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# Large SI Engine Technologies and Costs

## Draft Final Report

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Assessment and Standards Division
Office of Transportation and Air Quality
U.S. Environmental Protection Agency

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**July 2001**

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# 1. Introduction

The United States Environmental Protection Agency (EPA) is seeking to set new emission standards for nonroad spark-ignited engines above 19 kW (25 hp). The future regulation will be similar to the one adopted in October 1998 by the California Air Resources Board (ARB) which will facilitate harmonization of standards. EPA standards would also regulate equipment such as farm and construction equipment under 175 hp over which ARB has no jurisdiction.

The ARB standards were adopted in compliance with the 1994 State Implementation Plan's measure M11. The standards apply to all non-preempted engines above 19 kW (25 hp) and are based on three-way catalysts and electronically-controlled closed-loop fuel systems. They are programmed to phase-in over three years starting in 2001 with full-lifetime compliance beginning in 2004. Table 1-1 presents the emission standards adopted by ARB for engines over one liter in displacement.

**Table 1-1. ARB Nonroad Large Spark-Ignited Engines Emission Standards**

| Year | Standards (g/bhp-hr) | | Useful Life |
|---|---|---|---|
| | NMHC+ $NO_x$ | CO | |
| Tier 1<br>2001-2003 (phase-in) | 3.0 | 37 | N/A |
| Tier 2<br>2004 and later | 3.0 | 37 | 5000 hours or 7 years |

This report's objective is to assess the economic impacts to nonroad large spark-ignited engine manufacturers of upgrading their production to include features such as electronically-controlled closed-loop fuel systems, three-way catalysts (and fuel injection for gasoline units), in order to comply with EPA's future standards. The EPA is also considering a requirement for diagnostic monitoring of the air/fuel ratio. This requirement will also affect the cost to the manufacturers.

## 2. Background

Spark ignited engines above 19 kW referred to as “Large SI engines” are used in a variety of industrial applications ranging from mobile to portable or stationary equipment. Table 2-1 summarizes the top ten nonroad Large SI engine applications, as well as the 1994-96 annual sales from Power Systems Research (PSR).

**Table 2-1. Application Sales Summary**

| Application | 1994-1996 Average Annual Sales | Percent of Total Sales |
|---|---|---|
| Forklift | 55,198 | 50% |
| Generator Set | 15,419 | 14% |
| Commercial Turf | 7,558 | 7% |
| Pump | 6,584 | 6% |
| Welder | 3,395 | 3% |
| Scrubber/Sweeper | 3,403 | 3% |
| Air Compressor | 2,691 | 2% |
| Chipper/Grinder | 2,320 | 2% |
| Gas Compressor | 1,919 | 2% |
| Aerial Lift | 1,812 | 2% |
| Irrigation Set | 1,761 | 1.6% |

Large SI engines can be categorized by cooling system and fuel type. Two types of cooling systems are available, air and water cooling. Gasoline, LPG (propane), and natural gas are the principal fuels used. Natural gas powered equipment is not very common and the cost of upgrading this equipment would be similar to the cost of upgrading LPG powered equipment. All costs calculated for LPG equipment will be assumed to represent appropriate estimates for the costs of upgrading natural gas equipment.

Water-cooled engines dominate the market in most of the application types presented in Table 2-1. Air-cooled engines represent approximately 6 percent of the total market and are more frequently used in applications that generate dust such as concrete saws and chippers/grinders. Water-cooled engines are often not appropriate for these applications because the dusty environments they operate in usually cause radiator clogging.

According to industry sources, LPG equipment represents about 65 percent of the Large SI engine inventory.  LPG engines are available in almost all application types.  LPG is especially dominant in a few applications with large populations such as forklift and generator sets.  About 95 percent percent of all Large SI engines in forklifts run on LPG.

Gasoline engines also are used in a wide variety of applications and especially prevail over LPG engines in air cooled applications.  The few LPG air-cooled engines are generally rated under 19 kW (25 hp).

Considering these inventory characteristics, the report will focus on three engine categories: water-cooled gasoline engines, air-cooled gasoline engines and water-cooled LPG engines.

# 3. Technology Description

Emission standards do not yet apply to Large SI engines and they therefore use little or no emission control technology. The sections to follow describe baseline Large SI engines and the technology needed to meet the proposed standards. Table 3-1 shows baseline and projected technologies for gasoline and LPG Large SI engines.

