UTAS

Performance appraisal of a four-stroke Hydrogen internal combustion engine

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Date: 14/7/05

for Patrick Burke

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Abstract

Fossil fuel depletion and environmental factors had lead the search for alternative transportation fuels. One such alternative is hydrogen. Of the potential transportation fuels of the future hydrogen is the only one which is both sustainable and environmentally friendly.

A good understanding of the quantitative and qualitative trends are available in the literature, for petrol driven vehicles, as established knowledge. However, understanding of the near zero emissions and associated conversion technology, using hydrogen as fuel, has been in the domain of few automotive applications around the world.

This work is aimed at converting a commercially available vehicle to operate on hydrogen as a design and manufacturing exercise to showcase the use of alternative fuel. The chosen vehicle is the Honda CT110 motor bike or better known as the Australia Post 'postie bike'.

In this thesis, a rigorous design process for conversion to hydrogen is proposed and implemented from first principles. The test rig development associated with the calculations for fuel flow rates and associated engine management systems are an integral part of this overall systematic design. As part of the investigation an innovative fuel injection system together with fuel-air-intake system is designed and incorporated. Traditional problems with pre-ignition in hydrogen engines are found to be minimized by developed systematic design techniques.

As part of this investigation a comprehensive range of engine operating conditions are investigated using both petrol and hydrogen as fuel. The comparisons have shown that for the same operating conditions, hydrogen powered vehicles suffer losses in power and thermal efficiency. With the performance requirements of the vehicle in mind the reductions in performance are not seen as a major compromise. Exhaust emission performance showed significant reduction in oxides of nitrogen and no significant emissions of hydrocarbons, carbon dioxide and carbon monoxide. Future potential developments suggested by this work is expected to improve performance outputs further.

Contents

CHAPTER 1 Introduction

The depletion of natural non-renewable resources has necessitated the development of alternative energy sources. Many countries around the world are channeling research efforts to both identify a alternative energy sources and build working prototypes to demonstrate the technology. It is estimated that in 2025 the demand for all forms of energy is projected to be 54 percent more than total consumption in 2001. On the other hand, Kyoto protocol has emphasized the need for reduced emissions and several countries joining the consortium have initiated efforts to reduce the environmental effects of fossil fuel usage in both stationary and mobile applications. World energy outlooks predict that third world energy use will increase by 91 percent over the next two decades, while rising 33 percent in industrialized nations. Furthermore, the carbon dioxide emissions is projected to rise from 23.9 billion tons in 2001 to 37.1 billion tons in 2025, whereas the developing world will account for 61 percent of the increase because of reliance on coal and other fossil fuels.

It has been established that the use of fossil fuels has led to climate changes and contributes towards the green house effect. The majority of fossil fuel combustion processes produce carbon monoxide, carbon dioxide, nitrous oxides, sulfur oxides and other harmful emissions. These pollutants have numerous health and environmental impacts, including urban smog and global environmental problems. In order to minimize the environmental damage, it is necessary to make the transition to a cleaner and renewable energy source. With limited fossil fuel resources and their depletion in the near future, the selection and use of renewable energy even more imperative.

Hydrogen is the most abundant element in the universe and unlike most other energy carriers is carbon free. Hydrogen can assume a key role covering the growing energy demand and lessen dependence on non-renewable energy sources. Hydrogen assisted fuel cell systems can produce electricity without harmful emissions. It is also demonstrated in the last century that hydrogen has the potential for automotive applications and stationary applications such as powering generators and motors. Extensive research and development needs to be done before hydrogen use in fuel cells before the technology can compete with conventional methods in economical terms.

Using of hydrogen in internal combustion engines can achieve the key benefits of fuel cell vehicles at a much reduced lower cost. While the combustion 'know how' of a gasoline engine is an established science, little or no information, in the public domain, is available that comprehensively explains the hydrogen powered internal combustion engines. Any matured knowledge related to hydrogen internal combustion engines is in the domain of major automotive companies such as BMW, Mazda, Toyota and more recently Ford.

The economic justification for building a fully-fledged hydrogen internal combustion engine plant for automotive applications is questionable, with current prices associated with hydrogen production and engine production relatively high. Nevertheless, a good understanding and parallel progress of the hydrogen internal combustion engine technology is essential when the unit cost of hydrogen production is affordable. Converting existing gasoline engines to operate on hydrogen as a fuel is currently seen as the most near term hydrogen transport technology. This creates a transition time where the current internal combustion engines are ready for 'conversion' to run on hydrogen rather than having to buy a brand new hydrogen engine. This will also alleviate large infrastructure changes to the internal combustion engine production. The need to understand and establish a 'modular approach' to converting gasoline internal combustion engines to run on hydrogen is essential. In this thesis, a Honda CT110 gasoline engine is converted to run on hydrogen. A methodology and systematic approach to modular changes to the engine to accommodate hydrogen as fuel is proposed. The innovative design proposed is built as a working prototype with 'tailor made' air-fuel intake systems, fuel injection, fuel ignition and state of the art engine management systems. The effect of the major process variables on the engine performance for power, thermal efficiency and exhaust emissions will be established for both gasoline and hydrogen running conditions. This work, as a routine, compares the power and thermal efficiencies of the gasoline and hydrogen powered engines for parallel running conditions. The unique fuel intake systems built in this work are seen as having generic applications to similar engines of higher capacity. While every effort is made to minimize required conversion changes and associated costs, it is shown in this work that the majority of the costs involved are with the engine management system. This work argues that a significant loss of power compared to the gasoline engine and associated thermal efficiencies do not justify the exclusion of this adaption with zero carbon based emissions and reduced nitrous of oxides of hydrogen engine. It is also argued that the socio-environmental benefits that these emerging technologies can bring have lot more significance in the long range.

University of Tasmania (UTAS), School of Engineering, has a growing research team in this emerging field. With an established new research laboratory for applied hydrogen research in 2004, the automotive applications of hydrogen can now be readily investigated. The new research facility has been build as a part of the HART (Hydrogen Allied Renewable Technology) program, which is joint research program between University of Tasmania and Hydro Tasmania. The thesis presents an important collaborative work between Australia Post and UTAS in order to design, build and appraise the performance of a Honda CT110 ('postie bike') engine converted to run from gasoline to hydrogen.

CHAPTER 2 Literature Survey

"I believe that water will one day be employed as a fuel,
that hydrogen and oxygen will constitute it, used singly or together,
will furnish an inexhaustible source of heat and light..."
Jules Verne

2.1 Internal Combustion Engines

2.1.1 Introduction

Heat engines convert chemical energy into mechanical energy by the process of combustion. Internal combustion engines are a special type of heat engine wherein the process of heat addition (combustion) is achieved inside the engine. Conversely, other heat engines such as Stirling engines and steam engines can be categorized as external combustion engines since the process heat addition into the working fluid occurs outside the engine.

One of the most prevalent places combustion engines are used is in the transport sector, namely automobiles, trucks and aeroplanes. Small internal combustion engines are also used in more diversified applications such as motorbikes, outboard engines, lawnmowers, chainsaws and generators to name only a few.

2.1.2 History

The first to experiment with the internal combustion engine was Dutch physicist Christian Huygens shown in figure 2.1. Although these first attempts occurred as far back as the 1860s, it was not until 1859 that an effective gasoline powered engine was developed. This was achieved when French engineer J J Tienne Lenior built a double acting (spark) ignition engine that could be operated continuously [11]. It was during this same period that another Frenchman named de Rochas formulated basic internal combustion theories and the German, Dr. Nicholas Otto, developed the four stroke principle of operation. Even today four stroke engines are sometimes referred to as Otto cycle engines [12].

Figure 2.1: Christian Huygens [10]

2.1.3 The Automobile

The main components of an automobile are:

1. the basic structure including the frame, suspension system, axles and wheels;
2. the engine;
3. the transmission systems;
4. auxiliaries such as starter motors, lights and electronics;
5. controls such as steering and brakes [13].

The automobile as we know it was not invented in a single day by a single inventor. The history of the automobile reflects an evolution which took place over time. It is estimated that over 100,000 patents created the modern automobile [3].

In 1769, the very first self powered road vehicle was a military tractor invented by French engineer and mechanic, Nicolas Joseph Cugnot (1725 - 1804). Cugnot's vehicle was powered by a steam engine built at the Paris Arsenal (by mechanic Brezin). By the early 1900s, gasoline cars started to outsell all other types of motor vehicles. The market was growing for economical automobiles and the need for industrial (scale) production was pressing [14].

Manufacturers became more common and the production line, which revolutionized the industry, came into place. Even today, developments in the automobile are ongoing with new structural materials, more efficient engine designs and electronics and intelligent systems are acting today to develop the market.

Automobiles can be classified as:

1. Auto cycles;
2. Motor cycles and scooters;
3. Cars, jeeps;
4. Buses and Trucks [13].

2.1.4 Types of combustion engines

Internal combustion engines are classified according to the cycle of operation and the mode of combustion [15]. There are two cycles of operation, namely the two stroke cycle and the four stroke cycle. The cycle of operation refers to how many strokes are required for the completion of one power stroke. Cycle of operations can be subdivided into the gas exchange process, where the products of combustion are exhausted and replaced by fresh gasses and the power process in which the charge is compressed, ignited and the hot gas is expanded for useful work.

The two modes of combustion, spark ignition (SI) and compression ignition (CI) are also commonly used as a means of classification. Each of these is characterized by differing forms of ignition.

SI and CI engines use fuels with differing combustion characteristics. More commonly in Australia we see the use of petrol (commonly referred to as gasoline) as the fuel source. Petrol fuels are designed to resist autoignition during the compression stroke and should normally ignite only under the presence of an initiating source (electric spark).

The common fuel in CI engines is Diesel. Diesel fuels are produced so they autoignite in the high pressure and temperature conditions associated with the compression stroke .

2.1.5 Internal combustion engine operation and function

A reciprocating engine, also often known as a piston engine, is an engine that utilizes one or more pistons in order to convert pressure into a rotating motion [16]. The movement of the piston occurs in a space called the engine cylinder. The periodic linear movement of the piston inside the engine cylinder generates an enclosed region of space with constantly moving volume. This region of space is called the combustion chamber and is where the air fuel mixture is ignited and combustion takes place.

The four stroke engine has four major phases which are shown in figure 2.2 and classified as:

- Intake stroke
- Compression Stroke
- Power Stroke
- Exhaust Stroke

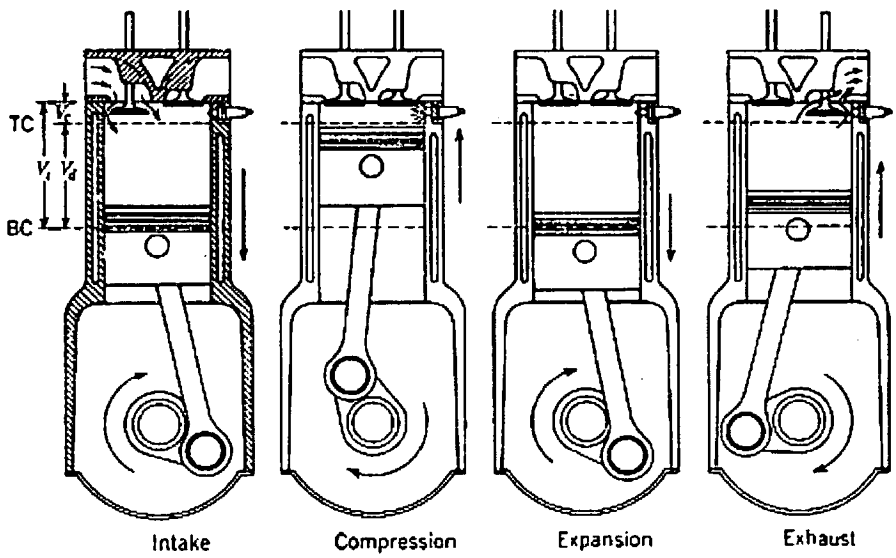

Figure 2.2: The four stroke cycle [3]

These four phases (in whole) describe the stages of a single power (thermodynamic) cycle and are controlled by the positions of the intake and exhaust valves as well as the piston inside the cylinder. The intake valve allows a new charge of air-fuel-mix to enter the cylinder, whilst the exhaust valve allows burnt gases to leave the cylinder. The timing of the closure and opening of these valves is governed by the camshaft. Both the camshaft and the piston are driven by the crankshaft. In this way, the rates of motion for both the piston and the camshaft (valves) are governed by the rate of rotation of the crankshaft. It is this rate of rotation that is also displayed in the Rev/Min counter in a vehicle.

Variations in the timing of the closure and opening of valves as well as the point at which ignition (sparking) occur have a great effect on the performance of internal combustion engines.

2.1.6 Two Wheeled Vehicles

Two wheeled vehicles such as motor cycles and scooters have been an integral part of the transportation sector for many years. These vehicles are seen by many as an efficient and convenient method of transport. This view stems from the fact that a smaller total weight (rider plus vehicle) arises, which optimizes fuel economy. Such vehicles are also more convenient to maneuver and park particularly in busy metropolitan areas and high population centres. However, pollution from many of such vehicles causes health problems as well as serious deterioration in the quality of air. Fuel conversion technologies are seen as an excellent way to combat this problem.

The first successful two-wheeler was the Hildebrand & Wolfmueller, patented in Munich in 1894 shown in figure 2.3. The engine for this vehicle was a parallel twin, mounted low on the frame. It was water-cooled, and had a water tank/radiator built into the top of the rear fender [17]. Since then two wheeled vehicles have also undergone continued development.

Figure 2.3: The first successful two wheeled vehicle [9]

Today in Australia most owners of two wheeled vehicles consist of recreational users and inner city riders. In much more densely populated countries across Asia much inner city travelling is achieved on two and three wheeled vehicles and this market is rapidly growing with them occupying 50-90% of vehicles [18]. In 1999 China produced fifty percent of the world's motorcycles [19].

2.2 *Alternative Powering of Vehicles*

2.2.1 Rationale of Alternately Powered Vehicles

In 2003-2004 Australia imported 23511 ML[1] of crude oil and other refinery feedstock valued at over 6500 million dollars [20]. Of this amount more than half came from the Middle East and Indonesia. Much of this import market was used by the automotive industry which increased automotive fuel sales by 1% across the sector in 2004 [20]. From a consumer perspective there are 1000 cars to each 675 people in Australia and this number has been increasing steadily over the past 33 years [21]. This continual growth and reliance on foreign strategic energy resources threatens national and economic security and is a non-sustainable practice [22]. The fact that these imports occur from highly turbulent areas of the globe can also make this supply prone to instability.

One way of alleviating (and gradually phasing out) the reliance on imported fossil based fuels destined for the automobile market is through the development of vehicles which run on alternative sources of fuel. Environmental awareness and the application of more stringent pollution standards from vehicle emissions is another impetus behind the rationale for the use of alternative fuels and methods of powering vehicles. This is true whether the (fossil based) fuels are locally or externally sourced. Indeed, it is believed that the surface temperature of the earth has risen by 0.6°C since the late 19th century. This rise could be a result of increased fossil fuel usage over this period [23]. CO_2 emissions have also increased by 33% since 1987 in the Oceania region alone. On a national scale, Australia is in the top 20 CO_2 emitting countries worldwide and along with Japan, contributes to 97% of the CO_2 emissions from the region [24]. The steady rise in CO_2 emissions is shown in figure 2.4. Replacing gasoline in vehicles with alternate (renewably sourced) fuels is expected to significantly reduce CO_2 emissions from the transportation sector. Additionally, alternate fuels offer reduced emissions of ozone-forming pollutants such as carbon monoxide (CO) and nitrogen oxides (NO_x) [22].

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[1] megalitres

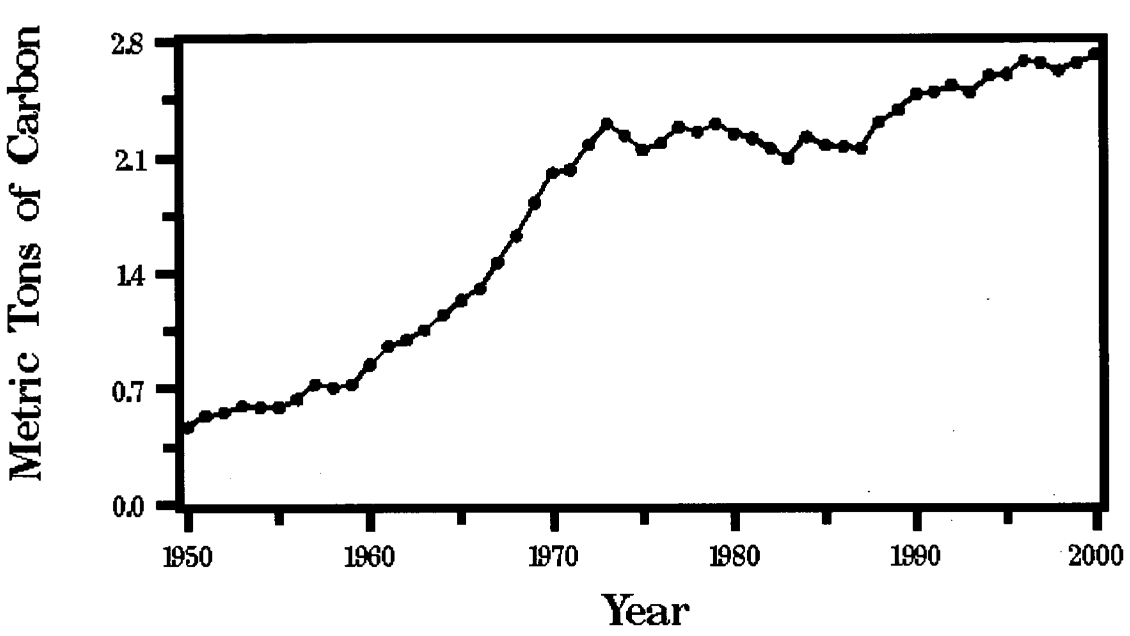


Figure 2.4: Worldwide emissions of Carbon Dioxide over the past 50 years [4]

The following section outlines the most prevalent alternative fuels which are likely to become available. It details their advantages, disadvantages and strategic developments which are required for their implementation.

2.2.2 Compressed Natural Gas

In the transportation sector, natural gas has been considered as an alternative to gasoline for many years. The first natural gas vehicle was developed in the 1930s. Today, there are over 30 different models of CNG busses available in the US [25].

Natural Gas is a significant component of the world's energy supply. It is a fossil fuel and is drawn from gas wells or in conjunction with crude oil production shown in figure 2.5. Like oil and coal, this means that it is, essentially, the remains of plants and animals and microorganisms that lived millions of years ago. Also like oil and coal natural gas is a limited non-sustainable resource. A typical composition of Natural gas shown in table 2.1:

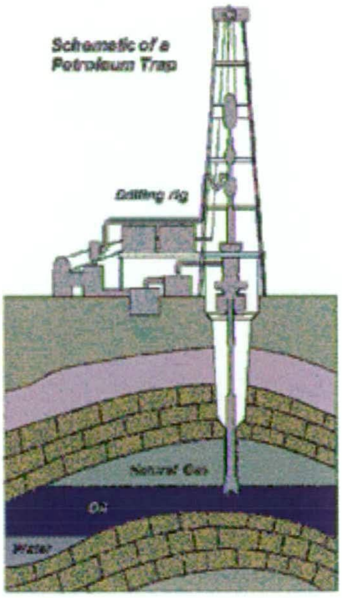


Figure 2.5: Natural Gas capture

Table 2.1: Natural Gas typical composition [26]

Constituent	Chemical Symbol	% of Natural Gas
Methane	CH_4	70-90
Ethane	C_2H_6	0-20
Propane	C_3H_8	0-20
Butane	C_4H_{10}	0-20
Carbon Dioxide	CO_2	0-8
Oxygen	O_2	0-0.2
Nitrogen	N_2	0-5
Hydrogen sulphide	H_2S	0-5
Rare Gases	A, He, Ne, Xe	trace

CNG is odourless, colourless and tasteless. For this reason an odorant is normally added to the gas for safety reasons. CNG vehicles store natural gas in high pressure cylinders usually at 20-25 Mpa [27].

Because natural gas is mostly methane, natural gas vehicles have much lower non-methane hydrocarbon emissions than gasoline vehicles, but higher emissions of methane [28]. Reductions of carbon monoxide has been shown to be 90-97%, carbon dioxide by 25% and nitrous oxide emissions by 35-60% due to the combustion of natural gas compared to gasoline. [27].

CNG will most likely be seen in heavy-medium duty fleet vehicles initially before commercially viable vehicles are available due mainly to costing.

2.2.3 Liquefied Natural Gas

Liquefied Natural Gas (LNG) is produced when natural gas is cooled to 126°C below zero. It is odorless, colorless, non-corrosive and nontoxic. The result of further processing is the end product being almost 100% methane [29]. Trace elements of ethane, propane and heavier hydrocarbons are also present. When vaporized and mixed with air it burns only in concentrations of 5% to 15% on a volumetric basis.

The process of liquefying natural gas to LNG reduces the volume of the fluid by almost 600 times. This high density means that LNG is easy to transport, it can serve to make economical those stranded natural gas deposits for which the construction of pipelines is uneconomical [30]. For many countries where natural gas is not in abundance LNG provides an option where compressed natural gas could not be economically transported as shown in figure 2.6.

Figure 2.6: LNG import terminal in Maryland, US [8]

To date LNG vehicles have been mostly restricted to heavy duty vehicles because the complexities of on board storage make LNG not suited for light duty vehicles. The storage limitations make the gas currently unsuitable for use with two-wheeled vehicles. As the heavy duty market is mostly made up of diesel engines, the comparison of LNG performance and emissions wise is best done against diesel.

LNG produces significant reductions in emissions compared to diesel. From a general perspective, LNG engines [29]

- Produce half the particulate matter of diesel vehicles;
- significantly reduce carbon monoxide emissions;
- reduce nitrogen oxide emissions by 50%;
- potentially reduce carbon dioxide by 25% and;
- can drastically reduce toxic and carcinogenic pollutants.

2.2.4 Liquefied Petroleum Gas

Liquefied Petroleum Gas (LPG) is predominantly a mixture of hydrocarbon gases (mainly propane C_3H_8 and butane C_4H_{10}). When pressurized, these gases liquefy . LPG can also occur naturally with other hydrocarbons in oil and gas fields, or it can be extracted at oil refineries during the production of other petroleum products [31].

Figure 2.7: LPG Converted vehicle showing storage tank [2]

LNG has seen relative success in converted vehicles that are running commonly on the road today. Figure 2.7 (above) shows an LNG converted vehicles.

The main component gases of LPG are :

- Propane ($C3H8$)
- Propylene ($C3H6$)
- Butane ($C4H10$)

In 1999-2000, Australia produced 4,367 ML of naturally occurring LPG and 1,674.4 ML of refinery produced LPG. In the period, Australia exported 2,858.9 ML of LPG and imported 518.9 ML of this fuel[31].

Combustion of LPG is a more environmentally friendly solution for transportation applications than petrol and diesel [32].

However, LPG (like gasoline and diesel) is a finite resource which will inevitably run out. Tests have shown that LPG engines produce approximately 15 per cent less greenhouse emissions than their petrol powered counterpart.

Comparisons of the levels of noxious gas emissions from LPG and petrol vehicles are inconclusive, with test results indicating both higher and lower levels than petrol vehicles. [33]

2.2.5 Electric

Electric vehicles are propelled by electric motors powered through batteries. Such vehicles do not produce any tailpipe emissions, although the elegant image of George Jetson driving his electric vehicle to work without polluting the environment is ambiguous to say the least. Batteries (in electric vehicles) need to be constantly charged . If this electric (battery charging) power is sourced from a non-renewable some level of pollution must also occur. Despite this, electric motors possess greater efficiency than their internal combustion engine counterpart and, if charged from a renewable energy source can reduce environmental damage. The Electric Auto Association claims that even with the effect of electricity generation, electric vehicles are 95% cleaner than the average 2002 vehicle [34].

There are several sources of batteries that can be utilized in battery powered electric vehicles. Table 2.2 shows the various types of potential batteries for electric vehicles:

Table 2.2: Electric vehicle potential battery types and properties [35]

Type	Notes
Lead-Acid	• Low cost • Low range (less than 160km) • 3 year life cycle
Nickel-Metal Hydride	• Greater driving range • More expensive than Lead-Acid
Nickel-Cadmium	• Long Life • Fast recharging • Expensive • Low peak power and recharging efficiency
Lithium-Ion	• Long driving range • Long life cycle • Expensive
Zinc-Air	• Under development • Superior performance
Flywheels	• Under development • Large energy storage • Smaller, lightweight systems

It is difficult to see a future for purely electric powered vehicles due to the constant refueling costs and initial cost associated with the vehicles. They are likely to be more prevalent as fuel cell/combustion engine hybrids.

A hybrid vehicle is one that is powered by more than one source [36]. Near term hybrid vehicles are powered by an electric engine and a gasoline powered internal combustion engine such as the Toyota Prius (shown in figure 2.8) or the Honda Insight (shown in figure 2.9). The electric motor does not need an external power supply for recharging. Its batteries are recharged by regenerative braking. This means that energy from forward momentum is captured during braking. This energy is then used to recharge the batteries. At very slow speeds, the car runs on its electric motor. Driving around the city and at higher and freeway speeds, it shifts to both the gasoline motor and the electric motor, while also recharging the battery [37]. Manufacturers of these vehicles boast excellent fuel efficiency when compared with their non-hybrid counterparts. Toyota claims one tank (45 litres) can drive the vehicle over 1000 kms. The vehicles are currently priced at $37999 and are available in Australia [38]. The Honda Insight is not currently available in Australia but its efficiency is claimed to be 155 km/litre [39].

Figure 2.8: The Toyota Prius [4]

The future of Hybrid electric vehicles could well include alternative fuels. This is because the performance losses accounted in many alternative fuels when compared with gasoline could be overcome with a Hybrid vehicle. Ford currently runs a vehicle prototype which it a Hydrogen internal combustion engine / electric engine Hybrid.

Another promising electrical energy source for transportation is the fuel cell. Like a battery a fuel cell uses electrochemical energy to create electricity. Most car companies are researching fuel cell technology for future developments. Fuel cell technology is detailed further in the Hydrogen section of this chapter.

Solar power is another way of powering an electric vehicle. Solar vehicles either use direct sunlight to power vehicles or use solar energy to charge batteries which run electric motors. Either way, this requires the use of photovoltaic (PV) cells (or modules made of PV cells) to convert sunlight into electricity [40]. However, solar cars are not likely to be the main power source of electric transportation. Most prototypes produce less than 1500 watts which is not enough to power a standard vehicle. It is for this reason that such vehicles are generally designed to be very light (less than 200kg) which is not desirable in an accident situation [37].

Figure 2.9: The Honda Insight [5]

2.2.6 Bio-Diesel

Bio-diesel is a diesel replacement fuel made from natural, renewable sources such as soybean oil, canola oil, sunflower oil, cottonseed oil and animal fats. Up to 20% bio-diesel blends (mixed with petroleum diesel) can be used in most diesel engines without any design modifications. Higher blends are attainable with small engine modifications but storage of the fuel becomes more complicated [41].

Bio-diesel provides similar horsepower, torque and fuel economy as petro-diesel. It has a higher cetane number which increases engine performance. It also has high quality lubricant properties which can extend the life of heavy duty engines [35].

The most common blends in use today are B20 and B100. B20 is 20% biodiesel mixed with 80% gasoline diesel. B100 is 100% biodiesel.

Bio-diesel shows excellent environmental performance when compared with regular diesel. Reductions in carbon monoxide, particulate emissions, hydrocarbon emissions and sulfate emissions have all been observed [35].

Bio-diesel has had a complete evaluation of emission results and potential health effects submitted to the U.S. Environmental Protection Agency (EPA) under the Clean Air Act Section 211(b) [42]. Results are shown in table 2.3 below:

Table 2.3: Percentage reductions in emissions with Bio-Diesel fuels compared to conventional diesel [42]

Emission Type	*B100*	*B20*
Total Unburned Hydrocarbons	-93%	-30%
Carbon Monoxide	-50%	-20%
Particulate Matter	-30%	-22%
NOx	13%	2%
Sulfates	-100%	-20%
PAH (Polycyclic Aromatic Hydrocarbons)	-80%	-13%
nPAH (nitrated PAH's)	-90%	-50%
Ozone potential of speciated HC	-50%	-10%

Bio-diesel is a near term alternative fuel source. Technology barriers are not as great as with many of the other (alternative) transportation fuels. The fuel can be used in existing vehicles without expensive modifications. In general B20 costs less than 10 cents more per litre than conventional diesel [43]. Barriers exist in feedstock supply whereby there is not a sustainable industry to support the supply of oil. It is possible that bio-diesel has the opportunity to be integrated into the market slowly with mixture strength.

2.2.7 Ethanol

Ethanol (CH_3CH_2OH) is made up of a group of chemical compounds whose molecules contain a hydroxyl group, -OH, bonded to a carbon atom [44]. Ethanol is mostly derived from crops which contain sugar (e.g. sugar cane or sugar beet), or by pretreatment of starchy crops (e.g. corn or wheat) or cellulose to produce sugars [33]. In fact anything containing sugar, starch or cellulose can be fermented and distilled into ethanol. Despite this, the need for huge land (plantation) areas to produce significant amounts of ethanol is a serious consideration from an environmental perspective. Additionally many believe that food itself is too precious to burn.

Many vehicles on the road today can or are being run on ethanol blended fuels. Most of today's commercially available vehicles can run on ethanol blends (E10) which is 10% Ethanol and 90% gasoline. In some areas this has been mandated to improve air quality [44]. Strictly speaking though this mix is not classed as an alternative fuel. Under the US Energy Act of 1992, ethanol blends of 85% (E85) are classed as an alternative fuel. E85 is the most common and popular blend for light duty vehicles. Vehicles which can run on such blends are called flexible fuel vehicles (FFV's). Figure 2.10 shows an E85 refueling station at the Kennedy Space Centre in the US.

Figure 2.10: Refueling station at Kennedy Space Station in the US [6].

Ethanol is advantageous as an alternative fuel because it comes from a sustainable feedstock. The National Corn Grower's Association of America has been supporting Ethanol as an alternative fuel for over 20 years, possibly due to the reduction in corn sales and the need for product diversification. Ethanol is sold into the gasoline blending market where it competes with other oxygenates and octane components and with gasoline itself. Therefore, ethanol's price is significantly affected by its value to refiners in these markets [45].

From the perspective of tailpipe emissions, ethanol offers significant reductions in pollution when compared to conventional gasoline. Generally, pure ethanol combustion when compared to gasoline combustion:

[46]

- produces fewer total toxins;
- 15 % reductions in ozone-forming volatile organic compounds
- 40% reductions in carbon monoxide
- 20% reductions in particulate emissions
- 10% reductions in nitrogen oxide emissions
- 80% reductions in sulfate emissions

2.2.8 Hydrogen

From an environmental point of view, hydrogen is the most likely candidate for alternative fuels in the foreseeable future [47]. This prognosis arises from the fact that hydrogen has the potential to provide ultimate freedom from the fuel crisis [48]. Hydrogen also provides the possibility of providing a sustainably fueled transport sector. Moreover, hydrogen fuelled engines have the potential for substantially cleaner emissions than other engines [49].

The use of hydrogen to power vehicles holds advantages over other fuels in that:

- it can be made by splitting water using electricity derived from renewable sources such as wind and solar energy;
- there are wide methods of production;
- when combusted produces low levels of nitrous oxide

- can be used to power both internal combustion engines as well as fuel cells
- has a heating value three times that of petrol;
- is not toxic (but can cause asphyxiation in large concentrations);
- it dissipates quickly in air;
- can be stored both in gas as well as liquefied form;
- has wide flammability limits making it readily ignitable in combustion engines.

The interest in Hydrogen as a transportation fuel has increased significantly over the past few decades with applications in automobiles, light and medium duty vehicles, buses and mining vehicles [50]. In Australia, the 2003 National Hydrogen Study predicts that for the years 2030 and 2050, transport will be the largest demand sector for hydrogen. Almost every car manufacturing company has some sort of prototype Hydrogen powered vehicle. However some features of Hydrogen also constitute barriers to its adoption as an alternative transportation fuel. These include:

- electrolysis (production of hydrogen from water) is a relatively energy expensive process; [51]
- gaseous hydrogen has a low energy density when calculated per unit volume;
- the wide flammability limits of hydrogen together with its low ignition energy make it a fire and explosion hazard; [51] [52].

However the use of all transportation fuels (flammable fluids) requires adherence to stringent safety considerations For the successful implementation of any of the alternative fuels mentioned, certain developments will need to be made. As far as most desirable outputs and sustainability, Hydrogen is definitely the fuel which shows the greatest potential.

2.3 *Hydrogen Uses*

Hydrogen can be utilized to power two different types of vehicles: fuel cells and internal combustion engines.

2.3.1 Fuel Cells

A fuel cell is an (electrochemical) energy conversion device which uses hydrogen and oxygen(from air) to produce electricity and heat (Larminie et al 2000As such, a fuel cell can be likened to a battery in that it operates silently and uses a chemical processes to produce electricity. Basic operation governs that a fuel cell consists of an anode, cathode, electrolyte and catalyst similar in principle to battery operation. However, unlike a battery, a fuel cell provides power directly so long as fuel is supplied to it, like an engine. Figure 2.11 shows the basic operation of the fuel cell.

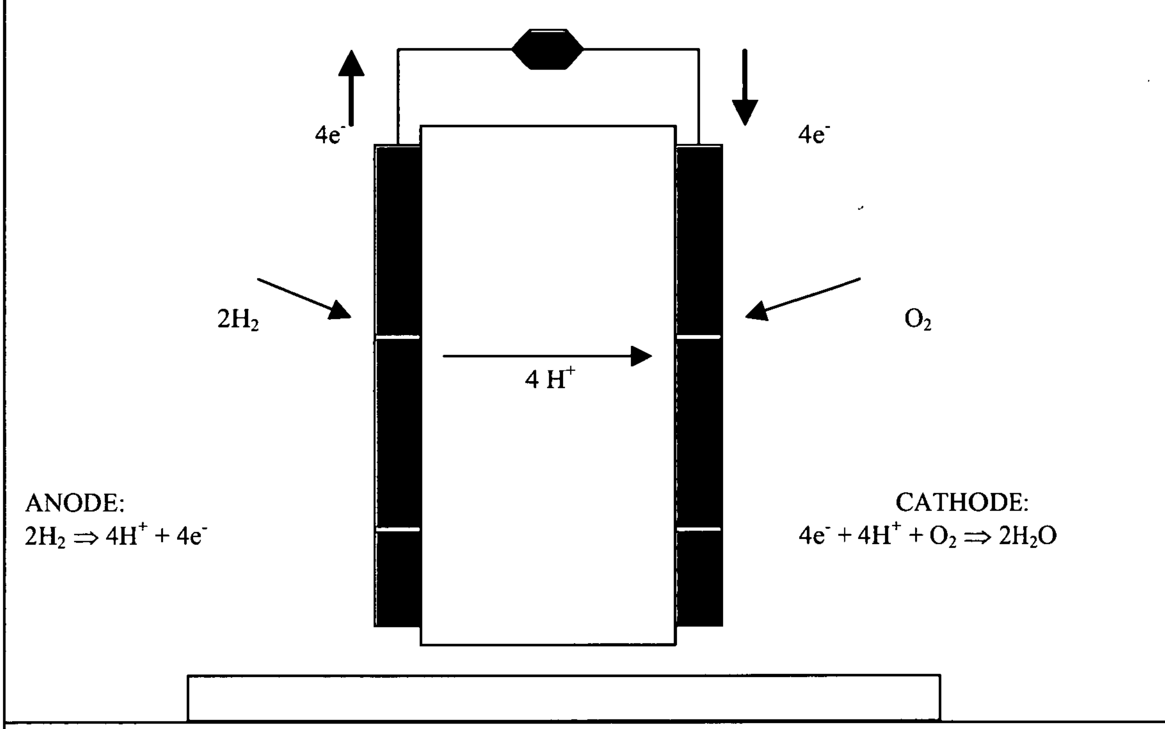


Figure 2.11: Electric flow in a fuel cell

The elegance and simplicity of fuel cells has ensured a steady rate of development since its invention. At the same time the development has been retarded somewhat by the highly competitive energy market.

In 1800, scientists William Nicholson and Anthony Carlisle described the process of using electricity to decompose water into hydrogen and oxygen. William Robert Grove, however took this idea one step further or, more accurately, one step in reverse in 1838. Grove discovered that by arranging two platinum electrodes with one end of each immersed in a container of sulphuric acid and the other end separately sealed in containers of oxygen and hydrogen, a constant current would flow between the electrodes (Cahan D et al 2000).

In 1977 the International Energy Agency launched the 'Production and Utilization of Hydrogen Program' to accelerate the acceptance and widespread use of hydrogen technology (Elam et al, 1999). The agency identified that fuel cell and hydrogen technology has potential for locations where energy supply infrastructure does not exist. It followed on that applications were developed in submarines and space crafts (Wilder 2001).

Recent developments in fuel cells have been driven more so by the commercial sector than in early development. This has led to a plethora of companies becoming involved in fuel cell development and sales. Several of the large car companies have released prototype vehicles powered by fuel cell and hydrogen power. The marketing of these 'clean vehicles' has become an integral part of promoting companies as environmentally friendly rather than manufacturing the cars for commercial use.

There are at least five unique fuel cell types, each with differing strengths providing advantages and disadvantages in certain applications. These are mainly known by the type of electrolyte material used (Wilder 2001).

Table 2.4 shows the five current fuel cell types distinguished by their electrolyte.

Table 2.4: Types of Fuel Cells (Wilder 2001).

Fuel Cell Type	**Operating Range (°C)**
Proton Exchange Membrane (PEM)	50 – 100
Alkaline Fuel Cell (AFC)	50 – 200
Phosphoric Acid (PAFC)	≈ 220
Molten Carbonate (MCFC)	≈ 650
Solid Oxide (SOFC)	≈ 500 – 1000

The two major physical problems which resulted in the development of these fuel cell types are:

1. Slow reaction rate (leading to slow current flows);
2. hydrogen is not always readily available and that it exists in different forms and states.

(Larminie et al 2000)

The Ford Focus fuel cell hybrid is shown in figure 2.12.

Unfortunately the development of fuel cell vehicles is still in its infancy and faces several barriers. Firstly the market is not there for fuel cell vehicles costing $80000 [53]. Technical developments in material and manufacturing science are a crucial factor in the acceptance of fuel cells. Currently there are no companies that have the skills and resources to bring fuel cells to the market [53]. Due to high costs and lack of thorough technology development, a transport hydrogen economy through fuel cells is not expected to be realized until beyond 2050 [54].

There is a common school of thought however, that we do not need to wait for fuel cell vehicles to become available before we start reaping the benefits of hydrogen as a transportation fuel. The cost of a Hydrogen Internal Combustion Engine is much less than that of a fuel cell and the power system of the vehicle which it propels [55].

Figure 2.12: Ford Focus Hybrid Fuel Cell Vehicle [7]

2.3.2 Hydrogen Internal Combustion Engines

The use of Hydrogen in internal combustion engines and hybrid(electric vehicles) can achieve all the key benefits of fuel cell vehicles much sooner and at lower cost. Hydrogen use in internal combustion engines can pave the way for the future development of fuel cell technology through creating infrastructure and improving public awareness [56].

The market penetration of Hydrogen in the transport sector is initially likely to be a combination of fuel cell demonstration projects and hydrogen internal combustion engines and their related hybrids. This trend has been recognized by Ford with the development of the H2RVa hybrid electric/hydrogen engine vehicle being used in the US. [57] . Another vehicle being considered by Ford in this respect is the Model U vehicle (shown in figure 2.13) which is estimated to achieve more than 400 km per tank of Hydrogen [1].

Figure 2.13: The Ford Model U [1]

Considered potentially even more near term than hybrid vehicles are vehicles which would be converted to run from gasoline to hydrogen. Converting existing vehicles on the road to be operated by hydrogen would increase the potential market for the fuel significantly. Realistically speaking people will not be prepared to spend tens of thousands of extra dollars in order to have a brand new Hydrogen vehicle. Simple, economic conversion technologies may be the initial solution to the development of the Hydrogen economy.

The basis of this project is to develop conversion techniques for a small engine which could be applied further to more commercial markets. The hydrogen internal combustion is detailed further in section 2.5.

2.4 Hydrogen Properties

The hydrogen molecule is the smallest and lightest in nature with a molecular weight of 2.016. Hydrogen is a colorless and odorless gas with a density of about 14 times less than air [58].

Some properties of hydrogen are listed in Table 2.5

Table 2.5: Hydrogen Properties [58]

Property	Unit	Value
Density	kg/m^3	0.0838
Higher Heating Value	MJ/kg $MJ/\ m^3$	141.90 11.89
Lower Heating Value	MJ/kg $MJ/\ m^3$	19600 10.05
Boiling Temperature	K	20.3
Density as Liquid	kg/m^3	70.8
Critical Point • Temperature • Pressure • Density	 K Bar kg/m^3	 32.94 12.84 31.40
Self ignition temperature	K	858
Ignition limits in air	(vol. %)	4-75
Stoichiometric mixture in air	(vol. %)	29.53
Flame temperature in air	K	2318
Diffusion coefficient	cm^3/s	0.61
Specific heat (c_p)	kJ/(kg.K)	14.89

In its natural (room temperature) state hydrogen exists as a gas. It has the second lowest boiling and melting point of all substances, second only to helium. It is a liquid below its boiling point of 20K (-253°C) and solid below its melting point of 14K (-259 °C) (atmospheric pressure). [59]. These properties become important in design when storage technologies are being decided upon. The BMW 7i series is powered by liquid hydrogen which requires the fuel to be kept between 14 and 20K.

Pure hydrogen is clear in appearance. In daylight a stream of leaking hydrogen is invisible which is a major safety issue [59]. Scent compounds are often added to other gases to increase the chance of leak recognition. These gases include Mercaptan and Thiophane [60]. Gases of this type are not commonly added to hydrogen because a pure strain of the gas is usually preferred. Developments in this field may make hydrogen a safer gas, especially in combustion engine hydrogen use where purity is not of such great importance.

The difference between the volume occupied by liquid and gaseous hydrogen can be appreciated by considering its expansion ratio. Expansion ratio between liquid and gas is 1:848 at atmospheric conditions. From this it can be seen why we require pressurized vessels to store hydrogen, as to store a useful amount of gas at atmospheric conditions would be worthless. When hydrogen is stored in a high pressure vessel (3600psig) the expansion ratio changes to 1:240 [59]. Releasing such a gas into the environment around it must be done in a controlled manner. The use of regulators, both single and duel stage is an important part of the design of a gaseous system. (The advantage of duel stage regulators is that the outlet pressure remains constant even as the inlet pressure changes).

2.5 Hydrogen as an Internal Combustion Engine fuel

Hydrogen has many properties that make it an advantageous fuel for combustion engines. The byproducts of hydrogen with air consist of water, oxygen and nitrogen. This has obvious positive implications in the ongoing journey to reduce damaging tail pipe emissions [61].

Hydrogen is not a newly conceived transportation fuel. The earliest recorded attempt to operate an engine on Hydrogen was Rev. W. Cecil in 1820. The attempt was not considered successful but Cecil pointed out some special features for the potential of Hydrogen as fuel [62]. In the 1920s German engineer Rudolf Erren converted the internal combustion engines of trucks, buses and submarines to use hydrogen or hydrogen mixtures. British scientist and Marxist writer J.B.S. Haldane introduced the concept of renewable hydrogen in his paper, *Science and the Future,* by proposing that "there will be great power stations where during windy weather the surplus power will be used for the electrolytic decomposition of water into oxygen and hydrogen." [63]. It is reported that over 100 vehicles were converted to hydrogen and gasoline/hydrogen mixtures operation in England and Germany in the 1930s. These conversions were more out of laboratory curiosity than necessity. During the World Wars it was discovered that there may be shortage of petroleum fuels and some more investigations were undertaken. The third phase of Hydrogen internal combustion engine development began in the 1970s when scientists and environmentalists realized that there was going to be a fuel crisis and that vehicles were having an effect on the environment [62].

The research that continues today is still based on the final phase of Hydrogen development: to find a fuel that is both sustainable and environmentally friendly. Much work has been world wide to advance the Hydrogen engine as a possible replacement for its petroleum engine. Most of the work has considered ways of reducing phenomena such as backfire, pre-ignition and knocking which have previously troubled the Hydrogen engine.

Today the Hydrogen engine stands stronger than ever before with rising instability in fuel sources and increasing environmental problems due to vehicles. This coupled with the expense and technical developmental flaws of fuel cell technology has seen Hydrogen powered internal combustion vehicles built by car manufacturers, with the vision of making them available for trial on the road. The intrinsic advantages of Hydrogen over its alternative fuel counterparts have generated great excitement in the vehicle manufacturing market, with greater coverage and support given to the concept.

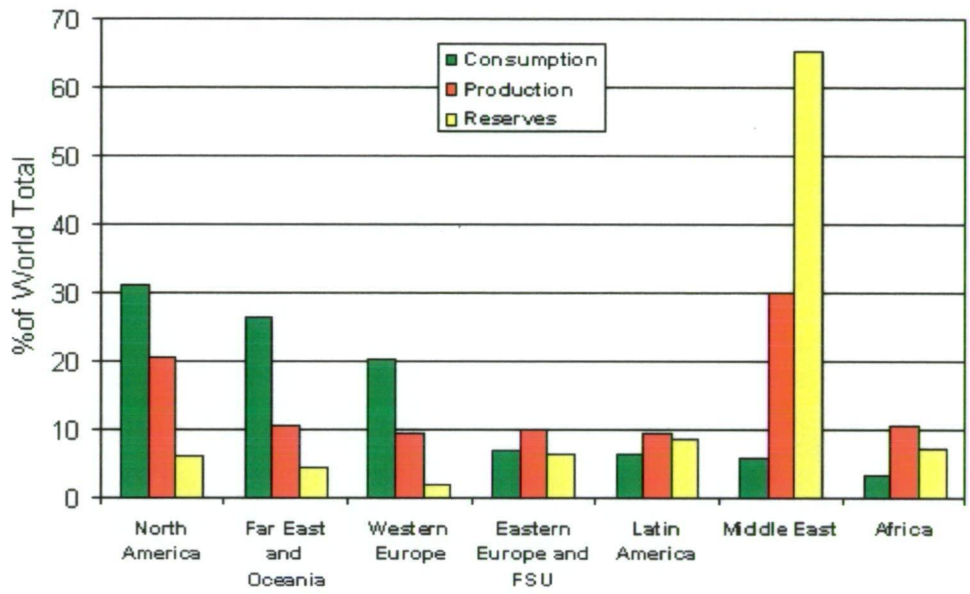


Figure 2.14: World Oil Consumption, Production and Reserves [66]

The following section gives an overview of some of the advantages and challenges which the Hydrogen internal combustion engine possess and face.

