ANALYSIS OF EFFECTIVENESS AND COSTS of RETROFIT EMISSION CONTROL SYSTEMS for USED MOTOR VEHICLES

volume I

summary

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ANALYSIS OF EFFECTIVENESS AND COSTS of RETROFIT EMISSION CONTROL SYSTEMS for USED MOTOR VEHICLES

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ENVIRONMENTAL PROTECTION AGENCY
Office of Air Programs
Division of Emission Control Technology
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FOREWORD

The Environmental Protection Agency, as Administrator of the Clean Air Amendments Act of 1970, is required to assist States and air pollution control agencies in meeting national ambient air quality standards and mobile or stationary source emission standards, by issuing information on control techniques. Contract 68-04-0038 was performed with the Office of Air Programs, Division of Emission Control Technology, to determine what emission control techniques are feasible for retrofit to used cars, considering emission reduction effectiveness, costs, effect on vehicle performance, and the facilities and labor skills required for retrofit device installation and eventual maintenance and inspection. This report documents the results obtained, the pertinent data upon which the results are based, the techniques of test and analysis, and the recommendations for future programs to implement the results. The report consists of the following six volumes:

I. Program Summary: Highlights the principal program results and conclusions as to the overall feasibility of retrofit methods for vehicle emission control. Provides guidelines for the evaluation of retrofit approaches and the implementation of control programs.

II. System Descriptions: Documents the physical, functional, and performance characteristics of the candidate retrofit methods and their installation requirements and costs.

III. Performance Analysis: Documents the relative effectiveness and costs of retrofit methods, the techniques of analysis and testing, and the assumptions and rationale upon which the analysis was based.

IV. Test and Analytical Procedures: Documents the approach to the overall program objectives and the tasks and procedures implemented to meet the objectives.

V. Appendices: Documents the raw data obtained from retrofit development sources and data of overall applicability to the report.

VI. Addendum for Durability Tests: Documents the results of 25,000-mile durability tests on four representative retrofit devices.

ABSTRACT

The purpose of this EPA-contracted program was to examine the effectiveness and costs of retrofit methods for control of emissions from gasoline-powered, light-duty used automobiles. This six-volume report provides the results of an extensive evaluation of current retrofit technology to States and agencies which have to establish or evaluate automotive emission control programs. It also provides detailed guidelines and an evaluation methodology to assist in the development of specific air pollution control programs or abatement strategies using retrofit devices as they apply to used car emission control requirements. The report presents a summary of all known retrofit emission control techniques for used cars in terms of emission reduction effectiveness, costs, effect on the vehicle's performance, and the facilities and labor skill needed for device installation, maintenance, and inspection.

The term "retrofit method" as used in this program is defined as "any device or system that may be added to a car and/or any modification or adjustment, beyond that of regular vehicle maintenance, which may be made to vehicles to reduce their emissions."(1) Regular vehicle maintenance, engine tuneup, the General Motors, Ford, and Chrysler used car retrofit systems, as well as vehicle inspection programs, were specifically excluded from study. Other programs have studied, or are currently studying, these alternate approaches.

A thorough search was made for all sources of information on all known retrofit methods, developers, and producers. Input data from the participating developers and producers were used in the evaluation process and to categorize the principles of retrofit device operation. Generic groups of: (1) exhaust emission control, (2) crankcase blowby control, (3) evaporative emission control, and (4) combinations were evaluated. The study emphasis, however, was placed on exhaust emission control approaches.

Several representative devices were actually tested to provide exhaust emissions, fuel consumption, and driveability performance data which are considered to be typical for the existing used car population. The test program was performed on used cars without factory installed exhaust control systems.

Concurrent with the test program an engineering analysis was conducted on each retrofit system to document technical characteristics, costs, and effects on vehicle performance. The data obtained, both from the retrofit tests and the engineering analysis, were then processed through an evaluation methodology especially developed

(1) Environmental Protection Agency Contract 68-04-0038, Analysis of Effectiveness and Costs of Retrofit Emission Control Systems for Used Vehicles, 30 June 1971

to analyze the principal performance parameters of the different retrofit systems. The methodology developed is applicable to the evaluation of any exhaust emission control method, whether for cars that may or may not already be equipped with other emission control systems.

The study showed that a large number of retrofit methods and prototype devices are available for the majority of the used car population. Most can be readily mass produced and marketed if the necessary economic incentives arise. They cover a wide spectrum of effectiveness and cost. Those devices which are most effective in reducing emissions are also generally the most expensive. The study indicated that certain of these retrofit devices are technically feasible, but that careful tradeoffs may be required between emission reduction effectiveness and costs to achieve an optimum solution to the air quality control requirements of different regions.

The problem of durability (device performance versus mileage accumulation) was also investigated in the program. The evaluation of the durability test results is being completed and will be covered in Volume VI, which is to be published shortly.

ACKNOWLEDGMENTS

This program was conducted under the direction and with the assistance of Dr. Jose L. Bascunana, Project Officer of the Environmental Protection Agency. Emission Control Technology, Inc., provided the methodology for performance analysis under a subcontract agreement with Olson Laboratories, Inc.

The accomplishment of this program was made possible by the cooperation and assistance of the many developers and manufacturers of retrofit devices. Their contribution of coordination time, data, and retrofit device hardware is very much appreciated.

GLOSSARY

AMA	Automobile Manufacturers Association
CEI	Cost Effectiveness Index
CI	Cost Index
CID	Cubic inch displacement
CNG	Compressed natural gas
CO	Carbon monoxide
CVS	Constant volume sampling
DI	Driveability Index
EGR	Exhaust gas recirculation
EI	Emission Index
EPA	Environmental Protection Agency
gm/mi	Grams per mile
HC	Hydrocarbons
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MMBM	Mean-miles-before-maintenance
MMBPF	Mean-miles-before-partial-failure
MMBTF	Mean-miles-before-total-failure
mph	Miles per hour
mpg	Miles per gallon
MTTM	Mean-time-to-maintain
MTTR	Mean-time-to-repair
NDIR	Nondispersive infrared
NOx	Oxides of nitrogen
OEM	Original equipment
PCV	Positive crankcase ventilation
PI	Performance Index
ppm	Parts per million
SAE	Society of Automotive Engineers
WOT	Wide open throttle

CONTENTS (CONTINUED

CONTENTS

CONTENTS (CONTINUED)

ILLUSTRATIONS

TABLES

1 SUMMARY OF RESULTS AND CONCLUSIONS

SECTION 1

SUMMARY OF RESULTS AND CONCLUSIONS

1.1 FUNDAMENTAL RESULTS AND CONCLUSIONS

The fundamental results and conclusions of the study of retrofit method effectiveness and costs are summarized as follows:

- Retrofit Emission Reductions and Costs - Retrofit devices which are designed to control emissions from gasoline-powered light duty vehicles can be classified according to the following sources of vehicle emissions they control:

  a. Crankcase Blowby Emission Control Systems

  b. Fuel Evaporative Emission Control Systems

  c. Exhaust Gas Emission Control Systems

  It has been estimated that reliable crankcase blowby control systems can reduce up to 20 percent of all the hydrocarbons emitted by cars without any emission controls. Twenty-three percent of the current national car population do not have controls for crankcase emissions. Feasible retrofit crankcase blowby control systems are currently available. The conventional types cost up to $40 installed.

  It has also been estimated that reliable evaporative control devices could reduce all the hydrocarbons emitted from an uncontrolled car as much as 20 percent. About 85 percent of the current total car population do not have evaporative controls. There were no retrofit fuel evaporative emission control devices for used vehicles at the time of this study. However, on the basis of the systems being supplied on new vehicles, it was estimated that a used car retrofit evaporative control could cost as much as $140.

  Exhaust gas emissions account for about 60 percent of the hydrocarbon emissions, essentially 100 percent of the carbon monoxide, and 100 percent of the oxides of nitrogen from an uncontrolled vehicle.

  A group of 11 retrofit exhaust devices was selected for testing in the retrofit program. Four of these devices received up to 18 tests. The emission reductions with 90 percent confidence limits of the mean reduction for these four representative retrofit exhaust emission control systems are presented in the following table:

DEVICE NUMBER AND DESCRIPTION	PERCENT EXHAUST EMISSION REDUCTIONS (1)					
	HC		CO		NOx	
	Pooled Mean Reduction	90% Confidence Limits of the Mean Reduction	Pooled Mean Reduction	90% Confidence Limits of the Mean Reduction	Pooled Mean Reduction	90% Confidence Limits of the Mean Reduction
1 Air Bleed to Intake Manifold	21	10 to 32	58	22 to 80	-5	-15 to 5
96 Catalytic Converter with Distributor Vacuum Advance Disconnect	68	53 to 90	63	37 to 97	48	17 to 64
175 Ignition Timing Modification with Lean Idle Adjustment	19	9 to 29	46	-8 to 77	37	27 to 47
246 Speed-Controlled Exhaust Gas Recirculation with Distributor Vacuum Advance Disconnect	12	3 to 21	31	6 to 60	48	43 to 52

(1) Exhaust tests conducted by the 1972 Federal Test Procedure.

Retrofit emission control systems include initial installation costs and recurring costs to operate and maintain the device. Additional costs for engine tuneup prior to device installation must also be considered if this procedure is specified as part of the installation. The costs for engine tuneup were excluded in the scope of this study, except for those tuneup related parts and/or adjustments required by the retrofit device installation. The study indicated that those retrofit control systems which are most effective generally cost more money to install and maintain. However, the question of reasonable costs for retrofit systems ultimately depends on the emission reduction objectives of State or air pollution control agencies, and the options which may be available to meet those objectives.

Typical costs of retrofit systems tested in the program ranged from $21 to $175. The catalyst system evaluated in the retrofit program reportedly has an initial cost of $175 when installed with an air pump on an 8-cylinder vehicle. The ignition timing modification system and the exhaust gas recirculation system have initial costs of $45 and $89, respectively. The air bleed system which received 18 tests costs between $56 and $64. Another air bleed system evaluated reportedly costs about $23. These prices are estimates for prototype systems based on information provided by the retrofit developers.