**Table 3-1. Large SI Air and Water Cooled Engine Rule Technology Changes**

| **Baseline System (Gasoline air and water cooled)** | **Baseline System (LPG water cooled)** |
|---|---|
| Fuel System<br>*Carburetor*<br>*Low-pressure fuel pump*<br>Cooling System<br>*94% Water cooled*<br>*6% Air cooled* | Fuel System<br>*Mechanical mixer*<br>Cooling System<br>*100% Water cooled* |
| **Advanced System (Gasoline)** | **Advanced System (LPG)** |
| Fuel System<br>Water-cooled - *PFI*<br>Air-cooled - *TBI*<br>*High-pressure fuel pump*<br>Three-way Catalyst<br>Oxygen Sensor- *single pre-cat non-heated sensor, two for V engines*<br>ECM - *16-bit computer*<br>Diagnostics - *Air/Fuel Control* | Fuel System<br>*Electronic Mixer*<br>Three-way Catalyst<br>Oxygen Sensor- *single pre-cat non-heated sensor, two for V engines*<br>ECM - *16-bit computer*<br>Diagnostics - *Air/Fuel Control* |

## 3.1 Baseline Technologies

Baseline technologies on air and water cooled gasoline Large SI engines include a carburetor and a low pressure fuel pump. Large SI engines usually have automotive counterparts, but are governed to lower engine speeds to derate engine power and modify the horsepower and torque versus engine speed curves.

Baseline LPG water cooled Large SI engines typically have an open-loop mechanical mixer. LPG is stored at 130 to 170 psi, remaining in a liquid state at normal ambient temperatures. The mixer typically consists of a diaphragm, exposed to manifold air pressure, attached to a needle and orifice assembly. The diaphragm responds to changes in intake manifold vacuum (which in turn is controlled by the engine load and throttle setting), raising and lowering the needle within the orifice to finely adjust the amount of LPG admitted and mixed with engine intake air.

## 3.2 Advanced Technologies

The following sections describe advanced technologies for gasoline and LPG engines. All engines will be expected to use closed loop control with oxygen sensors and three-way catalytic (TWC) converters. Since most Large SI engines are derived from automotive counterparts, much of the technology developed for cars and trucks can be utilized for Large SI engines.

### 3.2.1 Fuel System Technologies

To facilitate better control of the air/fuel ratio when using three-way catalysts, gasoline fuel systems will probably need to be closed-loop controlled with port fuel injection. In some cases, throttle body fuel injection systems might be used, but better air/fuel ratio control and less cylinder-to-cylinder maldistribution will be gained with port fuel injection systems. Since these systems are already in use in counterpart automotive engines, a great deal of the technology already exists. Port fuel injection systems will include a fuel injector per cylinder, a fuel rail, a pressure regulator, an electronic control module (ECM), manifold air pressure and temperature sensors**,** an oxygen sensor, a high pressure fuel pump, a throttle assembly, a throttle position sensor, and a magnetic crankshaft pickup for engine speed. Port fuel injection systems typically operate at 30 psi. Throttle body systems will only need one fuel injector (although significantly larger) for the engine and will use a lower pressure fuel pump. Throttle body systems typically operate at 10 psi. There is also no need for a fuel rail on a throttle body system.

Future LPG fuel systems will most likely consist of an electronically-controlled closed-loop gas regulator on a throttle body. An LPG convertor temperature controller placed on the coolant return line from the vaporizer/regulator will maintain the temperature in the regulator at a level to prevent the condensation of heavy hydrocarbons from the fuel. The condensed hydrocarbons can form deposits that prevent the regulator from working properly.

While some manufacturers have been investigating the use of gaseous fuel injection systems, the anticipated standards can likely be met with an electronic closed-loop regulator on a throttle body. This system will be typically composed of an electronic mixer, an oxygen sensor, a manifold air pressure sensor, an electronic control unit, and a throttle assembly. If developed, gaseous injection systems would require substantial filtering before the injector due to contaminants in LPG.

### 3.2.2 Oxygen Sensors

Oxygen sensors will need to be added before the catalyst for closed-loop control. Heated oxygen sensors are not necessary to meet the proposed standards as the emission certification tests currently do not include cold starting. It is expected that most manufacturers will use one oxygen sensor in each exhaust manifold of V-6 and V-8 engines to minimize maldistribution between cylinders. At least one manufacturer of LPG engine systems uses only one oxygen sensor in V engines, inferring the air fuel ratio in the other bank from the one that is measured. However, this manufacturer is redesigning the intake manifold to insure more even air/fuel ratio between cylinders.