2.5.1 Sustainability

Hydrogen is seen as an important future energy carrier and provides potential for sustainable development [49]. Current automotive technologies predominantly use fossil fuel technology which is a finite resource. Of probably greater significance is that oil may become an uneconomical resource in the future due to several factors. For example, the oil we purchase today is largely from coastal areas. Coastal oil is easier to locate, easier to set up for safe pumping, and easier to transport to a refinery [64]. Access to oil refineries will become more difficult and hence more expensive due to difficulties in transportation and location.

Of similar importance to oil sustainability could be political issues. Oil is more likely to become unavailable before it runs out. 56% of world oil reserves exist in the politically unstable Middle East with Saudi Arabia possessing 39% of this figure. Figure 2.14 shows the distribution of world oil supplies and the consumption of the product between countries. Recent unstability in the Middle East region has meant a spike in oil prices [65]. From a political point of view to have a sustainable fuel source which is not reliant on imports would advantageous.

Hydrogen has the potential to be derived from a variety of different sources, many renewable and readily available. Given economics of scale, hydrogen could become economically and environmentally sustainable.

Perhaps instability in the Middle East would not exist if oil was not a valued commodity.

2.5.2 Emissions

When used as a combustion fuel Hydrogen burns 'cleaner' than its industry counterparts such as petroleum. The combustion process emits low levels of pollutants in the form of nitrous oxide, but these can be virtually eliminated by various combustion control methods [52]. In the context of current transportation fuels, Hydrogen is classed as exceptionally clean. Emissions from a Hydrogen operated engine are free of noxious pollutants such as carbon monoxide, carbon dioxide and other greenhouse gases, hydrocarbons, sulfur oxides, smoke, lead or other toxic metals, sulfuric acid, ozone and other oxidants, formaldehydes and benzene and other organic compounds [48].

The road vehicle has traditionally been one of the major sources of harmful gasses in our environment. Motor vehicles currently on the road emit large quantities of carbon monoxide, hydrocarbons, nitrogen oxides and such toxic substances like fine particulates. Because of the rapid growth of Third World countries and vehicle population, the effect is having serious air pollution problems in both built up city areas and even lakes, streams and remote forests [66].

2.5.3 Ignition Limits

Hydrogen/air mixtures can burn over a wide volume ratios, between 4% and 75% [58]. This means that as a combustion fuel hydrogen has very attractive properties, in that it can burn over a wider range of flammability limits compared to other fuels as shown in table 2.6 (below).

Table 2.6: Ignition limits of various transportation fuels [58].

Fuel	Ignition limits in air (%)
Hydrogen	4-75
Methane	5.3-15
Propane	2.2-9.6
Methanol	6-36.5
Gasoline	1-7.6
Diesel	0.6-5.5

The relatively wider flammability limits of hydrogen add to its danger if leaked. In a small enclosure, even a limited amount hydrogen could easily make the area an explosion hazard.

Despite this, other characteristics of hydrogen gas make it attractive as a fuel. For example, hydrogen has a minimum ignition energy of approximately 0.02mJ, which is about an order of magnitude less than that of natural gas [67]. However, this same property means that with hydrogen come additional safety and operational implications.

2.5.4 Pre-ignition, Backfiring and Flashback

Hydrogen has a low ignition energy when mixed with air. The low ignition energy also yields a fast flame speed in comparison with mixtures of methane and iso-octane [51]. The implications of this fast burning flame means that ignition timing can be delayed with regards to top dead centre (TDC).

However, the lower ignition energy of Hydrogen can also mean that relatively weak energy sources like static electricity can readily become a source of ignition [50]. Additionally, hot spots in the cylinder or manifold can also serve as ignitions sources.

This latter situation creates problems with premature ignition (pre-ignition), flashback and backfiring. Preventing this type of erratic operation is one of the challenges in running a hydrogen engine [68].

Pre-ignition, defined as the early ignition of the fuel-air charge due to hot spots present in the cylinder chamber. It can cause power loss and piston damage [69].

Backfires occur in the intake or exhaust system and take the form of a loud explosion. It can be a result of engine pre-ignition in the inlet or excessive fuel in the exhaust. Flashback occurs when the flame in a gas torch burns back (upstream) into a fuel supply line [70]. Most serious fire accidents with gaseous fuel systems are caused by flashbacks. A flashback can travel through a supply system at speeds of up to 13 metres per second .[60].

To avoid the occurrence of such behavior, a number of design features can be included in hydrogen powered internal combustion engines and include:

- Timed injection either into the inlet manifold or directly into the cylinder. Such injection of Hydrogen means that fuels mixtures are less likely to pre-ignite which results in better engine performance [51]. It should also be noted that optimum fuel injection should start at, or before, top dead centre and be advanced with engine speed [71].
- Variable spark ignition timing facilitates the control of the burning mixture. The variation in spark timing with Hydrogen is more effective in controlling the combustion process than with other fuels due to the ease of flammability that the hydrogen fuel possess.
- Greater attention to heat transfer off the design of Hydrogen engines can lead to the elimination of potential pre-ignition points which results in reduced backfiring [51].
- Leaner engine mixtures can be employed to reduce backfiring. Air to fuel ratios (λ) of 2 have resulted in backfire safe operation. However with such lean mixtures power output decreases [71].
- Flashbacks can be eliminated by using fuel injectors in combination with flashback arrestors. Gas specific fuel injectors facilitate one way through flow and so the potential for flashbacks is virtually eliminated. The use of flashback

arrestors in tandem with these fuel injectors only serves to further avoid the hydrogen storage vessel from igniting. Such flashback arrestors are fitted with a sintered flame trap which quenches the flame. Additionally, an integral non-return valve closes off the gas supply in the event of a pressure wave entering the flashback arrestor [60].

2.5.5 Engine Performance

Hydrogen fuelled engines suffer from reduced power output due mainly to the lower heating value of hydrogen gas (on a volume basis) and the lean mixtures which are usually employed [51]. At a stoichiometric air-to-fuel ratio, hydrogen displaces only 29% of the combustion chamber. As a result the energy content of the mixture will be less than it would be if a denser fuel such as gasoline was used [68].

Comparisons between the power output of hydrogen engines with the their gasoline fuelled counterparts have varied with (theoretically) as little 15% loss for carburetted and port injected engines and up to a 15% increase in power for direct (cylinder) injected engines [68]. In this context, several methods can be used to improve the performance of hydrogen engines.

- Using accurate fuel metering (e.g., via solenoid controlled fuel injectors) to control the air-to-fuel ratio and enable hydrogen engines to run at wide open throttle. This type of unthrottled operation leads to increased power output. However, a throttle body or choke may still be required during start-up and idling [72]. The wider flammability limits of hydrogen allow the omittance of the throttle valve, the greatest benefit being better engine efficiency due to reduced suction losses[71]
- Higher compression ratios can be applied satisfactorily to increase the power and efficiency. This is due to the fast burning characteristics of the lean burning hydrogen-air mixtures [51]. The increase of compression ratio results in a sharp increase of the cylinder's top pressure [55]. From a conversion point of view it is important to consider an engine's physical strength before drastically altering the compression ratio.
- Variable valve timing is a feature which enhances higher volumetric efficiency [51]. Gasoline engines are usually designed with large overlaps in valve timing. This is not

a highly desirable feature of a Hydrogen engine. Overlap can increase the chances of pre-ignition hence increased power losses and erratic engine operation.

- Injector or fuel pressure can also have an effect on the power output of a Hydrogen engine [71]. Having said this however, the pressure of the fuel only affects the amount of fuel entering the cylinder, which in turn affects the air to fuel ratio. Injector opening time, fuel pressure and air flow should all be considered in the overall systematic design of air-to-fuel mixture control.
- The variation of spark timing can have a significant effect on the performance of a Hydrogen engine. Variable spark timing allows for greater control at differing engine speeds. There is need with Hydrogen as a fuel for uniquely optimized variations in the spark timing throughout so as to improve performance whilst also avoiding knock.
- Hydrogen engines are usually built 40-60% larger than their gasoline engine counterparts to compensate for the power losses [51].

2.5.6 Storage limitations

Compressed hydrogen gas (at 200 bar) has about 5% the energy content to that of gasoline (of the same volume) [51]. Consequently, from a transport application perspective this is a major shortcoming. Additionally, the energy required to compress this gas is relatively large which further reduces the efficiency from a (whole) systems perspective. Realistically for hydrogen to become a major transportation fuel, further development must occur in the storage technologies. Some of these technologies and developments are discussed below in the section *Hydrogen Storage Techniques*

2.5.7 Other Limitations

- High exhaust temperatures involved with lean operation of Hydrogen has the potential to cause engine damage and high exhaust emissions of oxides of nitrogen [55].
- The wide flammability limits and low ignition energy of Hydrogen mean extra safety measures must be adhered to.

- Care must be taken to ensure material compatibility. Hydrogen embrittlement is a well known phenomena and could potentially destroy engine parts over time.
- Water in the exhaust system must be managed to avoid undesirable corrosion and lubricating oil contamination [51].

2.6 Hydrogen Storage

2.6.1 Storage based on needs

Despite the possibility of more than one way in which hydrogen can be used to propel vehicles, through internal combustion engines, fuel cells or hybrid vehicles, one common challenge remains, that of storage [73].

There are six major storage methods currently being investigated with hydrogen [74]. Hydrogen can be stored using compressed gas, liquid, metal hydride systems, complex hydride systems, physisorption and in carbon nanostructures. Some of these methods are still in their developmental phases while others are more established and common. However, each storage method has its own advantages and disadvantages . Factors such as economics, volume of gas required, release rate, storage space, atmospheric conditions and volatility of space are some of the critical parameters governing the selection of storage method.

Of the six methods listed above, there are only three which are currently commercially viable and which are candidates for this project. These methods are compressed gas cylinders, liquefied hydrogen cylinders and metal hydride containers

2.6.2 Compressed Hydrogen Gas

Compressed Hydrogen Gas (CHG) storage is one of the simplest methods of hydrogen storage [75]. It is simple in that the only equipment required is a compressor and a pressure vessel. The main problem with the method is the low storage density of compressed CHG, which is dependant on the pressure at which the gas is stored [76]. Because of the low density of CHG, the gas must usually be compressed to 2000 to 2800 psi [77] for useful amounts of the gas to be available.

Low pressure tanks can hold as much as 1300 kg of Hydrogen at 1.2-1.6 MPa but these tanks by nature are physically large [76]. Traditionally high pressure vessels have been operated at a maximum pressure of 20-30 Mpa but recent research has advanced high pressure storage capabilities. Tensile strength of materials varies widely from 50Mpa for Aluminum to 1100 MPa for steel. New lightweight cylinders have been developed to withstand pressures of up to 80 Mpa, giving Hydrogen at a volumetric density of 36 kg/m^3. It is envisaged that future vessels will consist of three layers: an inner polymer liner over wrapped carbon fiber composite and an outer layer of aramid material [74]. These tri-shield containers are becoming commercially available.

Quantum Technologies have developed a composite TriShield hydrogen storage cylinder as an alternative that will be compatible with the cost expectations of the automotive industry [78].

Conventional tanks are usually made from common grade steel and over time Hydrogen can migrate into the metal. This makes the metal brittle to a point where Hydrogen can leak from the vessel. This process is called embrittlement and can be overcome by using high-quality steel [78]. This high quality steel makes the storage option expensive.

2.6.3 Liquid Hydrogen Storage

Hydrogen can be stored as a liquid in cryogenic tanks at 21.2K (at ambient pressure) [74]. Liquid Hydrogen Storage is seen as advantageous due to the higher volumetric density when stored in its compressed form. However the process itself is energy expensive and much energy is expended in the liquefaction process and continual energy required to keep the material at low temperatures. Liquefaction is achieved by cooling a gas to form a liquid. The process uses a combination of compressors, heat exchangers, expansion engines, and throttle valves to achieve desired cooling [76].

The simplest method of liquefying hydrogen is the Joule-Thomson or Linde cycle. In this method the gas is compressed and then cooled in a heat exchanger, before passing through a throttle valve where it undergoes isenthalpic Joule-Thomson expansion producing liquid [74].

The large amount of energy required to produce liquid Hydrogen (15.2 kW/kg) limits the potential for its application. Air and space applications where the cost of Hydrogen is not an issue and the gas is consumed quickly are the most ideal candidates for this storage option [74].

Liquefied Hydrogen has long been used in the space shuttle and more recently BMW produced a vehicle powered by liquid Hydrogen [79]. More modern Hydrogen transport technology supports either metal hydride or compressed gas storage of the liquid option.

2.6.4 Metal and Complex Hydrides

Metal Hydrides store Hydrogen by chemically bonding the hydrogen to metal or mettalloid elements and alloys. This storage method is unique because some can absorb

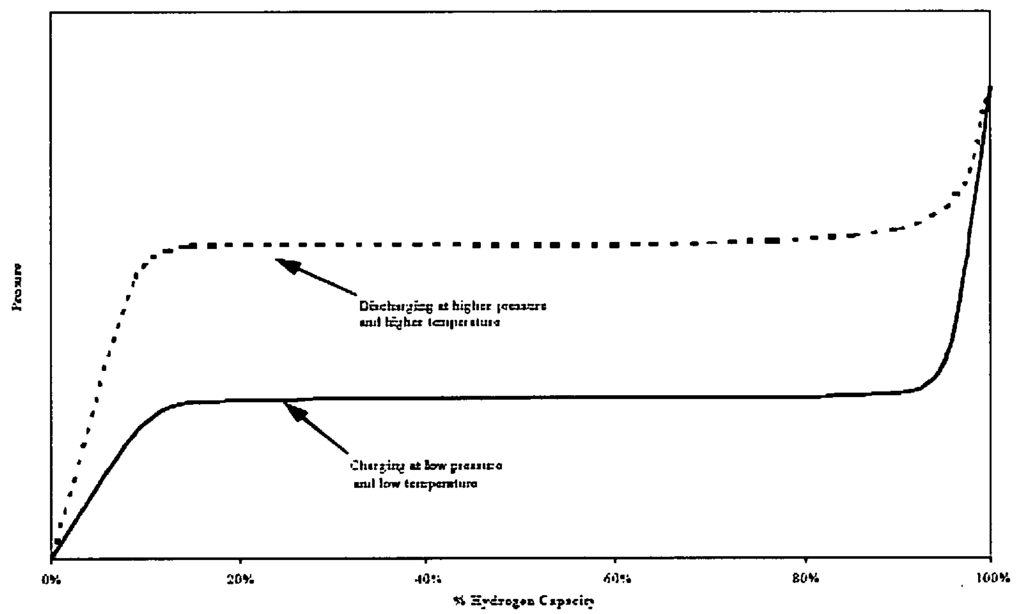


Figure 2.15: Metal Hydride Pressure Behavior [76]

Hydrogen at one pressure then when heated release it at a higher pressure as shown in figure 2.15. This chemical bonding process can be thought of as an absorption procedure. Each of the 50 elements on the periodic table that can absorb hydrogen have different performance characteristics which suit different applications [73]. Developments in metal hydride storage systems have increased in recent years.

Metal hydride alloys are characterized in several families depending on the ratio of the alloying elements. An example is Hydralloy C which is an AB2 alloy. It has A = titanium and zirconium, and B = vanadium, iron nickel, chromium and manganese [75].

Charging and discharging of metal hydride cylinders is achieved at different temperatures. Recent developments have found hydrides that operate at atmospheric temperatures, such that auxiliary heating and cooling systems are not required in conjunction with the cylinder.

Metal Hydride storage containers are heavy in comparison with some of the other storage options. For example the above mentioned alloy stores 2% hydrogen by weight [75]. This weight is of greatest concern to the transport industry. Nonetheless metal hydrides possess one of the largest volumetric energy density of all the storage techniques currently being researched which is making it its biggest advantage.

Another developing hydride storage technique is complex hydrides. The main difference between metallic hydrides and complex hydrides is the transition to an ionic or covalent compound upon hydrogen absorption [74]. The method could be more conducive to mobile hydrogen storage due to the or relative light weight. Compounds can store up to 18% mass of Hydrogen giving the complex hydrides a huge advantage where weight is an issue. While complex hydrides have been investigated for more than six years there is a whole field of new compounds ready to be explored as an option for Hydrogen storage [74].

CHAPTER 3 Experimental Design

3.1 Testing Equipment

3.1.1 Honda CT110

The Honda CT110 (more commonly know as the 'postie bike') is the primary vehicle for local home post delivery in Australia. The vehicle has been the traditional method for several years now due to the maneuverability in busy metropolitan areas. Australia post is the only customer in Australia which can purchase the vehicle new. The CT110 is shown in figure 3.1.

The CT110 is powered by an air cooled 4 stroke, single cylinder 105.1 cc engine. Prior to conversion fuel flow is controlled by a carburetor and air flow by a butterfly valve. The vehicle is a four speed with an automatic centrifugal clutch. Ignition is controlled by a Capacitor Discharge Ignition (CDI) unit. This equipment sends an electrical signal to the coil to provide spark. Ignition is wasted spark and is varied with engine speed. Signal for the unit is taken from a magnetic sensor on the crank.

Figure 3.1: The Honda CT110 'Postie Bike'

The vehicle is chosen for experimentation due to:

- it's simplistic engine layout;
- the commercial relevance of the vehicle;
- availability in Australia; and
- the Australia Post sponsorship.

Further details of the bike are detailed in table 3.1 below.

Table 3.1: Honda CT110 Specifications

Item	Specification
Dry Weight	91.1 kg
Vehicle Capacity Load	95 kg
Bore and Stroke	52.0 x 49.5 mm
Max Horsepower	7.11
Cylinder Compression	1.177 kPa
Idle Speed	1500 ± 100 rpm
Battery	12V
Spark Plug gap	0.6-0.7 mm
Engine weight	23.5 kg

Intake and exhaust valve open and closing in shown in figure 3.2.

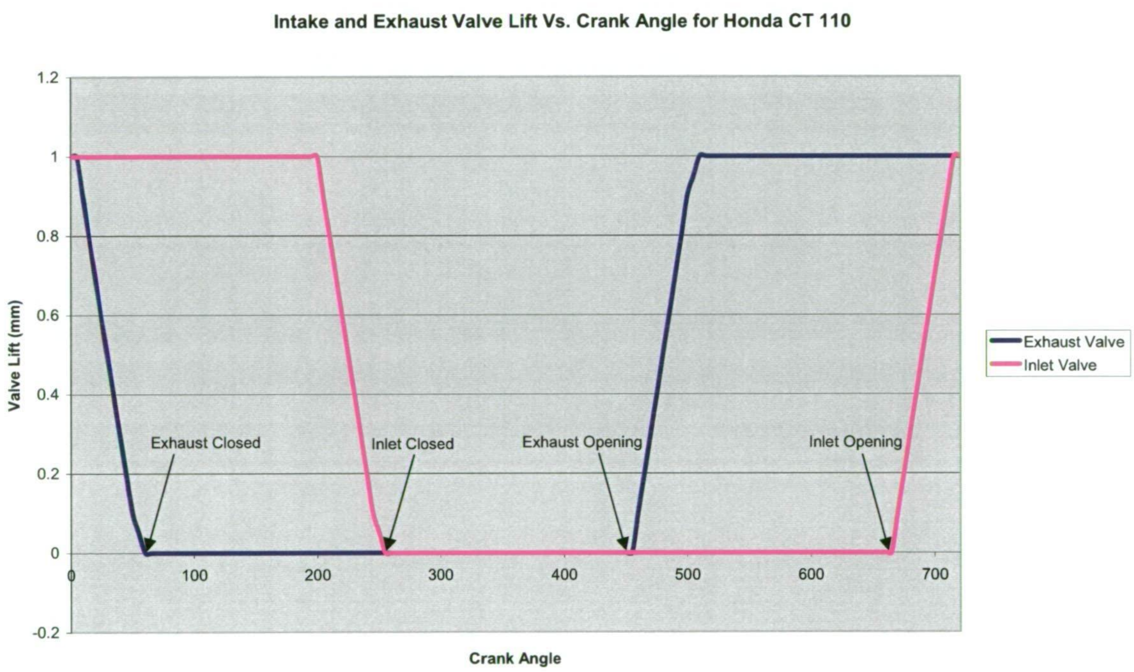


Figure 3.2: Intake and exhaust valve open and closing times for Honda CT110

3.1.2 Dyno Dynamics 450M Dynamometer

Dynamometer testing is done using a motorbike chassis 450kW capacity dynamometer. This unit features a single tyre roller and allows simulated bike speeds of up to 300 km/hr. A PC based control system operates the dynamometer and also allows for the acquisition of relevant data during testing. Of particular interest to this testing procedure is the ability to set a constant speed and vary the load on the wheel with throttle variance.

Figure 3.3: CT110 being tested on Dynamometer

A chassis dynamometer was chosen to perform testing so that dismantling of the vehicle was not required, as would be necessary with an engine dynamometer. Such equipment was not available at the University of Tasmania, so a local industry was sourced for the testing. The testing was done on the dynamometer at *Reds Motorcycle Repairs* in Moonah, Tasmania. The equipment was used on a hire basis with staff at the workshop responsible for the operation of the dynamometer. The equipment is shown in figure 3.3 during testing.

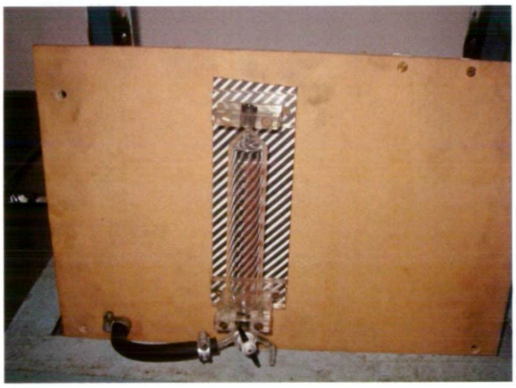
The dynamometer adjusts for changes in power due to atmospheric conditions. This procedure was scrutinized by comparison to the determination of power due to change in atmospheric conditions from AS 4594.11 as shown in Appendix D.

Full specifications of the equipment are detailed in Appendix B1.

3.1.3 Gasoline Flow Board

During the progress of this investigation, a gasoline flow board was designed and built. This unit essentially comprises of a glass sight glass, a mounting frame, fuel tank, fuel lines, valves and a fuel filter. As fuel flowed through the glass sight glass the amount of fuel and the corresponding time for that displacement was noted, thus giving data for flow rate calculation. To comply with accuracy requirements a minimum of 10 millilitres of fuel was required to flow through the tube before measurement could be made. This arrangement allows for the accurate metering of gasoline usage during testing which is necessary for the calculation of thermal efficiencies.

During testing, the fuel flow board was earthed so the possible build up of electrostatic charge did not occur, causing an explosion hazard (as per MSDS for unleaded petrol). Figure 3.4 shows the front and rear views of the flow board.



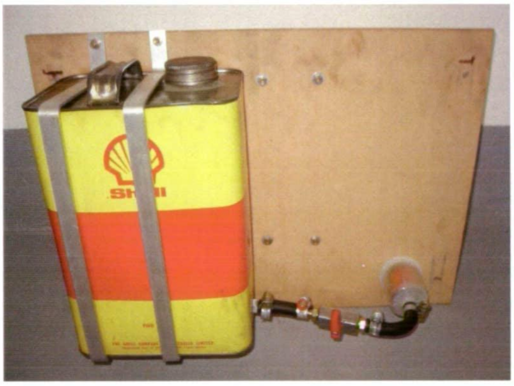


Figure 3.4: Front and rear views of the gasoline flow board

3.1.4 Hydrogen Flow Board

Similar to the metering of fuel usage rates for the calculation of thermal efficiencies (during gasoline testing) an alternate method needed to be used to meter the usage of hydrogen gas once the vehicle was converted. For this purpose a variable area flow meter manufactured by Tecfluid of Spain (model: 2100) was used. The meter consists of a tube and float. The gas flows through the tube displacing the float which corresponds to a flow rate. The flow rates are found using a factor multiplied by the reading on the tube. These are found by using a procedure from the Tecfluid manual detailed in Appendix B2. The flow tube being used in testing is shown below in figure 3.5.

Figure 3.5: Flow tube (left) being used during testing procedure

Data obtained from the flow board does not give immediate indication of the hydrogen flow rate. As the flow tube is calibrated for air a calibration factor must be applied for hydrogen flow. This calculation is shown in Appendix E.

3.1.5 RPM Counter

An RPM counter (tachometer) is required during testing for accuracy purposes. The variance in engine speed is indicative of the variance in output results. The counter is also critical in insuring that the engine is not extend beyond its maximum rpm. The rpm is also compared to that of the dynamometer for accuracy purposes. A Hengstler DC Powered tachometer was attached to the vehicle shown in figure 3.6.

The counter takes a signal from the crank and samples it for six seconds and then displays an updated RPM. The magnetic sensor located on the crank used for ignition timing is also used for the counter.

Further details of the counter is detailed in Appendix B3.

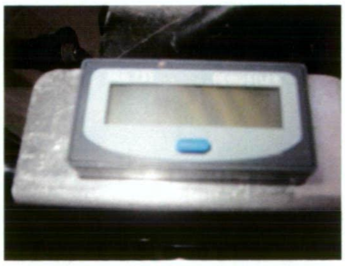


Figure 3.6: Hengstler RPM Counter

3.1.6 Gas Analyzer

Exhaust emission analysis and comparison is a critical part of this study. The comparison between the hydrogen and gasoline engines on an emission basis is one of the major impetus behind the conversion. A measurement of these emissions is thus a critical element in the testing procedure.

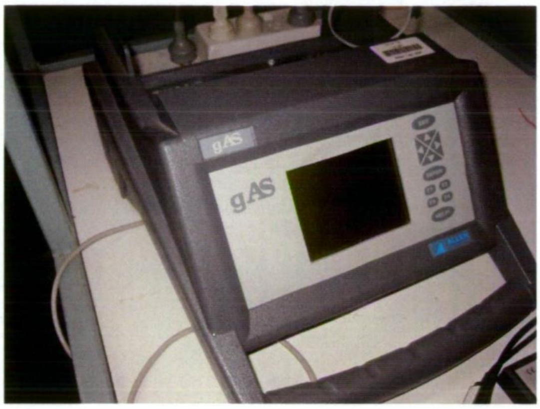


Figure 3.7. The OTC MircoGas Analyzer used for testing.

A 5 gas analyzer was available for use at the University of Tasmania. The unit samples carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxide (NOx) and oxygen (corresponding to lambda or air-fuel ratio). The exhaust gases are sampled and transported to the analyzer by means of a small tube. Prior to the analyzer there are a series of filters which prevent moisture and particulate matter from entering the analyzer. The length of the sampling tube directly effects the update time of the equipment and should be limited as much as possible.

An OTC MicroGas Analyzer is used for the experimental process. The unit is shown in figure 3.7.

3.1.7 Throttle Position Sensor

To provide a means for controlling the load setting on the CT110, a Throttle Position Sensor (TPS) was installed. The sensor was used to ensure that a wide range of data, from minimum to maximum throttle position, could be obtained. The TPS is basically a potentiometer. So as the throttle was advanced the output resistance was increased. For gasoline testing a multimeter was used to measure this output resistance and for hydrogen testing an engine management software program was used to monitor the position.

It is important to note that the control parameters for fuel delivery methods for the two engines will be different so their respective throttle positions mean different things. Advance in throttle position in the gasoline engine results in more air flowing into the engine whilst advance in throttle position for the hydrogen engine results in more fuel entering the engine.

A Bosch TPS was attached to the existing throttle of the CT110. The sensor is shown in figure 3.8 and detailed further in Appendix C6.

Figure 3.8: Throttle Position Sensor

3.1.8 Engine Temperature Sensor

Engine temperature is required during testing for equipment protection and comparison of process outputs with the engine temperature as the dependent variable. By monitoring the engine temperature during the testing procedure excessive temperatures can be avoided by halting testing and allowing the engine to cool. Due to the air cooled nature of the CT110 engine care must be taken whilst running it in a stationary environment. Fans can be employed to keep the engine temperature below that of it's limits.

Outputs such as thermal efficiency and oxides of nitrogen (NOx) can be monitored against the engine temperature for trend analysis.

A K type thermocouple is inserted in the engine oil for engine temperature measurement. The oil gives a good indication of the engine temperature because it is located throughout the engine.

The thermocouple is connected to a thermocouple display unit shown in figure 3.9.

Figure 3.9: Thermocouple display unit

3.1.9 Atmospheric Temperature and Humidity probe

Atmospheric temperature and humidity are required for indicated power corrections. The power developed by an engine will in large part be determined by the mass of air and fuel it can consume. The mass flow rate of air entering the engine will be effected by density. As the density of the atmospheric air in effected by the temperature and humidity, these factors can be taken into consideration.

A TSI VelociCalc Plus that is located at the University of Tasmania was used for these experiments. It has a temperature accuracy of ± 0.3°. The probe is shown in figure 3.10. Further details are available in Appendix B4.

Figure 3.10 TSI Atmospheric Temperature and Humidity Probe

3.2 Testing guidelines

3.2.1 Introduction

An extensive literature search was conducted to find relevant standards for engine testing. Of the local standards available for application to this testing procedure AS 4594 Internal combustion engines-Performance is the most relevant. In particular Part 11 of this standard specifies a method for testing motorcycle engines. The standard aims to present power and specific fuel consumption curves at full load as a function of engine speed.

The purpose of this projects experimental procedure is to attain data for power, thermal efficiency and exhaust emissions for two engines over a range of loads. The applicability of the previously mentioned standard to the testing procedure in this study is not ideal due to the difference in full and ranged engine loads. It is important to range all operating conditions for the CT110 as the vehicle spends most of its operation time below full engine load. Despite the discrepancy between the standard and the testing procedure the document is used as a guideline for testing accuracies and definitions.

Extracted from the standard for application to this testing procedure are:

- definitions;
- requirements for accuracy of measuring equipment and instruments; and
- testing conditions.

In the following section the relevant sections of the standard which are applied to this testing procedure are detailed.

3.2.2 Accuracy of equipment

Table 3.2 shows the accuracy of measurements required by AS4594.11 and the accuracy of testing equipment used in this study.

Table 3.2: Accuracy of measuring equipment both required and produced

Variable Measured	Accuracy Required of equipment AS4594.11	Accuracy of testing equipment in this study
Torque	± 1%	<1%
Engine Speed	± 1%	
Fuel Consumption	± 1%	<1%
Engine inlet air temp	± 1C	0.3°C
Barometric Pressure	± 70Pa	N/A
Back Pressure in Exhaust System	± 25Kpa	N/A

3.2.3 Test Conditions

- Net power test will consist of run at full throttle (AS4594.11-5.3.1, Annex A: A.1);
- Vehicle is to be tested with standard production equipment, such as air filters, inlet manifold, inlet silencer (AS4594.11-5.1)
- Performance data obtained under stabilized normal conditions (AS4594.11-5.3.2);
- Air Inlet Temp measured within 0.15m of entry to air cleaner. (AS4594.11-5.3.3, Annex A: A.3);
- Torque, engine speed and temperature must be stabilized for at least 30 seconds before measurements are taken. (AS4594.11-5.3.4);
- Engine speed shall not deviate by more than ± 1% during a run (AS4594.11-5.3.5, Annex A: A.4);
- Observed brake load, fuel consumption and inlet air temp shall be taken virtually simultaneously (AS4594.11-5.3.6);
- For automatic measurement, no less than 10 seconds will be the duration of the measurement time for engine speed and fuel consumption and 20 seconds for hand held measurements. (AS4594.11-5.3.7);

- Air temperature, fuel temperature and lubricating oil temperatures should all be kept within manufacturer limits. (AS4594.11-5.3.8-5.3.11).

3.3 Testing calculations and relevant background

3.3.1 Thermal Efficiency

Thermal efficiency is a critical parameter in engine performance and is measure through engine power and fuel flow rate. The comparison of thermal efficiencies between the hydrogen and gasoline engines is a good indication of the fuel economy of each of the engines. Thermal efficiency is calculated as:

$$\eta = \frac{Power\ Output\ of\ Engine\ (\dot{W})}{Power\ Input\ of\ Fuel\ (\dot{Q})}$$
$$= \frac{kW\ (from\ dyno)}{LHV\ ({}^{kJ}/_{kg}) \times \dot{m}\ ({}^{kg}/_{s})}$$
$$= \frac{kW\ (from\ dyno)}{LHV\ ({}^{kJ}/_{kg}) \times \dot{V}\ ({}^{m^3}/_{s}) \times \rho\ ({}^{kg}/_{\dot{m}})}$$

Where

LHV- Lower Heating Value of the fuel

$\dot{m}$ - Mass flow rate

$\dot{V}$ - Volumetric flow rate

ρ - Density of fuel

3.3.2 Emissions

An important outcome of the conversion of an engine to hydrogen is that it has less tailpipe emissions. Therefore this must be one of the major goals of this project. We must as a result be able to quantify the term *'emissions'*. It is a very general term but we can define emissions as the composition of the gases leaving the combustion chamber and entering the atmosphere as a result of the ignition of the air-fuel mixture.

The most prolific tailpipe emissions are defined as carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx) and hydrocarbons (HC). These will be measured in the testing procedure.

3.4 Gasoline Testing

The purpose of testing the bike in its original (unconverted) state is to attain baseline data which will be used to compare the original bike with the engine once it is converted to hydrogen. The acquisition of baseline data also serves to validate the testing procedure prior to investigation on the converted engine. In its original state, the CT100 has a gasoline powered (carburetted engine) with CDI ignition control. Further details of the engine are detailed in section 3.1.1 (above).

In drawing up the testing plan in this investigation, parts of Australian Standard 4594 (Internal combustion engines-Performance) have been consulted and used to make inferences. Testing conditions detailed in section 3.2.3 (above) have been adhered to by the procedure itself and experimental technique.

3.4.1 Power Output vs. Air-Fuel Ratio (AFR)

Aim: To determine the relationship between Power Output vs. Air Fuel Ratio over different RPM as shown in figure 3.11.

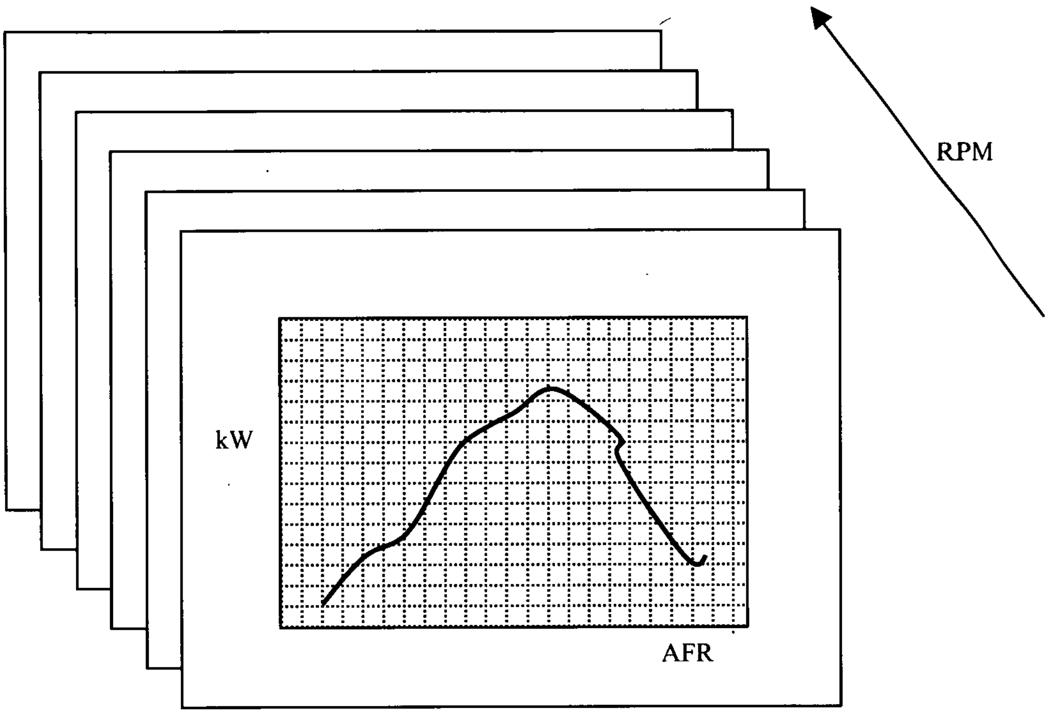


Figure 3.11: Schematic of Power Output vs. Air-Fuel Ratio

Variables:

Dependent - Air Fuel Ratio (%) - Variable of Throttle Position

Independent - Power Output (HP/kW)

Procedure

Experimental produre is represented in figure 3.12.

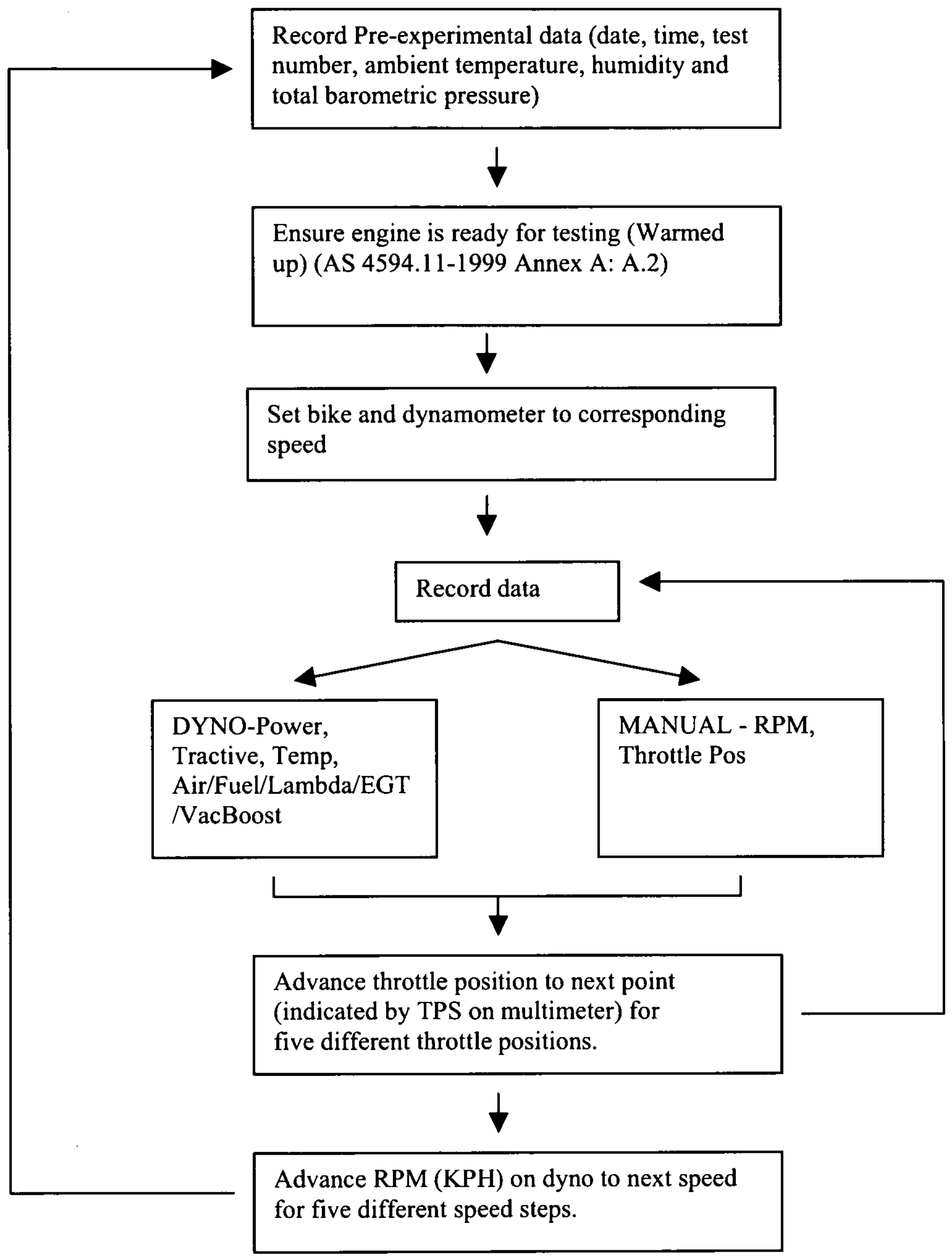


Figure 3.12: Experimental procedure for power vs. air-fuel ratio

3.4.2 Thermal Efficiency vs. Air Fuel Ratio (AFR)

Aim: To determine the relationship between Thermal Efficiency vs. Air to fuel ratio over different RPM as shown in figure 3.13.

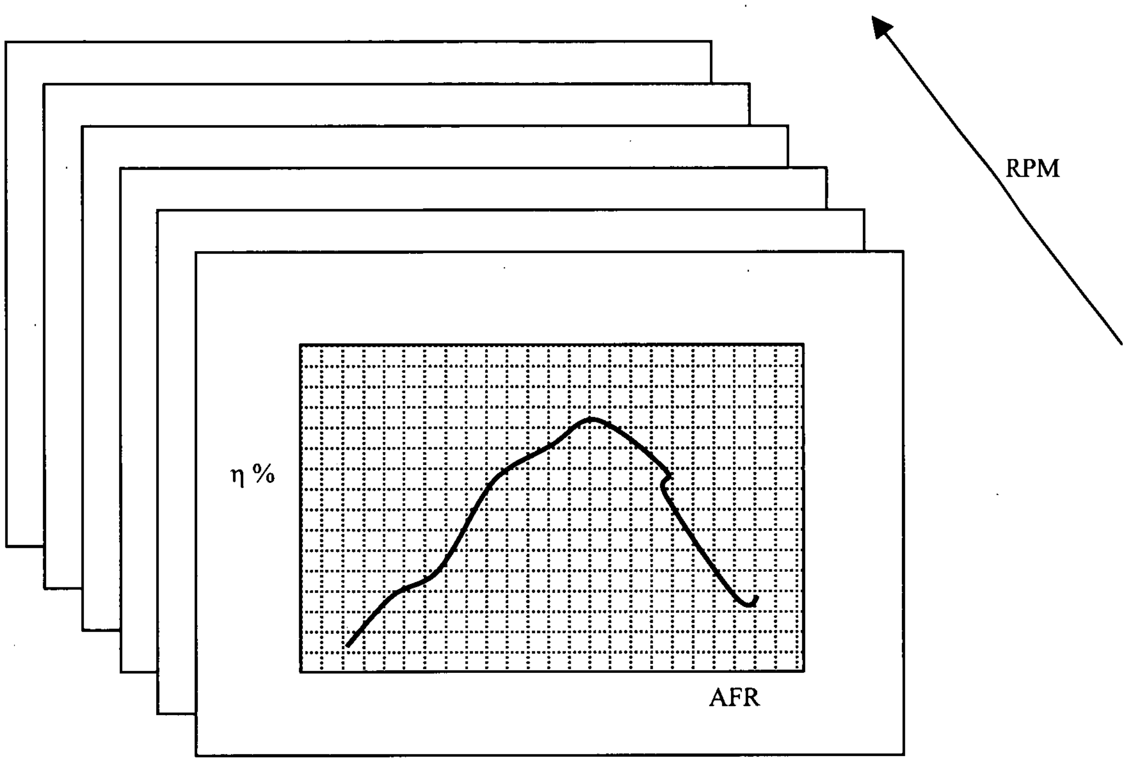


Figure 3.13 Schematic of Thermal Efficiency vs. Air-Fuel Ratio

Variables:

Dependent - Air Fuel Ratio (%) - Variable of Throttle Position

Independent - Power Output (HP-kW) / Fuel Flow Rate (m^3/s)

Procedure:

Experimental procedure is represented in figure 3.14

**Note- This experiment can be run in conjunction with "3.2.3 Power Output vs. Air Fuel Ratio (AFR)"*

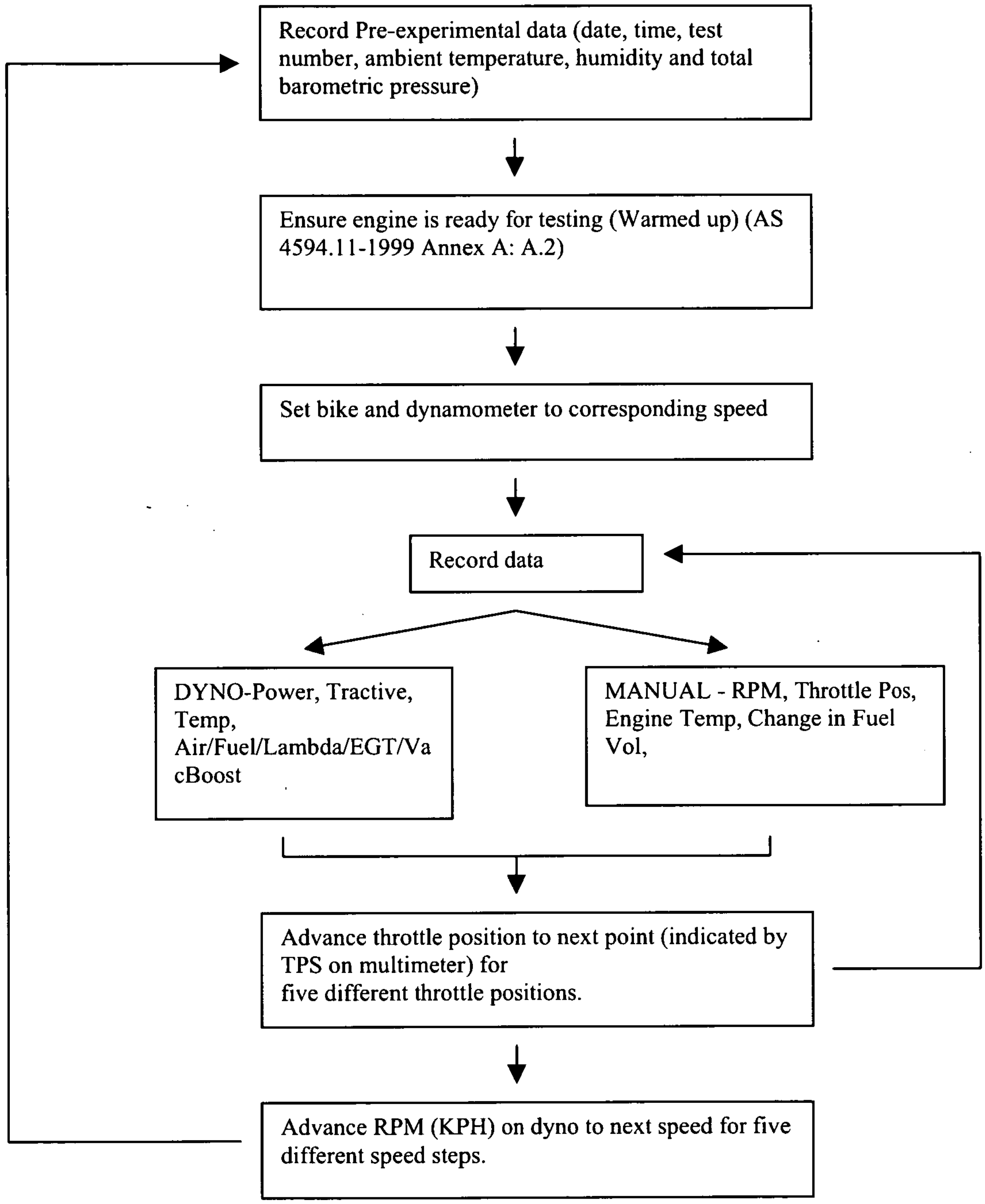


Figure 3.14: Experimental procedure for Thermal efficiency vs. air-fuel ratio

3.4.3 Emissions vs. Air Fuel Ratio (AFR)

Aim: To determine the relationship between Power Output vs. NOx, HC, CO_2, CO over different RPM as shown in figure 3.15.

