THE PENNSYLVANIA STATE UNIVERSITY
SCHREYER HONORS COLLEGE

DEPARTMENT OF MECHANICAL & NUCLEAR ENGINEERING

DESIGN AND CALIBRATION OF AN ELECTRONIC FUEL INJECTION SYSTEM FOR A COMPRESSED NATURAL GAS SPARK IGNITION INTERNAL COMBUSTION ENGINE IN A HYBRID VEHICLE

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ABSTRACT

The United States has been dependent on foreign oil for many years. In 2011, the United States of America imported 45% of its petroleum from other nations [1]. In addition, efforts are being made to identify more eco-friendly options for fuel to serve as gasoline alternatives. One such fuel, which could decrease the United State dependence on foreign oil while helping the environment, is natural gas. An abundance of natural gas is found in the United States, and the burning of natural gas in internal combustion engines (ICE) releases less pollution and greenhouse gas emissions than gasoline. One of the most complex parts of natural gas ICE is the electronic fuel injection system. These systems are controlled by an electronic control unit (ECU), which is essential for optimizing engine efficiency, performance and emissions. The goal of this research was to reconfigure a hybrid-electric vehicle for compressed natural gas usage.
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Chapter 1: Introduction

Oil prices have reached all time highs in the last few years. In the United States, the price is related to dependence of oil imports from the Middle-East, a region in turmoil for many years. In addition, the need for new modes of transportation with decreased CO$_2$ emissions has been identified as an important issue in many of today’s political discussions. For these reasons, many are looking for alternative energy sources that are produced in America for the nation’s future transportation needs. One such solution is natural gas (NG) propulsion technology.

Natural Gas is a very clean alternative to gasoline or diesel and is abundant in the United States. NG can be used, with limited modification, in gasoline spark-ignition (SI) engines as well as diesel engines. With the creation of infrastructure for refueling, NG could be utilized as a transportation fuel and pave the way for future hydrogen fuel technologies.

The goal of this study is to create a NG Electronic Fuel Injection (EFI) system for the conversion of a range extender hybrid-electric vehicle’s engine to compressed natural gas (CNG) and hydrogen fueling. The main components of this research model will be: 1) compiling the components for the CNG injection system, and 2) programming of a customized electronic control unit (ECU) control for the injection system. This study will be a continuation of the study done by Wade McCorkel in the spring of 2010 [2].
Chapter 2: Literature Review

Chapter 2 overviews the main properties of NG that are crucial for understanding and designing NG EFI systems. The chapter also reviews the main advantages of NG vehicles today to provide reasons for the pursuit of NG injection technology. Problems or disadvantages with the usage of NG are considered, as well as potential solutions needed to improve existing NG vehicles. Finally, the components of alternative fuel delivery methods will be discussed for comparison.

2.1 NG Properties

The combustion properties of NG make it a viable alternative fuel to gasoline and diesel. This section will compare the fuels’ properties with regard to the engine’s performance. Much the same as the alternative fuel hydrogen, the conversion of a gasoline engine to NG requires very few modifications. NG properties, as compared to gasoline, will be discussed and analyzed to illustrate why NG may be a suitable alternative to gasoline. These NG and gasoline properties are shown in Table 2.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>Natural Gas</th>
<th>Gasoline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy (Mj/kg)</td>
<td>53.6</td>
<td>45.7</td>
</tr>
<tr>
<td>Density, (kg/m³)</td>
<td>.72</td>
<td>730⁴</td>
</tr>
<tr>
<td>Energy Content (MJ/L)</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>Research Octane Number</td>
<td>130</td>
<td>91-98</td>
</tr>
<tr>
<td>Quenching distance (mm)</td>
<td>2.1</td>
<td>2</td>
</tr>
<tr>
<td>Flammability Limits (%)</td>
<td>3.5-15.0</td>
<td>1.4-7.6</td>
</tr>
<tr>
<td>Stoich. air/fuel ratio by mass</td>
<td>17.2:1</td>
<td>14.7:1</td>
</tr>
<tr>
<td>Minimum ignition energy (mJ)⁵</td>
<td>0.28</td>
<td>0.24</td>
</tr>
<tr>
<td>Autoignition temperature (°C)</td>
<td>482-632</td>
<td>257</td>
</tr>
<tr>
<td>Flame Velocity (m/s)</td>
<td>0.38</td>
<td>0.37-0.43</td>
</tr>
</tbody>
</table>

⁴at stoichiometry
NG has a higher energy per mass ratio than gasoline. However, NG’s density is much lower than that of gasoline. Consequently, the energy density of a NG-air mixture is lower. To make up for this low energy density, NG is compressed to about 250 bar for storage in large high pressure tanks to give a CNG vehicle sufficient driving range [8]. The volumetric efficiency of a NG-fueled engine is low compared to a gasoline or diesel engine because of the low density of NG [9]. The NG engine’s power output can be increased with higher compression ratios, incorporation of intake and exhaust valves with increased lift, low back-pressure mufflers, and/or forced induction systems [10].

NG has a very high octane number (Research Octane Number=130), which causes it to have a large knock resistance except at heavy loads [11]. Engine knock, often accompanied by an audible “pinging” noise, occurs when portions of the air/fuel mixture spontaneously ignite before being reached by the flame front [12]. This spontaneous combustion occurs as a result of the further compression of unburned air/fuel mixture within the chamber by the combustion flame. This further compression allows some portions of the compressed air/fuel mixture to attain temperatures high enough to induce spontaneous auto-ignition. Engine knock causes intense heat and immense pressure peaks, which lead to enormous mechanical and thermal loads on the pistons, bearings, cylinder head, and head gasket [12]. Large amounts of engine knock can lead to blown head gaskets, pierced piston crowns and engine seizure, which lead to the final destruction of the engine [12]. The high knock resistance of NG makes it ideally suited for turbocharging and enables the compression ratio to be increased to approximately 13:1 (gasoline engine compression ratio approximately 9 to 11:1) [8]. With the additional use of a downsizing concept (reduction of displacement), it is possible to improve a NG engine’s efficiency and further reduce CO₂ emissions [8].
Backfire occurs when there is an explosion outside of the engine’s cylinder combustion chamber. The explosion may occur in the intake or exhaust system of the engine. A fuel’s quenching distance helps to determine its tendency to result in a backfire. Quenching distance is the distance between an external surface and the flame at which quenching begins. The quenching distance for NG is slightly larger than gasoline. NG’s larger quenching distance causes the flame to burn farther from the cylinder walls than gasoline. NG flames large quench distance hinders its ability to readily pass a nearly closed intake valve. This decreases the tendency for a NG-air flame to backfire. However, backfire of NG is still possible under certain conditions [5]. In comparison with other fuels, in particular hydrogen, NG has a small flammability range [13]. For this reason, NG can only combust over a narrow range of air/fuel mixtures. Despite this narrow range, many combust NG at lean mixtures to increase the engine’s efficiency [14]. When an air-to-fuel mixture is lean, the amount of fuel is less than the stoichiometric or chemically-ideal amount needed for combustion. During stoichiometric combustion, all the fuel and air is combusted completely, with nothing left over. The stoichiometric air/fuel ratio (AFR) of NG is about 17.2:1 [3]. Although NG can be run more efficiently at leaner mixtures, a lean mixture will cause a NG flame to extinguish. In addition, barely lean mixtures that cause complete combustion of all fuel in the air-fuel mixture lead to large increases in flame temperatures since there are no unburned fuel particles to absorb extra heat energy. For this reason, it is imperative that NG injection system sensors be precise in measuring the changes in A/F ratios. In addition, lean mixtures decrease the power output of the engine. Finally, the low flame velocities of CNG greatly restrict the lean operating limits of CNG engines [11]. For this reason, through this research, a slightly rich AFR ratio of 16.8:1 is being pursued. This corresponds to an equivalence ratio of $\varphi=1.024$ as shown in the calculation below:
The minimum energy required for methane ignition within the flammability range of a fuel-air mixture is relatively high [6]. Therefore, since NG is comprised of 83-99% methane, it has a high ignition energy. This is the reason NG engines require high-performance ignition systems that can generate more than three times the energy required by gasoline engines (30-40 mJ) [6]. This fact prevents the unwanted phenomena of NG preignition. Preignition occurs when the air/fuel mixture in the cylinder ignites before the spark plug fires.

NG is relatively difficult to autoignite. Autoignition occurs when an air/fuel mixture spontaneously ignites without an external source of ignition. This may occur under high pressures or temperatures in the absence of a flame or spark. It may result directly from high compression or hot spark plugs. The autoignition temperature is very important when it comes to determining the proper compression ratio to use for an engine, since the temperature increase during compression is related to the compression ratio. The temperature increase is shown by the equation:

\[
T_2 = T_1 \left( \frac{V_1}{V_2} \right)^{\gamma - 1}
\]

Where:

\[
\frac{V_1}{V_2} = \text{the compression ratio}
\]

\[
T_1 = \text{absolute initial temperature}
\]

\[
T_2 = \text{absolute final temperature}
\]

\[
\gamma = \text{specific heats ratio}
\]
If the temperature inside the engine exceeds NG’s autoignition temperature, then preignition occurs. Thus, the absolute final temperature limits the viable compression ratio. Diesel engines operate using a compression ignition (CI) system in which autoignition is used to ignite the air/fuel mixture in the engine cylinders. On the other hand, the temperature needed to autoignite natural gas (580°C) is significantly higher than that of diesel (210°C) [15]. For this reason natural gas is more optimal in a SI engine. This high auto-ignition temperature coupled with NG high octane rating of RON=130 allows natural gas to use higher compression ratios to improve thermal efficiency by about 10-20 percent above that of a petrol engine [16].

2.2 Natural Gas Advantages as an Internal Combustion Engine (ICE) Fuel Source

This section of the literature review is to emphasize the reasons why NG is a good ICE fuel alternative to gasoline within the United States of America, and why gasoline to NG conversion of motor vehicles should be pursued.

