CONSUMPTION AND POLLUTANT EMISSIONS OF LIGHT DUTY VEHICLES USING ALTERNATIVE FUELS

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ABSTRACT

One of the biggest challenges that the transport sector faces currently is to find alternative ways to fuel the vehicles and keep providing the same mobility level. Whatever this new energy source/vector technology is (either biofuels, natural gas, hydrogen, electricity…) it has to be able to address the major environmental concerns. Not only must it contribute to the diversification of energy sources but it also should decrease global GHG emissions and attenuate the levels of local pollution.

Fuels that can be used as direct replacement for conventional Diesel or gasoline are particularly interesting as they require minimal changes to vehicle technology and, depending on the fuel, on the distribution network. This is the case of the two fuels analyzed in this work: ethanol and natural gas, that can be used in Otto cycle engines that remain compatible with regular gasoline.

The light duty vehicles measured were a flex fuel (gasoline/ethanol) car and a bi-fuel (gasoline/natural gas) car. The two vehicles are monitored during regular operation using a Portable Emissions Measurement System (PEMS). The system was developed around a portable gas analyzer, an on-board diagnostics (OBD) reader, a GPS receiver and a logging computer. All vehicles were measured on the road during regular operation. The laboratory developed was able to monitor the vehicles in real time and measure and record the dynamic profile, topography and tailpipe pollutant emissions with a frequency high enough (1 Hz) that an evaluation of instantaneous emissions of carbon monoxide (CO), nitrogen oxides (NO_x) and unburned hydrocarbons was possible.

To compare the different vehicles and fuels the vehicle specific power (VSP) methodology was used, where different operating conditions are grouped in homogeneous bins of similar power demand. An analysis was made on the relative performance of each fuel/technology in different operating modes regarding energy consumption (engine efficiency) and pollutant emissions (NO_x, CO and HC).

Keywords: Alternative fuels, PEMS, Light duty vehicles

INTRODUCTION

The biggest challenge that the transport sector faces currently is to find alternative ways to fuel the vehicles and keep providing the same mobility level. Whatever this new energy source/vector technology is (either biofuels, natural gas, hydrogen, electricity…) it has to be able to address the major environmental concerns, and not only must it contribute to the diversification of energy sources but it also should decrease global greenhouse gas (GHG) emissions and attenuate the levels of local pollution.

Current methodologies for emissions regulations from vehicles calculate pollutant emissions based on pre-defined drive cycles that are run on test benches. This is the case for Euro regulations and those used in the United States and Japan. This way it is possible to compare all vehicles under similar conditions. But these results are not representative of typical driving situations.

The only way to actually know what the emissions during regular driving are is to measure the vehicles during operation using a so-called PEMS – Portable Emissions Monitoring Systems. These systems measure in real time and simultaneously the dynamic parameters of the vehicle, engine parameters and pollutant emissions.

The increasing interest in the use of alternative fuels for conventional vehicles (both in Europe and the United States) introduces one additional dimension to the issue of fuel consumption and emissions, as the one aspect that up to now had remained fairly unchanged – fuel used, Diesel or gasoline - is now one of the main variables.

Several authors have worked on the evaluation of the energy and environmental implications of the use of alternative fuels in vehicles, considering the life-cycle implications on pollutant emissions (Beer 2007, Hu 2004, MacLeana 2003) and the impact on vehicle use, using different methodologies to measure emissions: chassis dynamometers (Leonga 2002, Schifter 2004, Durbin 2008), engine dynamometers (Aslam 2006), sampling methods (Corrêa 2005, Nakagawa 2005) or remote sensing (Pokharel 2002).

Of the results reported some are particularly relevant to the present work, namely: HC reductions using E15 (Leonga 2002), CO and HC reductions using CNG (Durbin 2008, Aslam 2006) and similar to higher emissions of NOx using CNG (Durbin 2008, Aslam 2006)

Of significance here is that none of these tests were conducted during the regular operation of the vehicle, and authors who performed test on the road using PEMS and conventional fuel vehicles (Pelkmans 2006, Collins 2007) have concluded that some of the emissions measured in the certification cycle differed dramatically from the real traffic emissions.

The significance of Portable Emissions Measurement Systems (PEMS) is that by measuring emissions during real world driving, they eliminate reliance on the artificial driving cycles necessary for use during laboratory dynamometer measurements.

It is then the objective of this paper to present an evaluation of the energy and environmental characteristics of alternative fuel vehicles under regular operation conditions and compare these characteristics with those of similar conventional fuel vehicles for different ethanol/gasoline mixtures and compressed natural gas (CNG). Results are presented for energy consumption, tailpipe pollutant emissions (NO, CO and unburned hydrocarbons – HC) and tailpipe CO_2 emissions. This final result does not provide a complete picture on the

GHG emissions, as for this a complete well-to-wheel analysis must be performed, and that analysis falls outside the scope of this work.

METHODOLOGY

The main components of the monitoring system used in this work are presented in Figure 1.