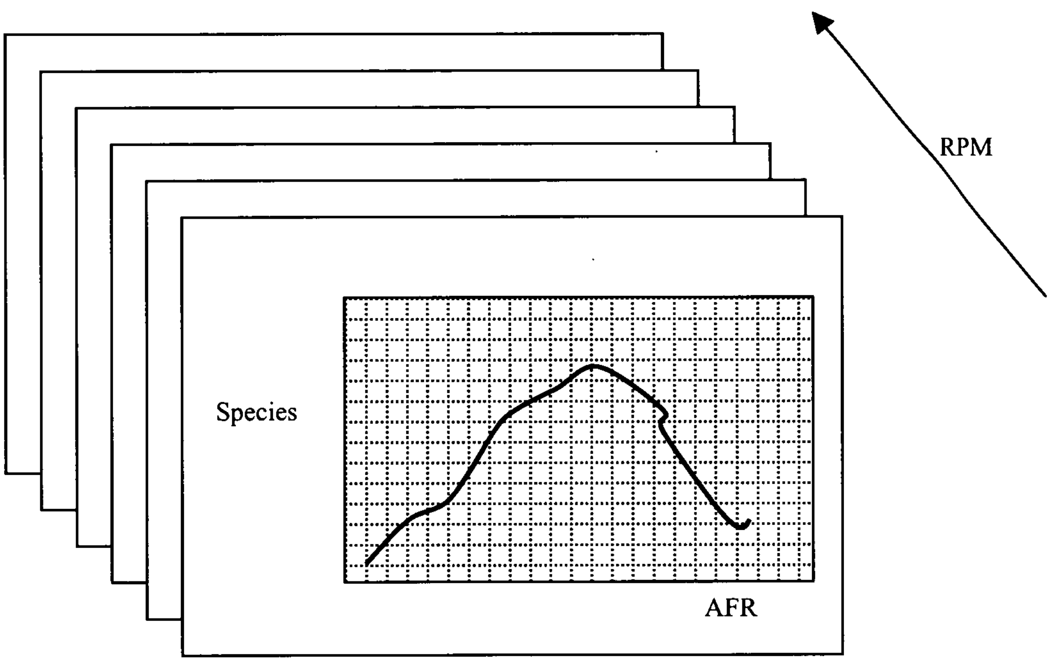


Figure 3.15: Schematic of Exhaust emission species vs. Air-Fuel Ratio

Variables:

Dependent - Air Fuel Ratio (%) - Variable of Throttle Position

Independent - Exhaust Emissions (carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NOx), hydrocarbons (HC))

Procedure:

Experimental procedure is represented in figure 3.16.

**Note- This experiment can be run in conjunction with "3.2.3 Power Output vs. Air Fuel Ratio (AFR)"*

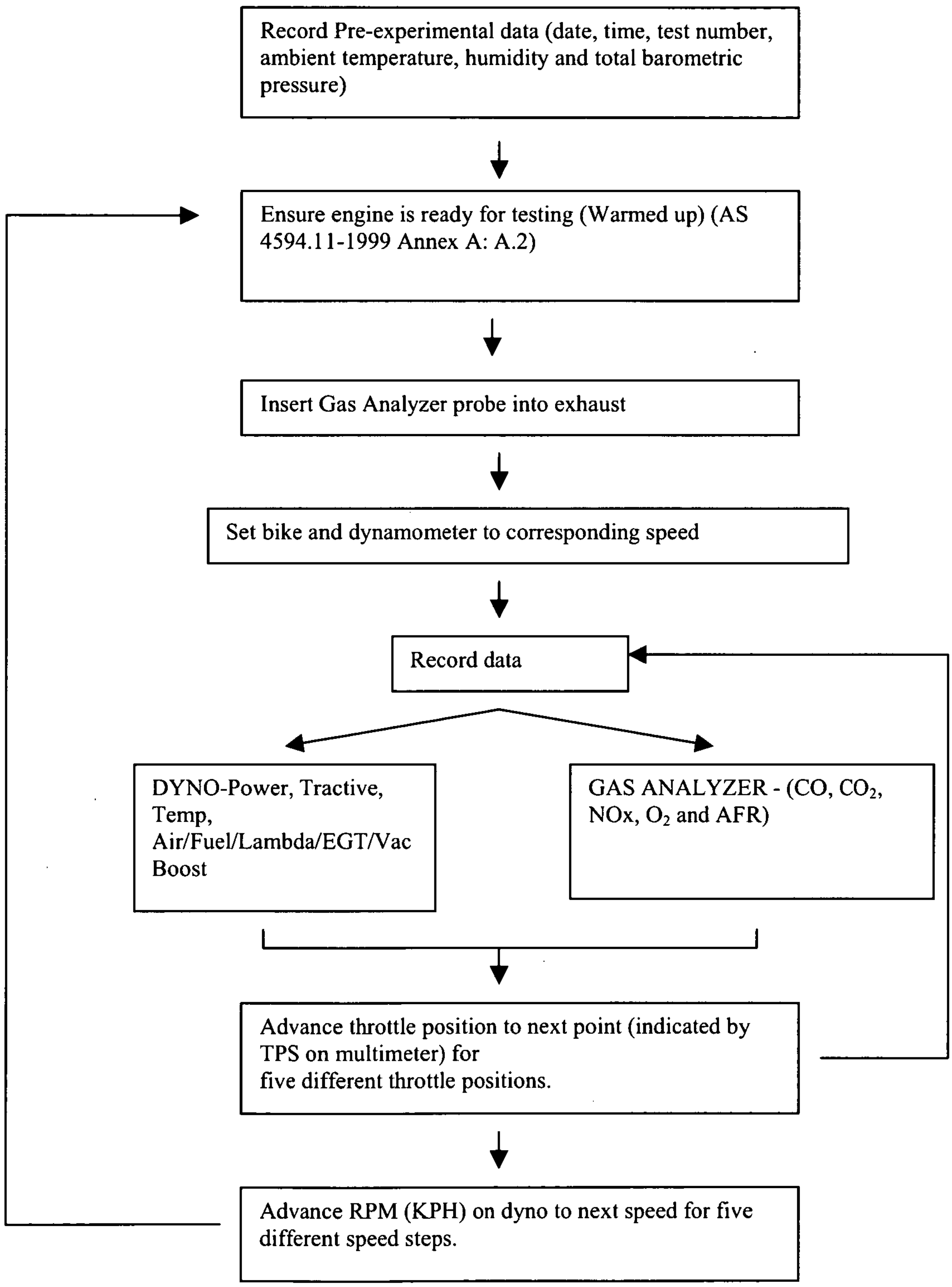


Figure 3.16 Experimental procedure for exhaust emissions vs. air-fuel ratio

3.5 Hydrogen Testing

Dynamometer testing of the converted CT110 allows for a comparison of performance with the (original) gasoline powered engine. Such a comparison needs to be made bearing in mind the design modifications implemented to the CT110. The hydrogen powered CT110 is different from the gasoline powered engine mostly in the method in which the fuel is delivered to the engine. The vehicle as it stands for the following testing procedures is electronically duel fuel injected with controlled variable spark timing. The air-fuel mixture in the hydrogen engine is controlled by the amount of fuel delivered whilst the gasoline engine controls by means of air flow.

The dependent variable in the Hydrogen testing is the throttle position rather than the air fuel ratio. This is due to the lack of accuracy in the narrow band lambda sensor which was used for testing. As the throttle position essentially controls the air-fuel ratio it can be used as the dependent variable.

3.5.1 Power Output vs. Throttle Position (TP)

Aim: To determine the relationship between Power Output vs Throttle Position over different RPM as shown in figure 3.17.

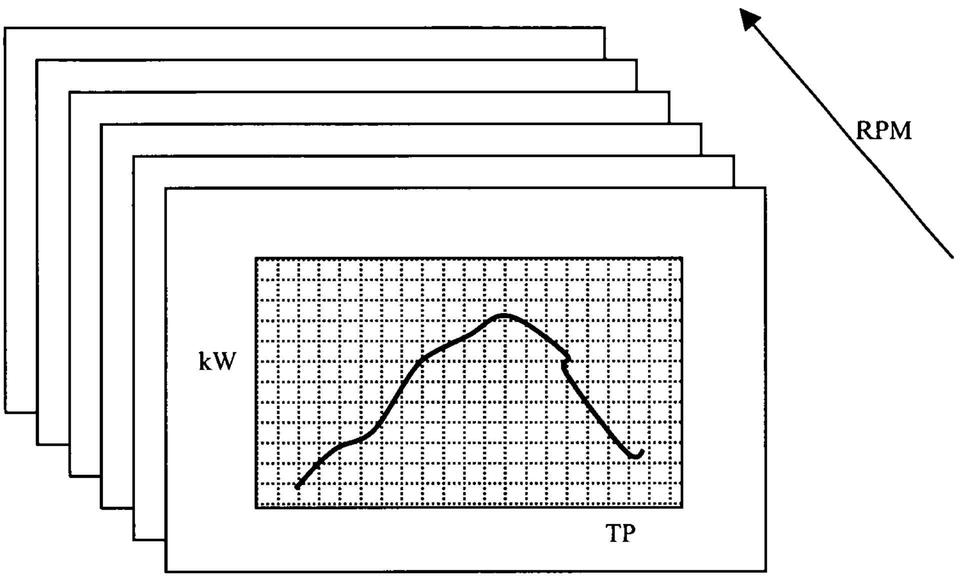


Figure 3.17: Schematic of Power Output vs. Throttle Position

Variables:

Dependent - Throttle Position (%)

Independent - Power Output (HP/kW)

Procedure:

Experimental procedure is represented in figure 3.18

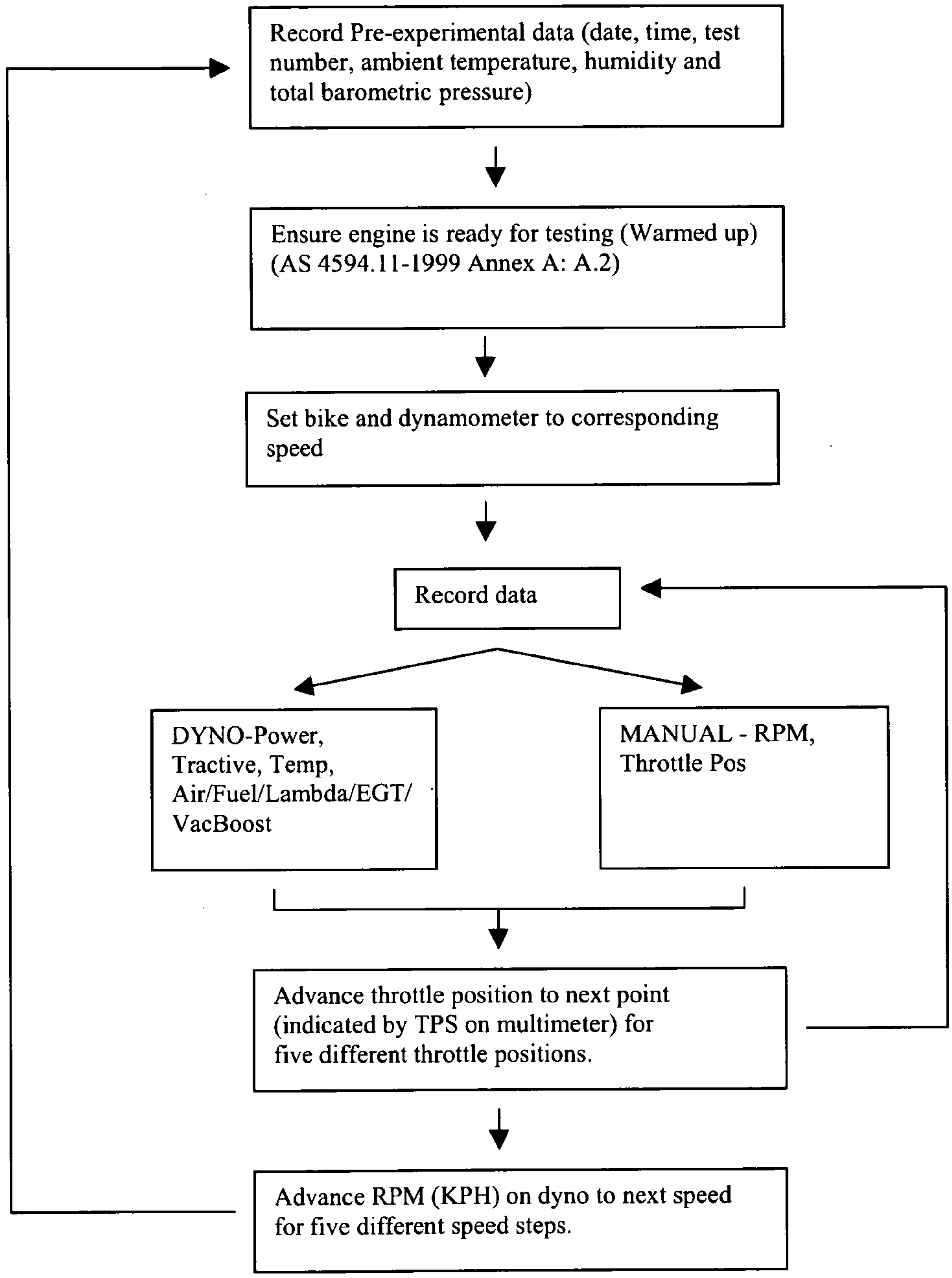


Figure 3.18: Experimental procedure for power vs. throttle position

3.5.2 Thermal Efficiency vs. Throttle Position (TP)

Aim: To determine the relationship between Thermal Efficiency vs. Throttle Position over different RPM as shown in figure 3.19.

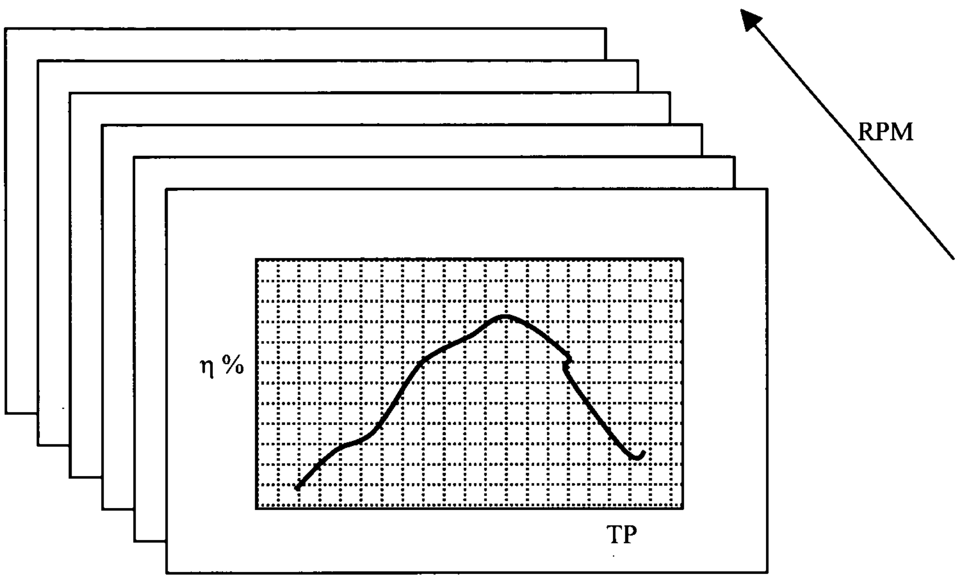


Figure 3.19: Thermal Efficiency vs. Throttle Position

Variables:

Dependent - Throttle Position (%)

Independent - Power Output (HP-kW) / Fuel Flow Rate (m^3/s)

Procedure:

Experimental procedure is represented in figure 3.20

**Note- This experiment can be run in conjunction with "3.3.1 Power Output vs. Air Fuel Ratio (AFR)"*

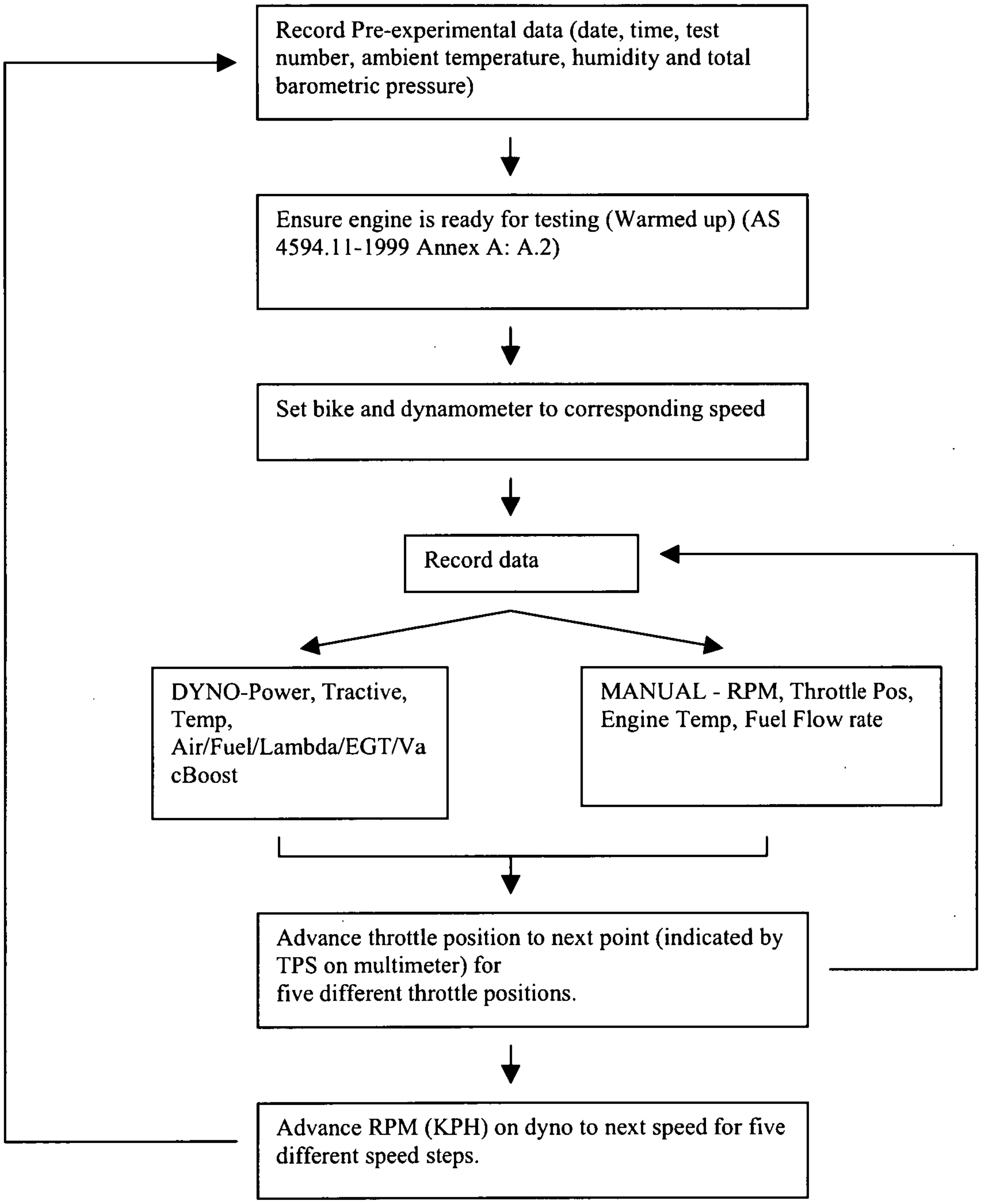


Figure 3.20: Experimental procedure for thermal efficiency vs. throttle position

3.5.3 Emissions vs. Throttle Position (TP)

Aim: To determine the relationship between NOx, HC, CO2, CO vs. Throttle Position over different RPM as shown in figure 3.21.

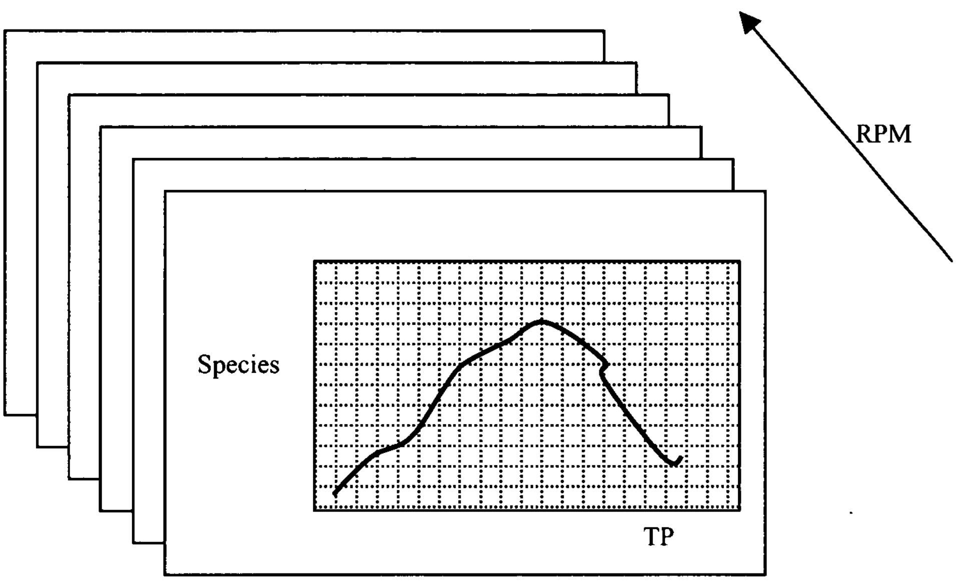


Figure 3.21: Exhaust emission species vs. Throttle Position

Variables:

Dependent - Air Fuel Ratio (%) - Variable of Throttle Position

Independent - Exhaust Emissions (carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxide (NOx), hydrocarbons (HC))

Procedure:

Experimental procedure is represented in figure 3.22.

**Note- This experiment can be run in conjunction with "3.3.2 Power Output vs. Throttle Position (TP)"*

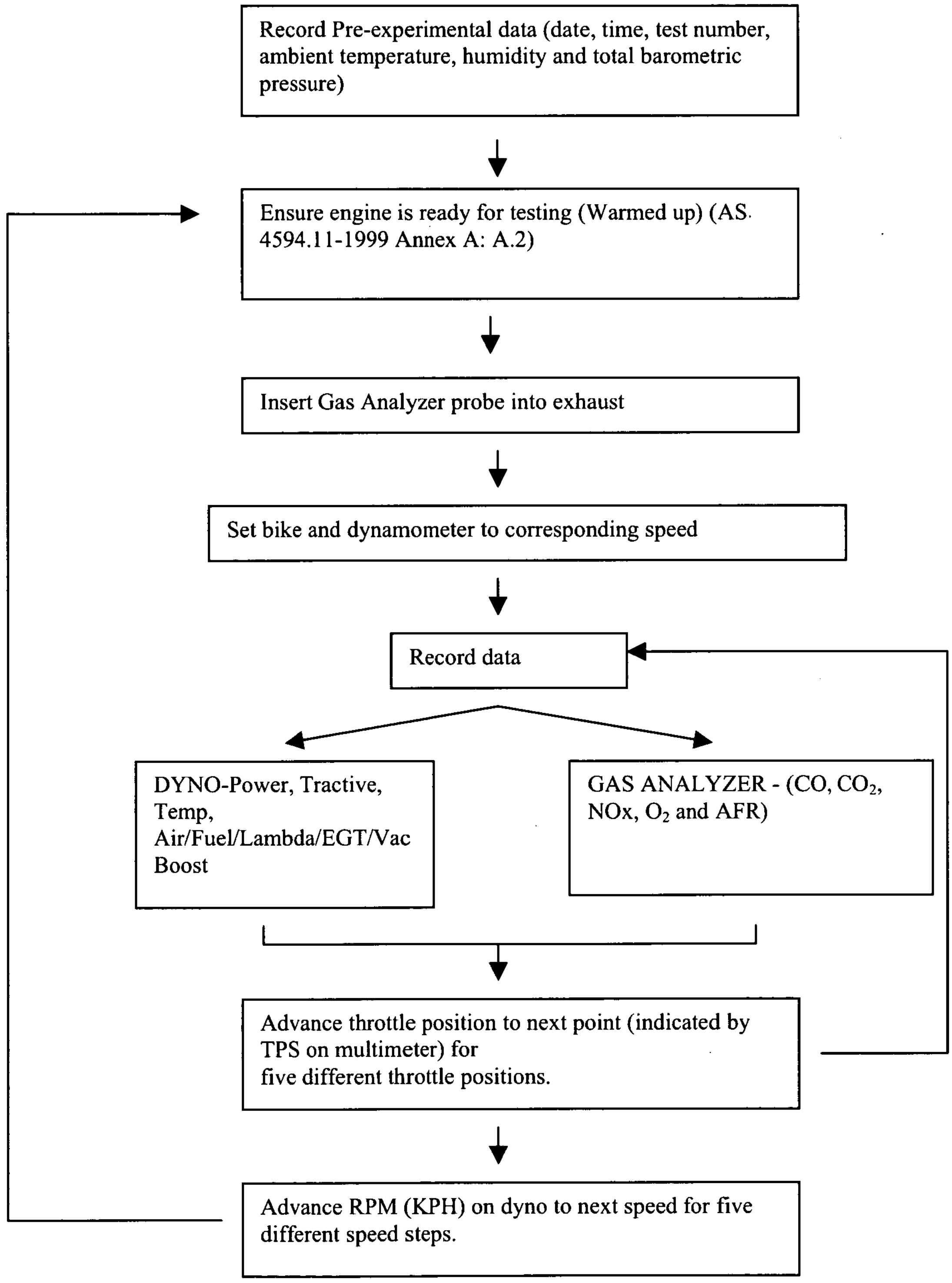


Figure 3.22: Experimental procedure for exhaust emissions vs. throttle position

CHAPTER 4 Vehicle Conversion to Hydrogen

4.1 Introduction

There are a number of design modifications required for a carburetted gasoline (internal combustion) engine to be converted to operate with (fuel injected) hydrogen. These modifications extend to include the following:

- Fuel delivery & storage system
- Ignition system
- Engine control system
- Inlet manifold
- Auxiliary sensors

The conversion from the gasoline to the hydrogen internal combustion engine seeks to be repeatable, safe and economical. This chapter seeks to detail this conversion process along with some relevant safety practices.

Costing of various parts in the project are shown in Appendix J.

4.2 Fuel Delivery Method

Fuel delivery methods for internal combustion engines is a well established topic [13]. The development of electronic fuel injection has meant greater control and user interface for the fuel delivery system of a vehicle. By converting the original fuel system delivery on the CT110 (carburetted) to a fuel injected one, timed delivery of the fuel can be achieved. Additionally, the prevalence of pre-ignition can be minimized. Pre-ignition occurs when the cylinder charge becomes ignited before the ignition by the spark plug. Pre-ignition is considered one of the primary problems encountered in the development of operational hydrogen engines [72].

There are 3 basic methods of fuel delivery available for an internal combustion engine. These are carburetted port (fuel)injection or direct (fuel)-injection. These methods are briefly discussed here along with their applicability to hydrogen internal combustion engines.

With a carburetted fuel delivery system, a device called a carburetor mixes fuel vapor into the (intake) air as it flows into the engine. The unconverted CT110 uses a carburetor to deliver gasoline to the engine. A needle valve (shown in figure 4.1) controls the amount of fuel entering the engine.

Figure 4.1: Needle valve inside the carburetor

The main functions of a carburetor are:

- to keep a small reserve of fuel;
- to vaporize the fuel and prepare a homogeneous air-fuel mixture and
- to supply an air fuel mixture that is of suitable stoichiometry under various load and speed conditions.

[69]

The carburetor is seen as simple and economical option for the internal combustion engine operation. The device requires no electronic control like other (fuel injected) fuel delivery systems. The use of hydrogen in carburetor type systems has previously resulted in pre-ignition due to the low ignition energy of the air fuel mixture in the inlet manifold [72]. This rules out the use of the existing or a modified carburetor.

In a fuel-injected engine, the fuel is injected either within the intake manifold (before the intake valve), known as port fuel injection, or directly into the cylinder chamber, known as direct fuel injection)

Direct fuel injection is seen as the most efficient method of delivering fuel to the engine. With the introduction of the first commercially successful direct-injection gasoline powered vehicle in 1996, the level of research and development into direct injection engines has intensified [80]. From a conversion point of view the development of a direct fuel injected hydrogen internal combustion engine would be challenging. Such a system would require major changes to the engine block, and for successful application most likely a redesigned engine. This is not seen to be an economically viable nor a practical outcome.

The other and most appropriate option for fuel delivery and control in a converted hydrogen engine is port injection. Port injection systems which tend to have less (residual) fuel in the manifold at any one time, can minimize the effect of pre-ignition [72].

For port injected engines, hydrogen is injected into a custom designed inlet manifold to reduce pre-ignition and increase control. Using a control system for injection means that hydrogen can be injected into the cylinder with more accurate timing. Injecting only whilst the inlet valve is open will mean that little unburnt fuels can escape the chamber prior to ignition.

A method of controlling engine power also needs to be considered. Essentially the power can be controlled by fuel regulation, air regulation or a combination of the two. As in the carburetted engine, power is controlled by the mass of air entering the engine. Quality regulation was chosen as the method of control for this engine. In this method the mixture is controlled by the amount of fuel entering the engine. Controlling engine power in this manner allows for the removal of the air throttle valve which is a source of efficiency loss and thus running the engine in a wide open throttle manner. Quality regulation also takes advantage of hydrogen's wide flammability limits by giving the engine the ability to be operated at a wide range of air-fuel mixtures. Literature on hydrogen engines tends to support quality control as the best method of fuel control over air throttle control.

To convert the fuel delivery system to port injected (hydrogen), the following components are needed.

4.2.1 Fuel Lines

Selected fuel lines have to have the following properties:

- be able to withstand pressures (between 100-500kPa);
- have the ability to withstand temperatures of that of the engine and exhaust system (engine temperatures up to 165°C and above 200°C for exhaust as seen in Appendix G);
- durability (have the ability to withstand knocks without puncturing or leaking);
- be able to withstand the effects of Hydrogen embrittlement.;
- be readily available and replaceable.

There were two types of fuel lines used in this investigation. For hosing to the inlet manifold and other engine hosing stainless steel braided hose was used. This hose is particularly resistant to engine temperatures, leakage, physical damage and hydrogen embrittlement. For testing Teflon rubber hose was used to connect between the cylinders, flow boar. and the engine. The hose was rated to withstand 10 bar of pressure; five times that of the operating conditions. This hose is also resistant to environmental temperatures, possible physical damage and hydrogen embrittlement.

4.2.2 Fuel Injectors

Selection of fuel injectors is a critical parameter in the design of a hydrogen internal combustion engine. The function of the fuel injector is to aid in the delivery of precise amounts of hydrogen to the inlet manifold at an accurately defined time (with the assistance of a suitable engine management system or control devise). A fuel injector is fundamentally an electronically controlled valve. The amount of fuel that the injector is required to deliver is a function of engine size, engine speed, fuel properties, atmospheric conditions and desired air/fuel mixture.

Prior to selecting fuel injectors for the hydrogen engine, calculations were made to ensure selected injectors would satisfy the requirements. A fuel flow calculator was developed to ascertain fuel flow required to run the engine at differing conditions. It is shown in figure 4.2. The program is also available as a softcopy in Appendix CD1.

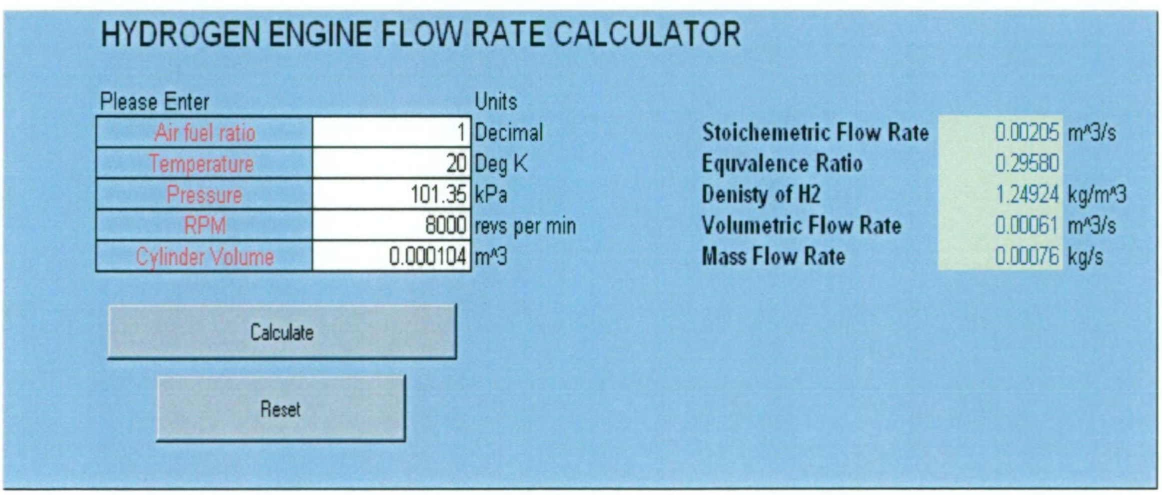


Figure 4.2: Hydrogen Engine flow rate calculator

Flow rates were calculated as follows:

<u>Calculation of Hydrogen Flow Rates</u>

Cylinder Volume = 105.1 cc

= 1.05×10^{-4} m^3

Rev rate = R rpm

Intake stroke per 2 rev = 1

Intake stroke per rev =0.5

Hydrogen stoichiometric volume = 29.58% [51]

Hydrogen density at Standard Temperature and Pressure (STP) = 0.0838 kg/m^3 [51]

*Note STP 20°C, 760mm Hg

Hydrogen density = 0.0838 x (298/T) x (P/101.3)

T is temperature in Kelvin

P is *pressure* in kPa

Stoichemetric volumetric flow rate = Number Intake Stokes/sec x Volume x Stoichemetric Vol H2

= ((0.5 x R)/60) *[rev/sec]* x (1.05×10^{-4}) *[m^3]* x (0.2958) *[no unit]*

= R x 2.59×10^{-7} m^3/s

Volumetric flow rate = $\phi \times R \times 2.59 \times 10^{-7}$ m^3/s

ϕ is the equivalence ratio

Equivalence ratio is defined as the stoichiometric air/fuel ratio divided by the actual air/fuel ratio i.e. $\phi = AF_{stoich}/AF_{actual}$

Mass flow rate = density (H_2) *[kg/m^3]* x Volumetric flow rate *[m^3/s]*

= $\rho \times \phi \times R \times 2.59 \times 10^{-7}$ kg/s

From these calculations it can be seen that there are a number of factors affecting the flow rate of fuel. These include engine parameters and atmospheric conditions which are essentially uncontrollable. There are also a number of engine parameters which can be controlled such as air fuel ratio and RPM. To initially determine the number of fuel injectors, the extreme case of the highest engine RPM and richest engine mix (within the flammability limits of hydrogen) were used. This approach gives the operational flexibility of running the engine at over all possible conditions within the RPM range allowed and also provides for future research and development to be undertaken.

Due to the low density of hydrogen, compared to liquid transport fuels, a relatively high flow injector must be utilized. Liquid (fuel) injectors can suffer from premature failure and orifice contamination if used with gaseous fuels. Additionally, injectors designed for liquid are not capable of delivering the appropriate flow rates if gases are used. Gaseous fuel injectors are generally designed to work with natural gas, propane and hydrogen in internal combustion engines.

A limited number of manufacturers supply gaseous fuel injectors, one of which is Quantum Technologies. This company can supply high flow gaseous injectors used with hydrogen (model 100078 shown in Appendix C1). However, it should be noted that whilst these injectors have been used with hydrogen, they are not specifically designed for this gas but have nevertheless been applied to many hydrogen vehicles such as the Ford Model U SUV [1].

The Quantum 100078 injector selected is advantageous in that:

- it utilizes standard injector electrical connector and control;
- is easily adapted to port injection;
- it offers flexibility of both high and low flow rates;

The Quantum fuel injector claims Hydrogen flow rates of 0.8 g/s at 70-80 psi. It was calculated for these to work that at 8000 rpm (which was determined to be maximum RPM during baseline testing) a short injection of 1.25 g/s of hydrogen gas would be required. From these calculations the best solution was to install two injectors. Furthermore, it is more desirable to have small pulse width (amount of time injector is open for) in large injectors rather than having small injectors open for longer periods of time. With smaller pulse widths the amount of fuel entering the cylinder can be more precisely controlled.

4.2.3 Ignition System

The ignition system of an engine has three main purposes. Firstly, it must generate an electric spark that has enough energy to ignite the air-fuel mixture in the chamber. Secondly, it must maintain that spark long enough to allow all air/fuel to ignite. Thirdly, it must deliver the spark in a timely manner to the cylinder, so combustion can occur at the precisly correct time with regards to piston position. This is to optimize the thermal efficiency of the engine and ensure smooth operation.

All ignition systems consist of a primary (low voltage) and secondary circuit (high voltage).

Depending on the type of ignition required, components of the primary circuit include

- Battery
- Ignition Switch
- Ignition Coil (primary winding)
- Triggering Device

The secondary circuit includes these components

- Ignition coil (secondary winding)
- Ignition (spark plug) cables
- Spark Plugs

The gasoline Honda CT110 uses a pulse generator (triggering device), switch, Capacitor Discharge Ignition (CDI) unit and a series of coils and switches to produce a spark at the correct time. The system is 'wasted spark' ignition and hence fires a spark each engine revolution. The system alters ignition timing with engine speed by the means of the CDI unit. At 1500 rpm the spark is generated at 10° before top dead centre (BTDC) whilst at 3400 rpm the spark is generated at 32° BTDC. The circuit diagram for the ignition system on the CT110 is shown in figure 4.3.

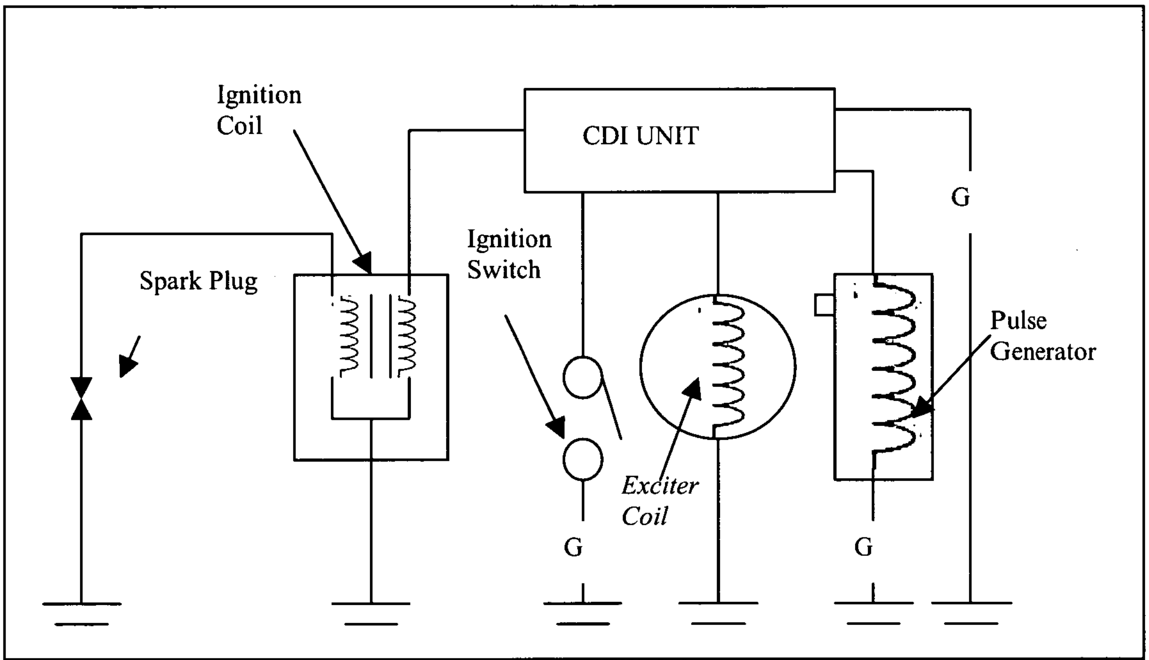


Figure 4.3: Ignition circuitry of the Honda CT110

This ignition system (of the Honda CT110) is much simpler than more modern systems. This is because:

- the bike has only one cylinder, and timing between cylinders is not applicable;
- the cylinder is relatively small, a smaller spark voltage is required to promote effective combustion;
- the lack of sensors and associated control systems on the engine does not allow the ignition system to access information required for programmable ignition.

The converted (hydrogen powered) CT110 however requires a programmable ignition system so that process variables can be controlled. Additionally, if the existing CDI unit was used wasted spark ignition would be employed. This would be a source of pre-ignition as the engine would be sparking during the exhaust stoke as well as the prior to the power stroke. Due to this the system needs to be replaced with a more complex system that avoids unwanted sparking.

The chosen replacement is a high-energy inductive ignition system. Commercially available (replacement) CDI units are not generally designed for single cylinder engines. The use of a Bosch ignition module (model number 1 227 022 008 shown in Appendix C3) and Bosch ignition coil (MEC 717 shown in Appendix C2)) was therefore necessary a more compatible, replaceable, cost effective and available method of ignition. The compatibility of the new ignition system with the MoTec engine management system (detailed below) was also one of the major advantages of the Bosch ignition module and coil configuration.

High energy inductive ignition systems are common on most modern road vehicles. Their spark energy is similar to that of CDI but they offer a longer spark duration, which may promote better combustion at low engine speeds.

Due to the single cylinder ignition distributorless (direct fire) ignition can be employed. The existing spark plug (NGK DR8ES-L) was used with a new ignition lead installed along with the system. The existing lead was attached to the coil from the original CT110 coil and hence a new lead was required. The spark plug gap was reduced slightly (0.7mm to 0.5mm), as the energy required to ignite a hydrogen mixture is less than that of the gasoline charge.

4.2.4 Inlet Manifold Design

Pre ignition and backfiring of fuel in hydrogen engines is a well known problem. Pre-ignition can be minimized with several design techniques. The low ignition energy of hydrogen means that care must be taken to avoid the air-fuel mixture contacting sources of ignition such as hot spots prior to entering the cylinder.

Assisting the design of the inlet manifold was data attained in the baseline testing. Surface temperatures of the gasoline inlet manifold was recorded at full load and engine speed so effective heat transfer design could be applied to the new design. The temperature distribution is shown in Appendix F.

Flow patterns of gas in the manifold must ensure that hydrogen does not gather in any area of the inlet. To combat this problem manifold design includes proximity, angular and flow considerations. Also the design must fit into the limited space available and combat the harsh atmospheric and environmental factors. The design was first established using plastacine-modeling clay to ensure the final design would fit into the required area. The current design incorporates the duel injectors and air intake into a single piece. Design views are shown in figures 4.4-4.7.

Injectors are orientated so as to spray hydrogen directly towards the inlet valves at the top of the cylinder. The injectors are positioned as close to the cylinder as possible to minimize unnecessary contact with potential hot spots prior to reaching the cylinder. This is the most critical parameter in inlet manifold design. The further the gas has to travel to the cylinder the longer its potential be affected by conditions (such as high temperatures) and pre-ignite.

Due to availability, compatibility with hydrogen [78] and heat transfer characteristics Aluminum was used as the material for the fabrication.

Attached to the air intake is a butterfly valve which is used during start up and idling shown in figure 4.11.

Between the engine block and the manifold and between the manifold and the choke plastic gaskets were used to minimize heat transfer between the individual parts. Significant heat transfer to the manifold from the engine block could cause frequent pre-ignition through the air inlet.

The design has successfully incorporated the existing engine assembly. Injector orientation, complete assembly and engine inlet of the completed design are shown in figures 4.8-4.10. Further drawings are shown in Appendix H.