Recurring costs are significantly influenced by the change in gasoline mileage as a result of a retrofit system installation. Fuel consumption measurements were conducted while using the 1972 Federal Exhaust Emissions Test Procedure (which covers typical urban driving and speeds up to 57 mph). Average penalties in fuel consumption as high as 10 percent (less miles per gallon) and improvement as high as 7 percent (more miles per gallon) were measured during these tests for some of the devices which received up to 18 tests. Additional testing must be undertaken to determine fuel consumption for freeway driving and to establish the statistical significance of the data.

Catalyst systems require lead free fuels to maintain satisfactory effectiveness over service periods of 25,000 miles. The other types of systems tested in the retrofit program did not require special fuels.

In addition to the fuel costs, maintenance of a retrofit device adds to the recurring costs. Typical maintenance for air bleed systems requires air filters to be changed every 12,000 miles. Exhaust gas recirculation systems require cleaning of the control valve every 6,000 miles. Catalyst systems require a change of catalyst at 25,000-mile intervals. Electronic ignition modification systems require no maintenance, in general, and in most cases their repair is not possible; in the event such devices fail, replacement with a new unit is required.

- Driveability and Safety - In general, the devices that received driveability tests in the retrofit study appeared to degrade vehicle driveability; however, driveability was still acceptable. Average acceleration times at wide open throttle were about 5 to 10 percent slower. High altitude (6,000-8,000 ft) did not affect the operation of the vehicle with the retrofit installed any differently than the driveability tests conducted near sea level.

  In general there were no gross safety problems due to retrofit installation. Some of the devices appeared to have potential safety hazards, but it is believed these could be eliminated by redesign.

- Reliability - Reliability in mean-miles-before-partial and total failure was estimated to be 50,000 service miles or more for all devices for which sufficient data could be obtained or developed.

- Installation, Inspection and Skill Level Requirements - Although the devices evaluated did not require special tools for installation, practically all require special equipment for low emission adjustment. In most cases, the retrofit developer specified that the engine be well tuned prior to device installation. To ensure low emissions, an HC and CO meter would be required for effective retrofit device and related tuneup adjustments. The installation of the devices requires normal automotive mechanical skills. However, most auto mechanics are not presently capable of properly adjusting a retrofit device and related engine tuneup parameters for low emissions without some additional training. Technician upgrading through training programs would be required for a successful and effective retrofit program.

- Retrofit Device Vehicle Applicability - The retrofit systems evaluated in this study are applicable to most pre-1968 domestic model vehicles (pre-1966 for California) not originally equipped with exhaust controls. Catalyst systems appear to be applicable as retrofits for additional emission reductions on 1968 and later model vehicles. Distributor vacuum advance and exhaust gas recirculation systems may also be applicable for NOx control of these later model-year vehicles. Air bleed systems can be easily installed on vehicles already equipped for HC and CO control, but consideration must be given to the possibility of over-leaning the carburetor mixture, since these vehicles already have relatively lean carburetor mixtures. Foreign car retrofit devices were generally not available for analysis during the program; however, two retrofit devices were tested on a small foreign car.

- Feasibility Conclusions - The study of retrofit method effectiveness and costs performed under EPA Contract 68-04-0038 indicated that certain exhaust emission control systems are technically feasible for retrofitting used cars. The major consideration is one of cost. In general, the amount of money spent for a device determines the emission reduction effectiveness to be gained.

Some of the main problems likely to be encountered with the retrofit approach may not be attributable to the devices. The vehicles themselves have to be in good running condition and well tuned if retrofit devices are to be effective. Vehicle engine defects and malfunctions may degrade device performance, and even cause device failure. Thus, the use of retrofit devices presupposes good vehicle condition prior to device installation and good continued maintenance.

Additional results, related to the durability of retrofit devices, will be presented in Volume VI.

1.2 RETROFIT DEVICE CLASSIFICATION AND DESCRIPTIONS

Retrofit devices which are designed to control emissions from gasoline-powered motor vehicles can be classified according to the sources of vehicle emissions they control:

Group 1: Exhaust Emission Control Systems

Group 2: Crankcase Blowby Emission Control Systems

Group 3: Fuel Evaporative Emission Control Systems

Group 4: Combinations of these groups

Table 1-1 shows the detailed classification structure used to categorize retrofit devices studied in this program.

Exhaust gas accounts for about 60 percent of the hydrocarbon (HC) emissions and essentially 100 percent of the carbon monoxide (CO) and oxides of nitrogen (NOx) from an uncontrolled vehicle. Crankcase blowby accounts for about 20 percent of the HC emissions, and evaporative emissions from the fuel tank and carburetor vents account for the remaining 20 percent of the HC emissions. Control of the pollutants from these three sources requires devices or methods of varying complexity and, correspondingly, the effectiveness of retrofit devices can vary over a wide range. Furthermore, the addition of a retrofit control device to a used car normally cannot be expected to be as cost effective for control of emissions as the inclusion of control methods at the time of vehicle manufacture.

1.2.1 Exhaust Emission Control Systems

In considering the control of exhaust emissions, retrofit devices may be designed to either work on the exhaust gases after they leave the combustion chambers and enter into the exhaust system, or they may be designed to decrease the emission formation by modifications to the induction system and/or the ignition and combustion processes. Within these two broad categories there were several approaches which were represented by the devices evaluated in this program.

The three automotive exhaust pollutants currently controlled by law for new light-duty vehicles (6,000 pounds or less) are hydrocarbons (HC), carbon monoxide (CO) and oxides of nitrogen (NOx). Smoke emissions (or particulate matter) are controlled in some States by local ordinance, but not presently by Federal requirements. The combination of HC and NOx in the atmosphere plus sunlight causes photochemical reactions to occur. This, in turn, forms the reactive compounds which constitute smog. Carbon monoxide does not enter into the smog reaction, but in itself is a poisonous gas.

Modification of engine operating parameters, including idle speed, air-fuel ratio and spark timing, can affect the concentration of these exhaust gas pollutants from uncontrolled engines. The objective of applying these modifications is to optimize the engine operation with respect to exhaust pollutant emissions. In some cases, those modifications which reduce HC and CO emissions tend to increase NOx emissions. When air-fuel ratios exceed about 15-16 to 1, NOx formation normally decreases with additional mixture leaning. When adjustments are made which optimize engine characteristics with respect to low emissions, vehicle driveability performance parameters, such as acceleration, may be degraded.

Table 1-1. CLASSIFICATION OF RETROFIT METHODS

GROUP	TYPE	SUBTYPE	TITLE
1			EXHAUST EMISSION CONTROL SYSTEMS
	1.1		Exhaust Gas Control Systems
		1.1.1	Catalytic Converter
		1.1.2	Thermal Reactor
		1.1.3	Exhaust Gas Afterburner
		1.1.4	Exhaust Gas Filter
		1.1.5	Exhaust Gas Backpressure
	1.2		Induction Control Systems
		1.2.1	Air Bleed to Intake Manifold
		1.2.2	Exhaust Gas Recirculation
		1.2.3	Intake Manifold Modification
		1.2.4	Carburetor Modification
		1.2.5	Turbocharger
		1.2.6	Fuel Injection
	1.3		Ignition Control Systems
		1.3.1	Ignition Timing Modification
		1.3.2	Ignition Spark Modification
	1.4		Fuel Modification
		1.4.1	Alternative Fuel Conversion
		1.4.2	Fuel Additive
		1.4.3	Fuel Conditioner
2			CRANKCASE EMISSION CONTROL SYSTEMS
	2.1		Closed System
	2.2		Open System
3			EVAPORATIVE EMISSION CONTROL SYSTEMS
	3.1		Crankcase Storage
	3.2		Canister Storage
4			EMISSION CONTROL COMBINATIONS

1.2.1.1 Exhaust Gas Control Systems

One approach for reducing HC and CO is to subject the exhaust gas to an oxidation process. Among the retrofit devices studied, this was done by using either a catalytic converter, a thermal reactor, or an afterburner.

In the catalytic converter approach (Device 96), the exhaust gas is passed through a catalytic bed for oxidizing HC and CO to carbon dioxide (CO_2) and water.(1) The catalyst is not consumed in the oxidation reaction, but deterioration may result from use of fuels poisonous to the catalyst (such as leaded gasoline). The heat required to initiate oxidation comes from the exhaust gas itself. The oxygen needed for oxidation in the catalytic converter is provided either by leaning the fuel mixture at the carburetor or by the addition of air into the exhaust system.

The thermal reactor works in much the same way. In the case of the rich mixture reactor (Device 244), oxidation occurs as a result of air being pumped directly into the exhaust manifold near the exhaust valves. At that location the exhaust gas temperature is usually high enough to support oxidation of HC and CO without having to use a catalyst, if there is enough oxygen available. With the lean reactor (Device 468), additional air is not required, since the carburetor is set at an air-fuel mixture ratio which provides the required oxygen.

The exhaust gas afterburner (Device 308) also requires a fuel rich exhaust mixture. The exhaust gases are oxidized by incorporating an ignition source (such as a spark plug) in a muffler type container installed in the exhaust system.

In some designs, the catalytic, thermal, and afterburner approaches for oxidizing exhaust gas HC and CO also indirectly reduce NOx. Frequently, a fuel rich carburetor mixture inhibits NOx formation, mainly because of the lack of oxygen in the engine combustion chamber. These systems, however, require air to be pumped into the exhaust system to complete the oxidation of HC and CO.

The purpose of exhaust gas filters, such as Device 164, is to reduce or eliminate particulate emissions such as lead, carbon, or soot from the exhaust stream. There are several approaches for removing particulates, including mechanical filtering, electric precipitators, cyclone separators, fiberglass filters, and scrubber type devices.

