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Development of a low cost mixed fuel hydrogen/petrol system for reducing vehicle emissions

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Abstract

Discussions surrounding the hydrogen economy centre primarily on the use of ultra clean hydrogen to power Fuel Cells. This paper examines the potential for burning hydrogen in ICEs as part of a mixed fuel charge in order to take advantage of cheaper brown hydrogen and the advanced nature of the modern petrol ICE. This paper presents a low-cost mixed fuel ICE solution that was developed and fitted to a gasoline spark ignited production vehicle. The findings from a series of investigative performance tests are presented, which show a reduction of three primary pollutants: CO_2; CO and hydrocarbons along with a set of drive cycle tests from which full emission results were collected. These showed that in a full driving cycle care must be taken with the engine mapping in order to ensure a complete burn in all modes of operation. In addition the anticipated NO_x increase was impossible to avoid but the authors suggest practical steps to reduce this to acceptable levels.

Keywords: hydrogen, spark ignition, mixed fuel, emissions reduction

1 Introduction

There is growing concern regarding the level of harmful emissions that are contained within the exhaust gases of internal combustion engines. Various works have been carried out to reduce these emissions including the drive by the European Union and the EPA in the USA to improve the performance of engines and so reduce emissions [1]. However, automotive Original Equipment Manufacturers (OEM) struggle to achieve adequate performance from their engines under such strict regulations as graphically shown by the recent diesel emissions scandal. It is clear that a new approach will be required if the world is to continue to take advantage of the internal combustion engine without suffering from excessive pollution.

It is agreed that the addition of hydrogen to petrol will clean up certain emissions such as CO_2, CO, and Hydrocarbons due to a more complete burn and the substitution of hydrocarbon fuel for hydrogen [2, 3, 4]. Several issues remain however that will require attention prior to a wide scale adoption of hydrogen injection into petrol or diesel fuels. One is the increase in NO_x emissions reported by some [3, 4, 5] due to an increase in in-cylinder temperature. On the other hand some authors claim a reduction in all harmful emissions including NO_x [6, 7]. This issue is often controlled however, through the use of novel control systems or water injection to reduce combustion temperature [6, 8, 9]. In the opinion of the authors these solutions would increase the cost and complexity of any aftermarket conversion that might reduce the cost of reducing the emissions across the existing fleet. Instead they sought to develop a low cost system that utilised off the shelf components and systems that were readily available from EU suppliers as part of the Interreg IV project HyTrEc.

2 Literature Review

The key harmful emissions from internal combustion engine exhausts are Carbon Monoxide (CO), Carbon Dioxide (CO_2), Hydrocarbons (HC) and Nitrogen Oxides (NO_x).
Burning a hydrocarbon fuel such as petrol in air will always produce the aforesaid emissions to varying degrees depending upon the specific circumstances of combustion. The carbon in the fuel will combine with oxygen in the air to produce CO and CO_2 and the nitrogen (N_2) which constitutes approximately 80% of the air will also combine with the oxygen to for various oxides of nitrogen (NO_x) as a function of the combustion reaction. One method used to reduce these gases is to substitute the hydrocarbon fuel for one with a reduced amount carbon in it such as gaseous natural gas or none such as hydrogen. Neither of these fuels has high energy densities compared with gasoline however and therefore often exhibit reduced performance either in terms of power or efficiency or both.
Hydrocarbons are unburned fuel that exits the cylinder on the exhaust stroke. Combustion efficiency will determine how much HC will be emitted following combustion. However, the introduction of particulate filters, three way catalytic converters and the substitution of some of the hydrocarbons with hydrogen will improve this situation significantly and reduce NO_x, HC and CO emissions to below the standards [10].

2.1 Reducing Emissions

A number of harmful emissions such as NO_x, CO, CO2 and HC may be reduced via post combustion techniques such as:

2.1.1 Sacrificial Catalytic Conversion (SCR)

SCR introduces ammonia into the exhaust stream effectively changing nitrogen oxide into nitrogen [11]. The ammonia is typically urea and is held in a separate tank that the driver needs to fill regularly in order to maintain acceptable emissions performance. The fluid is relatively expensive and so some operators are tempted to skip this addition leading to policing of the system to ensure adherence. It is not practical with Spark-Ignited (SI) petrol engines due to the unfeasibly large urea tank required [12] and the need to reduce sulphur levels in petrol [13]. A typical cost for a system is estimated at €2400 without the cost of Urea fluid.