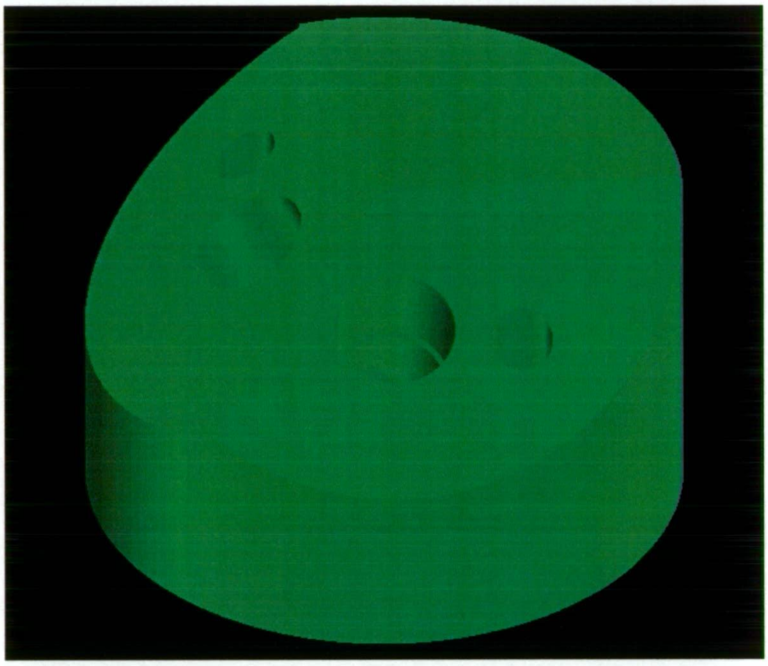


Figure 4.4: Isometric view of inlet manifold design

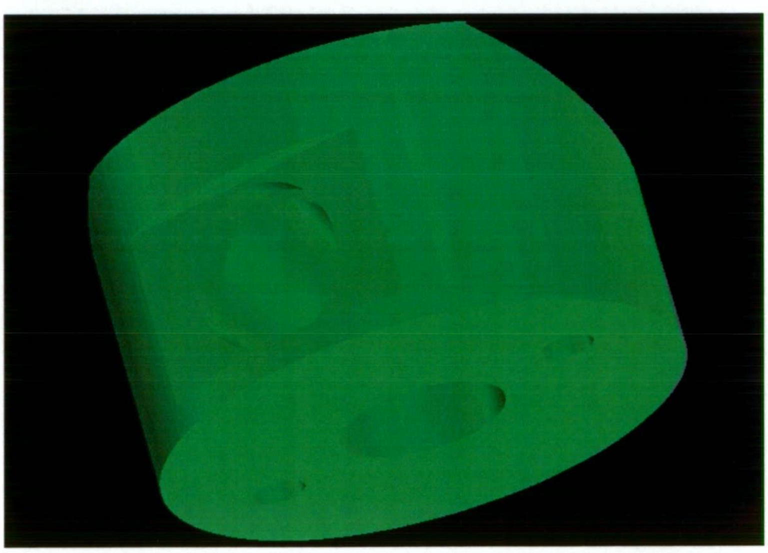


Figure 4.5: View of air intake and engine intake (underside) on inlet manifold

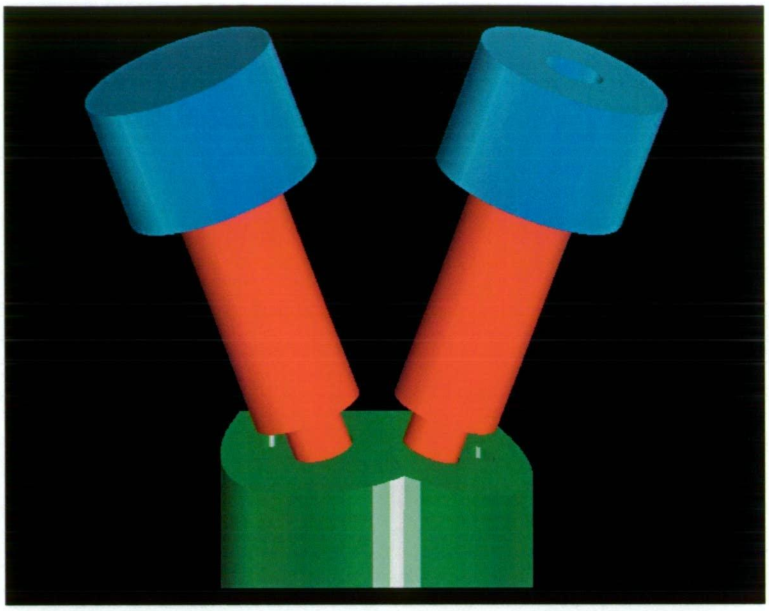


Figure 4.6: View of inlet meanifold design with injector positioning

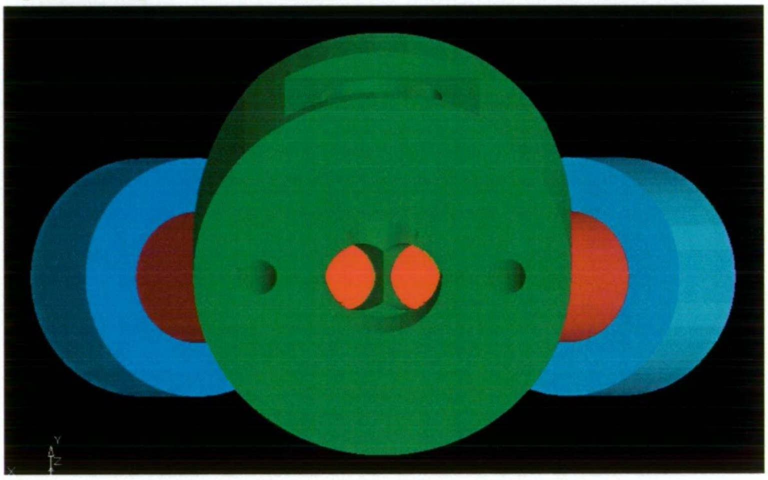


Figure 4.7: View from below inlet manifold

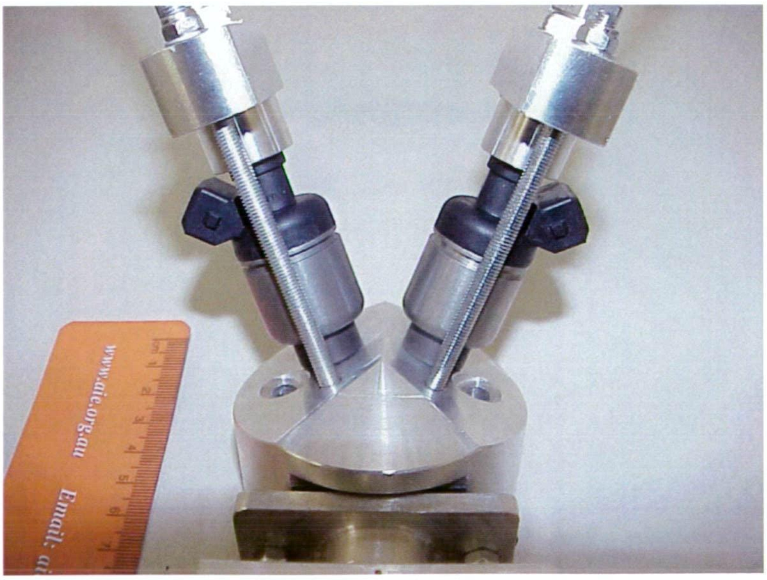


Figure 4.8: View of injector orientation at 10° to the vertical on the inlet manifold

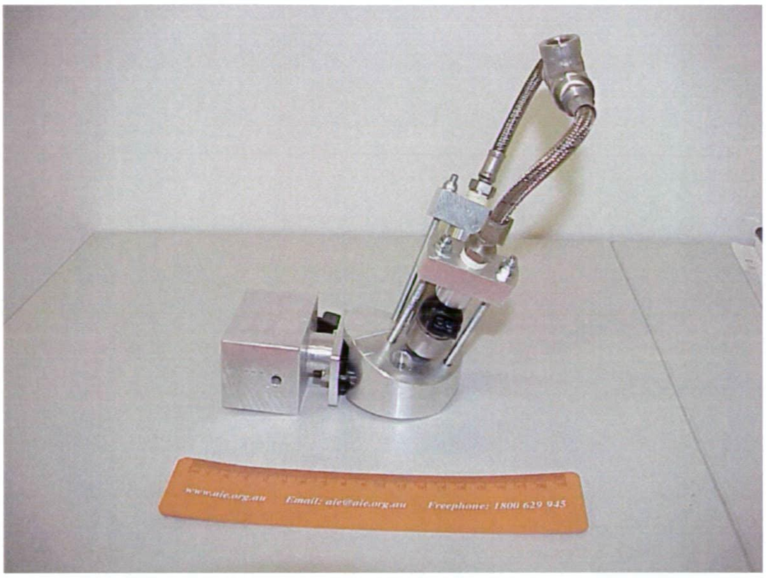


Figure 4.9: Completed inlet manifold, air throttle, injectors and fuel rail assembly

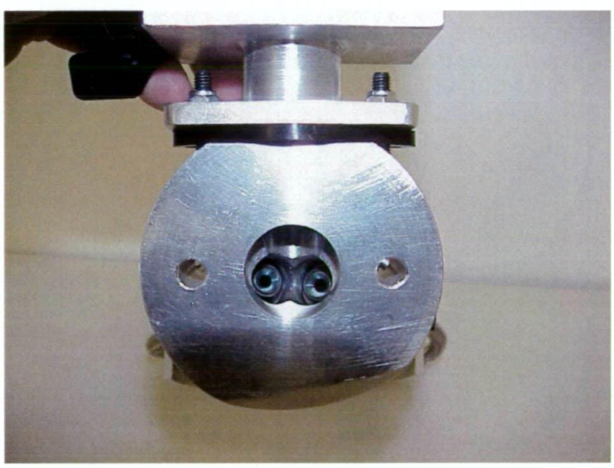


Figure 4.10: Inlet manifold view from below

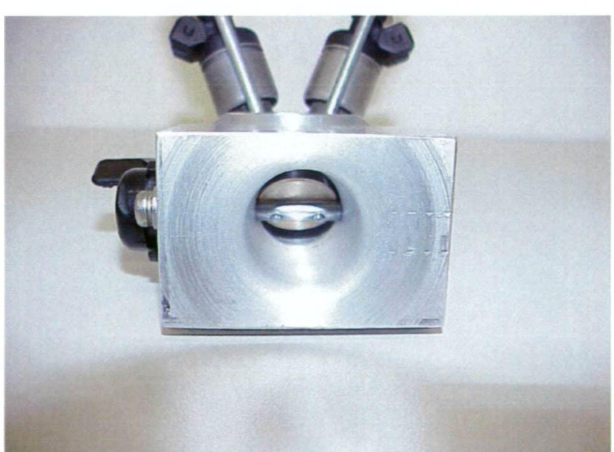


Figure 4.11: View of air inlet with choke

4.3 Fuel Injection and Spark Ignition Control

4.3.1 Engine Management System

An engine management system (EMS) is the basic means of controlling the fuel and ignition systems of an internal combustion engine. An EMS takes measurements from various sensors and then controls the outputs according to the calibration and setup data stored in the EMS's (programmable) memory. Basic functionality of an EMS is shown in figure 4.12.

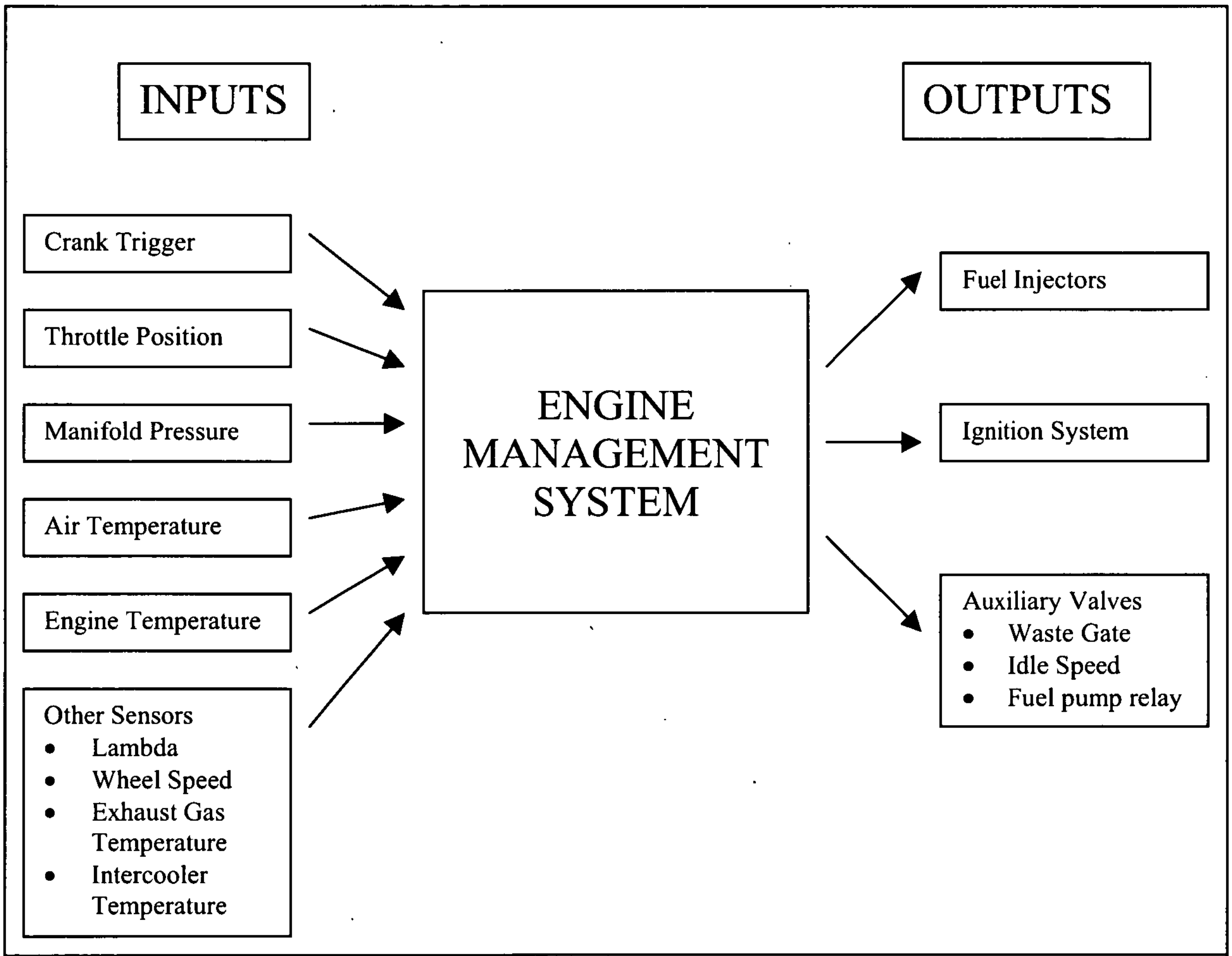


Figure 4.12: Functionality of an engine management system with the range of (possible) sensors (Note: not all these are relevant to the CT110 conversion)

A programmable EMS allows the user to control the output parameters depending on the inputs supplied. The EMS can control parameters by both open and closed loop methods. Parameters such as lambda can be used to modify outputs in real-time. Figure 4.13 shows the functionality the modern day EMS. Most modern road vehicles come supplied with a non-programmable EMS (or ECU) which means that the user has no control over the parameters which affect the engine outputs.

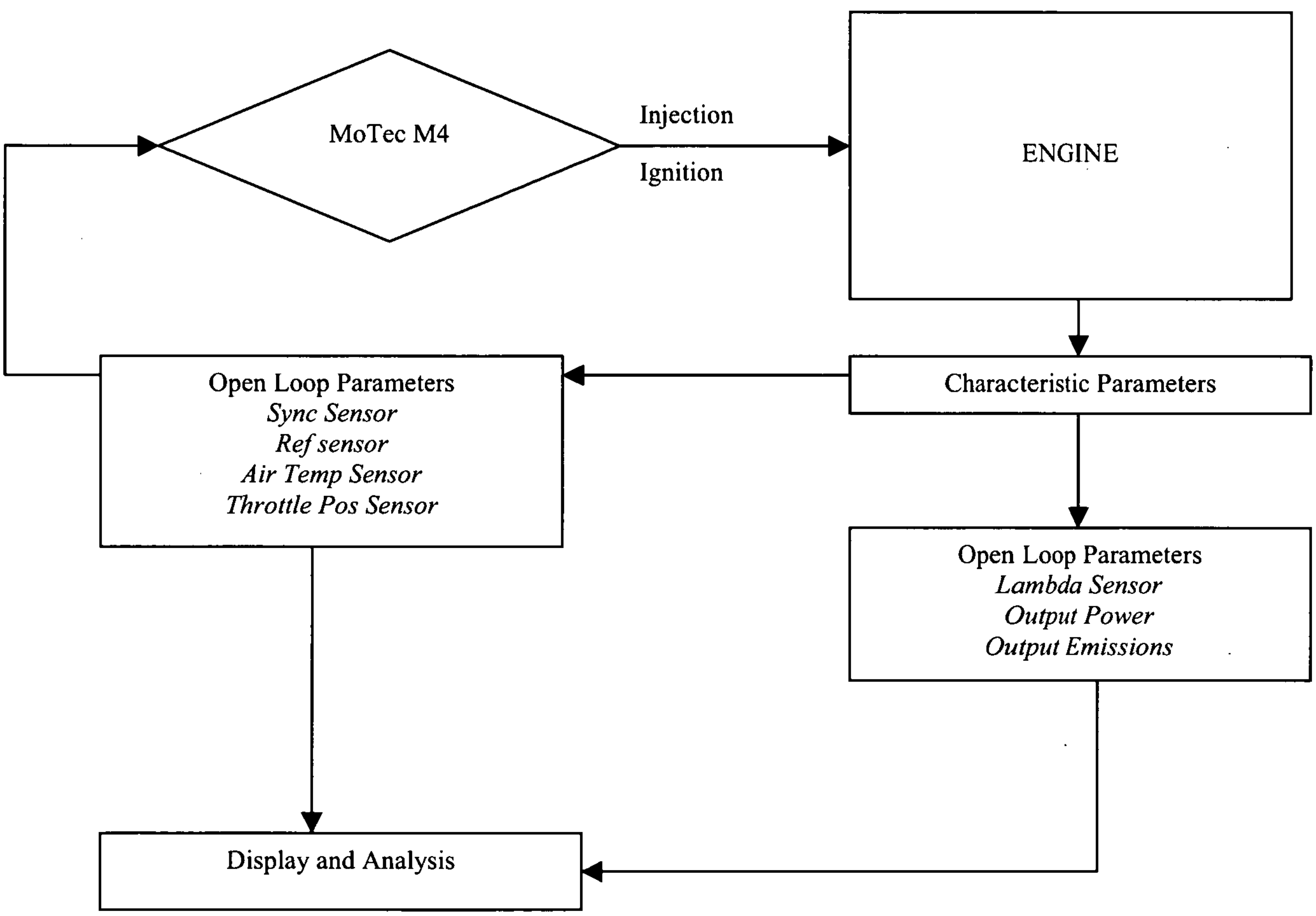


Figure 4.13: Loop control of an engine management system

For a hydrogen engine, control of fuel injection and ignition is a critical factor in the effective operation of the engine. Accurate engine control, via an EMS, assists in avoiding pre-ignition in hydrogen engines

Modern EMS use lookup tables to define the specific outputs. The EMS obtains data from sensors which correspond to numbers in the lookup table which the EMS transmits to the output functions.

Of the many commercially available programmable engine management systems the MoTec M4 unit is used in this conversion. It was chosen due to:

- performance of Motorola 32 Bit 33 MHz gives fast enough feedback and control for this process
- compatibility with most commercially available engine sensors;
- compatibility with small single cylinder engines;
- Simultaneous control of engine parameters (e.g. throttle position and engine speed) under varying load and rpm .
- the sensor, ignition and injector diagnostics functions;
- auxiliary outputs for control
- data logging capabilities;
- support and familiarity with the MoTec M4.

Specification of the MoTec M4 are shown in Appendix C4.

Figure 4.14: The MoTec M4 Engine Management System

It is important to note that since 1998 over seven research higher degree candidates at the University of Tasmania have successfully implemented and used such an engine management system [81] [82] [83] [84]. This internal knowledge is of great assistance.

4.3.2 EMS Set up and Programming

The engine management system is controlled by a corresponding MoTec program whereby the variables can be changed to suit various vehicles and tuning configurations. The software is called the Engine Management Program (EMP) and requires particular inputs to be entered and changed prior to successful operation of the EMS.

The EMP is the means of altering parameters in the EMS for engine tuning. Injection timing, injection period, ignition timing and RPM limit are some of the many outputs that can be controlled by the EMS. Figure 4.14 shows the various options inside the EMP.

The tuning of the EMS is done over all possible operating conditions. Simulation of load is required to ensure that all operating conditions can be covered. An extensive period of time is usually required to effectively tune an EMS.

The setup and tuning programming that occurred for this engine is detailed in Appendix I.

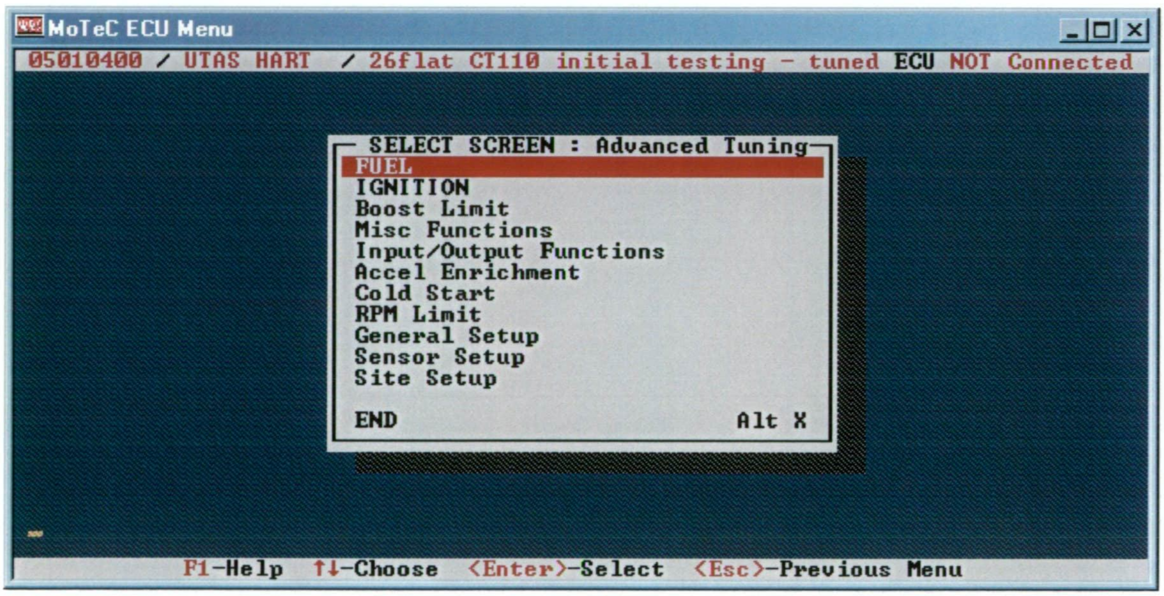


Figure 4.14: The main selection screen in the EMP

4.3.3 Sensors

Sensors are required so that the EMS can effectively control the output functions. Of the many sensors available to control the EMS the following were used in the hydrogen internal combustion engine:

4.3.3.1 Reference Sensor

The reference signal generates pulses to indicate crank position and RPM to the EMS for the purpose of specifying ignition and injection timing. The signal is usually indexed to the rotary motion of the crank, cam or distributor.

The sensor assembly used for this purpose is a Honeywell GT101. This is a reluctance type Hall effect sensor that consists of a magnet, a hall effect sensor and associated circuitry. The sensor detects the movement of a ferromagnetic material (e.g. a steel gearwheel) caused by changes in the magnetic flux (shown in figure 4.15). The tooth of a gear wheel moving in and out of the magnetic field of the sensor influences this magnetic field in different degrees. The sensor element measures the change of the Hall voltage. This allows the changes in the magnetic field to be converted into an electric pulse/signal, reflecting the rotational movement of the gearwheel (after the appropriate filtering and conditioning of the output signal). The output changes from low to high when the leading edge of the tooth passes the center of the sensor as shown in figure 4.16.

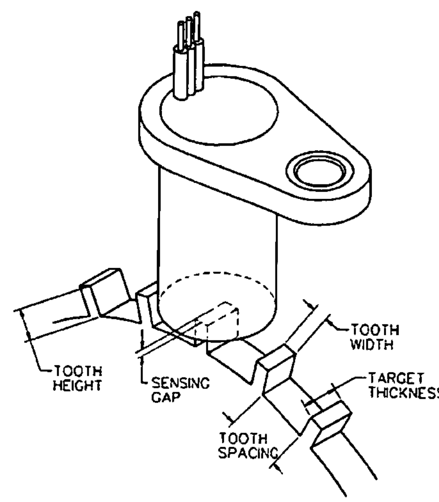


Figure 4.15: Reference Sensor and gear tooth wheel motion

Details of the Honeywell GT101 are shown in Appendix C5.

The sensor is attached to a housing on the cam shaft. A steel gear tooth wheel was

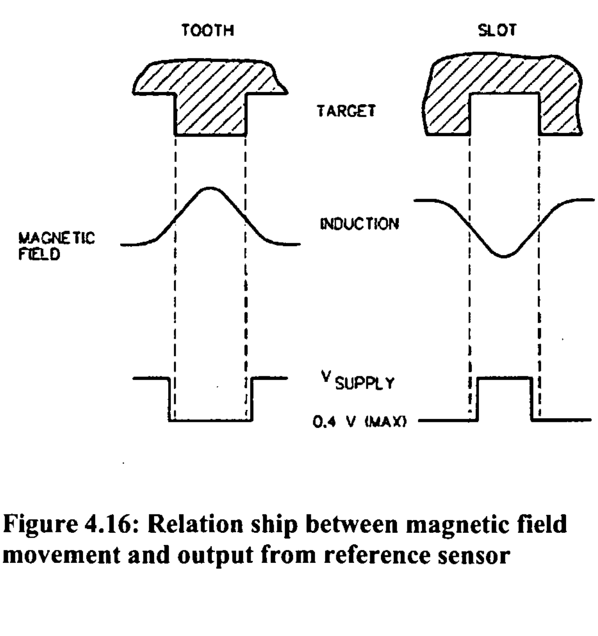


Figure 4.16: Relation ship between magnetic field movement and output from reference sensor

also made up to be attached to the cam shaft. The wheel (shown in figure 4.17) has 16 teeth. As it is located on the camshaft each engine revolution the sensor sends 8 signals to the EMS. Usually 1 tooth per top dead center is sufficient for the EMS but for a single cylinder engine the EMS requires a larger RPM resolution so a larger number of signals is required. Further diagrams of the cam sensor assembly are shown in Appendix G.

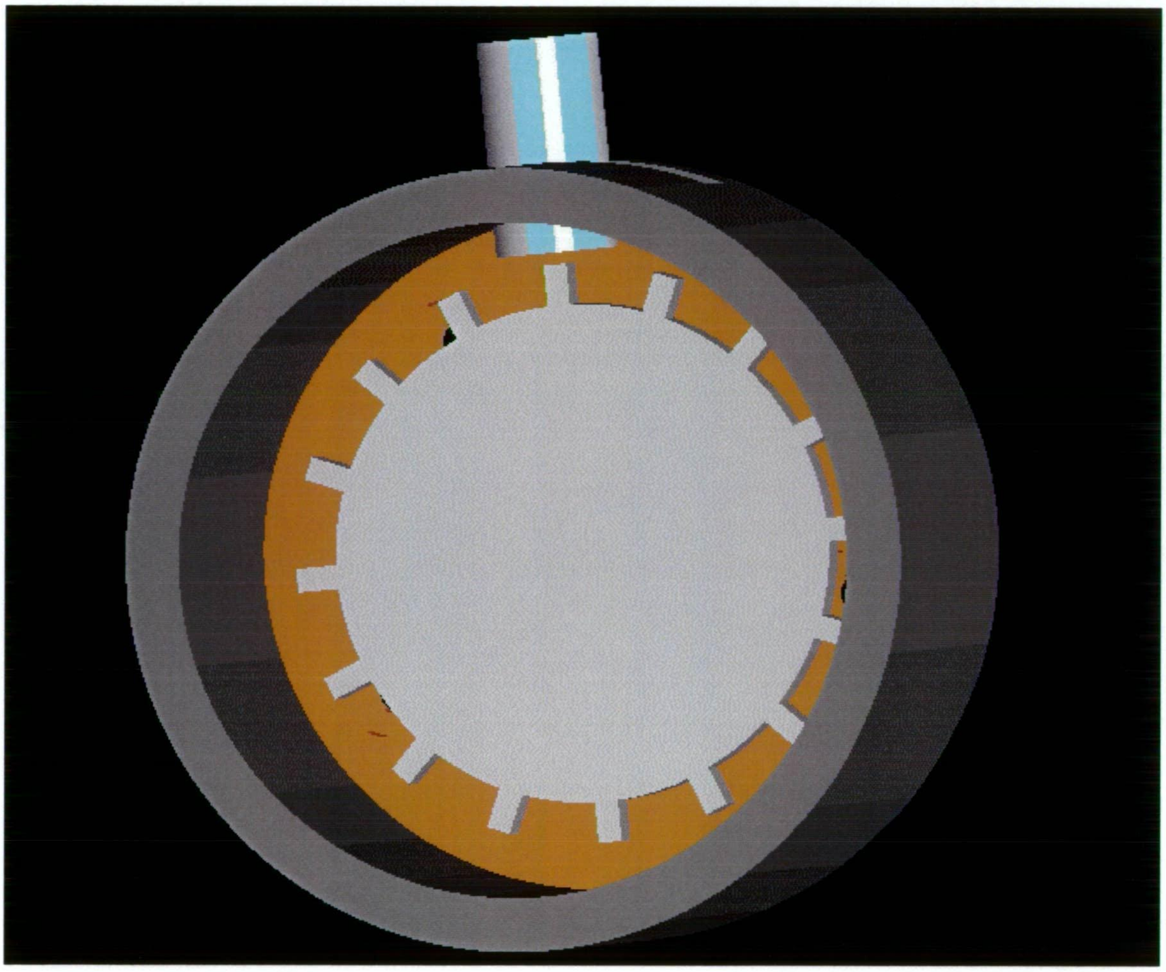


Figure 4.17: Gear tooth sensor, gear tooth wheel and housing design

4.3.3.2 Sync Sensor

The sync sensor provides the EMS with the location of the piston in a thermodynamic cycle. Thus the sync sensor is triggered once every camshaft cycle (720°) and is therefore located on the camshaft. It is required to be placed here for multi coil ignition, sequential injection and non-wasted spark systems. In the hydrogen internal combustion engine it is critical that fuel is not injected during the exhaust stroke and that the ignition system only fires once per thermodynamic cycle hence making the system non-wasted spark. The EMS uses the sync sensor to assist in avoiding such limitations and further avoiding pre-ignition problems.

Like the reference sensor the sync sensor is also a hall effect sensor. Unlike the reference sensor the sync sensor is not a gear tooth sensor. A small rare earth magnet is located on the cam shaft gear tooth disk in figure 4.17. Each time this magnet travels past the sensor, which is perpendicular to the disk, a signal is generated and sent to the EMS. This signal tells the EMS exactly where the piston is relative to the top dead center (TDC).

4.3.3.3 Air Temperature Sensor

The air temperature sensor is used to correct changes in density due to variations in ambient temperature. The air temperature sensor is manufactured by Delco and works on the principle of varying electrical resistance of metals with changes in temperature. Within the EMS programming phase, changes in atmospheric temperature can be compensated for in terms of injection period and ignition timing. Engine running condition can be greatly improved by allowing for changes in atmospheric temperatures. To give an idea:

$$\rho = P \div (R \times T) \qquad \textit{Equation 4.1}$$

where

ρ is Density (kg/m^3)

P is Pressure (Gauge) (Pascals)

T is temperature (degK)

R is gas constant (J/(kg*degK))

It can be seen from Equation 4.1 that density is directly affected by temperature change. This will in turn affect the mass flow rate of air into the engine and hence the air-fuel mixture as well. The EMS uses the relationship to develop correction factors for the atmospheric conditions.

4.3.3.4 Engine Temperature Sensor

The engine temperature sensor is used in a similar manner to the air temperature sensor. It is a K type thermocouple mounted in the engine oil. The sensor was initially used during engine testing to monitor the temperature of the vehicle. The EMS also has the ability to use the engine temperature sensor in programming. When the vehicle is cold more fuel is required for smooth operation. Little information exists about the cold start enrichment process and a 'trial and error' approach is generally employed.

The sensor is mounted in the oil for several reasons. Firstly, the oil temperature gives a good indication of the engine temperature because the liquid is flowing throughout the whole engine. Secondly, problems may arise if a surface temperature probe (mounted externally on the engine block) was used to acquire temperature. This is because such a configuration would make readings susceptible random factors such as splashes from road puddles, rain or intense sunlight. Thirdly, oil itself is a good conductor of heat. The oil temperature sensor is mounted in the oil dip stick. A hole has been bored through a treaded section and the thermocouple placed through the hole and into the oil as shown in figure 4.18.

Figure 4.18: Engine oil temperature sensor

4.3.3.5 Throttle Position Sensor

The Throttle Position Sensor (TPS) indicates to the EMS the load being applied to the engine. The TPS is a potentiometer with a linear characteristic curve. It generates a voltage ratio, which is proportional to the throttle's angle of rotation. The sensor consists of a wiper arm and resistor, each of which are constantly touching. As the throttle position changes, this resistance changes which influences the output voltage. The output voltage is proportional to the throttle position inputted by the driver unit (e.g., a multimeter or an EMS). This data is calibrated in the EMS as a major parameter in fuel ignition and ignition timing. A full (load) throttle setting in the EMS corresponds to 0.94Ω whilst a low throttle setting corresponds to 2.35Ω.

The sensor used is a Bosch TPS (0 280 122 001) which is attached to the throttle on the handlebar. In most applications the TPS is attached to the butterfly valve on the throttle body. This usually gives an accurate reading of how much the throttle as the sensor does not need to allow for possible slack in the throttle cable. As the H2 CT110 had no throttle cable, the best indication point for the throttle position was the handlebar.

The inner sleeve of the sensor was fixed to the inner part of the handle bar which remains still, whilst the outside of the sensor was mounted to the handle which moved anti-clockwise as the operator desires more throttle. The throttle position sensor is shown below in figure 4.19 and detailed in Appendix C6.

Figure 4.19: Throttle of unconverted bike (left) and throttle of converted bike (right) showing attachment of throttle position sensor

4.4 *Fuel Storage*

A number of options exist for the issue of fuel storage medium on the converted CT110. Considerations in this regard were operational conditions and the requirements for each storage medium. The bike was set up on four different fuel delivery configurations:

1. Laboratory operation;
2. Dynamometer tuning operation;
3. Dynamometer testing operation;
4. Road operation.

Each system had different equipment and varied safety features.

4.4.1 Laboratory Testing

Initial testing of the CT110 occurred at the Hydro Tasmania Hydrogen Research Facility located at the School of Engineering at the University of Tasmania. The laboratory is set up with piped (compressed) hydrogen being supplied from G size cylinders. The hydrogen is transported through an on/off valve through a regulator, a flashback arrestor, solenoid valve, through copper lines to the test rig location. Prior to the test rig there is a pressure regulator and two on/off valves. From here stainless steel braided hose runs hydrogen to the fuel rail to the fuel injectors. The engine exhaust is ejected to the environment through flexible hose to the exhaust system of the laboratory.

The solenoid valve is controlled by the laboratory safety system which detects the amount of hydrogen in the laboratory environment. If the environment becomes unstable (greater than 0.4% hydrogen in air) the solenoid valve is activated, and flow of hydrogen halts.

This system was used initially to test the bike and operate it under idling conditions. The hydrogen was supplied to the injectors at a pressure of two bars (gauge). Some load tuning was achieved by running the bike in gear and simulating the bike brake as a load.

The laboratory provided the safest environment for the operation of hydrogen in the bike. It was an important step to operate several hours of running in this environment to ensure that safety issues on the bike could be covered.

The fuel delivery system is shown in figure 4.20 below:

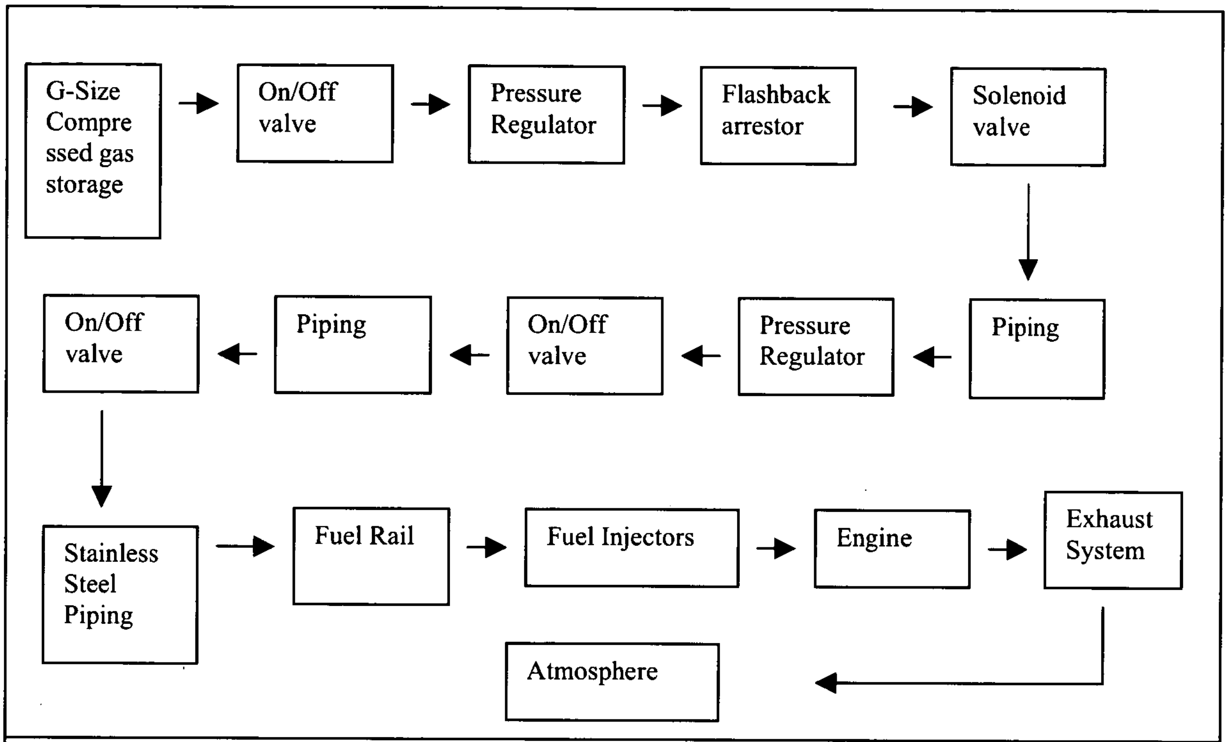


Figure 4.20: Fuel delivery system for laboratory operation

4.4.2 Dynamometer tuning operation

Once the initial tests had been carried out in the Hydrogen Laboratory, the next step was to tune the engine under accurate load conditions. The idling conditions were successfully tuned in the laboratory, but load conditions were not really attainable in this environment. Usually with EMS tuning the vehicle can be run on the road and the EMS will log the data and subsequent tuning occurs. This was not really an option for the hydrogen engine because storing explosive fuel on the bike while still tuning the engine is considered unsafe.

Another tuning option is to use a dynamometer, given that one was used previously for gasoline testing it was decided that this option could be used for tuning the hydrogen engine. On the dynamometer the engine could be tuned at several points in a controlled environment.

Attaining tuning data on the dynamometer involved loading the engine (at relatively high load) and tuning the engine (lambda values) for that specific load condition. This occurred over a wide range of load conditions and intermediate values (not tested) were then interpolated. In this way, an initial engine map was obtained. An initial tuning was done on the engine prior to testing. Given more time further tuning of the engine could have occurred. Tuning operation is shown in figure 4.21.

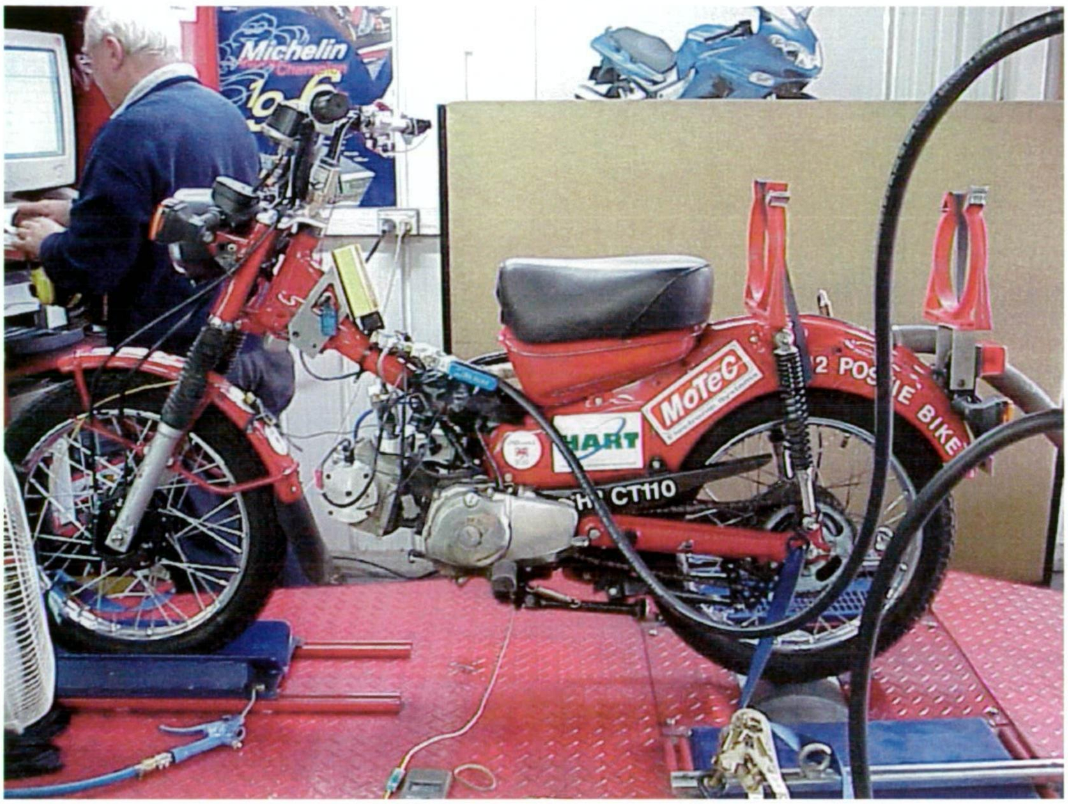


Figure 4.21: Dynamometer tuning of engine

Storage and delivery of hydrogen for dynamometer tuning included a "G-size" cylinder which was transported to the workshop in (open) load bay of a vehicle. In this way, the hydrogen bottle was not enclosed during transport. The cylinder was attached to a trolley for transport and stored outside the workshop

Figure 4.22: Cylinder, regulator and flashback arrestor for dynamometer tuning and testing

affixed to a wall with ratchet tie downs. Attached to the cylinder was a regulator, flashback arrestor (shown in figure 4.22), flexible hosing and a manual on/off ball valve (shown in figure 4.23). This system was connected to the fuel rail which intern delivered hydrogen to the fuel injectors.

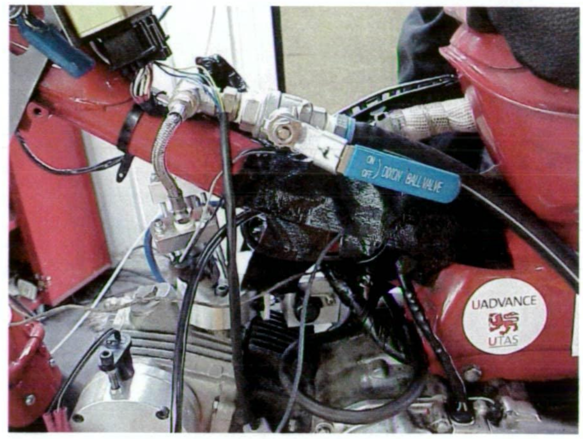


Figure 4.23: On/off ball valve for dynamometer tuning and testing

The system is detailed in figure 4.24:

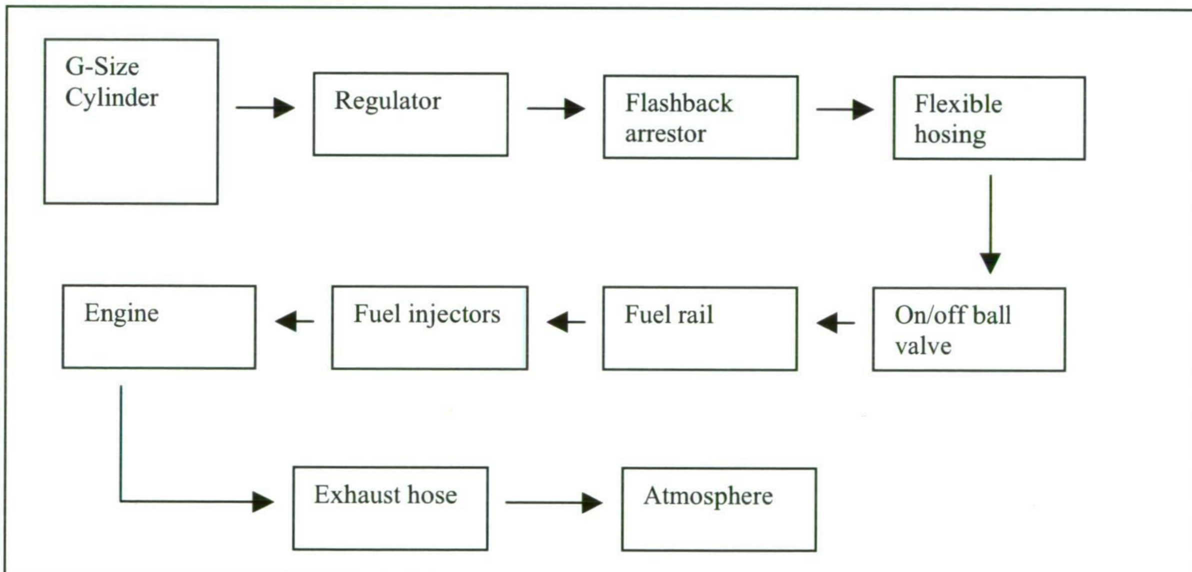


Figure 4.24: Fuel delivery for dynamometer tuning

4.4.3 Dynamometer testing operation

Dynamometer testing of the hydrogen engine was carried out on the same equipment used to tune the engine with one major change. During testing the flow rate of the fuel is also required in order to establish thermal efficiencies for the engine. Thus the flow board was included in the system (section 3.1.4). The only alteration to the system shown above then was the flow tube which occurred after the hosing from the cylinder and extra hosing between the flow tube and the on/off valve. Flashback arrestor, cylinder, regulator and on/off valve are shown in figures 4.22-4.23.

