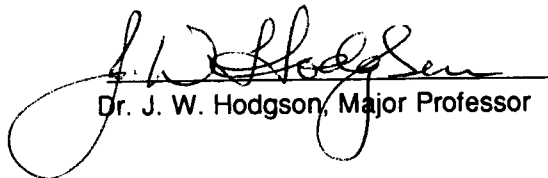
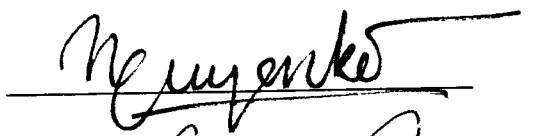
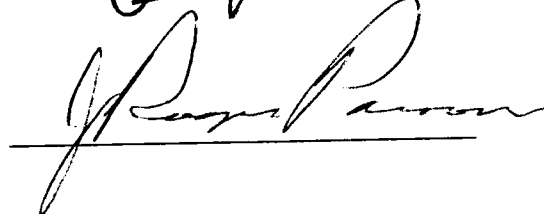


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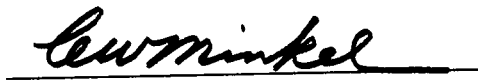
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Dr. J. W. Hodgson, Major Professor

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THE EVALUATION OF A DEDICATED NATURAL GAS VEHICLE CONVERSION

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Stephen R. Lampley

May 1995

to Julie

ACKNOWLEDGMENTS

I would like to thank my advisor Dr. J.W. Hodgson for all the time and attention he has given over the past year and a half. I would like to thank the rest of my advising committee Dr. J. R. Parsons and Dr. Ke Nguyen for fitting me into their busies schedules even when I gave them a only twenty-four hour notice. Thanks are extended to Mr. Scott Sluder and Mr. John Preston for rescuing Julie and I from a dark and deserted interstate when we had the fortune of running out of gas. I would like to thank Ms. Stacey Dickenson and Ms. Robin Tipton for the use of their vehicles and many of their warranty miles.

Thanks to the Saturn Corporation for both their monitary and technical support. I would like to extend my appreciation to Dr. Kenneth Knapp, Mr. Peter Gabele, Mr. Richard Snow, and Mr. Ned Perry for their undivided attention and support during emission testing. Thanks are given to Mr. Kurt Schimelpfnig of Allied Signal and Mr. Matt Henry of A.C. Rochester for all of their support on catalysts. I would also like to thank Mr. Bill Deitz at Rockwood Airport who allowed me to run up and down his runway even though he knew I would never get off the ground.

I would like to express my appreciation to the mechanical and aerospace engineering faculty for all of the challenges they set before me and my fellow graduate students who through peer pressure forced me to accept them. Thanks especially to the following who gave me substantial amounts of assistance and an occasional harassment.

Mr. Danial Graham
Mr. Gary Hatmaker
Mr. Dennis Higdon
Mr. Stephen Hunley

Mrs. Janine Jennings
Mrs. Betty Carmon
Mrs. Linda Stooksbury

Finally, I would like to thank my wife Julie, my parents Herlie and Sandra, my brother Mitch, and the families of both Julie and myself for all of the love, help, and encouragement throughout the last twenty-three years.

ABSTRACT

Due primarily to environmental concerns, the California Air Resources Board has developed an aggressive series of transitional emission standards for automobiles operating in that state. With many other states following California's lead, a substantial amount of research has been initiated, both by federal and industry leaders, to lower the regulated emissions of production vehicles. One facet of this research focuses on obtaining these low vehicle emissions through the use of an alternative fuel. This study demonstrates that compressed natural gas through some specific engine modifications can be used to meet the 1997 Ultra Low Emission Vehicle (ULEV) standard. An evaluation was performed to determine what effect these modifications had on the performance characteristics of the vehicle.

The conversion vehicle utilized was a 1991 Saturn SL1 sedan dedicated to natural gas operation. This vehicle was modified to use a very small amount of exhaust gas recirculation and a Palladium/Rhodium catalytic converter developed for the natural gas fuel. Utilizing multi-point fuel injection and an exhaust gas oxygen sensor for closed-loop control over fuel metering, an air/fuel ratio providing the highest overall catalytic conversion efficiency was implemented. With this configuration and a detailed analysis of hydrocarbon emissions, the conversion vehicle was found to meet the 1997 ULEV standard.

With these engine modifications, the vehicle was subjected to two types of vehicle energy efficiency evaluations. These tests, in addition to supplying a miles per equivalent gallon (mpge) value, were used to determine a vehicle range estimate. The vehicle was also compared to the gasoline-fueled stock model during two types of vehicle acceleration tests. These different vehicle performance tests demonstrated that the vehicle's energy efficiency increased by 12 to 25 mpge. Yet with this improvement in energy efficiency, the vehicle's range decreased by 200 to 150 miles because of the restrictions on vehicle fuel storage. The vehicle's acceleration was several seconds slower than the gasoline-fueled vehicle but still quite acceptable for a vehicle of this type.

It was shown by this research, through a more precise fuel metering system and emission control devices designed specifically for the natural gas fuel, that the conversion vehicle could meet the California 1997 Ultra Low Emission Vehicle standard. It was also shown that with the engine modifications required for this level

of vehicle emissions, the vehicle's performance characteristics were above acceptable levels and proved to be comparable to the gasoline-fueled model.

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CHAPTER I

PURPOSE OF STUDY

Introduction

Within the past two decades, there has been a social movement in the United States toward environmental preservation. This movement is a result of a combination of economic concerns and the establishment of several processes of environmental destruction. Despite the tremendously positive aspects of the automobile, a significant portion of this movement's concern is fixed on the automobile and the substantial role it plays in society's energy consumption and pollution production [1]. This research examines one of the means for reducing both the environmental and economical concerns associated with the automobile.

Background

Economic Considerations

The United States, through both industrial and private demands for energy, has fostered over the years a dependency on fossil fuels as an energy source. With its overwhelming need and insufficient domestic supplies, the United States has had to import a majority of its fossil fuels from Middle Eastern countries. After the creation of O.P.E.C. and its subsequent control over fossil fuel prices, the United States has come to realize what a threat fossil fuels are to national security. Such a threat has resulted in the involvement of the United States in several military conflicts, the most recent being the 1991 Gulf War.

As a result of the security threat, the United States initiated an effort to reduce its fossil fuel dependency through two different methods. The first entailed a process of reducing its fossil fuel consumption in both industry

and private environments. This process was centered on the technical aspects of energy conservation, but the social implications proved to be the most challenging. With the American people having grown accustomed to their intensive energy consumption, any reduction by this process implied a compromise to their way of life. The U. S. government's urgency in reducing this compromise prompted the promotion of technologies such as solar and nuclear power and the reevaluation of such established operations as wind power and heat engines. However, this reevaluation, still underway, is not presently driven by energy dependency of the country alone. Energy efficiency has been incorporated into many facets of industrial competition and capitalism as a procedure for evaluation and improvement.

The second method involved the development of processes which allowed a domestic fuel to be used as an alternative to those imported. This development has sparked much research over the past two decades particularly in the area of automotive applications. Like the first method, alternative fuel development is not presently driven by the energy security of the country alone. The environmental movement in the United States has recruited the energy dependency problem and the alternative fuel solution into its arsenal of reasons for a reduction in environmental pollution.

Environmental Considerations

Also included in the environmental movement arsenal are two environmental issues in which automotive fuels have been shown to be involved. The first issue is photochemical smog. Automotive fuels were established as a major contributor in the formation of photochemical smog in the Los Angeles area around 1962. Since that time, the process by which smog is produced and its relationship with automotive fuels have been studied extensively and to understand how this study addresses the smog issue, this process should be discussed.

The production of smog results from complex photochemical reactions in which nitrogen dioxide found in the atmosphere decomposes into nitric oxide and an oxygen atom. This oxygen atom (O) then bonds with an oxygen molecule (O_2) forming ozone (O_3). The stable ozone molecule then reacts with nitric oxide returning to the original molecule nitrogen dioxide. Uninterrupted, this chain of reactions will result in no net accumulation of any specie and do nothing but warm the atmosphere. However, in the presence of certain hydrocarbons the final

ozone consuming reaction is interrupted. It has been found that certain reactive hydrocarbons are capable of oxidizing nitric oxide back into nitrogen dioxide. This alternative reaction results in an accumulation of ground level ozone and modified hydrocarbons which comprise the basic elements of smog. The reaction process is shown symbolically in Equations 1, 2, 3, and 4.



The automobile was found to be one of the main contributors to the supply of these reactive hydrocarbons through incomplete combustion and evaporation of its volatile fuel, gasoline [2].

The second environmental issue is the greenhouse effect. Although the relationship between this effect and global warming is poorly understood and not universally accepted, it is soundly based in theory and unfortunately includes automotive contributions. The automobile has been found to contribute a significant portion of the atmospheric carbon dioxide produced by fossil fuel burning [3]. The carbon dioxide molecule is one of the primary greenhouse gases with water vapor, chlorofluorocarbons, and methane being others. A greenhouse gas is defined as an atmospheric gas which absorbs and re-emits downward a large fraction of the long wavelength radiant energy emitted by the earth [4]. This process of energy transfer subsequently increases atmospheric temperatures through "unnatural" means.

Unfortunately, this is not the only way which the automobile contributes to the greenhouse effect. The automobile also produces low concentrations of nitric oxide. This molecule migrates to the upper levels of the earth's atmosphere where it destroys stratospheric ozone. This destruction of ozone has led to the deterioration of the protective atmospheric shield over the polar regions. This allows more radiation from the sun to enter the atmosphere and subsequently more energy to be absorbed by greenhouse gases [4].

Legislative Actions

Concerned by these environmental problems, the American people turned to the government for leadership. In this case, it was a state government which responded. The California Air Resources Board (CARB) was founded in 1948 to confront the increasing smog dilemma in that state [5]. Since that time, CARB has set the standards for air pollution control which the rest of the country has strived to achieve. Some of the most stringent of these standards are, of course, for automotive emissions. It is from these upcoming automotive emission standards, that this research has obtained much its motivation. Table 1.1 demonstrates the upcoming automotive emission standards for the state of California.

Compressed Natural Gas

To meet these environmental standards and in the process alleviate economic concerns, several alternative fuels have been researched extensively. These include ethanol, methanol, liquefied petroleum gas, hydrogen, electricity, and liquified or compressed natural gas. This study will focus on compressed natural gas which is thought of as "the most economic fuel for cleaner air in the near term" [7]. There are several characteristics of natural gas which lead to this belief. The most dominating characteristic deals with the reduced emission of reactive hydrocarbons. This characteristic is due mainly to the fact that natural gas consists of 85 to 99% methane [8]. As a result, a high percentage of any unburned hydrocarbon emitted by engines fueled with natural gas will be methane. Because methane is a relatively inert gas, it will not become involved in the photochemical process of smog production. Even with its high percentage of methane, natural gas does contain more reactive hydrocarbons, but it is believed that many of the reactive hydrocarbons found in the exhaust of natural gas-fueled engines, originate from the lubricating oil [9]. This belief is supported by the measured emission of hydrocarbons during testing of an engine fueled with hydrogen. The use of natural gas also eliminates the so-called "evaporative emissions" of reactive hydrocarbons during vehicle shut-down because of the sealed fuel system required by the gaseous fuel.

As a result of its hydrocarbon emission characteristic, natural gas-fueled vehicles should demonstrate a lower potential for forming photochemical smog. However, natural gas-fueled vehicles' contribution to the green-

Table 1.1 - Future California emission standards [6]

	Transitional Low Emission Vehicle (TLEV) (g/mile)	Low Emission Vehicle (LEV) (g/mile)	Ultra Low Emission Vehicle (ULEV) (g/mile)
Non-Methane Organic gases	0.125	0.075	0.04
CO	3.4	3.4	1.7
NO _x	0.4	0.2	0.2

house effect is not so clean cut. Methane, which makes up a substantial portion of the hydrocarbon emissions, is a very powerful green-house gas with approximately thirty times the warming effect of CO_2 [4]. Fortunately, these emissions are very small relative to the methane production from coal-burning power plants and decomposing organic materials [7]. In fact, some researchers believe that the use of natural gas-fueled vehicles could potentially make up for their small methane contribution through a reduction in other vehicle emissions involved in the green-house effect [10]. Natural gas could potentially offer a reduction in the stratospheric ozone destroying NO emission depending on the control strategy implemented [7]. Table 1.2 shows the carbon content per BTU for several fuels and as it can be seen, natural gas has a relatively low value. Through this property, natural gas should offer a reduction in CO_2 which is the largest green-house gas emission from fossil fuel burning [10].

Natural gas, is not only a "clean" burning fuel, it also has many characteristics which make it a suitable alternative in automotive applications. Natural gas has a motor octane number (MON) ranging from 85 to 135 depending on its composition. At the time of this study, the natural gas in Knoxville, Tennessee had the composition shown in Table 1.3 [13]. Using this composition the MON of the natural gas was calculated to be 133 using the procedure found in Appendix B [12]. This high octane number, as will be discussed in the conversion vehicle description, can be used to increase engine efficiencies. Natural gas also has the ability to burn over a wide range of air/fuel ratios. This characteristic can be used to improve fuel economy and/or vehicle emissions. In addition to its high octane number and burning characteristics, natural gas also offers a better starting characteristic. Since it is gaseous at normal engine operating temperatures, natural gas does not have to vaporize in the engine. This characteristic reduces starting problems which are often experienced with liquid gasoline engines during cold weather. Finally, natural gas offers an economic advantage over gasoline with natural gas being currently priced at approximately \$0.25 per equivalent gallon less than gasoline [7].

Even with these advantageous characteristics, natural gas has several shortcomings compared with gasoline. Natural gas reduces the range of most vehicles because of the way which it must be stored. Natural gas, because of its state, must be held at a very high pressure in order to get an acceptable amount on-board the vehicle. As a result of this high pressure, large, often heavy, cylinders must be used to store the fuel. In the compact packaging of today's vehicles, finding the space to install these cylinders can be difficult. Often these

Table 1.2 - Carbon content per BTU for several fuels [11]

Fuels	C atoms / BTU (1×10^{-30}) *
Octane	6.028
Ethanol	6.018
Methanol	5.685
Natural Gas **	4.829
Methane	4.818

* Calculated with lower heating value at constant volume

** Calculated with Knoxville's current composition

Figure 1.3 - Natural gas composition in Knoxville, Tennessee [12]

Component		Mole %
Hexane	C_6H_{14}	0.062
Propane	C_3H_8	0.453
I-Butane	C_4H_{10}	0.059
N-Butane		0.097
I-Pentane	C_5H_{12}	0.033
N-Pentane		0.028
Carbon Dioxide	CO_2	0.460
Ethane	C_2H_6	2.212
Nitrogen	N_2	0.416
Methane	CH_4	<u>96.18</u>
	total	100

space restrictions mandate the use of smaller cylinders which in return carry less gas. With less gas on board the vehicle, its driving range is inherently shortened.

Another drawback of the fuel, is related to the refueling of a natural gas powered vehicle. The refuelling infrastructure currently in place in the United States is for a liquid fuel. The storage tanks necessary for high pressure gas will require a major reconstruction of current refueling stations. However, supplying gas to such storage tanks would not be difficult. The gas suppliers, similar to electricity suppliers, use a grid of pipelines to distribute the fuel. This grid would allow natural gas to be obtained at almost any potential refueling site in the country. The challenges associated with the delivery and storage of this fuel are beyond the scope of this study and will, therefore, not be addressed.

The subject which will be addressed by this study is the process by which this fuel may be exploited to meet the previously mentioned emission standards. Unfortunately, there have been only a handful of programs which have developed a process that could meet the ultra low emission vehicle standard [14]. Therefore, it is the goal of this study to achieve the following problem statement.

Problem Statement

It will be demonstrated by this research through the utilization of a more precise fuel metering system and an emission control strategy developed specifically for natural gas, that the 1997 California Ultra Low Emission Vehicle Standard can be met in a dedicated natural gas conversion vehicle. With the engine control scheme needed to achieve this emission standard in place, an evaluation will be performed to document the effect of this scheme on the conversion vehicle's energy efficiency, range, and acceleration.

CHAPTER II

THEORETICAL ASPECTS OF THE RESEARCH

The development of a process by which this problem statement can be accomplished begins with the examination of current natural gas emission research. The emission control systems being devised by this research have several non-conventional aspects. To better understand the overall system and its implementation into a dedicated conversion vehicle, each of these aspects needs to be discussed separately and in detail.

Conventional Emission Control System

To emphasize the non-conventional aspects of this research's emission control system, it is first necessary to discuss conventional systems. The emission control system commonly used in production gasoline fueled vehicles consists of four subsystems. These are the fuel metering system, the catalyst, the exhaust gas recirculation (EGR) system, and the evaporative emission control system.

Fuel Metering

The fuel metering system of conventional vehicles operates with an exhaust gas oxygen (EGO) sensor which is used to indicate the stoichiometry from the exhaust stream produced. This relation between input and output allows the fuel metering system to operate under what is called a closed loop control. This means that the engine control module (ECM) can input a prescribed amount of fuel and then monitor the EGO sensor output to measure the effect of that input. It can then correct the fuel input to obtain the desired effect. Therefore, the EGO sensor allows the ECM to operate in a self-correcting or closed loop mode. To understand how it does this, the EGO sensor should be described.

The EGO sensor is a small electrochemical device which produces a voltage signal proportional to the oxygen concentration in the exhaust [15]. This sensor produces a voltage according to the Nernst equation which, as can be seen in equation 5, depends on the ratio of the oxygen partial pressure in air to that in the exhaust.

$$V_O = \frac{RT}{4F} \ln \frac{P_{O_2, AIR}}{P_{O_2, EXH}} \quad (5)$$

When stoichiometric conditions are reached, the oxygen partial pressure in the exhaust decreases by several magnitudes. This partial pressure decrease, in return, causes a significant increase in voltage as can be seen in Figure 2.1. Through engine testing, the oxygen concentrations which result from the combustion of several different fuel stoichiometries are measured. These measurements produce a relation between EGO voltage and fuel stoichiometry, thus allowing the ECM to monitor the EGO voltage and correctly change the fuel input to obtain a certain exhaust composition. It might seem strange that the engine is controlled by this closed loop system to obtain not power or torque, but a certain exhaust composition. It must be remembered that this device is implemented for emission reasons only and its sole purpose is to prepare the exhaust for the next emission control device, the catalyst.

Catalyst

The basic operation of the catalyst is to convert CO, HC, and NO_x in the engine's exhaust by either oxidation or reduction to CO₂, H₂O, and N₂ which are normally found in the atmosphere. The catalyst accomplishes this conversion by exposing the engine exhaust to as many as three noble metals. These metals are dispersed across a very porous alumina base, either in a monolith (honeycomb-like) configuration or in the shape of several thousand small beads, each of which is used to give the catalyst a large surface area. Each pore of this alumina base, which contains a noble metal, is called an activation site. The exhaust gas enters the catalyst and is adsorbed onto these activation sites. While there, the noble metal, given certain conditions, will initiate a reaction causing exhaust constituents to combine or separate into the desired forms. Since the desired

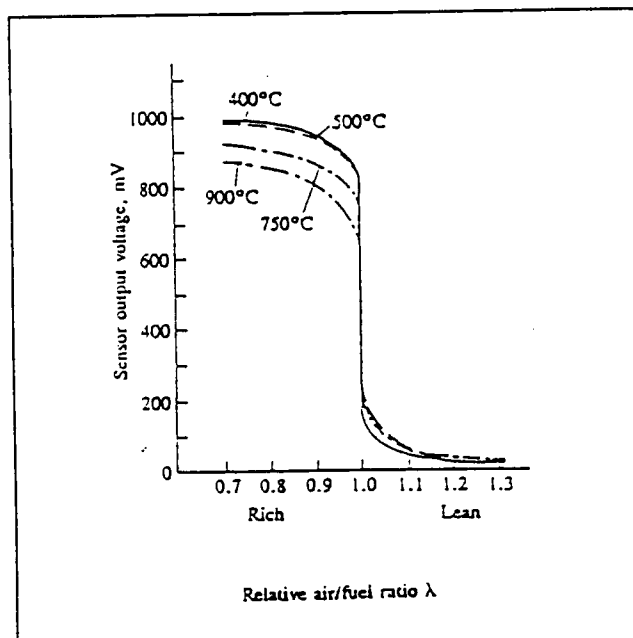


Figure 2.1 - EGO sensor characteristics [15]

reactions depend on the existence of the proper exhaust constituents, the importance of the EGO sensor on catalyst performance becomes apparent.

Although the reactions depend heavily on exhaust composition, they also depend on the noble metals loaded onto the catalyst. The catalyst in conventional systems is comprised of Platinum, Palladium, and Rhodium and is called a three-way catalyst because it converts HC, CO, and NO simultaneously. The HC and CO concentrations are oxidized, meaning that these two species combine with O_2 to form CO_2 and H_2O . The NO concentration must be reduced, meaning that the amount of oxygen bonded to nitrogen must be lowered. Table 2.1 demonstrates these two types of reactions.

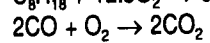
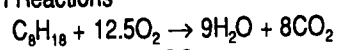
Oxidation and reduction reactions are inherently different. One reaction adds oxygen atoms, while the other reaction removes oxygen atoms. These two opposing oxygen requirements introduce a dilemma in choosing the air/fuel ratio which the vehicle will use for emission purposes. However, this dilemma is overcome through the use of the three noble metals. Platinum and Palladium have very good conversion efficiencies for HC and CO when they operate under oxygen rich or fuel lean conditions. Unfortunately, these two metals have very poor conversion efficiencies for NO at this operating condition. Therefore, Rhodium is introduced into the catalyst loading for its ability to reduce NO at slightly fuel lean conditions. The introduction of Rhodium allows the catalyst to have an optimum three-way conversion efficiency while operating very close to stoichiometric conditions with a slight fuel lean bias. Even though this air/fuel ratio will increase the conversion efficiency of NO over Rhodium, it will not lower NO emissions to acceptable levels in most cases. As a result, exhaust gas recirculation (EGR) is used in conventional emission control systems.