2.2.1 Natural Gas Safety

Compared with gasoline, natural gas is very safe. Its improved safety is based upon its properties and related fuel tank specifications. Compressed natural gas (CNG) is neither toxic, carcinogenic nor caustic. If released into the environment, it would not contaminate groundwater [14]. On the other hand, it should be noted that unburned methane is a potent greenhouse gas and pound for pound, the comparative impact of CH$_4$ on climate change is more than 20 times greater than CO$_2$ over a 100-year period [17]. For this reason, any leaks of unburned methane from the CNG vehicle could be very detrimental to the environment.
Also, NG is lighter than air, which means it will not puddle (like gasoline) or sink to the ground like propane [6]. Furthermore, NG has a relatively high flammability limit as compared to other fuels. This means that for continuous flame propagation, NG requires a minimum of 5% by volume as compared to 1% for gasoline vapor. Also methane, the primary ingredient of NG, has a relatively narrow range of flammability limits. This means NG can only generate a small amount of a combustible mixture relative to gasoline. For example, the release of one unit volume of methane in air would produce a maximum volume of combustible mixture that is around 20% the volume of the mixture created following the release of a similar amount of gasoline vapor [6]. Also, NG has a much higher auto-ignition temperature (540˚C) than gasoline (227-500˚C) [18]. In conjunction with this property, NG has a greater minimum spark-ignition energy (0.28) than gasoline [3]. In the event of an accident, these combined factors significantly reduce the chance of natural gas auto-ignition as compared with gasoline. Another common belief is that CNG fuel tanks are less safe than regular gasoline tanks since they under high pressure. On the contrary, CNG vehicle fuel tanks are as safe or safer than gasoline fuel vehicle tanks. Conventional liquid fuel tanks are relatively fragile and may have the tendency of developing hot spots in a fire [6]. These hot spots could lead to the eventual rupture and spillage of the contents of the tank with devastating effects [6]. Heating of a NG fuel cylinder in a fire would increase the pressure inside the tank. If this increase in pressure became great enough and the pressure release valve malfunctioned, the tank could explode. However, cylinders are currently made of special materials that will not fragment and explode at high pressures. Instead, cracks develop in the tank, and the gas is slowly released [6]. In addition, metallic fuel tank mesh can be designed for quenching of methane-air flames by cold surfaces, so a flame leak from a NG fuel tank is less likely than from gasoline tanks [6]. Furthermore, fuel tanks/cylinders of NG
must meet strict safety regulations in the USA and be tested at regular intervals [6]. Based on these regulations of all fuel tubes, connectors, pressure switches, indicators, and regulators, NG fuel cylinders are at least as safe, if not safer than gasoline fuel tanks.

2.2.2 Energy Diversification & Security

The United States, along with many other countries around the world, has made efforts to decrease its dependence on foreign oil and energy. In recent years, the prices of gasoline have increased with no projected reversal in sight. Increased usage of natural gas would diversify energy sources, thereby decreasing the consumption of gasoline and diesel fuels. Natural gas is abundant in North America and would allow the United States to decrease its dependence on foreign oil imports, increasing national energy security [18]. Finally, the use of natural gas in vehicles would help the United States transition to hydrogen vehicles, which can be fully renewable. Hydrogen-powered vehicles will require many of the same modifications as NG vehicles including building codes and standards, and training mechanics, inspectors and users [6].

2.2.3 Lower Fuel Prices and Maintenance Costs

Natural gas has historically had a lower price than gasoline as seen in Figure 2.1. Currently, the price of natural gas per gallon gasoline equivalent ranges from as little as $1 / gge to about $3 / gge [19]. The lower fuel costs can help outweigh the increased initial purchase price of natural gas vehicles. In addition, many NG properties are beneficial to engine components and decrease maintenance requirements of engines. For example, NG fuel should be free of impurities like sulfur and water [6]. Also, NG fuel does not mix with or dilute engine lubricant
and will cause less unwanted deposits in combustion chambers or on spark plugs than petroleum, thereby extending the spark-plug and piston-ring life [14].

Figure 2.1: Comparison of Gasoline, Diesel and CNG Retail Prices [20]

![Gasoline, Diesel and CNG Retail Price Comparison](image)

2.2.4 Lower Pollution and Greenhouse Gas Emissions

One of the most important perceived advantages of natural gas fuel is its low pollution and greenhouse gas emissions compared to other petrol fuels. The primary component of natural gas, methane (CH$_4$), is present in proportions of 80-90% [8]. NG fuel also contains small amounts of inert gases, such as carbon dioxide, nitrogen and low-chain hydrocarbons [8]. This allows NG hydrogen-carbon ratios to be approximately 4:1 compared to gasoline’s 2.3:1 [8]. Since NG has such a high hydrogen-carbon ratio, its combustion results in emission of more H$_2$O and less CO$_2$. For example, an SI engine converted to natural gas, without any further optimizations, can produce roughly 25% fewer CO$_2$ emissions than a gasoline engine [8]. Also, the NO$_x$ emissions are reduced for NG due to its slow combustion reaction [6]. In fact,
experiments have shown non-methane hydrocarbons to be reduced by approximately 50%, NO\textsubscript{x} by 50-87%, CO\textsubscript{2} by 20-30% and CO by 70-95% compared to gasoline [16]. NG additionally emits very limited amounts of particulates. Interestingly, the combustion of lubricants is the principle source of particulate emissions from NG vehicles [5]. In addition, NG vehicles do not emit benzene and 1,3-butadiene which are common toxins emitted from diesel powered vehicles [14]. NG vehicle’s reduction in emissions and pollution is one of the driving forces in the pursuit of NG transportation systems around the world.

2.3 Natural Gas Disadvantages as an ICE Fuel Source

In this section, the disadvantages of NG as a fuel source will be discussed to show the obstacles that are in place in adaptation of gasoline to NG as a fuel source and how these disadvantages may be overcome.

2.3.1 Infrastructure Launching Costs

The creation of infrastructure, specifically commercial natural gas refueling stations in the United States of America, is still in its developmental stages. There are approximately 574 natural gas refueling stations currently in the USA, excluding private stations [21]. This is small compared to the approximately 121,446 gasoline refueling stations in the USA [22]. There are many reasons for this difference in refueling stations. For example, when first creating NG vehicle infrastructure, there must be a balance between the number of NG vehicles and refueling stations. Any imbalance would result in either very low profit for refueling station owners, blemishing the image of the NG vehicle industry for investors, or long queues for vehicle drivers that tarnish the industry’s public image [5]. Also, the cost of constructing a NG refueling station
can be very expensive. According to a 2010 report published by Pacific Northwest National Laboratory for the U.S. Department of Energy, the cost of building a CNG fueling station ranges from $10,000 to $2 million depending on the size and application [23]. Without proper demand, the justification of these costs is too great for the installation of new CNG refueling stations.

Finally, natural gas is difficult to store for transport to refueling stations because of its physical properties and the need for high pressure and/or low temperatures to increase its bulk density. By comparison, oil is readily stored in large, relatively simple and inexpensive tanks for transport to refueling stations [6]. As NG vehicles gain popularity and demand increases, the economic viability of creating a national system of refueling stations will also increase. Such demand has been steadily climbing over the past century as shown in Figure 2.2.

Figure 2.2: NG Vehicle Totals Worldwide [24]
2.3.2 Refueling Systems Disadvantages

The two types of fill stations for CNG fuel are fast fill and slow fill. Fast fill stations allow a vehicle to refuel their tank in about three minutes [6]. A fast fill station uses a cascade type storage vessel to store the high-pressure gas, which allows such quick refueling times [6]. Cascade storage is divided into several compartments, which independently connect to the refueling pump. Generally, only about 40% of the stored gas is available for refueling in a three-bank cascade arrangement [6]. Since fast-fill stations dispense fuel at a faster rate, the gas in the NG vehicle fuel tank/cylinder does not have time to lose heat to the environment. For this reason, the gas in the tank becomes slightly warmer than the atmosphere upon completion of a fill. This increase in temperature leads to the tank being under-filled. It was found that fast-filling in Poitiers, France lead to a 15-20 percent under-fill [5]. Such under-filling reduces the driving range of the vehicle, which is very undesirable.

Slow fill is the second type of CNG refueling system and has a few advantages compared to fast fill. Slow fill requires half an hour or more to fill a NG tank, which is substantially longer than a fast fill station [5]. On the other hand, slow fill stations do not under fill the fuel tanks, increasing the driving range. Since slow fill stations do not require cascade storage, they are less expensive. Slow filling may be accomplished at the NG vehicle owner’s home, so the parked vehicle could be refueled overnight while the owner sleeps.

2.3.3 Fuel Storage and Vehicle Range

Partly based on its bulky fuel storage tanks, the CNG vehicle’s driving range is less than a similar gasoline-fueled vehicle. Based on natural gas’s low energy density, CNG compression to 250 bar in large fuel tanks with thick walls is required to increase the driving range [5]. The
extra space used by the fuel tank is very undesirable for smaller passenger vehicles such as taxis since there is a large reduction in trunk space. Furthermore, the increase in weight added by these bulky fuel tanks not only decreases the fuel economy of the vehicle, but also potentially accelerates the tire and brake wear [5]. Future focus should be placed upon reducing the size and weight of CNG fuel cylinders by improving fuel economy and incorporating lightweight storage tank materials in the vehicle design. One example of such materials is fiber-reinforced aluminum alloy, or even all composite, which have significant weight saving (up to 57%) over steel [14]. Also, dedicated NG vehicles in the future will have decreased space used by fuel tanks that are fully integrated into the vehicle structure, a goal that is difficult to achieve for conversions. In addition, new research is progressing in the use of absorbent materials in a tank in order to reduce the required pressure (from 250 bar down to 30 bar) and thereby decrease the weight of the tanks [14]. A few of the absorbent materials that researchers are testing include activated carbon, zeolites, clays and phosphates [14].