The system is shown diagrammatically in figure 4.25 below:

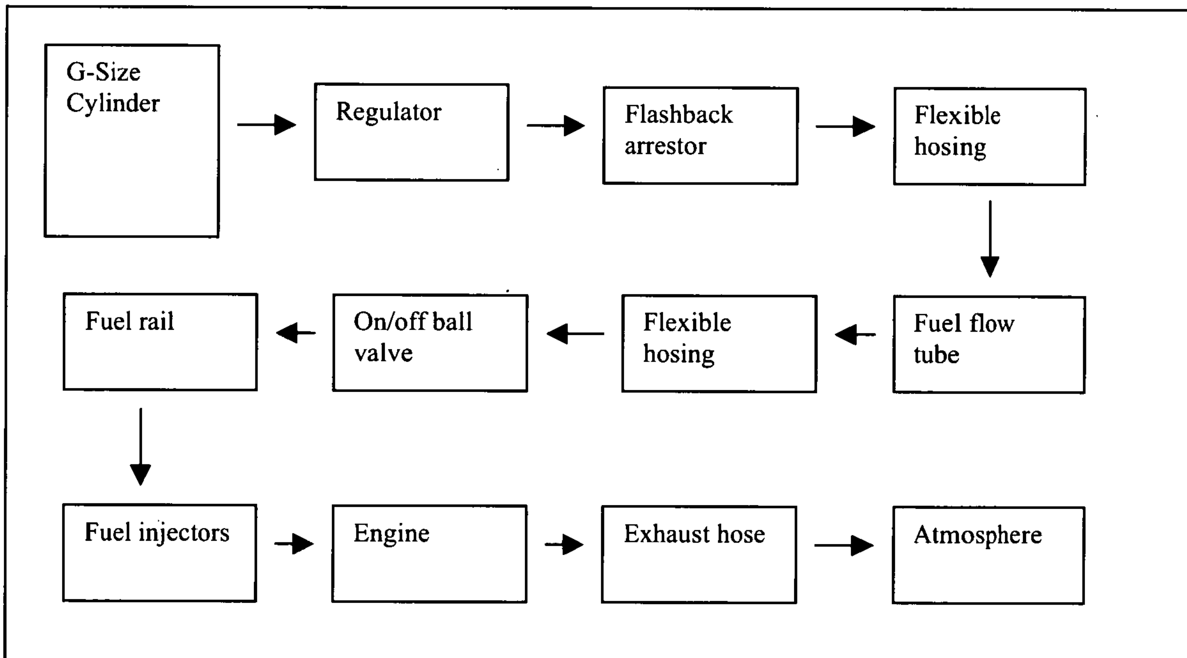


Figure 4.25: Fuel delivery for dynamometer testing

4.4.4 Road operation

The final aspect of fuel storage and design was the operation of the vehicle on the road. This was seen as an important step in the public acceptance as hydrogen as a transportation fuel and was an important goal of this project. It also provided some realistic indication of the maneuverability of the vehicle with the design changes included (and the presence of a heavy gas bottle at the rear). The design includes a compressed gas cylinder attached to the rear of the bike with ancillary equipment safely delivering the fuel to the engine. It was found that the compressed gas cylinders were quite cumbersome and really not the ideal option for storage on a small vehicle such as a motorbike. The weight distribution was acceptable yet the cylinder left no space for other onboard equipment. Nevertheless it was important to display the first prototype vehicle on the road.

Sourcing of small compressed gas cylinders for hydrogen application proved to be a difficult task. Cylinders that gas manufacturers such as BOC and Air-Liquide supply are generally not designed for transport application but more for stationary applications due mainly to the needs of the average customer. Consequently the smallest cylinder that can be supplied filled with hydrogen is a D-Size cylinder. This was chosen to be the applied storage method for road use Given time a smaller cylinder could be purchased or manufactured although refilling issues would have to be overcome. The properties are shown in table 4.1.

Table 4.1: D Size Hydrogen Cylinder Properties [60]

Nominal Fill Pressure (kPa)	16600
Approx. capacity (Ideal Gas Liters)	1500
Outside Diameter (mm)	175
Height (mm)	620
Tare Weight (hg)	10
Internal Water Capacity (liters)	10

The storage system on the bike for road operation was similar to other systems used previously in that it included a cylinder and ancillary equipment to deliver the gas. The system included a D-size cylinder connected to a regulator, flashback arrestor, stainless steel braided flexible hose, manual on/off ball valve, fuel rail and fuel injectors. The exhaust system was the standard exhaust that comes with the bike and this was vented to the atmosphere as any exhaust system would.

The system is shown diagrammatically in figure 4.26 below:

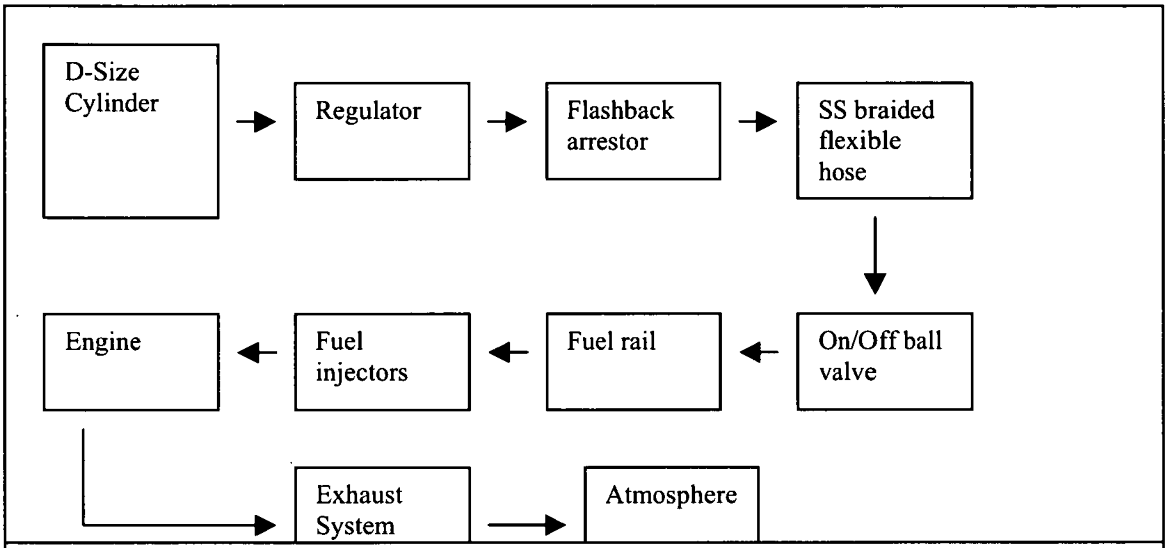


Figure 4.26: Fuel delivery for road operation

4.4.5 Safety Issues

Various safety features needed to be included in each of the fuel storage systems to ensure the safety of operators, onlookers and equipment. These features included both design aspects as well as procedures. The low ignition energy of hydrogen and it's wide flammability limit means that a wide variety of safety issue need to be considered and appropriate precautions are taken.

The hydrogen engine itself had some safety features specific to the hydrogen engine. All piping used in the storage systems were selected to be able to withstand:

- maximum pressures that the equipment would be subjected to (100-500kPa gauge);
- maximum temperatures that may occur (up to 165°C on engine, above 200°C on the exhaust);
- the effects of hydrogen embrittlement;
- the effects of hydrogen leakage;
- the effects of any impacts that may occur;

The piping was located so that regular testing and possible replacement could occur. Pressure and temperature requirements were adhered to with at least a factor of safety of two. Sealant tape was used in every joint where there was metal to metal contact. Tape used was specifically designed for gas applications with a compatibility to hydrogen. When switched off, the engine cut off the operation of the fuel through the EMS setup. This meant that once the engine stopped running no fuel was delivered. Beyond 8000 rpm the engine was programmed not to work also by means of the EMS. This meant the engine could not be damaged which could lead to a hydrogen leak. Regulators, flashback arrestors, piping and valve on the bike were all hydrogen compatible. Baseline testing on gasoline provided information that the maximum rpm of the engine was 8000 and thus this value was taken on for the hydrogen engine.

The engine uses crankcase ventilation to remove residual gases in the crankcase. A valve at the top of the crankcase allowed gases that build up in the crankcase to be vented to the atmosphere. Crankcase ventilation reduces the possibility of explosion within the crankcase which can possibly cause engine damage leading to possible hydrogen leaks.

Other than safety consideration on the engine itself, there were several other safety measures which were implemented to protect operators, onlookers and peripheral equipment . They are detailed below.

- Leak testing was performed regularly before and whilst the engine was running. This was done with soapy water (shown in figure 4.27) which was sprayed onto all connections from the cylinder through to the injectors. If there was a leak the soapy water would bubble at the surface. Using soapy water to test for gaseous leaks is in accordance with *AS 2508, Safe Storage and Handling Information Card.* Pressure testing is another way to check for leaks. Once under pressure the cylinder can be turned off and over a period of time the regulator can be watched to see if the pressure drops. If the pressure reduces, this indicates that there is a leak in the system and soapy water is then used to find the source of leakage. Leak testing is a critical safety aspect of the engine and must be continually applied to ensure safety is maintained. As detecting hydrogen through sight and smell is virtually impossible these leak testing procedures are further validated.

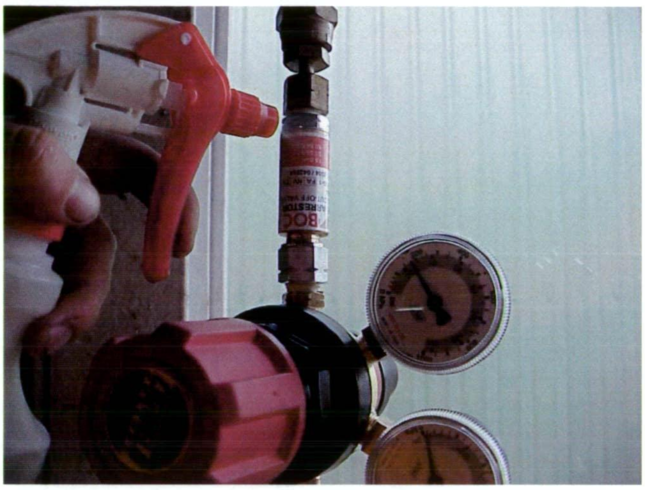


Figure 4.27: Leak testing being performed whilst testing

- In testing and laboratory conditions operators are required to wear flame repellant suits in the event of hydrogen or other flames being emitted from the engine. The suits are classed as flame retardant are used in applications where fire is a hazard or potential hazard. Initial testing produced backfiring through the inlet manifold which definitely necessitates this safety measure. In the event of a hydrogen leak and explosion the suits reduce the risk of injury or death to area occupants.

- Other personal protection equipment such as eyewear, ear protection and enclosed footwear are required to be worn at all times when the bike was in an enclosed environment.
- Whilst in enclosed areas all mobile phones and electrical equipment was switched off. All laptops and recording equipment was used outside the rigs safety area which is 1.6 meters from the engine. In the event of a leak mobile telephones and electrical equipment could potentially cause a spark which could ignite leaking hydrogen.
- Whilst in enclosed areas static discharge was performed by personal. In the event of a hydrogen leak static electricity has enough energy to ignite a leaked hydrogen mixture. Equipment such as flow boards where also earthed.
- Whilst the bike was being used in a enclosed area gas storage was outside that area. The most dangerous part of the hydrogen fuel system is the storage itself. This is because the greatest concentration of hydrogen is in this area. Storing the fuel outside the occupied area means that in the event of a cylinder explosion the occupants are safe from the effects of the accident.
- Access and use of the hydrogen storage and delivery system is limited to primary researchers and supervisor. Reducing contact to critical parts of the system is one of the best preventative measures in reduction of risk of explosion.

CHAPTER 5 Performance of Gasoline and Hydrogen internal combustion engines

5.1 Testing accuracy

Prior to presenting experimental results, a basic appraisal of the accuracy obtained is required for data validation. The accuracy is based upon the testing procedure set out in Chapter 2, which was under the guidance of AS 4594.11. Testing accuracy is a parameter of variance in obtained measurement data and adherence to specified guidelines outlined.

5.1.1 Compliance with testing guidelines

- Testing procedures were attained under stabilized normal conditions for all tests. Power compensations were applied for all tests that varied from standard laboratory conditions. A period of at least 30 seconds holding the test conditions was attained prior to any measurements being undertaken.
- Air inlet temperature was measured within 0.15m of the air cleaner (in compliance with AS 4594.11: Annex A: A.3)
- Variation in engine speed during a test run was averaged at 0.14% for gasoline and 0.99% for hydrogen during the test periods. This is less than the 1% specified by AS 4594.11: Annex A: A.4.
- Brake load was taken three times over the testing period whilst the gasoline fuel consumption was measured. This served as a simultaneous measurement. For hydrogen testing the flow tube data allowed for instantaneous fuel flow measurements. (AS 4594.11: 5.3.6).
- Duration of engine testing period was at least one minute for each test point. This was both for automatic and hand held measurements that were taken after the 30 second stabilization period (AS 4594.11: 5.3.7).
- During testing engine conditions stayed within the manufacturer's limits. As the engine was stationary and it is air cooled fans were employed to simulate the air cooling effect to protect the engine and adhere to relevant standards(AS 4594.11: 5.3.8-5.3.11).
- Testing equipment used fell within the limits specified for accuracy in AS 4594.11: 4.1-4.6).

5.2 Gasoline Engine Qualitative Analysis

5.2.1 General comments about engine and equipment performance

The CT110 exhibited rich burning operation throughout the whole duration of the testing for varied load and throttle position conditions. It is well known that partial rich burning improves the power of the engine. Being a small single cylinder engine powering a motorbike the rich operation may compensate for the loads that it may need to carry. It has been shown previously that maximum power is often seen in rich mixtures. The downside to this tuning configuration is that the engine may not be as efficient. It is noted that the thermal efficiency of the engine was not relatively high, this efficiency is dependant on the air-fuel ratio. For a small engine using a relatively small amount of fuel this is not of great importance. However, burning the mixture rich would also increase the prevalence of unburnt fuel and other emissions in the exhaust.

The range of test data was taken between 30kph to 80kph. It was found that under small speeds the results were inconsistent and non-repeatable. The reliable quantitative results were found at higher engine speed; so the testing was focused at these speeds. A combination of the engine capabilities and the dynamometer size are the most likely explanations for this discrepancy at low speeds. Under low speeds the engine found it difficult to undertake a full range of throttle positions whilst maintaining speed. The variation of air entering the cylinder at this speed would be difficult to control as it would be quite sensitive in the throttle body. Although the dynamometer is rated to be able to test vehicles with small power ratings, the likelihood is that it is more designed for engines with higher power capabilities. The equipment is rated at 450 horse power which is 75 times larger than the maximum capacity of the CT110. It is therefore possible that the equipment lacks clarity at lower speeds. The tractive effort for the engine to spin the roller may have been too large under small loads for accurate results to be obtained.

Gas analyzer data was highly reliable throughout however, adequate care was taken of filters and water traps. It was observed that moisture in the exhaust would build up in the water trap in the line between the exhaust and gas analyzer. Excessive moisture and particulate matter build up in the analyzer line at times caused blockages which would stop the equipment from working. Once a more efficient water trap was used in conjunction with a filter to stop particulate matter, the analyzer worked without interruption.

5.2.2 Qualitative trends of the effects of major process variables on power

Power analysis was done over a number of different speeds. The dependant variable in this experiment was the air to fuel ratio which itself was a function of the throttle position. It can be seen from the results in Figure 5.1 (below) that the engine possessed maximum power prior to the stoichiometric value of 14.7 for gasoline. This is to be expected for most internal combustion engines [3]. The results also show the rich burning nature of the engine. It can be seen that as the fuel mixture becomes more rich the power is reduced. It would be expected that increased richness beyond stoichiometry would result in the cylinder charge not undertaking full combustion.

Between the speed sites it can be seen that the maximum power is relatively constant, which shows that the engine can produce full power at a range of different operating conditions. For a utility vehicle (such as the Honda CT110 'postie bike') which is constantly stopping and starting this is an advantageous feature.

It can be seen in figure 5.1 that the air-fuel ratio is highly influential on the power output of the engine. The reduction in this ratio causes a change in engine combustion, which directly affects the power.

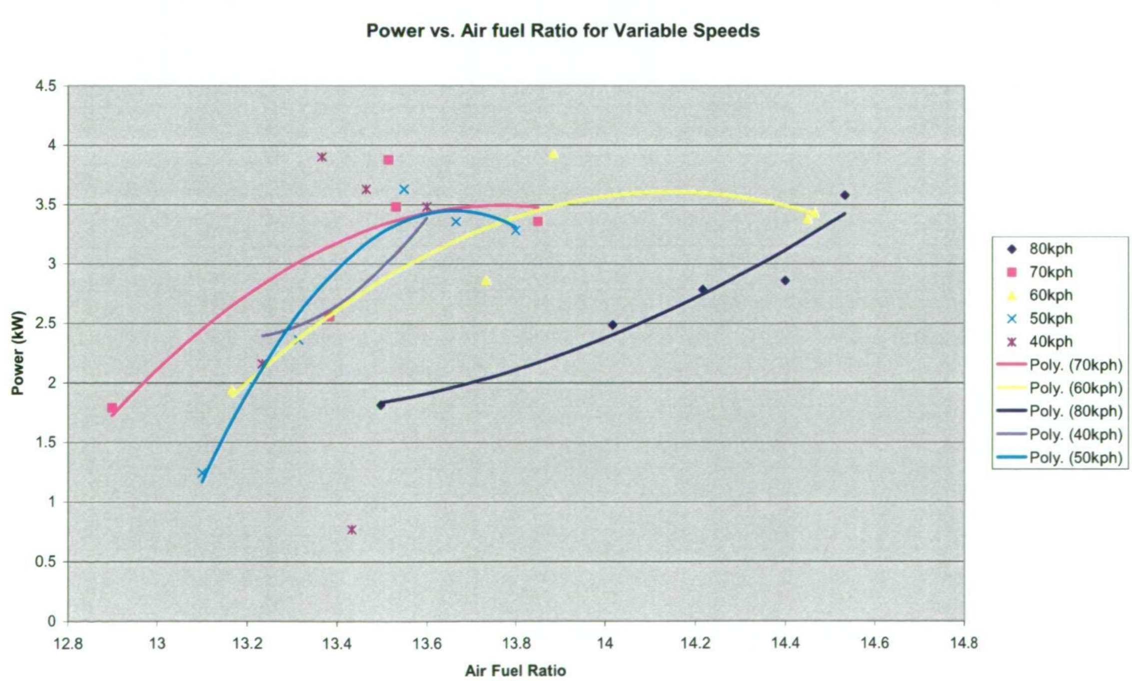


Figure 5.1: Power vs. Air to Fuel ratio over a series of speeds

5.2.3 Qualitative trends of the effects of major process variables on thermal efficiency

The thermal efficiency is defined as the ratio of the work done by an engine to the work due to the heat supplied to it. Expected maximum thermal efficiency for an internal combustion engine is at stoichiometric air to fuel ratio of 14.7. This is because at stoichiometry complete combustion of the air-fuel mix is occurring. As the gasoline driven CT110 operates only rich the maximum thermal efficiency is never reached. The thermal efficiency is often used as a means of assessment of fuel economy. Basically the more work an engine can get out of it's fuel the higher the thermal efficiency and better fuel economy.

It can be seen from the results in Figure 5.2 (below) that the thermal efficiency is increasing towards stoichiometry for all the speed values. The clearest indication of this is in the highest speed value. It is also noted that at the highest speed value that the overall efficiency is decreased. This is most likely due to the additional heat energy produced at higher engine speeds and loads. Also at very low engine temperatures the thermal efficiency is reduced. This is because the fuel is providing energy to heat the engine rather the provide power to the engine.

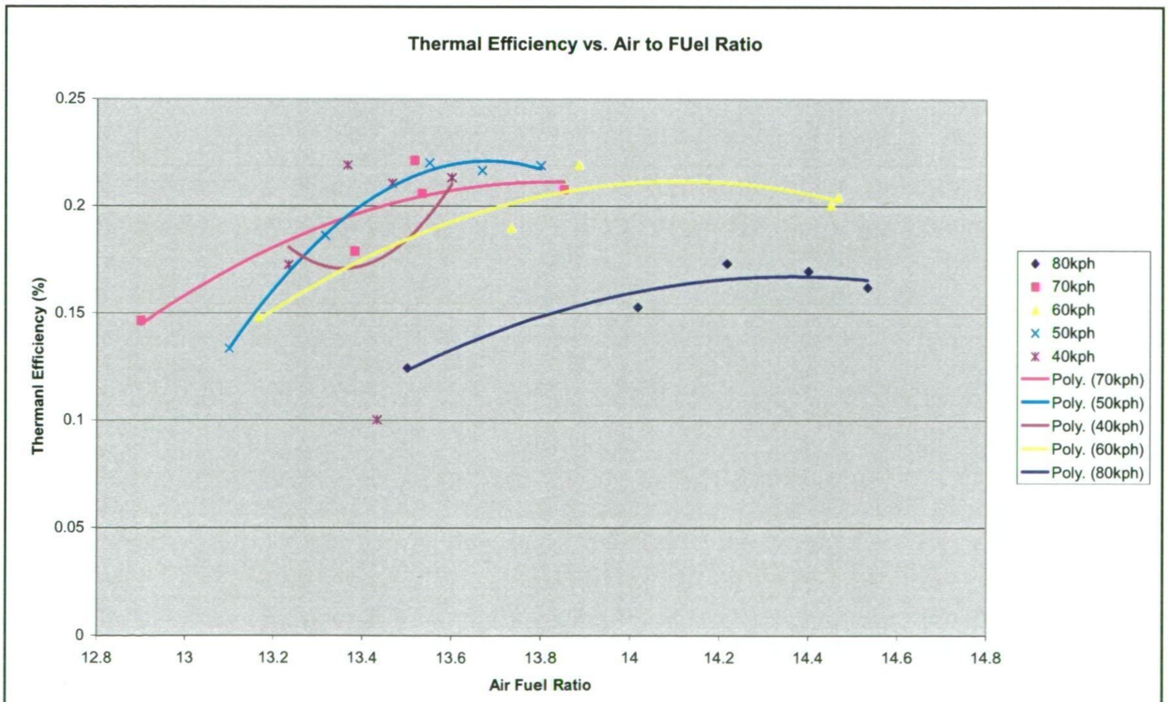


Figure 5.2: Thermal efficiency vs. Air to Fuel ratio over a series of speeds

5.2.4 Qualitative trends of the effects of major process variables on exhaust emissions

Results below show the emissions measured from the CT110 whilst testing over a range of different speeds. The brown line in each figure shows what a typical internal combustion engine emits in accordance with literature [85]. The main process variable in the composition of exhaust gases is the air to fuel ratio which is indicated on the horizontal axis.

Over the limited range of air-fuel ratios which the engine exhibits various trends in emissions can be drawn. For all emissions tested over the engines operating range significant values were observed.

Hydrocarbon (HC) emissions are a result of unburnt fuel in the exhaust. It can be seen (figure 5.3 below) that at the rich operational limits of the CT110, there are large amounts of HC in the exhaust and as the air to fuel ratio approaches stoichiometry the figure reduces. This is because at stoichiometry complete combustion should occur.

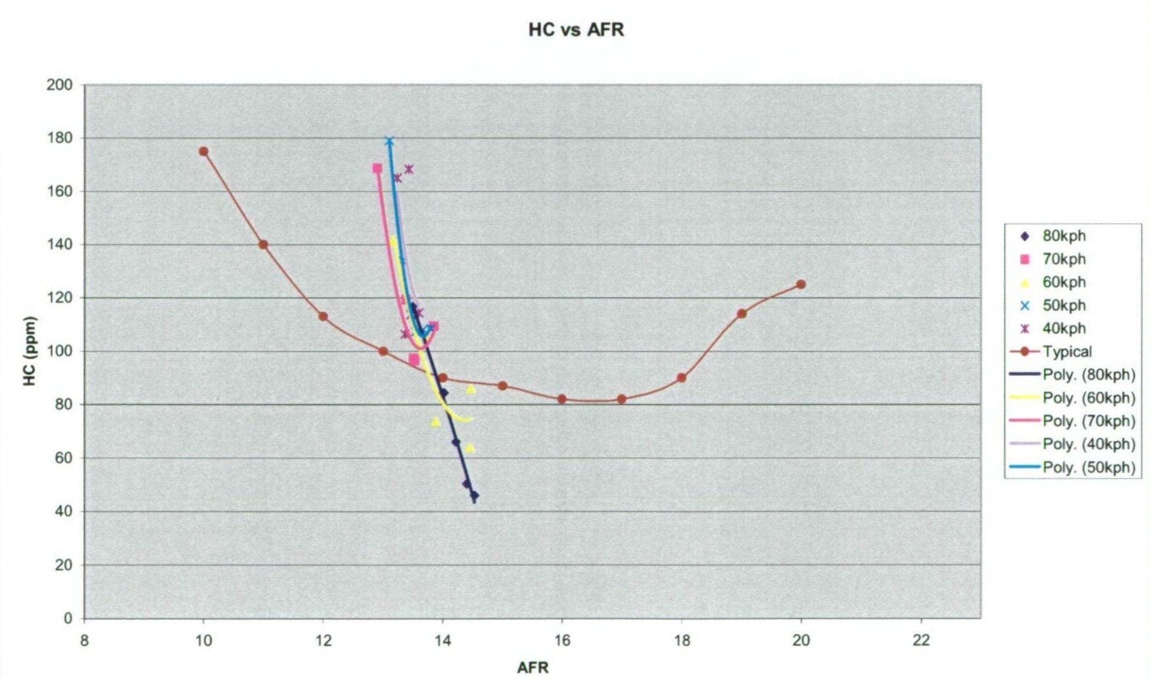


Figure 5.3: Hydrocarbon emissions vs. Air to Fuel ratio over a series of speeds

Carbon Monoxide (CO) is partially burnt fuel which is also a byproduct of incomplete combustion. As with HC emissions the prevalence of CO emissions is greater in a rich mixture due to the lack of oxygen. This is shown by the results displayed in figure 5.4 (below). When combustion takes place in an oxygen starved environment there is insufficient oxygen to oxidize the carbon atoms to CO_2 and CO results. It can be seen that the rich operation of the CT110 engine is causing considerable CO emissions. As the mixture comes closer to stoichiometry CO emissions become less because there is enough oxygen to oxidize the carbon atoms.

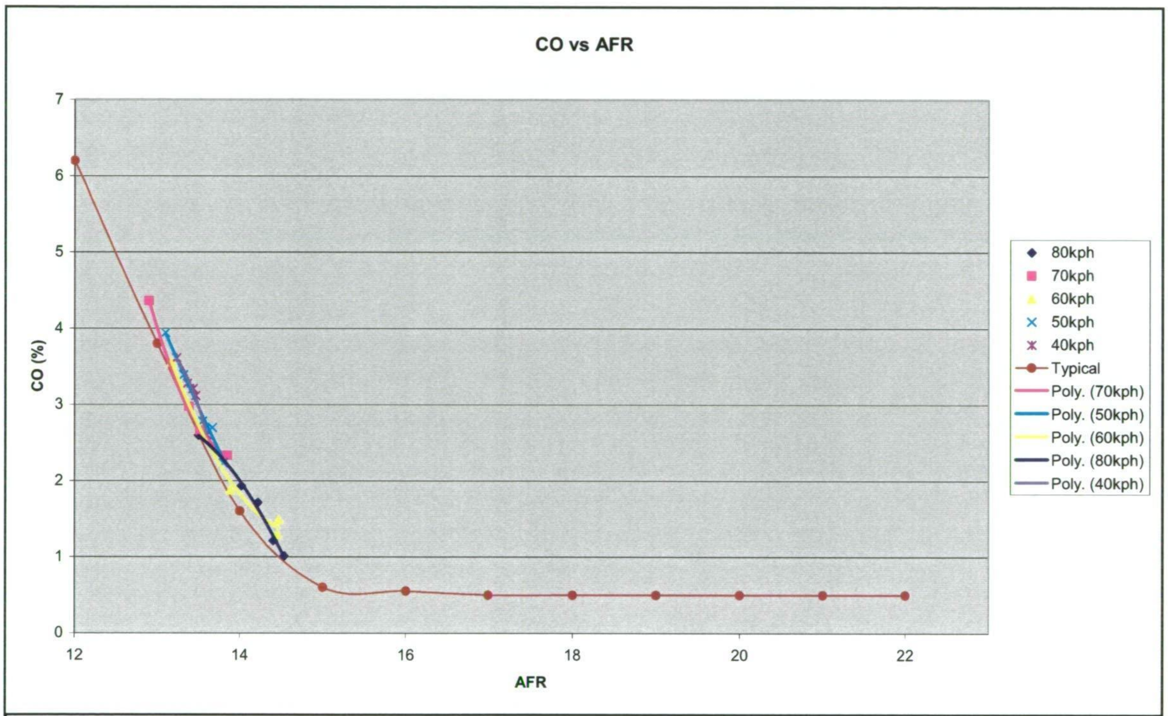


Figure 5.4: Carbon Monoxide emissions vs. Air to Fuel ratio over a series of speeds

High cylinder temperatures and pressure cause the engine to produce oxides of nitrogen (NOx). The production is caused by nitrogen in the air reacting with the oxygen in the air to form the compounds. NOx are most prevalent during high load conditions when combustion temperatures are the highest. It can be seen that NOx emissions (figure 5.5 below) in the CT110 are significant particularly in the air to fuel ratio range of the engine operation. The relatively high temperatures of the air-cooled engine also would have an effect on the NOx formation in the engine.

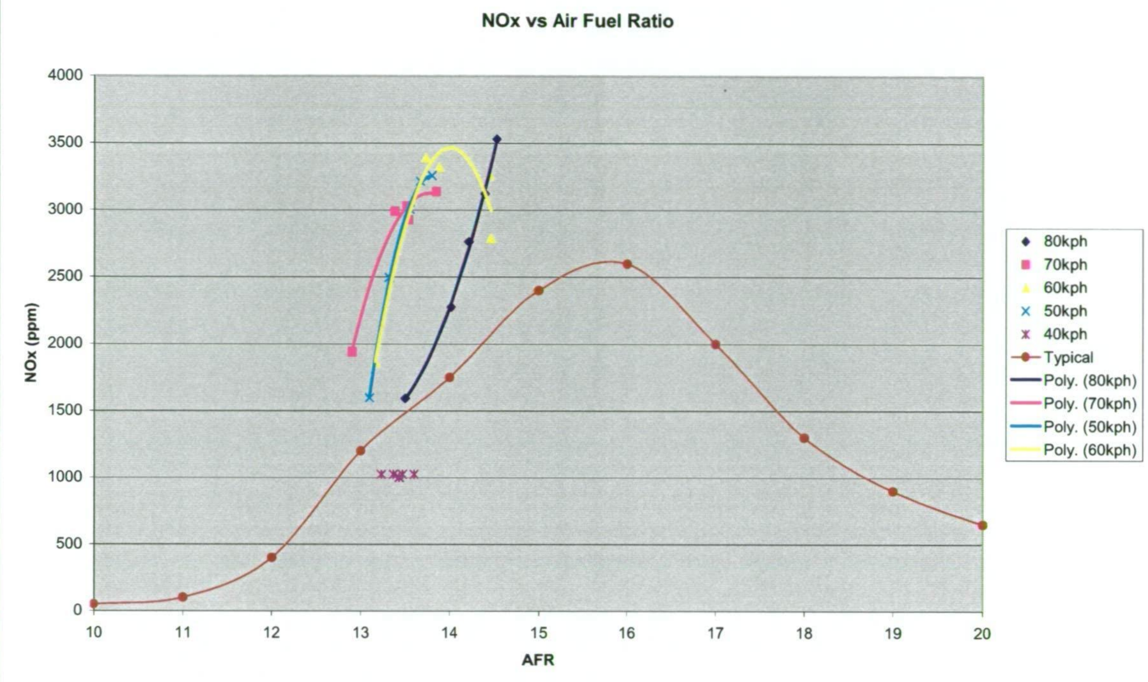


Figure 5.5: Oxides of Nitrogen emissions vs. Air to Fuel ratio over a series of speeds

Carbon Dioxide (CO_2) emissions are a result of complete combustion in the engine. In normal combustion the hydrocarbons in the fuel react only with oxygen forming water and CO_2. Thus, the concentration of CO_2 is most prevalent at stoichiometry when complete combustion is occurring. It can be seen in figure 5.6 (below) that the test rig shows the trend of increasing CO_2 emissions as the air to fuel ratio approaches stoichiometry. It is expected that as the engine operation approaches stoichiometry more complete combustion would be occurring, promoting the formation of CO_2.

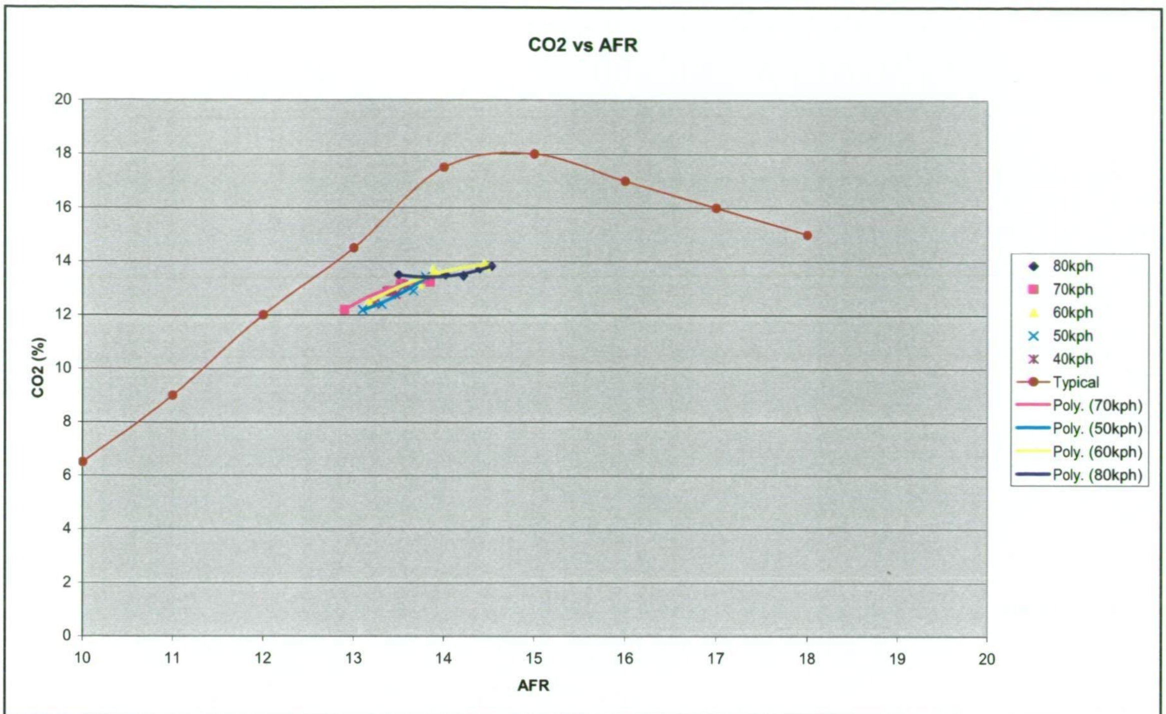


Figure 5.6: Carbon Dioxide emissions vs. Air to Fuel ratio over a series of speeds

5.3 Qualitative Analysis of the Hydrogen IC engine

5.3.1 General comments about the engine and equipment performance

The purpose of testing the engine operating on hydrogen was to get an initial idea on the performance of the prototype hydrogen CT110 engine. The performance features include the analysis of power, thermal efficiency and exhaust emissions. The testing procedure closely emulated the gasoline testing procedure for effective comparative analysis.

Backfiring and pre-ignition problems were mostly ironed out during the tuning process. However, infrequent backfiring through the inlet manifold still existed during the testing procedure. Engine pre-ignition caused an instantaneous loss in engine power. This meant that in the observed occurrence of pre-ignition, measured data was not indicative of the intended data point and the test had to be repeated. The phenomenon is caused by a build up of combustion gases in the inlet manifold. Due to the buoyancy of hydrogen gas, any fuel that is not pulled into the cylinder is likely to rise to the top of the inlet manifold. Once the temperature is hot enough to excite the low ignition energy and the gases in the area accumulate to a combustible level combustion occurs and backfire occurs. Another explanation for the phenomenon is that the valve overlap is causing ignition of not only the charge but also gases in the manifold. Loss of power suggests that the ignition is not only combusting excess fuel but also the charge intended for the cylinder. Effective engine design parameters suggested earlier in the thesis could further reduce the existence of pre-ignition.

Effective measurement of the air to fuel ratio of the engine was mostly unsuccessful for hydrogen operation. The lambda sensor used was a narrow band sensor and did not have adequate range. Rather than using the air to fuel ratio as the process variable for analysis it has been decided to use the throttle position as the dependant. As the throttle of the engine controlled the amount of fuel entering the cylinder (wide open throttle operation), the throttle position is a good indication of the mixture of the fuel in the charge. As the throttle position is advanced the amount of fuel entering will be increased, as shown in the MoTec engine management system fuel maps. This increase will make the mixture richer. The limited data obtained from the lambda sensor analysis agrees with this point. For lower throttle positions in most of the tests the sensor indicated that the mixture was lean and as the throttle was advanced it indicated a rich mixture. As the throttle is advanced more fuel is being injected into the engine, the result being an increase in lambda. The use of a wide band lambda sensor and calibration of that sensor for hydrogen use would give a more accurate way of measuring the air to fuel ratio.

Care was taken with the use of the gas analyzer during the testing period. The additional moisture content in the exhaust of the hydrogen engine was resolved by continual emptying the water trap and cleaning of the test lines to ensure flow was not restricted.

During the testing period hydrogen was delivered to the engine at a pressure of two bar. This pressure was chosen because two bar (gauge) was found to be an appropriate fuel pressure during the tuning operation. A duel stage regulator was used to keep this pressure stable as the pressure inside the cylinder dropped whilst emptying. This is an extremely important design feature of the test rig. The use of a single stage regulator would have meant that the pressure would have changed as the cylinder pressure changed. This would change the flow rate at the injectors which would intern effect the engine operation. As tuning was undertaken at that pressure it is critical that constant fuel pressure is maintained for the entire duration of engine running conditions.

5.3.2 Qualitative trends of the effects of major process variables on power

Speed was changed several times to obtain a reasonable spread of data for the analysis of power. Points in Figure 5.7 (below) show maximum power occurring prior to half throttle position on all tests. Trends show that power is initially increased with throttle position and as throttle position is advanced to 100% the power drops. It is known from the lambda readings that each of the first data points is lean operation and the remainder are rich. This suggests that at the fully advanced throttle positions are too rich for effective power control. Like gasoline operation the maximum power is likely to occur on the rich side of stoichiometry for the hydrogen engine. Power curves shown below are similar to that of the gasoline engine (in reverse obviously because lambda not air to fuel ratio is represented as the dependent). This validates the data acquisition process and the experimental test rig measurement techniques.

The data attained in this testing procedure is import for subsequent tuning operations. The programmable nature of the engine management system could be used to tune for more power across the operational range. Accurate indication of the air-fuel ratio would first be required so mapping could occur against that ratio rather than throttle position.

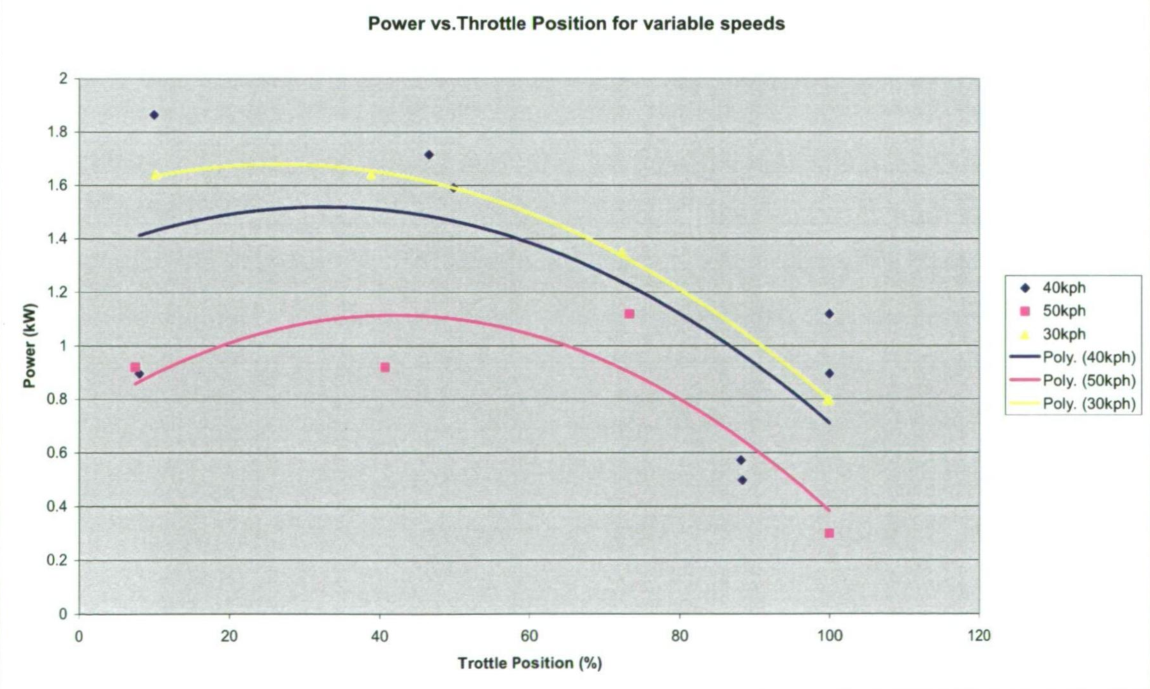


Figure 5.7: Power vs. Throttle Position over a series of speeds

5.3.3 Qualitative trends of the effects of major process variables on thermal efficiency

As stated earlier the thermal efficiency is defined as the ratio of the work done by an engine to the work due to the heat supplied to it. The data for thermal efficiency of the hydrogen engine (figure 5.8) shows that the lean burn possess greater efficiency than that of the rich burn engine. It is seen above in figure 5.7 (above) that the least power was generated at open throttle position. Hence the minimum efficiency will also be at that fully advanced throttle position because the most amount of fuel is being supplied for the least amount of power.

Lean burn hydrogen engines are more efficient than rich burn hydrogen engines as suggested in literature [51]. This effect is verified in the data acquired in that the less the throttle is advanced (less fuel entering; lower lambda value) higher the indicated thermal efficiency. This is one of the main reasons for running hydrogen engines lean. The fuel efficiency of the hydrogen engine must be as high as possible to conserve fuel due to the limited volumetric storage efficiencies.

Thermal efficiency data obtained could also be important in future tuning operations. To attain higher values lean burn mixtures will need to be employed over the entire range of operating conditions, not just at low throttle positions

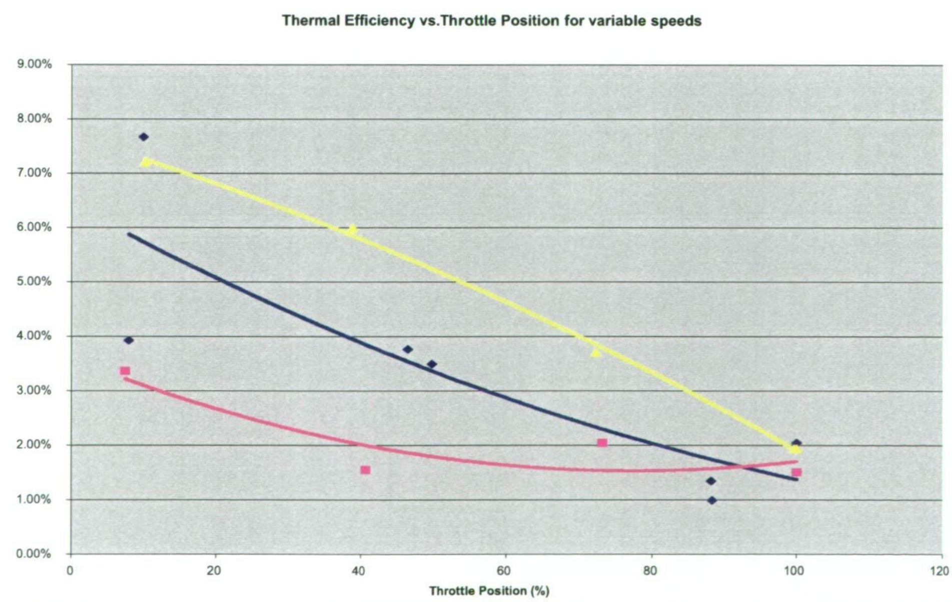


Figure 5.8: Thermal Efficiency vs. Throttle Position over a series of speeds

5.3.4 Qualitative trends of the effects of major process variables on exhaust emissions

The major contributing process variable on the exhaust emissions was found to be the engine temperature rather than the throttle position or air to fuel ratio. The amount of fuel in the engine does affect the temperature significantly but it is not the only contributing factor so we cannot analyze it with throttle position as the process variable.

Chemistry of hydrogen combustion produces very little harmful exhaust emissions. Combustion of hydrogen with oxygen produces only water as shown in equation 5.1:

$$2H_2 + O_2 = 2H_2O \qquad \textit{Equation 5.1}$$

Since air is not purely oxygen there oxides of nitrogen (NOx) can also be formed as shown in equation 5.2:

$$H_2 + O_2 + N_2 = H_2O + N_2 + NO_X \qquad \textit{Equation 5.2}$$

As can be seen no hydrocarbons, carbon dioxide or carbon monoxide are yielded in the combustion of hydrogen. However burning of engine oil can result in trace elements of hydrocarbons in the exhaust. During testing trace elements of hydrocarbons were observed but in such small and irregular amounts they were not considered as part of this analysis.

Figure 5.9 below shows the emissions of the oxides of nitrogen (NOx) with engine temperature. Literature suggests that high temperature combustion is the cause of NOx in exhaust emissions [85]. Of the NOx produced by combustion (NO, NO2, N2O, N2O5), NO is the most prevalent as shown in the equation 4.3. It can be formed in the following mechanisms each of which is only prevalent with the existence of heat:

$$\begin{aligned} &N_2 + O = NO + N \\ &N + O_2 = NO + O \qquad \textit{Equations 4.3} \\ &N_2 + O_2 = 2NO \end{aligned}$$

Results obtained for the hydrogen engine confer the expected trends of NOx in the exhaust. It is noted that as engine temperature increases the concentration of NOx also increases. Design techniques to reduce engine temperature are a possible solution to reducing NOx in the exhaust of hydrogen engines. Alternatively, catalytic converter technology could treat NOx exhaust emissions.