2.1.2 Three way catalytic conversion

A catalytic converter removes harmful nitrogen oxides (NO_x) and carbon monoxide (CO) from the exhaust stream before they are released into the environment by converting CO into CO_2 and NO_x into N_2 and O_2 through chemical reactions on a solid catalyst. All modern vehicles are fitted with catalytic convertors so the cost of this is ignored for this paper.
Other technologies are designed to reduce the generation of harmful emissions within the actual combustion process rather than cleaning up the result of said combustion. The generation of nitrogen oxides (NO_x) is governed by the following factors:

1. Combustion or in cylinder temperature. Once this reaches 1800K the generation of NO_x increases exponentially as nitrogen (N2) breaks down into monatomic N and other gases oxygen and water vapour also break down leading to the formation of NO_x.
2. The amount of nitrogen present in the air fuel charge. Air is approximately 80% nitrogen and so it is very difficult to eliminate N2 from the combustion process [7].

2.2 Temperature reduction

Temperature reduction within the combustion chamber is the main method used to reduce NO_x and this may be achieved through several methods. The primary methods used are:

1. Exhaust Gas Recirculation
2. Water injection
3. Restricting the oxygen available for combustion usually via EGR

The presence of carbon may be mitigated by Hydrocarbon substitution with alternative fuels such as hydrogen.

2.2.1 Exhaust Gas Recirculation (EGR)

A small amount of exhaust gas is added to the fuel, oxygen, and combustion product to increase the specific heat capacity of the cylinder contents, which lowers the combustion temperature. In a typical SI engine, 5% to 15% of the exhaust gas is fed back to the intake. The maximum quantity is limited by the need to sustain a continuous flame front during combustion and sometimes leads to a

compromise between efficiency and NO_x emissions.
EGR is typically not employed at high loads because it would reduce peak power output as oxygen is deliberately reduced through the introduction of inert exhaust gases such as CO. EGR is also not used at idle (low-speed, zero load) because it would cause unstable combustion, resulting in rough idle. Since the EGR system recirculates a portion of exhaust gases, over time the valve can become clogged with carbon deposits that prevent it from operating properly. Clogged EGR valves can sometimes be cleaned, but replacement is necessary if the valve is faulty [14, 15]. Costs for these valves vary and it is difficult to establish an accurate cost of the entire system which may include fuel sensors, pressure sensors and ancillary items. However, a typical EGR valve is estimated to cost between €222 and €536. The costs of any ancillary sensors have not been included in this cost as the number and type will vary depending upon the system.

2.2.2 Water Injection

Water injection is not a new technique having been introduced as early as the 1940s into aircraft engines to boost performance and F1 Turbo engines during the 1980s. Also known as Anti-Detonant Injection (ADI), it introduces a small quantity of water mixed with alcohol (usually methanol) into the cylinder or the incoming fuel air mixture [16]. The water absorbs large amounts of heat as it vaporises so reducing the peak temperature and NO_x generation [8, 7]. Systems can be purchased for between €580 and €1080 depending upon the application but commercial systems appear to be primarily aimed at turbocharged engines although the authors see no reason why these systems could not be applied to non-turbocharged engines.

2.2.3 Substituting hydrocarbon fuel for hydrogen

This involves mixing a cleaner fuel such as hydrogen or methane into the fuel/air mixture or completely replacing the gasoline with a cleaner fuel. Liquid Petroleum Gas (LPG) and Compressed Natural Gas (CNG) produce lower emissions of greenhouse gases but to obtain comparable NO_x emissions it is necessary to avoid using specific lean burn strategies that would have yielded better fuel consumption. [17]. CNG in particular require the use of a high pressure storage tank and valves which are costly.
Supplementing or replacing petrol with hydrogen will reduce HC, CO and CO_2 emissions through the reduction of hydrocarbons in the combustion process [18]. However, the higher combustion temperature will encourage the formation of NO_x [7, 19], especially when total substitution is employed. In addition this solution requires a high pressure tank. The trade-off between the volume that may be stored and the pressure required to store this can mean that relatively low amounts of hydrogen are stored (74 ltrs at 350 Bar) or higher amounts at much higher pressures (700 Bar). Unfortunately the cost of these tanks is much higher than the equivalent CNG tank and the range that may be achieved on pure hydrogen is very low: somewhere in the region of 60 to 80 Km for a 350 Bar 74 ltr tank. To overcome these undesirable outcomes and significant cost penalties it has been suggested that mixing hydrogen into a conventional fuel stream will yield benefits [2, 3, 4, 5, 6, 8]. However, NO_x emissions remain a significant issue due to the increased combustion temperature. It should be noted that these findings were as a result of stationary testing and do not represent real world road conditions.
To overcome this issue some authors have suggested combining EGR and hydrogen injection as a means of improving both NO_x and PM emissions simultaneously [20, 21] although this is suggested for diesel engines rather than SI engines (unless turbocharged) the authors of this paper do not see any reasons other than cost and reliability of the valve to rule this option out.
As a result of this the team decided to investigate the viability of using an adapted off the shelf system to develop a low cost system to mix hydrogen into a gasoline air fuel stream in order to establish a foundation for further work in the anticipation that NO_x will increase by an unknown amount as a result of this action.