1.2.1.2 Induction Control Systems

Retrofit devices of this type operate in general on the basis of either leaner air-fuel mixture ratio or improved distribution of the mixture. Lean fuel mixtures provide HC and CO reduction by reducing the amount of fuel taking part in the combustion process or by increasing oxygen availability. Although this same effect could be partially accomplished by adjusting the carburetor idle circuit to a lean mixture, some of the retrofit devices studied provide lean mixtures under all engine operating conditions. Device 1 does this by means of a variable valve that allows air to enter the intake manifold as a function of the manifold vacuum. Device 42 is another air-bleed system which provides lean mixture, but in this model the effect of the air

(1) All retrofit devices were assigned an identification number. Refer to Table 4-1 of this volume for summary descriptions.

bleed is to increase the air-fuel ratio during normal operation, not during idle or deceleration. Device 317 combines air bleed with richened fuel intake under high vacuum.

Device 33 provides leaner fuel mixtures by means of a carburetor modification in which the fuel bowl is vented to the intake manifold rather than to the atmosphere (as is the usual case). In this case, the high manifold vacuum conditions which occur at idle and deceleration reduce the pressure differential between the bowl and the carburetor venturi, thereby tending to decrease the amount of fuel entering the venturi.

The intake manifold modification systems depend on improved air-fuel distribution as a means of reducing emission levels. The intake manifold modification approaches (Devices 172, 430, and 440) use various intake manifold inserts (typically between the manifold and carburetor) to either diffuse the air-fuel mixture or to equalize distribution to the cylinders. Other approaches, such as carburetor modifications to improve the air-fuel mixture diffusion in the venturi section, were offered in the program (Device 295).

Recirculating a portion of the exhaust gases back into the induction system reduces peak combustion chamber temperatures, and is an effective method of reducing NOx. For example, recirculating 15-20 percent of the exhaust gas and mixing it with the intake gases may reduce NOx up to 60-80 percent. Those exhaust gas recirculation devices which were offered in this program also included disconnect of the distributor vacuum advance as a method of further reducing the formation of NOx and also enhancing the HC oxidation.

1.2.1.3 Ignition Control Systems

These retrofit types are based on two approaches to emission reduction. First the ignition timing modification approach uses the principle of retarding the ignition spark which increases the exhaust gas temperatures to the point where the exhaust will continue to burn in the exhaust manifold. This is an alternate way of accomplishing the same effect as that of the exhaust reactor systems. In addition, the combustion cycle peak temperatures are reduced, inhibiting NOx formation.

Second, the ignition spark modification approach is based on the concept that improved spark ignition, either through longer spark duration (Device 259) or higher voltage spark (Device 268) will improve combustion efficiency.

1.2.1.4 Fuel Modification

Fuel modification systems alter the normal combustion process by using different fuels (other than gasoline) or by adding a fuel additive to gasoline. Gaseous fuel conversion systems are designed to prolong engine life and to lower emission levels. However, special tuning is required for lower emission levels.

Fuel additives are designed to clean up carburetor and engine deposits with mileage accumulation or tend to keep deposit levels low when the engine and carburetor systems are new. In this program, fuel additives were not tested, because of the substantial mileage accumulation required to show the effect of the additive in reducing emissions.

1.2.2 Crankcase Blowby Emission Control Systems

Engine blowby results when the air-fuel mixture in the cylinder escapes past the piston rings during the compression stroke. A smaller amount of the blowby leaks past the rings during the power stroke. The blowby gases enter the crankcase and subsequently escape to the atmosphere from an uncontrolled vehicle.

Crankcase control systems provide a means of circulating ventilation air through the crankcase, mixing the air with the blowby gases, and recirculating the mixture into the intake manifold through a variable or fixed orifice control valve. The flow rate through the valve is normally controlled by intake manifold vacuum. Crankcase ventilation air is drawn either directly from the engine compartment (referred to as an open system), or from the engine air cleaner through a tubing into the crankcase (a closed system).

Among the retrofit blowby control devices studied, Devices 170 and 315 are closed systems. Devices 160 and 427 can be installed as open or closed systems. Devices 160 and 170 are currently accredited for use in California. All of these devices are basically the same, except that Devices 160 and 427 also have filters.

1.2.3 Evaporative Emission Control Systems

These systems control fuel evaporation from the fuel tank and the carburetor. No retrofit devices in this category were found to exist (except for the Device 165 combination system); however, a production fuel evaporative control system for new model vehicles was evaluated for retrofit feasibility.

Gasoline tanks and carburetors are vented to the atmosphere on pre-1970 vehicles sold new in California and on pre-1971 vehicles sold new nationally. Losses at the carburetor occur almost entirely during the hot soak period after shutting off a hot engine. The residual heat from the engine causes the temperature of the fuel bowl to reach 150-200°F, resulting in substantial boiling and vaporization of the fuel.

With high ambient temperatures (90-110°F), fuel tank temperature may increase up to 120°F while driving or parked. During driving, the hot air from the engine flows beneath the car and increases the fuel tank temperature. When parked over a hot surface, fuel tank temperatures are also increased. As a result, fuel evaporation occurs through the tank vents.

In one type of evaporative emission control system installed on 1971 and later model vehicles, the crankcase is used as a storage container for vapors from the fuel tank and carburetor. During the hot soak period after engine shutdown, the declining temperature in the crankcase causes a reduction in crankcase pressure sufficient to induct the evaporative emissions from the tank and the carburetor. Vapors emanating from the carburetor are drawn directly to the crankcase, while vapor from the fuel tank is first carried to a liquid-vapor separator. The liquid condensate returns to the fuel tank and the remaining vapors are drawn into the crankcase. When the engine is started, the crankcase is purged of the evaporative emissions through the positive crankcase ventilation system. A sealed fuel tank with a fill-limiting device is required to ensure that enough air is present in the tank at all times to allow for thermal expansion of the fuel. A pressure/vacuum relief gas tank cap is used to provide a safety valve for excess vacuum or pressures in the fuel tank.

In the absorption-regeneration system, a canister of activated charcoal traps the vapors. During a hot soak period, vapor from the fuel tank is routed to a liquid-vapor separator, and liquid fuel is returned to the tank. The remaining vapor, along with fuel vapor from the carburetor, is vented through the canister filled with activated charcoal that traps the fuel vapor. The vapors are purged from the canister and drawn back into the induction system for burning in the combustion chamber during engine operation.

A sealed fuel tank with a fill limiting device is also required in this system to allow for thermal expansion. A pressure/vacuum relief gas tank cap is used with this system to prevent excess vacuum or pressures in the tank.

1.2.4 Emission Control Combinations

Most of the retrofit devices evaluated combine two or more of the basic techniques of emission control. Because of the difficulty in classifying all combinations, the emission control combination group was reserved for those devices combining two or more of the group level control functions; for example, exhaust with crankcase emission control and/or with fuel evaporation emission control. Combinations within a group were classified according to the major type of retrofit hardware required; thus a catalytic converter with vacuum advance disconnect was classified as a catalytic conversion system within the exhaust gas control type, whereas an exhaust gas recirculation system with vacuum advance disconnect was classified as an EGR control within the induction modification type.

Under this classification system, four retrofit devices were classifiable as emission control combinations. Device 165 combines control techniques for all three sources of vehicle emissions. Device 408 combines exhaust gas control with blowby control. Device 469 combines exhaust gas and particulate control. The fourth device (Device 59) was not described by the developer other than that it controls all exhaust emissions.

1.3 RETROFIT DEVICE PERFORMANCE

The feasibility of using retrofit devices as a means of controlling emissions from cars that are either partly or totally uncontrolled is determined by the effectiveness and the costs of the devices. Effectiveness is determined mainly by the extent to which a device reduces vehicle emissions, and does so without causing unacceptable drawbacks in vehicle driving quality and general operating safety.

Costs are determined by the initial purchase price of the device, including the cost of installing it on a vehicle, plus the subsequent cost of operating and maintaining the vehicle with the device installed. Operating and maintenance costs of the installed devices are calculated by the change in vehicle fuel consumption, by the number of times it may fail partly or wholly during the vehicle's operating life, and by the frequency and type of maintenance required, including the cost of labor and materials.

1.3.1 Emission Reduction Effectiveness

All of the retrofit devices studied were evaluated for emission reduction effectiveness in terms of their capability to reduce exhaust emissions - the source of approximately 60 percent of vehicle HC emissions and essentially 100 percent of the CO and NOx emissions. The exhaust emission reductions of the devices were evaluated by comparing test data measured on a standard vehicle without the device installed (baseline) with test data on the same standard vehicle with the device installed (retrofit).

The mean emission reductions of the representative devices tested in the retrofit program are shown in Figure 1-1. These pooled mean reductions represent from 10 to 18 complete tests on each of the representative devices using the 1972 Federal Test Procedure. (Approximately half of the tests on each device were conducted in California and the other half were conducted in Michigan.) Figure 1-1 illustrates the pooled mean reduction that the representative retrofit systems can achieve, and the confidence levels for these data are shown in Figure 4-1 (see paragraphs 4.1.1.2 and 4.1.1.3).