### 3.2.3 Electronic Control Modules

Manufacturers will need electronic control modules (ECM) to handle fuel injection, ignition timing, and diagnostic functions. Since advanced diagnostic functions are not expected, 16-bit computers should suffice. Large SI engine industry contacts have confirmed this assumption.

### 3.2.4 Catalysts

In order to accomplish the level of emission reduction necessary to meet the proposed standards, three-way catalysts will be essential. In some equipment models today, catalysts are offered as an option. The three-way catalysts expected to help meet emission standards are derived from gasoline vehicle catalysts. Since the NOx reductions needed are only around 90 percent, low precious metal loadings can be used. It is estimated that catalyst volumes will be approximately 60 percent of engine displacement with ceramic substrates and tri-metal formulations. At least one engine supplier is using catalysts at 70 percent of engine volume to maintain durability, but it is unlikely that this will be necessary to meet the proposed standards. Also, several manufacturers claim that metal substrates are necessary to minimize deterioration due to engine vibrations and high exhaust temperatures. Precious metal loading of 2.8 g/liter with tri-metal catalysts are assumed here, but some manufacturers are using lower levels. Detailed catalyst assumptions used in this report are shown in Table 3-2.

**Table 3-2. Three-Way Catalyst Characteristics**

| | |
|---|---|
| Catalyst Size | 60% of engine displacement |
| Substrate | Ceramic<br>400 cells per square inch |
| Washcoat | 50% ceria/50% alumina<br>Loading 160 g/liter |
| Precious Metals | Pt/Pd/Rh 1/14/1<br>Loading 2.8 g/liter |

The cost estimates in Section 4 include the cost of a muffler with the price of the catalyst. In general the catalyst does not provide adequate muffling and it is therefore important to integrate a dedicated muffler to the catalyst. Space constraints on many applications make it necessary to combine the catalyst and muffler in one can.

### 3.2.5 Diagnostic Functions

Effective diagnostic functions are possible on Large SI engines with a 16-bit electronic control unit. The most fundamental is air/fuel ratio control, but others might include oxygen sensor malfunction, or other catalyst performance variables, that the manufacturer wants to monitor. Diagnostic functions will illuminate a malfunction indicator light (MIL) on the equipment.

The air/fuel ratio control diagnostic will monitor oxygen sensor output and time the switching function. If the oxygen sensor does not switch within a specific amount of time, the engine is either running rich or running lean and is therefore not at the optimal stoichiometric air/fuel ratio.

## 3.3 Fuel Economy Improvements

Carbureted Large SI engines can run rich or lean at steady state. Stoichiometric operation provides a direct benefit for those engines set to fuel-rich operation but a penalty for those that are set lean. However, in-use operation of Large SI engines usually includes a large amount of transients, in which carburetors usually over-fuel. Feedback control during transients significantly reduces fuel use in all engines, whether set to operate rich or lean. In fact, engines that operate lean on steady state, compensate during transients by over enriching the mixture. Since transients are high fuel use conditions, keeping the air/fuel ratio at stoichiometric during these periods will ultimately reduce fuel consumption in-use.

Manufacturers and engine suppliers have estimated the benefits of gasoline fuel injected systems and electronic closed loop control LPG mixers over open loop carburetors and mixers at 10 to 20 percent. We have calculated a 10 percent improvement in fuel economy; this percentage can be scaled up or down to meet equipment specific estimates.

## 3.4 Maintenance and Engine Life Improvements

By minimizing over rich operation, carbon build-up in cylinders will be less. This has a direct effect on oil contamination which allows longer oil change and maintenance intervals. In addition, engines will last longer between rebuilds. A good indication of this phenomenon is seen in the automobile industry where fuel injected closed-loop controlled engines now last significantly longer and have less frequent maintenance requirements than their carbureted predecessors. We have assumed a 15 percent increase in engine life between rebuilds and a 15 percent longer maintenance interval, which is much less than the changes seen in the automotive industry.

## 4. Cost Methodology

In order to determine the costs to manufacturers to upgrade their engines to comply with future emission regulations, this report focuses on the three engine categories described earlier: gasoline water cooled, LPG water cooled and gasoline air-cooled engines. Representative models of each category were chosen among several manufacturers' engine lines and cost information was collected for each. No single model's costs were used to develop the estimates presented in this report, but rather representative averages of all costs collected were used for each technology. In addition to hardware and fixed costs to the manufacturer, we also estimated fuel consumption and maintenance costs. All costs are reported in year 2001 dollars.