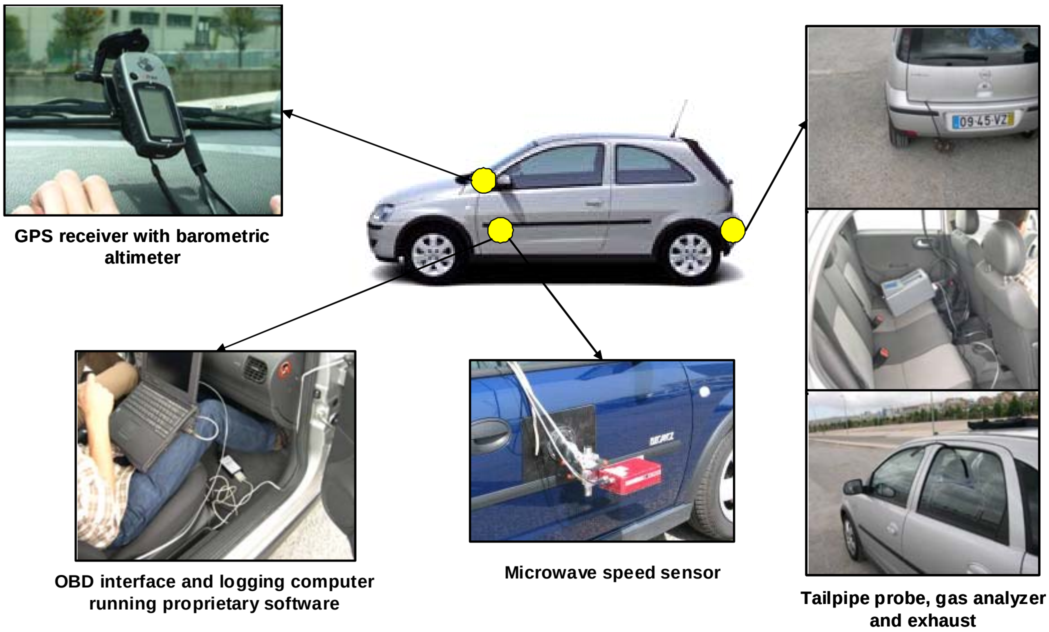

Figure 1 – Components of monitoring system

The monitoring system is built in a way that all sensors and sources of information mentioned here can be connected, and thus providing greater flexibility to the measurements. As a result, the same information can be obtained from a number of different sources. In that event the different sources of information will be compared. All the information is collected in one computer running software specifically designed for this application. As so, the signals must reach the computer either through a serial communications port or via the data acquisition board. Proprietary interfaces are of no use as it would not be feasible to synchronize the signals for all devices if several different programs were used. The preferred communications method is the serial port. When a raw signal is used, either an analog signal or a pulse signal, a data acquisition board (DAQ) is needed. The DAQ used in monitoring system is manufactured by Ontrak Control Systems, model ADU100. The signals to be collected are:

Dynamic profile – obtained using information from the OBD port (using a Harrison R&D OBDScan/CANScan), GPS receiver (eTrex Vista and GPSMap 76CSx) or dedicated speed sensor (Corrsys-Datron model M3).

Engine Operating Parameters - obtained using information from the OBD port, the most relevant parameters (for the purpose of calculating pollutant emissions and fuel consumption) are speed, rpm and air flow.

Topography - obtained using information from the OBD (includes a barometric altimeter)

Gaseous emissions - The gas analyzer adopted is produced by Vetronix Corporation, works on 12V and weights ca. 6 kg. This analyzer uses an NDIR cell (Non-Dispersive Infrared) for CO, CO_2 and HC measurements and separate electrochemical sensors for oxygen and NOx. The analyzer is calibrated on a regular basis and zeroes itself on startup using outside air. Zeroing is also requested during measurements at regular intervals. Specifications are presented in Table 1.

Table 1 – Specifications of the gas analyser used.

Gas	Range	Resolution	Accuracy
HC	0-20,000 ppm	1 ppm	6 ppm greater than absolute or 5% of reading
CO	0-10%	0.01%	0.06% greater than absolute or 5% of reading
CO_2	0-20%	0.1%	0.5% greater than absolute or 5% of reading
O_2	0-25%	0.01%	0.01% greater than absolute or 5% of reading
NO_x	0-4000 ppm	1 ppm	32 ppm at 0-1000 ppm 60 ppm at 1001-2000 ppm 120 ppm at 2001-4000 ppm

The integration of all the signals is made using a laptop computer running specifically designed software for this purpose. The data is collected in text files and then exported to an Excel spreadsheet in order to calculate mass emissions based on air and fuel flow and exhaust gas composition. The road grade is calculated from the collected altitude profile. The barometric altimeter has a resolution of approximately 0.5 meters, and moving average of the values was used to obtain a smooth profile.

Two vehicles were tested, both with spark ignition engines, one flexfuel (gasoline/ethanol) vehicle and one bi-fuel (gasoline/natural gas) vehicle (**Figure 2**). Specifications for the vehicles tested are presented in Table 2. When tested the vehicles had different mileages, the VW Golf bi-fuel model had approximately 5 years, having been used as a taxi and is property of APVGN (Portuguese Natural Gas Vehicle Association). The Ford Focus Flex was kindly lent by Ford Portugal. During the tests the vehicles carried on board the driver, one operator and the measuring equipment for an extra total weight of ~150kg. Both vehicles had air conditioning, which was used on to maintain the level of comfort on board. The properties considered for the fuels used in the trials are presented in Table 3. In the Ford Focus Flex trials three fuels were used, gasoline, E24 (24% ethanol, 76% gasoline) and E85 (85% ethanol, 15% gasoline).

Figure 2 - Vehicles tested: Ford Focus Flex (left) and VW Golf bi-fuel (right)

Table 2 – Specifications of vehicles tested

	Ford Focus Flex	VW Golf bi-fuel (gas)	VW Golf bi-fuel (NG)
Curb weight (kg)	1351	1505	
Engine Displacement (cm3)	1798	1984	
Engine Type	4L, 16V	4L, 8V	
Max Power (kW/rpm)	92/6000	85/5400	75/5400
Fuel	Gas/Ethanol	Gasoline	Natural gas
Emissions standards	Euro IV	Euro III	
Transmission	Manual, 5 speed		
Mileage when tested (km)	<5,000	~90,000	

Table 3 – Properties of fuels considered in calculations

	Gasoline	Ethanol	E24	E85	Natural gas (methane)
Chemical Formula	C_8H_{15}	C_2H_5OH	-	-	CH_4
Reference density [kg/m3 @ 15ºC]	750	790	744	780	0.717
Octane Number (RON)	95	107	-	100	120
Vapor Pressure [kPa @ 38ºC]	48-103	15.9	-	-	n.a.
Stoichiometric Air/Fuel ratio [kgair/kgfuel]	14.5	9.0	13.1	9.7	17.2
Typical Lower Heating Value	44.0 MJ/kg 33.0 MJ/l	27.0 MJ/kg 21.3 MJ/l	39.2 MJ/kg 29.2 MJ/l	29.1 MJ/kg 22.7 MJ/l	50.0 MJ/kg 35.9 MJ/m3

The vehicles were tested on the open road and were subject to regular traffic conditions.
The route selected was driven twice for each vehicle and fuel combination, for a total of approximately 128 km for each combination of vehicle and fuel (VW Golf bi-fuel using gasoline and compressed natural gas - CNG, Ford Focus flex using gasoline, E24 and E85) for a total of approximately 640km. In all the trials the cars were driven by the same two drivers, and each drove in the same sectors. Traffic conditions cannot be considered equal on all test runs as average speeds varied considerably.
In order to ensure correct operation of the gas analyzer, monitoring was stopped approximately every 16 km and the gas analyzer was purged and zeroed.

The route selected consists of a trip from Lisbon to Cascais and return and a mixed route was selected comprising:

- Urban traffic inside Lisbon (ca. 6 + 6 km)
- Highway traffic (ca. 8 + 8 km)
- Mixed national road/urban traffic up to and inside Cascais (ca. 18+18 km)

A sample of the topography profile is presented in **Figure 3**. As can be seen, the highway portions are very hilly (approximately km 5 to 15 and 50 to 60), and this allowed that even if the driving was made on open roads, combinations of high speeds and loads where measured. The mixed route is relatively flat with low average speeds.