Based upon the bulkiness of the tanks and NG’s low energy density, the driving range of NG vehicles is greatly reduced. For example, NG vehicle’s only have a driving range of about 150 km (93.2 miles) with a full tank [6]. This leads to CNG vehicles refueling two to three times as often as their gasoline or diesel counterpart [6]. Bi-fuel vehicles may help solve the problem of reduced driving range. Such vehicles use gasoline and natural gas interchangeably, which allows a driver, on longer trips, to switch to gasoline to drive to the closest NG refueling station and refill.
2.3.4 Natural Gas Vehicle Power Reduction

Natural gas vehicles of the past and present have been criticized for their low power. One such reason for this marginal power is that only 10 percent of induced airflow in the intake manifold is replaced by gas in CNG engines [14]. Also, methane combustion is very slow, which causes deterioration in engine performance but can be overcome with the creation of turbulence in the engine cylinders [6]. Bi-fueled vehicles have been known to have power decreases between 15 and 20 percent [14]. To the contrary, new research and developments have allowed dedicated NG vehicles to attain equivalent power outputs with higher efficiencies than gasoline-powered vehicles [16]. Improved power outputs may be achieved using multi-port fuel injection, newly developed pressure regulators and injectors, and precise AFR control [14].

2.3.5 Vehicle Safety and Initial Purchase Cost

Although strict regulations on natural gas vehicles are enforced in the United States, there are still cases of NG leaks from the fuel lines and tanks. As discussed above, such leaks are very unlikely to ignite in an open environment. On the other hand, CNG vehicles parked in domestic garages or car parks present a risk of explosion. Since NG is only 60% the density of air, NG would accumulate at the ceiling and be ignited by fluorescent light fittings if a leak were to occur [6]. Such a threat could easily be avoid by installing ventilation shafts in NG car parks and garages or by parking the car outside in an open environment.

Another current disadvantage of NG vehicles is their increased initial purchase price. This is caused by current low production volumes and greater costs for fuel storage tanks [6]. As NG vehicle demand increases and storage tank technology improves, costs for NG vehicles will decrease.
2.4 Fuel Delivery Schemes

2.4.1 Carburetion

Carburetion is a fuel induction system that uses the Venturi effect to induce the flow of fuel into the throttle body that feeds into the intake manifold [25]. Carburetion is the cheapest form of fuel induction for SI engines. A basic carburetor is comprised of restricted air passageway, one or more fuel jets fed from a float chamber, and a throttle or butterfly valve for controlling the amount of mixture inducted into the engine [26]. As air is pulled past the metering jet, its velocity increases and the pressure at the Venturi is reduced in proportion to the air flow [26]. Meanwhile the pressure acting on the fuel bowl is substantially atmospheric, so the resultant pressure difference forces the fuel through the metering jet into the air stream. There, the fuel is further atomized by the high-velocity air [26]. After the Venturi and fuel jet sizes have been chosen, the amount of fuel drawn from the jet depends on the pressure drop produced by the Venturi effect [26]. A carburetor may use a fixed Venturi, in which the air opening diameter ahead of the throttle valve remains constant, or a variable Venturi, which changes area to satisfy the changing demand [25]. Other than the accelerator pump, choke valve, idle circuit, and Venturi jet, there are no other devices within a carburetor to control the air AFR or injection timing (Figure 2.3). For this reason, compared to other injection techniques, carburetion is imprecise and can decrease the efficiency of the engine. On the other hand, if the carburetor is located in close proximity to the intake of the engine and there are not highly variable load demands, the system works very well. For this reason, a carbureted fuel induction system, though imprecise, could successfully be converted for CNG usage through the tuning of the idle and open adjustment screws.
2.4.2 Port Fuel Injection

Similarly to carburetion, port fuel injection (PFI) introduces fuel into the intake ports. PFI employs fuel injectors, which are attached to the intake ports near or directly above the cylinder’s intake valves (Figure 2.4). These injectors are actuated by solenoids to discharge a specific amount of fuel. An Engine Control Unit (ECU) manages these injectors by sending signals for the injectors to open and close in relation to the spark timing. The location of the injector in relation to the intake valves is very important. The best performance has been achieved with injectors located about 4 to 7 inches ahead of the intake valve to permit good distribution of the fuel spray into the incoming air [26]. The fuel is usually injected during the intake stroke of each cylinder while the intake valve is fully open. The fuel injectors can all open at the same time for all cylinders. In contrast, each injector opens just before the intake valve for
its cylinder during sequential multi-port fuel injection. The advantage of sequential fuel injection is that the system can respond more quickly if there is a sudden change in demand to the engine. With a change in demand, sequential fuel injection only has to wait until the next intake valve opens, instead of for the next complete revolution of the engine [27].

PFI provides several advantages over carburetion. One advantage of PFI over carburetion is an increase in power output, which is a significant problem for bi-fuel natural gas vehicles. These power gains are usually attributed to improved filling of the cylinder based upon fuel being injected closer to the intake valves. PFI virtually eliminates the possibility that fuel will condense or collect in the intake manifold creating AFR fluctuations. Another advantage of PFI is injection timing and duration is controlled by the ECU, which can decrease the risk of preignition and backfire [28]. Also, through the use of the ECU, the AFR can be regulated continuously depending on precise throttle and engine speed settings.

Despite its benefits, PFI includes a few disadvantages. More cost and complexity is added to the fuel-injection system with the addition of the ECU and fuel injectors. To implement a PFI system on the vehicle, a custom fabricated intake port would be required. Though PFI would be costly and complex to implement, its use could be justified when compared to existing technologies.
2.4.3 Throttle Body Injection

Throttle body injection (TBI), also known as single point or central fuel injection, combines different features of carburetion and PFI, as shown in Figure 2.5. Similar to carburetion, a throttle body injects fuel before the throttle plate. Rather than using the Venturi effect, a throttle body, as shown in Figure 2.5, uses an injector like PFI. Similar to PFI, throttle body injection uses an ECU and oxygen sensor to control the injection timing and the AFR. This allows TBI to deliver the NG more accurately in accordance with engine demand than carburetion. However, the injectors for TBI are still some distance from the valve inlets, and not directly attached to the intake port above the cylinders. This makes TBI less precise and slower at responding to abrupt changes in conditions than PFI [24]. Although the addition of an ECU with sensors is necessary for the throttle-body fuel injector, a TBI system may be easily installed by removing the carburetor and replacing it with the throttle body. This allows the use of a TBI setup to be inexpensive and simple.
2.4.4 Direct Fuel Injection

Direct fuel injection (DFI), as illustrated in Figure 2.6, injects fuel directly into the engine cylinders instead of injecting into the throttle body like TBI or intake ports like PFI. Direct fuel injection allows easier starting, prompt acceleration and permits the use of a wider range of fuel volatilities without sacrificing performance [26]. Direct fuel injection utilizes higher-pressure fuel lines than PFI. For this reason, DFI requires injectors capable of handling higher flow rates and pressures. Since DFI injects fuel directly into the cylinder, it has a higher potential power output than any other fuel-injection system [2]. When natural gas is injected, the combustion chamber is already full of air since the cylinder has already completed a full intake and
compression stroke. For this reason, the air/fuel mixture is more pressurized and has a larger mass than an air/fuel mixture formed with carburetion and PFI. This occurs in the intake manifold, which is outside of the cylinder. This increase in mass leads to the increase in power output and volumetric efficiency [31].

Unfortunately, direct fuel injection has many disadvantages. First, the entire system has to operate at higher pressure, which would require the installation of additional high-pressure fuel lines. Secondly, fuel injection directly into the cylinders increases the complexity of DFI. This would require the custom modification of the engine cylinder head to allow the injectors to spray directly into each cylinder unlike TBI, which only requires only one injector. Within these custom cylinder heads, the nozzle spray should not be directed toward the spark plug to prevent fouling [26]. Custom cylinder heads and fuel lines make DFI very costly. Finally, inhomogeneous mixtures within the cylinders are more probable for DFI because the air and fuel have a short amount of time to mix and NG has a slow mixing rate. Consequences from inhomogeneous mixtures include decreased thermal efficiency and higher NOx emissions. On the other hand, if designed correctly, direct fuel injection could increase the efficiency and power output of the engine through the creation of a controlled stratified mixture. Also, new developments in High Pressure Direct Injection (HPDI) NG engines have lead to the use of diesel as a pilot ignition fuel and NG as the main fuel source. HPDI NG engines are emerging in the over the road truck market.
2.5 Fuel Injection System Components

2.5.1 Engine Control Unit (ECU)

The ECU is the microprocessor circuit board that controls the quantity of fuel injected into the engine based on information it receives from sensors placed throughout the engine. Through the use of an ECU, modern cars can achieve lower emissions and higher fuel economy. While these microprocessors can make it more difficult for an untrained user to work on his/her own car, they can make the car easier to service with the correct equipment and software. The ECU utilizes closed-loop control, a control scheme that monitors outputs of a system to control the inputs to a system, to manage the emissions, fuel economy, and power output of the engine. Gathering data from dozens of different sensor outputs, the ECU identifies engine characteristics such as the coolant temperature and the amount of oxygen in the exhaust. With this data, the ECU performs millions of calculations per second, including determining values contained in
multidimensional tables, to calculate the results of complex equations. Ultimately, the ECU determines the best spark timing and how long the fuel injector is open [33].

For such applications as CNG injection, where a wide range of flexibility is required for injection tuning, a custom programmable ECU is desirable. One such ECU is Megasquirt, an open source EFI system for racing and do-it-yourself applications. The Megasquirt can be customized to user specifications and programmed with TunerStudio MS tuner software. Megasquirt and TunerStudio are also inexpensive options designed for the do-it-yourself setup.