### 4.1 Hardware Cost to Manufacturer

The fuel system and the catalytic converter/muffler are the two main components of the hardware cost. The cost estimates for the different parts of the fuel system are averages of retail prices obtained from Large SI engine manufacturers, fuel systems manufacturers, and engine dealers. Component costs were estimated from dealer and parts supplier prices less various markup, the ARB study on nonroad engines done by SwRI[1], and studies done by Arthur D. Little[2,3] and Lindgren[4] on gasoline truck engine technology costs.

Catalyst manufacturers were the main source of information for the cost of manufacturing a three-way catalytic converter for a nonroad Large SI engine. They provided generic information on precious metal and washcoat loadings as well as catalyst volumes. Precious metal costs were taken from the 2007 heavy-duty vehicle rule analysis.[5]. The labor cost assumes a medium scale production of catalysts of a similar size of a couple thousand units per year and an average labor time of two hours per unit including the time necessary to weld the catalyst to the muffler. Because of the diversity of equipment types and configurations especially among forklifts, the catalyst manufacturers' process will be less automated than in the automotive industry. Labor

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[1] White, Jeff et al. "Three-Way Catalyst Technologies for Off-Road Equipment Powered by Gasoline and LPG Engines," prepared for the California Air Resources Board, November 1998.

[2] Browning, Louis and Kassandra Genovesi. "Cost Estimates for Heavy-Duty Gasoline Vehicles," prepared for the U.S. Environmental Protection Agency, September 1998.

[3] Browning, Louis and Fanta Kamakaté. "Sterndrive and Inboard Marine SI Engine Technologies and Costs, " prepared for the U.S.. Environmental Protection Agency, September 1999.

[4] Lindgren, Leroy H. "Cost Estimations for Emission Control Related Components/ Systems and Cost Methodology Description", Rath & Strong, Inc., Report No. EPA 460/3-78-002, December 1977.

[5] EPA, "Regulatory Impact Analysis: Heavy-Duty Engine and Vehicle Standards and Highway Diesel Fuel Sulfur Control Requirements," EPA420-R-00-026, December 2000.

rates used in this study are $17.50 per hour plus a 60 percent fringe rate for a total labor cost of $28 per hour.

All hardware costs are subject to a 29 percent mark up which represents an average manufacturer mark up of technologies on new engine sales[6]. The 5 percent warranty markup was added to the incremental hardware cost to represent an overhead charge covering warranty claims associated with new parts.

## 4.2 Fixed Cost to Manufacturer

The fixed costs to the manufacturer consist of the cost of researching, developing and testing a new technology. They also include the cost of retooling the assembly line for the production of new parts. The estimate of research and development costs used in our cost calculations reflects the fact that a great part of the technology needed for compliance with future emissions standards has already been developed by the automotive industry. The research and development efforts will concentrate on adapting the existing technology to nonroad applications and ensuring that engines control emissions over a wide range of operation. Many of these efforts have begun and an electronic fuel injected nonroad gasoline engine is already commercially available. The $500,000 of R&D represents 9 months of engine test time utilizing 2 engineers and 3 technicians.

The number of units per manufacturer and the number of years to recover are used to determine the fixed cost per unit in year 1999 dollars. The number of units per year is derived from Power Systems Research data adjusted using confidential sales data from major manufacturers. Five years is a typical length of time used in the industry to recover an investment in a new technology.

## 4.3 Fuel Economy

As discussed in Section 3.3, switching from carbureted to fuel injected or electronically-controlled engine powered equipment can lead to fuel cost savings for the operator. We developed an estimate of these savings by using engine characteristics such as annual use (hrs/year) and lifetime provided by the EPA nonroad inventory data and load factors developed by Southwest Research Institute[7]. Each engine's usage characteristics are population-weighed averages of annual use, lifetime, and load factors of all the applications in the particular fuel type. As LPG engines mostly operate in forklift

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[6] Jack Faucett Associates. "Update of EPA's Motor Vehicle Emission Control Equipment Retail Price Equivalent (RPE) Calculation Formula,", Report No. JACKFAU-85-322-3, September 1985.