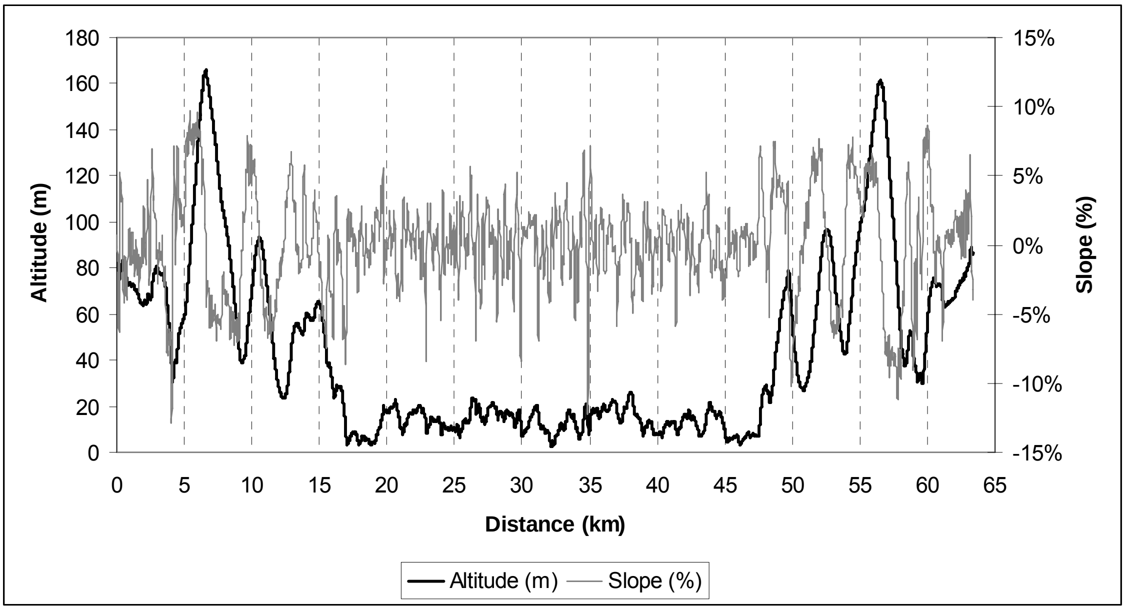

Figure 3 – Topography profile

When collecting data from on-road measurements, due to the variability of driving conditions, it is very difficult (unlike with test bench measurements) to correlate specific events with emissions and obtain enough data for statistical validation and compare different vehicle performances as well as driving behaviour. The engine while providing a specific amount of mechanical energy to vehicle is in fact not “aware” of what the car is doing, and from the perspective of power output, accelerating, driving uphill or cruising at high speed can all have the same power requirements. Similarly, decelerating, braking or going downhill with no throttle applied and with vehicle in gear will very likely result in a fuel cutoff situation, while the vehicle could even be accelerating at high speed if going downhill. With this in mind it is useful to have a methodology to identify those points that correspond to similar operating conditions or power outputs and group them.

The methodology selected for this comparison is VSP – Vehicle Specific Power (Zhai 2007), a modelling methodology that takes into account aerodynamic drag, tire rolling resistance and road grade in order to calculate power per unit mass of the vehicle and is a function of vehicle speed, acceleration, and road grade. The VSP methodology allows the construction for a vehicle of the equivalent of an emissions and fuel consumption map of the engine. In this case VSP groups all different driving situations that require the same power from the engine, the higher the VSP mode the higher the power output of the engine. Power output is a product of rpm and load, and generically speaking higher VSP modes are a result of both high rpm and load.

The equation used to calculate VSP at each measured second was:

$$VSP = v \times (a + g \times \sin(\varphi) + 0.132) + 0.000302 \times v^3$$

Where:

- VSP is vehicle specific power (m2/s3);
- v, a and φ are the instantaneous speed (m/s), acceleration (m/s2) and inclination (rad) of the vehicle;
- 0.132 is the rolling resistance term coefficient;
- 0.000302 is the aerodynamic drag term coefficient.

VSP was estimated for each second of measured in-use data. The VSP values calculated are then grouped in modes that provide an homogeneous distribution across the most common driving modes (Table 4).

Table 4 – VSP modes

VSP Mode	VSP Range (m^2/s^3)	VSP Mode	VSP Range (m^2/s^3)
1	$VSP < -2$	8	$13 \leq VSP < 16$
2	$-2 \leq VSP < 0$	9	$16 \leq VSP < 19$
3	$0 \leq VSP < 1$	10	$19 \leq VSP < 23$
4	$1 \leq VSP < 4$	11	$23 \leq VSP < 28$
5	$4 \leq VSP < 7$	12	$28 \leq VSP < 33$
6	$7 \leq VSP < 10$	13	$33 \leq VSP < 39$
7	$10 \leq VSP < 13$	14	$39 \leq VSP$

RESULTS AND DISCUSSION

The average values for each fuel used are presented in Table 5 and Table 6.

Table 5 - Summary of results for the different fuels tested

Fuel	Distance [Km]	Time [s]	Average speed [km/h]	Fuel used [g]	Fuel used [g/km]	Fuel used [l/m^3]	Fuel used [l/100km]	Fuel used [MJ/km]
Gasoline (Flex-fuel)	142.7	11101	46.3	8489	59.5	11.3	7.93	2.62
E24	143.2	12338	41.8	9870	68.9	13.3	9.26	2.70 (+3.2%)
E85	142.8	11940	43.1	12957	90.7	16.6	11.63	2.64 (+0.9%)
Gasoline (Bi-fuel)	120.1	9772	44.2	6938	57.8	9.3	7.71	2.54
NG	127.0	10452	43.8	6230	49.0	8.0	6.29	2.45 (-3.6%)

Table 6 - Summary of the emissions for the different fuels tested

Fuel	CO_2 [g]	CO_2 [g/km]	HC [g]	HC [mg/km]	CO [g]	CO [mg/km]	NO[1] [g]	NO [mg/km]
Gasoline (Flex-fuel)	26557	186.1	0.282	1.98	230.4	1615	3.137	22.0
E24	27977	195.4 (+5.0%)	0.685	4.78 (+142.1%)	121.6	849 (-47.4%)	3.663	25.6 (+16.4%)
E85	26959	188.8 (+1.4%)	0.302	2.11 (+7.0%)	90.8	636 (-60.6%)	5.257	36.8 (+67.5%)
Euro IV standard	--	--	--	100	--	1000	--	80
Gasoline (Bi-fuel)	21175	176.4	1.13	9.4	525.1	4374	24.3	202
NG	16812	132.3 (-25.0%)	2.83	22.3 (+136.7%)	199.9	1574 (-64%)	15.5	122 (-39.7%)
Euro III standard	--	--	--	200	--	2300	--	150