### 2.5.2 Sensors

Sensors represent the interfaces between the ECU, the processing unit, and the vehicle’s engine. As a rule, a circuit in each sensor converts the signals from certain engine parameters to processable data available to the ECU. These sensors allow the ECU to calculate the amount of fuel injection needed to create an optimum A/F ratio within the engine. The ECU, through the use of a closed-loop feedback system, then regulates the fuel-injection quantity depending on the current engine needs. These sensors include:

1. **Throttle Position Sensor (TPS)**
2. **Manifold Absolute Pressure sensor (MAP)**
3. **Idle Air Temperature sensor (IAT) or Manifold Air Temperature sensor (MAT)**
4. **Universal Exhaust Gas Oxygen sensor (UEGO)**
5. **Crankshaft position sensor (CKP)**
6. **Coolant Temperature sensor (CLT)**

A simple, yet important, sensor required in every engine is the throttle valve sensor otherwise referred to as the throttle position sensor (TPS). This sensor monitors the angle of rotation of the throttle butterfly valve and is mounted to the butterfly spindle. The TPS uses
potentiometers to correlate the angles of rotation of the throttle butterfly valve into voltage signals [7]. When a driver steps on the gas pedal, the throttle valve opens up more, letting in more air. The ECU registers the throttle valve opening based on voltage signals sent from the TPS and increases the fuel rate in anticipation of more air entering the engine. It is critical to increase the fuel rate in synchronization with the throttle valve opening; otherwise, when the gas pedal is first pressed, there may be a hesitation as some air reaches the cylinders without enough fuel mixed in [27].

The MAP sensor monitors the pressure of the intake manifold air relative to atmospheric pressure. The MAP sensor is referenced to ground and therefore outputs a voltage signal between 0 and 5 volts depending on the pressure it senses [34]. This pressure indicates the amount of air that is being drawn into the engine, which is a good indication of how much power it is producing. As engine load increases, the intake manifold absolute pressure also increases. For this reason, the MAP sensor helps to determine fuel and spark delivery to the engine. Furthermore, the volumetric efficiency of the engine can be determined with the MAP sensor reading in combination with engine RPM. Volumetric efficiency (VE) is the percentage of air within the engine vs. the maximum amount of air it can actually possess. Though a VE of 100% is optimum, most naturally aspirated engines typically achieve an 80-90% VE without a tuned intake design.

The IAT sensor, otherwise known as the MAT sensor, as implied by the name, registers the temperature of the air within the intake manifold before it enters the engine. The IAT sensor is a simple thermistor and therefore changes resistance with changes in temperature. The ECU equates these resistance signals to temperatures, which it uses to calculate fuel and spark delivery. For liquid fueled engines, the colder the manifold air temperature, the richer the AFR.
mixture. This is because air becomes denser at low temperatures, which requires more fuel to achieve the desired AFR.

The Universal Exhaust Gas Oxygen sensor (UEGO) is mounted in the exhaust system of the car and is responsible for helping the ECU make adjustments to the AFR delivered to the engine. The UEGO sensor produces voltage signals based upon the amount of oxygen in the exhaust system [34]. The ECU in turn uses these voltage signals to calculate the AFR. For example, if the AFR is lean, there will be more oxygen content in the exhaust system and the O$_2$ sensor will output a lower voltage. The UEGO sensors can either be wide band or narrow band. Narrow-band UEGO sensors are only effective at reading oxygen levels in a narrow AFR range, usually close to the stoichiometric AFR. On the other hand, wide-band sensors can measure oxygen levels within a large range of AFR allowing for more optimum tuning of the engine.

The Crankshaft position sensor (CKP) is an electrical device, which outputs the crankshaft position. Several pins are placed in the metal of the crankshaft at equal distances apart from each other. A strong magnet is also mounted to the crankshaft, generating a magnetic field [35]. As the crankshaft spins, the rotating pins cause fluctuations in the magnetic field. These fluctuations are registered by the CKP as voltage signals, which are sent to the ECU. Since the pins are placed at known locations, the ECU uses these voltage signals to determine the engine crank position and revolutions per minute. The engine RPM is then used to fine-tune the timing of fuel injection.

The Coolant Temperature sensor (CLT) measures the temperature of the coolant of the engine. MegaSquirt has a CLT that is electrically identical to the IAT sensor. It functions as a resistor in same fashion as the IAT, but it instead is used for warm-up enrichment, cranking pulse-width determination, and controlling the idle valve. When the coolant air is cold, for
example on a cold winter day, the resistance registered by the CLT will be high until the engine warms up to normal running temperatures [36]. These resistance signals are sent to the ECU, which equates the resistances to temperatures. The ECU uses these engine temperature readings to adjust the AFR for optimum engine performance. For example, when the air temperature is cold, additional fuel must be injected into the cylinders creating a richer mixture. This is based on the fact that when the air is cold, it is also denser, which causes the mixture to become lean [36]. In other words, at low temperatures, fuel vaporizes poorly, and more fuel is needed to ensure enough vaporized fuel for adequate combustion.

2.5.3 Throttle Body and Fuel Lines

The throttle body is the part of the air intake system that controls the airflow rate into an engine combustion chamber. If an engine uses throttle body injection, the throttle body consists of a housing that contains a throttle plate (butterfly), a fuel injector and a pressure sensor. When a driver presses harder on the accelerator pedal, the throttle plate opens and allows more air/fuel mixture to flow into the engine. This process regulates the speed of the engine and ultimately the speed of the vehicle.

Since the pressure of the fuel flowing into the injectors is around 7 bar, flexible low-pressure fuel lines can be used for CNG applications [8]. This pressure is lowered from the 200-250 bar storage pressure in the CNG tank by a pressure regulator. These fuel lines link the pressure regulator to the injectors, and though flexible, must meet strict safety protocols in case of an accident.
2.5.4 Electromagnetic Fuel Injectors

A fuel injector is an electronically controlled valve, which regulates how much fuel is delivered to the engine. Fuel injectors are supplied with pressurized fuel from a fuel pump or pressure regulator, and are capable of precisely opening and closing numerous times per second. The ECU sends signals to the injector to open. These signals cause the injector electromagnet to move a plunger that opens the valve allowing the pressurized fuel to squirt out through a tiny nozzle [27]. The nozzle is designed to fully atomize the fuel, for a liquid fuel, so it can burn easily. The amount of time the fuel injector stays open, called the pulse width, determines the amount of fuel supplied to the engine. The ECU controls the pulse width to create an optimum AFR. Injectors must be sized for their prospective engines. If the fuel flow of the injector is too small, the engine will be starved of fuel under fuel power. On the other hand, if the injector flow rate is too large, the engine will be unable to effectively idle. The injectors are mounted on the throttle body in the intake manifold or directly onto the engine cylinder. Finally, injectors can have fuel input ports located on the side or on the top, which are referred to as top-feed injectors. A top-feed injector, as shown in Figure 2.7, can be easier to install and test.
Figure 2.7: Basic Fuel Injector Diagram [37]
Chapter 3: Engine and Vehicle Background

3.1 Engine and Vehicle Specifications

The Kawasaki FD620D V-twin engine was installed as the power generator for a hybrid-electric Ford Escort station wagon for the 1992-1995 Hybrid Electric Vehicle (HEV) challenge. The engine’s compression ratio has been increased to 10.5:1 from 9.0:1. The vehicle was in a range extender series hybrid setup. A 144-volt battery pack supplied the power to the electric motor, which powered the wheels, and the propane engine assisted the electric motor to extend its range. The battery pack only provided enough power to the vehicle for a range of 40-60 miles range. On the other hand, with the NG engine charging the battery pack throughout operation, the vehicle had an estimated travel range of almost 600 miles.

The engine was a Kawasaki FD620D V-twin used in a John Deere lawnmower and other industrial applications. It had a stock gasoline power rating of 20 HP available in carbureted and TBI versions. Table 3.1 provides important engine specifications and Figure 3.1 supplies engine performance curve characteristics.

Table 3.1: Engine Specifications [38]

<table>
<thead>
<tr>
<th>Engine Model</th>
<th>Kawasaki FD 620D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine Type</td>
<td>Liquid cooled 4-stroke, horizontal shaft, OHV gasoline engine</td>
</tr>
<tr>
<td>Cylinder Layout</td>
<td>90°V-Twin</td>
</tr>
<tr>
<td>Bore x Stroke</td>
<td>76 x 68mm (2.99 x 2.68 in.)</td>
</tr>
<tr>
<td>Piston Displacement</td>
<td>617 cm$^3$ (37.7 cu. in.)</td>
</tr>
<tr>
<td>Compression Ratio</td>
<td>10.5:1</td>
</tr>
<tr>
<td>Max.Horse Power</td>
<td>14.9 kW (20.0 Hp) / 3600 RPM</td>
</tr>
<tr>
<td>Max.Torque</td>
<td>44.6 N-m (32.9 ft-lbs) / 2200 RPM</td>
</tr>
<tr>
<td>Min.Specific Fuel Consumption Ratio</td>
<td>333 gr / kW-hr (245 gr / Hp-hr)</td>
</tr>
<tr>
<td>Net Weight</td>
<td>47.2 kg (104.1 lbs) with Muffler</td>
</tr>
</tbody>
</table>
Figure 3.1: Kawasaki FD 620D Performance Curves [38]
Chapter 4: EFI System

4.1 Market Study

4.1.1 Engine Control Unit Decision- Megasquirt I V3.0

There are many engine control units (ECUs) being sold for a wide variety of automobile applications. Many of these ECUs come preprogrammed for specific engines running on specific fuels. Since the Kawasaki FD620D engine was originally manufactured with a carbureted gasoline fuel system, ordering a preprogrammed ECU for an injection system fueled by CNG was not possible. For this reason, a fully customizable ECU was needed to handle the unique parameters of a CNG injection system. A company, which sells relatively cheap built-it-yourself engine ECUs, is Megasquirt [39].

Wade McCorkel, for a previous thesis, reviewed the ECUs available from Megasquirt, chose a specific ECU setup and fully assembled this ECU for hydrogen injection of the Kawasaki FD620D [2]. His final decision was the MS-I with a V3.0 Main Board. Other possible models included the MS-II, Microsquirt, or MS-II Sequencer. These models come with the option of three different circuit boards: V2.2, V3.0 and V3.57. This Megasquirt ECU configuration was acceptable for CNG injection for similar reasons. First, since the engine already has an ignition control unit, the ECU would not need to control ignition timing or idle valves. While Megasquirt models MS-II, Microsquirt and MS-II all include the unneeded ignition control, MS-I does not. Second, CNG requires a similar volumetric flow rate as compared to hydrogen gas based upon calculations in the Appendix and McCorkel’s thesis. Since these flow rates are calculated for the relatively small Kawasaki engine, smaller injectors would be required. MS-I is recommended for small injectors, where MS-II, Microsquir and MS-II Sequencer are recommended for large injectors for power performance racing engines. Third,
MS-I is a do-it-yourself system allowing full customization of components, while Microsquirt and MS-II Sequencer come preassembled. Fourth, MS-II, Microsquirt and MS-II sequencer are more expensive than MS-I because of unneeded ignition control features. It is to be noted that a new model has been released recently called the MS-III. This board is most comparable to the MS-II Sequencer, but can come unassembled. The MS-III is recommended for large injectors and has unneeded ignition control. For these reasons, as listed in Table 4.1, McCorkel’s already assembled MS-I V3.0 main board was recycled for use in a CNG injection system.