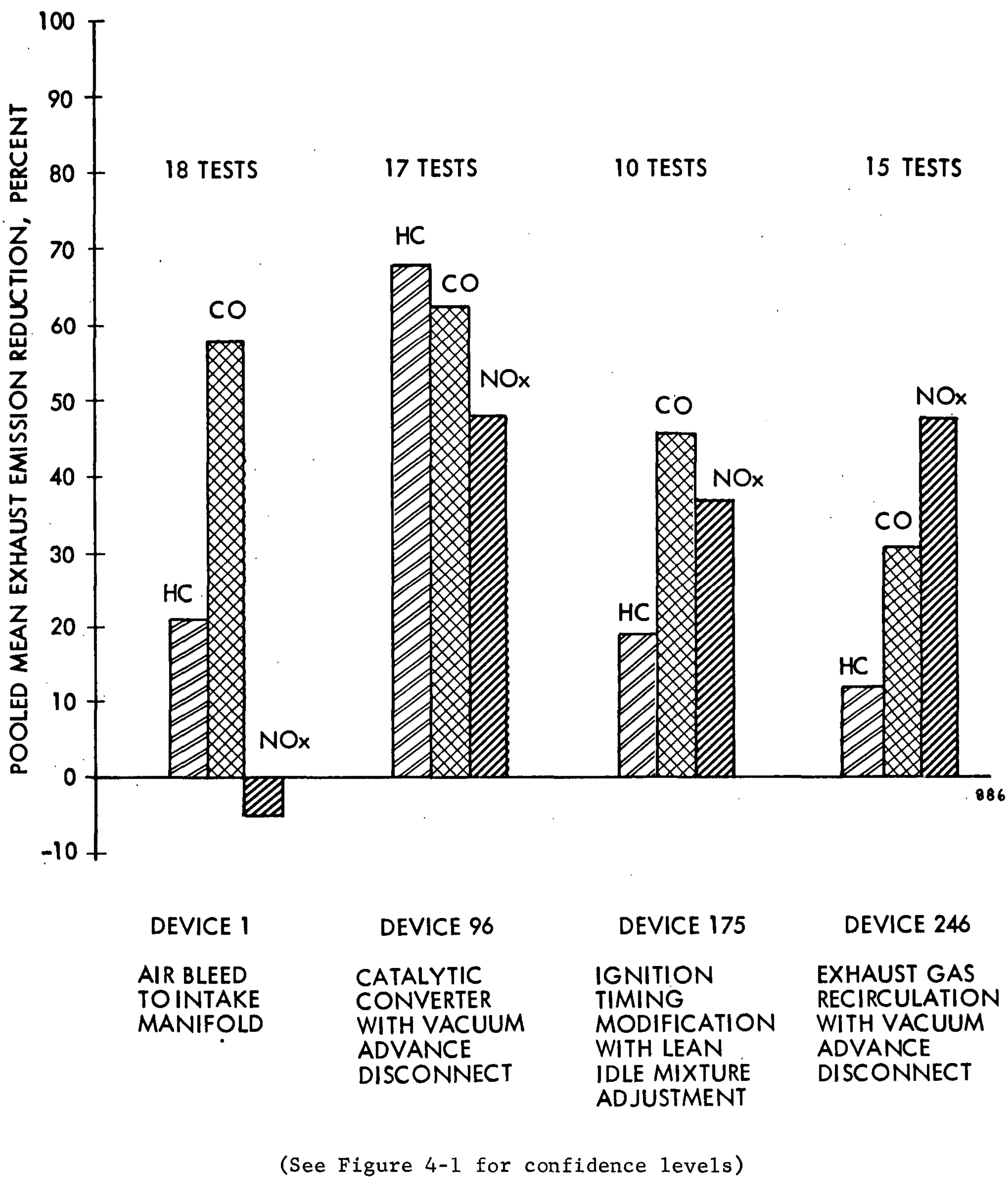
Figure 1-1 shows that catalyst systems with vacuum advance disconnect have the greatest potential for reducing all three exhaust pollutants (HC, CO, NOx). Air bleed to the intake manifold systems primarily reduce CO and, to a lesser extent, HC. The air bleed systems may show a slight increase in NOx because of the added availability of oxygen. The ignition timing modification (spark retard) retrofit device with lean idle adjustment is effective in reducing HC, CO and NOx. The exhaust gas recirculation system with vacuum advance disconnect is primarily an NOx control device, but some reduction of HC and CO is also obtained.

The results for the devices that received limited testing in the retrofit program are presented in Sections 4 and 5. Some of the other systems which were not tested in the retrofit program also showed substantial emission reduction. These data were supplied either by the retrofit developer (from a recognized test laboratory) or from tests conducted by the Environmental Protection Agency.

Thermal reactor systems with air pumps and exhaust gas recirculation showed average reductions of 80 percent for HC, 44 percent for CO, and 65 percent for NOx. These data are based on the EPA 9-cycle by 7-mode constant volume sampler test cycle.

A gaseous fuel (LPG) system showed an average emission reduction (based on 18 tests) of 81 percent for HC, 85 percent for CO, and 65 percent for NOx. Gaseous fuel systems have been found to have exhaust emissions of lower photochemical smog reactivity than gasoline systems (refer to paragraph 4.1.1.4 for additional comments on this subject).

Because previous studies have substantiated the potential of crankcase blowby and fuel evaporative control systems for reducing the HC associated with those emission



(See Figure 4-1 for confidence levels)

Figure 1-1. POOLED MEAN EXHAUST EMISSION REDUCTION OF DEVICES TESTED IN THE RETROFIT PROGRAM (ANAHEIM AND TAYLOR RESULTS COMBINED) sources, this aspect of the vehicle emission problem was not studied.(1) However, devices in both categories were evaluated for their installation requirements and costs as retrofit methods, and exhaust emission data provided by developers of blowby devices were evaluated.

Approximately 20 percent of an uncontrolled vehicle's total hydrocarbon emission comes from crankcase blowby. Closed blowby control systems will control all of the HC emissions at all operating conditions and will provide air ventilation to the crankcase. Open blowby control systems will control blowby emissions and provide crankcase ventilation at most operating conditions. At heavy engine loads, some blowby could escape from the crankcase through the open oil fill cap. The quantity of escaping blowby would depend on the flow characteristics of the blowby control valve. Since open blowby control systems are no longer legal on new cars, they would not be likely candidates for retrofit; their operational limits are noted to caution future evaluators who may be involved in the selection of retrofit devices for use.

A potential problem with combination air bleed and blowby systems is that, if improperly designed, they could cause excessively lean carburetion with resulting "lean misfire" and "surge."

About 20 percent of an uncontrolled vehicle's total hydrocarbon emissions come from the carburetor and fuel tank vents by evaporation of the fuel. Most of these emissions occur during periods when the engine is off. No retrofit fuel evaporation control system was available for evaluation as a single approach to evaporative loss control. One retrofit system was a combination of exhaust, crankcase, and fuel evaporation control, but no baseline emission data were provided by which to calculate reductions.

1.3.2 Driveability and Safety

Information on driveability and safety was usually unavailable from retrofit device developers, and that provided was, in most cases, unsubstantiated as to test procedure. Controlled driveability tests were conducted, however, on 11 devices tested in the retrofit program. In general, there were no driveability characteristics that would cause any of the devices to be considered infeasible. All of the systems tested slightly degraded the operating characteristics of the vehicles; however, a basic characteristic of most retrofit devices is the compromise of

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(1) Representative studies that have been performed in blowby and fuel evaporative emissions include the following:

- Rose, A. H., and R. C. Stahman, "The Role of Engine Blowby in Air Pollution," Journal of Air Pollution Control Association, Volume 11, No. 3, pp 114-7, March 1961.
- Bennett, P. A., M. W. Jackson, C. K. Murphy, and R. A. Randall, " Reduction of Air Pollution by Control of Emission from Automotive Crankcases," Selected SAE Papers on Vehicle Emissions, Volume 6, pp 224-53, 1964.
- Wentworth, J. T., "Carburetor Evaporation Losses," SAE Technical Progress Series, Vehicle Emissions, Volume 6, pp 146-156, 1964.
- Wade, D. T., "Factors Influencing Vehicle Evaporative Emissions," SAE Paper 670126, January 1967.

optimum driving and mileage performance to provide a degree of emission reduction. Acceleration times at wide open throttle were generally between 5 and 10 percent slower.

Fuel consumption variations were measured during the 1972 Federal Test Procedure for emissions and the results of the four devices that received up to 18 tests were as follows:

The ignition timing modification system caused an average 10 percent less miles per gallon, and the catalyst system with distributor vacuum advance disconnect had essentially no effect on gasoline mileage. The exhaust gas recirculation system with vacuum advance disconnect and the air-bleed-to-intake-manifold system caused an average miles-per-gallon increase of 7 percent and 4 percent, respectively.

The exhaust gas control systems, such as catalytic and thermal reactors, were found to be relatively free of adverse driveability characteristics. Since these devices have to operate at high temperatures (up to 2,000°F), they have potential safety problems unless adequately insulated.

On cars that already have lean carburetion, the air-bleed-to-intake-manifold retrofit systems could possibly cause excessively lean carburetor mixtures which might lead to surging and hesitation problems.

The ignition timing modification system indicated a minor adverse effect on acceleration, but appeared to present no additional safety or driveability problems.

1.3.3 Reliability, Maintainability, and Inspection Requirements

All retrofit devices were found to have acceptable reliability and maintainability characteristics provided that conventional automotive design standards are applied to production models. Almost any retrofit component designed to normal automotive functional, cost, and production standards may be expected to exhibit a useful life of 50,000 miles or more, provided that good maintenance habits are followed.

Most of the retrofit devices evaluated in the program have acceptable periodic maintenance requirements. Most of these devices require 0.5 hour or less to maintain, and have a maintenance parts cost of $3.00 or less. Maintenance costs are generally higher for those devices incorporating ignition timing or spark duration as a control technique if the whole unit must be replaced when failure occurs. Only two devices indicated maintenance requirements at less than 12,000-mile intervals. About one-third of the devices evaluated indicated maintenance requirements only after 25,000 or more miles. The catalyst system tested in the retrofit program requires a new charge of catalyst at 25,000-mile intervals at a cost of $20 for an 8-cylinder engine and $15 for a 6-cylinder engine.

Increased maintenance and reduced reliability imposed on the vehicle as a result of a retrofit device was also evaluated. For example, spark retard generally increases temperature of gases passing through exhaust valves and may induce engine overheating. Exhaust gas recirculation may cause induction system deposit buildup. Use of catalytic reactors, thermal reactors, and afterburners poses potential problems of increased exhaust system backpressure and increased temperature which may cause excessive valve operating temperatures. To investigate the long-term effect of some of these operating characteristics, durability tests were performed on four representative devices. These tests will be documented in Volume VI.