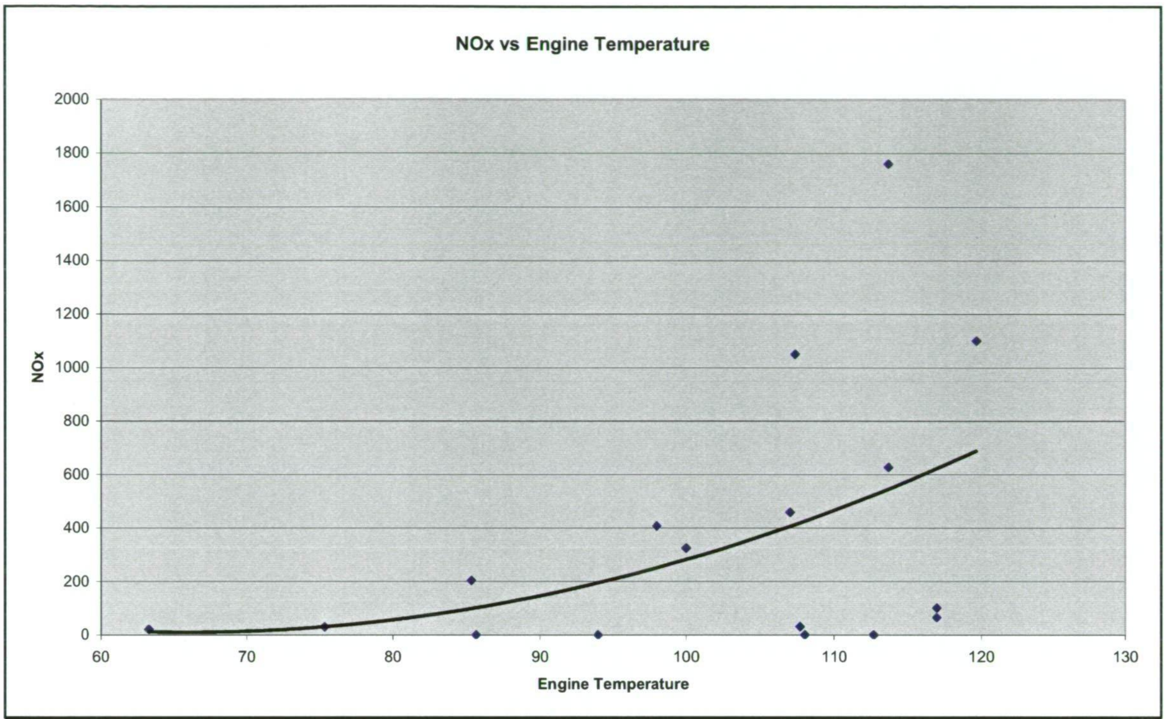


Figure 5.9: NOx emissions vs. Engine Temperature

5.4 Quantitative Comparison of Performance

Due to the differing air to fuel ratio control mechanisms between the two engines, a direct quantitative comparison cannot be undertaken. The control mechanism being the throttle variance. The difference in the two being that the gasoline engine used the throttle to control the amount of air entering the cylinder whilst the hydrogen engine used the throttle to control the amount of fuel entering the engine.

Ideal comparison between the two engines would be completed with the air-fuel ratio as the dependent variable. As previously discussed, however, this is not possible due to the inadequate lambda measuring equipment for the hydrogen engine. This should be a future consideration in test rig improvements. Despite this useful analysis can still be undertaken.

It is noted that the trends for power and thermal efficiency vs. their respective dependent variables are quite similar. From the quantitative analysis performed above, it is observed that maximum power occurs prior to stoichiometry and as the mixture becomes richer the power decreases for both fuels. For thermal efficiency we can ascertain information about differing maxima and where they occur in respect to stoichiometry. Thermal efficiency for both applications reduces with richness beyond stoichiometry. As the trends are comparable, a comparison of their respective maximum values is a useful initial assessment in the evaluation of overall comparative engine performance.

5.4.1 Power as a means to compare gasoline to Hydrogen Engines

Engine power is compared over three different speed variables. Maximum power varied for each of the speeds and differences in comparative power between the engines also differed. Figure 4.10 shows the range of maximum power attained at the various speeds.

For 30 km/h maximum power for the hydrogen engine was 1.64kW whilst the gasoline engine maximum was 2.36kW. This represents a 30% loss in power for the conversion to run on hydrogen. This shows how the hydrogen engine particularly performed well at reduced speed and load settings. The vehicles road use is targeted at this low speed/load requirements so this result is positive.

For 40 km/h maximum power for the hydrogen engine was 1.86kW whilst the gasoline engine maximum was 3.90kW. This represents a 53% loss in power for the conversion to hydrogen.

For 50 km/h maximum power for the hydrogen engine was 0.92kW whilst the gasoline engine maximum was 3.63kW. This represents a 75% loss in power for the conversion to hydrogen. It was noted that at this speed the hydrogen engine did not perform the full range of throttle positions particularly well. This erratic engine behavior significantly reduced the power output. It is thought that further tuning could significantly improve the performance of the engine at this speed.

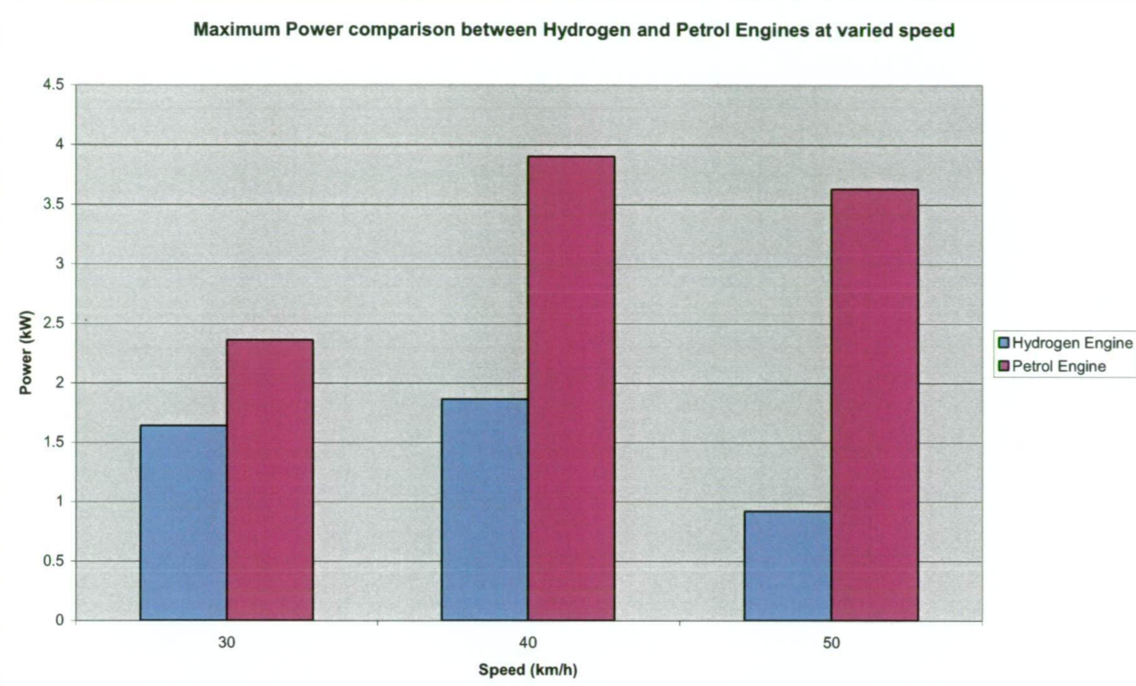


Figure 5.10: Maximum Power comparison between Hydrogen and Gasoline Engines over varied speeds.

There are several explanations for the loss in power exhibited by the hydrogen engine indicated in figure 5.10.

Firstly, the energy density of a hydrogen-air mixture is significantly less than that of the gasoline. For stoichiometric operation the air to fuel ratio for hydrogen is 34:1. At this ratio the fuel only displaces 29% of the combustion chamber. As a result the energy content of the mixture is reduced.

Secondly, the method of fuel delivery effects the potential power that the engine can produce. The College of the Desert's document *"Hydrogen Use In Internal Combustion Engines"* suggests that for port injected fuel delivery (as is used in this engine) maximum theoretical power attainable is limited to 85% to that of gasoline engines. This is calculated at the maximum power load site also which this engine was not designed to run at.

Thirdly, improvement in the tuning of the hydrogen engine would substantially improve power output. It was noted that during testing the 50 km/h data was effected by tuning problems. At this speed the engine struggled the full array of throttle positions at the given speed. It is though that ignition and injection timing could be further tuned to encompass smooth operation at all operating conditions.

Finally, further physical modifications could be made to the engine to increase its power output. To range power that the initial engine gained changes could be made to the valve timing to optimize injection timing. Injection position changed to below the engine block may reduce the effects of the buoyancy of the hydrogen fuel. Increase in compression ratio would significantly effect the pressure within the cylinder which may increase power. Also the cylinder size could be altered to better suit the application required.

5.4.2 Thermal efficiency as a means to compare gasoline to Hydrogen Engines

Maximum thermal efficiencies are compared over three speed variables ranging between 30 and 50 km/h. Results obtained varied for both engines between the variables. The changes highlight the difference in tuning patterns. As both engine spent most time on the rich side of their respective air to fuel ratios the efficiencies shown are relatively low. For the gasoline engine closer operation to stoichiometry would increase this number and for the hydrogen engine leaner operation throughout the full range of operating conditions would significantly increase the thermal efficiency of the engine.

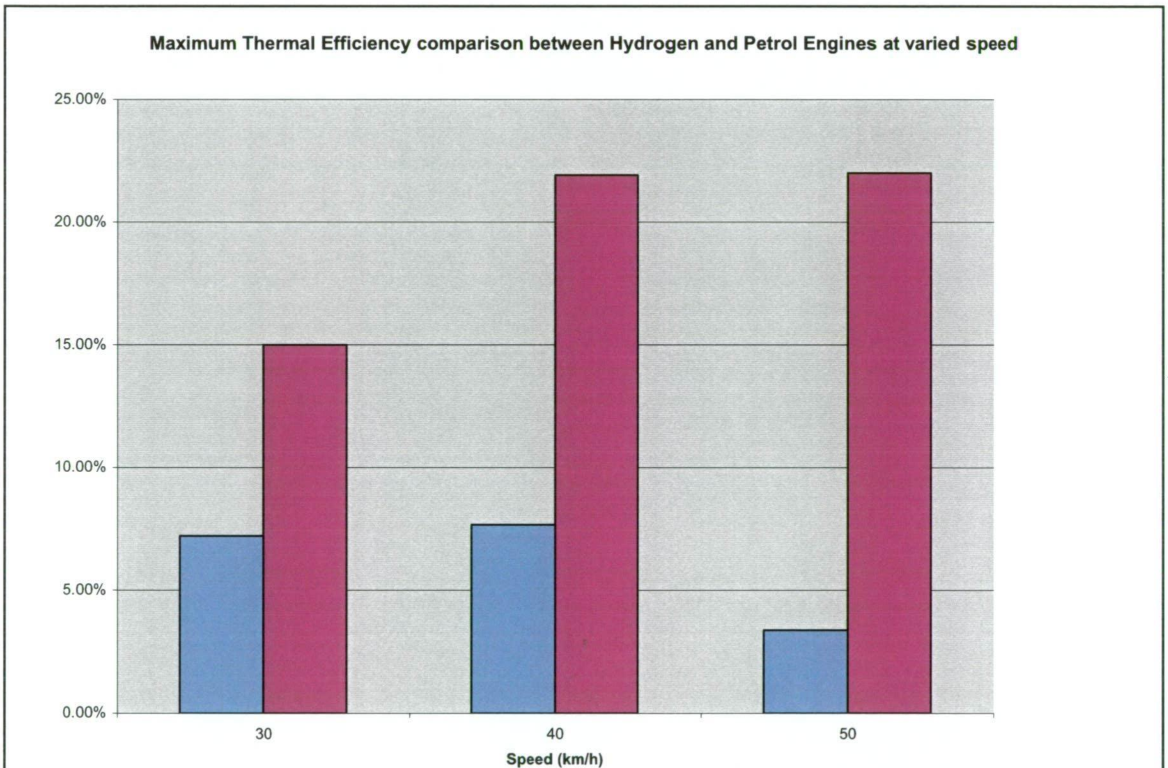


Figure 5.11: Maximum Thermal Efficiency comparison between Hydrogen and Gasoline Engines over varied speeds.

Figure 5.11 shows the comparison between the two engines over the varied speed.

For 30 km/h maximum thermal efficiency for the hydrogen engine was 7.2% whilst the gasoline engine maximum was 15.0%. This represents a 52% loss in thermal efficiency for the conversion to hydrogen.

For 40 km/h maximum thermal efficiency for the hydrogen engine was 7.7% whilst the gasoline engine maximum was 21.9%. This represents a 65% loss in thermal efficiency for the conversion to hydrogen. This was the most efficient that the hydrogen engine was capable of running. This loss could be attributed to the rich operation of the hydrogen fuel and other energy losses associated with hydrogen operation.

For 50 km/h maximum thermal efficiency for the hydrogen engine was 3.4% whilst the gasoline engine maximum was 22.0%. This represents an 85% loss in thermal efficiency for the conversion to hydrogen. This result further amplifies the need for further work to be undertaken on the engine at higher engine speeds and loads.

The loss in efficiency between the gasoline and hydrogen engines can be attributed to three factors.

Firstly, the high burning rates of hydrogen produce high pressures and temperatures during combustion. This is especially prevalent during the rich operational conditions which this engine was subjected to. These high temperatures are a source of systematic energy loss which results in less power being transferred to the crankshaft. The significance of the problem could lessened by applying leaner mixtures and using heat transfer techniques to control the combustion temperatures.

Secondly, the high rates of pressure rise in the cylinder also resulted in significant increases in noise and vibrations in the system. Over the range of engine operating conditions this was observed. Additional energy expired in this medium would also be a source of loss of efficiency in the system.

Thirdly, the existence of pre-ignition would have a significant effect on the thermal efficiency. It is noted that at higher engine speeds and loads the temperature of the engine was increased. This may have caused unnoticed pre-ignition which use energy from the intended engine charge in pre-ignition. The loss of this charge would mean that engine power would be reduced which intern would reduce the thermal efficiency as fuel is still being supplied to serve this pre-ignition.

5.4.3 Emissions

Maximum exhaust emission quantities are compared over a series of three speed steps, namely 30, 40 and 50 km/h. One of the two main impetus behind hydrogen conversion technology is the environmental performance of the combustion fuel. This section details the environmental improvements over the major exhaust emission classifications of carbon dioxide (CO_2), carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NOx).

Carbon dioxide emissions were observed in the gasoline engine with a maximum value of approximately 13% for all compared speeds as shown in figure 5.12. This was a common value across the whole operating conditions of the gasoline engine. This suggests that similar complete combustion was occurring across the testing data as the pattern indicates. The hydrogen engine produced no significant emissions of CO_2 as is expected. The combustion of hydrogen with air contains no carbon atoms so no CO_2 is present in the exhaust.

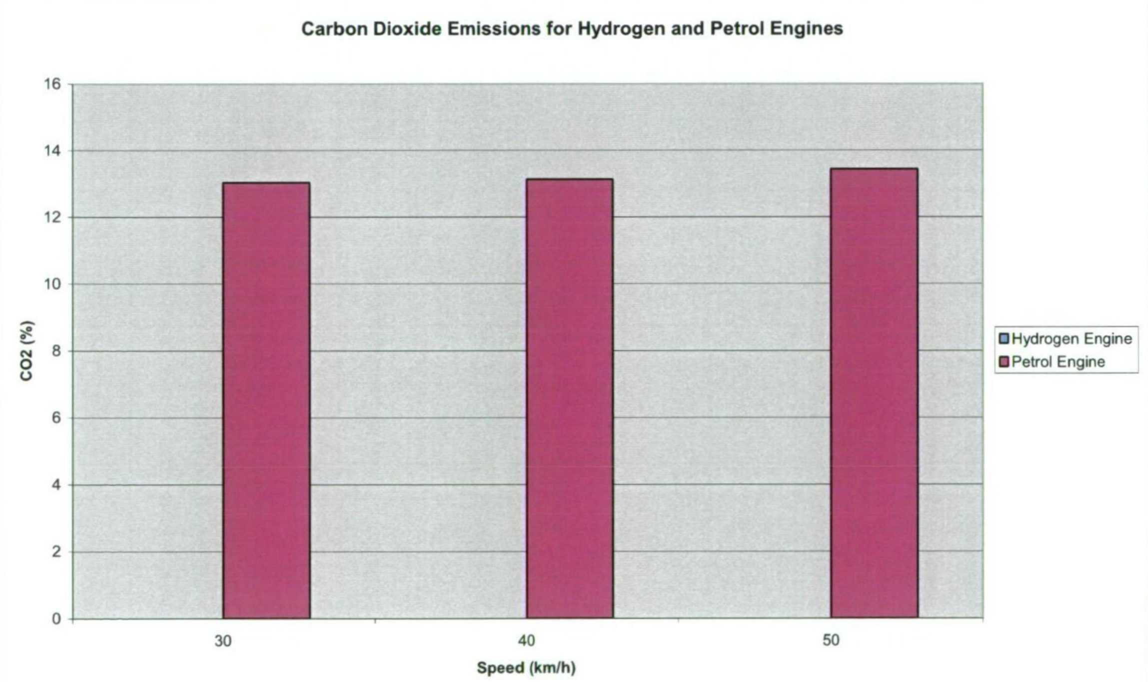


Figure 5.12: Carbon Dioxide emissions for Hydrogen and Gasoline engines

Carbon monoxide (CO) emissions were observed in the exhaust of the gasoline engine. Levels as high as 3.94% were detected over the testing period as shown in figure 5.13. Levels altered over the period between 1% at minimum to almost 4% at maximum. The prevalence of CO suggests incomplete combustion. The hydrogen engine produced no significant emissions of CO in the exhaust. As mentioned previously there is no carbon present in the combustion of hydrogen so CO do not exist either.

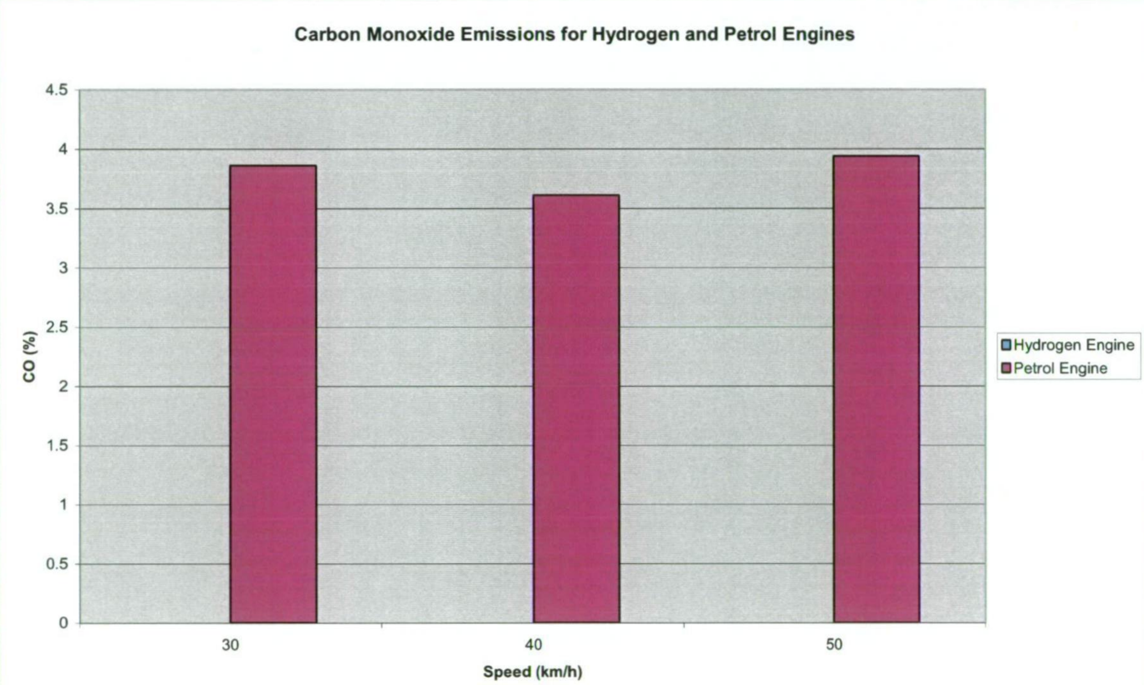


Figure 5.13: Carbon Monoxide emissions for Hydrogen and Gasoline engines

Hydrocarbon emissions were observed in the exhaust of the gasoline engine in levels up to almost 180ppm as shown in Figure 5.14. The prevalence of the emission was greater with increase speed for the gasoline engine. It ranges from 154ppm for 30km/h to 179ppm for 50km/h. This suggests less complete combustion as the speed of the engine increases. The hydrogen engine produced no significant emissions of Hydrocarbons in the exhaust.

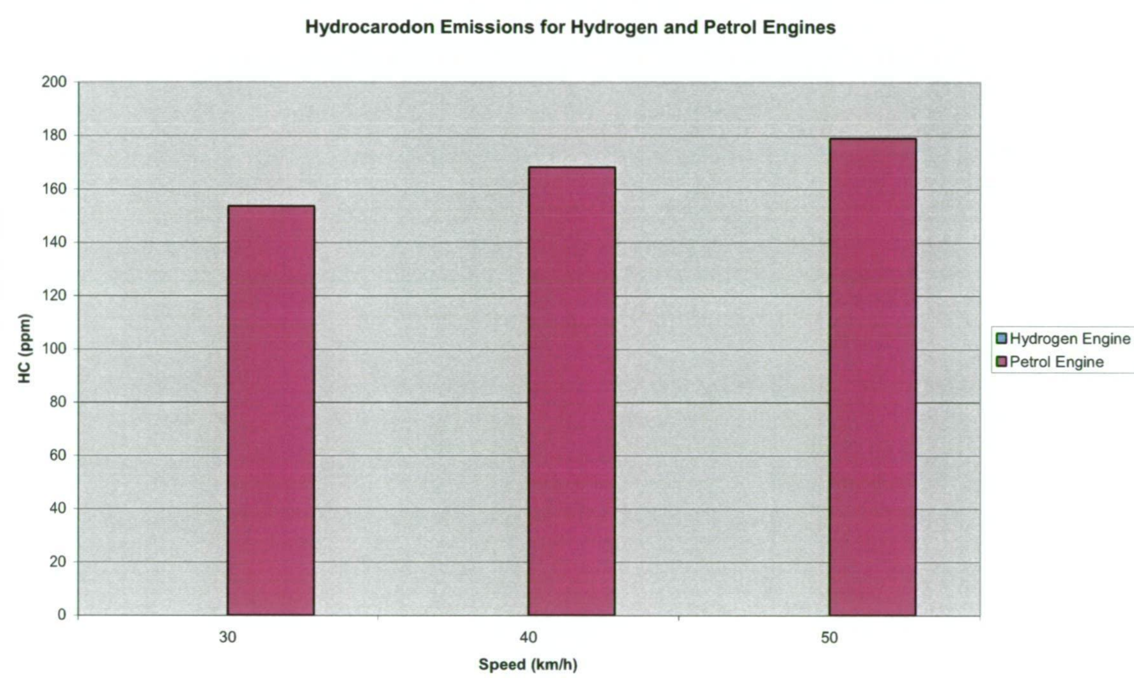


Figure 5.14: Hydrocarbon emissions for Hydrogen and Gasoline engines

Oxides of Nitrogen (NOx) emissions were compared over the three speeds for the two engines. The emissions analysis shown that both engines produced NOx with the gasoline engine emitting a significantly larger amount of the pollutant.

At 30km/h the gasoline engine produced a maximum of 1906ppm of NOx whilst the hydrogen engine produced a maximum of 458ppm. This is a significant reduction by converting to hydrogen, with the hydrogen engine producing only 24% of NOx that the gasoline engine produced.

At 40km/h the gasoline engine produced a maximum of 1023ppm whilst the hydrogen engine produced a maximum of 407ppm. In this case the hydrogen engine produced 39% NOx of the gasoline engine.

At 50km/h the gasoline engine produce a maximum of 3258ppm of NOx whilst the hydrogen engine produced 1761ppm. The hydrogen engine produced 54% of the NOx that the gasoline engine did under the same conditions.

Figure 5.15 shows the comparison of maximum NOx emissions.

The reduction in NOx is an obvious advantage of the hydrogen engine. The rich operation and air cooled nature of the gasoline engine means that high temperatures are in existance throughout the operation. This causes a significant amount of NOx emissions. Reduction in this operational temperature for the gasoline engine would significantly reduce the NOx emissions as well as raising the thermal efficiency of the engine. Although there were significant reduction in NOx emissions by using the hydrogen engine this too could be reduced by reducing engine temperatures.

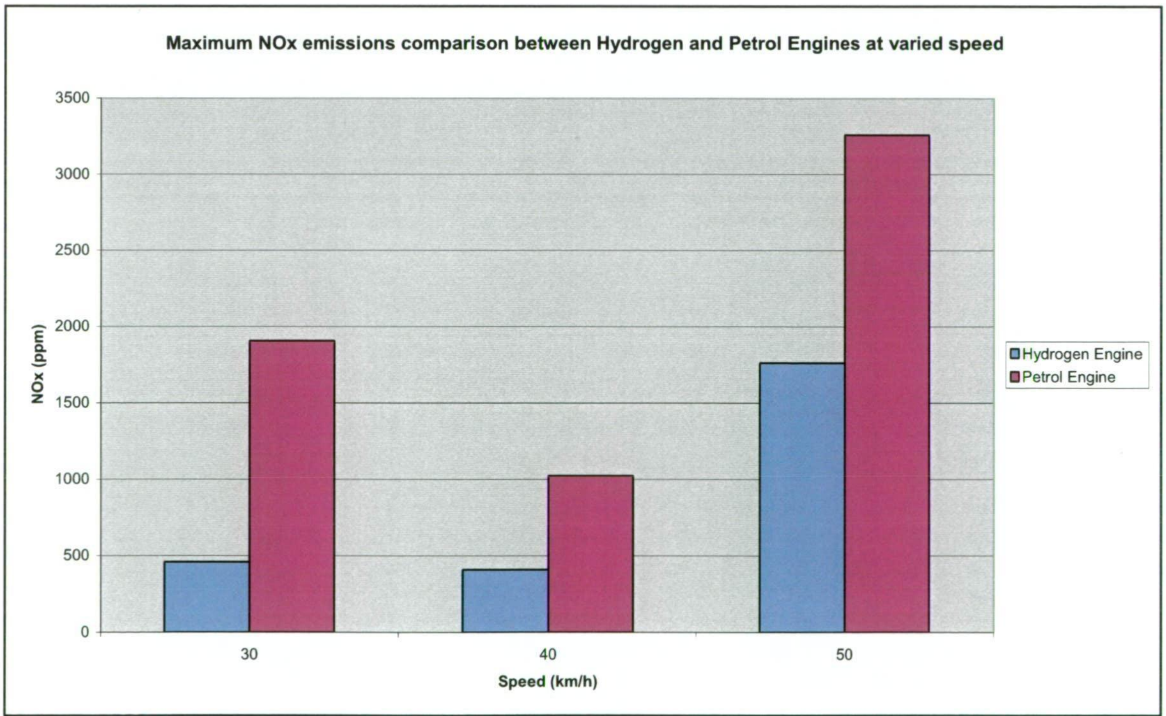


Figure 5.15: Oxides of Nitrogen emissions for Hydrogen and Gasoline engines

5.5 Testing and Data Analysis Conclusions

The baseline testing by acquiring performance data on the CT110 yielded positive results. Testing procedures were adhered to and the guidelines extracted from AS 4594.11 were followed, further validating results. It is important to note that the qualitative trends for power, thermal efficiency and emissions are comparable to the established trends. Incomplete combustion explains the trends in increased HC and CO.

The testing of the hydrogen engine yielded results for the comparison to the previously acquired baseline data. Power and thermal efficiency trends obtained were consistent with internal combustion engine trends observed in literature [3]. The emission trends yielded are consistent with the associated combustion chemistry. The results obtained will also serve as a means of future design assistance in the development of the engine.

Comparison of the two engines generated consistent results between the speed variables. The gasoline engine produced better power and significantly better thermal efficiency over all compared values. At lower speed values the hydrogen engine performed better than at higher speeds. The hydrogen engine produced no significant emissions of carbon dioxide, carbon monoxide and hydrocarbons and reduced emissions of oxides of nitrogen when compared to the gasoline engine. The gasoline engine produces considerable amounts of all measured emissions.

CHAPTER 6 Final Concluding Remarks and Proposed Future Work

6.1 *Final Concluding Remarks*

6.1.1 Literature Study

From an extensive literature survey carried out on hydrogen engines, it is shown that much of the technology and conversion methods are within the realms of some automotive companies. It is shown that little extensive literature is available on the performance of hydrogen engines. This project demonstrated a careful design and prototype development of working Honda CT110 hydrogen engine to power a common commercial fleet vehicle, the 'postie bike'. From a design point of view, the intricate air intake system and innovative fuel injection systems were built from first principles. The test rig development predominantly covered conversion intricacies and a systematic approach to experimental data acquisition and analysis. MoTec as an established engine management system was used for advanced tuning and to acquire data for post processing.

The qualitative trends of the effect of major process variables on power, thermal efficiency and exhaust emissions were established for both gasoline and hydrogen engines. It is noted that the qualitative trends are comparable with the established trends in the literature for gasoline engines. This is a reassurance that the experimental test rig performed well along with associated measuring equipment. The design, development and installation of the hydrogen storage is well described in this work.

6.1.2 Power and Thermal Efficiency Comparison

The qualitative trends of the hydrogen engine for power, thermal efficiency are comparable to that of the gasoline engine. From a quantitative comparison both maximum power and maximum thermal efficiency are taken as bench marks for various engine speeds. Across various speeds power reductions between 30-85% were observed for the converted hydrogen engine when compared to its gasoline counterpart. The maximum speed of the hydrogen CT110 ('postie bike') for normal road running conditions was shown to be 50km/h. It is also argued that for normal Australian driving conditions in built-up regions, a maximum speed of 50km/h is adequate.

6.1.3 Emissions

The hydrogen engine produced no exhaust emissions of carbon monoxide, carbon dioxide or hydrocarbons whilst the gasoline engine produced significant emissions of all these pollutants. Nitrogen oxide emissions were reduced by between 46-76% by converting the engine to hydrogen. This is seen as a major success in the conversion process and is a major validation for the process itself.

6.1.4 Social Acceptance

Another aspect to the conversion of the CT110 to hydrogen was to increase the community acceptance and knowledge of the hydrogen fuel as an alternative to traditional fossil based fuels. Introducing a new technology such as a new fuel requires two basic necessities: consumer acceptance and working infrastructure. One of the best methods of increasing consumer acceptance is by means of exposure to the associated technology. Such exposure reduces the risk perception of the public and also familiarizes potential users the technology. On completion of the conversion the hydrogen CT110 was exposed to the public through various media sources such as print, television, internet and radio. The project was covered locally, nationally and internationally.

6.2 Proposed Future Work

From a future development point of view there are several research areas of interest that will enhance the performance of the CT110. The Hydrogen CT110 that has been developed to this point is still in its infancy as a first generation prototype. The performance of the bike could be enhanced to make the vehicle more comparable with its gasoline counterpart. Additionally the bike can be developed to include greater safety features and become more aesthetically pleasing. Potential developments have been detailed in order to assist future research goals. An essential part of this investigation are these proposed works.

6.2.1 EMS Development

The current hydrogen engine has a basic engine management system tuning maps installed in it. They are the result of about four hours of dynamometer tuning, which is sufficient for basic operation. However, the current fuel injection map in the engine could be further improved. The map was the result of a series of test point and interpolation. Injection timing was altered quite substantially over the tuning process in this study. It was found that by adjusting this parameter backfiring could be reduced and the engine would produce more power. In the event of valve timing changing this parameter may have greater effect on engine performance.

An extensive study on the effect of ignition timing on the combustion was not carried out in this process. A study on the development of this parameter will better control the combustion process and produce better power results.

6.2.2 Compression Ratio

Compression ratio has a strong influence on the pressure inside the cylinder of the engine. Increase in compression ratio usually results in a sharp increase in the cylinders top pressure. Hydrogen engines can run higher compression ratios due to the high flame speed and high specific-heat ratio. The compression ratio has a strong influence on the thermodynamic efficiency of the engine. A lean hydrogen mixture is expected to be less susceptible to knock (the critical parameter in maximum compression ratio) than conventional gasoline mixtures and therefore can be run at higher compression ratios. The higher the compression ratio the higher the indicted thermal efficiency of the engine. A future research in this area should take the compression ratio into consideration.

6.2.3 Valve Timing

It is important to note that valve timing in the CT110 engine is a fixed parameter. Due to this fact, the tuning had to be adapted around the valve timing of the engine. Improved valve timing configuration could be employed to better suit the hydrogen application. Injecting hot gases into the manifold onto a hot inlet valve is thought to be one of the sources of backfiring in the engine. In an ideal situation the inlet gases should spend as little time as possible in the inlet manifold. Once injected the fuel should travel directly into the cylinder. Fixed valve timing meant that this was not entirely possible as there was to be no injection during valve overlap. By reducing the valve overlap and introducing variable valve timing would increase the volumetric efficiency of the engine whilst also better controlling backfiring and pre-ignition in the inlet manifold. Control over the variance of the valve timing would also open options of further testing on the effect of valve timing on the hydrogen engine. Very little study has been done on the effect of valve timing on the hydrogen engine and further investigation could enhance the understanding of the effect of this important parameter.

6.2.4 Fuel Pressure

Alteration of fuel pressure and the subsequent amount of fuel entering the cylinder can be readily measured and changed. By increasing the fuel pressure the fuel injectors would not need to be open for such long periods and greater precision could be attained. Fuel injectors have a minimum speed at which they can open and shut. The fuel pressure should be a function of this and engine speed so that the correct amount of fuel can be administered to the engine at the correct time. By increasing fuel flow it is thought that perhaps the valve overlap would not need to be so small. Parameters such as cylinder pressure and volumetric efficiency must also be considered when studying the effect of fuel pressure.

6.2.5 Sensor Accuracy and Repeatability

Sensors used in the study are 'off the shelf' type sensors from a range of manufacturers. The accuracy of the test rig and sensors are taken from a combination of manufacturers specifications and relevant standards. Further work could consider the accuracy of the equipment in a repeatability study.

6.2.6 Storage Development

The current storage system on the hydrogen CT110 is not suitable for road usage. As a demonstration prototype the compressed gas cylinder serves as good alternative but for greater acceptance the volumetric storage efficiency will need to be improved. Due to the lack of storage space on the vehicle metal hydride storage would be the best storage option. Metal hydride cylinders are commercially available and their technology has been proven to work. An ancillary temperature control system would be required to keep to hydride cylinder at is optimum release temperature. This system would not be overly complicated but study into release rates would be essential to ensure that the engine could operate at all required conditions.

6.2.7 Solenoid Valve

The current method for stopping fuel flow from the delivery system to the engine is two fold; a manual on/off ball valve and the operation of the fuel injectors being closed. With miniscule rates of leakage through the injectors the system is considered safe. Given injector failure however the situation could be different. If the engine was stopped and the injectors were leaking into the inlet manifold then there could be potential for explosion. Furthermore, if the injectors were not to seal properly a flash back could occur along the fuel delivery line. To compensate for this possibility a solenoid valve put in the fuel delivery system in place of the manual ball valve would serve as an automatic fuel shut off once the engine was stopped. The MoTec EMS has the facility to produce auxiliary voltages for such equipment as turbo chargers and waste gate valves in performance automobiles. This feature could be used to operate a solenoid valve. Once the engine stopped the signal could close the solenoid valve and hence stop the flow of fuel to the injectors. The valve could be beneficial also in that the injectors would not be constantly under fuel pressure which may cause eventual wear.

6.2.8 Control of Air Flow

As it stands now the hydrogen CT110 engine is run at wide-open throttle. This method is thought to take advantage of hydrogen's wide flammability limits and increase engine efficiency by removing the throttle body. However, the inclusion of a modified air throttling operation on this bike would give the operator and researcher more control over the engine parameters. Wide-open throttle operation means the bike idles at a very high rpm. Attempts to reduce this rpm results in extremely lean operation, backfiring and eventually engine stall. For an engine specifically designed to run on hydrogen this could be overcome with inlet design allowing the exactly correct amount of air to enter the manifold. The introduction of a air throttle would mean the engine could idle much lower and the control over air-fuel ratios would be much greater. Under greater load and rpm the throttle could be wide open again increasing the efficiency as desired.

6.2.9 Further Emission Development and Study

The hydrogen engine exhibited in this project produced some nitrous oxides. This amount was significantly less than the petrol engine but to totally reduce emissions undesirable fuel mixtures would need to be used. Lean mixture invariably in this engine produced less power than it's richer counterpart. With the use of a catalytic converter NOx emissions in the exhaust could be captured and high concentrations of hydrogen could be employed.

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APPENDIX A: Experimental Data

APPENDIX A1: Hydrogen Testing Data

Test No.	Amdient Temp	Humidity	Pressure	Engine Temp	Air Inlet Temp	Gear	Speed	RPM
	(deg C)	(%)	(mPa)	(deg C)	(DegC)		(KPH)	
1	20.5	42.0	1008	63.3	20.0	3	39.3	6493.3
2	21.0	42.0	1008	75.3	20.3	3	40.0	6756.7
3	21.0	45.0	1008	85.7	20.6	3	33.3	4760.0
4	21.2	45.0	1008	94.0	20.8	3	40.5	6660.0
5	20.8	47.7	1008	85.3	27.6	2	40.7	6756.7
6	20.9	48.0	1008	98.0	29.4	2	40.0	6663.3
7	22.0	45.0	1008	107.7	29.2	2	32.3	5406.7
8	23.0	45.6	1008	113.7	28.4	2	40.0	6650.0
9	22.2	46.9	1008	100.0	27.0	3	49.7	8276.7
10	22.2	47.0	1008	107.3	28.7	3	38.7	7050.0
11	22.2	46.2	1008	113.7	28.1	3	44.0	7060.0
12	23.0	45.9	1008	117.0	28.3	3	49.7	5936.7
13	23.0	46.1	1008	107.0	25.4	2	30.0	5036.7
14	22.0	45.9	1008	108.0	27.1	2	30.0	5043.3

Test No.	CO2	CO	HC	NOx	Mass Flow Rate	Lambda	Power	Thermal efficiency
	(%)	(%)	(ppm)	(ppm)	(kg/s)		(kW)	(%)
1	0	0	0	20.7	0.0001905	1.53	0.8948	3.93%
2	0	0	0	10.0	0.0003810	0.69	1.7151	3.76%
3	0	0	0	0.0	0.0003556	0.69	0.5717	1.34%
4	0	0	0	0.0	0.0004953	0.69	0.8948	1.51%
5	0	0	0	203.0	0.0002032	1.23	1.8642	7.67%
6	0	0	0	407.7	0.0003810	0.69	1.5908	3.49%
7	0	0	0	30.7	0.0004191	0.69	0.4971	0.99%
8	0	0	0	626.7	0.0004572	0.69	1.1185	2.05%
9	0	0	0	325.0	0.0002286	0.83	0.9197	3.36%
10	0	0	0	1050.0	0.0004953	0.69	0.9200	1.55%
11	0	0	0	1761.0	0.0004572	0.69	1.1185	2.05%
12	0	0	0	100.0	0.0004953	0.69	0.8948	1.51%
13	0	0	0	458.3	0.0001905	1.32	1.6405	7.20%
14	0	0	0	0.0	0.0002286	0.69	1.6400	6.00%

APPENDIX A2: Gasoline Testing Data

Test No.	Amdient Temp	Humidity	Pressure	Engine Temp	Air Inlet Temp	Gear	Speed	RPM
	(deg C)	(%)	(mPa)	(deg C)	(DegC)		(KPH)	
1	13.0	52.3	1000	40.0	14.8	4	79.7	7966.7
2	13.3	52.1	1000	91.0	17.5	4	80.0	8010.0
3	14.0	50.0	1000	112.3	19.2	4	79.7	8003.3
4	14.6	49.7	1000	136.3	19.4	4	80.0	8053.3
5	14.6	48.0	1000	145.0	20.9	4	80.0	8033.3
6	14.9	47.4	1000	154.0	19.6	4	70.0	6983.3
7	14.7	47.0	1000	167.0	19.6	4	70.0	7023.3
8	15.0	45.8	1000	156.0	20.9	4	70.0	7026.7
9	15.1	45.6	1000	155.7	19.9	4	70.0	7030.0
10	15.3	45.4	1000	155.3	21.0	4	70.0	7030.0
11	15.5	44.9	1000	153.0	19.8	3	60.0	7426.7
12	15.4	44.9	1000	156.0	18.9	3	59.7	7423.3
13	15.2	45.0	1001	140.0	17.4	3	60.0	7470.0
14	13.3	46.3	1001	143.3	17.4	3	60.0	7510.0
15	13.2	47.0	1001	150.0	18.7	3	60.0	7480.0
16	13.6	47.1	1001	157.0	17.5	3	50.0	6173.3
17	13.6	47.3	1001	157.0	18.4	3	50.0	6210.0
18	13.7	47.3	1001	153.0	18.0	3	50.0	6230.0
19	13.1	47.1	1001	154.0	17.8	3	50.0	6230.0
20	12.9	47.1	1001	153.0	18.4	3	50.0	6256.7
21	13.3	47.6	1001	150.3	18.9	2	40.0	6650.0
22	13.4	47.5	1001	150.3	18.6	2	40.0	6726.7
23	14.0	47.5	1001	148.3	18.4	2	40.0	6790.0
24	14.2	47.1	1000	150.0	19.1	2	40.0	6766.7
25	14.4	46.9	1000	153.3	19.5	2	39.7	6780.0
26	14.5	45.6	1000	157.3	19.1	2	30.0	4963.3
27	14.5	45.6	1000	146.7	19.0	2	30.0	5010.0

Test No.	CO2	CO	HC	NOx	Volmetric Flow Rate	Lambda	Power	Thermal efficiency
	(%)	(%)	(ppm)	(ppm)	(m^3/s)		(kW)	(%)
1	13.5	2.59	116.7	1593.3	0.0004585	0.90	1.8145	12.44%
2	13.5	1.93	84.3	2276.3	0.0005111	0.95	2.4857	15.28%
3	13.5	1.71	66.0	2763.3	0.0005054	0.95	2.7839	17.31%
4	13.7	1.21	50.3	3122.7	0.0005298	0.97	2.8585	16.96%
5	13.8	1.01	46.0	3531.3	0.0006944	0.98	3.5794	16.20%
6	12.2	4.36	168.7	1940.3	0.0003840	0.87	1.7897	14.65%
7	12.9	2.97	119.3	2991.3	0.0004499	0.89	2.5602	17.88%
8	13.2	2.33	109.3	3140.3	0.0005076	0.94	3.3556	20.78%
9	13.2	2.64	96.3	2930.3	0.0005313	0.91	3.4799	20.58%
10	13.1	2.66	97.3	3032.7	0.0005505	0.91	3.8776	22.14%
11	12.5	3.55	141.3	1857.7	0.0004112	0.89	1.9388	14.82%
12	13.2	2.38	105.7	3392.3	0.0004733	0.92	2.8585	18.98%
13	13.8	1.49	86.0	2789.3	0.0005281	0.98	3.4302	20.41%
14	13.9	1.30	64.0	3262.0	0.0005298	0.98	3.3805	20.05%
15	13.7	1.88	73.7	3321.7	0.0005629	0.94	3.9274	21.93%
16	12.2	3.94	179.0	1597.3	0.0002927	0.88	1.2428	13.34%
17	12.4	3.39	134.0	2497.0	0.0003988	0.89	2.3614	18.61%
18	13.4	2.23	108.3	3258.3	0.0004713	0.93	3.2811	21.88%
19	12.9	2.70	108.0	3217.3	0.0004870	0.91	3.3556	21.65%
20	13.0	2.78	107.3	3007.3	0.0005182	0.91	3.6291	22.01%
21	12.9	3.21	168.3	999.7	0.0002415	0.90	0.7706	10.03%
22	12.4	3.61	165.0	1023.0	0.0003940	0.89	2.1625	17.25%
23	13.1	2.60	114.3	1023.0	0.0005129	0.92	3.4799	21.32%
24	12.8	3.12	113.7	1023.0	0.0005416	0.90	3.6291	21.06%
25	12.9	3.28	106.3	1023.0	0.0005597	0.89	3.9025	21.91%
26	13.0	1.76	94.7	991.0	0.0001575	0.00	0.6115	12.20%
27	11.9	3.86	153.7	1906.3	0.0002796	0.00	0.7606	8.55%

APPENDIX B: Experimental Equipment

APPENDIX B1: Dyno Dynamics 450M Dynamometer

DYNO DYNAMICS AUSTRALIA 450 M

As used by Mobil Honda race team

- 450 kW (600Hp) Capacity
- Wide Run Up Ramp and Platform
- Phase 3 Computerised Control System
- 300 kph Speed Rated
- Electromagnetic Eddy Current Retarder
- Single (lightweight) 405mm Roller
- Unique Square Cut Knurled Roller

Bike Max 450 Features:
Electronically controlled load:

Constant Speed Mode -
Dial in the speed you want and vary the load with a twist of the throttle.

Constant Load Mode -
Dial in the load you want and vary the speed with a twist of the throttle.

Light Weight Roller:
Able to run comfortably 50cc right through to the largest race bikes.
Very low rotating inertia which will give you more sensitivity and feel of what the bike is really doing; especially at light and partial throttle openings without the problems on over-run.
More accurate (no power losses due to tyre slippage)
It will handle all bike capacities
Simple, Easy & Safe Set up.