<table>
<thead>
<tr>
<th></th>
<th>MS-I</th>
<th>MS-II</th>
<th>Microsquirt</th>
<th>MS-II Sequencer</th>
<th>MS-III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Control</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Do-it-yourself</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Recommended for Large</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Ignition Control</td>
<td></td>
<td>✔</td>
<td>✔</td>
<td></td>
<td>✔</td>
</tr>
<tr>
<td>Cost</td>
<td>Free/Recycled</td>
<td>$278</td>
<td>$339</td>
<td>$550</td>
<td>$378</td>
</tr>
</tbody>
</table>

Table 4.1: ECU Comparison Chart

4.1.2 Injector Decision

Since CNG EFI systems use gas under high pressure, CNG injectors must be able to handle high gas volumes and the high through flow velocity. There are a few injectors on the market that are specifically designed for CNG injection. The viable injectors include the Honda Civic GX GBRemanufacturing injectors, the Dymco CNG injectors, the SMP CNG injectors, the Bosch NG12 injectors and the KEIHIN KN3 and DM4 injectors. The main criteria used to make the final injector decision were fuel flow rate, size, sealing mechanism, impedance value, and accessibility. These criteria are shown in Table 4.2 with the prospective injectors’ characteristics. Pictures of the prospective injectors can be seen in Figure 4.1.
Table 4.2: CNG Injector Specification

<table>
<thead>
<tr>
<th>Features:</th>
<th>Honda Civic GX by GBRemanufacturing</th>
<th>Keihin KN3</th>
<th>Keihin DM4</th>
<th>Dymco</th>
<th>SMP</th>
<th>Bosch NG12 EV6</th>
<th>Bosch NG12 210 lb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model/Part #</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>M1000</td>
<td>01D177B</td>
<td>280158827</td>
</tr>
<tr>
<td>Flow Rate - Static</td>
<td>(NG @ 101.35 kPa): 96.46 L/min</td>
<td>75 L/min</td>
<td>80-172 L/min (@255kPa)</td>
<td>34-66 L/min (@1.2 bar)</td>
<td>1235.00 gm/min ± 5% (@8.28 bar)</td>
<td>160 lb/hr (@300kPa) w/Gasoline</td>
<td>210 lb/hr (@300kPa) w/Gasoline</td>
</tr>
<tr>
<td>(Gasoline@300kPa): 18.92 lb/hr</td>
<td>NA</td>
<td>69.45 g/min</td>
<td>75 L/min</td>
<td>80-172 L/min (@255kPa)</td>
<td>34-66 L/min (@1.2 bar)</td>
<td>1235.00 gm/min ± 5% (@8.28 bar)</td>
<td>160 lb/hr (@300kPa) w/Gasoline</td>
</tr>
<tr>
<td>High Impedance</td>
<td>NA</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Low Impedance</td>
<td>NA</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Total length</td>
<td>NA</td>
<td>80mm</td>
<td>68mm</td>
<td>71.9 mm</td>
<td>NA</td>
<td>NA</td>
<td>No</td>
</tr>
<tr>
<td>O-ring to O-ring length</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>~ 50mm</td>
<td>54.7 mm</td>
<td>62 mm</td>
<td>37.5 mm</td>
</tr>
<tr>
<td>Top O-ring diameter</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>~ 13.2mm</td>
<td>31.1 mm</td>
<td>14.5mm Viton</td>
<td>14.5mm Viton</td>
</tr>
<tr>
<td>Bottom O-ring diameter</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>~ 19.1mm</td>
<td>13.5 mm</td>
<td>14.5mm Viton</td>
<td>14.5mm Viton</td>
</tr>
<tr>
<td>Injector body diameter</td>
<td>NA</td>
<td>27mm</td>
<td>26.3mm</td>
<td>24 mm</td>
<td>16mm</td>
<td>16mm</td>
<td>16mm</td>
</tr>
<tr>
<td>Accessible</td>
<td>NA</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Price</td>
<td>$57.42/$132.53</td>
<td>~ $100</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
<td>$119.99</td>
<td>$137.99</td>
</tr>
</tbody>
</table>

Figure 4.1: CNG Injectors From Left to Right (Honda, Keihin KN3, Keihin DM4, Dymco, SMP, Bosch 1NG12 EV6, Bosch NG12 210lb)

One very important issue that arose when picking an injector was comparing the calculated flow rate, which is based on a standard cubic foot of natural gas, and flow rates of
injectors, which are specified online based on gasoline and different pressures. The required flow rate calculated for a cubic foot of natural gas, as described in Appendix A.1, was determined to be between 89.25 and 96.46 L/min of NG at standard conditions. A standard cubic foot of gas is defined as a cubic foot at a temperature of 21°C (70°F) and a pressure of 101.35 kilopascals [40]. Since some injector’s fuel flow rates were in different units, at different pressures, and for gasoline rather than natural gas, units were equated for NG and gasoline. These calculations can be found in Appendix A.3. Also, the flow rates recorded for each prospective injector were at static flow. Static flow is defined as the maximum amount of fuel that can flow in a given amount of time at a given pressure. Since the required flow rate was calculated for the maximum horsepower, this flow rate was compared to the prospective injectors’ maximum flow rate.

The Honda Civic GX GBRemanufacturing injector was a CNG injector taken under consideration. Online information about this injector was very scarce. For example, its flow rate was not specified. Also this injector’s dimensions were not displayed online and could not be acquired over the phone with a dealership. The only real information available about this injector is its picture and the prices of the model year 2005 and 2013 injectors. The 2005 model year injector’s picture indicated there were no sealing o-rings on the bottom half of the injector, which could cause sealing complications during the design and manufacturing of its custom high-pressure manifold. Since the information about this injector was very limited, it was not chosen.

The Dymco GISM-i1000 injectors were also taken into consideration. This injector’s static CNG flow rates are 34L/min, 44L/min, 49L/min, 54L/min and 66L/min at a pressure of 1.2 bar. Through calculations shown in Appendix A.3, the predicted required static flow rate of natural gas at 1.2 bar (129kPa) is 104 L/min. Therefore, if only one Dymco CNG injector were used, it would not have the flow capacity to fuel the engine under full throttle. To solve this
problem, two 54L/min Dymco CNG injectors would need to be employed and discharged in unison in a custom manifold. In addition, these injectors have been shown to come with fuel rails, which makes the design of a custom fuel-injection manifold easier. On the other hand, this injector is manufactured in Korea and for that reason all attempts to purchase these injectors have failed.

The SMP CNG injectors are one of the options that are accessible at this time. These injectors can be purchased directly from Standard Motor Products. Also, SMP provided detailed dimensioned drawings and specification sheets for these injectors. These injectors need to be operated exclusively with Compressed Natural Gas (CNG) at minimum oil content of 25 ppm. If the oil content drops lower than this, these injectors could experience premature failure. Also, these injectors are too large for the custom manifold. The SMP state their injectors’ static flow to be 1235.00 g/min ± 5%. The maximum operating pressure is 8.28 bar. For this reason, it is assumed that the static flow rate is measured at a pressure of 8.28 bar. Based on calculations done in Appendix A.3, the predicted required flow rate of CNG at 8.28 bar (828kPa) would be 198.5 g/min. These injectors would not be able to handle the low flow rate required when the engine is idling or at small throttle positions and therefore were not chosen.

The next injectors considered were the Bosch NG12 injector variants. These injectors were available on EBay and can be purchased easily. Also, Bosch NG12 injector’s surface is specially coated to prevent wear when used with oil-free gas. In addition, pressure losses before the throttling point and operating noise are minimal based on a special flow guide. Finally, these injectors are the only injectors that have high impedance. Since these injectors have high impedance, they can take a 12-volt supply directly, without a form of current control. On the other hand, these injectors may have too large a flow rate for our application. On EBay, these
injectors were rated at a static flow rate of 160 lb/hr and 210 lb/hr at 300 kPa with gas. It was assumed that gas meant gasoline. As shown in calculations in Appendix A.3, the required static flow rate of gasoline for our engine at 300 kPa is 18.92 lb/hr. Since the Bosch NG injectors have such a large static flow rate, they may not be able to provide a small enough flow rate to allow the engine to idle.