3 The Vehicle Conversion

3.1 The Vehicle

The vehicle chosen was a Nissan Qashqai, LHD 2011 Model year, 1.6 petrol with 5 speed Manual Transmission. It produces 115 BHP and has a quoted average fuel consumption of 42 mpg from a 65 litre tank.

3.2 The Conversion

An off the shelf CNG conversion Zavoli Bora 4 injector CNG kit was adapted to operate with

Figure 1: The vehicle being refuelled from manifold cylinder pack (MCP)

hydrogen. This was chosen due to the similarities between CNG and Hydrogen (as opposed to LPG) and to keep costs as low as possible. This was coupled to a Dynetek DyneCell Cylinder, Model: V074H350X8N 74L (1.79 kg (@ 350 Bar) 350 Bar (5075 PSI) Hydrogen storage tank and a Dynetek BV351 Hydrogen solenoid valve. The Qashqai has eight injectors with an operating voltage of 3V. The gas injectors from Zavoli operated at 12V. This issue was overcome by using a separate supply for the additional injectors.

It had been planned to use a pressure regulator capable of supplying up to 9 Bar to reduce the pressure down from the high pressure in the tank. However, this proved to be inadequate and led to fuel starvation particularly at load. A new pressure regulator which capable of supplying to 30 Bar was used instead. Testing revealed good operation at 25 Bar and 3 mm jet stream injectors.

Standard safety features are implemented in the valve such as thermal and PRD (Pressure Relief Device). In addition the permanent live which powers the tank and the CNG kit is taken from the fuel pump line ensuring shut-down in case of an accident.

A relay controlled by a hydrogen sensor (HydroKnowz sensor) is placed in line with the ECU signal: warning with sound and light if a gas leak is detected and interrupts the permanent live closing the valve.

The power for the hydrogen sensor comes from the permanent live. The ECU will take 30 seconds to start before it will switch the tank valve. During this period the H2 sensor can start up and prevent valve operation in case of a leak. The sensors relay is normally open, which means that as long as it is not active yet the valve will not receive a switch signal.

An excess flow valve is installed in the output from the tank, which closes if an open tube occurs (and the flow increases above a certain value).

Filling is achieved via a WEH TN1 receptacle coupled to a TK16 H2 (350 Bar) Filling nozzle with hose set which connected up to a L800 – 172 Bar regulator connected directly to a K cylinder or Manifold Cylinder Pack (MCP), Figure 1. This method of filling was a compromise due to the unavailability of compression refuelling. As a result the tank was only filled to 150 Bar (less than half its capacity). Never the less the vehicle performed flawlessly as the pressure at inlet was controlled to 25 Bar.

4 Methodology

The vehicle was set up and calibrated prior to being tested on the Gateshead College Performance Test Track (adjacent to the Nissan production facility in Washington, Tyne and Wear). This allowed the team to evaluate different hydrogen mixes and select the most suitable ones for emissions testing. During these tests the vehicle was subjected to hill starts, start-stop and high speed running.

Once the road evaluation was completed the vehicle was transported to Gateshead College's Automotive Centre of Excellence where it was placed on a rolling road for emissions testing using a standard MOT exhaust analyser. Here it was subjected to constant load constant speed tests at four conditions:

1. 100% petrol (PE_1000)
2. 50/50 H_2 – petrol mix (50_1000)
3. 40/60 H_2 – petrol mix (40_1000)
4. 32.5/67.5 H_2 – petrol mix (32.5_1000)

The standard VOSA MOT testing station is capable of measuring levels of CO, CO_2 and HC in the exhaust stream via nozzle inserted into the exhaust pipe. This system is not set up to measure NO_x and was used to understand the performance of the system with different levels of hydrogen injection.