[7] White, Jeff et al. "Three-Way Catalyst Technologies for Off-Road Equipment Powered by Gasoline and LPG Engines," prepared for the California Air Resources Board, November 1998.

applications, their average load factor (0.31), annual use (1,729 hrs/year) and lifetime (8.4 years) are very close to the median forklift engine characteristics. Gasoline engines are used in a wider variety of applications with higher average load factor (0.57), lower annual use (694 hrs/year), and longer lifetime (13 years). These three factors multiplied together give an indication of the total work done by an engine over its lifetime. Even though the individual figures vary considerably, the calculated total lifetime work is comparable for gasoline and LPG engines.

The brake specific fuel consumption (bsfc) for each engine type was based upon engine test data[8]. The price of gasoline and propane are based on year 2000 averages from the Energy Information Administration without highway taxes[9]. The taxes were estimated from national average data provided by the American Petroleum Institute[10] and U. S. DOE Transportation Energy Data Book[11].

Using the following formulas we determined an estimate of the yearly fuel consumption and yearly fuel cost for both baseline and compliant equipment.

$$\text{Yearly Fuel Consumption (gal / year)} = \frac{\text{Hp * Load Factor * Annual Operation (hrs / yr) * bsfc (lb / bhp - hr)}}{\text{Fuel Density (lbs / gal)}}$$

$$\text{Yearly Fuel Cost (\$ / yr)} = \text{Yearly Fuel Consumption (gal / year) * Fuel Cost (\$ / gal)}$$

The difference between the yearly fuel cost for carbureted and fuel injected equipment is the savings in fuel consumption due to the increased fuel economy of the fuel injected gasoline equipment or the electronically controlled LPG equipment.

## 4.4 Maintenance Cost

The changes in maintenance intervals described in Section 3.4 can also result in cost savings for the operator. To determine these potential cost savings we estimated the intervals between scheduled maintenance tasks such as oil change, tune up and engine rebuild using several engines' operation and maintenance guides. The advanced

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[8] White, Jeff et al, "Three-Way Catalys Technology for Off-Road Equpment Powered by Gasoline and LPG Engines," Final report from Southwest Research Institute (SwRI 8778), April 1999.

[9] US Energy Information Administration, "Monthly Energy Review, April 2001," www.eia.doe.gov\emeu\mer.

[10] Barnes, Tina. "Nationwide and State-by-State Motor Fuel Taxes", American Petroleum Institute, May 1999.

[11] Davis, Stacy. "Transportation Energy Data Book," U.S. DOE, Oak Ridge National Laboratory, Edition 19, 1999.

technology engines were estimated to have 15 percent longer maintenance intervals than the baseline engines. This estimate is borne out by trends seen in the automotive industry when passenger car engines were upgraded from carburetion to fuel injection. The cost of each one of these activities was estimated from quotes provided by forklift servicing businesses and forklift manufacturers. The total maintenance cost obtained is an estimate of the lifetime spending on maintenance in year 2001 dollars.

As observed with automotive engines, the new Large SI engines will likely last longer. The analysis, however, does not attempt to quantify the economic impacts of extended engine life.

## 4.5 Results

Preliminary results were submitted for review to the industry contacts who provided cost information. Their comments were incorporated in the final version of the cost estimates which are presented in Tables 4-1 to 4-4.

Table 4-1 shows incremental consumer costs for baseline and projected water-cooled gasoline engines using either throttle body injection systems or port fuel injection systems. It should be noted that incremental costs for both the throttle body and the port fuel injection cases are referenced to the baseline case. Throttle body systems cost an additional $771, while port fuel injected systems cost an additional $869 over the baseline carbureted version. The improved fuel economy and reduced maintenance requirements more than compensate for the increased cost of the new technologies.

Table 4-2 shows the incremental consumer costs for baseline and advanced air-cooled gasoline engines using either throttle body injection systems or port fuel injection systems. Incremental costs for both the throttle body and the port fuel injection cases are referenced to the baseline case. Throttle body systems cost an additional $842, while port fuel injected systems cost an additional $940 over the baseline carbureted version. As in the previous case, improved fuel economy and reduced maintenance requirements more than compensate for the increased cost of the new technologies.

Table 4-3 shows the incremental consumer costs for baseline and closed-loop controlled water-cooled LPG engines. The advanced LPG engine costs an additional $616 over the baseline version. Once again, improved fuel economy and reduced maintenance requirements more than compensate for the increased cost of the new technologies.

Table 4-4 shows catalyst costs to the engine manufacturer. These costs assume that the same catalyst will be used for gasoline air and water cooled and LPG water-cooled applications and also that the same catalyst will be used by manufacturers producing similar-sized engines. Catalyst costs to the engine manufacturer are estimated to be $229 per engine, which included the cost of integrating the muffler.