The Keihin KN3 and DM4 CNG injectors were two other possibilities for injectors. These injectors’ sizes are small enough to fit in a custom manifold and have two o-rings to help seal the system under high pressure. Also, these injectors come with a fuel rail, which will decrease the time needed to create a custom manifold. In addition, the KN3 CNG injectors are available for purchase from the company American Alternative Fuel (AAF) for about $100. These AAF Keihin CNG injectors are rated at about 75 L/min at 255 kPa. If our predicted flow rate calculation uses a pressure of 255 kPa, the flow rate increases to 153 L/min. For this reason, two AAF Keihin CNG injectors discharging simultaneously into a custom manifold would need to be utilized. These injectors have low impedance, which means that current would need to be limited from the battery. By adding resistors in series with the injector, the current sent to the injector can be lowered. Based upon these injectors being fully accessible from AFF and having the ability to provide the required flow rate to the engine, they will be purchased in the future.
4.2 Injection Method Decision

The main options for injection for the Kawasaki FD620D engine are carburetion, port fuel injection, throttle body injection or direct fuel injection. The first method to be eliminated was direct fuel injection since conversion of the current engine would require the machining of a hole at the top of the both cylinder heads in the engine. This process would require extensive design and the need of engine characteristics, which are not available to the public. Also, if designed incorrectly, the engine cylinder head would be unusable and dangerous complication could occur. Carburetion is the current method of fuel delivery on the engine. Though natural gas fuel could be delivered through carburetion, the actual method of carburetion is relatively imprecise. The only method of tuning for carburetion on this engine is idle and open throttle adjustment screws. Since natural gas has a relatively narrow range of combustible mixtures, carburetion will not be precise enough to accurately tune the engine. This left throttle body injection and port fuel injection methods as the last two options available. Ultimately, throttle body injection was chosen. Port fuel injection would require injectors for each cylinder. This would require the creation of holes in the intake manifold near the intake valves. This process would require a large amount of design and engineering for minimal reward over throttle body injection. Comparatively, conversion to throttle body injection would be relatively simple and cheap. A throttle body specifically designed for this engine is already available. This throttle body would be installed by removing the carburetor and bolting the throttle body directly into the same holes. None of the injectors found have dimensions that fit into the small injector entry hole of the throttle body as shown in Figure 4.2. The outer ring diameter of the injector seat of the throttle body is about 0.85 inches and the inner diameter is about 0.5 inches. To allow injection into the throttle body, an external custom manifold will be designed and manufactured.
This manifold will house the Keihin injectors and have a chamber into which the injectors fire CNG. This chamber will then be connected with a low-pressure fuel tube to the injector seat hole allowing fuel to flow into the throttle body.

Figure 4.2: Kawasaki FD620D Engine Throttle Body
4.3 Megasquirt I – V 3.0 Testing and Wiring

A Megasquirt I V3.0 ECU, originally assembled in 2010 by McCorkel, was chosen to control the injection timing of the CNG injection system [2]. Many tests were completed to assess the functionality of the 3 year old ECU. First, tests using a voltmeter were used to check the main integrated circuit chip as specified on the Megasquirt website. Once the main integrated chip was tested for function, then the MegaSquirt I was connected to the stimulator and the laptop with an USB to R232 DB9 conversion cable as shown in Figure 4.3. At first there was no communication between the Megasquirt I ECU and the computer. To allow communication between the ECY and the computer, a new laptop was used with a DB9 serial port so the USB to DB9 conversion could be removed.

Figure 4.3: MegaSquirt System Connection [41]
The stimulator is a circuit board that allows the user to input values in the place of real engine sensors to test the Megasquirt I ECU. Figure 4.4 shows a more detailed picture of the stimulator and its knobs. Turning the knobs changes the values the ECU reads for the theoretical sensor values. The RPM knob changes the revolutions per minute value that a Crankshaft Position Sensor (CKP) would supply to the ECU. The O₂ knob changes the amount of oxygen the ECU reads, which would usually be provided by the Universal Exhaust Gas Oxygen sensor (UEGO). The TPS, IAT and CLT knobs are self-explanatory and are abbreviations already explained in the sensor section. When these knobs are turned, if the ECU is functional, the changes will be registered in laptop tuning software. Such input was registered when the ECU/stimulator was connected to the laptop with the DB9 jack. For this reason, the ECU was determined to be fully functional and the tuning process with this ECU was started.

Figure 4.4: Megasquirt Stimulator
To properly connect the ECU to the engine sensors and the injectors in the final vehicle configuration, a relay board will be used. This relay board, as shown in Figure 4.5, is connected to the ECU via a DB37 cable as shown in Figure 4.3.

Figure 4.5: MegaSquirt Relay Board

A user also has the option of connecting the sensors directly to the ECU via the DB37 jack. The wiring schematic for this connection is shown in Figure 4.6. One sensor that directly connects to the Megasquirt I ECU and not through the DB37 jack is the MAP sensor. This sensor is mounted on the underside of the Megasquirt I, with the vacuum port facing the DB37 jack. This MAP sensor will need to be connected to the intake manifold or throttle body via a small tube for it to give usable manifold absolute pressure readings.
4.4 Software – Tuner Studio

The two tuning software options for MegaSquirt are Megatune and TunerStudio MS. The decision was made to use TunerStudio MS since it is more user friendly, refined and has more advanced tuning features than Megatune. This is mainly because Megatune is free software whereas the full version of Tunerstudio, TunerStudio MS, costs $59.95. TunerStudio MS also has extensive directions online for engine tuning along with an online support group to ask specific questions about the software.
Before the engine can be tuned, three main tables must be fully completed. These tables include the standard constants table, the enrichments table and the volumetric efficiency table. The engine will not start if the values in these tables are not specifically tailored to the engine and fuel choice. Also, if these values are wrong, the engine could be damaged during the initial tuning stages [42]. This section will review the base tune table values based upon the characteristics of an AFF CNG Keihin Injector.

4.4.1 Standard Constants Table:

This table allows the user to enter specific information about the fuel, injectors and injection system. The first value which must be entered is the required fuel, which is the base reference pulsewidth required to achieve a stoichiometric AFR at 100% VE and a Manifold Absolute Pressure (MAP) of 100 kPa. TunerStudio provides a required fuel calculator as shown in Figure 4.7. The value for engine displacement (617 cc) and number of cylinders (2) were used from the Kawasaki data sheet found online. The injector flow rate was calculated to be 8.876 lb/hr CNG as shown in the Appendix A.4. The required air-fuel stoichiometric ratio used was 17.2 based upon Matt Cramer’s Performance Fuel Injection Systems book value [42].
The next value required in the standard constants table was injection opening time as shown in Figure 4.9. Injection opening time, or dead time, is the net time current is provided to the injector during which it is not injecting fuel due to opening and closing. Dead time was estimated to be about .75 ms for the Keihin injector based upon other CNG injector times found online. The next value entered into the table is battery voltage correction, which is the battery voltage correction factor for fuel pulse width. Since the dead time of the Keihin injector is about .75ms at 14 supplied volts, the battery voltage correction is .0535ms/V. The PWM Current Limit (%) is the pulse width modulator current limit percent, which is used to limit the current flow in low impedance injectors. Although the Keihin injector is low impedance (1.25 Ω resistance), PWM will not be used to limit the current to the injector. Instead, resistors will be connected in series with the injector to limit the current sent to injector to prevent the injector from overheating. For this reason, PWM will be disabled. To disable the PWM current limit, a value of 100% will be used. For this same reason, the PWM Time (ms) will be set to 25.4 ms since this is the time after the injector pulse starts PWM. The value of 25.4 disables the PWM [41]. The
Fast Idle Threshold value is the coolant temperature at which the fast idle solenoid is turned on. A typical value for this parameter is 145° Fahrenheit [41]. The Fast Idle valve will be turned on below this temperature (145°F) and turned off above 145°F. Since this CNG injection system does not have this solenoid, the value entered is unimportant. The barometric correction is a calculation that alters fuelling based on the ambient air pressure. This parameter is important to turn on at higher elevations but is of little importance in low-lying areas [41]. For this reason, barometric correction should be turned off for State College tuning.

The control algorithm value allows the choice between Speed Density and Alpha-N. The Alpha-N algorithm uses the throttle position and RPM to calculate the amount of fuel to inject. On the other hand, the Speed Density algorithm uses the manifold absolute pressure (MAP) and RPM to calculate the amount of fuel to inject [41]. Since this CNG injection system will be using the MAP sensor, the speed density algorithm was chosen. The squirts per engine cycle value is how many squirts per 720° rotation of the crankshaft for the Kawasaki 4-stroke engine. This value is used to allow proper tuning of the idle mixture while maintaining the ability to apply enrichments under full throttle. This value will be fine tuned with testing, but at the moment the lowest value will be more practical since the CNG fuel does not require enrichment. The lowest value TuneStudio MS will allow with this specification is 2. The injector staging parameter has the option of simultaneous or alternating. Since the CNG injection system will use two Keihin injector feeding into the same throttle body, this parameter was set to simultaneous. Since the Kawasaki FD620D engine is a four stroke, two-cylinder engine, engine stroke was set to a four-stroke and number of cylinders set to two. The system will employ a throttle body so the injector port type was set to throttle body. Since the Keihin injector has about half the flow rate required for the engine, two injectors will be required to reach the optimum AFR. For this reason, the
number of injectors was set to two. The MAP type box allows either a 250 kPa or 115 kPa entry. The Megasquirt I V3 main board uses the MPX4250AP MAP Sensor, which is rated at 2.5 bar or 250 kPa. Finally, the engine-type drop-down box allows odd fire or even fire. This refers not to the firing order, but rather to the interval between successive firings. Most V-Twins (usually motorcycle engines), as well as a few others, have odd-fire arrangements [41]. Since the engine is a Kawasaki 90°V-twin, the odd fire parameter was selected.

Figure 4.8: TunerStudio MS Standard Constants Table

4.4.2 Enrichments Table:

To fully understand the values entered for the enrichment table, one must first understand the meaning of injection enrichment. When the engine is first started or warming up, especially on cold winter days, the cold intake manifold and combustion chambers keep gasoline fuel from completely vaporizing at optimum levels [42]. This is because gasoline tends to condense on the walls of the engine. Since condensation decreases the amount of gasoline vapor available for combustion, more gasoline vapor must be injected to keep the engine running. Since natural gas
is already vaporized before injection and has a very high dew point of condensation, its chances of condensation on the engine walls are very low [43]. For this reason, CNG needs almost no cranking, after-start and acceleration enrichments compared to gasoline [42]. Accordingly, the enrichment table values were generated for no enrichment, which can be slightly increased after the base tune is complete.

The final enrichment table values can all be seen in Figure 4.9. The cranking pulsewidths (ms) will need to be fine tuned when engine is running, but since cranking enrichment is unneeded for CNG, all these values can be equal. Also, based upon CNG not needing enrichment the cranking pulse widths were set to a lower value of 2 ms. The after-start warm-up enrichment is set to zero to eliminate enrichment in base tune.

The EGO sensor type can either be wide-band or narrow-band. Since wide-band sensors work in reverse to narrow-band sensors, the correct entry of this parameter is very important. Most narrow-band sensors can only read oxygen values close to the stoichiometric AFR, which only tells the ECU if the mixture is rich or lean [44].