Following this the vehicle was transported to the Nissan Test Facility where it underwent emissions testing using the New European Drive Cycle (EUDC and ECE drive cycles). The exhaust gases were analysed via a Horiba test station (Motor Exhaust Gas analyser MEXA – 7400LE, Constant volume Sampler CVS – 7200S and PC – VETS) to collect data on CO, CO_2, NO_x, Total Hydrocarbons

(THC) and Non Methane Hydrocarbons (NMHC) emissions over the drive cycle rather than at fixed speed and loads. These are presented as a combined result although the original data allowed the team to analyse the performance during either the ECE (urban) cycle or the EU (extra urban) Drive Cycle. For this paper only full gasoline and 50/50 mix of gasoline and hydrogen were chosen to be subjected to the drive cycle. This is due to the nature of the mixing process with the Zavoli equipment. The exact proportion of gas injected at amounts below 50% for this engine is very much dependent upon engine speed and load and so outside of fixed speed and load tests it is very difficult to calculate the correct proportion of gas injected. Prior to the test work an oil sample was taken and this was compared with a sample taken after approximately 320 Km (200 miles) of running.

5 Results

5.1 Constant speed and Load Tests

The results for the constant speed and load tests are normalised with petrol/gasoline representing 1.0 and summarised in figures 2 and 3.
As a result of the experimentation using fixed speed and load it is estimated that mixing hydrogen into a petrol fuel stream at percentages between 32% and 50% will reduce emissions by the following amounts on average:

- CO_2 29% by volume
- CO 75% by volume
- Hydrocarbons by 52% (ppm)

Additional improvements following these constant speed, constant load tests and the set up runs on the test track were estimated as follows:

- Fuel consumption improves from 42 mpg to 57 mpg
  - Based on 208 miles from 16.25 litres (estimated)
- Giving a range of 823 miles per tank of petrol
- Hydrogen tank range is estimated at 120 miles/Kg (at 50/50 mix) or
- 167 miles per 1.79 Kg tank
  - More than enough to carry out deliveries around a city during one day.
  - No detectable change was found in the engine oil although very low mileage has to be taken into account

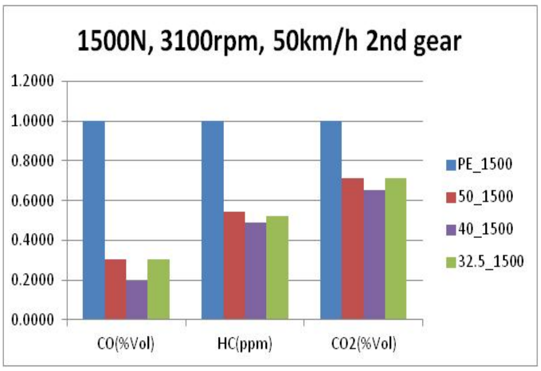

Figure 2: Results for different fuel mixes (3100RPM)

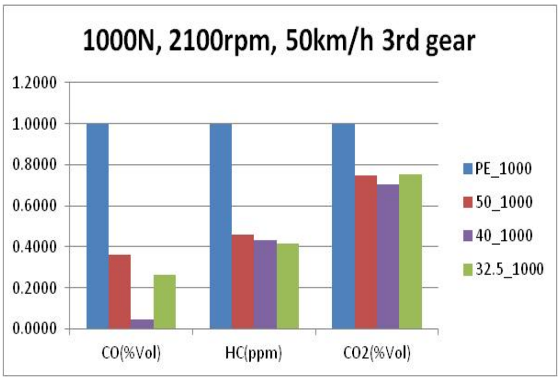

Figure 3: Results for different fuel mixes (2100RPM)

5.2 Drive Cycle Tests

However, these tests could not measure NO_x and were felt not to represent real world driving. Thus the results of the drive cycle tests are summarised in Table 1-2.

Table 1: Summary of results from ECE and EUDC combined

	gms / Km				
Fuel Mix	**C0**	**CO_2**	**THC**	**NOx**	**NMHC**
Limit	1	144	0.1	0.06	0.068
Petrol	0.3952	144.16	0.0279	0.0113	0.0223
50-50	0.5028	67.94	0.0264	0.2207	0.0183

Table 2: Fuel consumption

Fuel Mix	km/l	mpg
Petrol	16.46	46.49
50-50	34.65	97.88

5.3 Costs

Table 3: Cost summary

Component	Price GBP ex. VAT
Conversion (including labour)	2119
Tank + Valve	4200
Hydrogen Sensor	150
Electronics	100
Tubing and valves	561
Receptacle	180
Total	7310

6 Discussion

6.1 Emissions

Whilst the constant load, constant speed tests confirmed what had been expected from literature, the results obtained from subjecting the vehicle to NEDC (urban and extra urban) diverge from what was anticipated significantly. CO_2 was reduced by 53% (higher than the 29% reported in the constant speed and load tests).
On the other hand CO increased by 27% overall. This directly contradicts the expected results of a reduction by up to 75% as seen in the constant speed and load tests. More detailed analysis of the two phases of the drive cycle (ECE and EUDC) reveal that CO generation reduced during the ECE urban drive cycle by approximately 68% which would be in line with the earlier constant speed, constant load results. However, once the drive cycle moved onto the extra urban phase this result was reversed and CO generation increased from 0.19gms/Km to 0.66gms/Km (an increase of 71%). This result seemed to contradict literature which suggests that substitution of the hydrocarbon based fuel for hydrogen would lead to a direct reduction in CO. The detailed results may be seen in table 4.