A periodic vehicle inspection program is recommended as a necessary part of any program of vehicle emission control incorporating retrofit devices. The purpose of this program would be to ensure that the retrofit device functions effectively after installation as well as during its lifetime. Inspection of vehicles equipped with retrofit devices would require measuring HC, CO, and possibly NOx levels. An emission limit would have to be established for each pollutant. For those retrofit devices and systems that perform as a function of engine speed, such as the ignition timing modification type, the desired test procedure would have to simulate different road speeds to provide complete evaluation of the installed retrofit system. If the exhaust control technique is independent of road-load conditions, then an idle test may be sufficient.

Retrofit crankcase emission control systems should be subjected to an operational check and a visual component inspection. These devices may be inspected using crankcase vacuum or pressure as a means of establishing failure levels.

There is no information on what would be the inspection requirement for retrofit fuel evaporative emission control systems. The pressure/vacuum safety relief systems could be inspected with pressure gage instrumentation.

1.3.4 Initial and Recurring Costs

Initial costs consist of the material costs and labor costs necessary to complete a retrofit installation.

Additional costs for engine tuneup prior to device installation must also be considered if this procedure is specified as part of the installation. However, because of the contract exclusion of tuneup as a retrofit method, only the tuneup requirements directly related to the retrofit device installation were considered.

Recurring costs are those associated with retrofit repair and maintenance. Fuel consumption increase or decrease, where it was known, was also included in this category.

The initial costs of the more effective devices were generally higher than the less effective devices. For example, the initial cost of the catalytic converter with vacuum advance disconnect, which controls all three pollutants, was reported to be $175, including an air pump. At the other extreme, the less effective air-bleed-to-intake-manifold systems ranged from $23 to $64. For the NOx control systems, ignition timing modification and exhaust gas recirculation, initial costs ranged from $45 to $89.

Because the gasoline mileage factor is a sensitive factor in the amount of recurring cost, it should be accurately determined prior to drawing final conclusions on the total costs of any particular retrofit method. When recurring costs were computed in the retrofit study, the effect of fuel consumption changes were included for those devices which were tested. This effect was excluded from the recurring cost of the other evaluated systems because most developers did not submit fuel consumption data, and many of those who did submit data reported improvements in economy which were questionable.

1.3.5 Installation Skill Level and Training Requirements

Analysis of the detailed installation and adjustment procedures for retrofit devices showed that most retrofit system types would require a skilled automotive mechanic to perform the installation. The principal consideration in this requirement is the need for regulated quality control of device installation and subsequent maintenance, inspection, and repair. It is essential that device installation include emission testing to verify that the emission control effectiveness of a device is achieved (see paragraph 4.3.3).

The physical installation of the devices evaluated requires normal automotive mechanic skills. However, most auto mechanics are not presently trained to properly adjust a retrofit device and related engine tuneup parameters for low emissions. Technician upgrading and training programs would be required for a successful and effective retrofit program. Such training would provide certified mechanics to operate licensed retrofit installation and maintenance centers. Further, the training would also provide the inspectors for quality surveillance of the retrofit program.

1.4 EVALUATION METHODOLOGY

The relative effectiveness and costs of retrofit devices were analyzed by means of an evaluation methodology which quantitatively and qualitatively considered all significant device performance parameters and criteria. This methodology was structured in three general segments for evaluation. These segments were criteria, performance, and cost effectiveness, each providing successively refined evaluations. The basic evaluation criteria used in the retrofit program are listed in Table 1-2.

The emission standards and installation cost criteria used in this study were identical to those specified by law in California's used car standards. The used car emission standards were applied only to the 7-mode exhaust emission test data supplied by the developer (see Note 1 in Table 1-2). Other criteria, such as the installation and maintenance labor rate, were developed on the basis of standards in the automotive industry. These criteria can be adjusted by States and other agencies responsible for vehicle emission control to meet their special requirements.

Results of the evaluation methodology are summarized in Section 5.

1.5 DEVELOPMENT STATUS AND APPLICABILITY

Most retrofit devices are available in at least the prototype form. At least 25 devices are either being marketed or are ready to be marketed. Some are being marketed for purposes other than emission control, such as improved engine performance. The study indicated that several devices could become readily available shortly after there is a clear definition of specific standards or criteria, if these criteria are less stringent than California's.

Table 1-2. PERFORMANCE PARAMETERS AND EVALUATION CRITERIA

FACTOR	CRITERIA
1. Emission Index Factors	
a. Emission standards (1)	
HC	Less than 350 ppm or 4.5 gm/mi
CO	Less than 2.0% or 47.6 gm/mi
NOx	Less than 800 ppm or 3.0 gm/mi
b. Emission baseline	No increase of any pollutant beyond an allowable experimental error (2)
2. Driveability and Safety Index Factors	
a. Safety	No hazardous conditions
b. Critical driveability	No stall on acceleration No hot idle stall No backfire
c. General driveability	Driveability Index less than 1.0 (refer to para. 3.1.5)
3. Cost and Cost-Related Index Factors	
a. Installation cost (including kit)	Less than $85.00, including labor at $12.50 per hour (3)
b. Recurring cost	Less than $15.00 per year ($0.125 per 100 miles) (4)
c. Reliability	At least 50,000 miles of operation before total failure
d. Maintainability	At least 12,000 miles of operation before periodic maintenance is required
e. Availability	Less than 1 repair hour per 12,000 miles of operation (4)

(1) The volume concentration values are the California used car device accreditation standards as specified in California Health and Safety Code Chapter 4, Article 2, paragraph 39107 (refer to Volume IV, Appendix E). These standards are for the 7-mode cold-start test cycle specified in the 1970 Federal Test Procedure (see pertinent comments and cautions in Volume III, Section 5.1). The grams per mile (gm/mi) correlated with the above standards were calculated for a 4,000-pound vehicle in accordance with the method set forth in the 1970 Federal Test Procedure. If the evaluator intends to use the 1972 Federal CVS Test Procedure, appropriate used car standards must be established for that test procedure.

(2) In this report, an experimental error of +10% was used.

(3) $12.50 per hour based on California repair labor average.

(4) Average miles driven per year assumed to be 12,000 miles.

The retrofit evaulations conducted in this study were primarily aimed at uncontrolled vehicles, which were not originally equipped with exhaust control devices (pre-1968 nationally and pre-1966 in California). However, some retrofit methods are applicable to vehicles which already have partial exhaust control devices installed as original equipment (1968 and later model-year cars nationally and 1966 and later model-year cars in California).

Almost all of the retrofit exhaust control systems evaluated are applicable to pre-1968 domestic vehicles with varying degrees of emission reduction effectiveness. In general, retrofit systems are not yet available for foreign used cars.

The study showed that the catalytic converter systems might be applicable for retrofitting all used cars. Exhaust gas recirculation systems would be applicable to both uncontrolled and partially controlled cars. Distributor vacuum disconnect would also be applicable to both groups of cars.

Air bleed to intake manifold systems can be easily retrofitted to both controlled and uncontrolled vehicles. However, on vehicles which are already factory equipped with exhaust and crankcase blowby control systems, the use of air bleed retrofit systems may cause excessively lean carburetion that may lead to lean misfire.

In summary, it cannot be concluded that retrofit technology is directly applicable to 1968 and later model-year cars without further testing of individual devices. However, some of the retrofit methods evaluated may be feasible on these cars.

Of the devices evaluated, seven have been specifically developed for used car retrofit to the extent necessary for approval in California, the only State presently with a specified retrofit program and used car emission standards. These devices were approved by the California Air Resources Board and are currently being developed or produced for mass marketing in California. Device 175, the ignition timing modification system tested in the retrofit program, was accepted in November 1971. Devices 160 and 170, crankcase blowby controls, were accepted in 1963 and 1965, respectively. The other four (Devices 52, 459, 460, and 466) are all gaseous fuel systems approved since 1969.

1.6 GUIDELINES FOR SELECTING AND IMPLEMENTING FEASIBLE RETROFIT METHODS

The implementation of a retrofit method of vehicle emission control must consider the present and future requirements with respect to changing vehicle control conditions, to ensure a continuous, satisfactory program. The recommended steps for implementation are:

a. Defining the emission reductions required from the used car population.

b. Defining the characteristics of the used vehicle population to which retrofit methods are applicable.

c. Identifying candidate retrofit methods for application to that vehicle population.

d. Determining which retrofit methods are most cost effective for the emission controls to be implemented, giving due consideration to facilities and labor requirements for implementing the retrofit program.

e. Identifying the retrofit device certification program.

f. Conducting the cost effectiveness studies required to verify the retrofit approach as being the most appropriate method of emission control.

g. Preparing an implementation plan.

h. Initiating and maintaining the implementation plan.

The evaluation methodology developed through this study should provide an essential tool in the planning and implementation of optimum retrofit programs.

A retrofit device is feasible if its overall effectiveness in reducing emissions and maintaining reasonable driving quality is sufficient to justify the costs of obtaining that effectiveness. More specifically, the feasibility of a retrofit device depends on its effectiveness and costs for particular emission control applications. A device might appear infeasible when compared with other devices because of the fewer number of pollutants it controls or the lesser magnitude of control it achieves. However, it could be entirely adequate for a particular emission control situation in which the scope and magnitude of control offered by the device is exactly what is needed. Ultimately, therefore, retrofit device feasibility depends on the emission control situations faced by individual air quality control regions.

In addition, the success of a retrofit program depends heavily on the availability of the required facilities for installation and maintenance of the retrofit devices.