The results presented show how the alternative fuels compare with gasoline when used on the same vehicle, and from this we can observe that, when compared to the respective emission standards (Euro 3 and Euro 4) both vehicles complied when using the alternative fuels, had very low HC emissions but showed higher than standard emissions for CO when using gasoline and for NO when using gasoline in the bi-fuel vehicles. The speed cycles are however much more demanding, with average speeds above 40 km/h, compared with the certification cycle NEDC – New European Driving Cycle, with an average speed of ~34km/h.
However, it is not possible to conclude on how they compare with each other, in particular different ethanol mixes vs. natural gas. The vehicles used are from different manufacturers,

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[1] All results for NO_x in this work are reported as NO. To report as NO_2 multiply by 46/30

have very different mileage and obey different emission regulations and therefore a comparison of absolute emissions is not feasible. However both vehicles have one thing in common, they can both run on gasoline, and if the emissions and fuel consumption using the alternative fuels are normalized using the values for gasoline it is possible to perform a comparative analysis of the different fuels. This analysis is presented in the following charts.

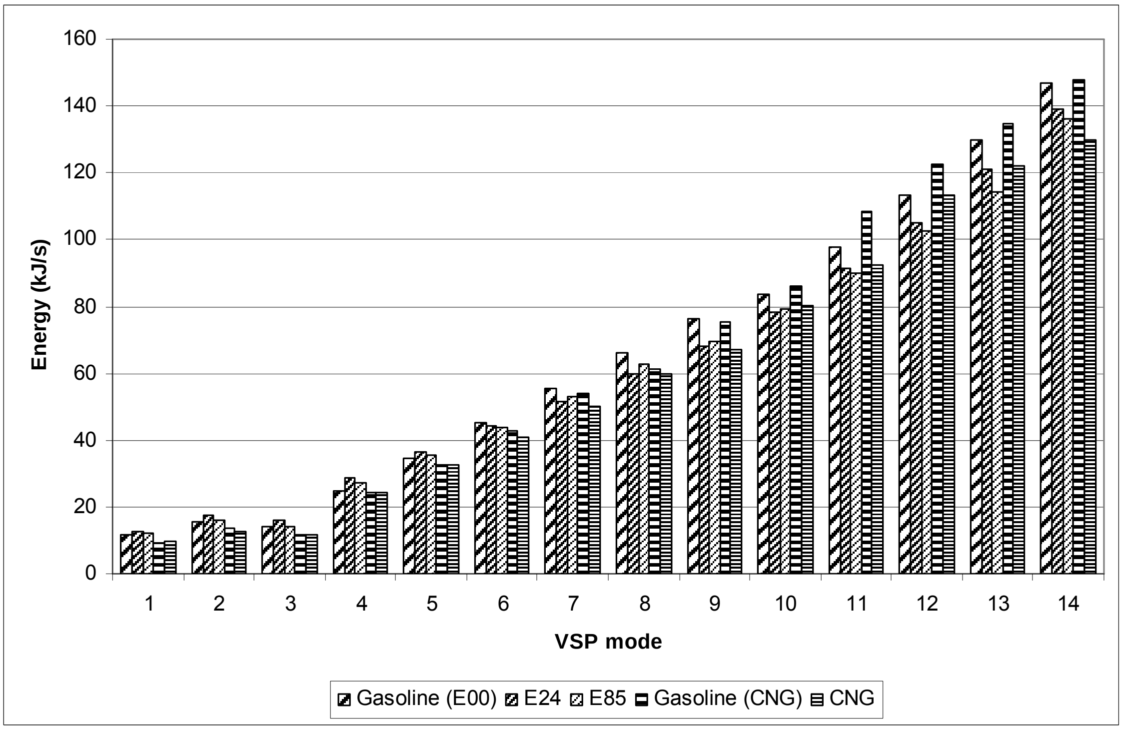

Figure 4 - Energy consumption for the vehicles and fuels analyzed

Energy consumption (Figure 4) is the only value that can be directly compared between all the vehicles and fuels, as this is not dependant on any emissions standard for these vehicles. Comparing both vehicles using gasoline one should expect some advantage for the flexfuel vehicle (lower weight and less mileage) over the bi-fuel vehicle. Observing the data we see that this is effectively the case for higher VSP modes, the reverse occurs in lower VSP modes, probably an indication of how much energy is spent accelerating the vehicle (more critical in higher VSP modes).

Using the normalized energy consumptions (Figure 5) we can see that ethanol mixes are at disadvantage at the lower VSP modes. In the higher VSP modes they are even with natural gas and perform better than gasoline.

Natural gas has an advantage over the entire operating range and this can be explained by better air-fuel mixture and higher octane number. This last factor allows the engine to maintain optimum ignition timing even in situations where if using gasoline knock would cause the engine management system the change the ignition timing.

The properties of each fuel influence such variables as flame speed, octane number and fuel mixture and all play a part in improving the performance of the alternative fuels in the higher VSP modes.