**Table 4-1. Water-cooled Gasoline Engine**

| Hardware Cost to Manufacturer | Baseline | TBI | PFI |
|---|---|---|---|
| Carburetor | $51 | N/A | N/A |
| Injectors (each) | | $19 | $17 |
| Number Required | | 1 | 4 |
| Pressure Regulator | | $11 | $11 |
| Fuel filter | $3 | $4 | $4 |
| Intake Manifold | $35 | $37 | $50 |
| Fuel Rail | | | $13 |
| Throttle Body/Position Sensor | | $76 | $60 |
| Fuel Pump | $15 | $26 | $30 |
| Oxygen Sensor (each) | | $19 | $19 |
| Number Required | | 1 | 1 |
| ECM | | $140 | $150 |
| Governor | $40 | $60 | $60 |
| Air Intake Temperature Sensor | | $5 | $5 |
| Manifold Air Pressure Sensor | | $11 | $11 |
| Engine Speed Sensor | | $12 | $12 |
| Wiring/Related Hardware | | $45 | $45 |
| **Fuel System** | **$144** | **$465** | **$538** |
| **Catalyst/Muffler** | | **$229** | **$229** |
| Muffler | $45 | | |
| **Total Hardware Cost** | **$189** | **$694** | **$767** |
| Markup @ 29% | $55 | $201 | $222 |
| Warranty Markup @5% (incremental hardware cost) | | $25 | $29 |
| **Total Component Costs** | **$244** | **$920** | **$1,018** |

| Fixed Cost to Manufacturer | Baseline | TBI | PFI |
|---|---|---|---|
| R&D Costs | $0 | $500,000 | $500,000 |
| Tooling Costs | $0 | $100,000 | $100,000 |
| Units/yr. | 1,750 | 1,750 | 1,750 |
| Years to recover | 5 | 5 | 5 |
| **Fixed cost/unit** | **$0** | **$95** | **$95** |
| **Total Costs ($)** | **$244** | **$1,015** | **$1,113** |
| **Incremental Total Cost ($)** | | **$771** | **$869** |

| Fuel Economy | Baseline | TBI | PFI |
|---|---|---|---|
| Horsepower | 76 | 76 | 76 |
| Load Factor | 0.57 | 0.57 | 0.57 |
| Annual Operating Hours, hr/yr | 694 | 694 | 694 |
| Lifetime, yr | 13 | 13 | 13 |
| BSFC, lb/bhp-hr | 0.605 | 0.545 | 0.545 |
| BSFC improvement | | 10% | 10% |
| Fuel Density (lbs/gal) | 6.1 | 6.1 | 6.1 |
| Fuel Cost ($/gal) | 1.103 | 1.103 | 1.103 |
| Yearly Fuel Consumption (gal/yr) | 2982 | 2684 | 2684 |
| Yearly Fuel Cost ($/yr) | $3,289 | $2,960 | $2,960 |
| **Lifetime Fuel Cost (NPV at 7%, $)** | **$27,487** | **$24,739** | **$24,739** |
| **Incremental Lifetime Fuel Cost (NPV at 7%, $)** | | **-$2,748** | **-$2,748** |

| Maintenance | Baseline | TBI | PFI |
|---|---|---|---|
| Oil Change Interval (hrs) | 150 | 172.5 | 172.5 |
| Oil Change Cost ($) | $30 | $30 | $30 |
| Tune-up Interval (hrs) | 400 | 460 | 460 |
| Tune-up cost ($) | $75 | $75 | $75 |
| Rebuild Interval (hrs) | 5,000 | 5,750 | 5,750 |
| Rebuild Cost ($) | $800 | $800 | $800 |
| **Lifetime Maintenance Cost (NPV at 7%, $)** | **$2,573** | **$2,354** | **$2,354** |
| **Incremental Lifetime Maintenance Costs (NPV at 7%, $)** | | **-$219** | **-$219** |