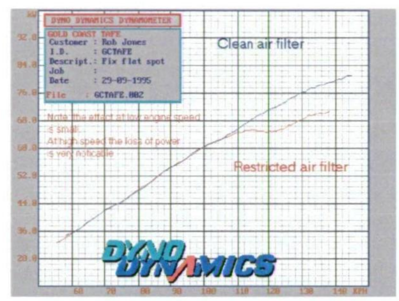
Unique Square Cut Knurl :
More traction than bitumen
Cooler tyre temps (saving tyres)

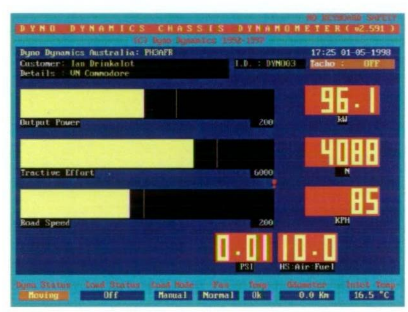
450 kW (600 HP*):*
Power to spare (never pushing it to the limit)

Wide Run up Ramp & Platform*:*

Instrumentation and Control System

Phase 3 Computerised Control System
Hand held Command Module
Full colour computerised display
Auto Temperature Compensation
Snapshot and Detail Module,
Ability to Edit Snap Shot File
Plot "live to screen", Store & Print, Graphs:
    High Resolution, fine line graphing
    Step Ramp graphing
    Speed Step graphing
    Snap graphing
Ability to Edit graphs, add comments
Scan and insert customer logo
Computer
Colour Monitor
Keyboard
Mouse
High Quality Ink Jet Colour Printer
Registered version of Neopaint
Odometer Module





Full (Atmospheric) Correction
Enables entry of atmospheric pressure, relative humidity, and room temperature. The Dynamometer compensates for these (in addition to inlet air temperature).
Optionally prompts operator for entry of these at start-up. Optionally prints all correction factors in the header for each set of snapshot records.

APPENDIX B2: Hydrogen Flowmeter

TECFLUID

Instrumentation for fluids

Variable Area Flowmeter

Series 2100/2150 2300/2340

Measurement of Low GAS & Liquid Flows

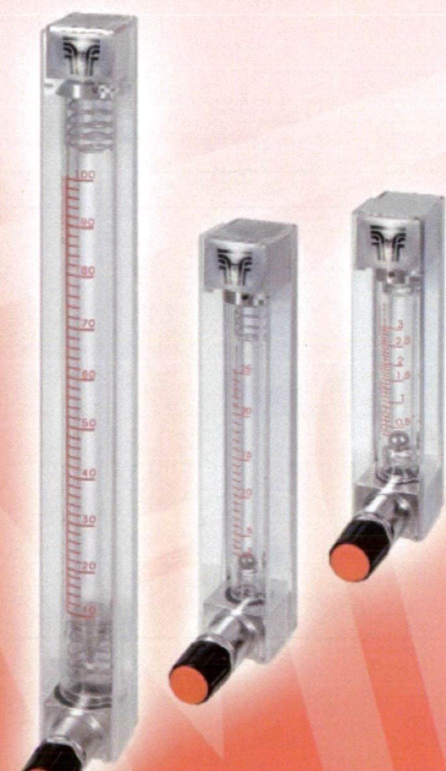
The Measurement

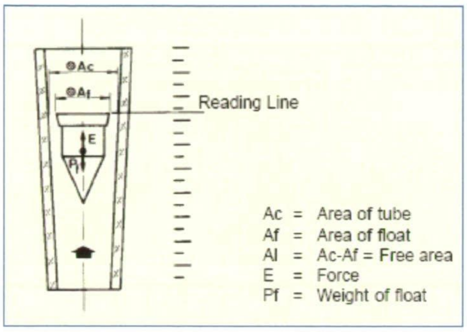
Measurement with a float in a tapered borosilicate glass tube.

- Series 2100 with a 100 mm flow tube
- Series 2150 with a 150 mm flow tube
- Series 2300 and 2340 with a 300 mm flow tube
- Regulating valve with a tapered plug and fine thread for precise flow adjustment
- Compact construction with reduced dimensions to facilitate easy installation and mounting on control panels
- Scales calibrated in flow units of l/h, %, l/min or cc/min
- High & Low flow alarms (Optical, inductive or hall sensor)
- Constant flow regulators RCA or RCD
- A large number of applications in a wide range of manufacturing and laboratory processes, such as:
  - Control panels
  - Pilot plants
  - Measurement & control on machinery
  - Water purification (Osmosis)
  - Control in research laboratories
  - Control of gas burners
  - Chemical / pharmaceutical / cosmetic industry
  - Flow control for industrial refrigeration
  - Heat treatment
  - Level control with the RCD regulator

Benefits

- Easy installation
- Short mounting length
- No straight pipe required before or after the flow meter
- Vertical mounting for rising fluid flow
- Horizontal inlet & outlet connections
- Low pressure loss
- Temperatures up to 100°C
- Compact construction





Operation

A fluid flowing vertically through a tapered tube will provide a lifting force on a weighted float, holding it in a fixed position for a fixed flow.
The float's resting position is a function of; the free area of flow Al (annulus between the float and the measuring tube), the weight of the float Pf and the force E of the fluid flow. Each position of float height corresponds to a different flow, which is shown by the equivalent scale engraved on the metering tube.

Model 2150 with inductive sensor

Technical Data

- Connections
  - 2100 / 2150 / 2300 R1/4", (Female) BSP or NPT
  - 2300 R1/4", (Female) BSP or NPT
  - 2340 R1/2", R3/4" (male only) BSP or NPT

  (BSP parallel according to standard ISO 228-1)
  (NPT according to ANSI B2 1968)
- Length:

Length	Flow Tube	Body
- 2100	100 mm	165 mm
- 2150	150 mm	215 mm
- 2300	300 mm	365 mm
- 2340	300 mm	390 mm

- Accuracy, according to VDE / VDI 3513 standards:
  - 2100 ± 3.5%
  - 2150 ± 3%
  - 2300 / 2340 ± 1.6 %
- Scales calibrated directly in
  - l/h for water
  - l/h up to 700 Nl/h for air
  - Nm^3/h from 1-17Nm^3/h for air
  - l/s, cc/min, %, or others on request
- Materials:
  Ends: AISI-316L (1.4404)
  Body: AISI-316L (1.4404)
  Valve: AISI-316L (1.4404)
  Valve Seat: PTFE
  O-Rings/gaskets NBR (Viton or EPDM on request)
- Temperature:
  Fluid: 0...+100°C
  Ambient: 0...+80°C
- Alarm Options:
  - 20-AMD (1...2): Inductive sensor (relay amplifier on request)
  - 20-AMO (1...2): Optical detector (relay infrared in Aluminium case)
  - 20-AMH (1...2): HALL effect sensor (relay in Aluminium case)
- Constant Flow Regulators:
  - Series RCA: For gases when the inlet pressure varies and the outlet pressure is constant.
    For all liquid applications.
  - Series RCD: For gases when the outlet pressure fluctuates and the inlet pressure is constant.
- Regulator Materials:
  Body: AISI-316
  Membrane: NBR (Viton or PTFE on request)
  Spring: AISI-316
- The minimum allowable pressure difference between the inlet and outlet of the regulator is 200 mbar.

Float AC **Float ECG**

APPENDIX B3: RPM Counter

Technical data tico 731

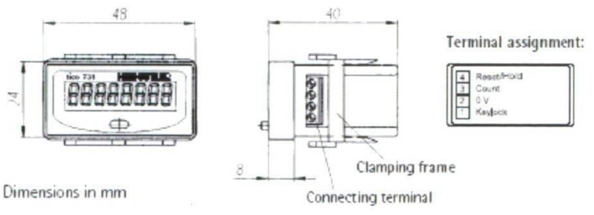
TYPE 1

- LCD display
- Lithium battery
- COUNT: programmable count input for voltage signal or contact, frequency 7.5 kHz or 30 Hz
- HOLD: Display memory input contact (negative, 30 Hz)
- KEYLOCK: locking of the Hold buttom
- Gate measurement with 6 s measuring time in Imp/min

TECHNICAL DATA

Operating temperature	-10 ... 50 °C
Strorage temperature	-20 ... +60 °C
Electrical connection	screw terminals
Mounting	with clamping frame
Front panel cutout	45 + 0.6 x 22 + 0.3 mm
Protection class (IEC 144)	front side IP 54, terminals IP 20
Dynamic strength	10 m/s2 (10 ... 150 Hz) according to IEC 68-T2-6
Shock stability	100 m/s2 (18 ms) according to IEC 68-T2-27
General rating	according to EN 61010, protective system II
Pulse shape	any square wave (1:1 for max. frequency)
Input resistance	< 50 kOhm (static)
Min. pulse length	17 ms (30 Hz), 70 µs (7.5 kHz)
Display	8-digit LCD, 7 mm
Supply voltage U_b	internal lithium battery
Nominal data retention	lithium battery: 7 years
Inputs:	
Amplitude thresholds	voltage input up to 7.5 kHz: < 0.7 V and > 5 V, max 30 V DC
Active edge	negative or positive edge programmable
Counting frequency	max. 7.5 kHz
Control inputs:	
Display Hold	- manual via keyboard (can be locked) - external Hold with static behaviour, active edge negative 30 Hz

DIMENSIONS
CONNECTION DIAGRAM



ORDER NUMBER

Model tico 731

0 731 | 1 | 0 2 | S*

* Option: with plug-in screw terminals

Software function
01 impulse counter
02 tachometer (1/min)
03 time counter (hhhh:mm:ss)
04 time counter (hhhhhh.hh)

APPENDIX B4: Atmospheric Temperature and Humidity Probe

Click to go to www.geotechenv.com

Air Velocity Meters

TSI VelociCalc Plus

TSI's VELOCICALC® Plus Meters simultaneously measure and data log several ventilation parameters using a single probe with multiple sensors. Based on the model, these hand-held instruments measure velocity, temperature, differential pressure and humidity. All versions calculate volumetric flowrate. The Model 8386 also performs dew point, wet bulb temperature and heat flow calculations.

FEATURES VelociCalc Plus

- Wide velocity range of 0 to 50 m/s
- Flowrate feature makes simple calculations of volumetric flowrate when the user inputs the duct shape and size, K factor or horn size
- Velocity measurements are made from the thermal sensor or a Pitot tube
- Automatic conversion between actual and standard velocity readings
- Direct calculation of dew point and wet bulb temperature - no psychrometric chart needed (Model 8386 only)
- Heat flow function calculates heat transferred after a heating or cooling element (Model 8386 only)
- Stable digital display when measuring fluctuating flows
- Back-lit display is easy to read in poor lighting conditions
- 101.6 cm telescoping probe with etched length marks to make duct traverse measurements easier
- Optional articulating probe available
- Optional portable printer provides hard copy documentation of your measurements

VelociCalc Plus

	Model	Datalogging/Downloading	Air Velocity	Temperature Reading	Flowrate	Differential Pressure	Humidity	Dewpoint, Wet Bulb	Density Correction	K Factor	Review Data	Statistics	Variable Time Constant	Field Calibration Adjustment	Printer Output	Back-lit Display	Articulating Probe
VelociCalc	8384	X	T	X	T				X	X	X	X	X	X	X	X	O
	8385	X	T,P	X	T,P,C	X			X	X	X	X	X	X	X	X	O
	8386	X	T,P	X	T,P,C	X	X	X	X	X	X	X	X	X	X	X	O

Key
T = Thermal Anemometer
X = Feature of Instrument
C = Calculated from Differential Pressure
O = Optional

Geotech Environmental Equipment, Inc.
8035 East 40th Avenue • Denver, Colorado 80207
(303) 320-4764 • **(800) 833-7958** • FAX (303) 322-7242
email: sales@geotechenv.com website: www.geotechenv.com

Air Velocity Meters

TSI VelociCalc Plus

SPECIFICATIONS VelociCalc Plus

Velocity from Thermal Sensor (all models)	
Range	0 to 9,999 ft/min (o to 50 m/s)
Accuracy[1&2]	±3.0% or reading or ±3 ft/min (0.015 m/s) whichever is greater
Resolution	1 ft/min (0.01 m/s)
Velocity from a Pitot Tube (models 8385 (A) and 8386 (A))	
Range[3]	250 to 15,500 ft/min (1.27 to 78.7 m/s)
Accuracy[4]	±1.5% at 2,000 ft/min (10.16 m/s)
Resolution	1 ft/min (0.01 m/s)
Volumetric Flowrate (all models)	
Range	Actual range is a function of maximum velocity, pressure, duct size, and K factor
Duct Size (all models)	
Range	1 to 250" in increments of 0.1" (1 to 635 cm in increments of 0.1 cm)
Static/Differential Pressure (models 8385 (A) and 8386 (A))	
Range[5]	-5 to +15 in. H_2O
Accuracy[6]	±1% or reading ±0.005 in. H_2O (±1 Pa or ±0.01 mmHg)
Resolution	0.001 in H_2O (1 Pa, 0.01 mmHg)
Instrument Temperature Range	
Operating (Probe 8384 (A) and 8385 (A))	0 to 200°F (-17.8 to 93.3°C)
Operating (Probe 8386 (A))	14 to 140°F (-10 to 60°C)
Operating (Electronics)	40 to 113°F (5 to 45°C)
Storage	-4 to 140°F (-20 to 60°C)
Resolution	0.1°F (0.1°C)
Accuracy[7]	±0.5°F (±0.3°C)
Relative Humidity (model 8386 (A) only)	
Range	0 to 95% rh
Accuracy[8]	±3% rh
Resolution	0.1% rh
Wet Bulb Temperature (model 8386 (A))	
Range	40 to 140°F (5 to 60°C)
Resolution	0.1°F (0.1°C)
Dewpoint (model 8386 (A) only)	
Range	5 to 120°F (-15 to 49°C)
Resolution	0.1°F (0.1°C)

Heat Flow (model 8386 (A) only)	
Range	Function of Flow Rate, Temperature, Humidity, and Barometric Pressure
Measurements Available	Sensible heat flow, Latent heat flow, Total heat flow, and Sensible heat factor
Units Measured	BTU/h, kW
Logging Capability (all models)	
Range	Up to 1394 samples and 275 test id's (one sample can contain up to all eleven measurement types)
Intervals	2 sec, 5 sec, 10 sec, 15 sec, 20 sec, 30 sec, 60 sec, 2 min, 5 min, 10 min, 15 min, 20 min, 30 min, 60 min
Time Constant (all models)	
Intervals	1 sec, 2 sec, 5 sec, 10 sec, 15 sec, 20 sec
External Meter Dimensions (all models)	
Probe Length	40" (101.6 cm)
Probe Diameter of Tip	0.276" (7.01 mm)
Probe Diameter of Base	0.395" (10.03 mm)
Articulating Probe Dimensions (models 8384A, 8385A, 8386A)	
Articulating Section Length	6.4" (16.26 cm)
Diameter of Articulating Knuckle	0.375" (9.44 mm)
Meter Weight Dimensions (all models)	
Weight (with batteries)	1.2 lbs (0.54 kg)
Power (all models)	
Requirements	Four AA batteries (included) or AC adapter (optional)

1 Temperature compensated over an air temperature range of 40 to 150°F (5 to 65°C).
2 The accuracy statement of ± 3.0% of reading or ±3 ft/min (±0.015 m/s), whichever is greater, begins at 30 ft/min through 9,999 ft/min.
3 Pressure Velocity measurements are not recommended below 1,000 ft/min and are best suited to velocities over 2,000 ft/min. Range can vary depending on barometric pressure.
4 Accuracy is a function of converting pressure to velocity. Conversion accuracy improves when actual pressure values increase.
5 Overpressure range = 275 in H_2O (520 mmHg, 69 kPa)
6 Accuracy with instrument case at 77°F (25°C), add uncertainty of 0.02/°F (0.03%/°C)
7 Accuracy with instrument case at 77°F (25°C), add uncertainty of 0.05°F/F (0.03°C/°C)
8 Accuracy with probe at 77°F (25°C). Add uncertainty of 0.1%RH/°F (0.2%RH/°C) for change in probe temperature. Includes 1% hysteresis.

Specifications are subject to change without notice.

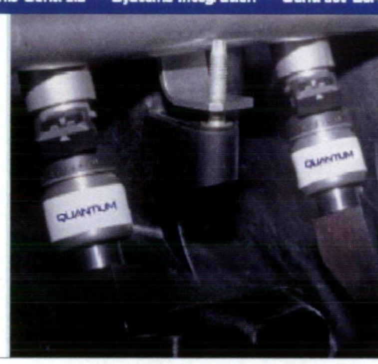
APPENDIX C: Conversion Equipment

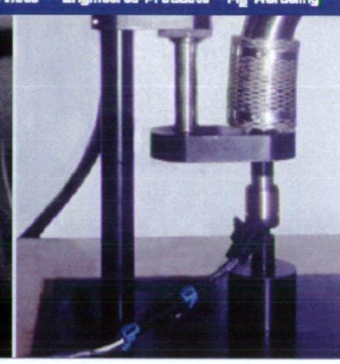
APPENDIX C1: Gaseous Fuel Injectors

GASEOUS FUEL INJECTOR

QUANTUM
TECHNOLOGIES

Fuel Storage | Fuel Metering | Electronic Controls | Systems Integration | Contract Services | Engineered Products | H_2 Refueling

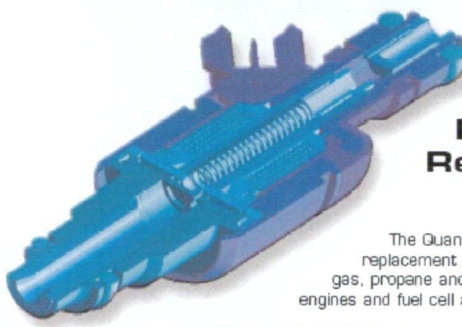




At Quantum, we design and manufacture state-of-the-art fuel storage, fuel metering and electronic controls, and provide advanced systems integration services that bring concept to reality for the world's largest automotive and non-automotive original equipment manufacturers of fuel cell products and alternative fueled motor vehicles.

Specializing in internal combustion engine and fuel cell applications including:

- Automotive
- Truck
- Bus
- Industrial
- Marine
- Aerospace
- Defense
- Power Generation
- Hydrogen Refueling



The First Injector to Handle Your Power & Flow Requirements.

The Quantum gaseous fuel injector is a direct replacement injector designed to work with natural gas, propane and hydrogen in internal combustion engines and fuel cell applications.

Existing injector designs suffer from premature failure in dry gas applications, orifice contamination and insufficient flow capacity for today's applications. Quantum's multi-port gaseous fuel injector addresses these shortcomings. Furthermore, the Quantum gaseous fuel injector is the first automotive-type fuel injector capable of handling the high flow rate fuel delivery requirements of 300+ horsepower V8 engines.

A simple design to provide freedom from frictional wear and sticking allows for enhanced durability. Quantum's gaseous fuel injector is designed to achieve over 500 million cycles.

FEATURES

- Suitable for all port injection internal combustion engines and fuel cell applications.
- Unique disc valve design permits high gas flow and sustained durability.
- Fits typical port and fuel rail applications.
- Design is proven for high-volume manufacturing.
- Flexible design allows for low and high flow rates with minimal cost impact.
- Validated for use in typical automotive applications.
- Utilizes a standard electrical connector.
- Submitted for ECE-R110 approval for European applications.

DURABILITY

QUANTUM
TECHNOLOGIES

GASEOUS FUEL INJECTOR

PRODUCT VALIDATION

- Temperature
- Vibration
- Thermal shock
- Water intrusion
- External corrosion
- Internal corrosion
- Immunity to conducted transients
- Immunity to jumpstart voltages

ELECTRICAL INTERFACE

Connector:
Injector mates with AMP™ connector
Supply Voltage:
8-16 Volts typical
Injector Coil Characteristics:
Resistance:
2.05 +/- 0.25 Ω at 20°C
Inductance:
3.98 +/- 0.3 mH at 1000 Hz typical
Drive Circuit: Peak and Hold

The Quantum injector is a low impedance device requiring a peak and hold drive circuit. The characteristics are shown in Figure 1, where system voltage is supplied during the peak current time followed by a hold current for the remaining of the pulse.

Applying direct battery voltage to the injector during crank and the first ten seconds of run time helps make the injector performance less sensitive to fuel-born contaminants in gaseous fuel applications.

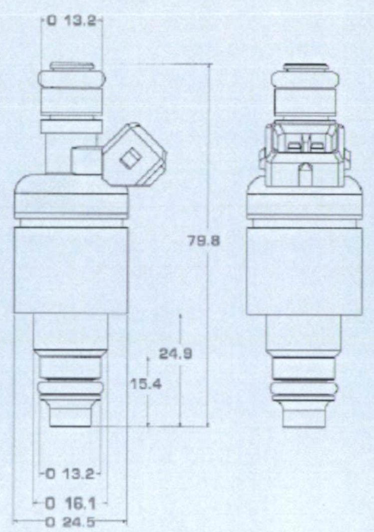
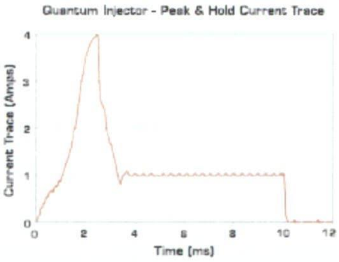


Figure 1



- **Length:** 79.8 mm
- **Diameter (Max):** 24.5 mm (excl. connector)
- **Flow Capacity (Static):**
  CNG: 2.0 g/s @ 276-310 kPa / 40-45-psi
  LPG: 2.0 g/s @ 117-138 kPa / 17-20-psi
  Hydrogen: 0.8 g/s @ 483-552 kPa / 70-80-psi
- **Working Pressure:** 103-552 kPa / 15-80-psi
- **Durability:** >500 million cycles (tested on CNG)
- **Dynamic Range:** 12:1 typical

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APPENDIX C2: Ignition Coil

BOSCH **MOTORSPORT COMPONENTS**

IGNITION COILS

Purpose and Function.
Modern ignition systems are required to generate high ignition energy outputs in the most efficient way possible. Transformer type coils filled with high temperature epoxy resin are available in different formats including double output "waste spark" style units for 4 or 6 cylinder applications.

IGNITION COIL TECHNICAL DATA

Part Number	High Voltage Outputs	Construction Type	Primary Resistance [ohms]	Secondary Resistance [ohms]	Primary Connector	Secondary Terminal	Comments
GT40R	1	Oil Filled	1.2	8 - 10 K	M4/M5	Standard	Canister type
GT40RT	1	Transformer	1.5	8.6 K	M4/M5	Standard	Type "A"
HEC 715	1	Transformer	0.41	7.8 K	M4/M5	Standard	Type "A"
HEC 716	1	Transformer	0.41	7.8 K	M4/M5	DIN type	Type "B"
MEC 717	1	Transformer	0.45	6.6 K	M4/M5	Standard	Type "A"
MEC 718	1	Transformer	0.45	6.6 K	M4/M5	DIN Type	Type "B"
9 220 061 710	1	Transformer	0.4	7.8 K	M4/M5	DIN Type	Type "B"
0 221 503 407	2 x 2	Epoxy Filled	0.5	13.3 K	1 237 000 039	Standard	Double ended coils
0 221 503 002	3 x 2	Epoxy Filled	0.5	13.3 K	1 287 013 900	Standard	Double ended coils

Type A

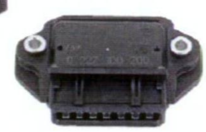
Type B

APPENDIX C3: Ignition Module

MOTORSPORT COMPONENTS **BOSCH**

IGNITION MODULES

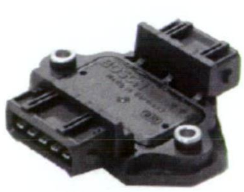
Purpose and Function.
Modern ignition systems are required to generate high ignition energy outputs in the most efficient way possible. Transformer type coils filled with high temperature epoxy resin are available in different formats including double output "waste spark" style units for 4 or 6 cylinder applications.



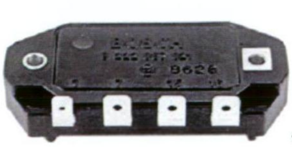
IGNITION MODULE TECHNICAL DATA

Part Number	Number of Output Stages	Maximum Primary Current [A]	Number of Pins	Type of Trigger	Connector	Type	Comment
0 227 100 123 [BIM 123]	1	8 - 10	6	Inductive	1 287 013 005	A	
0 227 100 124 [BIM 027]	1	8 - 10	6	Hall Effect	1 287 013 005	A	
0 227 100 137 [BIM 137]	1	8 - 10	7	Hall Effect	1 287 013 005	A	
0 227 100 200 [BIM 200]	2	8 - 10	7	ECU Control	1 287 013 005	A	2 channel pwr transistor
0 227 100 203	3	8 - 10	7	ECU Control	1 287 013 005	A	3 channel pwr transistor
0 227 100 209	3	8 - 10	3 & 4	ECU Control	1 287 000 039 & 1 287 013 900	B	3 channel pwr transistor
0 227 100 211	4	8 - 10	4 & 5	ECU Control	1 287 013 900 & 1 287 013 006	B	4 channel pwr transistor
9 222 067 024 [BIM 024]	1	8 - 10	4	Inductive	N/A	C	
9 222 067 027 [BIM 027]	1	8 - 10	6	Hall Effect	1 287 013 005	A	
9 222 067 034 [BIM 034]	1	8 - 10	3	ECU Control	1 237 000 039	D	1 channel pwr transistor

Type A



Type B



Type C

Type D

APPENDIX C4: MoTec M4 Engine Management System Specifications

General

- Microprocessor 32 Bit 33 MHz with Time CO Processor
- Quality Standard ISO 9001
- Manufacturing Standard IPC-S-815-A Class 3 High Reliability
- Warranty 1 year Parts & Labour
- Burn In -50 to 70□C for 32 Hrs
- ECU Control Software stored in updatable FLASH memory
- High RFI Immunity
- Low heat generation
- Battery transient protection
- Environmentally sealed electronics
- Water proof connector with gold plated contacts
- Case Size 120 x 100 x 36 mm (4.7 x 3.9 x 1.4 inches)
- Weight 0.4 kg (14 oz)
- Cylinders 1,2,3,4,6,8,12
- Engines 2 stroke, 4 stroke, Rotary (1~4), Odd or Even fire
- Maximum RPM >15,000 RPM

Fuel Calibration

- Accuracy 0.00001 seconds
- All RPM & Load sites are user programmable
- Main Table (3D) 40 RPM sites x 21 Load sites (840 points)
- End of Injection (3D) 20 RPM sites x 6 Load sites
- Overall Trim □99 %
- Individual Cylinder Trim □99 %
- Individual Cylinder Tables (3D) 20 RPM sites x 11 Load sites
- Hi / Lo Injector Balance (3D) 20 RPM sites x 11 Load sites
- Hi / Lo End of Injection (3D) 20 RPM sites x 11 Load sites
- Eng Temp & Air Temp comps
- MAP modifier compensation
- Two Auxiliary compensation
- Injector Dead Time Compensation
- Accel Clamp, Decay & Sensitivity
- Deccel Clamp, Decay & Sensitivity
- Cold Start

Injection

- 4 group sequential
- User programmable injector current 0.5~12 Amps peak
- Battery Comp to suit any injector

Boost Control Calibration

- Main Table (3D) 20 RPM sites x 10 Throttle sites or 10 Gear sites
- Overall Trim
- Engine Temp & Air Temp comps
- One Auxiliary compensation

Ignition Outputs

- Up to 4 Ignition Outputs
- One output may drive up to 8 coils using the MoTeC Ignition Expander
- Versatile Ignition Interface allows connection to most OEM ignition systems including:
    - Nissan Multi Coil modules
    - GM EST DFI systems
    - FORD EDIS DFI systems
    - Mazda Rotary DFI modules
    - Many Others

Ignition Calibration

- Accuracy 0.25 degrees
- All RPM & Load sites are user programmable
- Main Table (3D) 40 RPM sites x 21 Load sites (840 points)
- Overall Trim □99 %
- Individual Cylinder Trim □99 %
- Individual Cylinder Tables (3D) 20 RPM sites x 11 Load sites
- Rotary Split 20 RPM x 11 Load
- Eng Temp & Air Temp comps
- MAP compensation
- Two Auxiliary compensations
- Dwell Time 20 RPM x11 Battery
- Odd fire engine capability Each Top Dead Centre angle may be specified Resolution 0.5 degree

Trigger Sensors

- Directly compatible with most OEM trigger systems including :
  - HALL, Magnetic and Optical types
  - Multi Tooth (eg Mazda and Toyota)
  - 1 or 2 Missing Teeth (eg Porsche)
  - Many other special types, eg. Ford Narrow Tooth, Nissan Optical, Harley Davidson

Data Logging

- Optional Logging memory allows logging of all ECU parameters
- Memory Size 512 KByte
- Logging Rate 1~20 sets / sec
- Logging Time 38 minutes at 5 sets / sec (28 Parameters+Diags) PC Software is available for analysis of the logged data.

Air Fuel Ratio Sensor

- High accuracy Wide Band Air Fuel Ratio Sensor Input (Optional)
- Range 0.75 to 1.20 Lambda
- Resolution 0.01 Lambda

- Other Sensors
  - Throttle Pos, Manifold Pressure, Engine Temp & Air Temp
  - 2 Auxiliary Sensor inputs
  - 2 Digital / Speed Inputs

Special Functions

- Traction Control & Launch Control (2 wheel speed sensors) (or 4 sensors using the MoTeC TC Mux)
- Gear Change Ignition Cut
- Wide Band or Narrow Band Air Fuel Ratio Control (3D mapped)
- Over Run Boost Enhancement
- Warning Alarms (Sensor HI / LO)
- Gear Detection Ground Speed Limiting
- Dual RPM Limit
- Nitrous Oxide Enrich / Retard
- Air Conditioner Request
- Over Run Fuel Cut
- Sensor Calibration Tables RPM Limit Hard or Soft Cut Fuel and / or Ignition Cut

Auxiliary Outputs

- Four general purpose outputs (3 shared with ignition outputs)
- The outputs may be used for :
  - Turbo Wastegate Control
  - Idle Speed Control
  - Fuel Used Pulse
  - Tacho Output
  - Shift Light (Gear Dependent)
  - Driver Warning Alarm
  - RPM / Load dependant device
  - User Defined Table (20x11) with definable axis parameters
  - Slip Warning
  - Fuel Pump Relay
  - Thermatic Fan
  - Air Conditioner Fan or Clutch

Diagnostics

- Injectors Open Circuit, Short Circuit, Peak Current Not Reached
- Sensors Open & Short circuit
- Operating Errors RPM Limit Exceeded, Injector Overduty, Over Boost, Low Battery, REF Error etc.

Operating Conditions

- Internal Temp Range -10~85□C
- Ambient Temp -10~70□C (Depending on load & ventilation)
- Operating Voltage 6~22V DC
- Operating Current 0.4 A max
- Reverse Battery External Fuse

Telemetry Link

- Optional Telemetry Link allows real time monitoring and data logging

APPENDIX C5: Reference Sensor

Solid State Sensors
Hall Effect Gear Tooth Sensors

GT1 Series

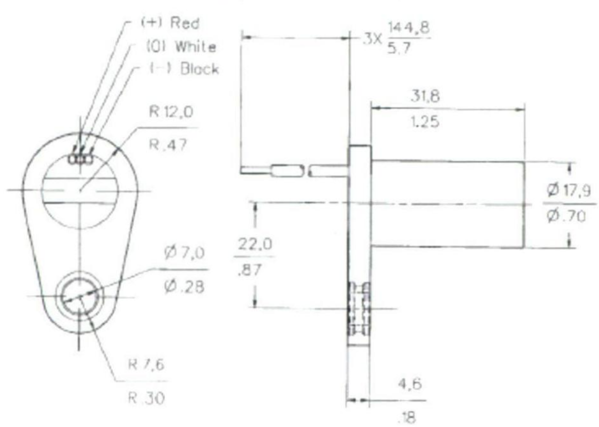
TYPICAL APPLICATIONS
Automotive and Heavy Duty Vehicles:
- Camshaft and crankshaft speed/ position
- Transmission speed
- Tachometers
- Anti-skid/traction control

Industrial:
- Sprocket speed
- Chain link conveyor speed and distance
- Stop motion detector
- High speed low cost proximity
- Tachometers, Counters

GT1 ORDER GUIDE

Catalog Listing	Description
1GT101DC	Gear Tooth Sensor

MOUNTING DIMENSIONS (For reference only)



FEATURES
- Senses ferrous metal targets
- Digital current sinking output (open collector)
- Better signal-to-noise ratio than variable reluctance sensors, excellent low speed performance, output amplitude not dependent on RPM
- Sensor electronically *self-adjusts* to slight variations in runout and variations in temperature, simplifying installation and maintenance
- Fast operating speed – over 100 kHz
- EMI resistant
- Reverse polarity protection and transient protection (integrated into Hall I.C.)
- Wide continuous operating temperature range (–40° to 150°C), short term to 160°C

GENERAL INFORMATION
1GT1 Series Gear Tooth Sensors use a magnetically biased Hall effect integrated circuit to accurately sense movement of ferrous metal targets. This specially designed I.C., with discrete capacitor and bias magnet, is sealed in a probe type package for physical protection and cost effective installation.

Units will function from a 4.5 to 24 VDC power supply. Output is digital, current sinking (open collector). Reverse polarity protection is standard. If power is inadvertently wired backwards, the sensor will not be damaged. Built-in protection against pulsed transients to +60V, –40V is also included.

Optimum sensor performance is dependent on the following variables which must be considered in combination:

- Target material, geometry, and speed
- Sensor/target gap
- Ambient temperature
- Magnetic material in close proximity

Solid State Sensors

Hall Effect Gear Tooth Sensors

GT1 Series

SENSOR SPECIFICATIONS

All values were measured using 1 K pull-up resistor.

Electrical Characteristics	Supply Voltage	4.5 to 24 VDC
	Supply Current	10 mA typ., 20 mA max.
	Output Voltage (output low)	0.4 V max.
	Output Current (output high)	10 μA max. leakage into sensor
	Switching Time Rise (10 to 90%)	15 μsec. max.
	Fall (90 to 10%)	1.0 μsec. max.
Absolute Maximum Ratings*	Supply Voltage (Vs)	±30 VDC continuous
	Voltage Externally Applied To Output (output high)	−0.5 to +30 V
	Output Current	40 mA sinking
	Temperature Range Storage	−40 to 150° (−40 to 302°F)
	Operating	−40 to 150° C (−40 to 302°F)
Switching Characteristics**	Operate Point	3.7±1.25° (3,28±1,13 mm)
	Release Point	4.7±2.50° (4,16±2,21 mm)
	Differential Travel	8.4±3.70° (7,45±3,34 mm)

* As with all solid state components, sensor performance can be expected to deteriorate as rating limits are approached; however, sensors will not be damaged unless the limits are exceeded.
** See Reference Target table.

TARGET GUIDELINES

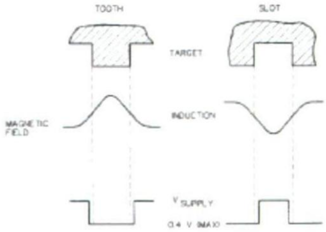
The Target Guidelines table provides basic parameters when an application is not restricted to a specific target.

Any target wheel that exceeds the following minimum specifications can be sensed over the entire temperature range of −40° to 150°C with any sensing gap up to .080 in. (2,0 mm). This data is based on a 4 in. (102 mm) diameter wheel, **rotating 10 to 3600 RPM.**

Reference Target Dimensions

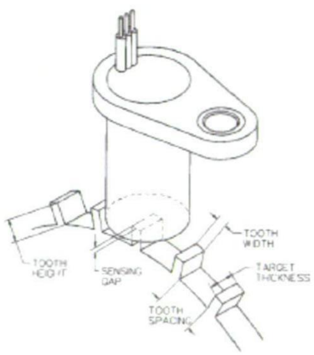
Tooth Height:	.200 in. (5,06 mm) min.
Tooth Width:	.100 in. (2,54 mm) min.
Tooth Spacing:	.400 in. (10,16 mm) min.
Target Thickness:	.250 in. (6,35 mm)

Sensor Output (with pull-up resistor added to output circuit)



REFERENCE TARGET/CONDITIONS

Characteristics will vary due to target size, geometry, location, and material. Sensor specifications were derived using a cold-rolled steel reference target. See table, right, for reference target configuration and evaluation conditions.



Target	
Diameter:	4 in. (101,6 mm)
Tooth Width:	.350 in. (8,89 mm)
Thickness:	.250 in. (6,35 mm)

Test Conditions	
Air Gap:	.040 to .080 in. (1,02 to 2,03 mm)
V Supply:	4.5 to 24 V
RPM:	10 min., 3600 max.

Integral Magnet

APPENDIX C6: Throttle Position Sensor

8 Angular-position sensors BOSCH

Throttle-valve angular-position sensor

Measurement of angles up to 88°

- Potentiometic angular-position sensor with linear characteristic curve.
- Sturdy construction for extreme loading.
- Very compact.

Application
These sensors are used in automotive applications for measuring the angle of rotation of the throttle valve. Since these sensors are directly attached to the throttle-valve housing at the end of the throttle-shaft extension, they are subject to extremely hostile underhood operating conditions. To remain fully operational, they must be resistant to fuels, oils, saline fog, and industrial climate.

Design and function
The throttle-valve angular-position sensor is a potentiometric sensor with a linear characteristic curve. In electronic fuel injection (EFI) engines it generates a voltage ratio which is proportional to the throttle valve's angle of rotation. The sensor's rotor is attached to the throttle-valve shaft, and when the throttle valve moves, the sensor's special wipers move over their resistance tracks so that the throttle's angular position is transformed into a voltage ratio. The throttle-valve angular-position sensor's are not provided with return springs.

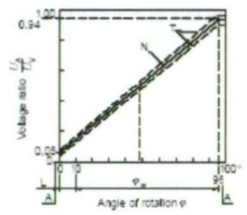
Design
The position sensor 0 280 122 001 has one linear characteristic curve.
The position sensor 0 280 122 201 has two linear characteristic curves.
This permits particularly good resolution in the angular range 0°...23°.

Explanation of symbols
U_A Output voltage
U_V Supply voltage
φ Angle of rotation
U_{A2} Output voltage, characteristic curve 2
U_{A3} Output voltage, characteristic curve 3

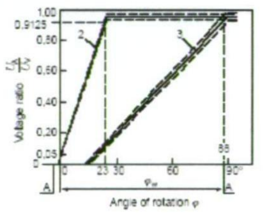
Accessories for 0 280 122 001	
Connector	1 237 000 039

Accessories for 0 280 122 201	
Plug housing	1 284 485 118
Receptacles, 5 per pack, Qty. required: 4	1 284 477 121
Protective cap, 5 per pack, Qty. required: 1	1 280 703 023

Characteristic curve 1.
A Internal stop, L Positional tolerance of the wiper when fitted, N Nominal characteristic curve, T Tolerance limit, φ_W Electrically usable angular range.



Characteristic curves 2 and 3.
A Internal stop, φ_W Electrically usable angular range.



Technical data / Range

Part number		0 280 122 001	0 280 122 201
Diagram		1; 2	3
Useful electrical angular range	Degree	≤ 86	≤ 88
Useful mechanical angular range	Degree	≤ 86	≤ 92
Angle between the internal stops (must not be contacted when sensor installed)	Degree	≥ 95	–
Direction of rotation		Optional	Counterclockwise
Total resistance (Terms. 1–2)	kΩ	2 ±20 %	–
Wiper protective resistor (wiper in zero setting, Terms. 2–3)	Ω	710...1380	–
Operating voltage U_V	V	5	5
Electrical loading		Ohmic resistance	Ohmic resistance
Permissible wiper current	µA	≤ 18	≤ 20
Voltage ratio from stop to stop Chara. curve 1		$0.04 \leq U_A/U_V \leq 0.96$	–
Voltage ratio in area 0...88 °C Chara. curve 2		–	$0.05 \leq U_{A2}/U_V \leq 0.985$
Chara. curve 3		–	$0.05 \leq U_{A3}/U_V \leq 0.970$
Slope of the nominal characteristic curve	deg^{-1}	0.00927	–
Operating temperature	°C	–40...+130	–40...+85
Guide value for permissible vibration acceleration	$m \cdot s^{-2}$	≤ 700	≤ 300
Service life (operating cycles)	Mio	2	1.2

APPENDIX D: Determination of Net Power

The following outlines the determination of net power as of AS4594.11. Although this calculation was not used in the final data analysis, the power correction factor was calculated for each experimental test to compare with the value obtained from the dynamometer data.

Observed power and actual engine power are not one in the same. Efficiency of transmission and reference atmospheric conditions result in a corrected power.

$$P_0 = \alpha_1 \alpha_2 P$$

Where

α_1 is the correction factor for efficiency of transmission

α_2 is the correction factor for reference atmospheric conditions

P is the measured power

Determination of α_1 (AS4594.11-6.3.1)

If measurement is taken at crankshaft α_1 is equal to 1.

Where measurement is not taken at the crankshaft

$$\alpha_1 = 1/\eta_t$$

Where η_t is the efficiency of transmission between the crankshaft and point of measurement.

η_t is calculated as the product of efficiency of each element constituting the transmission.

$$\eta_t = \eta_1 \times \eta_2 \times \eta_3 \times \ldots \times \eta_l$$

Component	**Type**	**Efficiency**
Gear	Spur gear	0.98
	Helical gear	0.98
	Beval gear	0.98
Chain	Roller	0.95
	Silent	0.98
Belt	Toothed	0.95
	V-belt	0.94

Hydraulic coupler or converter	Hydraulic coupler	0.92
	Non-locked Hydraulic converter	0.92

Determination of α_2 (AS4594.11-5.3.2)

Atmospheric Conditions

Reference Temperature – 298K (25°C) (AS4594.11-6.2.1.1)

Dry Pressure – 99kPa (AS4594.11-6.2.1.2)

For testing temperature will fall between 283K and 318K (10°C and 45°C) (AS4594.11-6.2.2)

Four Stroke Engine: (AS4594.11-6.3.2.2)

$$\alpha_2 = (99/p_d)^{1.2} (T/298)^{0.6}$$

Where

T is absolute temp in Kelvin at air inlet

P_d is dry atmospheric pressure in kPa

Formula only true for $0.95 \leq \alpha_2 \leq 1.05$

APPENDIX E: Calculated flow rate from flowmeter data

The flow data was calculated using the Meacon Tecfluid program CD. Aas shown below.