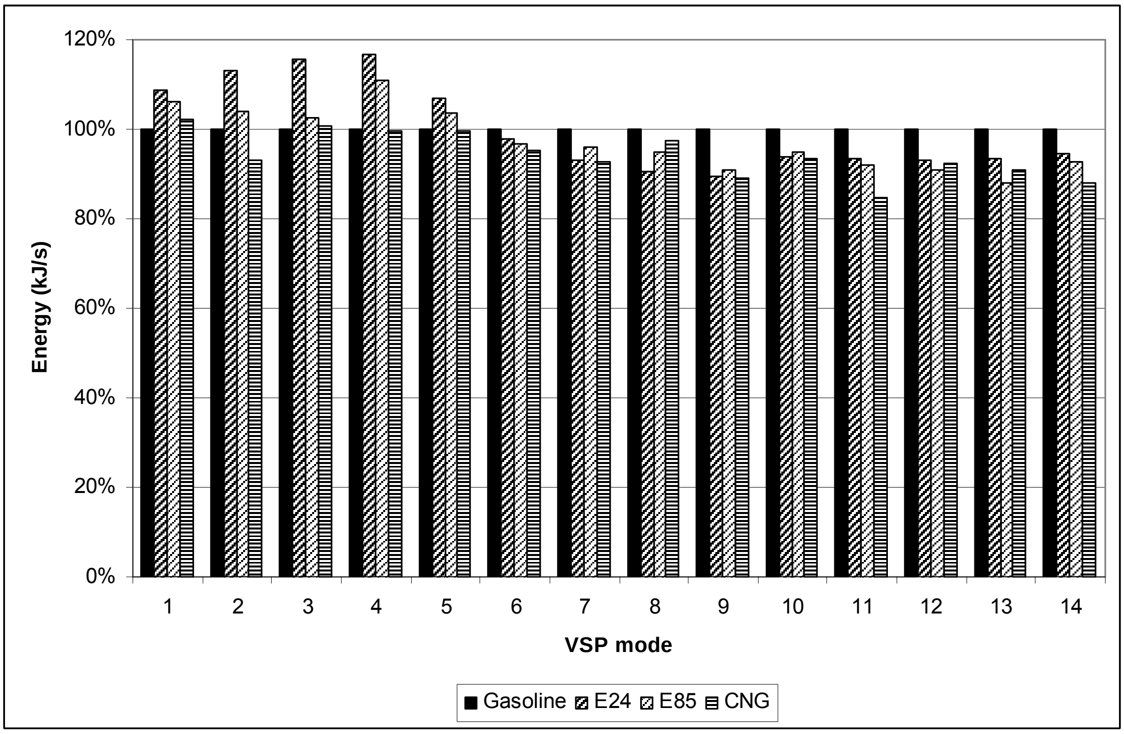

Figure 5 - Variation of energy consumption when compared to gasoline baseline

CO_2 emissions (Figure 6) indicate that tailpipe emissions for ethanol blends are very similar than those resulting from the use of gasoline. Natural gas however shows a considerable advantage in all VSP modes. This analysis however does not account for the emission balance in the fuel production. Gasoline and natural gas are both fossil fuels, and the carbon dioxide released when these fuels are burned is entirely fossil origin. The carbon dioxide resulting from the combustion of ethanol however very likely has been removed at least partially from the atmosphere during the growth of the feedstock used for producing the ethanol. As a result, the complete picture for global CO_2 emissions can only be presented when the life cycle of the fuels used is taken into consideration, an analysis that falls outside the scope of this work.

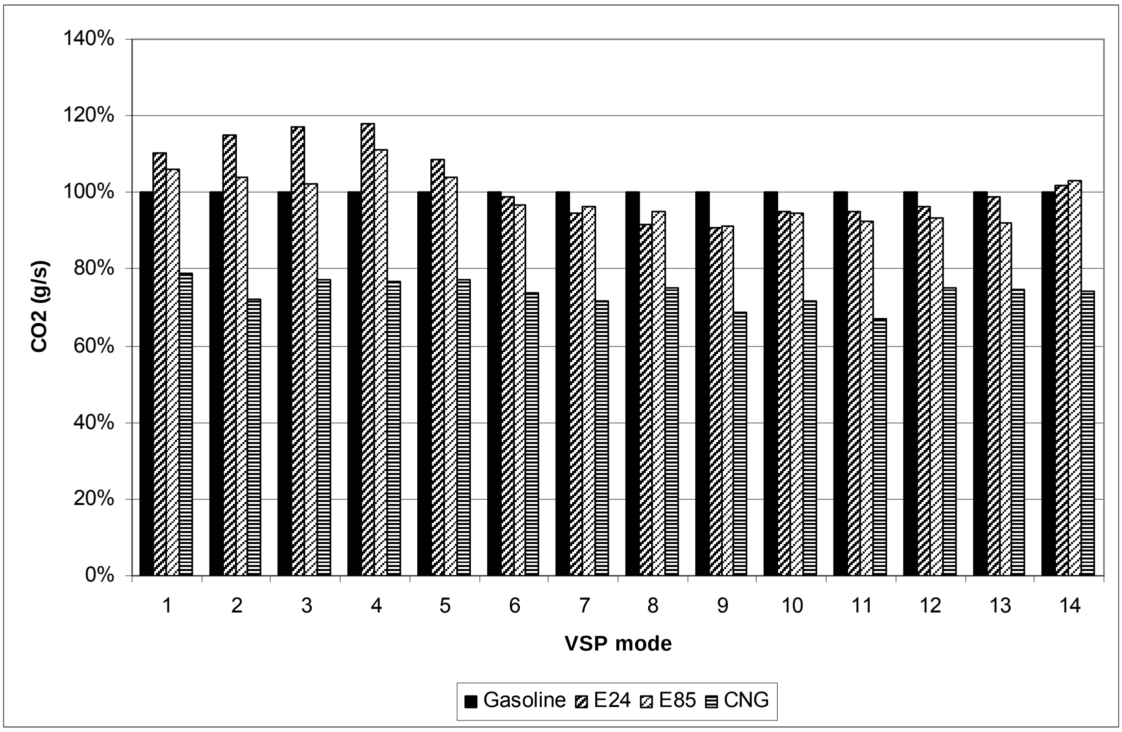

Figure 6 - Variation of CO2 emissions when compared to gasoline baseline

For absolute CO emissions (Figure 7) one should expect the emissions from the flex fuel vehicle to be lower than for the bi-fuel vehicle (Euro IV vs Euro III and different mileage). This is indeed the case for VSP modes up to 12. The last two VSP modes however show emissions from the flex fuel vehicle to be equal or higher than those for the bi-fuel vehicle.

This is probably an indication that emissions on these high VSP modes (and associated power levels) are more a result of specific engine management strategies (e.g. fuel enrichment) than any attempt to match the emissions to a Euro regulation, as this type of operating point does not occur during the standard test cycle. The results for HC emissions below also point to the same direction.