1.7 RECOMMENDATIONS

The following programs are recommended as future research and development efforts in support of retrofit method implementation:

a. The applicability of retrofit methods to vehicles factory equipped with emission control techniques should be studied as a means of achieving maximum continuity of the retrofit approach. An example of this recommendation would be to retrofit and evaluate NOx type control devices on 1966 through 1970 model cars in California and 1968 through 1972 vehicles elsewhere in the nation.

b. The maintenance requirements of the cost effective retrofit devices will require that provisions for a maintenance inspection program be planned and implemented concurrently with the promulgation of any legislation requiring the use of retrofit devices on a mandatory basis. A study should be implemented to determine the procedures, criteria, personnel, instrumentation, facility, and training requirements of a maintenance inspection program to support any mandatory use of retrofit devices. This program would be designed to ensure that the inherent cost effectiveness of a retrofit device is not compromised by inattention to maintenance requirements of the device.

c. Upgrading of the automotive service industry through supplemental training programs would be required to provide correct tuneup adjustments to vehicles with retrofit devices installed. The scope and requirements of such upgrading should be studied and specified for the principal types of devices. The cost impact of an upgraded service industry on the cost effectiveness of retrofit devices should also be determined.

2 — RETROFIT PROGRAM APPROACH

SECTION 2

RETROFIT PROGRAM APPROACH

The program objective to determine what methods of emission control can be feasibly retrofitted to light duty used cars required that the retrofit program approach be directed toward determining the effectiveness and costs of retrofit devices. This was accomplished by means of a comprehensive retrofit method and developer data survey, system tests, and engineering analysis. The data survey provided information of varying levels of completeness from all sources of available information on retrofit methods and developers that could be identified. The system tests provided a set of emissions, fuel consumption, and driveability test data from two widely separated geographical areas in the U.S. for a range of representative retrofit devices that could be tested within the schedule constraints of the program. The engineering analysis provided system descriptions of the devices for which adequate data were obtained through the data survey and the system tests. The results of this analysis were combined with the emissions and other performance data to provide quantitative inputs to the performance analysis of each retrofit method.

2.1 RETROFIT METHOD SURVEY

The retrofit program was initiated by performing a thorough search for all sources of information on retrofit methods and developers. The objective of the retrofit method survey was to search all reliable sources for available information, and to assemble as much relevant information as possible on retrofit emission control techniques existing for light duty vehicles. This information survey encompassed present and potential emission control retrofit methods applicable to pre-1972 motor vehicles in the light duty gasoline-powered class (less than 6,000 pounds gross vehicle weight). This search was performed on an international scale. Each potential source of information about retrofit devices being produced or manufactured was sent a letter describing the purpose of the program and requesting their participation in the program. Each respondent expressing interest in participating and who was an actual candidate retrofit method developer was sent a request to provide data on his device. These data were used to screen the devices by type of retrofit method, and to rank them based on their feasibility. The most feasible and representative devices were selected for the retrofit test program.

The Air Pollution Control Association (APCA) Directory and the Society of Automotive Engineers (SAE) Roster Issue were used initially to identify retrofit developer sources. Additional source identifications were made utilizing:

- Environmental Protection Agency (EPA) files
- California Air Resources Board (ARB) files
- Olson Laboratories Testing Services files
- Inquiry to air quality agencies at Federal and State levels
- A patent search conducted by the Northrop Legal Staff
- A general news release.

The approach to the retrofit method survey consisted of the following steps:

a. Identifying the sources of retrofit devices.

b. Transmitting a letter of inquiry to these sources, requesting their participation in the program or the identification of other retrofit developer sources. (The developer was requested to submit a letter of intent to participate in the retrofit program.)

c. Transmitting a survey questionnaire to interested sources to obtain detailed information about the technical and cost characteristics of their respective retrofit devices.

d. Recording of data questionnaire responses.

The data survey questionnaire was designed to obtain from the retrofit method developer the full scope and depth of information required to perform a comprehensive system analysis and evaluation of the device submitted. The questionnaire was structured to provide qualitative and quantitative data in the following categories:

a. System Information - Including system technical description, emission control category, development status, and vehicle adaptability.

b. Performance Data - Including emission reduction, reliability, maintainability, and driveability.

c. Cost Data - Including initial and recurring costs.

d. Marketing Plan

2.2 RETROFIT METHOD SCREENING EVALUATION

The information obtained from each retrofit developer source that responded favorably was reviewed to identify the device category, level and reliability of emission reduction, availability of device for testing, cost, and the adequacy of data by which to perform a complete system analysis of the device. This information was tabulated for each device to establish an overall preliminary ranking of devices. The test candidate devices were identified on the basis of how well they represented the generic retrofit groups, on average emission reduction potential, on development status, on availability for testing, and on cost. Members of the OLI-Northrop-EPA Technical Review Board then reviewed the test candidate retrofit systems and made the selections of the devices that would receive evaluation in the test program. The remainder of the candidate systems received an engineering analysis by a Northrop-Olson staff of engineers from the data supplied by the retrofit developer.

Table 2-1 lists those retrofit system types which were candidates for the test program. Crankcase blowby control devices were eliminated from test evaluations because adequate data were already available for the engineering evaluation. Fuel additives were also eliminated from the laboratory test evaluation because the required mileage accumulation to show the emission reduction effects was beyond the scheduled time limits of the study.

Nine systems were selected for evaluation on two vehicles. After the initial selection the device manufacturers were notified. One of the selected device manufacturers

Table 2-1. RETROFIT SYSTEM TYPES TESTED IN RETROFIT PROGRAM

DEVICE NO. (1)	DESCRIPTION
Up to 18 Tests Per Device	
1	Air Bleed to Intake Manifold
96	Catalytic Converter with Distributor Vacuum Advance Disconnect
175	Ignition Timing Modification with Lean Idle Adjustment
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect
Up to 3 Tests Per Device	
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect
33	Carburetor Modification, Main Jet Differential Pressure
42	Air Bleed to Intake Manifold
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification
245	Variable Camshaft Timing
288	Carburetor Main Discharge Nozzle Modification
295	Carburetor with Variable Venturi
(1) Devices evaluated are identified in Table 4-1.	

declined to participate and one system was not available during the test period. Four retrofit systems were selected to receive evaluation on 13 test vehicles. Detailed selection procedures and identification of the retrofit systems that were evaluated in the test program are presented in Volume III, Section 4.

2.3 ENGINEERING ANALYSIS

The purpose of the engineering analysis of retrofit control devices was to (1) determine the acceptability of the data provided by the development sources, and (2), when possible, develop additional or supplementary data that could be used as inputs to the evaluation methodology. The approach for the engineering analysis was to initiate the preparation of retrofit system descriptions from the information obtained through the retrofit method survey and the test program. These descriptions were used in the performance analysis. Each system description included physical, functional, and performance characteristics; driveability, maintainability, and safety analyses; installation description; initial and recurring costs; and a feasibility summary. Detailed system performance parameter analyses descriptions were prepared by a team of engineers representing the key technologies of retrofit device design. A discussion of the system description format and the approach to performance parameter analysis is presented in Volume III, Section 4.

2.4 TEST PROGRAM

A summary of the test vehicle fleet, test requirements, and test approach for the retrofit test program is presented in the following subparagraphs. The detailed test procedures are presented in Volume IV, and the test results are presented in Volume III.

2.4.1 Test Vehicle Selection

The contract called for a maximum of 24 cars to be divided into two replicate fleets; half in Taylor, Michigan, and half in Anaheim, California.

The rationale for the replicate fleets was to isolate retrofit system performance differences, if any, which could possibly be attributable to driving conditions, geographical location, and vehicle climatological exposure history at two disparate locations in the U.S., and any possible bias in testing facilities and personnel.

Table 3-1 of Volume IV briefly describes the test fleet by model year, engine size, and location. The California and Michigan fleets were identical in most respects. Backup vehicles were purchased to replace some of the initial fleet in the event of major vehicle failures.

Prior to the purchase of a test vehicle, an intensive screening inspection was conducted. First, an overall vehicle inspection included a visual check of safety related items such as tires, wheel alignment and brakes. Second, the vehicle received an engine condition inspection. Measured blowby flow rates were compared to the California Blowby Procedure (Volume IV, Appendix F). Cars were selected which had normal blowby flow rates within the fourth to seventh population decile. Cranking compression pressures were measured. If the cylinder compression pressures measured within a range of 10 psi between cylinders, the car was acceptable. The engine condition criterion was to accept cars which were in reasonable condition and would not need any major engine repair throughout the test program. Hydrocarbons and carbon monoxide emission levels were measured at idle and at 2,500 rpm (free running). These data were used to diagnose the condition of the carburetor prior to tuneup procedures. Ignition system malfunctions were determined with an ignition analyzer scope. The vehicles were accepted if they met the overall vehicle and engine condition criteria. However, carburetor and ignition system malfunctions were not grounds for rejection.

2.4.2 Test Program Procedures

As each vehicle was procured, an "as received" exhaust emission test and a driveability test were conducted. It was then tuned to the auto manufacturer's specifications to minimize the possibility of tuneup malfunction during the subsequent retrofit system tests and to establish a reproducible baseline. The basic objective here was to evaluate the performance of the retrofit device, not the effect of tuneup. The vehicle then received a series of baseline (after tuneup) exhaust emission tests and driveability tests. After each baseline test, the vehicle was equipped with the candidate retrofit system for exhaust emission and driveability tests. The tests alternated between the baseline and retrofit system tests until testing of all candidate systems was complete.

The 1972 Federal Test Procedure was used to measure the exhaust emissions of the baseline and retrofit vehicles.(1) The Federal exhaust emission tests consist of prescribed sequences of fueling, parking (cold soak), dynamometer operating conditions, sampling, and analytical calculations. The exhaust test is designed to determine hydrocarbon, carbon monoxide, and oxides of nitrogen on a mass emissions basis while the vehicle is simulating an average urban type trip of 7.5 miles. Following a 12-hour soak with the engine off, the test vehicle is "driven" on a chassis dynamometer through a prescribed driving schedule. All of the exhaust gas is collected and diluted with air, and then routed through a constant volume sampling (CVS) system. A proportional sample of the diluted exhaust emissions is collected continuously in an inert plastic bag for subsequent concentration analysis and the analytical calculations. After the driving cycle is completed, the diluted exhaust sample is analyzed for volumetric concentrations of hydrocarbons, carbon monoxide, and oxides of nitrogen. Mass emission levels are then calculated using applicable pollutant gas densities and correction factors.