On the other hand, wide-band sensors can read a large range of AFRs, making them far more accurate for tuning, especially for power. In our system we will be sourcing a wide-band sensor to allow a wide range of tuning to reach maximum power output since CNG has a lower energy density, which can decrease the engine’s power output without a proper tune. The EGO switch point (V) tells the ECU what oxygen-sensor voltage signal corresponds to a stoichiometric AFR. This value is usually 2.5 V for a wide-band sensor but can vary from sensor to sensor. For this reason, the value is set to 2.5 V currently until a specific wide-band oxygen sensor is chosen for the injection system. The coolant temperature activation (°F) is the minimum coolant temperature before EGO feedback is active. Since no enrichment is needed for CNG, the
EGO feedback will need to be activated immediately. For this reason the lowest value of -40 °F was chosen. The ignition events per step are the number of tachometer pulse counts between EGO corrections to fuel. This value should be set to cause a switch about four times a second at the car’s average cruising speed [44]. A four-cylinder engine, assuming 3500 RPM cruise, should have about 29 ignition events per step and a six-cylinder should have about 31 [44]. For this reason, a value of 27 was used based upon having a two-cylinder engine, not a four-cylinder engine. The EGO Step (%) is the percent step change in fuel for EGO corrections. The Megasquirt tuning site suggested an initial base tuning value of 1, so auto-tune does not do unstable jumps [41]. Similarly, the EGO plus/minus limit (%) was set a lower value of 15%, to decrease the chance of unstable jumps in autotune mode. The EGO Active Above (RPM) setting is the minimum RPM before the O2 closed-loop feedback is active. Since the CNG system does not need fuel enrichment, the O2 closed loop should be active immediately. For this reason the RPM is set at the lowest value of 100.

The next section of the enrichment table is the acceleration enrichment. Tuning acceleration/deceleration enrichments is not as crucial for CNG because NG does not stick to the intake walls or puddle like gasoline. Also, this engine will be used to power a computer-controlled generator. It will never accelerate quickly and will only decelerate quickly when the brake is depressed. For this reason, the acceleration enrichments values were set to completely disable acceleration enrichment. TPSdot Threshold is the rate of change of the TPS signal (Volts/s) at which acceleration enrichment will be activated. In an attempt to turn off acceleration enrichment, this value was set to the highest value of 49.609 percent. The acceleration time (ms) is the duration for acceleration enrichment. Since acceleration enrichment is unwanted for base tuning, this time was set to zero. The cold acceleration enrichment time is
the duration of acceleration enrichment in cold temperatures. Since NG does not condensate easily, this value was set to zero also. The cold acceleration multiply (%) is the acceleration multiply factor (%) in cold condition (-40°F). To eliminate cold acceleration enrichment this was set to 0. The deceleration fuel amount (%) reduces the amount of fuel injected when the throttle position and/or MAP are decreasing. A value of 100% causes no cut in fuel and a value of 0% completely cuts off fuel. To completely remove deceleration enrichment for the base idle tune, this value was set to 100%. The final portion of the enrichment table are the acceleration Bins (ms). To eliminate acceleration enrichment, the bin values were set to zero.

Figure 4.9: TunerStudio MS Enrichments Table

4.4.3 Volumetric Efficiency Table:

Volumetric Efficiency (VE) is the percentage of how much air is really drawn into the engine compared to the theoretical amount of air the engine is capable of drawing in [42]. On the
other hand, the VE number recorded on the table within TunerStudio may not always represent
the actual VE of the engine. Instead, this VE value is the percentage that is entered into a specific
Megasquirt equation, which allows the right amount of fuel to be injected into the engine when
needed [42]. The specific equation used by the MegaSquirt ECU to calculate injection pulse
width is shown below:

\[ PW = \text{REG\_FUEL} \times \text{VE} \times \text{MAP} \times E + \text{accel} + \text{Injector\_open\_time} \]

The \text{REG\_FUEL} is the value specified in the constants table based upon the AFR and
the fuel flow requirements. The \text{MAP} is the manifold absolute pressure and the
\text{Injector\_open\_time} is another parameter entered into the constants table based upon the
injector specifications. The \text{accel} is the acceleration enrichment, which will be small or disabled
for a CNG injection system since CNG dew point is very high. The \text{E} term is gamma
enrichment, calculated from all engine enrichments, and its equation is shown below:

\[ E = \text{gamma\_Enrich} = \left( \frac{\text{Warmup}}{100} \right) \times \left( \frac{\text{O2\_ClosedLoop}}{100} \right) \times \left( \frac{\text{AirCorr}}{100} \right) \times \left( \frac{\text{BaroCorr}}{100} \right) \]

\text{Warmup} stands for the warm-up enrichment value from the constants table, which is
disabled for the initial base tune. The \text{O2\_ClosedLoop} term is the EGO adjustment based on the
EGO sensor feedback and the EGO settings, which were custom entered into the enrichments
table. The \text{AirCorr} term is the adjustment for air density, based upon the intake air temperature
recorded by the IAT sensor. Finally, the \text{BaroCorr} term is the barometric correction based on
the ambient air pressure, which is usually recorded during start-up.

Based upon these equations, one can understand that a larger value of VE causes an
increase in fuel supply to the engine. The base VE table for Megasquirt is an 8x8 map with eight
RPM ranges and eight load ranges usually denoted as MAP values. Larger VE table maps have
higher table resolution, which gives the user more flexibility to deal with an engine with abrupt
changes in fuel and spark needs [42]. On the other hand, larger tables take considerably more time to tune. In addition, since the engine in this application is used to power the motor, abrupt changes in fuel supply and spark are highly unlikely. For this reason, the resolution of the Megasquirt I V3.0 setup 8x8 map will have plenty of resolution for this hybrid power-train injection application.

To create a base map for initial engine idle tuning, TunerStudio provides a VE table generator. This generator can be seen in Figure 4.10. Megasquirt defines VE mathematically in the following equation:

\[
VE = \left( \frac{\text{actual}_{\text{air}}\_\text{mass}}{\text{theoretical}_{\text{air}}\_\text{mass}} \right) \times \left( \frac{\text{AFR}_{\text{stoch}}}{\text{AFR}_{\text{actual}}} \right)
\]

Since the engine does not use a forced induction system, the engine type chosen in the VE table generator was naturally aspirated. The engine idle, redline, peak power and peak torque RPM values were taken from the Kawasaki specification sheet. The peak HP and peak lbs-ft along with the engine displacement value were also taken from the Kawasaki specification sheet. Finally, the MAP (kPa) values were created from the assumption that the greater the absolute pressure in the inlet manifold, the greater the amount of fuel/air mixture that will enter the engine. When more fuel and air are in the cylinder, more power can be produced. For this reason the MAP was set lower for the idle value when less power is needed and higher for peak torque. The exact MAP as estimated based upon an VE table found for a EQD180N-30 CNG engine and will need to be fine tuned before the engine will run at an optimum level [45]. The final VE table for base tuning the engine is shown in Figure 4.11 and will be used to initially start the engine at idle.
4.5 Injection System Tuning Setup

The most widespread technique to correctly tune an engine is to use steady-state analysis. Steady-state analysis is when the engine is held at a steady RPM so the user can hold the engine
at all different load points at that RPM while making changes to the tuning maps [42]. Most vehicles today have liquid-petrol-fueled engines that power the wheels directly. For this reason, to tune the engine a steady-state dynamometer is used. The steady-state dynamometer holds the vehicle’s wheels, and consequently its engine, at the specific RPM specified while recording the torque output in real-time. On the other hand, since the Kawasaki engine is used in a series hybrid powertrain vehicle the use of a dynamometer is not needed. The term series hybrid means that the engine is connected directly to a generator, which charges the hybrid vehicle’s batteries and/or powers the vehicles electric motor. This electric motor then powers the wheels of the car. The generator can be used to hold the engine at a specific RPM under different loads, instead of a steady-state dynamometer. The generator used in the HEV challenge Ford Escort hybrid is a Unique Mobility 20 kW, 3-phase rectified permanent magnet generator. The voltage output value for this generator is directly related to engine RPM at a ratio of about 160 volts/7000 RPM. The generator will be connected to the AeroVironment's ABC-150 power processing system, as shown in Figure 4.12. This ABC-150 will easily be able to handle a voltage range of 8 to 445VDC, and a current range of ± 530 ADC [46].

Figure 4.12: Series Hybrid Powertrain Engine Tuning Setup
Chapter 5: Future Recommended Work

5.1 Design Custom Injector Manifold

Since the injector seat on the throttle body is very small, no sourced CNG injectors can fit with a proper seal. To fix this issue, a custom manifold will be created, external to the throttle body, where injectors will be housed. Injectors will fire fuel into a specifically engineered chamber in this external manifold. This injection chamber will then be connected via a flexible fuel line to the throttle body where the old gasoline injector was seated. The main focus of this external manifold will be preventing leakage of the CNG fuel. Such a leak would decrease the fuel economy.

5.2 Fine-Tune Engine

After the engine has been fully assembled with the installation of CNG fuel lines, sensors, injectors, a throttle body and wiring the engine injection system can be optimally tuned. Based upon the vehicle employing a series hybrid power-train system, such tuning will not require a steady-state dynamometer. On the other hand, the generator will be programmed to hold the engine at certain specified RPMs. To absorb and record the extra current created by an increase engine load, an ABC-150 power processing system will be connected to this generator. Finally, this current change will be correlated to the change in engine load/torque and used to efficiently and precisely tune the CNG injection system.