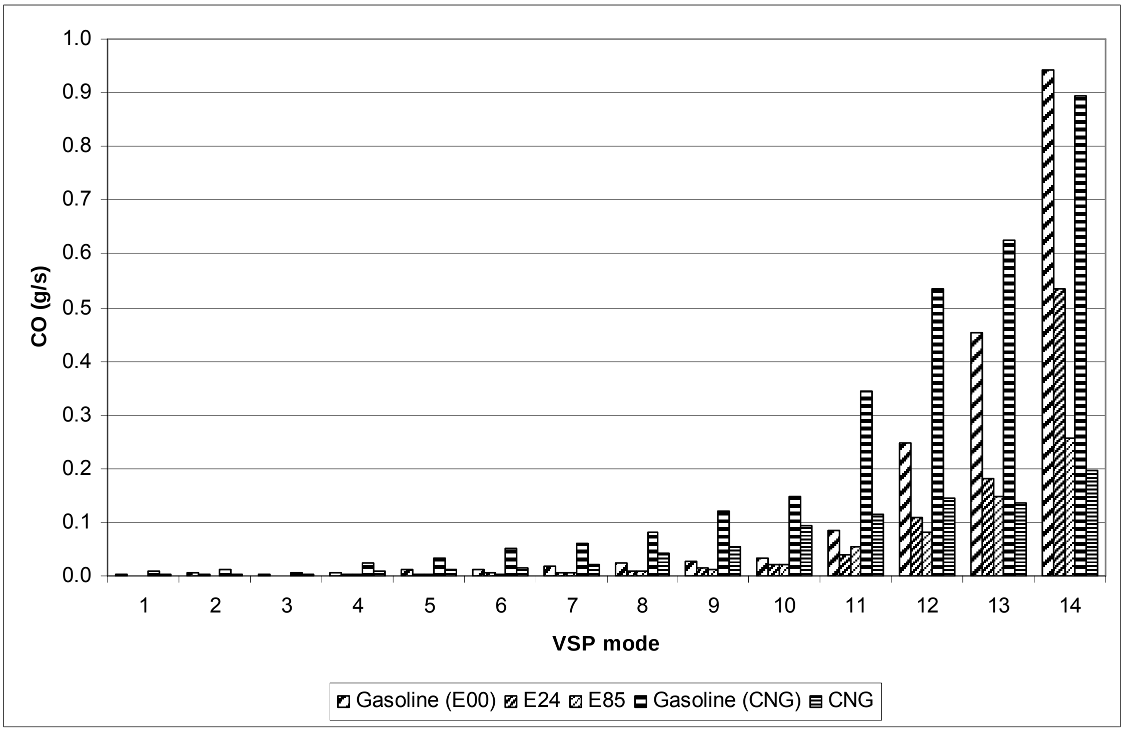

Figure 7 - CO emissions for the vehicles and fuels analyzed

The comparative analysis (Figure 8) shows that all the alternative fuels show a considerable advantage over gasoline, both alternative fuels show a substantial decrease in CO emissions on average of more than 50%, with natural gas providing the highest overall reductions.

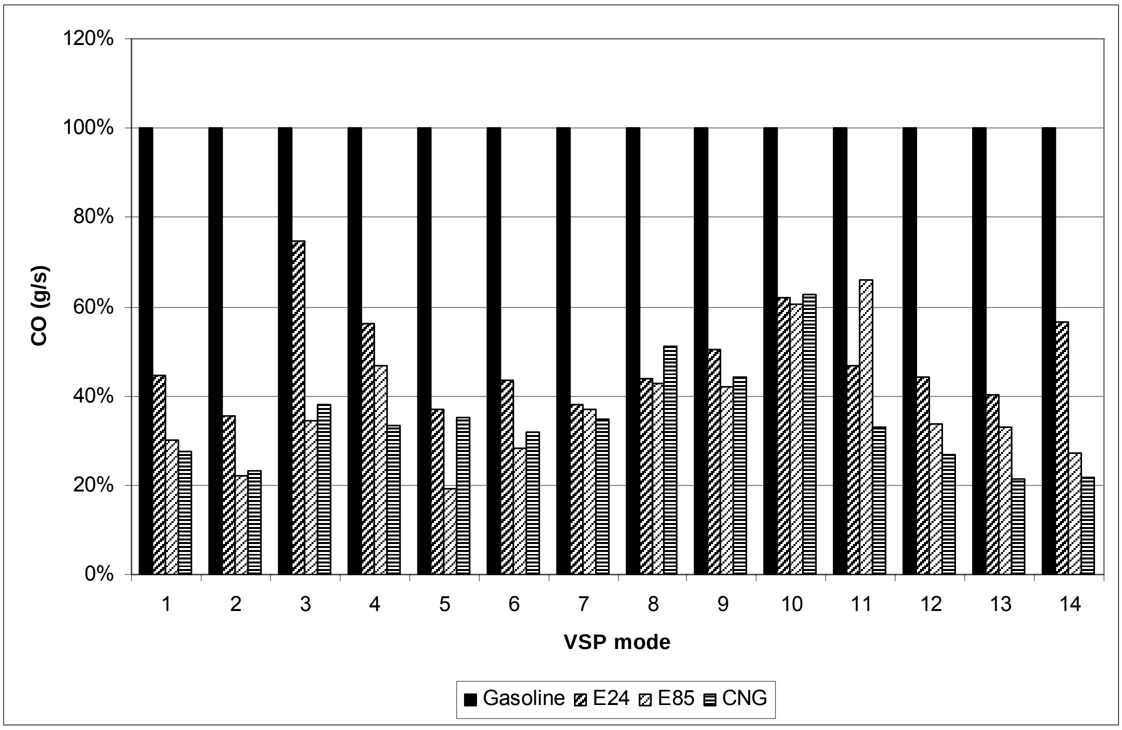

Figure 8 - Variation of CO emissions when compared to gasoline baseline

The same pattern observed for CO emissions is visible in absolute HC emissions (Figure 9), that is, the emissions for both vehicles are of the same order of magnitude at the higher VSP modes, with advantage for the Euro IV vehicle at lower VSP modes. Absolute values are however very low in comparison with Euro regulations, with E85 in particular showing very low emissions on all VSP modes (and below detection limits in the lower VSP modes). The analyzer used does not differentiate between methane and other hydrocarbons, invalidating any direct conclusions on the source of the unburned hydrocarbons. However, the lower emissions of CO with natural gas seem to indicate that combustion is more complete with this fuel, and if that is the case then the source of hydrocarbons should be fuel that does not pass through the combustion process, either caused by quenching of the reaction close to the cylinder walls (more critical for the more stable methane molecule) or caused by methane that escapes the combustion chamber because of valve overlap.