Fuel consumption was measured during the baseline and retrofit exhaust emission tests. The fuel consumed during the driving cycle was measured by weight. The net amount of fuel consumed during the test was calculated and converted to miles per gallon.

The Automobile Manufacturers Association (AMA) standard driveability test procedure was used to evaluate the operating characteristics of the vehicle on the road (refer to Volume IV, Appendix G). Basically, the procedure consists of a cold start driveaway following an overnight soak period. A hot start driveaway procedure follows the cold start driveability tests. The cold start evaluation consists of engine startup, idle, and part throttle and full throttle acceleration modes up to 30 mph. The hot start consists of a series of cruise, acceleration, and idle modes of operation, and hot start restart evaluations.

The quality of each driving mode was noted by the driver and recorded by an observer during each mode of operation. Vehicle performance was determined at wide open throttle from 0-60 mph by measuring the elapsed time. Driveability tests were also performed to determine whether environmental extremes (such as high altitudes and low temperatures) had any significant performance effect on vehicle driveability when a retrofit device was installed.

The durability tests consisted of driving the retrofit device equipped cars for 25,000 miles and measuring the exhaust emissions at 5,000-mile increments. Mileage accumulation was performed on a test route which consisted of freeway, urban, and suburban driving at an average speed of approximately 35 mph. Fuel consumption and driving anomalies were recorded daily.

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(1) Federal Register Volume 35, Number 219, Part II, dated 10 November 1970. The test procedure for NOx evaluation was published subsequently in Federal Register Volume 36, No. 128, Part II, dated 2 July 1971.

2.5 PERFORMANCE ANALYSIS

Data developed through the engineering analysis and system tests were utilized to evaluate the candidate retrofit systems for their relative effectiveness and costs.

A mathematical methodology was developed to organize the many effectiveness and cost variables for uniform and objective evaluations. This model was implemented on IBM Model 360/65 and 370/165 computers in H-level FORTRAN. Data obtained from the system tests and from the engineering analysis were processed through the methodology's qualitative and quantitative analysis of each retrofit system.

The methodology itself was a beneficial byproduct of the retrofit study, and is summarized more fully in the next section.

3 – EVALUATION METHODOLOGY

SECTION 3

EVALUATION METHODOLOGY

A major objective of the retrofit study was to compare the overall performance of the various devices relative to each other. Quantitative indexes were developed so that an objective evaluation could be made and the devices numerically ranked. Three principal numeric indexes - criteria, performance, and cost effectiveness - were developed. The detailed evaluation methodology is presented in Volume III, and is summarized below.

The evaluation methodology is structured in three equations:

a. Criteria Index: This is a qualitative index designed to provide a gross indication of whether a particular device meets the various legally imposed constraints such as emission reduction effectiveness, cost, and useful life, as well as fundamental customer demands such as gross safety and vehicle performance requirements.

b. Performance Index: This index quantitatively evaluates the performance of the device. It is composed of the weighted sum of an emission reduction index, a driveability index (what the device does to the vehicle operation), and a cost index. The performance index provides a more refined evaluation of device performance.

c. Cost Effectiveness Index: This index is the ratio of the emission reduction index to the cost index (both are from the performance index expression). It provides a measure of the emission reduction a given device would achieve for the money expended.

3.1 CRITERIA INDEX

The Criteria Index screens a device for a "yes" or "no" answer as to its basic feasibility. The Criteria Index can be expressed as a product of terms, each of which has a value of either 1 or 0. It provides the evaluator an indicator as to whether a device will meet the various legislated constraints or limiting values specified for each performance parameter.

If the Criteria Index calculation is 1, it means the device has met the legal and implicit requirements for all criteria factors. If the Criteria Index calculation is 0, it means the device did not pass one or more of the specified requirements. The device is thus flagged as being substandard for at least one of the given set of criteria used. Some of the limits, however, may be flexible to allow for criteria changes due to differences in State or regional air quality control requirements.

The Criteria Index comprises the following factors:

Emission Factors

1. Emission standards - for HC, CO, and NOx

2. Emission baseline - prevents emission increase

Driveability and Safety Factors

3. Safety - device affects vehicle operation and occupant safety

4. Critical driveability - stall on acceleration, idle, or backfire

5. General driveability - vehicle operation degradation due to device installation

Cost and Cost Related Factors

6. Installation cost - initial cost of parts and labor

7. Recurring cost - incremental costs related to device upkeep following installation

8. Reliability - mileage to partial or total failure of device

9. Maintainability - required periodic maintenance

10. Availability - time inconvenience to car owner due to device failure.

A check is easily made of the above terms to determine which one is causing a Criteria Index of zero. A decision can then be made regarding the significance of the problem. The Criteria Index is a gross screening process and may be used to exclude the device from further evaluation.

Detailed definitions of the Criteria Index are presented in Section 3 of Volume III.

3.2 PERFORMANCE INDEX

The Performance Index provides a quantitative evaluation of a device. The Performance Index (PI) shows whether the emission reduction benefit of a device is relatively greater than its cost and driveability penalties; and how much greater the benefit is.

The PI is represented by a summation expression to obtain relative and quantitative ratings of the devices under evaluation. This expression allows evaluation of a device even if it does not pass certain State or regional evaluation criteria.

The PI expression comprises three terms, each of which is quantified by a different unit of measure. The first term is the Emission Index. It has no dimension, since it is expressed as a per unit reduction. The second term is the Driveability Index. It is measured by rating points based on the driver's observation of various vehicle operating characteristics. The third term is the Cost Index, which carries the units of dollars per 100 miles.

In order to add these individual indexes together, scaling factors (S_i) have been included to establish a common measurement scale. Weighting coefficients (C_i) are required to reflect the evaluator's choice as to the relative degree of importance given to each index.

The overall Performance Index is expressed by the following equation:

$$PI = \frac{C_1 \left(\begin{array}{c} \text{Emission} \\ \text{Index} \\ \text{Per Unit} \\ \text{Reduction} \end{array} \right) - C_2 \left(\begin{array}{c} \text{Driveability} \\ \text{Index} \\ \text{Points} \end{array} \right) - C_3 \left(\begin{array}{c} \text{Cost} \\ \text{Index} \\ \$/100 \text{ Miles} \end{array} \right)}{C_1 + C_2 + C_3}$$

The Emission Index is the sum of the weighted percentage reduction of each of the considered pollutants. Emission tests are conducted both with and without the device installed to determine the emission reduction benefit. The Driveability Index is determined by assessing what might be considered demerits for abnormal driving characteristics (rough idle, detonation, surge, etc.). Again, the tests are conducted with and without the device installed to determine the degradation in driveability.

The Cost Index combines the initial costs of the device and the recurring costs. Cost Index parameters are measured in terms of the retail cost of the device in dollars, the installation cost (based on number of hours to install times the hourly labor rate), the cost of maintenance, the cost of repair, and the cost of operation over the estimated service life of the device.

To compute the overall Performance Index, experienced judgment must be exercised in assigning the three weighting coefficients, C_1, C_2, and C_3. The coefficients given to the Emission, Driveability, and Cost Indexes can greatly influence the relative ranking of the devices. For example, if one were to weight driveability by a high coefficient, as compared to a low coefficient used to weight the Emission Index and Cost Index, a device with high driveability rating could be ranked relatively higher than the more cost effective devices. If driveability is the evaluator's major concern, then such weighting is proper. However, one must be aware of the effect that the weighting coefficient decision can have on the relative ranking of the devices. The rationale for establishing coefficients used in this program is discussed in Volume III, and it is important to recognize that these values represent the best judgment of the study personnel. The equations were designed so that the coefficients could easily be changed depending on the judgment of the specific emission control agency using this evaluation methodology.

3.3 COST EFFECTIVENESS INDEX

The Cost Effectiveness Index (CEI) is intended to provide additional information to complement the Performance Index. Should two or more devices have essentially similar Performance Indexes, the one with the highest Cost Effectiveness Index would be preferred. Cost effectiveness is usually defined as the rate of the desired results or the desired output versus the required cost input. In this case the CEI is defined as the ratio of the Emission Index to the Cost Index. In evaluating an emission control device, the desired output is the per unit reduction of the objectionable pollutant (Emission Index). The required cost input may be expressed as the total cost in terms of dollars per 100 miles driven (Cost Index). The Cost Effectiveness Index (CEI) is expressed by the equation:

$$CEI = \frac{\text{Emission Index, per unit reduction}}{\text{Cost Index, \$/100 miles}}$$

3.4 SENSITIVITY ANALYSIS

A sensitivity analysis of the Driveability and Cost Indexes was conducted (see Volume III, paragraphs 6.2.2 and 6.3.4). Among all parameters measured for these indexes, a change in fuel consumption showed the most sensitivity. To illustrate, a 10 percent loss in fuel consumption caused by a device would increase the Cost Index by 62 percent. A 20 percent change in the other terms of the Cost Index would change the Cost Index by 10 percent or less. A 20 percent change in the various Driveability Index terms could cause a Driveability Index degradation up to 13 percent.

SECTION 4

RETROFIT DEVICE EVALUATIONS

Each retrofit device studied was evaluated to determine the effectiveness with which emissions are controlled, the influence of such control on vehicle operating performance, and total costs. This evaluation was performed on those devices for which adequate information either could be obtained from the retrofit developers of the devices, or could be developed by test and analysis within the time frame of the study. Based on data obtained or developed in this way, it was possible to evaluate 65 devices in varying degrees of completeness. These devices are listed in Table 4-1 by the control number used to identify each during the study. The system description for each device evaluated is presented in Volume II (see Appendix B). Volume V includes a list of all known retrofit developers, each of whom was invited to participate in the program. The effectiveness and costs of the devices evaluated are summarized in the following paragraphs.