Exhaust Gas Recirculation

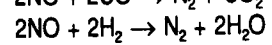
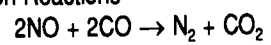
To explain how the exhaust gas recirculation system supplies an additional reduction in NO emissions, the process of NO formation must first be described. It is generally accepted that NO formation occurs by the slow Zel'dovich mechanism shown in Equations 6 and 7 [16].

Table 2.1 - Possible catalyst reactions

Oxidation Reactions



Reduction Reactions





The NO specie formed in automobile engines is believed to follow this mechanism when the combustion temperature obtains a high enough value. Given enough time, the NO specie should dissociate as the temperature drops during the expansion stroke. Unfortunately, the high speed of normal automobile operation does not provide sufficient time and the NO concentration is partially frozen by the process. It has been found that the formation of NO depends on both temperature and the availability of oxygen. As a result, maximum NO concentrations typically occur on the lean side of stoichiometric conditions.

Since temperature is an important factor in NO formation, the exhaust gas recirculation system focuses on lowering this temperature. It reduces this temperature by recirculating a portion of the exhaust gases back into the engine's intake. Because this gas consists of exhaust products, it is comprised of mostly CO_2 , H_2O , and N_2 . These gases are very inert and serve as an energy sink during the next engine cycle. This energy absorption lowers the system temperature and subsequently reduces NO formation. Care must be taken to ensure the amount of EGR used, because if too much is recirculated the combustion could suffer from poor flame propagation and this, in turn, could result in an increase in unburned hydrocarbon emissions from the engine.

The last emission control aspect of conventional gasoline fueled engines deals with the emission of unburned hydrocarbons. Unburned hydrocarbon emissions originate from two different sources. The first is incomplete combustion which expels hydrocarbons into the engine's exhaust system. The second is evaporative emissions which result from the release of unburned hydrocarbons through the evaporation and release of the fuel in its delivery system. Incomplete combustion's contribution of unburned hydrocarbons is taken care of in the catalytic converter. However, the contribution from evaporative emissions will not be dealt with by the fore mentioned conventional emission control devices and therefore needs to be discussed.

Evaporative Emission Control System

Evaporative emissions are comprised of unburned hydrocarbon vapor vented into the atmosphere from the fuel system. Before nationwide control of evaporative emissions in 1971, these emissions per car per day exceeded the emissions found in the exhaust [5]. The control of evaporative emissions is centered around the challenges of sealing the fuel system, providing a holding place for these emissions on the vehicle, and the appropriate disposing of them.

The first challenge has been addressed through the use of sealed fuel tank caps and the redesigning of fuel tank ventilation provisions. The phasing out of carburetors and the entry of fuel injection, has also served in sealing the engine side of the fuel system. Unfortunately, sealing the fuel system merely reinforces the last two challenges of this control system. The emissions, now sealed in the vehicle, must be held and then disposed of safely. This challenge has been addressed through a very unique way of holding the vapor and a very simple way of disposing it. The evaporative emissions from the fuel tank are routed to a canister filled with activated carbon. The carbon adsorbs the hydrocarbons and holds them until the engine is again started. The canister is then purged with air to remove the adsorbed hydrocarbons which are then sent to the engine's air intake, drawn in, and burned. Another type of unburned hydrocarbon emission, originates in the engine itself. This emission is eliminated by trapping the hydrocarbon emission in the crankcase and routing it through the positive crankcase ventilation valve into the air intake. When the engine is started the unburned hydrocarbon emission is drawn into the cylinder and burned.

This type of control system has significantly reduced the amount of evaporative emissions originating from everyday vehicle use. However, another large contributor to evaporative emissions is fuel tank refueling. This includes both the tank in the vehicle and the holding tank at the refueling station. When fuel is pumped into a tank, it pushes out the hydrocarbon enriched air already occupying the space. The size and number of these tanks produce significant hydrocarbon emissions. Therefore, the only way to eliminate evaporative emissions is to use a fuel which requires a completely closed delivery system.

Compressed natural gas not only uses such a sealed fuel system, it also offers properties which could be used advantageously in other emission control aspects. Because the emission control system used in this

research exploits these properties, a brief explanation of them will help in understanding the choices made in the emission control system development.

Natural Gas Conversion Properties

Additional Oxidation Reaction

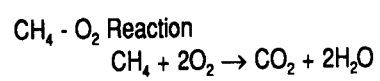
It was discussed earlier that the conversion of gasoline hydrocarbons involves oxidation with O_2 to create H_2O and CO_2 . Thus, to facilitate this oxidation process a gasoline fueled engine should be operated with an oxygen-rich bias. It has been found through testing that the conversion of methane also occurs by the O_2 oxidation process under oxygen rich conditions. However, under oxygen deficient or fuel-rich conditions, methane is converted by two parallel oxidation processes: one involving O_2 and another involving NO [17]. Both reactions are shown in Table 2.2. The second oxidation reaction not only furnishes another means of converting the very unreactive methane molecule, it also gives an additional process by which NO is reduced. This property of methane conversion suggests that a natural gas vehicle should be operated under fuel-rich conditions, however, this is not the only reason.

Adsorption Rate

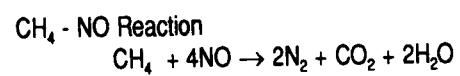
For a catalytic converter to work properly, reactants in the correct proportions must come in contact with the catalyst surface. For instance, if in the $CH_4 - O_2$ reaction only oxygen molecules were allowed to come in contact with the catalyst there would be no reaction. There cannot be a reaction between CH_4 and O_2 if CH_4 is not present. As simple as this thought process may seem, testing has shown that this is often the case and may explain some of the low methane conversion efficiencies reported in the literature. It has been found that under oxygen rich conditions, the critical step in methane conversion is getting the methane to be adsorbed on the catalyst surface [8, 18]. The oxygen molecule has a very fast adsorption rate on noble metals at these conditions, where methane's adsorption rate is rather slow and requires energy [8]. As a result of these differing adsorption rates, when the catalyst is subjected to excess oxygen, the activation sites needed for methane conversion are

Table 2.2 - Oxidation reactions used for catalytic methane conversion

CH₄ - O₂ Reaction



CH₄ - NO Reaction



occupied by only oxygen molecules. In order to get some methane at these activation sites, the two adsorption rates need to be made more equal. This is accomplished by reducing the amount of excess oxygen in the exhaust stream. With fewer oxygen molecules present, the methane molecules become more competitive for the activation sites. With both reactants on the catalyst surface, there is a much higher possibility for the conversion process to be accomplished. The catalyst adsorption rate is not a problem with gasoline-fueled vehicles mainly due to gasoline's large molecular weight [15]. Figures 2.2 and 2.3 show the common relationship between catalytic conversion efficiency and air/fuel ratio for gasoline and natural gas respectively.

Water Reactions

The final property of natural gas which will be discussed is related to the distribution of product species from the oxidation of methane. The oxidation of methane is a very complicated process which is not completely understood. However, several different studies have been performed and compiled to support the following thesis [8]. Methane's chemisorption onto noble metals involves its dissociation into methyl or methylene radicals and hydrogen (H_2). These radicals then react with adsorbed oxygen to form either CO_2 and H_2O or formaldehyde ($HCHO$). This formaldehyde is a small emission component of natural gas combustion, because it does not have time to become a large one [8]. Before formaldehyde is released from the activation sites, it apparently decomposes into adsorbed CO and H_2 [20]. These two molecules are then either released from the activation sites as CO and H_2 or combine with O_2 to form CO_2 and H_2O . The diagram in Table 2.3 depicts methane's oxidation process. From this process, it can be seen that the principal product species for methane oxidation are CO, H_2 , CO_2 , and H_2O . As a result of these specie concentrations, two common reversible reactions need to be examined. These reactions are the water-gas shift reaction and the steam reforming reaction, shown in Table 2.4. As it can be seen, both reactions involve only those molecules found in the exhaust and the impact of each reaction on the final specie concentrations needs to be considered.

The desired direction for the water-gas shift reaction is toward the formation of CO_2 and the consumption of CO. Unfortunately, since there is already a significant concentration of CO_2 in the exhaust the reaction might be driven in the opposite direction. To determine what role this reaction plays, research has been conducted with

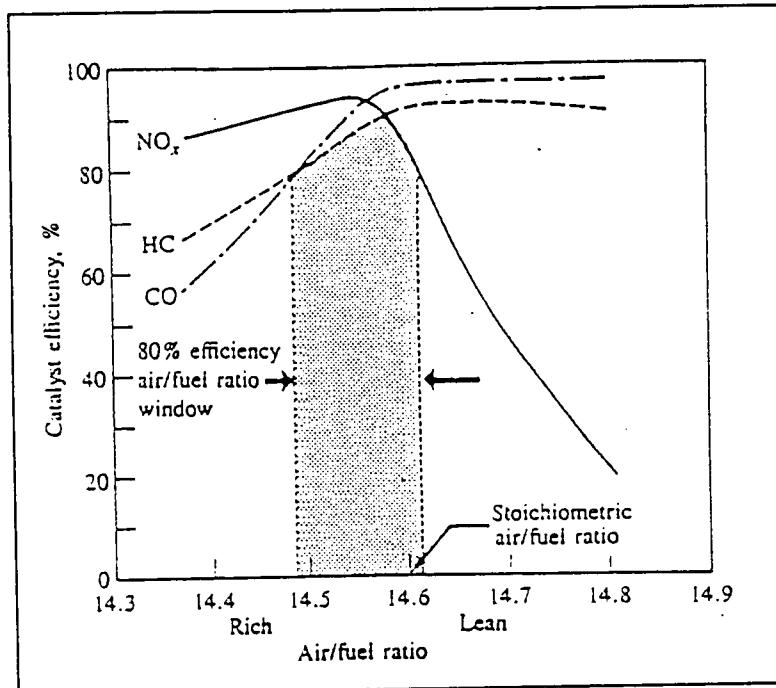


Figure 2.2 - Conversion efficiencies for gasoline-fueled vehicles [15]

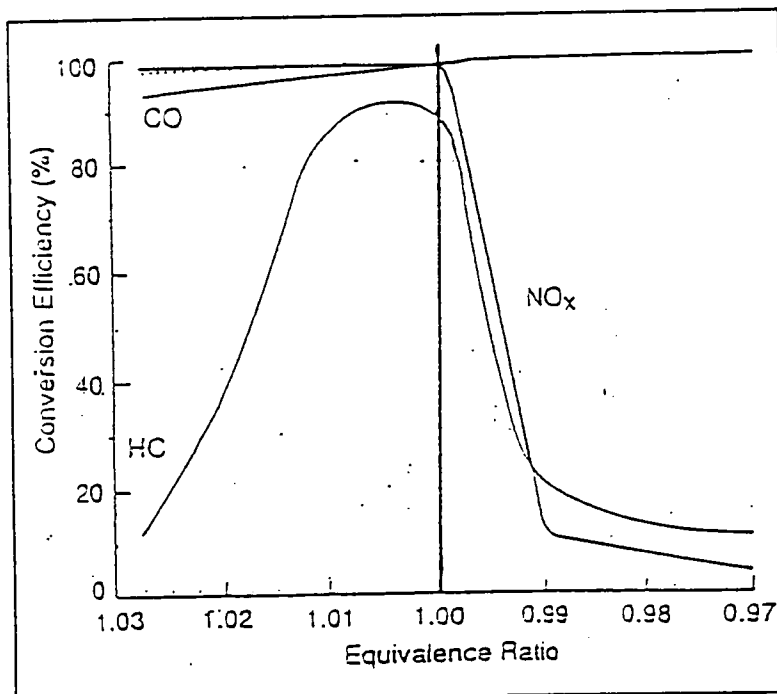


Figure 2.3 - Conversion efficiencies for natural gas-fueled vehicles [19]

Table 2.3 - The oxidation mechanism for methane [8]

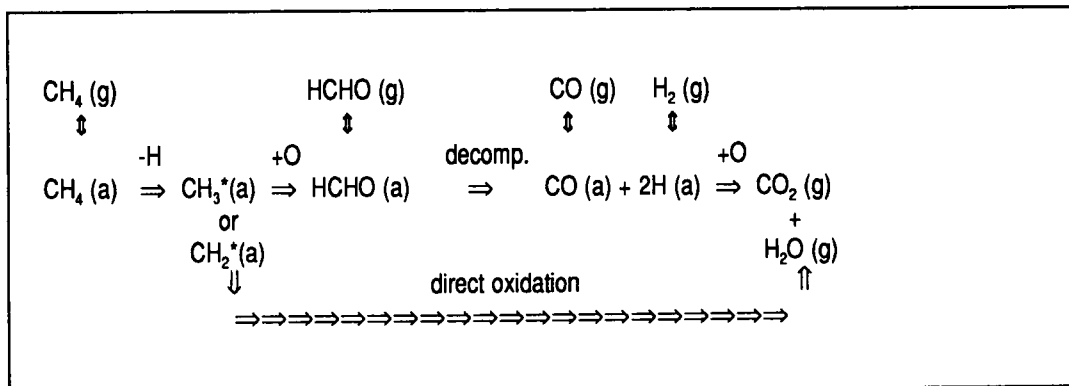
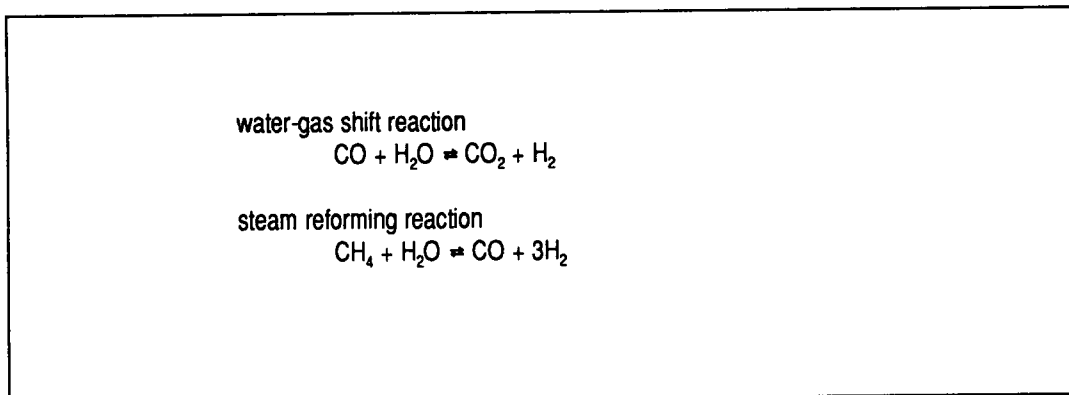


Table 2.4 - Reversible water related reactions [17]



higher than normal concentrations of CO_2 to see if the reaction would indeed produce CO [8]. Under reducing or fuel rich conditions, the water-gas shift reaction did not play a significant role in the concentrations of products for methane oxidation over a Palladium catalyst. However, this reaction did affect the product concentrations when Rhodium was used as the primary noble metal. Following a similar testing procedure, the steam reforming reaction was tested by introducing excess water vapor into the exhaust stream. It was found that the steam reforming reaction assisted in the oxidation of methane in small amounts [21]. Both of these reactions are temperature driven and should play a significant role only at extreme low and high temperatures of the engine's operating range. However, it is under these start-up and transient conditions that emissions are at the highest levels, so these reactions should be kept in mind.

Research Emission Control System

The catalyst which was used in this research consists of only two noble metals; Palladium and Rhodium. Platinum, is normally used in conjunction with these two metals, but is excluded in this application. This exclusion is not only a result of its high cost, but also because of its relatively low conversion efficiency for methane compared with Palladium [22, 15]. It has also been found that Palladium may offer longer catalyst life as testing has shown that the catalytic activity of Palladium actually increases with controlled aging [21]. Because of these two findings, Palladium makes up a majority of the catalyst loading with the remainder being Rhodium. A high loading ratio of Palladium to Rhodium is also desired to offset any possible effects introduced by the water-gas shift reaction.

The next deviation from normal emission control systems was in the fuel metering. In gasoline-fueled vehicles the air/fuel ratio is maintained at or around stoichiometric to obtain the highest catalytic conversion efficiencies. Natural gas-fueled vehicles should use a fuel metering system which delivers a slightly fuel rich mixture to ensure that an adequate adsorption rate of methane on the catalyst surface and to facilitate the additional oxidation reaction by NO at the catalyst surface. It was also anticipated that this fuel rich mixture would also assist methane oxidation through the steam reforming reaction.

The exhaust gas recirculation system of the conversion was not radically different from that of the gasoline-fueled production vehicle. The natural gas fuel should require less EGR than a conventional fuel because of the additional oxidation reaction and the lower peak combustion temperatures associated with methane. However, these two factors were not expected to reduce substantially the NO concentration. Thus, Rhodium was loaded onto the catalyst and EGR utilized as much as the engine's performance would allow.

The fourth subsystem of conventional emission control systems involves evaporative emissions. Since the natural gas-fuel is contained in a sealed fuel system, evaporative emissions from a natural gas fueled vehicle will be by definition zero. However, the release of unburned hydrocarbons may not necessarily be zero. The sealed fuel system of natural gas does eliminate emission of hydrocarbons during high operating temperatures and greatly reduces the release during the process of refueling, but it does not necessarily eliminate emissions at the fuel injectors. Natural gas fuel injectors have a tendency to leak during extended periods of non-operation. This leaking, although not very large, does introduce natural gas into the intake manifold where it can either move back through the air intake system or along the valve stem into the valve cover. Such a small leak may not seem significant, but it can be eliminated very simply. Since natural gas is lighter than air, a correctly designed intake manifold can trap the fuel and hold it until the engine is restarted. By connecting the valve cover to the air intake system, the emissions in the valve cover may be drawn into the engine and burned. By these two modifications, the "evaporative" emissions of a natural gas vehicle can be eliminated.

Dedicated Conversion Vehicle

The vehicle which was used in this study is a 1991 Saturn SL1 sedan converted to dedicated natural gas service by the University of Tennessee and is shown in Figure 2.4. This is powered by an 1.9 liter in-line four cylinder engine with a single overhead cam and multi-point fuel injection. Because natural gas has a high octane rating, the compression ratio of this engine was raised from the production value of 9.8 to 11. This increase in compression ratio was accomplished by the installation of flat-head pistons shown in Figure 2.5. As a result of the flat-head pistons two engine characteristics were changed for the better. First, the clearance volume of each