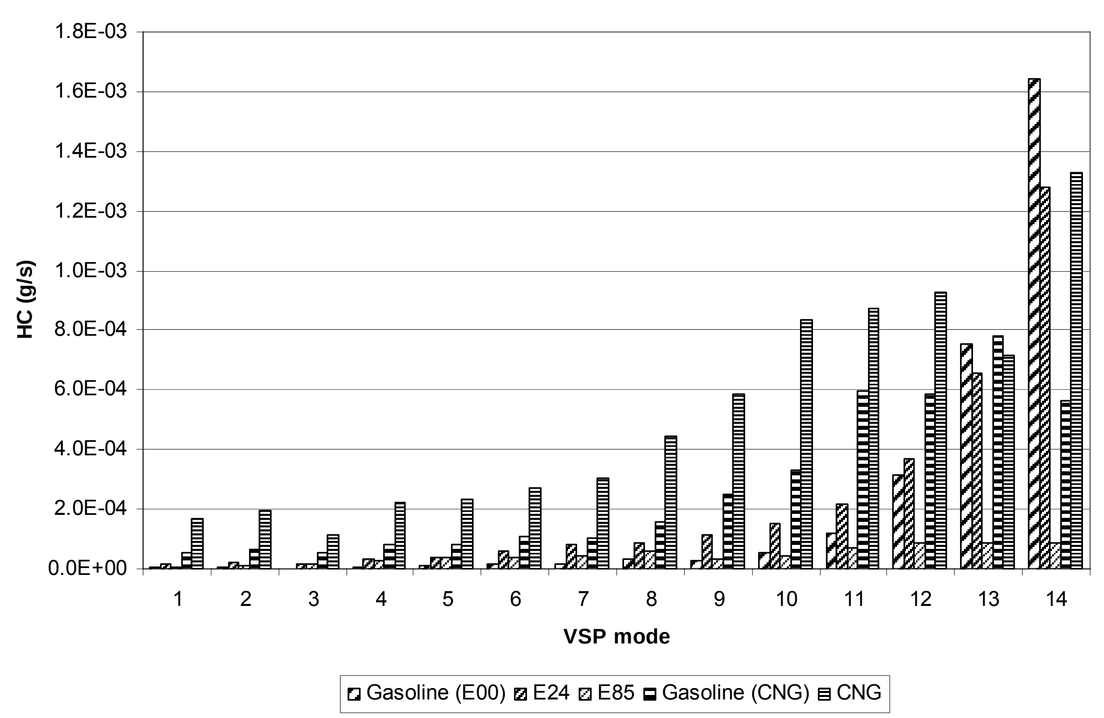

Figure 9 - HC emissions for the vehicles and fuels analyzed

The comparative analysis (Figure 10) indicates very high differences in the lower VSP modes, but as these results are based on overall very low emissions they must be interpreted with caution. Only the higher VSP modes (10 and higher) where HC emissions are overall higher allow some conclusions to be drawn, and here we can note that E24 and in particular natural gas are at a considerable disadvantage.

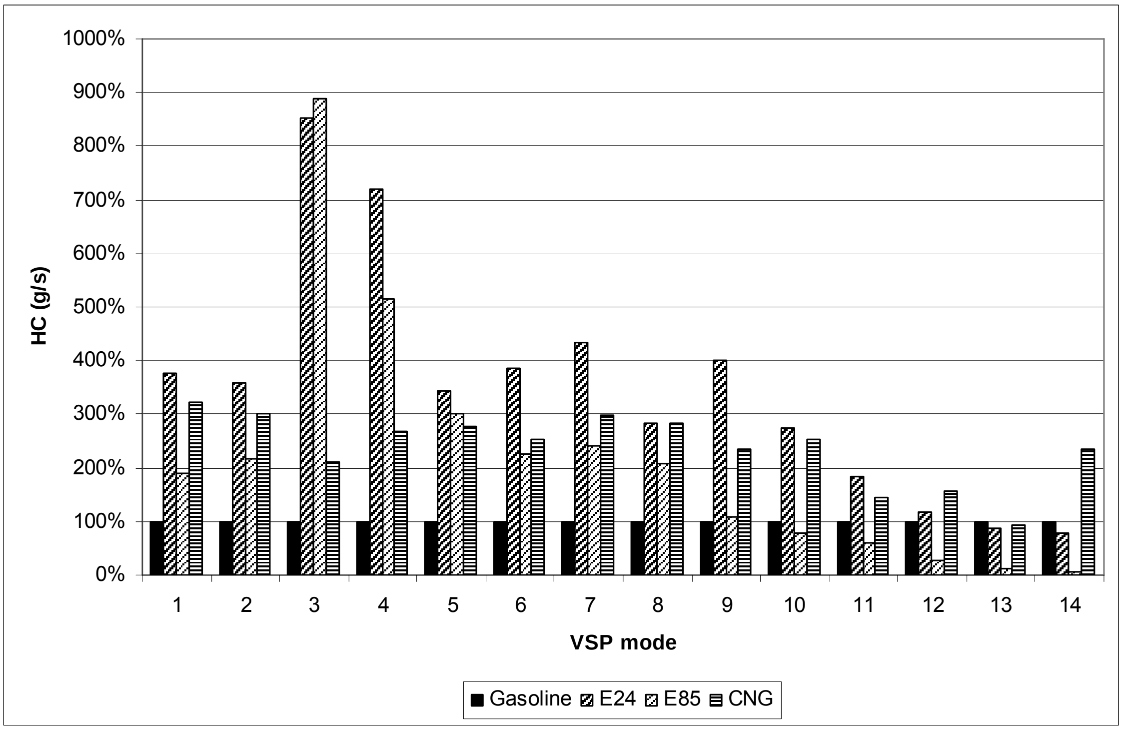

Figure 10 - Variation of HC emissions when compared to gasoline baseline

NO (Figure 11) is the only pollutant for which the differences between the two vehicles are consistent in all VSP modes, with a clear advantage for the Euro IV flexfuel vehicle.

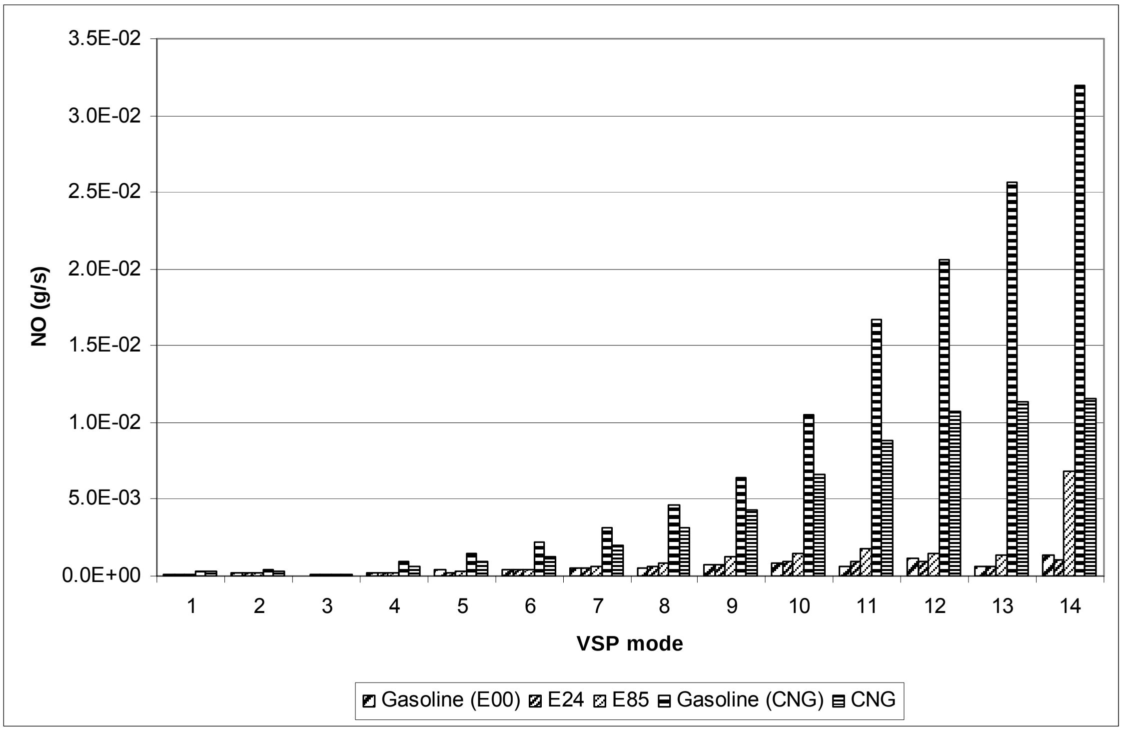

Figure 11 - NO emissions for the vehicles and fuels analyzed

The comparative analysis (Figure 12) shows that the two alternative fuel have opposite behaviors, while natural gas shows an increasing advantage with increasing VSP mode the ethanol blends result in higher NO emissions than the other fuels.