Air to Water:	30.81448	Temp	20.0 C		293 K
		Press	200.0 kPa g	psi g	3.01 Bar abs
		SG	0.07	Hydro	
Gas Conversion Factor:	120.265	Float	2.850 Kg/l	Al	
Overall Conversion Factor	1.203E+02	nl/hr			

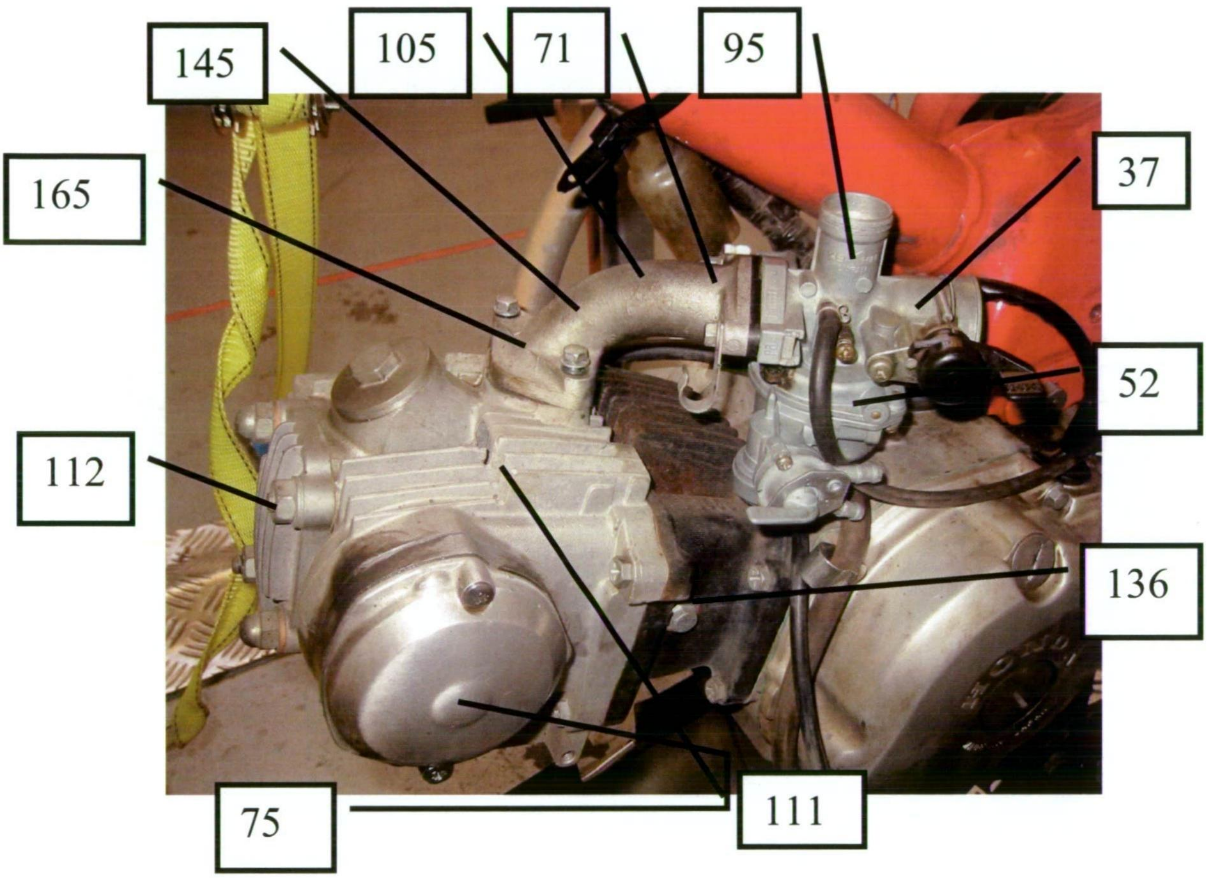
Std Rate	from Bottom end	Eqv Scale
l/hr	mm	nl/hr
630	0	[illegible]
		[illegible]
	Mass Rate, kg/hr	6.857
	g/sec	1.905

Data required in yellow sections

ECG	SS	7.95	30.81
(Round)	Glass	2.6	17.62
	Plastic	1.25	12.21
		7.95	from SS
Size	Material	Density	Factor
312	SS	7.950	30.81
16mm	SS/Mag	7.463	29.86
	Al	2.850	18.45
	Al/Mag	3.461	20.33
	PVDF/Pb	7.950	30.81
	PVDF/Pb/Mag	7.821	30.56
	PVDF	1.778	14.57
	PTFE	2.155	16.04
	PTFE/Mag	2.765	18.17
	PVC	1.400	12.93
	PVC/Mag	2.256	16.41
	PVC/Pb	7.950	30.81
313	SS	7.950	30.81
23mm	SS/Mag	7.680	30.29
	Al	2.850	18.45
	Al/Mag	3.552	20.60
	PVDF/Pb	7.950	30.81
	PVDF/Pb/Mag	7.487	29.90
	PTFE	2.155	16.04
	PTFE/Mag	2.958	18.80
	PVC	1.400	12.93
	PVC/Mag	2.347	16.74
	PVC/Pb	7.950	30.81
314	SS	7.950	30.81
33mm	SS/Mag	7.620	30.17
	Al	2.850	18.45
	Al/Mag	3.888	21.55
	PVDF/Pb	7.950	30.81
	PVDF/Pb/Mag	7.475	29.88
	PTFE	2.155	16.04
	PTFE/Mag		
	PVC	1.400	12.93
	PVC/Mag		
	PVC/Pb	7.950	30.81

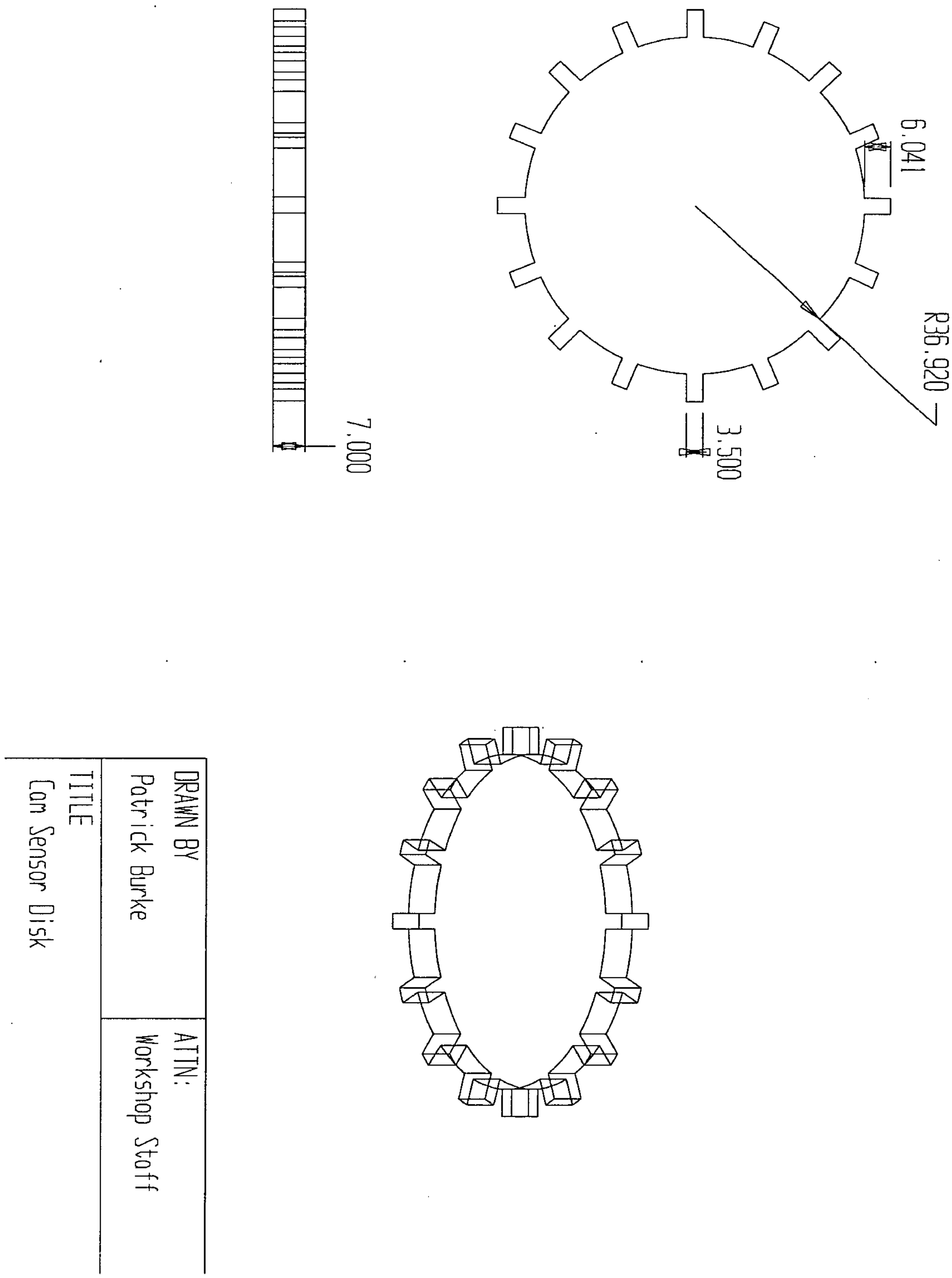
APPENDIX F: Manifold Temperature Distribution for Honda CT110 under gasoline operation

** All figures are in Degrees Celsius (℃).*

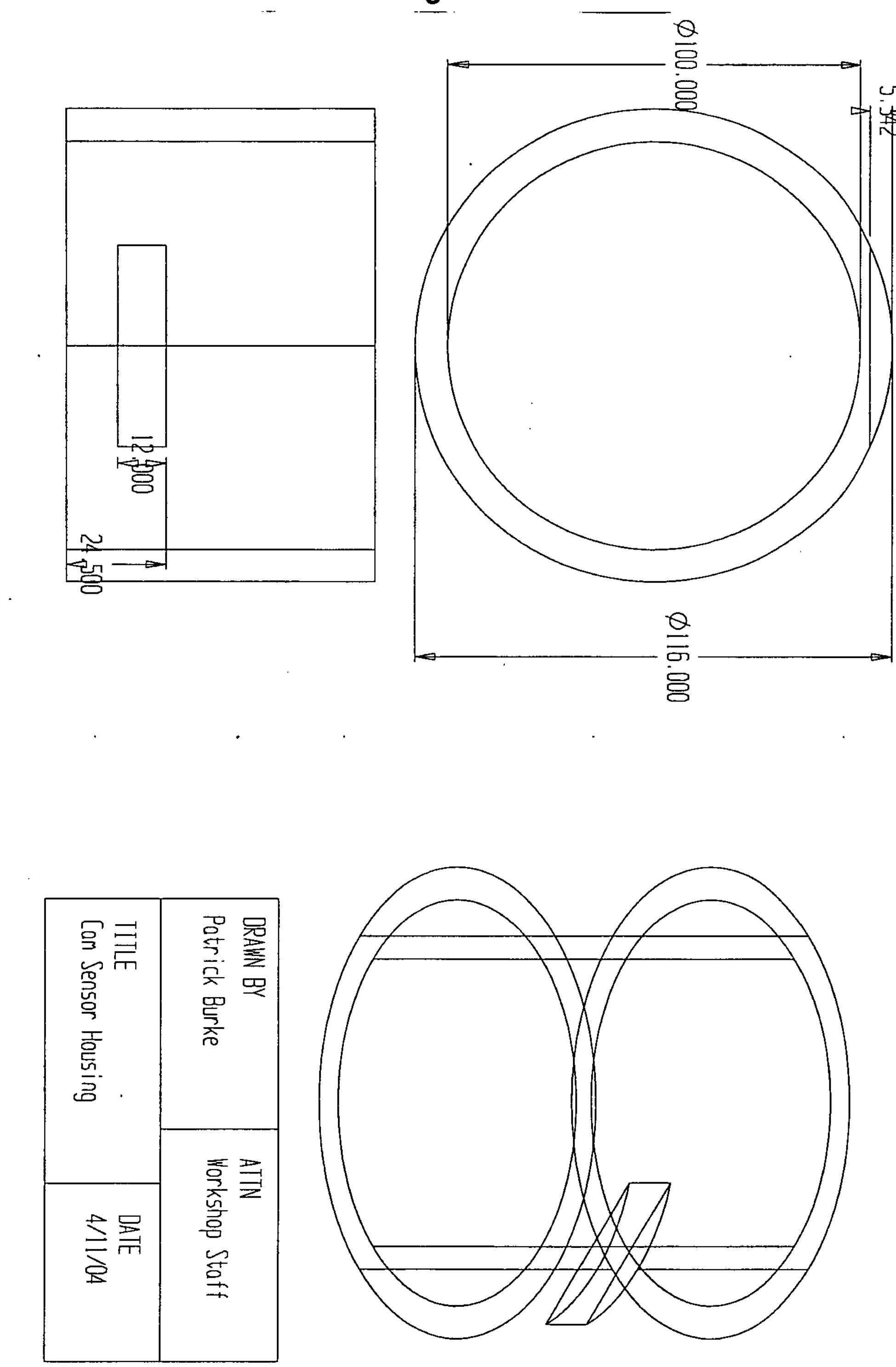


APPENDIX F: Cam sensor Design

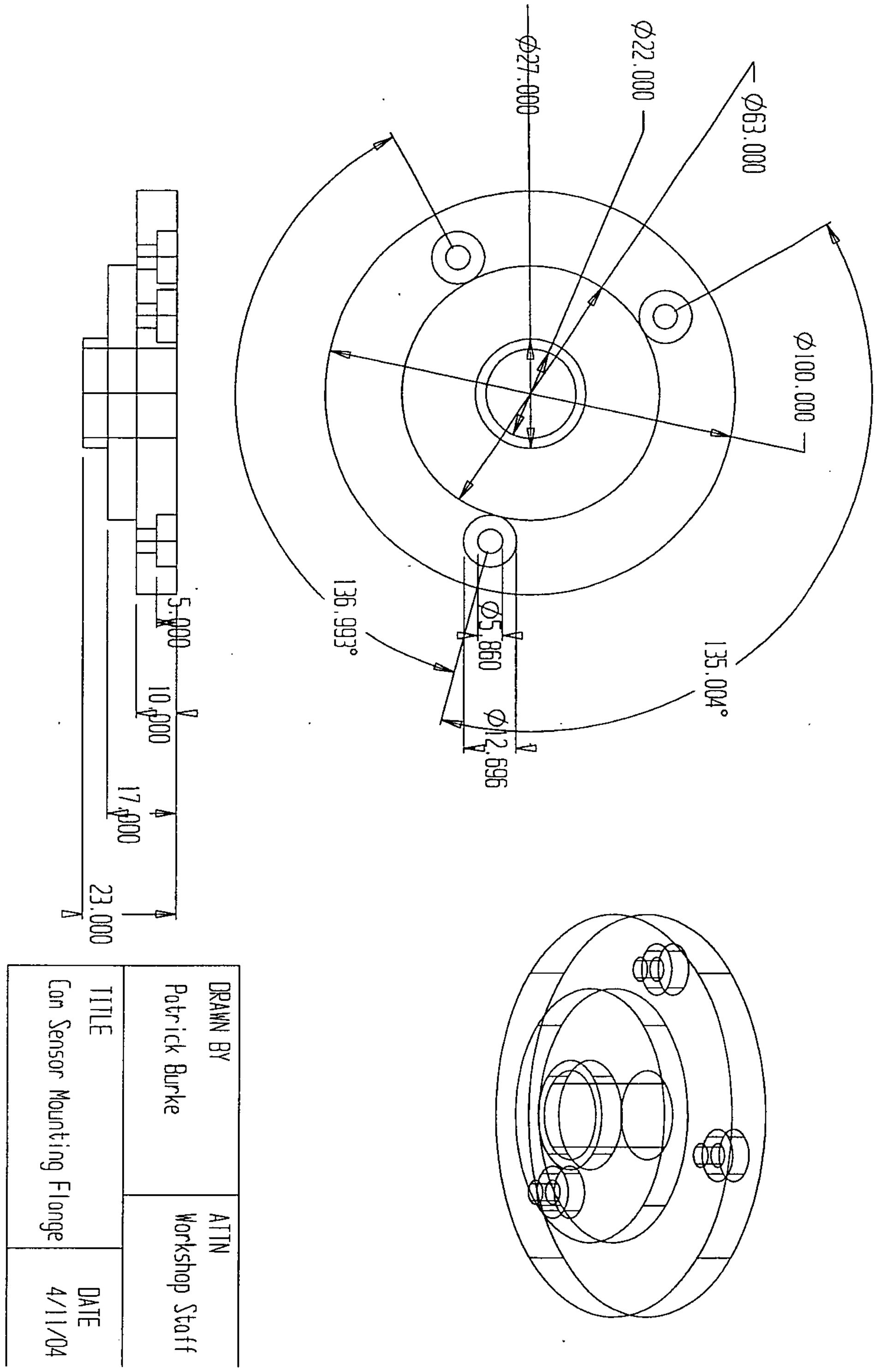
APPENDIX F1: Toothed Gear



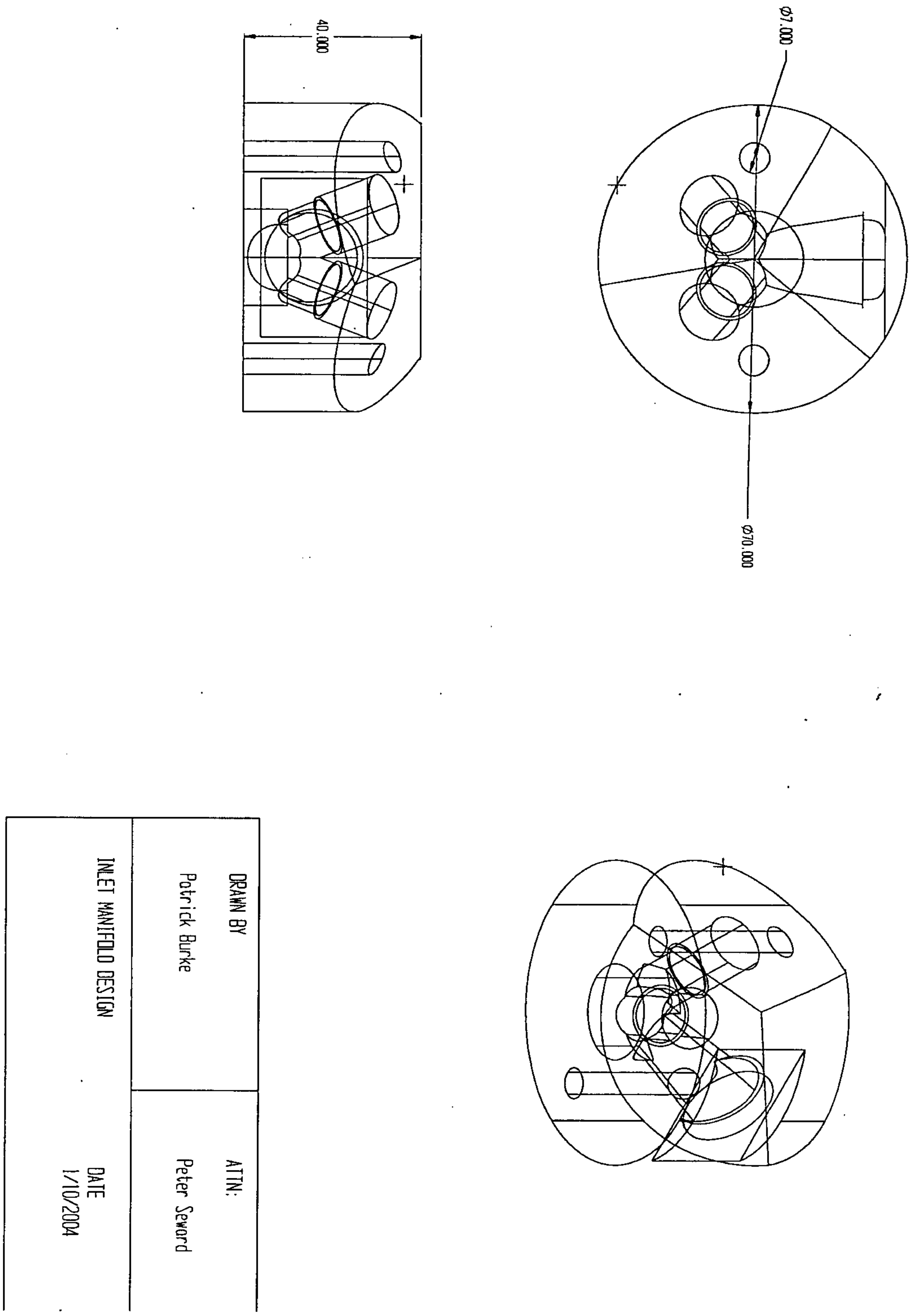
APPENDIX F2: Cam Housing



APPENDIX F3: Cam Housing Mounting Flange



APPENDIX G: Inlet Manifold Layout Design



APPENDIX H: EMS Programming Setup

The following will describe the various parameters changed and the rationale for such changes.

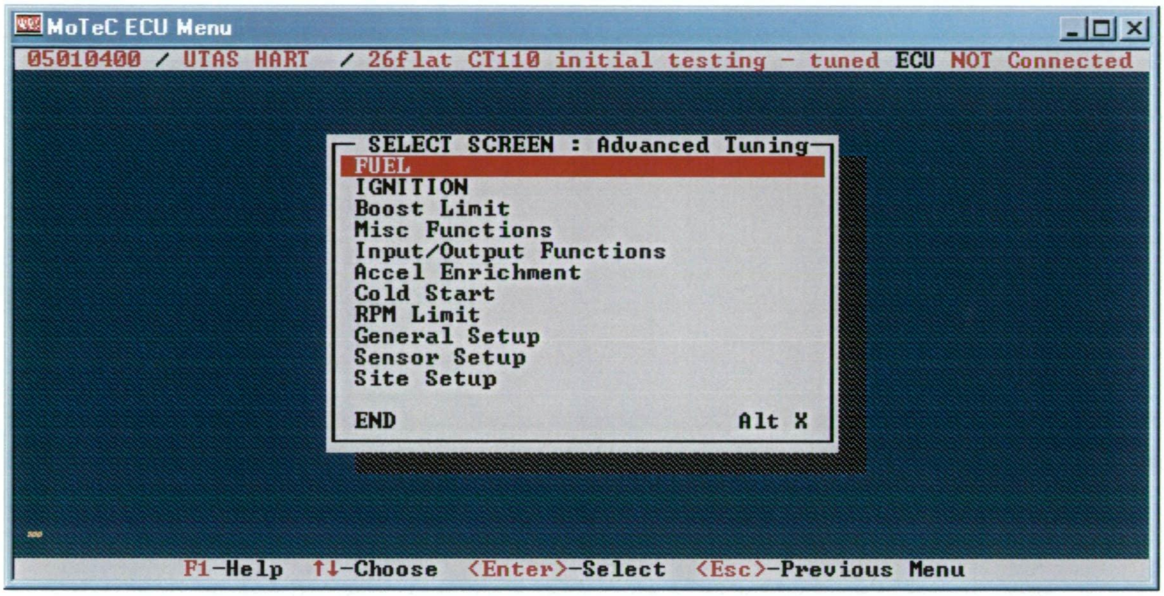


Figure 4.17: The main selection screen in the EMP

Figure 4.17 (above) shows the various options inside the EMP. This section will show the programming changes in the following sections:

- General setup
- Sensor setup
- RPM limit
- Fuel Main Table
- Fuel injection Timing
- Injection air temperature compensation
- Ignition main table
- Ignition air temperature compensation, and

- Acceleration Enrichment

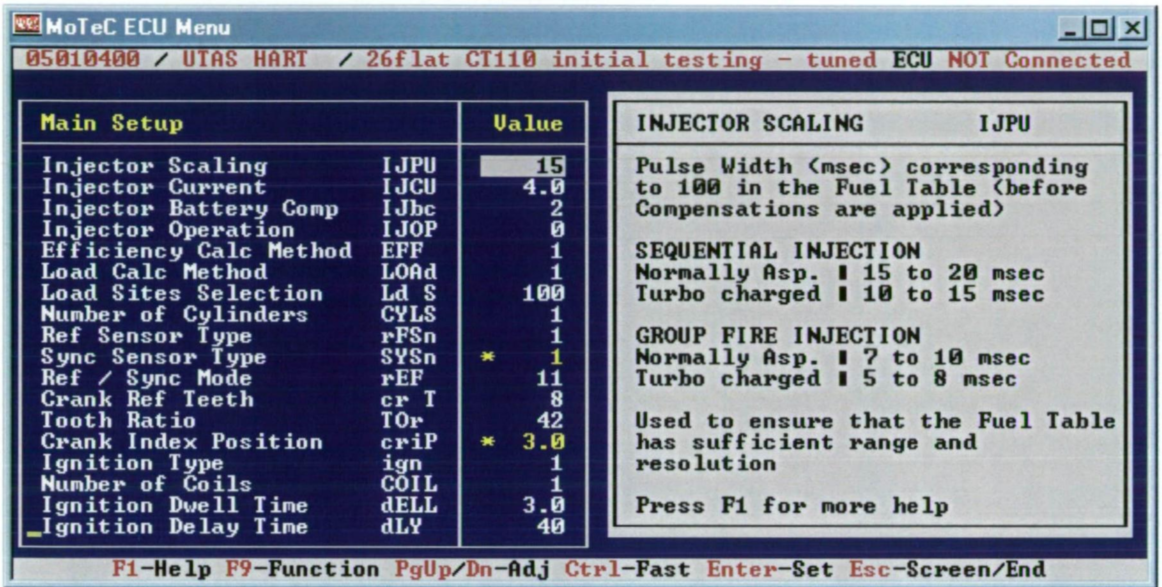


Figure 4.18: The main setup table

The main setup shown in figure 4.18 (above) defines important hardware parameters connected to the EMS.

- The injector scaling corresponds to the pulse width (in ms) of the injector, corresponding to 100% in the fuel injection table. Set to 15 as a default.
- The injector current is the peak current required to open the injector. Set to 4 Amps from injector specifications.
- Injector operation defines the firing order of the injectors. As there is only one injector it is set to 0 or sequential injection.
- Efficiency load calculation method is the method by which the EMS calculates the load on the engine. This is set to 1 or throttle position calculation.
- Load site calculation is also calculated by the throttle position and is thus set to 1.
- The load site selection defines how many load sites are active on the fuel and ignition main tables. A higher number gives greater resolution but also greater complexity. It is thus defaulted to 100.
- Number of cylinders is set to 1 for a single cylinder engine.
- Ref and Sync sensor types are set to 1 as they both hall effect sensors.

- The ref/sync mode specifies the type of sensor configuration is used. As the signal type is multi tooth per engine firing the value of 11 is taken.
- The crank ref teeth is the number of teeth per crank rev. As there are 16 teeth per camshaft revolution (720°) there will be 8 teeth per crankshaft revolution (360°).
- The crank index position is the number of degrees before top dead centre the ref tooth directly after the sync tooth fires. This tooth is three degrees before top dead center.
- The ignition type is a fall trigger so this parameter is set to 1.
- Number of coils is one.
- Ignition dwell and delay times are default values for the given ignition system.

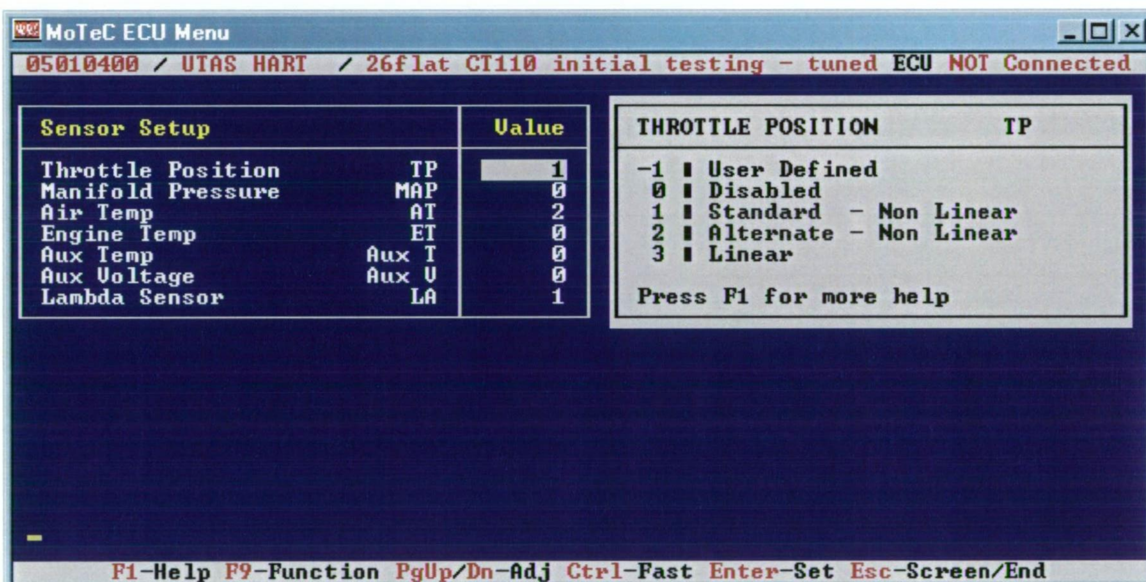


Figure 4.19: Sensor calibration table

The sensor calibration screen shown in figure 4.18 (above) allows the user to define the sensors in use and manually calibrate these sensors.

- Throttle position sensor is a standard Bosch non-linear sensor and the value of 1 is taken. In the sensor setup function, the throttle position sensor can be manually calibrated to correspond to the correct values by entering the full and zero throttle positions into the program.
- Manifold pressure and engine temperature are currently disabled and take on the value of 0 correspondingly.

- Air temperature takes on the value 2 for the Delco air temperature sensor and 0 whilst the sensor is not being used
- Aux temperature and voltage are not in use and thus take on the value 0.
- The lambda sensor that is used in a narrow band, and thus its value is 1 which corresponds to this sensor

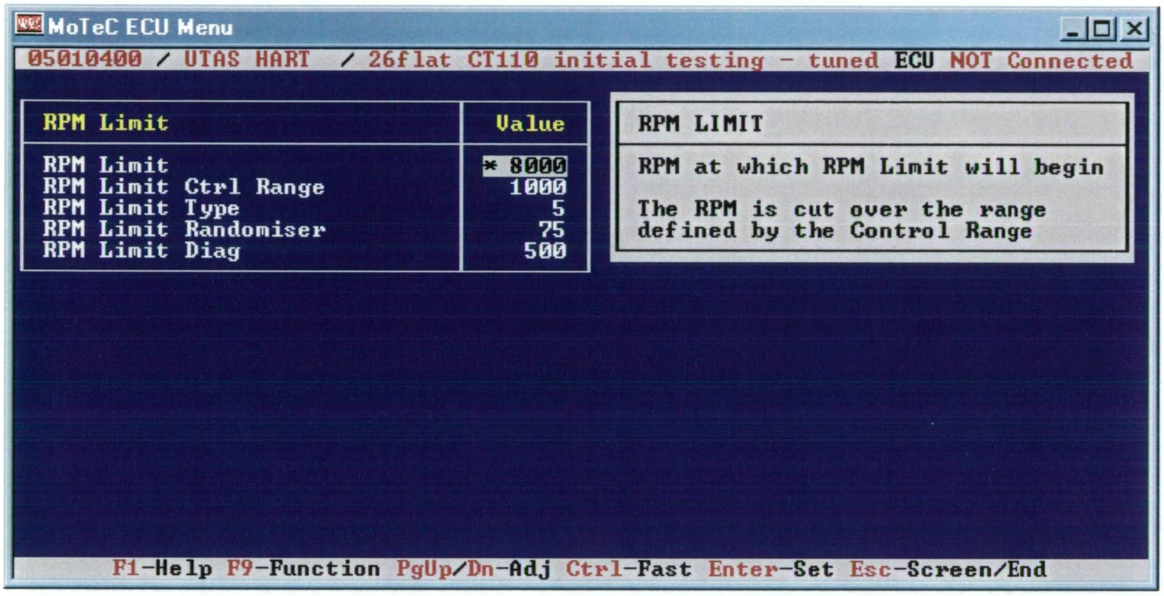
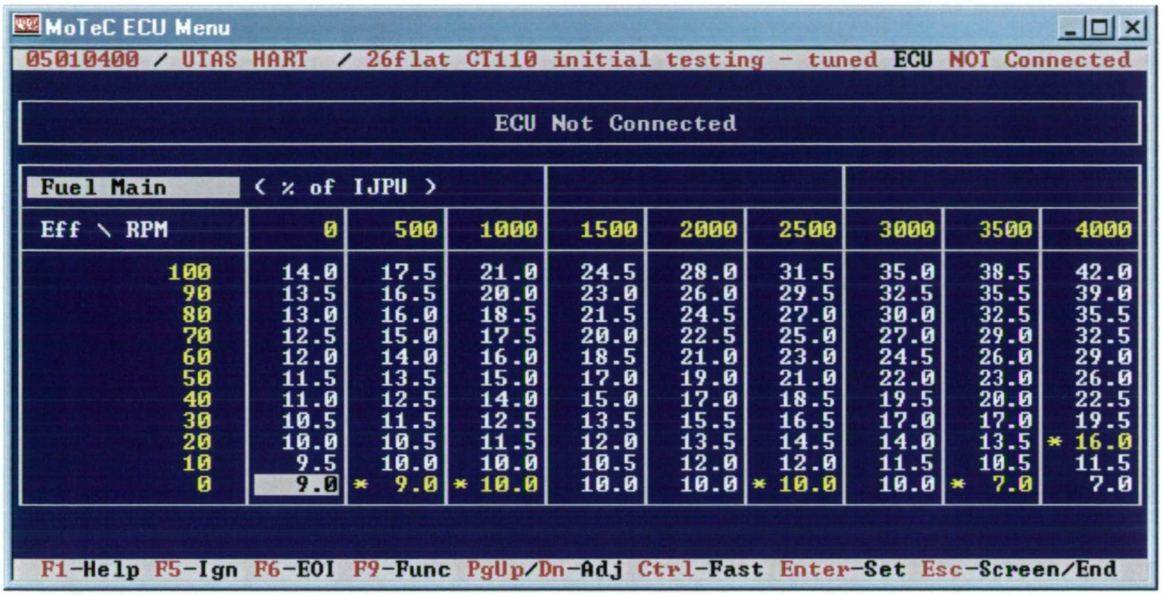


Figure 4.19: The RPM limiting function

The RPM limit function shown in figure 4.19 (above) as the name suggests does not allow the engine to go above a certain defined engine speed. The function was set to cut ignition and injection above 8000 RPM. This function serves as a safe limit for both the equipment and operators. The limit was ascertained from previous gasoline testing.



MoTeC ECU Menu
05010400 / UTAS HART / 26flat CT110 initial testing - tuned ECU NOT Connected

ECU Not Connected

Fuel Main (% of IJPU)

Eff \ RPM	0	500	1000	1500	2000	2500	3000	3500	4000
100	14.0	17.5	21.0	24.5	28.0	31.5	35.0	38.5	42.0
90	13.5	16.5	20.0	23.0	26.0	29.5	32.5	35.5	39.0
80	13.0	16.0	18.5	21.5	24.5	27.0	30.0	32.5	35.5
70	12.5	15.0	17.5	20.0	22.5	25.0	27.0	29.0	32.5
60	12.0	14.0	16.0	18.5	21.0	23.0	24.5	26.0	29.0
50	11.5	13.5	15.0	17.0	19.0	21.0	22.0	23.0	26.0
40	11.0	12.5	14.0	15.0	17.0	18.5	19.5	20.0	22.5
30	10.5	11.5	12.5	13.5	15.5	16.5	17.0	17.0	19.5
20	10.0	10.5	11.5	12.0	13.5	14.5	14.0	13.5	* 16.0
10	9.5	10.0	10.0	10.5	12.0	12.0	11.5	10.5	11.5
0	9.0	* 9.0	* 10.0	10.0	10.0	* 10.0	10.0	* 7.0	7.0

F1-Help F5-Ign F6-EOI F9-Func PgUp/Dn-Adj Ctrl-Fast Enter-Set Esc-Screen/End

Figure 4.20: The main fuel injection period table

The main fuel table shown in figure 4.20 (above) is a three dimensional table which is defined by throttle position and engine speed. The numbers of the table correspond to a percentage of the specified maximum injection period time in the general setup. For example, if the IJPU is 15ms and the table shows 10, then the injector will be opened for 1.5ms.

The values in the table are decided during the tuning process. A certain load site and rpm is chosen and that point is optimized. Then the same procedure is followed for another point and the points in-between are interpolated.

The main fuel table is most likely the most important parameter in the initial setup of the EMS. Once this table is accurate then other subsequent tuning can be attempted.

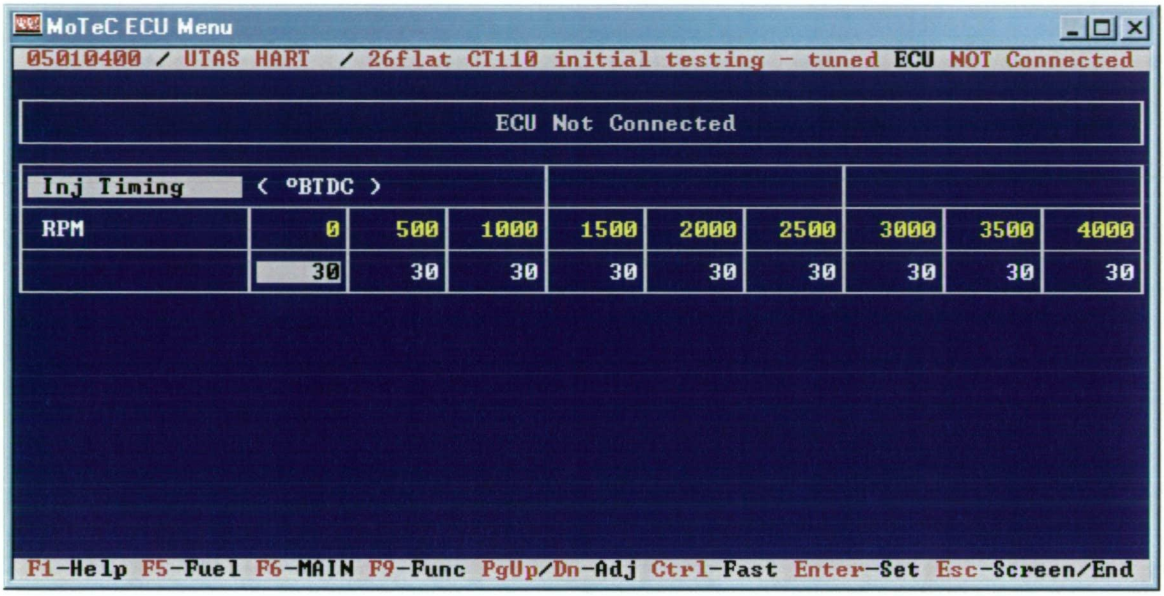


Figure 4.21: Fuel injection timing table

Fuel injection timing defines when the fuel injectors will open or close relative to before top dead centre. This function shown in figure 4.21 (above) is critical in the optimization of valve timing with respect to injection timing. The function gives the user a two dimensional map with engine speed being the process variable. For each 500 rpm the user can change the injection timing. Inbetween other RPM sites the software interpolates the correct value.

The values in this table were determined by the given valve timing and experimental tuning on the dynamometer. For each site the injection timing was varied to achieve maximum power and best running conditions. It was found that a 'flat' (all value the same) map was the best option for this engine throughout the tuning process.

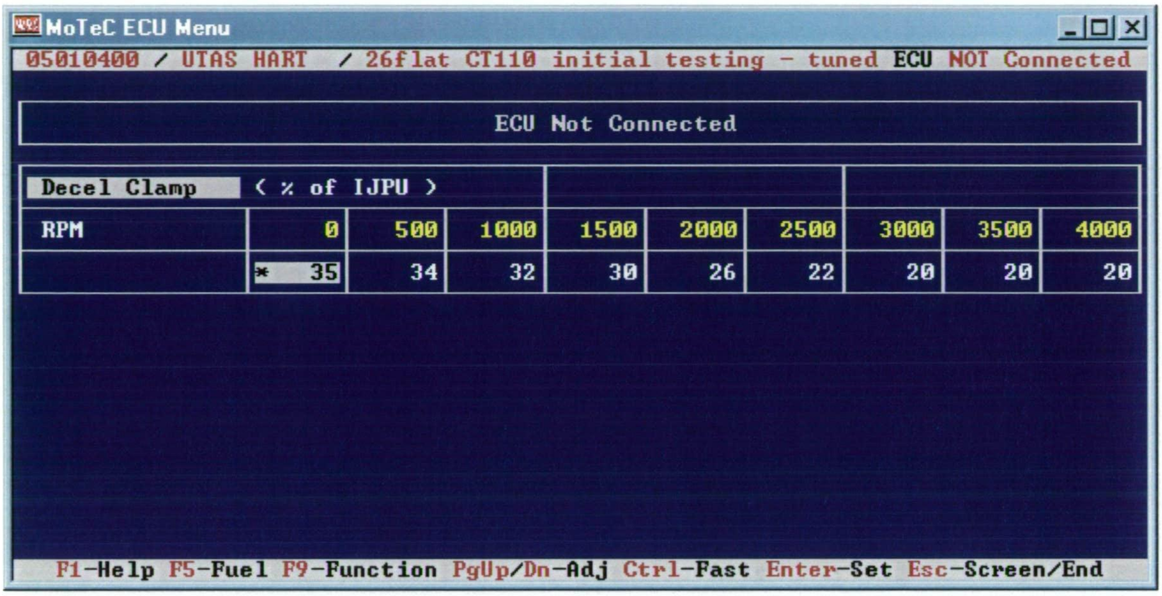


Figure 4.24: The deceleration clamp function

The purpose of acceleration enrichment is to provide more fuel to the engine whilst accelerating, as the power requirements whilst accelerating are generally greater than that of deceleration. This was not a requirement for the hydrogen engine, however, during deceleration not as much fuel was required than in acceleration. The result of the additional fuel being present pre-ignition through the inlet manifold. By reducing the amount of fuel injected during deceleration, the amount of backfiring was severely reduced. As the table shown in figure 4.24 (above) is two dimensional, the data was obtained during the trial and error tuning process. The result was that during moderate deceleration backfiring was reduced.

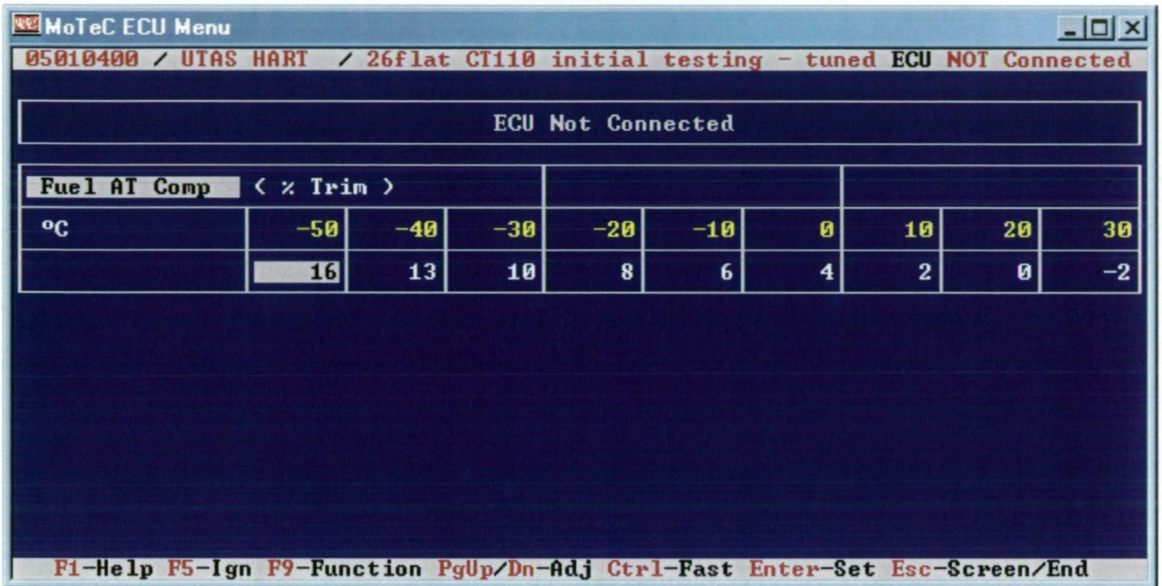
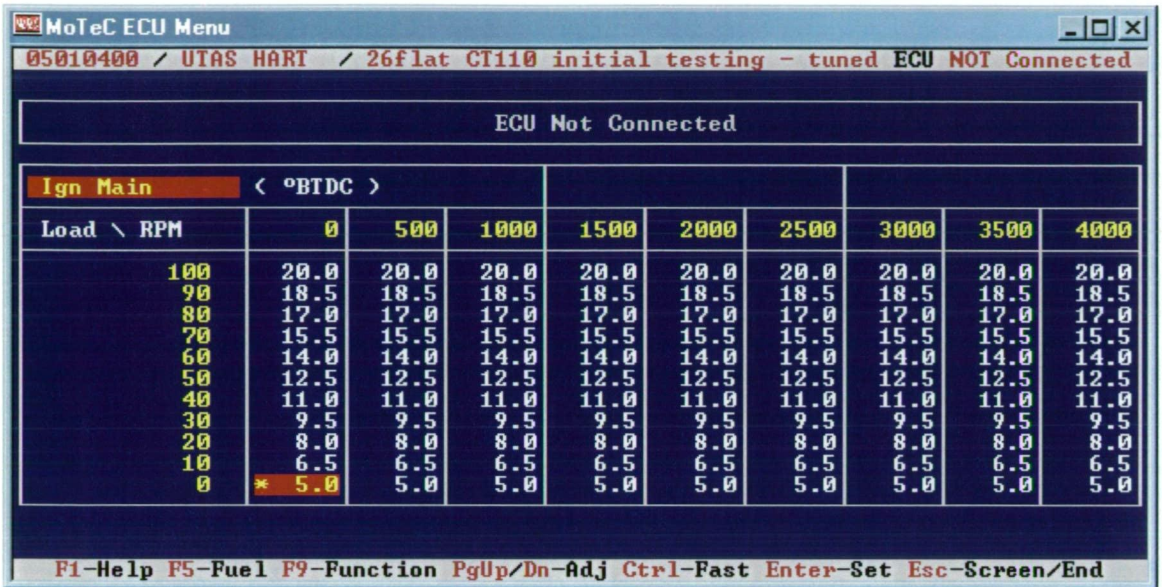


Figure 4.22: Air Temperature compensation function

Alterations in atmospheric air temperatures can have an effect on the density of the air as previously stated. The injection air temperature compensation shown in figure 4.22 (above) compensates for this effect by the user discretion. The air density has an effect on the mass flow of air into the engine and the parameters entered into this table were determined by a combination of previously acquired tuning data and the relationship between air density and mass flow rates.

The ignition characteristics also can be affected by atmospheric temperature. The associated ignition compensation table is similar in set up to the fuel compensation table. As the temperature decreases the engine needs less advance to operate well, due to the decrease in air density. The charge inside the cylinder is affected by the air density which in turn affects the mass flow rate of the air entering the cylinder.

The development of this parameter was done through previous engine maps for similar engines. Due to the stagnant atmospheric conditions whilst tuning, it is very difficult to tune the parameter during the tuning process. Better data is obtained by and ongoing monitoring process to refine the function.



MoTeC ECU Menu

05010400 / UTAS HART / 26flat CT110 initial testing - tuned ECU NOT Connected

ECU Not Connected

Ign Main (°BTDC)

Load \ RPM	0	500	1000	1500	2000	2500	3000	3500	4000
100	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
90	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5	18.5
80	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0	17.0
70	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5	15.5
60	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0
50	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
40	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0	11.0
30	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5	9.5
20	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0	8.0
10	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.5
0	* 5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0

F1-Help F5-Fuel F9-Function PgUp/Dn-Adj Ctrl-Fast Enter-Set Esc-Screen/End

Figure 4.23: The main ignition table

The main ignition table shown in figure 4.23 (above) is a three dimensional table which uses the variables of throttle position and engine speed to decide the degrees before top dead center at which the spark plug is fired. The ignition advance is influential on both the engine power and the running condition of the engine.

The table is constructed initially with a flat map where all the values are the same. By increasing the ignition advance, the output power can be noted until an optimum value is found. This needs to be done for at least two points both horizontally and vertically so that interpolation for the other points can occur. For this reason it is critical to tune for a high load, high rpm site and a low load, low rpm site so that good resolution can be found across the whole range of engine operation conditions.

The initial EMS tuning through the EMP was a successful operation. The process highlighted some of the important factors in the operation of hydrogen in an internal combustion engine. Further tuning modifications as suggested in future developments would advance the capabilities of the EMS.

APPENDIX I: Costing

Hydrogen Related Project Costings

Please note

1. Fill in details of all green area's. Yellow areas are optional. Please avoid adding anything outside these areas.
2. Include under "Description" the names of parts/services required.
3. The sums will automatically be generated.
4. Enter all costings in Australian Dollars only.
5. Avoid changing cell locations and calculations.
6. In the last column, confirm if the item you have listed (under "Description") has already been spent.

	First Name	Family Name
Investigator	Patrick	Burke
Thesis title	Conversion of a Single Cylinder 4 stroke engine to Hydrogen	

Date (dd/mm/yy): 07/01/05

Item	Description (end use)	No. Reqd.	Unit Price ($ Aust.)	Total Price	Spent (Yes/No)	Notes
1	Bike	1	0	0.00		
2	H2 Injectors	2	161.98	323.96	y	
3	Engine Management system	1	2013	2013.00	y	
4	Lamda Sensor	1	0	0.00		
5	Air Temp	1	63.8	63.80	y	
6	Inlet Manifold Fabrication	1	0	0.00	n	
7	Cam sensor mounting fabrication	1	0	0.00	n	
8	Fabrication of Sync/Ref Gear tooth wheel	1	200	200.00	y	
9	Compressed Gas Cylinder	4	120	480.00	n	
10	Metal Hydride Cylinder	0	1256	0.00	n	
11	Regulator	1	327.84	327.84	y	
12	Hall effect Sensor	1	100	100.00	y	
13	Testing of bike/hr	14	100	1400.00	y	
14	Ingnition Module	0	280	0.00	n	
15	Tachometer	1	95	95.00	y	
16	EMS Loom	1	180	180.00	y	
17	Motec Enable Code	1	600	600.00	y	
18	On Off Manual Valve	1	43.5	43.50	n	
19	Coil	1	50	50.00	y	
20	Hosing	1	241.9	241.90		
21	Fittings	1	320	320.00		
22	Flashback Arrestor	2	46.5	93.00		
23	Flowmeter	1	808	808.00		
24						
			Estimated Costing	7340.00		