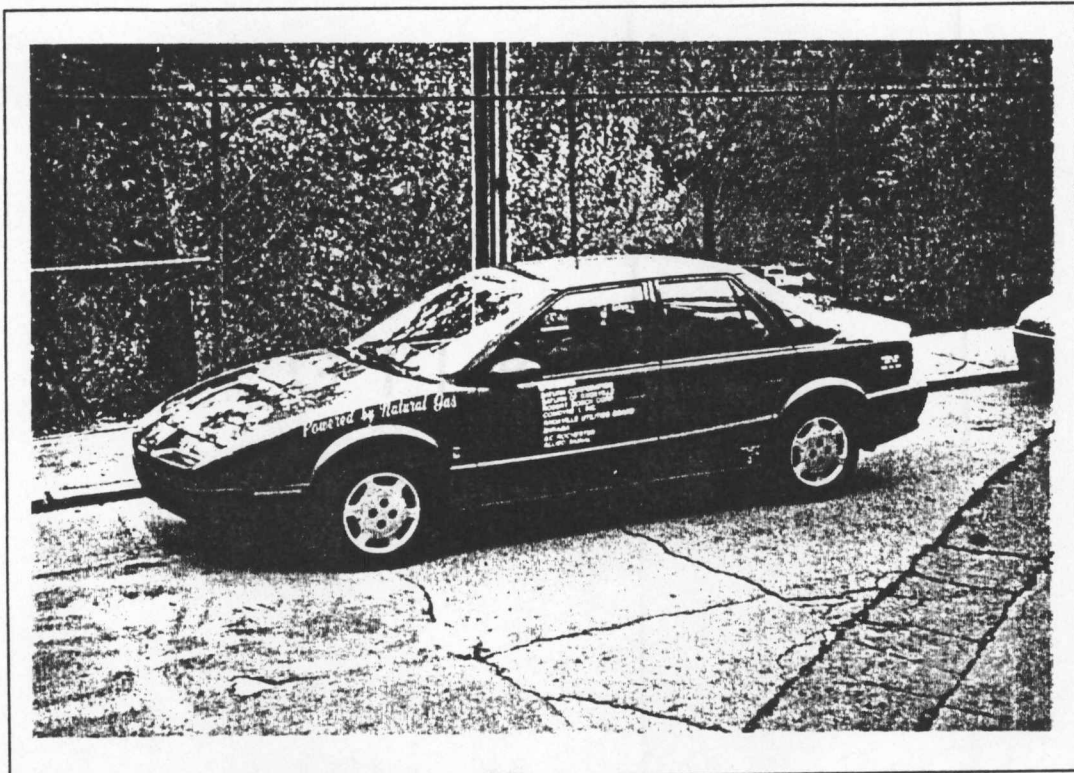


Figure 2.4 - The dedicated natural gas conversion vehicle

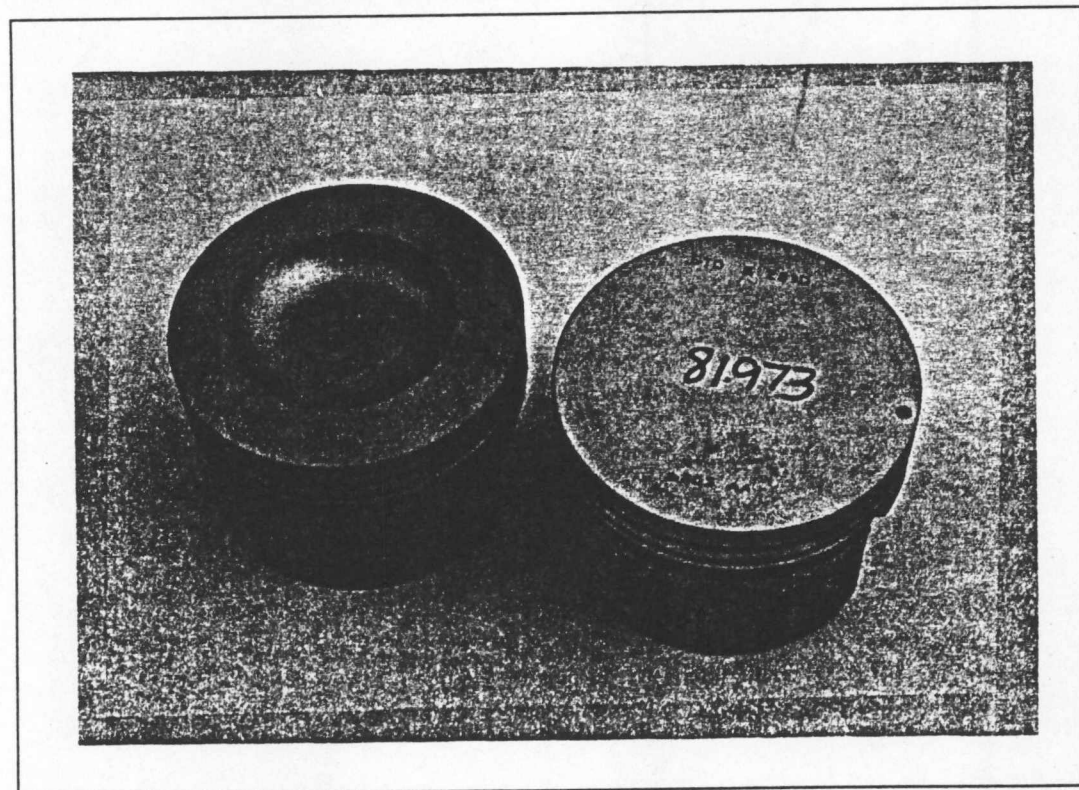


Figure 2.5 - The production vehicle piston compared to the flat-head piston used by the conversion vehicle

cylinder was reduced by 12% which subsequently reduced the amount of exhaust left in the cylinder after each engine event. This engine characteristic increased engine efficiencies by two processes. The smaller clearance volume facilitates a higher volumetric efficiency and does so through the following means. When the exhaust valve closes, the cylinder pressure in most cases has not fallen to atmospheric and the pressure in the cylinder is therefore higher than the pressure in the intake manifold. When the intake valve opens, the exhaust flows into the intake manifold. After the pressures equalize the drawing motion of the piston pulls this exhaust, mixed with fresh charge, back into the cylinder. By reducing the amount of exhaust initially found in the cylinder's clearance volume, less exhaust is drawn back into the cylinder. If a smaller mass of exhaust is being drawn in then a larger mass of fresh charge must be drawn in to replace it, thus increasing the volumetric efficiency of the engine [15]. The amount of power produced by an engine depends on the amount of mixture which can be inducted into the cylinder. By increasing the volumetric efficiency, more mixture is inducted and consequently more power is produced.

This larger amount of inducted air leads to the second process by which a reduction in clearance volume increases engine efficiency. By having more mass of combustible mixture in the cylinder and the same displaced volume, this mass must be at a higher pressure at the end of the compression stroke. This pressure increase raises the brake mean effective pressure on the piston which is equivalent to the brake power produced [11].

The second engine characteristic changed for the better with the installation of flat-head pistons, deals with the type of air flow. Studies have shown that pistons, which produce a lower surface area to volume ratio in the cylinder, reduce the turbulence of the air flow into the cylinder [24]. This reduction in turbulence results in a smaller heat transfer rate between the hot cylinder walls and the incoming air/fuel mixture. This smaller heat transfer rate lowers the air/fuel mixture's temperature and consequently allows more mixture to be drawn into the cylinder. With more air/fuel mixture inducted, the volumetric efficiency increases and consequently so does engine power. The effects of a smaller ratio of surface area to volume was listed by Beau de Rochas as one of the conditions for increasing engine efficiencies as early as 1862 [15]. Through these efficiency increases, the induction problems related with natural gas should be overcome and the performance of the conversion vehicle should closely approximate the gasoline-fueled model [14, 23].

CHAPTER III

PROCEDURE

With the necessary emission control system and the dedicated conversion vehicle described, the procedure for achieving the problem statement can be discussed. This procedure was logically broken down into three stages each depending somewhat on the successful achievement of the previous. The first stage dealt with the examination of the conversion vehicle's current engine control program and the determination of what changes had to be made for the successful implementation of an emission control system. The second pertained to the actual implementation of the emission control system. The final stage was the evaluation of the conversion vehicle's performance characteristics. This chapter will discuss each stage of the procedure. Included in the discussion of each stage will be a brief description of the equipment used. Appendix F contains further equipment details.

Stage One - ECM Evaluation

Upon initiation of the research, there was a great deal of uncertainty related to the air/fuel ratio being delivered by the engine's fuel metering system. This uncertainty was believed to originate in the imprecise calibration procedure used in the ECM's installation. With natural gas' wide range of combustible air/fuel ratios and this imprecise calibration procedure, the possibility that the conversion vehicle's current engine control program was delivering a stoichiometric mixture seemed very minute. Therefore, to implement any type of selective fuel metering system for emissions, the air/fuel ratio which the conversion vehicle was using under closed loop control had to be determined. To understand how this was accomplished, a description of the fuel metering system used by the conversion vehicle is necessary.

Original ECM Fuel Metering System

The engine control module in the conversion vehicle is the Total Engine Controller II (TEC2) produced by Electromotive Incorporated. The TEC2 controls both the engine's ignition system and the fuel metering system. It delivers the correct amount of fuel through a process of calculating a base enrichment and then adding to or subtracting from this enrichment to accommodate special operating requirements. The TEC2 obtains the base fuel enrichment from two different parameters programmed in its memory. The first is called the raw fuel curve and it is basically a linear curve fit between the fuel injector pulse width at wide open throttle to the pulse width at idling conditions. As might be expected, this linear curve does not satisfy the idiosyncrasies of the engine at different operating conditions. This mandates the second parameter in the base enrichment which is the volumetric efficiency look-up table. This table consists of corrective supplements or restrictions to the fuel enrichment at different combinations of manifold air pressure (MAP) and engine speed (RPM). Both of these parameters combine to give a base enrichment which theoretically should be very close to what the engine needs under normal operating conditions. However, to lower vehicle emissions, the TEC2 monitors an EGO sensor as discussed earlier and makes corrective changes to this base enrichment.

The following summarizes the process which the TEC2 undergoes to deliver fuel. The TEC2 reads the manifold air pressure sensor and the engine speed sensor. It takes this MAP reading to the raw fuel curve and obtains the pulse width needed for the fuel injector. The TEC2 then inputs the MAP and RPM into the volumetric efficiency table to obtain the necessary change in the pulse width for that particular operating condition. The TEC2 then opens the fuel injector for this pulse width and fuel enters the combustion chamber. If the controller is in closed-loop operation, it will then read the EGO sensor voltage. The TEC2 compares this voltage to the EGO switch-point voltage, which is defined as the voltage specifying the switching-point from rich to lean engine mixtures. If these two voltages do not correspond, the TEC2 will introduce an EGO step enrichment supplement or reduction to trim the pulse width. If this pulse width does not introduce the correct amount of fuel and the engine's operating conditions have not changed significantly, the TEC2 will trim the pulse width further. This process will continue until one of three possible results has occurred: a set trim limit is reached, the desired EGO voltage is obtained, or the engine operating conditions significantly change.

This system introduces two questions: Does the EGO trimming have enough authority to insure the delivery of the desired air/fuel ratio under normal operating speeds? Within this authority, is the EGO switch-point voltage currently programmed into the TEC2 delivering a stoichiometric air/fuel ratio?

Air/Fuel Ratio Evaluation

When the converted vehicle was used for this research, it had undergone an extensive conversion process in which the fuel metering system had been calibrated for a particular EGO switch-point voltage. It was assumed that the EGO step enrichment had sufficient authority at this particular EGO switch-point voltage. The unanswered question was, "What air/fuel ratio did this particular EGO switch-point voltage provide?" To answer this question the following procedure was followed.

The air/fuel ratio is predominantly set through the two base enrichment parameters. However, given a sufficient length of time where these two parameter do not change, the EGO step enrichment will achieve and maintain the desired EGO switch point voltage. The conversion vehicle was transported to the Environmental Protection Agency's (EPA) emission testing facility at Research Triangle Park, North Carolina. While there, the vehicle underwent a procedure to determine the relationship between the EGO switch-point voltage and the air/fuel ratio. First, the catalytic converter was removed and a straight pipe fitting was put in its place so that engine-out emissions could be measured. Figure 3.1 shows this fitting. Next, the EGO switch-point voltage was set to a starting value. While on a chassis dynamometer, the conversion vehicle was accelerated up to a speed of 30 mph and held there. The real time vehicle emissions of CO, total HC, and NO were then monitored. When these emissions reached steady state values, each was recorded. The vehicle was stopped, the EGO switch-point voltage changed, and the procedure repeated. The specie concentrations at each EGO switch-point voltage were then plotted and compared to published charts such as that found in Figure 3.2. This figure demonstrates that when the engine's air/fuel ratio is varied, engine-out emission concentrations follow a very characteristic shape. The CO concentration undergoes a very explicit change when stoichiometry is passed along a fuel lean to fuel rich path. This almost exponential increase in CO concentrations was used to approximate stoichiometric conditions to be around an EGO switch-point voltage of 4.1 in the resulting data plot shown in Figure 3.3.

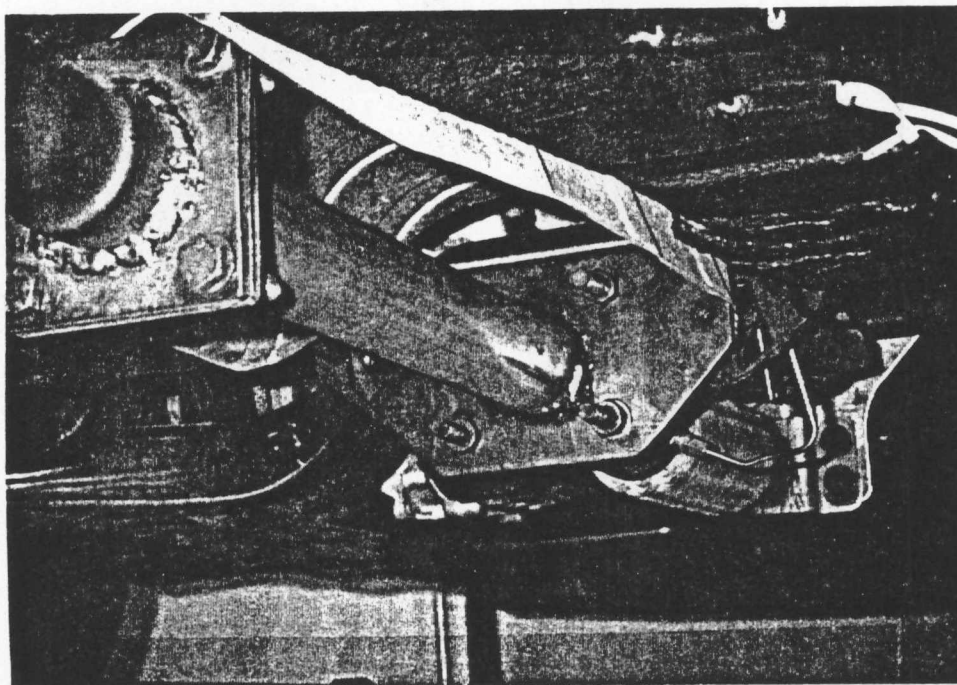


Figure 3.1 - Straight-pipe fitting used to sample engine-out emissions

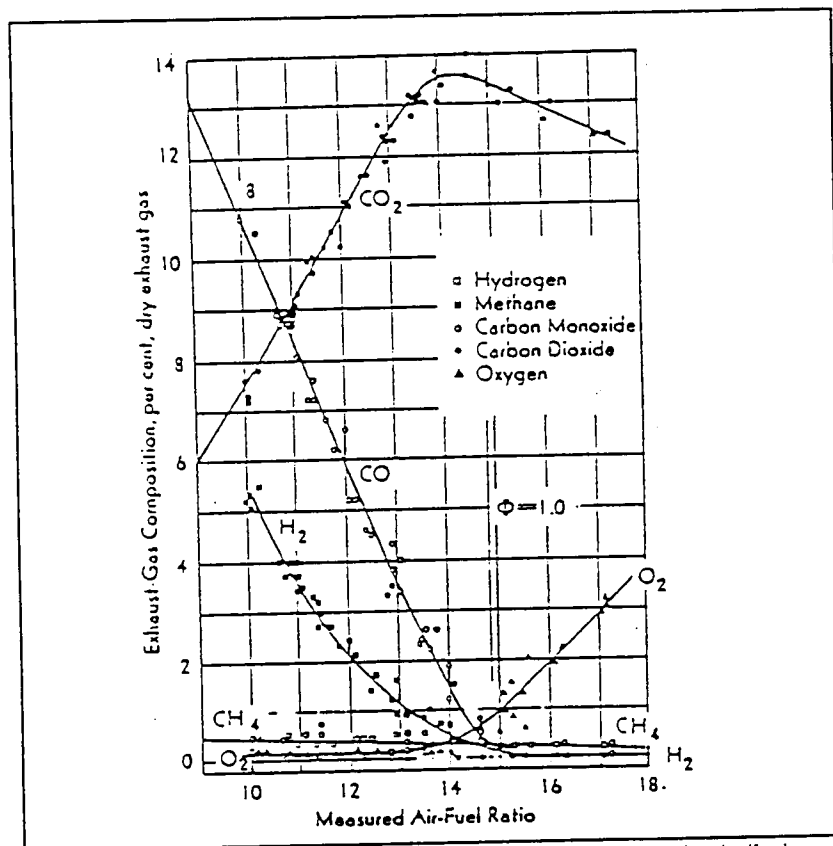


Figure 3.2 - Variation of exhaust species concentrations with air/fuel ratio (fuel C_8H_{17}) [11]

Air/Fuel Ratio Approximation

EGO Switch-point Voltage vs Exhaust ppm

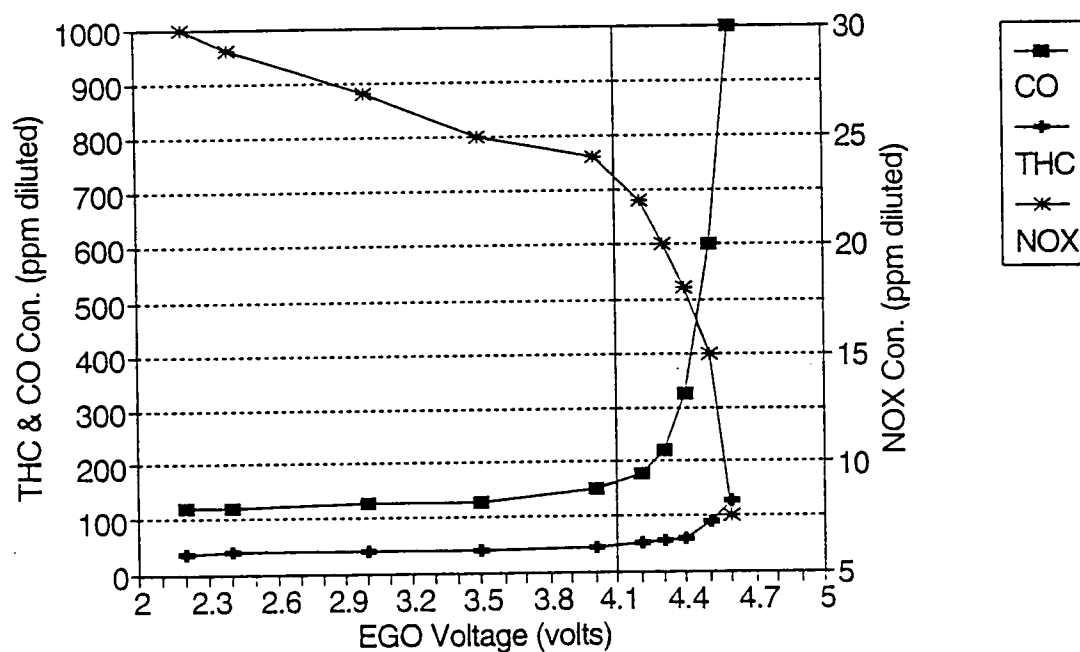


Figure 3.3 - EGO switch-point voltage versus diluted engine-out exhaust species concentrations

Exhaust Gas Recirculation Evaluation

During the initial inspection, it was found that the conversion vehicle did not have an operating EGR system. The conversion vehicle had a linear EGR valve on the engine and the TEC2 offered a means to control it, but neither were being utilized. Therefore, the first step in implementing an EGR system was to provide a suitable connection between these two devices. A linear EGR valve is basically a pulse-width modulated controlled solenoid that uncovers an opening between the intake and exhaust manifolds. To supply this pulse modulation, the General Purpose Output (GPO) port of the TEC2 was used. This driver samples the RPM and the MAP sensors and then uses these values to read a user-adjustable look-up table which supplies a percent duty cycle. The percent duty cycle in this case represents the amount which the valve is open. For example, if the percent duty cycle is set at 10 then the valve will be open ten percent of the solenoid's total travel. To allow the GPO to drive the linear EGR valve, a circuit had to be constructed which supplied sufficient current for the solenoid while protecting the TEC2. A schematic of this circuit is found in Appendix E.

The EGR control system which the circuit provided now had to be calibrated. This was accomplished by first substituting an extra EGR valve for the one found on the engine. This was done because, for soon to be obvious reasons, the vehicle had to be running for this calibration. The EGR valve to be calibrated was then connected to the driving circuit and held in such a manner that the solenoid could be observed. The GPO look-up table was then filled with zeros, so that at any operating condition of the engine, the EGR valve should have been closed. The engine was started and no motion was observed in the EGR valve solenoid. Then using a GPO offset parameter in the TEC2 heads-up display, the duty cycle for the GPO was increased above zero incrementally. When the solenoid began to move, the offset was recorded as the actual zero percent duty cycle. The GPO table was then set at all one hundreds and the procedure was repeated to find the upper bound duty cycle. It was found that the valve did not begin to open until a GPO duty cycle of 16% was reached and was open completely at a duty cycle of 65%. The determination of the values used in the GPO look-up table is described in the next section.

Stage Two - Research Emission Control Installation

Catalyst Installation

The first emission control device to be installed was the Palladium/Rhodium catalyst. The catalyst consists of two monoliths made of an alumina ceramic impregnated with noble metals, referred to as bricks, and the monolith's stainless steel canister, referred to as the can. The bricks were designed and manufactured by Allied Signal specifically for a natural gas fueled emission system. Both bricks were identical in shape, type 110GM OVAL, and each had a noble metal loading of one part Rhodium to every ten parts Palladium. The can used was the model produced by AC Rochester for the Saturn production vehicle. This model was chosen to insure an acceptable fit in the very molded underbody of the vehicle. The bricks were sealed into the can by AC Rochester using the normal production procedure. This was done to prevent the cracking of the brick during thermal expansion of the can and to eliminate any exhaust gases from passing around the brick. To obtain a leak-free fit and to simplify the installation and switching processes, the catalyst can ends and the conversion vehicle's exhaust system were modified according to the specifications shown in Appendix E.

Exhaust Gas Recirculation Installation

With the EGR valve and the TEC2 connection made, the difficult process of filling the GPO look-up table for the conversion vehicle was undertaken. To acquire a look-up table with which to start, a production vehicle look-up table was examined and mimicked. The conversion vehicle was then placed on a chassis dynamometer and the calibration procedure found in Appendix C was performed. While on the dynamometer, the vehicle was driven through a prescribed driving cycle. This procedure was achieved through the use of an X-Y plotter which was fitted with a pin that had no ink and a time driver which moved the inkless pin across the x-axis at a set velocity. The y-axis of this plotter was connected to the analog velocity output of the dynamometer. Next, a velocity versus time plot of the driving cycle was produced, using spreadsheet software, for the chosen time driver speed. This plot was then placed on the X-Y plotter and the inkless pin was centered on the plot's origin. By starting the time driver and then accelerating or decelerating the vehicle on the dynamometer rolls, the inkless pin

was made to follow the line on the speed versus time plot. By using this X-Y plotter set-up, a driving cycle could be driven repeatably for different EGR look-up table settings.

This set-up to repeat the same driving conditions allowed the driver to subjectively determine when the EGR became detrimental to the vehicle's power by observing when the vehicle could no longer keep up with the driving cycle. By manipulating the production vehicle based EGR look-up table, the EGR settings listed in Appendix A were tested and one was chosen which provided a small amount of NO_x reduction without significantly affecting vehicle power. This final set of GPO duty cycles is shown in Table 3.1.

Evaporative Emission System Installation

Upon inspection of the conversion vehicle it was found that an acceptable evaporative emission system was already in place. The conversion vehicle engine was equipped with a prototype intake manifold, which was shaped in such a way to trap and hold the escaping, lighter-than-air fuel. The original production vehicle's air intake system was fitted with a tube which connected it to the valve cover. Therefore, the conversion vehicle engine was already configured in such a way as to eliminate both processes of "evaporative" emissions.