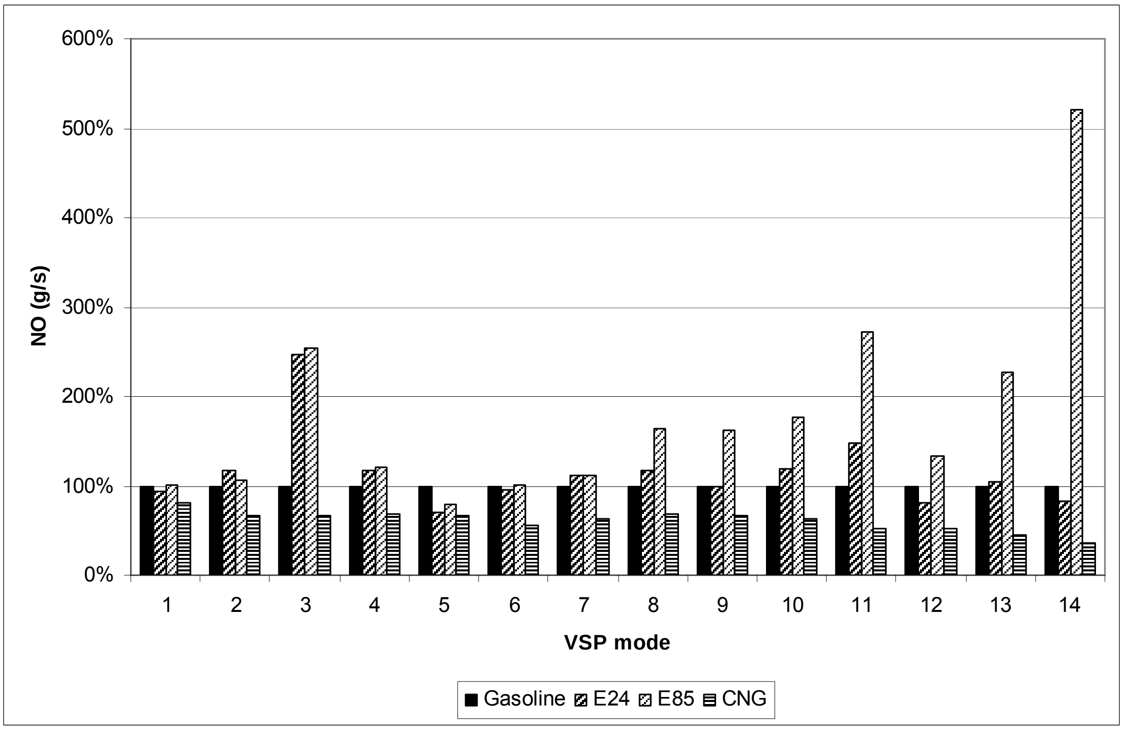

Figure 12 - Variation of NO emissions when compared to gasoline baseline

Considering the results presented, an appreciation of the overall merits of each alternative fuel analyzed depends on the drive cycle used, as the relative emissions change considerably with the VSP mode. However, a qualitative comparison can be made (Table 7) considering the lower VSP modes (typical of urban and moderate speed driving) and the higher VSP modes, that occur only in more demanding conditions.

Table 7 – Comparison of fuels relative to gasoline for low and high VSP modes (⇩⇩: more than 50% reduction; ⇩: less than 50% reduction;⇧⇧: more than 100% increase; ⇧: less than 100% increase; ≈: similar values)

Fuel	CO (VSP≤7)	CO (VSP>7)	HC (VSP≤7)	HC (VSP>7)	NOx (VSP≤7)	NOx (VSP>7)
E24	⇩⇩	⇩⇩	⇧⇧	⇧	⇧	≈
E85	⇩⇩	⇩⇩	⇧⇧	⇧	⇧	⇧⇧
CNG	⇩⇩	⇩⇩	⇧⇧	⇧	⇩	⇩⇩

Comparison with published results is difficult, as the vehicles measured, drive cycles, testing methods and reporting of results differ considerably. Overall, the HC reductions using E15 reported (Leonga 2002) are not verified. Reported CO reductions using CNG (Durbin 2008, Aslam 2006) were observed but contrary to reported by the same authors there is an increase in HC emissions (although absolute emissions are very low). NOx emissions for CNG are consistently lower over all the operating range, contrary to the similar or higher emissions of NOx reported (Durbin 2008, Aslam 2006).

CONCLUSIONS

A mobile laboratory was used to monitor the fuel consumption and gaseous emissions of two light duty vehicles. The vehicles used where able to run both on gasoline and different blends of ethanol (Ford Focus Flex) or natural gas (VW Golf Bi-fuel). The vehicles were monitored using a mobile laboratory capable of measuring and recording all the relevant variables for a comprehensive evaluation of the dynamic, energy and environmental characteristics of each vehicle and fuel combination. The vehicles were monitored in the same roads, driven by the same drivers and under comparable traffic and weather conditions, including several different traffic/road/speed conditions representative of the most common driving situations for light duty vehicles in an urban/suburban and freeway environment. While this allowed some conclusions to be drawn on the relative merits of each vehicle and fuel, a more precise comparison was made possible by adopting the VSP methodology to compare results. The VSP methodology allows us to characterize each moment of driving based on the speed and acceleration of the vehicle, road grade and vehicle characteristics, creating bins that are filled with the emissions and fuel consumption measured.

The results presented are not in complete agreement with previous works, but these were focused on using standard certification cycles and these have been demonstrated to differ considerably from regular driving cycles.

The final and most important outcome of this work, as these results were not previously available in the literature, are the fuel/energy consumption and emission results presented for each VSP mode, which can be used in any modeling or simulating software to calculate realistic fuel consumption and emissions for different drive cycles.

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