## Table 4-2. Air Cooled Gasoline Engine

| Hardware Cost to Manufacturer | Baseline | TBI | PFI |
|---|---|---|---|
| Carburetor | $51 | N/A | N/A |
| Injectors (each) | | $19 | $17 |
| Number Required | | 1 | 4 |
| Pressure Regulator | | $11 | $11 |
| Fuel filter | $3 | $4 | $4 |
| Intake Manifold | $35 | $37 | $50 |
| Fuel Rail | | | $13 |
| Throttle Body/Position Sensor | | $76 | $60 |
| Fuel Pump | $15 | $26 | $30 |
| Oxygen Sensor (each) | | $19 | $19 |
| Number Required | | 1 | 1 |
| ECM | | $140 | $150 |
| Governor | $40 | $60 | $60 |
| Air Intake Temperature Sensor | | $5 | $5 |
| Manifold Air Pressure Sensor | | $11 | $11 |
| Engine Speed Sensor | | $12 | $12 |
| Wiring/Related Hardware | | $45 | $45 |
| **Fuel System** | **$144** | **$465** | **$538** |
| **Catalyst/Muffler** | | **$229** | **$229** |
| Muffler | $45 | | |
| **Total Hardware Cost** | **$189** | **$694** | **$767** |
| Markup @ 29% | $55 | $201 | $222 |
| Warranty Markup @5% (incremental hardware cost) | | $25 | $29 |
| **Total Component Costs** | **$244** | **$920** | **$1,018** |

| Fixed Cost to Manufacturer | Baseline | TBI | PFI |
|---|---|---|---|
| R&D Costs | $0 | $500,000 | $500,000 |
| Tooling Costs | $0 | $100,000 | $100,000 |
| Units/yr. | 1,000 | 1,000 | 1,000 |
| Years to recover | 5 | 5 | 5 |
| **Fixed cost/unit** | **$0** | **$166** | **$166** |
| **Total Costs ($)** | **$244** | **$1,086** | **$1,184** |
| **Incremental Total Cost ($)** | | **$842** | **$940** |

| Fuel Economy | Baseline | TBI | PFI |
|---|---|---|---|
| Horsepower | 60 | 60 | 60 |
| Load Factor | 0.57 | 0.57 | 0.57 |
| Annual Operating Hours, hr/yr | 694 | 694 | 694 |
| Lifetime, yr | 13 | 13 | 13 |
| BSFC, lb/bhp-hr | 1.10 | 0.99 | 0.99 |
| BSFC improvement | | 10% | 10% |
| Fuel Density (lbs/gal) | 6.1 | 6.1 | 6.1 |
| Fuel Cost ($/gal) | 1.103 | 1.103 | 1.103 |
| Yearly Fuel Consumption (gal/yr) | 2639 | 2375 | 2375 |
| Yearly Fuel Cost ($/yr) | $2,911 | $2,620 | $2,620 |
| **Lifetime Fuel Cost (NPV at 7%, $)** | **$24,331** | **$21,898** | **$21,898** |
| **Incremental Lifetime Fuel Cost (NPV at 7%, $)** | | **-$2,433** | **-$2,433** |

| Maintenance | Baseline | TBI | PFI |
|---|---|---|---|
| Oil Change Interval (hrs) | 70 | 80.5 | 80.5 |
| Oil Change Cost ($) | $30 | $30 | $30 |
| Tune-up Interval (hrs) | 250 | 290 | 290 |
| Tune-up cost ($) | $75 | $75 | $75 |
| Rebuild Interval (hrs) | 4,000 | 4600 | 4600 |
| Rebuild Cost ($) | $800 | $800 | $800 |
| **Lifetime Maintenance Cost (NPV at 7%, $)** | **$3,024** | **$2,789** | **$2,789** |
| **Incremental Lifetime Maintenance Costs (NPV at 7%, $)** | | **-$235** | **-$235** |

## Table 4-3. Water Cooled LPG System

| Hardware Cost to Manufacturer | Baseline | Conttrolled Carburetor |
|---|---|---|
| Regulator/Throttle body | $50 | $65 |
| Intake Manifold | $37 | $37 |
| Fuel Filter w/ lock-off system | $15 | $15 |
| LPG vaporizer | $75 | $75 |
| Governor | $40 | $60 |
| Converter Temperature Control Valve | | $15 |
| **Closed Loop System** | | |
| Oxygen Sensor (each) | | $19 |
| Number Required | | 1 |
| ECM | | $100 |
| Wiring/Related Hardware | | $45 |
| **Fuel System** | **$217** | **$431** |
| **Catalyst/Muffler** | | **$229** |
| Muffler | $45 | |
| **Total Hardware Cost** | **$262** | **$660** |
| Markup @ 29% | $76 | $191 |
| Warranty Markup @5% (incremental hardware cost) | | $20 |
| **Total Component Costs** | **$338** | **$871** |