Fuel Metering System Installation

According to the research described earlier, to obtain the highest overall conversion efficiency in the catalyst the engine should be operated with a fuel rich bias. However, most of the research which supports this statement was performed on a bench flow reactor and the amount of research performed on an engine not at steady state did not necessarily call for such a bias [17, 14]. Therefore the air/fuel ratio required for this study was not very apparent and needed to be experimentally determined.

To obtain the desired air/fuel ratio, the vehicle was taken to the EPA emission testing facility and subjected to a procedure of driving cycles. This procedure was basically a trial and error method, where an EGO switch-point voltage was chosen and an emission test was performed. The results of this emission test were then examined and based on this examination a new EGO switch-point voltage was chosen and the process repeated. The only open decision was the initial EGO switch-point voltage with which to start. It was decided that a good

Table 3.1 - Exhaust gas recirculation look-up table

KPa	Percent Duty Cycle							
100	16	16	20	25	30	25	20	20
85	16	16	27	32	37	32	27	27
75	16	16	30	35	40	35	30	30
65	16	16	25	30	35	20	25	25
55	16	16	20	25	30	25	20	20
45	16	16	16	20	25	20	16	16
35	16	16	16	16	20	16	16	16
25	16	16	16	16	16	16	16	16
RPM	400	900	1600	2000	2500	3000	4000	5000

starting place would be an EGO switch-point voltage resulting in a rich bias. Therefore the specie concentration versus EGO switch-point voltage plot produced earlier was examined and a rich value of 4.3 was chosen. A Federal Testing Procedure (FTP) emission cycle was performed and the results shown in Table 3.2 were examined. These results were attributed to an excessively fuel-rich mixture and therefore suggested that the EGO switch-point voltage should be lower. With only limited testing time available at the EPA facility, a plan of action was devised. It was decided to bracket the desired value by performing another FTP at an EGO switch-point value which should be excessively fuel lean. Then with a series of shorter HOT505 emission cycles, EGO switch-point values between these two extreme cases would be examined. From this examination, an EGO switch-point value would be chosen and a FTP cycle performed at it to verify its performance. To better understand how these two cycles were compared and why the FTP was chosen initially, a brief description of both is in order.

The Federal Testing Procedure is the cycle on which California and Federal emission standards are based and as such it is used in this research as the primary measurement of emissions. The FTP consists of three phases in which emissions are sampled and a ten minute soaking section during which the vehicle is not operating. Each phase is slightly different and is labeled after the bag which samples the emissions produced during the phase. The first phase is 505 seconds long which starts with the engine cold and is called a COLD505. The second phase is 890 seconds long, and is a continuation of phase one. After the completion of this phase, the engine is turned off and the 600 second soak is performed. The third phase is the same as the first with one difference. In this phase the engine is already hot, so it is called a HOT505. Because the COLD505 requires an overnight soak of the vehicle, after an FTP has been performed the only phase that can be tested on that day is the HOT505 phase. However, since the third phase of the FTP is a HOT505, the emissions of these shorter phases could be used to evaluate the EGO switch-point settings.

Table 3.2 - FTP emissions resulting from an EGO switch-point voltage of 4.3

		Bag 1	Bag 2	Bag 3	Weighted

HC	(grams/mile)	1.54	0.06	0.36	0.448
NOX	(grams/mile)	0.06	0.00	0.02	0.017
CO	(grams/mile)	4.75	2.74	2.19	3.005
CO2	(grams/mile)	195	224	188	208.4

Stage Three - Conversion Vehicle Performance Evaluation

Vehicle Emissions

Through the procedure for tuning the fuel metering system, the emission testing of the vehicle was primarily accomplished. There was only one small detail omitted and it is introduced by the high methane content of natural gas. Because methane is not currently regulated by federal standards, the EPA facility does not distinguish between methane and non-methane hydrocarbons during the FTP testing cycle. As a result, the exhaust concentrations used in the fuel metering system installation was based on total hydrocarbons (THC). As stated earlier, the ULEV standard is based on non-methane concentrations, so these total hydrocarbon values could not be used for conversion vehicle's emission values.

The differentiation between hydrocarbons can only be performed by examining the actual bag emissions. This examination is complicated by the very low emission level of the ULEV standard and the effects that methane has on the testing equipment. Therefore, it takes a significant amount of laboratory time to determine accurately the percent of the total hydrocarbons which is methane. As a result, these concentrations must be received several weeks after the initial testing and to incorporate these finding into the FTP results some values must be recalculated. An example of this recalculation is shown in Appendix B. With these recalculate values, the conversion vehicle's emissions could be compared against the ULEV standard.

At this point in the research procedure, the vehicle modifications used for the achievement of the first part of the problem statement, the meeting of the ULEV standard, have all been implemented. Now the part of the problem statement which evaluates the vehicle's performance characteristics must be addressed.

Vehicle Energy Efficiency

This first vehicle performance characteristic investigated was energy efficiency. It is designated as energy efficiency instead of fuel economy because natural gas, as any gas, will expand to occupy all of its container's volume. Therefore, as the fuel is consumed during engine operation the volume which it occupies does not change. This introduces a problem when fuel consumption must be determined. The conventional unit

for this measurement is miles per gallon (mpg), but the volume, if measured in this case, could never change.

Thus, to measure fuel consumption in a manner which would allow comparison with conventional vehicles, a new unit called miles per gallon equivalent (mpge) must be used. This unit is a relation between the energy released by the gaseous fuel to a volume of gasoline which if burned would release the same amount of energy.

Consequently, the performance characteristic is called energy efficiency because the definite quantity measured is energy and any fuel economy measurement entails assumptions on the properties of gasoline.

To calculate the energy released, the heating value of the fuel and the mass of fuel burned had to be determined. The heating value of the natural gas was determined using a program created by Mr. Norm Malcosky of Columbia Gas System Service Corporation which accounts for different gas compositions, as well as, the compressibility of the fuel. Because the fuel was gaseous, the mass measurement depended on the fuel's temperature and pressure throughout the consumption process. To measure the temperature of the gas, four type T thermocouples were placed throughout the fuel supply system. A single thermocouple was placed on each of the exposed aluminum ends of the tank, while another measured the ambient temperature of the vehicle's trunk where the tank was located. The fourth thermocouple was placed on the stainless steel tubing in the engine compartment where the pressure transducer was located. This electronic pressure transducer was located on the higher pressure side of the regulator and because there were no obstructions between the regulator and the tank, the transducer was assumed to measure the tank pressure. To make sure there was no change in the fuel's temperature between the tank and the transducer, the fourth thermocouple was compared to the one located on the valve end of tank. By using the Campbell 21X data acquisition system program shown in Appendix D, it was possible to repeatably sample these readings during the consumption of fuel by a driving procedure.

The driving procedure called the exhaustion cycle consisted of driving the vehicle at a constant speed until the engine stopped running. To avoid traffic obstructions and to maintain a constant speed, this cycle was conducted on the relatively flat 19.8 mile loop made by I-40 and I-640 in Knoxville, Tennessee between the hours of 8:00 and 11:00 PM. The average speed of the vehicle and the total distance traveled, were measured using a Datron DLS non-contact speed and distance sensor. This sensor began taking measurements when the vehicle reached 55 mph and stopped when the vehicle came to a halt. From this distance reading and the mass

consumed, calculated from the data acquisitions temperature and pressure measurements, the energy efficiency could be calculated. This procedure was repeated three times to insure accurate readings.

Before any data could be reduced, the accuracy of the instruments had to be evaluated. The thermocouples were checked by wall mounted thermometers when the vehicle was at room temperature. When it was operating, the thermocouples were checked through additional hand-held thermocouples. The pressure transducer was checked during the refueling process. The refueling stations at Knoxville Utility Board (KUB) are designed with two valves. The first valve is at the hand-held refueling nozzle. The second is mounted on a post upstream from both the first valve and a pressure gauge. With this configuration shown in Figure 3.4, the hand-held valve could be opened while the second valve was left closed and the tank pressure could be read on the mounted pressure gage. Through reading this gauge and the vehicle's pressure transducer during several refueling operations, the deviation of the transducer reading from the linear relationship, called for by the manufacturer, could be seen. By fitting a line to these data points, a correction equation was developed for the transducer reading. This resulting curve can be seen in Figure 3.5 and the correction equation can be seen in Appendix A.

The temperature and pressure readings from the driving procedure were used to calculate a mpg value for the conversion vehicle. The first part of this process involved taking all of the pressure data points for a particular run and performing a curve fit. Using this curve equation, the beginning and ending pressures for that run were approximated. These starting and stopping pressure values were then read into the previously mentioned correction equation obtaining the actual tank pressures. The temperature of the fuel at the cycles start and end were approximated by taking the average of two tank end readings. With the starting temperature and pressure and the stopping temperature and pressure, the program created by Mr. Malcosky was again used. This program, after being fed the gas composition, took one set of temperature and pressure readings and calculated a V/V_0 value. This value is the ratio of the volume which the gas at the given temperature and pressure would occupy if it were allowed to expand to standard temperature and pressure to the actual tank volume. By multiplying this ratio by the tank volume and the density of the gas at standard temperature and pressure, the mass of fuel was obtained. After this was performed for both the starting and stopping values, their difference or

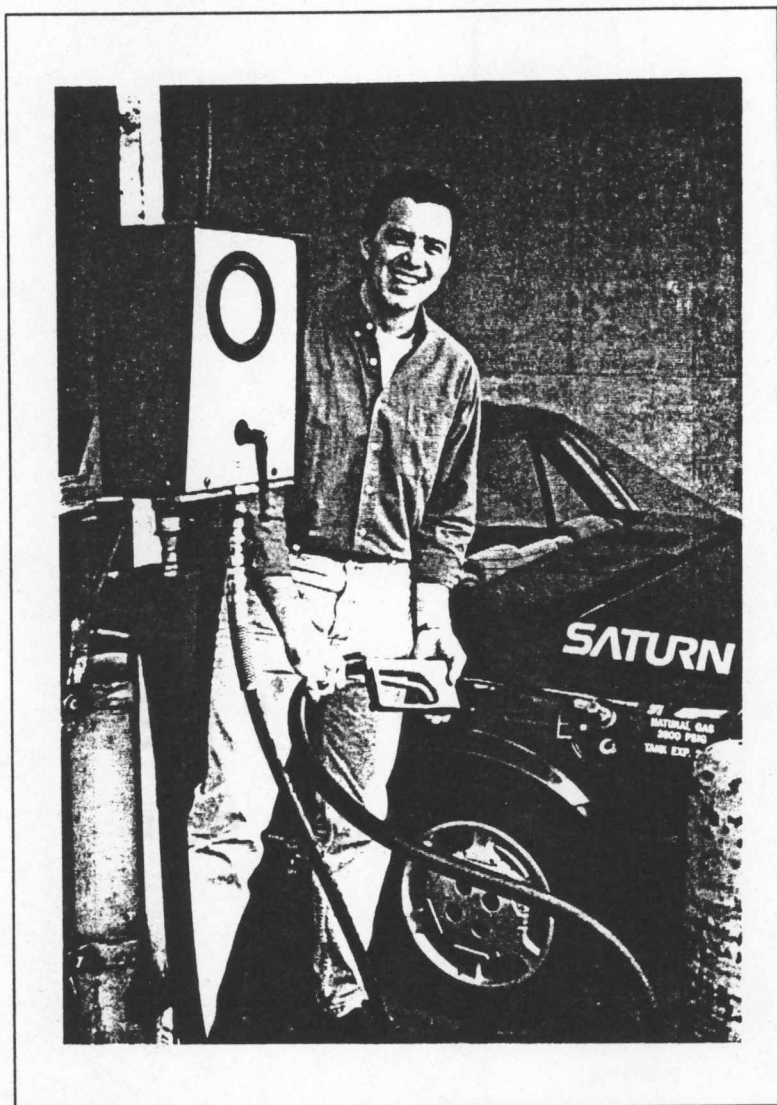


Figure 3.4 - Refueling station configuration used to calibrate the pressure transducer

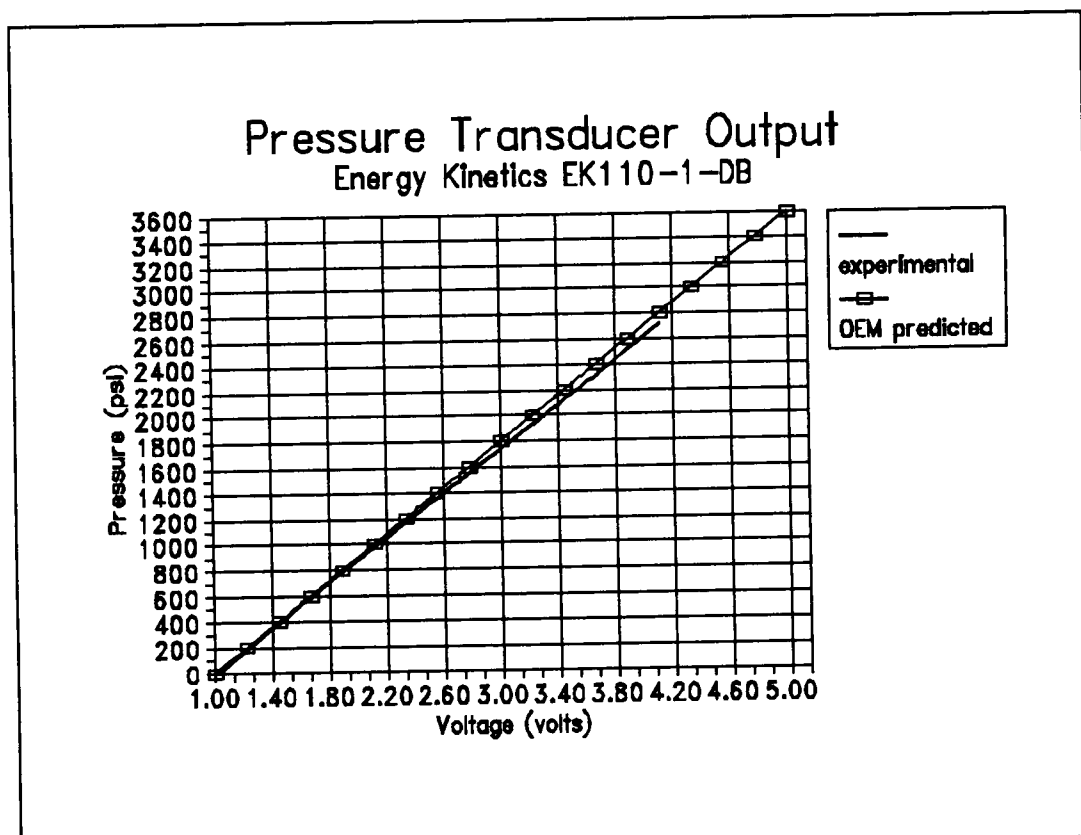


Figure 3.5 - Pressure transducer correction curve

the mass consumed over the duration of the cycle was found. Multiplying this value for mass consumption by the calculated heating value, the energy released was determined. This quantity of energy was then converted to equivalent gallons of gasoline using a heating value of 1.18×10^6 (BTU/gal) and used to divide the distance traveled resulting in miles per gallon equivalent [15]. The data sheets, along with an example of this calculation and its assumptions, are displayed in Appendix A & B. This process was repeated for each of the three sets of samples.

The energy efficiency was also measured during emission testing through the use of highway fuel economy test (HWFET) cycle. Instead of using tank temperature and pressure to approximate the mass consumed, this test uses a unique procedure. This HWFET measurement actually counts the number of carbon atoms leaving the vehicle through the use of exhaust gas analyzers. By knowing the number of carbon atoms in the fuel, the amount of fuel consumed throughout the cycle can be determined. By measuring the distance traveled by the driving cycle and knowing the amount of fuel consumed, the mpge value is very simply calculated.

Vehicle Range

The second vehicle performance characteristic evaluated was vehicle range. This characteristic was calculated by determining the amount of energy which the conversion vehicle was capable of holding and using the energy efficiency value previously determined. Using Mr. Malcosky's program the V_o / V value for the fuel at the maximum tank pressure of 3600 psig was found. This number was multiplied by the tank volume and density of the fuel at atmospheric conditions to obtain the mass of fuel in the tank. This value was multiplied by the heating value also determined by Mr. Malcosky's program to give the amount of energy found in the tank. Converting this energy value into equivalent gallons of gasoline and dividing the vehicle's energy efficiency in mpge by this number of equivalent gallons, the range of the vehicle was determined. A sample of this calculation is shown in Appendix B.

Vehicle Acceleration

The final vehicle performance characteristic evaluated was acceleration. This evaluation was performed by subjecting the conversion vehicle and an equivalent gasoline-fueled Saturn to two different types of acceleration tests and comparing the results. The first type of acceleration test was a 0 - 60 mph run. The throttling during this testing was steadily applied and repeatably positioned to wide open throttle. The shifting was done by predetermining rpm shift points and shifting at these points through monitoring the tachometer. The 0 - 60 mph run is a very common measurement of acceleration and power. However, because of the shifting and throttling involved, it is very dependent on driver repeatability. As a result the second type of acceleration tests performed consisted of 30 - 40 mph runs. This type of test involved bringing the vehicle up around 29 mph and into third gear. The vehicle was then held at this speed for a few seconds to allow the engine to settle and equalize its momentum. The throttle was then depressed opening the throttle completely. This procedure should have taken a majority of shifting and throttling error out of the measurement and have allowed a good comparison across that particular engine range.

Before performing these tests, the vehicles were first examined to insure each had the same engine type, gearing ratio, and weight. They were then taken to Rockwood Airport where the acceleration runs were performed along a runway. The runway had some slight inclines, but was believed to be flat enough for a good comparison. The speed was measured using the Datron speed sensor described in Appendix F. It started at either 0 or 30 mph, recorded time, distance, speed, and acceleration every one mile per hour change, and stopped at either 60 or 40 mph. Ten sets of samples were taken for each type of acceleration and for each vehicle. These time samples were then studied for any inconsistencies, resulting from driver error or runway grade, and then averaged. The data, recorded by the speed sensor during these runs, is displayed in Appendix A.

CHAPTER IV

RESULTS AND DISCUSSION

Problem Statement Evaluation

Fuel Metering System Installation

Using the procedure of bracketing the desired air/fuel ratio and using shorter emission testing cycles to locate this ratio, proved to be difficult. The first EGO switch-point voltage chosen was 4.3. This setting produced high CO emissions and was assumed to be too fuel-rich. As discussed in the procedure, it was decided to pick an excessively lean value. The EGO switch-point voltage of 4.0 was chosen and at initial observation had seemingly failed the ULEV standard for hydrocarbons. As a result, it was believed that this value was not fuel lean enough, so a group of HOT505 cycles were run from 4.2 past 4.0 to 3.9. Unfortunately, upon inspection of these results, no logical progression of emissions was observed. This was believed to be caused by the testing procedure, which lacked the 10 minute soak period and the vehicle cranking found in third FTP bag.

Therefore, returning to the assumption that the voltage of 4.0 was too fuel-lean, an EGO switch-point voltage of 3.9 was programmed and a FTP cycle performed. This value failed the ULEV standard for hydrocarbons by a larger amount than the 4.0 run. This increase in hydrocarbon emission was assumed to be a result of the proposed decline in catalysis' conversion efficiency with leaner mixtures. Thus, the desired air/fuel ratio had indeed been bracketed by the 4.0 EGO switch-point voltage and since the 4.0 voltage had come so close to passing the standard the only existing voltage which the vehicle could possibly pass the standard with was 4.1. However, the FTP cycle to support this deduction had to wait till after the mandatory overnight soak, so two HOT505 cycles were run without a catalyst at voltages of 4.0 and 3.9 paying very close attention to the 10 minute soak period and the cranking of the vehicle in each cycle. These two cycles, along with an previous 4.3 voltage cycle, would be used to calculate the conversion efficiency of the catalyst whichever of the three voltages was

chosen. After the designated soak period, the conversion vehicle was reprogrammed with the 4.1 voltage and tested. It too failed the ULEV standard, however by comparing the NO_x emission of the three FTP cycles it was seen that the 3.9 and 4.1 cycles had very close to the same value, while 4.0 had a much higher value. This insinuated that the 4.0 EGO switch-point value was near stoichiometric and since it came the closest to passing the ULEV standard, it was kept as the correct value. The regulated emission reports for each of these cycles are found in Appendix A.

Vehicle Emissions

As it appeared in the regulated emission reports, the conversion vehicle had not passed the ULEV standard. However, if the types of hydrocarbons are examined as explained in the procedure, it can be seen that the conversion vehicle does indeed meet the ULEV standard with a EGO switch-point voltage of 4.0. Table 4.1 summarizes the regulated emission report and the corrected emissions for this FTP cycle. Table 4.2 summarizes the conversion efficiencies calculated using the HOT505 / FTP bag 3 comparison.

Vehicle Energy Efficiency

The energy efficiency determined by the exhaust tests are shown in Table 4.3. These values reveal an average increase in "fuel economy" from the gasoline-fueled vehicle's 37 mpg to the conversion vehicle's 49 mpge. The final evaluation of energy efficiency was conducted during emission testing. Although the EGO switch-point voltage of 4.0 was not used for this evaluation, the voltages of 3.9 and 4.1 were evaluated. These two EGO switch-point values resulted in very similar energy efficiency values. The 3.9 voltage delivered 64 mpge, while the 4.1 voltage delivered 62.5 mpge. Therefore, it is logical to assume that the EGO switch-point voltage of 4.0 will deliver something inbetween, say 63 mpge. This value is considerably higher than the value calculated by the fuel exhaust driving cycle. This difference can be attributed to the somewhat unrealistic operating conditions of this testing procedure. If a gasoline-fueled Saturn SL1 sedan was also subjected to this test it was achieve 50.9 mpg. With either of the conversion vehicle's energy efficiency calculations, a significant improvement over the gasoline-fueled vehicle is seen.