Table 4: Detailed results from the two phases of the Drive Cycle (gms/Km)

		CO	CO_2	THC	NO_x
Petrol	ECE	0.75	180.68	0.064	0.02
	EUDC	0.19	122.86	0.0069	0.01
50/50	ECE	0.23	87.94	0.049	0.33
	EUDC	0.66	56.28	0.0133	0.16

The addition of hydrogen has indeed reduced CO and THC emissions during the urban phase at the expense of more NO_x. In addition significant reductions in CO_2 have been achieved. Unfortunately, NO_x is some 16 times higher than the petrol only configuration during the urban phase. During the extra urban phase, in which there is a large acceleration event that takes the vehicle in stages from 0 Km per hour to 120 Km per hour, a dramatic and unexpected increase in CO emissions were recorded. Whilst this is still under the limit for the regulation it requires an explanation. Despite the fact that both petrol and hydrogen increase due to the additional load on the engine there is a discrepancy between the amounts due to the map corrections the team made to improve drivability during the test track validation runs for the vehicle. As a result under high loads more hydrogen is injected into the fuel air mix and it is likely that this results in the available oxygen reacting with the hydrogen and monatomic nitrogen (N) created as a result of higher combustion temperatures as a preference. The remaining oxygen is insufficient to completely combust the hydrocarbon portion of the fuel air charge leading to a drop in CO_2, a rise in CO and THC. It is suggested therefore that a modification of the engine map in this area will bring about a better balance of the two fuel elements (hydrogen and gasoline) leading to a more complete burn and similar result to those seen during the ECE phase of the drive cycle. Further measures will be necessary to reduce combustion temperature to below the threshold temperature of 1800K to reduce NO_x to acceptable levels. The authors suggest that this may be best achieved via water injection, and may even be possible via recirculation of water produced as a result of combusting hydrogen. This would negate the need for additional tanks and pumps above those needed to inject the water into the fuel/air stream.

6.2 Fuel Economy

Substituting hydrogen for petrol fuel will always make it appear that the driver is using less fuel as less petrol will be burnt per Km. Whilst hydrogen is not taxed is the same way that gasoline is, there is an argument that this is an advantage from a fuel economy point of view. The team calculated that fuel economy would improve from 42 mpg to 57 mpg. The rolling road tests showed that fuel consumption was improved to a 97 mpg. This in part is most likely due to the lack of air resistance on the rolling road.
Hydrogen usage may be further reduced by use of “geo fencing” to ensure that hydrogen modes are only employed in urban areas rather than on the highway. This in turn would reduce the amount of

hydrogen that would be needed to be carried on board.

6.3 Cost

The largest cost (over 50%) in the conversion was the cost of the high pressure tank and valve necessary to operate with 350 Bar pressures. Whilst it would be beneficial with regard to range to operate at higher pressures, it is felt by the authors that this is not necessary. The primary objective of the conversion was to investigate the viability of using off the shelf (and thus less expensive) components to create a mixed fuel conversion that would be practical, particularly within urban areas. Whilst it would be necessary to use a high pressure tank for hydrogen-petrol mixes as high as 50-50, the authors are actively investigating lower mixes using the same low cost conversion that would enable them to take advantage of cheaper lower pressure storage which would have the additional benefit of not requiring very high pressure refuelling facilities. Thus it is anticipated that on board storage costs will be lower for production systems. Economies of scale would also benefit the final price of the conversion.

7 Conclusions

Mixing hydrogen into the fuel stream can improve CO_2 and HC emissions performance and range per tank of hydrocarbon fuel. Additional work to reduce the generation of CO and NO_x is required. This is important not only for environmental reasons but because this element of the fuel stream is the most heavily taxed.

The authors have been able to establish that it is possible to develop a low cost conversion to gasoline powered ICE vehicles that has the potential to significantly lower vehicle emissions, particularly in urban areas. The rise in NO_x was anticipated and the authors have made several suggestions regarding reducing this.

The cost of the conversion suggests that this may prove a suitable conversion for urban gasoline powered delivery vehicles and may breathe new life into the ICE.

Further research is necessary to establish engine maps for lower hydrogen mixes and to develop and test NO_x reduction strategies.

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