and the collaboration of the companies Cepsa-Elf Gas, Yamaha, Zona Franca de Vigo.

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