Table 4.1 - Emissions Report for an EGO voltage of 4.0

		Bag 1	Bag 2	Bag 3	Weighted	ULEV
HC	(grams/mile)	2.05	0.04	0.44	0.56	
NMHC	(grams/mile)	0.13	0.01	0.01	0.034	0.04
NOX	(grams/mile)	0.14	0.15	0.08	0.13	0.2
CO	(grams/mile)	5.14	0.7	1.02	1.69	1.7
CO2	(grams/mile)	192	223	173	203	---

Table 4.2 - Conversion efficiencies for different EGO switch-point voltages

	EGO Switch-point voltage		
	3.9	4.0	4.3
THC	85.2%	85.8%	84%
NO _x	82%	95%	98.6%
CO	98%	90%	86%

Table 4.3 - Energy efficiency results

	Test	#1	#2	#3	Gasoline Saturn
Exhaustion Cycle (mpge)		48.94	49.04	50.24	37
Emission Testing HWFET (mpge)		63.5			50.9

Vehicle Range

The range of the conversion vehicle with a 3600 psig charge of fuel was calculated to be 245 miles with the energy efficiency determined by the exhaustion cycle and 315 miles with the energy efficiency determined from emission testing. These values do not come close to equaling the gasoline-fueled vehicle's range of approximately 445 to 610 miles. The conversion vehicle at it's highest possible tank pressure can only carry the equivalent to five gallons of gasoline. Therefore, this smaller vehicle range should be expected. Figure 4.1 gives a graphic comparison between the conversion and the gasoline-fueled vehicles.

Vehicle Acceleration

The results from both acceleration tests are shown in Table 4.4. The 0 - 60 mph times may seem a little slow especially for the gasoline-fueled vehicle. It must be remembered that both vehicles were driven by an untrained driver and may not reflect results found in professional publications. The 0 - 60 mph time difference of 4.8 seconds, demonstrates that the conversion vehicle does not have the power of the gasoline-fueled model.

If the 30 - 40 mph acceleration runs are examined it can be seen that the gasoline-fueled vehicle was approximately half of a second faster than the conversion vehicle. This test may give a more accurate evaluation of vehicle power and suggests that the two vehicle's power production are closer than previously thought. However, it must be kept in mind that although the throttling and shifting error was removed by this test, the rpm range which this acceleration run was across may have suited one vehicle's tuning more than another. In any case, it can be seen that, although the conversion vehicle has inferior power to the gasoline-fueled model, it does have acceptable power for a vehicle of this class.

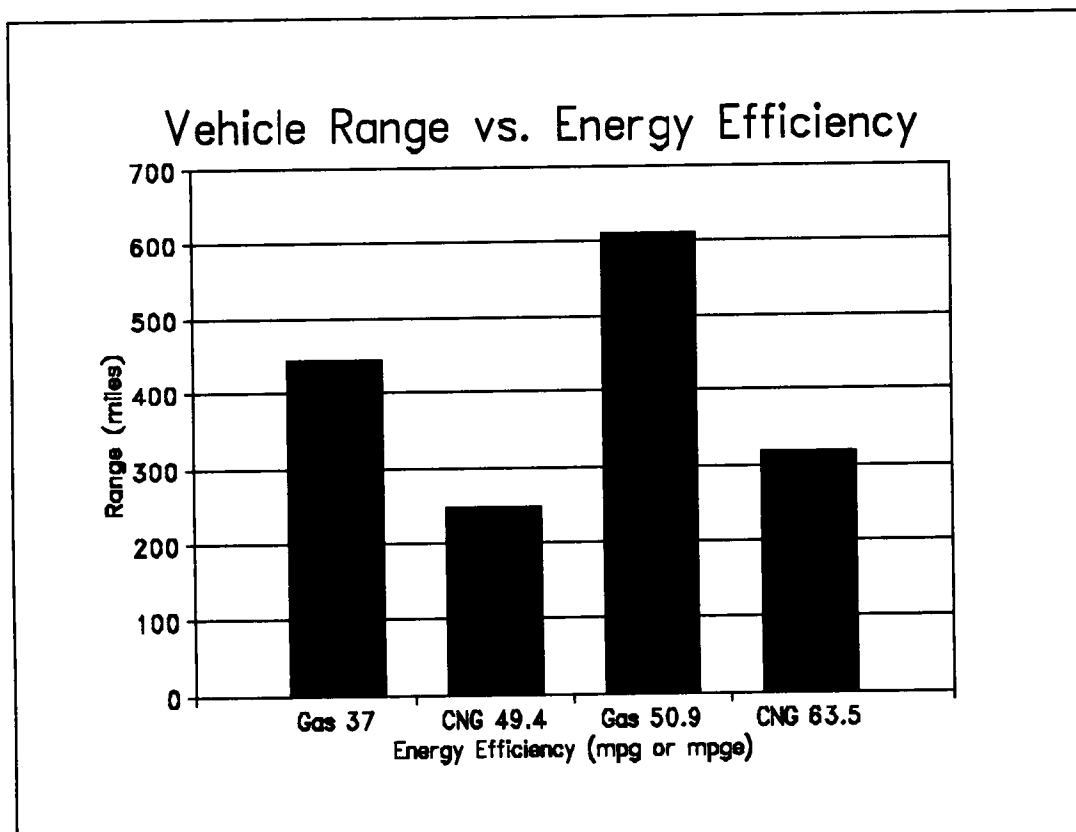


Figure 4.1 - Conversion vehicle range estimates

Table 4.4 - Vehicle acceleration results

		0 - 60 mph Test	30 - 40 mph Test
Conversion Vehicle	Time (sec)	19.2	4.67
	Distance (ft)	1131	238.4
Stock Vehicle	Time (sec)	14.4	4.03
	Distance (ft)	805	204.7

Follow-up Evaluation

Volumetric Efficiency Table Evaluation

After the EGO switch-point voltage for this research was found, it was decided to evaluate what effect this new voltage had on the EGO step enrichment's authority. To formulate a procedure for this evaluation, the two actions which are capable of increasing the EGO step enrichment authority need to be discussed. The first action is to enlarge the size of the EGO step enrichment supplement or reduction. This action is not recommended because it could induce engine stumble at operating points where a change is not required. Therefore, to maintain consistent engine operation the step size should be kept as small as possible. The second action is to calibrate the volumetric efficiency table so that it makes the correct change in the raw fuel curve, reducing the need for any EGO initiated action. By using this action, the authority of the EGO step enrichment could be increased without any detrimental effects. If this increase in authority affects the speed at which the correct amount of fuel is delivered, then it can be concluded that the combination of the new EGO switch-point voltage and the old volumetric efficiency look-up table was affecting the EGO step enrichment authority. The following procedure describes how this process was accomplished.

This procedure began by placing the vehicle on a chassis dynamometer and accelerating it up to a desired engine speed. At this point, the dynamometer was used to change the load on the engine by simulating a grade or hill. This additional load would require a throttle change to maintain the desired engine speed. This throttle change, in return, resulted in an increase in the engine's manifold air pressure. Through using this procedure it was possible to obtain and preserve a desired engine speed and a manifold air pressure value, the two input parameters of the volumetric efficiency table. The EGO sensor was then monitored using the TEC2's heads-up display to see if it was switching from rich to lean. If the sensor was switching rapidly, it was assumed that the volumetric efficiency table was making the correct changes to the raw fuel curve allowing the EGO sensor, with a small step enrichment, to oscillate around stoichiometry. If the sensor was not switching rapidly, an enrichment offset parameter in the heads-up display was set and the resulting effect on the EGO sensor monitored. This offset value was changed until the desired switching of the EGO was observed. This offset value

was then recorded for the particular engine speed and MAP values being evaluated. This procedure was repeated for several RPM and MAP combinations. Upon completion, these enrichment offset values were used to correct the volumetric efficiency table. The data sheets for this procedure are found in Appendix A.

The resulting volumetric efficiency table is shown in Table 4.5. It is noted from this table, that most of these values are negative or a fuel reductions. This may be attribute to the raw fuel curve used by the TEC2 which in this case seems to be slightly rich. Therefore, many of these negative values are required to get the air/fuel ratio closer to stoichiometric. The remainder of the negative values are a result of rounding the offset values. These values were rounded down because, It was found through bench flow reactor testing, that the conversion of methane in a catalytic converter is dependent on the enrichment direction. When a closed loop fuel control was operated from fuel lean to fuel rich, a substantial increase in methane conversion was found around stoichiometry [22]. Thus, by rounding down or more negative, the small correction which the closed loop system was required to make would be in a productive direction.

Final Air/Fuel Ratio

Although it was not the objective of this research to prove the that a fuel-rich bias is required for high catalytic conversion efficiency, it would be interesting to see if the final air/fuel ratio did indeed have this bias. To measure the air/fuel ratio, it was apparent that means of measuring the air and fuel flow rates into the engine were needed. The air flow rate was measured using a mass air flow sensor which is very common in General Motors vehicles. This sensor basically operates as a hot-wire anemometer, meaning it measures the flow of air across a wire by measuring the amount of energy required to keep the wire at a particular temperature. This energy measurement is converted to a frequency counted and recorded by the data acquisition system. Through the use of a calibrated curve, this frequency was then converted into grams of air per second. The fuel flow rate was initially measured using a variable area flow meter or rotameter. This meter was found to be too difficult to read because of the oscillatory nature of fuel flow. As a result, the fuel flow rate was measured using the data acquisition system, the configuration of thermocouples, and the pressure transducer discussed earlier. By operating the vehicle for a specific amount of time, the mass calculated from these measurements was

Table 4.5 - Volumetric efficiency look-up table

KPa	Gamma							
100	0	0	-.12	-.12	-.12	-.12	-.13	-.13
85	0	0	-.11	-.11	-.11	-.12	-.12	-.12
75	0	.01	-.1	-.1	-.1	-.11	-.11	-.11
65	0	.02	-.084	-.084	-.09	-.1	-.1	-.1
55	0	.03	-.067	-.067	-.08	-.09	-.09	-.09
45	0	.04	-.05	-.06	-.07	-.08	-.08	-.08
35	0	.05	0	-.02	-.03	-.03	-.04	-.04
25	0	.05	.05	.03	.02	.01	0	-.01
RPM	400	900	1600	2000	2500	3000	4000	5000

manipulated into a fuel flow rate. The air flow rate was then divided by the fuel flow rate giving the air/fuel ratio.

To make this evaluation of air/fuel ratio correspond to the evaluation performed with exhaust gas analyzers, a similar procedure was performed. First the vehicle was placed on a chassis dynamometer. The EGO switch-point voltage was set at a 3.8 volts and down loaded to the TEC2. Using the dynamometer/driver interface developed earlier, the vehicle was brought up to 30 mph and held there. The data acquisition system, reading the air flow rate and the mass of fuel consumed, was initiated and allowed to run for 360 seconds or the equivalent of three miles. The vehicle was decelerated and a new EGO switch-point voltage was installed. This procedure was performed six times with the EGO switch-point voltage being changed by one tenth each time. Upon completion, the mass air flow frequency was averaged and multiplied by 360 seconds. The mass of fuel consumed over the 360 second interval was approximated using the same procedure as in the energy efficiency evaluation. The ratio of these two numbers was then calculated to obtain the air/fuel ratio. The data sheets from these runs are displayed in Appendix A.

Before revealing the results of the air/fuel ratio calculations, the emissions of the conversion vehicle should be more closely examined to see what air/fuel ratio they imply. It has already been established through engine-out emissions, that stoichiometric conditions are around an EGO switch-point voltage of 4.1. Therefore, NO_x production should be rather constant through the 3.9 to 4.1 range. However, if NO_x emissions in the FTP cycles are examined, it can be seen that concentrations at 4.1 and 3.9 are very close to the same while the NO_x concentration at 4.0 is significantly lower. This implies that more NO_x is being converted at the EGO switch-point value of 4.0, possibly due to the additional reaction in methane's oxidation.

In Table 4.2's list of conversion efficiencies, it can be seen that the efficiencies for total hydrocarbons at the 4.0 and 3.9 voltages are very near the same. However, if the bag analysis is examined, a large difference in methane concentrations can be seen at these two voltages. It may also be noticed from this analysis, that the methane concentrations at EGO switch-point voltages of 4.0 and 4.1 are near the same. These observations demonstrate that while total hydrocarbon conversion is somewhat constant, the methane conversion across this voltage range increases. In fact, it seems to level off between the 4.0 and 4.1 EGO switch-point voltages, implying the highest conversion efficiency for methane to be somewhere inbetween.

From both the NO_x and HC concentrations in the exhaust, the highest conversion efficiencies should be obtained at an EGO switch-point voltage between 4.0 and 4.1. Table 4.6 shows the air/fuel ratios resulting from different EGO switch-point voltages. Using these ratios and the stoichiometric air/fuel ratio, calculated from the specified concentrations of natural gas in Knoxville, equivalency ratios were determined for each EGO switch-point voltages. From this evaluation, stoichiometric conditions should be between the EGO switch-point voltages of 4.0 and 4.1. Therefore, the highest conversion efficiencies for the conversion vehicle was obtained at stoichiometric conditions. This result contradicts previous research which found that the highest overall conversion efficiencies for natural-gas fueled vehicles are obtained from fuel rich operation.

This contradiction raises the question of the accuracy in the air/fuel ratio measurement. However, unlike the energy efficiency, temperature gradient induced error was not experienced in the air/fuel ratio measurement. It was overcome through a very simple and coincidental action. The ambient air temperature in the engine laboratory was raised to 85 degrees allowing the tank to be soaked overnight. Because it was already at elevated temperatures, the tank temperature did not change throughout the testing procedure. This resulted in very accurate mass approximations and thus accurate air/fuel ratio calculations. The air/fuel ratios at EGO switch-point voltages of 3.9 and 4.2, were inaccurate because they were performed last after ambient room temperatures had changed substantially.

Therefore, the air/fuel measurements were accurate, however, there is another inaccuracy which the contradiction can be attributed. The volumetric efficiency enrichments were found, through the previous evaluation, to be rich at the 4.0 EGO switch-point voltage. At constant load operation of the air/fuel ratio evaluation, the EGO closed-loop control had the authority to reduce this enrichment to stoichiometric. However, at transient conditions, such as those experienced during a FTP emission cycle, this error in the volumetric efficiency table might possibly translate into a fuel rich bias. This error induced bias allows the emissions obtained at the EGO switch-point voltage of 4.0 to agree with previous emission research.

Table 4.6 - Final air/fuel ratio measurements

EGO Switch-point Voltage	Air/Fuel Ratio	Equivalence Ratio
3.8	16.13	0.987
3.9*	16.18	0.99
4.0	16.22	0.993
4.1	16.36	1.001
4.2*	16.5	1.01
4.3	16.63	1.018
Stoichiometric	16.34	
* approximated values		

CHAPTER V

CONCLUSIONS

During emission testing, it was demonstrated that by changing the EGO switch-point voltage by as little as one tenth of a volt, the exhaust composition was significantly altered. From this it can be concluded that a precise fuel metering system is necessary for ultra low emission levels. It was also shown that under certain conditions the conversion of exhaust species was improved by the non-conventional emission control system. From this, it can be concluded that a dedicated natural gas vehicle requires an emission control system designed specifically for its fuel.

While delivering fuel in a manner which improves emissions through a non-conventional emission control system, it is important to monitor vehicle performance to insure that it is not damaged significantly by this process. It was shown through two types of driving procedures that the energy efficiency of a natural gas vehicle can be increased above that of a gasoline-fueled vehicle. However, even with this higher energy efficiency, the conversion vehicle significantly shorter driving range. By performing two types of acceleration tests, it was shown that through a few engine modifications a dedicated natural gas vehicle can provide acceptable levels of power. Through these findings, it can be concluded that what a dedicated natural gas vehicle might lack in power, it makes up for in energy efficiency.

By combining all of these findings, it is concluded, that a dedicated natural gas vehicle, through the use of a precise fuel metering system and an emission control system designed specifically for natural gas, can meet the 1997 Ultra Low Emission Vehicle standard and do so with an acceptable loss in vehicle performance.

CHAPTER VI

RECOMMENDATIONS

Through the results of this research, it can be seen that dedicated conversion vehicles, with the necessary modifications, offer a tremendous potential in reducing the environmental pollution from automobiles. To fully realize this potential, additional emission testing of the conversion vehicle is recommended. This emission testing should address two questions. First, what effect does the improved volumetric efficiency enrichment table have on emissions and the EGO switch-point voltage at which the lowest occur? Second, what effect does EGO switch-point voltage have on exhaust specie conversion in the catalyst? Both questions offer a significant challenge, but through a carefully planned emission testing procedure, each can be answered.

Another recommendation is the reevaluation of the constant gear, wide open throttle acceleration test. By choosing a different or larger speed range, the error introduced by vehicle tuning may be alleviated, giving a better power evaluation. It is believed that if these recommendations are fulfilled, the conversion vehicle's operating conditions will approach that found by emission research and its power production will approach that of the gasoline-fueled model.

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APPENDICES

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APPENDIX A1 - EGR Calibration Data

EGR Calibration Program #1

GENERAL PURPOSE OUTPUT TABLE								
KPA	DUTY CYCLE (PERCENTAGE)							
100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
85.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
75.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
65.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
55.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
35.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPM	400	800	1600	2000	3000	4000	5000	6000

EGR Calibration Program #2

GENERAL PURPOSE OUTPUT TABLE								
KPA	DUTY CYCLE (PERCENTAGE)							
100.0	0.0	0.0	45.0	50.0	55.0	50.0	45.0	45.0
85.0	0.0	0.0	40.0	45.0	50.0	45.0	40.0	40.0
75.0	0.0	0.0	35.0	40.0	45.0	40.0	35.0	35.0
65.0	0.0	0.0	30.0	35.0	40.0	35.0	30.0	30.0
55.0	0.0	0.0	25.0	30.0	35.0	30.0	25.0	25.0
45.0	0.0	0.0	20.0	25.0	30.0	25.0	20.0	20.0
35.0	0.0	0.0	0.0	20.0	25.0	20.0	0.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPM	400	800	1600	2000	3000	4000	5000	6000

APPENDIX A1 - EGR Calibration Data**EGR Calibration Program #3**

GENERAL PURPOSE OUTPUT TABLE								
KPA	DUTY CYCLE (PERCENTAGE)							
100.0	0.0	0.0	50.0	55.0	60.0	55.0	50.0	50.0
85.0	0.0	0.0	45.0	50.0	55.0	50.0	45.0	45.0
75.0	0.0	0.0	40.0	45.0	50.0	45.0	40.0	40.0
65.0	0.0	0.0	35.0	40.0	45.0	40.0	35.0	35.0
55.0	0.0	0.0	30.0	35.0	40.0	35.0	30.0	30.0
45.0	0.0	0.0	25.0	30.0	35.0	30.0	25.0	25.0
35.0	0.0	0.0	0.0	25.0	30.0	25.0	0.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPM	400	800	1600	2000	3000	4000	5000	6000

EGR Calibration Program #4

GENERAL PURPOSE OUTPUT TABLE								
KPA	DUTY CYCLE (PERCENTAGE)							
100.0	0.0	0.0	40.0	45.0	50.0	45.0	40.0	40.0
85.0	0.0	0.0	35.0	40.0	45.0	40.0	35.0	35.0
75.0	0.0	0.0	30.0	35.0	40.0	35.0	30.0	30.0
65.0	0.0	0.0	25.0	30.0	35.0	30.0	25.0	25.0
55.0	0.0	0.0	20.0	25.0	30.0	25.0	20.0	20.0
45.0	0.0	0.0	0.0	20.0	25.0	20.0	0.0	0.0
35.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPM	400	800	1600	2000	3000	4000	5000	6000

APPENDIX A1 - EGR Calibration Data**EGR Calibration Program #5**

GENERAL PURPOSE OUTPUT TABLE								
KPA	DUTY CYCLE (PERCENTAGE)							
100.0	0.0	0.0	25.0	30	35.0	30.0	25.0	25.0
85.0	0.0	0.0	30.0	35.0	40.0	35.0	30.0	30.0
75.0	0.0	0.0	30.0	35.0	40.0	35.0	30.0	30.0
65.0	0.0	0.0	25.0	30.0	35.0	30.0	25.0	25.0
55.0	0.0	0.0	20.0	25.0	30.0	25.0	20.0	20.0
45.0	0.0	0.0	0.0	20.0	25.0	20.0	0.0	0.0
35.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0
25.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
RPM	400	800	1600	2000	3000	4000	5000	6000

APPENDIX A2 - HOT505 Regulated Emission Cycle With EGO = 4.3

ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

7/1/1994 10:55

EPA Run = 32074 Cycle = HOT505 Test Date = 6/30/94 2:00
Driver/Operator = WW/VM Test Cell = A-CFV
Program = UT Test Temperature = 75
Fuel = CNG1
EPA Vehicle ID = SA4206
Odometer Reading = 0.0
Comment = W/O Catalyst
Barometric Pressure = 757.2
Relative Humidity = 68.8

Regulated Emission Report RE32

BAG 1

VMIX Cubic Feet	5677.00
Dilution Factor	37.23
Fuel Economy in Miles/Gallon	37.61
Test Distance in Miles	3.58

HC PPM	86.99
HC Grams	8.06
HC Grams/Mile	2.25

NOX PPM	15.60
NOX Grams	5.15
NOX Grams/Mile	1.44

CO PPM	307.03
CO Grams	57.47
CO Grams/Mile	16.085

CO2 %	0.18
CO2 Grams	532.27
CO2 Grams/Mile	148.68

****WEIGHTED VALUES****

Fuel Economy	Miles/Gallon	37.6138
Fuel Economy	BTU/Mile	
HC	Grams/Mile	2.2526
NOX	Grams/Mile	1.4386
CO	Grams/Mile	16.0521
CO2	Grams/Mile	148.6787
OMHCE	Grams/Mile	2.2526 (Aldehydes Absent)