| Fixed Cost to Manufacturer | Baseline | Controlled Carburetor |
|---|---|---|
| R&D Costs | $0 | $500,000 |
| Tooling Costs | $0 | $100,000 |
| Units/yr. | 2,000 | 2,000 |
| Years to recover | 5 | 5 |
| **Fixed cost/unit** | **$0** | **$83** |
| **Total Costs ($)** | **$338** | **$954** |
| **Incremental Total Cost ($)** | | **$616** |

| Fuel Economy | Baseline | Controlled Carburetor |
|---|---|---|
| Horsepower | 57 | 57 |
| Load Factor | 0.31 | 0.31 |
| Annual Operating Hours, hr/yr | 1729 | 1729 |
| Lifetime, yr | 8.4 | 8.4 |
| BSFC, lb/bhp-hr | 0.507 | 0.456 |
| BSFC improvement | | 10% |
| Fuel Density (lbs/gal) | 4.2 | 4.2 |
| Fuel Cost ($/gal) | 0.602 | 0.602 |
| Yearly Fuel Consumption (gal/yr) | 3688 | 3319 |
| Yearly Fuel Cost ($/yr) | $2,220 | $1,998 |
| **Lifetime Fuel Cost (NPV at 7%, $)** | **$13,750** | **$12,375** |
| **Incremental Lifetime Fuel Cost (NPV at 7%, $)** | | **-$1,375** |

| Maintenance | Baseline | Controlled Carburetor |
|---|---|---|
| Oil Change Interval (hrs) | 200 | 230 |
| Oil Change Cost ($) | $30 | $30 |
| Tune-up Interval (hrs) | 400 | 460 |
| Tune-up cost ($) | $75 | $75 |
| Rebuild Interval (hrs) | 7,000 | 8,050 |
| Rebuild Cost ($) | $800 | $800 |
| **Lifetime Maintenance Cost (NPV at 7%, $)** | **$2,902** | **$2,681** |
| **Incremental Lifetime Maintenance Costs (NPV at 7%, $)** | | **-$221** |

## Table 4-4. Three-way Catalysts Cost Estimates

### Gasoline/LPG

| | | |
|---|---|---|
| Washcoat Loading | g/L | 160 |
| *% Ceria* | *by wt.* | *50* |
| *% Alumina* | *by wt.* | *50* |
| *Precious Metal Loading* | *g/L* | *2.8* |
| *% Platinum* | *by wt.* | *6.3* |
| *% Palladium* | *by wt.* | *87.5* |
| *% Rhodium* | *by wt.* | *6.3* |
| *Labor Cost* | *$/hr* | *$28.00* |

| ***Material*** | ***$/troy oz*** | ***$/lb*** | ***$/g*** | ***Density (g/cm^3)*** |
|---|---|---|---|---|
| *Alumina* | | *$5.00* | *$0.011* | *3.9* |
| *Ceria* | | *$5.28* | *$0.012* | *7.132* |
| *Platinum* | *$412* | | *$13.25* | |
| *Palladium* | *$390* | | *$12.54* | |
| *Rhodium* | *$868* | | *$27.91* | |
| *Stainless Steel* | | *$1.12* | *$0.002* | *7.817* |

| | |
|---|---|
| *Engine Size* | *2.50* |
| ***Catalyst Volume (L)*** | ***1.50*** |
| *Substrate Diameter(cm)* | *12.70* |
| | |
| *Substrate* | *$12.00* |
| *Ceria/Alumina* | *$2.27* |
| *Pt/Pd/Rd* | *$47.41* |
| *Can (18 gauge 304 SS)* | *$2.17* |
| *Substrate Diameter (cm)* | *12.70* |
| *Substrate Length (cm)* | *9.9* |
| *Working Length (cm)* | *12.7* |
| *Thick. of Steel (cm)* | *0.121* |
| *Shell Volume (cm3)* | *48* |
| *Steel End Cap Volume (cm3)* | *33* |
| *Vol. of Steel (cm^3) w/ 20% scrap* | *98* |
| *Wt. of Steel (g)* | *762* |
| | |
| ***TOTAL MAT. COST*** | ***$63.85*** |
| ***LABOR*** | ***$56.00*** |
| *Labor Overhead @ 40%* | *$22.40* |
| *Supplier Markup @ 29%* | *$41.25* |
| ***Manufacturer Price*** | ***$183.50*** |
| ***Manufacturer Price with Muffler*** | ***$228.50*** |