5.3 Test Hydrogen and Natural Gas Fuel Mixtures

After the engine injection system is optimally tuned to run CNG, blends of CNG and hydrogen can begin to be explored. Hydrogen enriched compressed natural gas (HCNG) combines the advantages of both hydrogen and methane combustion. Since hydrogen’s flame velocity is nearly seven times higher than that of methane, the addition of hydrogen can increase
the burning velocity of the mixture allowing shorter combustion duration, greater constant volume degree, as well as improved indicated thermal efficiency [47]. On the other hand, hydrogen is more susceptible to pre-ignition in comparison to NG. For this reason, the tuning of these HCNG blends should be done with increased caution to decrease the chance of permanent engine damage.
Chapter 6: Conclusion

The research conducted during this thesis was primarily aimed towards the creation of a CNG vehicle platform to utilize NG as an alternative automotive fuel source to gasoline. Through this research an ECU was configured for CNG usage, a CNG injector was sourced and a base CNG tune was created with the tuning software TunerStudio MS. With the creation of a custom external injector manifold, the pre-existing engine throttle body can easily be installed. After installation is complete, the injection system can be tuned and refinements made accordingly. Since NG properties are close to those of hydrogen, the hope is that in the future, HCNG blends could be researched for use in series hybrid-electric vehicles through the use of this CNG injection system.
BIBLIOGRAPHY


Appendix

A.1 Calculation of Injector Flow Rate

During this calculation, the assumption is made that the maximum engine efficiency running on gasoline is approximately equal to the maximum engine efficiency running on compressed natural gas. The Kawasaki FD620D has a minimum specific fuel consumption of 333 g/kW*hr running on gasoline and maximum of 20 HP [38]. Gasoline has an energy content of 43.1 MJ/kg and 1 HP = 746 Watts [48]. Using these parameters the amount of power the engine produces can be calculated as shown below:

Gasoline:

\[
Power = (20\text{HP}) \left( \frac{746\text{W}}{1\text{HP}} \right) \left( \frac{1\text{kW}}{1000\text{W}} \right) \left( \frac{333\text{g}}{1\text{kHzr}} \right) \left( \frac{1\text{kg}}{1000\text{g}} \right) \left( \frac{43.1\text{MJ}}{1\text{kg}} \right) \left( \frac{1\text{hr}}{60\text{min}} \right) = 3.57\text{MJ/min}
\]

Using the assumption that the maximum engine efficiency running on gasoline is approximately equal to the maximum engine efficiency running on CNG, the range of flow rates of CNG required for a one-injector system can be calculated. In addition, CNG is assumed to have an energy density of 37-40 MJ [24].

\[
FlowRate_{\text{CNG}} = \left( 3.57\text{MJ/min} \right) \left( \frac{1\text{m}^3}{37\text{MJ}} \right) \left( \frac{1000\text{L}}{1\text{m}^3} \right) = 96.46\text{L/min}
\]

\[
FlowRate_{\text{CNG}} = \left( 3.57\text{MJ/min} \right) \left( \frac{1\text{m}^3}{40\text{MJ}} \right) \left( \frac{1000\text{L}}{1\text{m}^3} \right) = 89.25\text{L/min}
\]

Based on these calculations, the required flow rate of natural gas through a one-injector system would be between 96.46 L/min and 89.25 L/min (96460 cc/min – 89250 cc/min).

A.2 Re-Calculation of Engine Fuel Flow Rate

This calculation is similar the calculation performed by Wade McCorkel but applied to natural gas instead of hydrogen. The goal of this calculation was to confirm the flow rate calculation performed in A 1. The first step of this calculation is to calculate the volume flow rate of air. The volume flow rate of air is dependent on RPM, engine displacement, piston revolutions per engine cycle and volumetric efficiency.

Engine displacement = 0.617 L
RPM = 3600
VE = 0.90
Piston revolutions per engine cycle = 2 (for a 4-stroke engine)
$VolumeFlowRate_{\text{air}} = \frac{(0.617L)(3600\text{rev/min})(0.90)}{(2\text{rev})} = 1000\text{L/min}$

Next, the mass flow rate of air can be calculated using this volume flow rate of air and the Ideal Gas Law. In the Ideal Gas Law the instead of using mass and volume, the respective flow rates are used.

$$MassFlowRate_{\text{air}} = \frac{(\text{Pressure})(VolumeFlow_{\text{air}})(MolarMass_{\text{air}})}{(R)(\text{Temp})}$$

Pressure = 1 atm
Volume Flow Rate = 1000 L/min
MolarMassair = 29 g/mol
R = 0.08206 Latm/molK
Temperature = 298 K

$$MassFlowRate_{\text{air}} = \frac{(1\text{atm})(1000\text{L/min})(29\text{g/mol})}{(0.08206\text{Latm/molK})(298)} = 1185.91\text{g/min}$$

Next the mass flow rate of natural gas is calculated using the desired AFR. For this research, an AFR of 16.8:1 was pursued.

Mass Flow Rate air = 1185.91 g/min
AFR = 16.8:1

$$MassFlowRate_{\text{NG}} = (1185.91\text{g/min})(\frac{1}{16.8}) = 70.59\text{g/min}$$

Finally, considering the density of natural gas is .72 g/L, the fuel flow rate of natural gas can be calculated.

$$FuelFlowRate_{\text{NG}} = \left(\frac{MassFlowRate_{\text{NG}}}{Density_{\text{NG}}}\right)$$

$$FuelFlowRate_{\text{NG}} = \left(\frac{70.59\text{g/min}}{.72\text{g/L}}\right) = 97.92\text{L/min}$$

As expected this required flow rate is very similar to the previously calculated flow rate’s upper limit. The percent difference between these two values is shown below:
PercentageDifference = \left( \frac{96.46 - 97.92}{96.46 + 97.92} \right) x 100% = 0.99%

A.3 Unit and Fuel Conversions

Conversion of predicted NG flow rate at 101.35 kPa to a pressure of 255 kPa for comparison of Keihin injectors:

\[ Q_2 = \{\text{Square Root} (P_2/P_1)} \times Q_1 \]

- \( Q_1 \) = Original injector flow rate (L/min or lb/hr)
- \( Q_2 \) = Injector flow rate at modified pressure (L/min or lbs/hr)
- \( P_1 \) = Original fuel pressure set point (kPa or psi)
- \( P_2 \) = Adjusted fuel pressure set point (kPa or psi)

\[ Q_{\text{Keihin predicted}} = \sqrt{\frac{255 \text{kPa}}{101.35 \text{kPa}}} \times 96.46 \text{L/min} = 153.00 \text{L/min} \]

Conversion of predicted NG flow from L/min at 101.35 kPa to L/min at 1.2 bar (120 kPa) for comparison of Dymco injectors:

\[ Q_{\text{Dymco predicted}} = \sqrt{\frac{120 \text{kPa}}{101.35 \text{kPa}}} \times 96.46 \text{L/min} = 104.00 \text{L/min} \]

Conversion of predicted NG flow from L/min at 101.35 kPa to g/min at 828 kPa for comparison of SMP injectors:

\[ Q_{\text{static predicted NG}} = \left( \frac{96.46 \text{L}}{\text{min}} \right) \left( \frac{0.72 \text{g}}{\text{L}} \right) = 69.45 \frac{\text{g}}{\text{min}} \text{ at 101.35 kPa} \]

\[ Q_{\text{static pressure predicted SMP NG}} = \left( \sqrt{\frac{828 \text{kPa}}{101.35 \text{kPa}}} \right) \times 69.45 \frac{\text{g}}{\text{min}} = 198.5 \frac{\text{g}}{\text{min}} \]

Conversion of predicted power of gasoline to mass flow rate of gasoline at 300 kPa for comparison of Bosch NG injector flow rates:
\[
Power_{\text{predicted gasoline}} = \left( \frac{3.57 \text{ MJ}}{\text{min}} \right) \left( \frac{\text{60 min}}{1 \text{ hour}} \right) \left( \frac{1 \text{ kg}}{43.1 \text{ MJ}} \right) \left( \frac{2.205 \text{ lb}}{1 \text{ kg}} \right) = 11 \frac{\text{lb}}{\text{hr}} \atop @ 101.35 \text{kPa}
\]

\[
Q_{\text{bosch predicted}} = \left( \frac{43.51 \text{ psi}}{14.70 \text{ psi}} \right) \times 11 \frac{\text{lb}}{\text{hr}} = 18.92 \frac{\text{lb}}{\text{hr}} \atop @ 300 \text{kPa}
\]

A.4 Fuel Flow Conversion for TunerStudio MS Required Fuel Calculator

\[
Q_{\text{required NG}} = \left( 3.57 \frac{\text{MJ}}{\text{min}} \right) \left( \frac{1 \text{ kgNG}}{53.2 \text{ MJ}} \right) \left( \frac{2.20462 \text{ lb}}{1 \text{ kg}} \right) \left( \frac{60 \text{ min}}{1 \text{ hr}} \right) = 8.876 \frac{\text{lb}}{\text{hr}}
\]
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B.S. in Mechanical Engineering, May 2013
Schreyer’s Honors College – Honors in Mechanical Engineering
The Pennsylvania State University, University Park, PA
Dean’ List (3.5+ GPA) Fall 2009 to Present

Association Memberships/Activities
• Pennsylvania State Advanced Vehicle Team
• Society of Automotive Engineers
• American Society of Mechanical Engineers

Professional Experience
Pennsylvania State Lion Line Telefund Associate (Spring 2013)
State College, PA
  o Contacted alumni, parents and friends on behalf of Penn State's colleges, campuses, and programs.
  o Raised $ for Pennsylvania State Programs and Scholarships.

Ford Motor Company Global Engine Engineering Intern (Summer 2012)
Dearborn, MI
  o Designed machine washer/dryer manifold in AutoCAD saving $31,000 in design costs
  o Performed cost model for factory layout initial decisions with potential to save $1.5 million in factory expansion costs under certain economic and customer demand conditions.
  o Supported cylinder head washer machines inspection before shipment
  o Collaborated in global benchmarking and communization of cylinder head components

Data Collector for DOD WIN-T PQT-G Test (Summer 2011)
Aberdeen Proving Grounds, MD
  o Obtained DOD security clearance (level secret)
  o Recorded and interpreted test data for central advanced warfighter information network mobile system between multiple vehicles

Penn State Auxiliary Officer (Spring 2011 - Fall 2011)
University Park, PA
  o Directed traffic at events and assisted campus security officers

Research Interests
I have an interest in alternative energies and their roles in future car propulsion systems.
Specifically, I am interested in natural gas, hydrogen, solar, mini-turbine, hybrid-electric, and pure electric vehicles.

**Publications and Papers**