APPENDIX A2 - FTP Regulated Emission Cycle With EGO = 4.3ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
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MOBILE SOURCES EMISSIONS RESEARCH LABORATORY

ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

7/1/1994 10:55

EPA Run = 32075

Cycle = FTP

Test Date = 7/1/94 8:30

Driver/Operator = WW/VM

Test Cell = A-CFV

Program = UT

Test Temperature = 75

Fuel = CNG1

EPA Vehicle ID = SA4206

Odometer Reading = 0.0

Comment = W/O Catalyst

Barometric Pressure = 760.2

Relative Humidity = 73.5

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG2	BAG3
VMIX Cubic Feet	5677.00	9803.00	5677.00
Dilution Factor	32.67	44.53	35.27
Fuel Economy in Miles/Gallon	32.75	29.60	35.27
Test Distance in Miles	3.59	3.89	3.59

HC PPM	59.71	1.48	14.10
HC Grams	5.54	0.24	1.31
HC Grams/Mile	1.54	0.06	0.36

NOX PPM	0.60	0.00	0.20
NOX Grams	0.20	0.00	0.07
NOX Grams/Mile	0.06	0.00	0.02

CO PPM	91.03	33.02	42.03
CO Grams	17.04	10.67	7.87
CO Grams/Mile	4.75	2.74	2.19

CO2 %	0.24	0.17	0.23
CO2 Grams	700.59	872.95	673.61
CO2 Grams/Mile	195.15	224.41	187.63

WEIGHTED VALUES*

Fuel Economy	Miles/Gallon	31.6087
Fuel Economy	BTU/Mile	
HC	Grams/Mile	0.4484
NOX	Grams/Mile	0.0169
CO	Grams/Mile	3.0051
CO2	Grams/Mile	208.3518
OMHCE	Grams/Mile	0.4484 (Aldehydes Absent)

APPENDIX A2 - FTP Regulated Emission Cycle With EGO = 4.0ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY

ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/3/1994 15:1

EPA Run = 36232

Cycle = FTP

Test Date = 8/2/94 8:30

Driver/Operator = RS/NP

Test Cell = Q-CFV

Program = UT

Test Temperature = 75

Fuel = CNG1

EPA Vehicle ID = SA4206

Odometer Reading = 19676.0

Comment = None

Barometric Pressure = 761.2

Relative Humidity = 68.0

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG2	BAG3
VMIX Cubic Feet	5821.16	10050.40	5818.55
Dilution Factor	33.48	46.41	38.58
Fuel Economy in Miles/Gallon	37.40	34.39	43.70
Test Distance in Miles	3.55	3.81	3.56

HC PPM	76.40	0.88	16.48
HC Grams	7.26	0.14	1.57
HC Grams/Mile	2.05	0.04	0.44

NOX PPM	1.50	1.00	0.90
NOX Grams	0.50	0.58	0.30
NOX Grams/Mile	0.14	0.15	0.08

CO PPM	95.00	8.00	19.00
CO Grams	18.23	2.65	3.64
CO Grams/Mile	5.14	0.70	1.02

CO2 %	0.23	0.16	0.21
CO2 Grams	682.37	848.26	618.02
CO2 Grams/Mile	192.27	222.76	173.46

*WEIGHTED VALUES**

Fuel Economy	Miles/Gallon	37.1668
Fuel Economy	BTU/Mile	3452.1042
HC	Grams/Mile	0.5608
NOX	Grams/Mile	0.1318
CO	Grams/Mile	1.6995
CO2	Grams/Mile	203.0312
OMHCE	Grams/Mile	0.5608 (Aldehydes Absent)

APPENDIX A2 - FTP Regulated Emission Cycle With EGO = 3.9ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY

ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/3/1994 15:1

EPA Run = 36238

Cycle = FTP

Test Date = 8/3/94 9:35

Driver/Operator = WW/NP

Test Cell = Q-CFV

Program = UT

Test Temperature = 75

Fuel = CNG1

EPA Vehicle ID = SA4206

Odometer Reading = 19716.0

Comment = None

Barometric Pressure = 762.2

Relative Humidity = 58.2

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG2	BAG3
VMIX Cubic Feet	5824.20	10082.60	5835.30
Dilution Factor	34.99	49.39	40.35
Fuel Economy in Miles/Gallon	37.58	37.89	46.24
Test Distance in Miles	3.43	3.96	3.58

HC PPM	95.51	0.58	13.37
HC Grams	9.08	0.09	1.27
HC Grams/Mile	2.65	0.02	0.36

NOX PPM	5.20	2.60	3.20
NOX Grams	1.64	1.42	1.01
NOX Grams/Mile	0.48	0.36	0.28

CO PPM	73.00	4.00	4.00
CO Grams	14.02	1.33	0.77
CO Grams/Mile	4.09	0.34	0.21

CO2 %	0.22	0.15	0.20
CO2 Grams	655.15	803.37	592.46
CO2 Grams/Mile	191.23	202.72	165.26

*WEIGHTED VALUES**

Fuel Economy	Miles/Gallon	39.7812
Fuel Economy	BTU/Mile	3225.2288
HC	Grams/Mile	0.6552
NOX	Grams/Mile	0.3624
CO	Grams/Mile	1.0756
CO2	Grams/Mile	190.1318
OMHCE	Grams/Mile	0.6552 (Aldehydes Absent)

APPENDIX A2- HWFET Regulated Emission Cycle With EGO = 3.9
ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA
MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)
VERSION 7.00
8/3/1994 15:1

EPA Run = 36239 Cycle = HWFET Test Date = 8/3/94 10:55
 Driver/Operator = WW/NP Test Cell = Q-CFV
 Program = UT Test Temperature = 75
 Fuel = CNG1
 EPA Vehicle ID = SA4206
 Odometer Reading = 19714.0
 Comment = None
 Barometric Pressure = 762.3
 Relative Humidity = 47.4

REGULATED EMISSIONS REPORT RE32

BAG 1

VMIX Cubic Feet	8732.80
Dilution Factor	30.77
Fuel Economy in Miles/Gallon	64.26
Test Distance in Miles	10.25

HC PPM	0.30
HC Grams	0.04
HC Grams/Mile	0.00

NOX PPM	3.61
NOX Grams	1.60
NOX Grams/Mile	0.16

CO PPM	2.50
CO Grams	0.72
CO Grams/Mile	0.07

CO2 %	0.27
CO2 Grams	1227.34
CO2 Grams/Mile	119.75

WEIGHTED VALUES*

Fuel Economy	Miles/Gallon	64.2552
Fuel Economy	BTU/Mile	1996.7799
HC	Grams/Mile	0.0041
NOX	Grams/Mile	0.1561
CO	Grams/Mile	0.0702
CO2	Grams/Mile	119.7522
OMHCE	Grams/Mile	0.0041 (Aldehydes Absent)

APPENDIX A2 - HOT505 Regulated Emission Cycle With EGO = 4.0

ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/3/1994 15:1

EPA Run = 36240 Cycle = HOT505 Test Date = 8/3/94 1:55
Driver/Operator = WW/NP Test Cell = Q-CFV
Program = UT Test Temperature = 75
Fuel = CNG1
EPA Vehicle ID = SA4206
Odometer Reading = 19750.0
Comment = W/Catalyst
Barometric Pressure = 762.5
Relative Humidity = 54.6

REGULATED EMISSIONS REPORT RE32

BAG 1

VMIX Cubic Feet 5784.00
Dilution Factor 36.65
Fuel Economy in Miles/Gallon 41.93
Test Distance in Miles 3.53

HC PPM 117.77
HC Grams 11.12
HC Grams/Mile 3.10

NOX PPM 19.30
NOX Grams 5.92
NOX Grams/Mile 1.65

CO PPM 198.00
CO Grams 37.76
CO Grams/Mile 10.52

CO2 % 0.19
CO2 Grams 569.56
CO2 Grams/Mile 158.68

*WEIGHTED VALUES**

Fuel Economy	Miles/Gallon	41.9315
Fuel Economy	BTU/Mile	3059.8351
HC	Grams/Mile	3.0986
NOX	Grams/Mile	1.6478
CO	Grams/Mile	10.5176
CO2	Grams/Mile	158.6527
OMHCE	Grams/Mile	3.0986 (Aldehydes Absent)

APPENDIX A2 - HOT505 Regulated Emission Cycle With EGO = 3.9

ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/3/1994 15:1

EPA Run = 36241 Cycle = HOT505 Test Date = 8/3/94 1:55
Driver/Operator = WW/NP Test Cell = Q-CFV
Program = UT Test Temperature = 75
Fuel = CNG1
EPA Vehicle ID = SA4206
Odometer Reading = 19754.0
Comment = W/O Catalyst
Barometric Pressure = 762.5
Relative Humidity = 55.6

REGULATED EMISSIONS REPORT RE32

BAG 1

VMIX Cubic Feet	5792.2
Dilution Factor	38.67
Fuel Economy in Miles/Gallon	44.47
Test Distance in Miles	3.58

HC PPM	92.36
HC Grams	8.74
HC Grams/Mile	2.44

NOX PPM	18.40
NOX Grams	5.68
NOX Grams/Mile	1.59

CO PPM	179.00
CO Grams	33.99
CO Grams/Mile	9.49

CO2 %	0.18
CO2 Grams	543.20
CO2 Grams/Mile	151.60

WEIGHTED VALUES

Fuel Economy	Miles/Gallon	44.4692
Fuel Economy	BTU/Mile	2885.2246
HC	Grams/Mile	2.4383
NOX	Grams/Mile	1.5858
CO	Grams/Mile	9.4871
CO2	Grams/Mile	151.6035
OMHCE	Grams/Mile	2.4383 (Aldehydes Absent)

APPENDIX A2 - FTP Regulated Emission Cycle With EGO = 4.1
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NORTH CAROLINA
MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/4/1994 9:53

EPA Run = 36242 Cycle = FTP Test Date = 8/4/94 7:45
Driver/Operator = WW/RS Test Cell = Q-CFV
Program = UT Test Temperature = 75
Fuel = CNG1
EPA Vehicle ID = SA4206
Odometer Reading = 19759.0
Comment = W/Catalyst
Barometric Pressure = 762.3
Relative Humidity = 67.3

REGULATED EMISSIONS REPORT RE32

	BAG 1	BAG2	BAG3
VMIX Cubic Feet	5847.90	10101.50	5855.80
Dilution Factor	34.73	49.38	40.65
Fuel Economy in Miles/Gallon	39.15	37.33	47.29
Test Distance in Miles	3.57	3.84	3.59
HC PPM	81.42	0.59	19.48
HC Grams	7.78	0.10	1.86
HC Grams/Mile	2.18	0.03	0.52
NOX PPM	2.90	2.90	3.20
NOX Grams	0.87	1.50	0.96
NOX Grams/Mile	0.24	0.39	0.27
CO PPM	77.00	4.00	10.00
CO Grams	14.85	1.33	1.93
CO Grams/Mile	4.16	0.35	0.54
CO2 %	0.22	0.15	0.19
CO2 Grams	658.10	789.49	576.54
CO2 Grams/Mile	184.24	205.70	160.60

WEIGHTED VALUES*

Fuel Economy	Miles/Gallon	40.0146
Fuel Economy	BTU/Mile	3206.4145
HC	Grams/Mile	0.6027
NOX	Grams/Mile	0.3259
CO	Grams/Mile	1.1831
CO2	Grams/Mile	188.9776
OMHCE	Grams/Mile	0.6027 (Aldehydes Absent)

APPENDIX A2 - HWFET Regulated Emission Cycle With EGO = 4.1

ENVIRONMENTAL RESEARCH CENTER - RESEARCH TRIANGLE PARK,
NORTH CAROLINA

MOBILE SOURCES EMISSIONS RESEARCH LABORATORY
ARCHIVED MOBILE EMISSIONS (AME)

VERSION 7.00

8/4/1994 9:53

EPA Run = 36243 Cycle = HWFET Test Date = 8/4/94 9:10
Driver/Operator = WW/RS Test Cell = Q-CFV
Program = UT Test Temperature = 75
Fuel = CNG1
EPA Vehicle ID = SA4206
Odometer Reading = 19774.0
Comment = W/ Catalyst
Barometric Pressure = 762.2
Relative Humidity = 63.7

REGULATED EMISSIONS REPORT RE32

BAG 1

VMIX Cubic Feet	8830.80
Dilution Factor	30.03
Fuel Economy in Miles/Gallon	62.55
Test Distance in Miles	10.26

HC PPM	1.33
HC Grams	0.19
HC Grams/Mile	0.02

NOX PPM	1.01
NOX Grams	0.50
NOX Grams/Mile	0.05

CO PPM	15.03
CO Grams	4.38
CO Grams/Mile	0.43

CO2 %	0.27
CO2 Grams	1255.44
CO2 Grams/Mile	122.42

WEIGHTED VALUES

Fuel Economy	Miles/Gallon	62.5490
Fuel Economy	BTU/Mile	2051.2492
HC	Grams/Mile	0.0187
NOX	Grams/Mile	0.0488
CO	Grams/Mile	0.4268
CO2	Grams/Mile	122.4220
OMHCE	Grams/Mile	0.0187 (Aldehydes Absent)

APPENDIX A2 - Corrected Emission Reports**Table A2.1 - Corrected Emission Report for EGO = 3.9**

EPA RUN#	36238			
EGO VOLTAGE	3.9			
		BAG 1	BAG 2	BAG 3
CORRECTED FOR METHANE RESPONSE AND BACKGROUND				
HC (PPM)	107.7	0		10.6
HC (GRAMS)	10.2	0		1.0
HC (GRAM/MILE)	2.98	0		0.28
WEIGHTED (GRAM/MILE)	0.669			
CORRECTED NON-METHANE VALUES				
METHANE (PPM)	100.83	-0.02		10.11
NMHC (PPM)	6.87	0.02		0.49
NMHC (GRAMS)	0.651	0.0032		0.047
NMHC (GRAM/MILE)	0.189	0.0008		0.013
WEIGHTED (GRAM/MILE)	0.0418			

Table A2.2 - Corrected Emission Report for EGO = 4.1

EPA RUN#	36242			
EGO VOLTAGE	4.1			
		BAG 1	BAG 2	BAG 3
CORRECTED FOR METHANE RESPONSE AND BACKGROUND				
HC (PPM)	70.7	0.3		14.9
HC (GRAMS)	6.73	0.049		1.298
HC (GRAM/MILE)	1.88	0.0128		0.362
WEIGHTED (GRAM/MILE)	0.4966			
CORRECTED NON-METHANE VALUES				
METHANE (PPM)	65.76	0.45		14.3
NMHC (PPM)	4.94	-0.15		0.6
NMHC (GRAMS)	0.47	-0.025		0.052
NMHC (GRAM/MILE)	0.132	-0.006		0.015
WEIGHTED (GRAM/MILE)	0.028			

APPENDIX A3 - Volumetric Efficiency Table Calibration Data

RUN	MPH	GEAR	RPM	MAP	GAMA	EGO
1	24	3	1600	31.0	1.1	rich out
2	29	3	2000	30.0	1.05	alt
3	35	3	2400	29	1.14	alt
4	38	3	2700	31.4	1.03	alt
5	34	4	1650	31.7	1.06	rich out
6	42	4	2100	32.1	1.06	alt
7	48	4	2300	31	1.11	alt
8	50	4	2500	30	1.1	alt
9	--	ng	900	30	1.04	alt
10	23	3	1600	30	1.05	alt
11	29	3	2000	31	1.05	alt
12	30	3	2100	29	1.11	alt
13	34	3	2400	28.4	1.17	alt
14	23	3	1600	45	1.0	alt
15	28	3	2000	45	.99	alt correct
16	34	3	2300	43.5	1.04	alt
17		ng	900	30	1.05	alt
18	22	3	1600	31.0	1.1	rich
19	25	3	1800	30.6	1.07	rich
20	28	3	2000	30.6	1.04	alt
21	34	3	2400	28.8	1.12	correct
22		3	1600	41	.99	rich
23			1800	40	.98	rich
24			2000	41	.95	rich
25			2400	40.6	.98	alt to rich side
26			1600	45	.93	correct
27			1800	47	.91	rich
28			2000	46.5	.92	correct
29			2400	45	.96	correct
30			1600	76	.89	rich
31			2400	79.3	.91	alt

APPENDIX A4 - Vehicle Energy Efficiency Data

RANGE TEST

Run #1

$$F(x) = -0.2138x + 2,267$$

$$R^2 = 0.9993$$

Time (s)-	10100	
Avg. Speed (mph) -	54.28	
Distance (ft) -	805,435	
Pressure (in Hg) -	29.2	
Wet Bulb Temp (F°)-	57	
Dry Bulb Temp (F°)-	67	
	<u>START</u>	<u>STOP</u>
Corrected Pressure (psig)	2184.645	84.1012
Fuel Temperature (F°)	78.65	72.3
V/Vo	181.7	6.4
Energy Efficiency (mpge) -	48.94	

Run #2

$$F(x) = -0.2175x + 2,102$$

$$R^2 = 0.9995$$

Time (s) -	9190	
Avg. Speed (mph) -	54.6	
Distance (ft) -	736,883	
Pressure (in Hg)-	29.15	
Wet Bulb Temp (F°)-	64	
Dry Bulb Temp (F°)-	59	
	<u>START</u>	<u>STOP</u>
Corrected Pressure (psig)	2025.44	79.4477
Fuel Temperature (F°)	81.8	73.06
V/Vo	166	6.0
Energy Efficiency (mpge) -	49.04	

Run #3

$$F(x) = -0.2101x + 2,076$$

$$R^2 = 0.9995$$

Time (s) -	9370	
Avg. Speed (mph) -	55.08	
Distance (ft) -	747,653.7	
Pressure (in Hg) -	29.15	
Wet Bulb Temp (F°)-	61.5	
Dry Bulb Temp (F°)-	72	
	<u>START</u>	<u>STOP</u>
Corrected Pressure (psig)	2000.481	83.832
Fuel Temperature (F°)	80.9	78.4
V/Vo	164.3	6.3
Energy Efficiency (mpge) -	50.26	

APPENDIX A5 - Vehicle Acceleration Data

Table A5.1 - Stock Saturn Data Sheet

0-60 MPH TEST

Vehicle: Stock Saturn

Date: 10/18/94 12/9/94

Time: 1:00 10:37

Location: Rockwood Airport

Pressure (in Hg) 30.2 30.25

Temperature (F) start stop

Wet-bulb 55 57 56 55

Dry-bulb 65 58 66 57.5

Run	Top Gear	Comments
1	4	good run
2	4	broke loose at beginning
3	4	good run
4	4	good run
5	4	good run
6	4	headwind - sensor spike
7	4	good run
8	4	good run
9	4	broke loose at beginning
10	4	sensor spike

Shifting RPM

1-2 3500

2-3 4000

3-4 4000

4-5

30-40 MPH TEST

Temperature (F) start stop

Wet-bulb 56 56

Dry-bulb 66 67

Gear Used 3

Run	Speed @ Shift	Comments
1	29.3	good run - uphill
2	29.5	good run - flat
3	29.8	down hill - slight hesitation at start
4*	29.6	good run - uphill
5	29.3	good run - flat
6	29.4	good run - uphill
7	29.8	good run - flat
8	29.4	good run - downhill
9*	29.8	good run - uphill
10	29.3	good run - flat

APPENDIX A5 - Vehicle Acceleration Data

Table A5.2 - Natural Gas Satum Data Sheet

0-60 MPH TEST

Vehicle: NGV

Date: 10/18/94 12/9/94

Time: 12:00 11:14

Location: Rockwood Airport

Pressure (in Hg) 30.22 30.25

Temperature (F) start stop

Wet-bulb 53 55 54 53

Dry-bulb 63.5 57.5 64.5 58

Run	Top Gear	Comments
1	4	jerk at 4 gear
2	4	bad start headwind
3	4	good run
4	4	good run
5	4	good run
6	4	good run
7	4	good run
8	4	good run
9	4	good run
10	4	good run

Shifting RPM

1-2 3500

2-3 4000

3-4 4000

4-5 4000

30-40 MPH TEST

Temperature (F) start stop

Wet-bulb 54 56.5

Dry-bulb 64.5 62

Gear Used 3

Run	Speed @ Shift	Comments
1	29.5	good run - flat
2	29.8	good run - downhill
3	29.8	good run - uphill
4	29.8	good run - uphill
5	29.0	good run - flat
6	29.6	good run - slight uphill
7	29.7	good run - flat
8	29.7	good run - downhill
9*	29.0	good run - uphill
10	29.8	good run - uphill
11	29.7	good run - flat

APPENDIX A5 - Vehicle Acceleration Data

Table A5.3 - Stock Saturn Speed Sensor Data

STOCK VEHICLE 0-60

	<u>Total Distance</u>	<u>Total Time</u>
1.	711 ft	14.6 s
2.	797 ft	11.7 s
3.	748 ft	15.5 s
4.	997 ft	17.5 s
5.	755 ft	15.0 s
6.	508 ft	11.9 s*
7.	735 ft	12.1 s
8.	973 ft	16.9 s
9.	725 ft	12.1 s
10.	711 ft	9.7 s*
Avg.	805 ft	Avg. 14.4 s

STOCK VEHICLE 30-40

	<u>Total Distance</u>	<u>Total Time</u>
1.	226.3 ft	4.51 s
2.	208.3 ft	4.11 s
3.	174.8 ft	3.42 s
4.	235.4 ft	4.63 s
5.	204.7 ft	4.01 s
6.	201.7 ft	3.97 s
7.	187.1 ft	3.68 s
8.	174.1 ft	3.41 s
9.	231.7 ft	4.54 s
10.	203.3 ft	3.97 s
Avg.	204.7	Avg. 4.028 s

* values not included in average

APPENDIX A5 - Vehicle Acceleration Data

Table A5.4 - Natural Gas Saturn Speed Sensor Data

NATURAL GAS VEHICLE 0-60

	<u>Total Distance</u>	<u>Total Time</u>
1.	933 ft	17.1 s
2.	1216 ft	21.7 s
3.	978 ft	18.7 s
4.	1155 ft	17.3 s
5.	1094 ft	18.8 s
6.	1286 ft	21.6 s
7.	1148 ft	19.4 s
8.	1112 ft	16.7 s
9.	1120 ft	19.5 s
10.	1268 ft	21.3 s
Avg.	1131 ft	Avg. 19.2 s

NATURAL GAS VEHICLE 30-40

	<u>Total Distance</u>	<u>Total Time</u>
1.	225.9 ft	4.43 s
2.	216.6 ft	4.24 s
3.	261.2 ft	5.11 s*
4.	276.1 ft	5.43 s
5.	251.6 ft	4.92 s
6.	241.6 ft	4.74 s
7.	225.0 ft	4.39 s
8.	217.3 ft	4.27 s
9.	245.7 ft	4.81 s
10.	292.2 ft	5.74 s*
11.	245.7 ft	4.81 s
Avg.	238.4 ft	Avg. 4.67 s

* values not included in average

APPENDIX A6 - Air/Fuel Ratio Calculation Data

Testing Date - Monday 10-17-94

Cycle Distance - 3 mile runs

Pressure - 29.4 in. Hg

Wet Bulb Temperature - 65.5 deg. F

Voltage 3.8

Avg MAF (g/s) 53.98

Avg Air Temp (°F) 82.29

Data Point Curve Fit

$$F(x) = -0.1503x + 1060 \quad R^2 = .9963$$

STARTSTOP

Fuel Temp (°F)

82.7

82.75

Corrected Pressure (psig)

1033.2

981.2

V/Vo

78.6

74.2

Voltage 3.9

Avg. MAF (g/s) 53.58

Avg. Air Temp. (°F) 84.29

Data Point Curve Fit

$$F(x) = -0.1178x + 990.9 \quad R^2 = .9765$$

STARTSTOP

Fuel Temp (°F)

83

85.45

Corrected Pressure (psig)

966.76

925.84

V/Vo

72.8

69.0

Voltage 4.0

Avg. MAF (g/s) 54.71

Avg. Air Temp. (°F) 81.62

Data Point Curve Fit

$$F(x) = -0.1449x + 1125 \quad R^2 = .9972$$

STARTSTOP

Fuel Temp (°F)

81.2

81.8

Corrected Pressure (psig)

1095.57

1045.56

V/Vo

84.3

79.8

Voltage 4.1

Avg. MAF (g/s) 53.76

Avg. Air Temp. (°F) 86.89

Data Point Curve Fit

$$F(x) = -0.1475x + 927.6 \quad R^2 = .9967$$

STARTSTOP

Fuel Temp (°F)

85.7

86.2

Corrected Pressure (psig)

905.64

854.19

V/Vo

67.3

63.0

APPENDIX A6 - Air/Fuel Ratio Calculation Data

Voltage 4.2

Avg. MAF (g/s)	53.58
Avg. Air Temp (°F)	88.29

Data Point Curve Fit

$$F(x) = -0.1472x + 862.7 \quad R^2 = .9974$$

	<u>START</u>	<u>STOP</u>
Fuel Temp (°F)	86.5	83.4
Corrected Pressure (psig)	842.73	791.16
V/Vo	62	58.4

Voltage 4.3

Avg. MAF (g/s)	53.58
Avg. Air Temp (°F)	90.12

Data Point Curve Fit

$$F(x) = -0.1517x + 799 \quad R^2 = .9975$$

	<u>START</u>	<u>STOP</u>
Fuel Temp (°F)	84.15	83.8
Corrected Pressure (psig)	780.71	727.32
V/Vo	57.4	53.2

APPENDIX A7 - Pressure Transducer Calibration Data

<u>Voltage</u>	<u>Pressure (psig)</u>
0	18
0	27
490	513
500	531
650	666
700	711
700	720
800	828
910	936
940	945
1000	1035
1055	1080
1075	1100
1100	1152
1180	1206
1240	1260
1240	1278
1320	1350
1400	1431
1500	1539
1500	1548
1520	1584
1680	1728
1700	1746
1700	1764
1800	1863
1810	1890
1900	1962
1900	1971
1920	1989
1950	2007
1980	2061
2000	2070
2000	2079
2050	2115
2050	2142
2100	2160
2100	2187
2100	2205
2150	2223
2150	2232
2150	2259
2200	2277
2200	2313
2300	2385
2325	2400
2350	2421
2725	2800

APPENDIX B1 Octane Measurement Based on Natural Gas Composition in Knoxville, TN

$$MON = ax\% \frac{CH_4}{100} + bx\% \frac{O_2H_6}{100} + cx\% \frac{O_3H_8}{100} + dx\% \frac{C_4H_{10}}{100} + ex\% \frac{CO_2}{100} + fx\% \frac{N_2}{100}$$

a = 137.780 (CH₄ coefficient)
 b = 29.948 (C₂H₆ coefficient)
 c = 18.193 (C₃H₈ coefficient)
 d = 167.062 (C₄H₁₀ coefficient)
 e = 181.233 (CO₂ coefficient)
 f = 26.994 (N₂ coefficient)

$$MON = 137.78 \{0.9618\} + 29.948 \{0.02212\} - 18.193 \{0.00453\} - 167.062 \{0.00156\} + 181.233 \{0.0046\} + 26.994 \{0.00416\}$$

$$y = C_0 + C_1x + C_2x^2 + C_3x^3$$

$$MON = 133.8 \pm 2$$

y = MON

x = H/C ratio

$$C_0 = -406.14$$

$$C_1 = 508.04$$

$$C_2 = -173.55$$

$$C_3 = 20.17$$

$$H \text{ atoms} = 14 \{.062\} + 8 \{0.453\} + 10 \{0.156\} + 12 \{0.06\} + 6 \{2.212\} + 4 \{96.18\}$$

$$H \text{ atoms} = 404.776$$

$$C \text{ atoms} = 6 \{.062\} + 3 \{0.453\} + 4 \{0.156\} + 5 \{0.061\} + 2 \{2.212\} + 1 \{96.18\}$$

$$C \text{ atoms} = 103.264$$

$$H/C = 3.919$$

$$MON = 406.14 + 508.04 \{3.919\} - 173.55 \{3.919\}^2 + 20.17 \{3.919\}^3$$

$$MON = 133.43 \pm 1.63$$

APPENDIX B2 - Emission Test Correction Calculations

Given values from regulated emissions report

$$\begin{aligned} V_{\text{MIX}} &= 5821.16 \text{ ft}^3 \\ \text{Test distance TD} &= 3.55 \text{ miles} \end{aligned}$$

Given values from bag analysis

Corrected for methane values

$$\text{Total hydrocarbon concentration} \quad C_{\text{THC}} = 69.1 \quad \text{ppm}$$

Corrected non-methane value

$$\text{Methane concentration} \quad C_{\text{MHC}} = 64.21 \quad \text{ppm}$$

To calculate the non-methane hydrocarbon concentration

$$\begin{aligned} C_{\text{NMHC}} &= C_{\text{THC}} - C_{\text{MHC}} \\ C_{\text{NMHC}} &= 69.1 - 64.21 \\ C_{\text{NMHC}} &= 4.89 \text{ ppm} \end{aligned}$$

To calculate the grams of non-methane hydrocarbons

$$\begin{aligned} M_{\text{NMHC}} &= \frac{P_{\text{ATM}} * V_{\text{MIX}} * 1 \times 10^6 * C_{\text{NMHC}}}{R_u * T_{\text{ATM}}} \\ M_{\text{NMHC}} &= \frac{14.7 * 144 * 5821.16 * 1 \times 10^6 * 453.6}{(1543.3 / 13.86) * 530} \end{aligned}$$

$$M_{\text{NMHC}} = 0.4631$$

To calculate the grams of non-methane hydrocarbon per mile

$$\text{GPM}_{\text{NMHC}} = M_{\text{NMHC}} / \text{TD}$$

$$\text{GPM}_{\text{NMHC}} = 0.4631 / 3.55$$

$$\text{GPM}_{\text{NMHC}} = .13$$

This process is repeated for each bag of the FTP and inputted into this equation to obtain the weighted values.

$$\text{GPM}_{\text{WEIGHTED}} = 0.43 * \frac{M1_{\text{NMHC}} + M2_{\text{NMHC}}}{DT1 + DT2} + 0.57 * \frac{M2_{\text{NMHC}} + M3_{\text{NMHC}}}{DT2 + DT3}$$

APPENDIX B3 - Vehicle Energy Efficiency Calculation

Given values

specific gravity of gasoline	sg = 0.75	
gasoline's lower heating value	LHV _{GAS} = 44	(MJ/kg)
volume of the storage tank	Vol = 2.266	(ft ³)
distance traveled	DT = 154	(mile)
standard density of water	den _{WATER} = 998	(kg / m ³)

Values from Mr. Malcosky's program given the pressure and temperature of the gaseous fuel

$$(V / V_O)_{START} = 181.7$$

$$(V / V_O)_{STOP} = 6.4$$

$$LHV_{CNG} = 930.63 \quad (\text{BTU} / \text{scf})$$

To calculate the energy in one gallon of gasoline

$$\text{den}_{GAS} = \text{sg} * \text{den}_{WATER}$$

$$\text{energy}_{GAS} = (\text{LHV}_{GAS} * \text{den}_{GAS} / 264.17) * 9.4845 \times 10^{-4}$$

$$\text{energy}_{GAS} = 1.18 \times 10^6 \quad (\text{BTU})$$

To calculate the miles per gallon equivalent

$$\text{mpge} = \text{DT} / (((V / V_O)_{START} - (V / V_O)_{STOP}) * \text{vol} * \text{LHV}_{CNG} / \text{energy}_{GAS})$$

$$\text{mpge} = 49.2 \quad (\text{mpge})$$

APPENDIX B4 - Vehicle Range Calculation

Given Values -

Tank Maximum Pressure	3600	psig
Tank Ending Pressure	80	psig
Tank Temperature	80.9	deg. F
Volume of the tank vol	2.266	ft ³
Natural gas LHV _{CNG}	930.63	BTU/scf
Gasoline LHV _{GAS}	118243	BTU/gal
Exhaustion cycle	49.4	mpge
Emissions testing	63.4	mpge

From Malcosky Program -

$$\begin{aligned}V_O / V_{\text{START}} &= 281.6 \\V_O / V_{\text{STOP}} &= 6.4 \\ \text{Natural gas energy} &= ((V / V_O)_{\text{START}} - (V / V_O)_{\text{STOP}}) * \text{vol} * \text{LHV}_{\text{CNG}} \\ &= (281.6 - 6.4) * 2.266 * 930.63 \\ &= 580343 \quad \text{BTU}\end{aligned}$$

Calculations -

$$\begin{aligned}\text{Equivalent gallons of gasoline} \\ 580343 / 118243 &= 4.908 \quad \text{gal}\end{aligned}$$

$$\begin{aligned}\text{Range calculation using exhaustion mpge value} \\ 4.908 * 49.4 &= 242 \quad \text{miles}\end{aligned}$$

$$\begin{aligned}\text{Range calculation using emission mpge value} \\ 4.908 * 63.4 &= 311 \quad \text{miles}\end{aligned}$$

APPENDIX C - Dynamometer Calibration Procedure

Two dynamometer settings were found through this calibration. The first was the aerodynamic drag setting. This setting was found by taking the vehicle to a flat stretch of Neyland Drive and recording the manifold air pressures necessary to hold the vehicle at three different constant speeds. The vehicle was then placed on the dynamometer and a aerodynamic setting was arbitrarily picked. The vehicle was then brought up to these different constant speeds and the manifold air pressure was recorded. Three different aerodynamic settings were tested with this procedure. The manifold pressures obtained on the dynamometer were then compared to those found on the road. The aerodynamic setting corresponding to the closest match across all speeds tested was chosen. The Table E.1 summarizes the on-road testing results and Table E.2 summarizes the dynamometer testing results. From these results, an aerodynamic setting of 11 was chosen.

Table C.1 - On-road testing for aerodynamic setting calibration

On-road Testing				
Vehicle speed (mph)	Engine speed (mph)	Manifold Air Pressure (kPa)	Throttle Position Sensor (V)	Gear
50	1981	51.7	0.73	5
30	1529	42.8	0.57	4
60	2259	48.3	0.76	5
40	2071	36.5	0.59	4
40	2420	39.5	0.63	4
50	1865	50.2	0.69	5
hot idle	900	32.8	0.27	neutral

Table C.2 - Dynamometer testing for aerodynamic setting calibration

Dynamometer Testing			
	Aerodynamic Setting		
	13	12	11
Vehicle Speed (mph)	Manifold Air Pressure (kPa)		
30	39.1	36.2	35.8
40	45	43.2	42.1
50	59	54.6	52.4
60	69.7	66	65.3

The setting dynamometer setting calibrated was that for vehicle mass settings. This setting was found by performing on-road acceleration runs and comparing them to acceleration runs performed on the dynamometer. Driver error was removed by doing an acceleration run from 30 to 40 mph in third gear at wide open throttle. The Table E.3 and Table E.4 show the results of the on-road testing and dynamometer testing respectively. From these results, a mass setting of 3400 was chosen.

Table C.3 - On-road testing for mass setting calibration

run #1	4.67 sec.
run #2	4.29 sec.
run #3	4.83 sec.
run #4	4.23 sec.
average	4.5 sec.

Table C.4 - Dynamometer testing for mass setting calibration

	Mass Settings	
	3400	3600
run #1	4.56 sec.	4.76 sec.
run #2	4.34 sec.	4.56 sec.
run #3	4.12 sec.	4.65 sec.
run #4	4.25 sec.	4.78 sec.
average	4.32 sec.	4.68 sec.

APPENDIX D1 - Driver Interface Program

```
$INCLUDE: 'CB.BI'  
OPEN "C:\VEL926.DAT" FOR OUTPUT AS #2  
CLS
```

***** INPUT OF CYCLE DATA FILE *****

```
INPUT "filename: "; F$  
INPUT "total time of cycle in seconds: "; num  
INPUT "do you wish to save cycle velocities:(y,n)"; G$  
S = (2 * (num + 3))  
DIM C(S, 2), VA(S), RN%, BN%, CH%, TR%, X%, OF%  
OPEN F$ FOR INPUT AS #1  
CLS  
LOCATE 10, 25: PRINT "WAIT WHILE PROGRAM IS LOADING"  
  
FOR X% = 1 TO S  
    INPUT #1, C(X%, 1), C(X%, 2)  
NEXT X%
```

***** HEADS-UP DISPLAY CHARACTERISTICS *****

```
COLOR 7, 1  
SCREEN 9 ' screen 640 x 350  
VIEW (0, 0)-(560, 280), 1, 7  
LINE (40, 280)-(40, 275), 7  
LINE (120, 280)-(120, 275), 7  
LINE (200, 280)-(200, 275), 7  
LINE (280, 280)-(280, 275), 7  
LINE (360, 280)-(360, 275), 7  
LINE (440, 280)-(440, 275), 7  
LINE (520, 280)-(520, 275), 7  
REM LINE (0, 230)-(520, 230), 7
```

```
LOCATE 21, 6: PRINT "0"  
LOCATE 21, 15: PRINT "10"  
LOCATE 21, 25: PRINT "20"  
LOCATE 21, 35: PRINT "30"  
LOCATE 21, 45: PRINT "40"  
LOCATE 21, 55: PRINT "50"  
LOCATE 21, 65: PRINT "60"
```

```
LOCATE 22, 1: PRINT "CYCLE"  
LOCATE 22, 7: PRINT F$  
LOCATE 6, 74: PRINT "TIME"  
LOCATE 9, 74: PRINT "MPH"
```

T = TIMER ***** RECORDS STARTING TIME ON INTERNAL CLOCK *****

Count = -.5

strt = 0 ***** STARTING VARIABLE FOR INITIAL SCREEN SETUP *****

110 Count = Count + .5 ***** THE APPROXIMATE TIME INTO THE CYCLE *****

APPENDIX D1 - Driver Interface Program

```
CH% = 1 ***** CHANNEL NUMBER *****
BN% = 0 ***** BOARD NUMBER *****
RN% = 0 ***** GAIN SETTING *****
```

```
TR% = cbAln%(BN%, CH%, RN%, VA%) ***** COMMAND TO READ A/D BOARD *****
DC = 49.55 ***** DYNO-to-DA CALIBRATION 49.55 COUNTS PER MPH *****
```

***** DISPLAYS READING AND RECORDS INTO AN ARRAY *****

```
LINE ((VAOLD * 8 / DC + 40) - 10), 230)-(((VAOLD * 8 / DC + 40) + 10), 230), 1
LINE ((VAOLD * 8 / DC + 40), 220)-((VAOLD * 8 / DC + 40), 240), 1
LINE ((VA% * 8 / DC + 40) - 10), 230)-(((VA% * 8 / DC + 40) + 10), 230), 0
LINE ((VA% * 8 / DC + 40), 220)-((VA% * 8 / DC + 40), 240), 0
```

```
LOCATE 10, 74: PRINT (INT(VA% * 10 / DC)) / 10
VA(Count * 2) = VA%
150 VAOLD = VA%
```

***** LOOP USED TO APPROXIMATE A HALF SECOND WHICH THEN ADDS .5 TO THE COUNT *****

```
120 T2 = TIMER
TI = T2 - (T + Count)
IF TI >= .5 THEN 130 ELSE 120
```

130 OF% = 0 ***** VARIABLE USED FOR VERTICAL POSITIONING OF DATA POINTS *****

***** LOOP TO DRAW THE PART OF THE CYCLE CURRENTLY DISPLAYED AND TO *****
***** ERASE THE PREVIOUS HALF SECOND'S PART *****

```
FOR X% = (2 * Count) TO (2 * (Count + 20)) STEP 1
```

```
OF% = OF% + 1
IF (X% - 6) < 0 THEN 140
IF X% = S THEN
LINE ((C((X% - 1), 2) * 8 + 40), (280 - (OF% * 7)))-((C(X%, 2) * 8 + 40), (280 - ((OF% + 1) * 7))), 1
END IF
IF X% >= S THEN 140
LINE ((C((X% - 1), 2) * 8 + 40), (280 - (OF% * 7)))-((C(X%, 2) * 8 + 40), (280 - ((OF% + 1) * 7))), 1
LINE ((C(X%, 2) * 8 + 40), (280 - (OF% * 7)))-((C((X% + 1), 2) * 8 + 40), (280 - ((OF% + 1) * 7))), 7
```

```
140 NEXT X%
```

```
LOCATE 7, 74: PRINT INT(TIMER - T)***** TIME DISPLAY *****
```

***** INITIAL SCREEN SETTINGS *****

```
IF strt = 0 THEN
LOCATE 23, 1: INPUT "PRESS ENTER TO START"; e$
LOCATE 23, 1: PRINT "
```

```
LOCATE 23, 1: PRINT "CYCLE INITIATED"
T = TIMER
strt = strt + 1
Count = -.5
END IF
```

APPENDIX D1 - Driver Interface Program

```
***** LOOP TO DRAW THE CURSER TRACE ON THE DISPLAY *****

FOR X% = 0 TO 6 STEP 1
  IF (((Count - 1) * 2) - X%) < 0 THEN 160
  LINE ((VA((Count - 1) * 2 - X%) / DC * 8 + 40), (280 - (7 - X%) * 6)) - ((VA(Count * 2 - X% - 1) / DC * 8 + 40),
(280 - (7 - X% + 1) * 6)), 1
  IF (((Count - .5) * 2) - X%) < 0 THEN 160
  LINE ((VA((Count - .5) * 2 - X%) / DC * 8 + 40), (280 - (7 - X%) * 6)) - ((VA(Count * 2 - X%) / DC * 8 + 40),
(280 - (7 - X% + 1) * 6)), 4
160 NEXT X%

IF Count < num THEN 110 ***** RETURN FOR COUNT INCREASE *****

' ***** DATA RECORDING *****

IF G$ = "Y" THEN
  FOR X% = 0 TO S
    WRITE #2, VA%(X%), X%
  NEXT X%
END IF
END
```

APPENDIX D2 - Data Acquisition Program

11:1111:11

01:00

01:5.00 Execution time interval

01:P17

Temperature Panel

01:01

Location 1

02:P13

Thermocouples (Single Ended)

01:04

4 Repetitions

02:03

Range +/- 50 mV

03:01

Input channel 1

04:01

Thermocouple type T

05:01

Reference Location 01

06:02

Output location 2

07:1.8

Multiplier 1.8

08:32

Offset 32

03:P2

Volt Differential

01:01

1 Repetition

02:05

Range +/- 5000 mV

03:05

Input channel

04:06

Location 6

05:0.9

Multiplier 0.9

06:-900

Offset -900

04:P3

Pulse Counter

01:01

1 Repetition

02:02

Input channel 2

03:20

Output frequency high

04:0008

Location 0008

05:30.0

Multiplier 30.0

06:0.0

Offset 0.0

05:P3

Pulse Counter

01:01

1 Repetition

02:04

Input channel 4

03:20

Output frequency high

04:0007

Location 0007

05:1.0

Multiplier 1.0

06:0

Offset 0

06:P13

Thermocouple (Single Ended)

01:01

1 Repetition

02:04

Range +/- 500 mV

03:06

Input channel 6

04:03

Thermocouple type J

05:0001

Reference Location 0001

06:0010

Output Location 0010

07:1.8

Multiplier 1.8

08:32

Offset 32

APPENDIX D2 - Data Acquisition Program

07:P91	If Statement
01:15	If flag 5 is high
02:10	Set flag 0 high
08:P77	Real time
01:0011	Hour - Minute - Seconds
09:P70	Send sample to storage module
01:04	4 Repetitions
02:0002	Thermocouple location 0002
10:P70	Send sample to storage module
01:01	1 Repetition
02:0001	Temperature panel 0001
11:P70	Send sample to storage module
01:01	1 Repetition
02:0006	Voltage differential 0006
12:P70	Send sample to storage module
01:01	1 Repetition
02:0007	Pulse counter 0007
13:P70	Send sample to storage module
01:01	1 Repetition
02:0008	Pulse counter 0008
14:P70	Send sample to storage module
01:01	1 Repetition
02:0010	Thermocouple (single ended) 0010
15:P96	SERIAL OUT
1:30	SM192/716

APPENDIX D3 - Final TEC2 Program

1. RAW FUEL PARAMETERS

Tim on for one GAMA = 7.000 Milli-seconds
Injector offset time = 1.375 Milli-seconds
Minimum turn-on time for injectors (0 to 8 MS) .1
Number to divide tach by for injector output
Injectors are set to fire on alternate events.
MAP offset = 0.0
Voltage just above closed throttle = 0.49 Volts

2. ENRICHMENTS

CHOKE ENRICHMENTS

WARM-UP		ENRICHMENTS VS. COOLANT TEMPERATURES					
CLT Temp.		-30 C	-20 C	-10 C	0 C	10 C	20 C
GAMA Plus		0.00	0.00	0.00	0.00	0.00	0.00
CLT Temp.		30 C	40 C	50 C	60 C	70 C	80 C
GAMA Plus		0.00	0.00	0.00	0.00	0.00	ZERO

ONE-SECOND START UP ENRICHMENTS

SEO Temperature based start up enrichments = 0.00 GAMA
SE1 Fixed start up enrichments = 0.00 GAMA
PWO Fixed start up injector pulse width = 0.00 Milli-seconds
CLT0 Temperature below which to activate PWO = 25 DEG C
TWENTY-SECOND START UP ENRICHMENTS
ASE0 Temperature based 20-second enrichment = 0.00 GAMA
ASE1 Fixed 20-second enrichment = 0.00 GAMA

ACCELERATION ENRICHMENTS

SENSITIVITY OF ACCELERATION MODE

ACE0 Throttle Position Rate = 52.50 Volts/Sec
ACE1 Manifold Pressure Rate = 4.00 KPA/MS

ONE SECOND GAMA ENRICHMENTS

ACE2 Coolant based acceleration enrichment = 1.00 GAMA
ACE3 Fixed acceleration enrichment = 0.10 GAMA

VARIABLE TIME AND AMOUNT GAMA ENRICHMENTS

ACE4 Time period for enrichments = 0.25 Seconds
ACE5 Throttle position rate of change enrichment = 1.50 GAMA
ACE6 Manifold pressure rate of change enrichment = 0.00 GAMA
ACE7 Fixed acceleration enrichment = 0.10 GAMA

FIXED INJECTOR PULSE WIDTH ENRICHMENTS

ACE8 Fixed pulse width amount = 2.00 Milli-seconds
ACE9 Period to add fixed pulse = 0.20 Seconds

DE-ACCELERATION ENRICHMENT

RPM ACTIVATION

DCCL0 Cold RPM above which DECEL may activate = 2500 RPM
DCCL1 Period to add fixed pulse = 0.20 Seconds

POSITION RATE

DCCL2 Rate above which DECEL activates = 10.00 Volt/Sec

PRESSURE ACTIVATION

DCCL3 Manifold pressure during DECEL = 25.0 KPA

POST DE-ACCELERATION CUTOFF

APPENDIX D3 - Final TEC2 Program

DCCL4 1-second enrichment after injector cutoff = 0.00 GAMA
 DENSITY ENRICHMENT / ENLEANMENT
 DE0 = 0.20 GAMA

3. VOLUMETRIC EFFICIENCY TABLE

VOLUMETRIC EFFICIENCY (GAMA)

KPA

100	0	0	-0.12	-0.12	-0.12	-0.12	-0.13	-0.13
85	0	0	-0.11	-0.11	-0.11	-0.12	-0.12	-0.12
75	0	0.01	-0.1	-0.1	-0.1	-0.11	-0.11	-0.11
65	0	0.02	-0.08	-0.08	-0.09	-0.1	-0.1	-0.1
55	0	0.03	-0.67	-0.07	-0.08	-0.09	-0.09	-0.09
45	0	0.04	-0.5	-0.06	-0.07	-0.08	-0.08	-0.08
35	0	0.05	0	-0.02	-0.03	-0.03	-0.04	-0.04
25	0	0.05	0.05	0.03	0.02	0.01	0	-0.01
RPM	400	900	1,600	2,000	2,500	3,000	4,000	5,000

4. INITIAL ADVANCE AND BAR

Initial advance = 0 Degrees
 BAR = 1

INITIAL ADVANCE TABLE

ADVANCE (DEGREES)

KPA

100	0	1	8	10	13	16	20	23
85	0	1.5	12	16	18.5	21	25	28
75	2	4.1	19	21	22.5	24	27	30
65	5	6.9	20	23	25	27	31	34
55	9	11	25	26	28.5	31	35	38
45	14	16	30	31	33	35	39	42
35	15	17.6	36	38	38	38	43	46
25	15	15.6	20	29	30	31	33	36
RPM	400	900	1,600	2,000	2,500	3,000	4,000	5,000

APPENDIX D3 - Final TEC2 Program

6. COOLANT ADVANCE TABLE

CLT TEMP	-30 C	-20 C	-10 C	0 C	10 C	20 C
ADV (DEG)	14	12	10	8	6	4
CLT TEMP	30 C	40 C	50 C	60 C	70 C	80 C
ADV (DEG)	4	3	3	2	1	0

7. EGO PARAMETERS

EGO is enabled
Coolant temperature above which EGO is enabled = 25 DEG C
Throttle position above which EGO is disabled = 4.00 Volts
Voltage above which EGO is rich and below which EGO is lean = 4.00 Volts
Rich to lean GAMA step size = 0.008 GAMA
Lean to rich GAMA step size = 0.008 GAMA
Number of engine events between updates = 8
Authority range for EGO = 0.200 GAMA

8. KNOCK CONTROL PARAMETERS

Knock is disabled
Knock threshold A = 15
Retard rate B = 0.25 Deg/Engine Function
Max. retard C = 15 Degrees
Advance rate D = 0.25 Deg/Engine Function
Knock control inhibited above E = 4500 RPM

9. IDLE SPEED PARAMETERS

Idle speed is enabled
Temperature No. 1 = -10 Degrees C
RPM No. 1 = 1000
Temperature No. 2 = 30 Degrees C
RPM No. 2 = 950
Temperature No. 3 = 70 Degrees C
RPM No. 3 = 900
Number of steps to reset I.S.M. at power on = 150
Manifold pressure below which to disable I.S.M. = 25.0 KPA

COARSE IDLE SPEED CONTROL

RPM's off target at which to switch to coarse = 100
Number of steps to decrease speed per wait period = 2
Decreasing speed wait period = 250 Milli-seconds
Number of steps to increase speed per wait period = 2
Increasing speed wait period = 250 Milli-seconds

FINE IDLE SPEED CONTROL

Number of steps per wait period = 1

SPARK ADVANCE IDLE SPEED CONTROL

Retard timing rate if RPM is too high = 6
Advance timing rate if RPM is too low = 10

APPENDIX D3 - TEC2 Final Program

10. REV LIMITER PARAMETERS

Rev limiter is enabled
Rev limiter is set to cut coils off on rev limit.
Rev limit speed = 4500 RPM
Rev limit hysteresis = 150 RPM
Auxiliary rev limit engine speed = 12000 RPM

11. SENSOR FAILURE PARAMETERS

- A. CLT SENSOR
Voltage above which CLT sensor fails = 4.96 Volts
Voltage below which CLT sensor fails = 0.04 Volts
Default CLT sensor temperature = 70 Degrees C
- B. MAT SENSOR
Voltage above which MAT sensor fails = 4.96 Volts
Voltage below which MAT sensor fails = 0.04 Volts
Default MAT sensor temperature = 25 Degrees C
- C. TPS SENSOR
Voltage above which TPS sensor fails = 4.96 Volts
Voltage below which TPS sensor fails = 0.04 Volts
Default TPS sensor voltage = 0.20 Volts
- D. MAP SENSOR
Voltage above which MAP sensor fails = 5.00 Volts
Voltage below which MAP sensor fails = 0.04 Volts
Default MAP sensor pressure = 104.0 KPA
- E. EGO SENSOR
Time required for EGO sensor to fail = 30 Seconds

12. MAT SENSOR ENABLE / DISABLE

MAT sensor is enabled.

13. BATTERY VOLTAGE COMPENSATION

Battery voltage compensation = 75 Milli-seconds / Volt

APPENDIX D3 - TEC2 Final Program

14. GENERAL PURPOSE OUTPUT TABLE

DUTY CYCLE (PERCENTAGE)

KPA

100	16	16	20	25	30	25	20	20
85	16	16	27	32	37	32	27	27
75	16	16	30	35	40	35	30	30
65	16	16	25	30	35	30	25	25
55	16	16	20	25	30	25	20	20
45	16	16	16	20	25	20	16	16
35	16	16	16	16	20	16	16	16
25	16	16	16	16	16	16	16	16
RPM	400	900	1,600	2,000	2,500	3,000	4,000	5,000

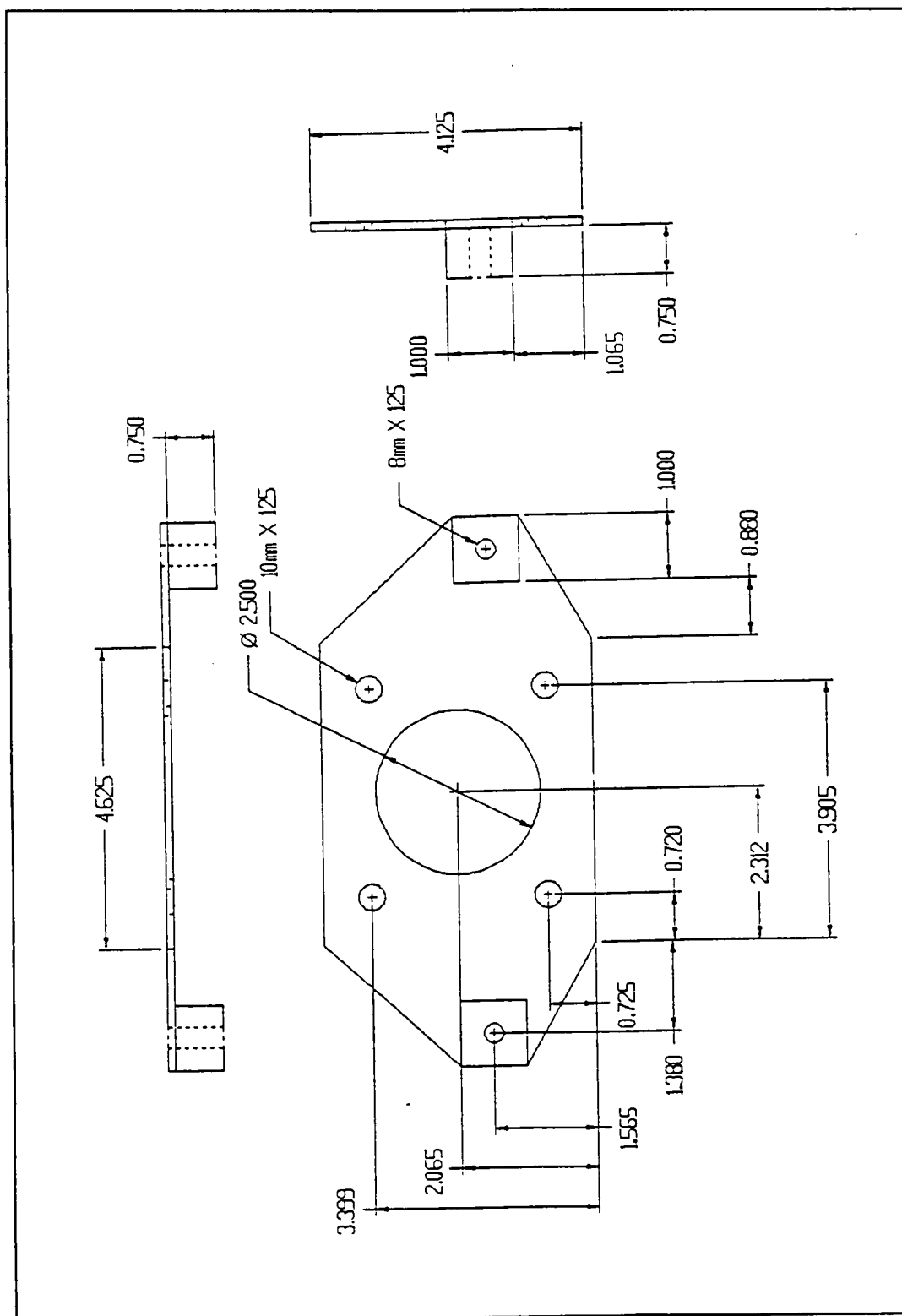
15. GENERAL PURPOSE OUTPUT FREQUENCY

The frequency of the general purpose output is 122 HZ

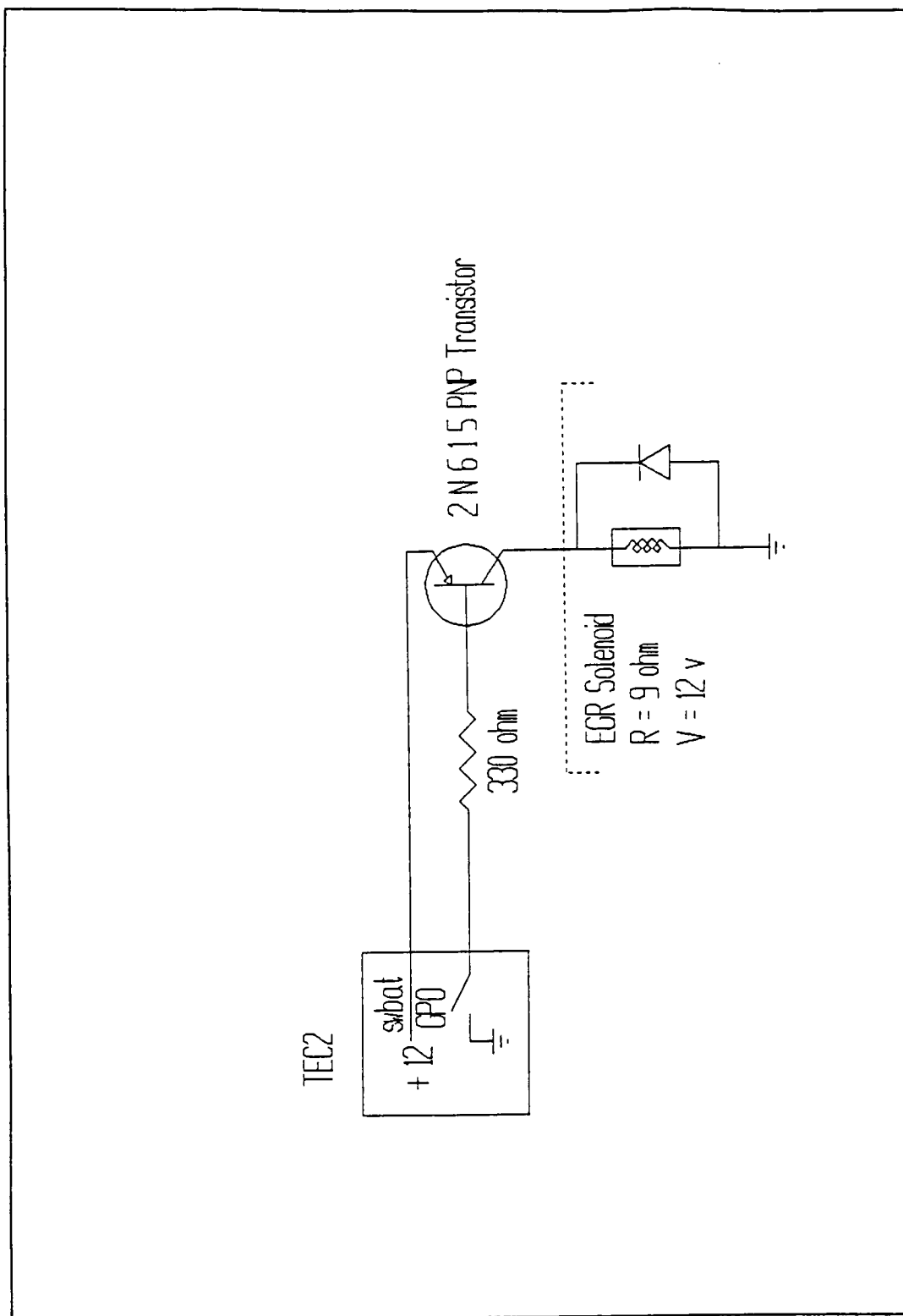
16. SOFTWARE VERSIONS

This file is for use with calibration software version 27.1 and TEC PROM
version 33

APPENDIX E1 - Catalyst Can Modifications



APPENDIX E2 - EGR Driving Circuit



APPENDIX F - Equipment Listing

Pressure Transducer

The pressure transducer manufactured by Energy Kinetics Inc. is the AutoSelect Model EK110-1-DB. This transducer measures fuel pressure and uses this reading to drive the OEM fuel gauge in the conversion vehicle. It takes this measurement just prior to the gas' entering into the regulator. It is located near the driver-side front wheel-well at the bottom of the engine compartment.

Serial #	001479
Spec #	149890
Input range	0-3600 psig
Output range	1-5 volts
Accuracy	+/- 18 psig

Data Acquisition

Data acquisition is performed using a Campbell Scientific Inc. 21X Micrologger and a SM192 storage module. As can be seen in Figure F1, the 21X Micrologger has two terminal strips used in this research to sample several sensor inputs. The 21X followed the program listed in Appendix D2 to perform the following tasks; thermocouple reading, single ended voltage reading, and frequency counter. Because of the large number of samples read by the system, the program called for the 21X to send its readings to the SM192 storage module which is the silver canister on the right in Figure F1.

	Micrologger	SM192
serial #	7538	3916

APPENDIX F - Equipment



Figure F1 - Data Acquisition Equipment

APPENDIX F - Equipment

Speed Sensor

The speed and distance measurement was performed by the Datron Davit Light Speed (DLS) Smart Sensor. This sensor is an optical non-contact speed and distance sensor with on-board signal conditioning and data acquisition. To condition the sensors signal and to collect data, an IBM-compatible laptop computer is required. This computer can also be used to monitor the sensor's output during testing through a heads-up display. The sensor measures speed and distance by basically producing two reflections of the surface or ground and measuring the relative motion between these two reflections using photo detectors. The sensor is mounted parallel to the side of the vehicle using suction holders.

serial #	01187	
speed range	0.3-250	mph
resolution	0.1	inch
accuracy		
typical	+/- 0.1%	
max	+/- 0.2%	
reproducibility	+/- 0.1%	
req. power	10.5-15	V DC
operating temp	-31 to 131	deg F
rel. humidity	80%	@100 deg F

APPENDIX F - Equipment

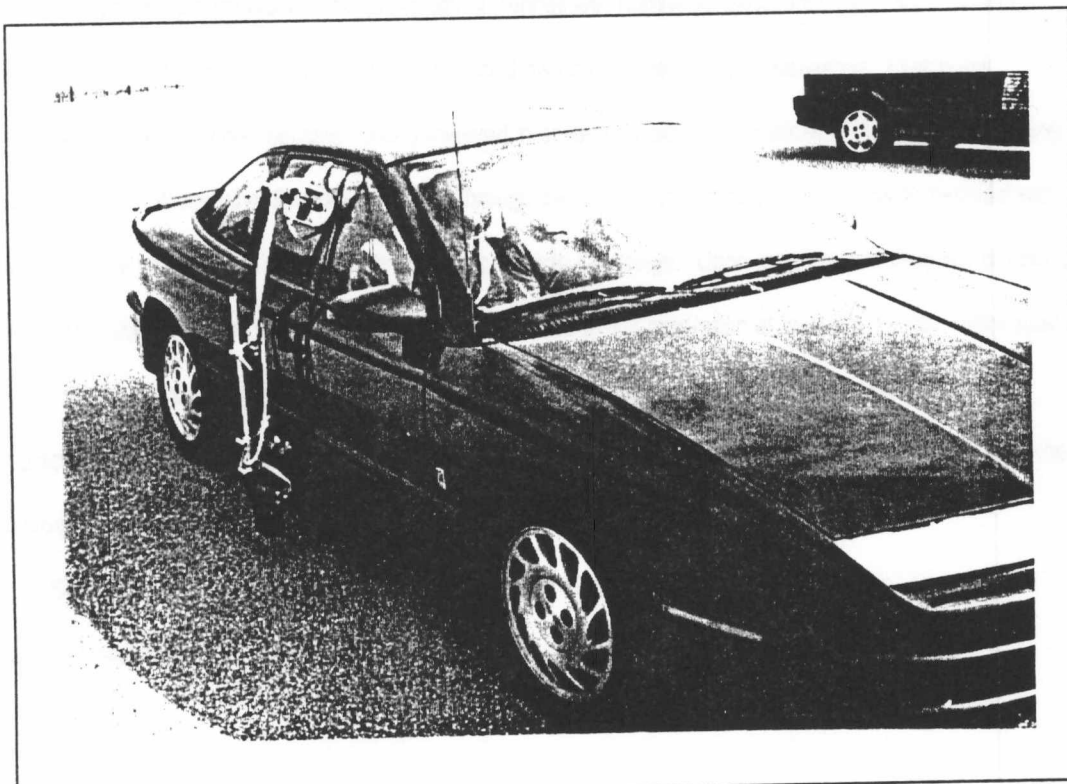


Figure F2 - Datron DLS speed and distance sensor