4.1 EMISSION REDUCTION

Eleven devices were tested using the 1972 Federal Test Procedure.(1) The average emission levels obtained for each device in these tests are listed in Table 4-2.

Use of these data in evaluating the emission reduction effectiveness of the devices has to consider that the reliability and significance of the data depends on the type of emission test procedure by which the data were measured and the number of tests that were performed. As shown by Table 4-2, the type and number of tests vary considerably among the devices evaluated. The higher the number of tests, the more reliable the emission data are. The 1972 Federal Exhaust Emissions Test Procedure is currently the most representative test for actual driving conditions and also the most accurate for determining the actual amount of automotive pollution being emitted to the atmosphere.

Table 4-3 lists the same devices by related retrofit categories, based on the similarity of the emission control approaches employed. Up to 18 tests were performed on one retrofit device from each of the following representative types within the Exhaust Emission Control Systems Group:

a. Exhaust Gas Reactors: CO and HC are oxidized to nonpolluting carbon dioxide and water either by catalytic or thermal reaction.

b. Exhaust Gas Recirculation with Distributor Vacuum Advance Disconnect: The recirculated gas and spark retardation decrease peak cycle temperature, thus inhibiting NOx formation. Spark retardation also produces higher exhaust gas temperature, which results in greater HC oxidation.

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(1) Refer to footnote, page 2-5.

Table 4-1. DEVICES EVALUATED IN THE RETROFIT PROGRAM

DEVICE	DEVICE TITLE	PURPOSE	GROUP
1 (1) (2)	Air Bleed to Intake Manifold: Air bleed to intake manifold through adjustable valve open to ambient airflow.	Lean air-fuel mixture.	1.2.1
10 (2)	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect: Carburetor fuel vaporization modification, combined with throttle-position controlled exhaust gas recirculation through intake manifold; and with temperature-controlled vacuum advance disconnect.	Improve air-fuel diffusion, lower combustion temperatures and increase exhaust gas oxidation.	1.2.2
22 (1)	Electronic Fuel Injection: Electronically regulated fuel injection.	Optimize air-fuel mixing.	1.2.6
23 (1)	Electronic Ignition Unit: Electronic modification to coil.	Enhance combustion ignition.	1.3.2
24 (1)	Heavy Duty Positive Crankcase Control Valve with Air Bleed: Crankcase blowby gas control with air dilution.	Recirculate unburned HC and exhaust gas from crankcase for combustion with lean air-fuel mixture.	2.1
31	Thermal Reaction by Turbine Blower Air Injection: Air injection into conventional exhaust manifold by means of air turbine operating off intake vacuum.	Oxidize unburned HC and CO combustion byproducts in exhaust gas.	1.1.2
33 (2)	Carburetor Modification, Main Jet Differential Pressure: Carburetor fuel bowl vented to intake manifold rather than atmosphere by means of tubing with adjustable valve.	Lean air-fuel mixture at high intake manifold vacuum during idle and deceleration.	1.2.4
36 (1)	Fuel Conditioning by Exposure to Electromagnetic Field: Intake fuel routing through magnetic field.	Condition fuel prior to entering carburetor.	1.4.3
42 (2)	Air Bleed to Intake Manifold: Air bleed from air cleaner to intake manifold through tubing with adjustable valve.	Lean air-fuel mixture	1.2.1
52 (1) (3)	LPG Conversion: Liquified petroleum gas (LPG) conversion.	Decrease pollutants by use of lower reactivity, cleaner burning gaseous fuel.	1.4.1
56	Crankcase Blowby and Idle Air Bleed Modification: Heated air bleed through special idle jets, combined with heated crankcase blowby into intake manifold.	Lean air-fuel mixture in combination with blowby control.	1.2.4
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect: Bleeds combination of exhaust gas and filtered ambient air to intake manifold, with temperature-controlled distributor vacuum advance disconnect.	Lean air-fuel mixture in combination with exhaust gas recirculation to reduce combustion temperature and retarded timing to increase exhaust gas oxidation.	1.2.1
59	Three-Stage Exhaust Gas Control System: (4)	Combustion byproduct control in exhaust system.	4.0
62 (1)	Catalytic Converter: Replaces standard muffler.	Oxidize unburned combustion byproducts in the exhaust system.	1.1.1
69 (2)	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification: Electronic control of distributor vacuum advance during idle through 1,600 rpm and during braked deceleration with temperature-controlled override and lean air-fuel mixture by modifying air screws.	Lean air-fuel mixture combined with retarded timing to increase exhaust gas oxidation.	1.3.1
93 (1)	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture: Catalytic reactor with air pump and exhaust gas recirculation, plus special ignition system and lean air-fuel mixture.	Improve oxidation of combustion byproducts and reduce combustion to inhibit NOx formation.	1.1.1
95 (1)	Ignition Spark Modification: Fits between spark plug leads and distributor.	Pre-condition combustion chamber gases in preparation for ignition event.	1.3.2

Table 4-1. DEVICES EVALUATED IN THE RETROFIT PROGRAM (CONT)

DEVICE	DEVICE TITLE	PURPOSE	GROUP
96 (1) (2)	Catalytic Converter with Distributor Vacuum Advance Disconnect: Catalyst contained in canister installed between exhaust manifold and muffler, combined with distributor vacuum advance disconnect, and/or air injection by special pump.	Oxidize unburned combustion byproducts by catalyst action and higher exhaust temperature. Reduce NOx by reduced peak cycle combustion temperature.	1.1.1
100 (1)	Turbocharger: Exhaust gas driven turbocharger.	Improve fuel oxidation during low intake vacuum by forced air injection to carburetor.	1.2.5
160 (3)	Closed or Open Blowby Control System with Filter: Filtered, volumetric-controlled blowby gas recirculation.	Recirculate blowby gas from crankcase to intake manifold for combustion, without impurities.	2.2
164	Exhaust Gas Filter: Two-stage exhaust gas filter with combined muffler function.	Incomplete data precludes full determination of purpose; however, one application appears to be particulate control.	1.1.4
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation: Combined exhaust gas afterburning and recirculation, with crankcase blowby and fuel evaporation.	Control all three major sources of vehicle emissions.	4.0
170 (3)	Closed Blowby Control System: Closed blowby gas recirculation through carburetor air cleaner and intake manifold combination.	To recirculate blowby gas from crankcase to intake manifold for combustion.	2.1
172 (1)	Intake Manifold Modification: Truncated conical nozzles inserted between intake port and intake manifold.	Equalize air-fuel mixture distribution.	1.2.3
175 (2) (3)	Ignition Timing Modification with Lean Idle Adjustment: Electronically controlled ignition spark retardation by sequenced regulation of the distributor ignition signal and the vacuum advance disconnect, combined with lean idle air-fuel mixture adjustment.	Spark retardation at idle and speeds below 35 mph in combination with lean air-fuel mixture.	1.3.1
182	Fuel and Oil Additives: Hydrocarbon-base fuel and oil additive.	Reduce engine deposits and fuel consumption and increase power.	1.4.2
244 (1)	Rich Thermal Reactor: Exhaust manifold replacement providing thermal insulated chamber and air injection.	Oxidize unburned combustion byproducts in exhaust manifold.	1.1.2
245 (2)	Variable Camshaft Timing: Cam timing gear replacement automatically varies valve timing from advance at idle and low rpm to retard at high speeds.	Provide exhaust gas recirculation.	1.2.2
246 (1) (2)	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect: Exhaust gas recirculation through intake manifold adapter controlled by speed-sensitive solenoid valve which also disconnects distributor vacuum advance during low speed modes.	Lower combustion temperature combined with higher temperature exhaust.	1.2.2
259	Photocell-Controlled Ignition System: Ignition spark modification by photo-cell controlled ignition system.	Increase spark duration and eliminate mechanical distributor breaker points.	1.3.2
268	Capacitive Discharge Ignition: Ignition spark modification by high-voltage capacitor discharge to ignition coil primary, operating in series to the distributor and coil.	Modify firing voltage across the spark plugs.	1.3.2
279	Fuel Conditioner: Intake fuel routing through electrical field.	Condition fuel prior to entering carburetor.	1.4.3
282	LP Gas Injection: Propane injection to carburetor air intake during acceleration and engine load conditions, based on intake manifold vacuum.	Addition of lower reactivity, cleaner burning fuel.	1.4.2

Table 4-1. DEVICES EVALUATED IN THE RETROFIT PROGRAM (CONT)

DEVICE	DEVICE TITLE	PURPOSE	GROUP
288 (2)	Carburetor Main Discharge Nozzle Modification: Air jet added to main circuit nozzle outlet.	Enhance air-fuel mixture diffusion.	1.2.4
292 (1)	Catalytic Converter: Platinum catalyst device installed in exhaust pipe.	Oxidize emission byproducts of combustion in the exhaust system.	1.1.1
294 (1)	Exhaust Gas Recirculation with Carburetor Modification: (4)	Optimize air-fuel mixing combined with lower combustion temperatures.	1.2.2
295 (2)	Carburetor with Variable Venturi: Replacement carburetor incorporating variable venturi and fuel nozzle.	Optimize air-fuel ratio and diffusion.	1.2.4
296	Ignition Timing and Spark Modification: Electronically controlled spark retardation by delaying distributor breaker point pulse to coil, combined with longer spark duration, up to mid-rpm range.	Enhance fuel combustion and increase exhaust gas temperature.	1.3.2
308	Exhaust Gas Afterburner: High voltage contino us-spark chamber ignites exhaust gas upstream of muffler in exhaust system.	Oxidize unburned byproducts of combustion in exhaust system.	1.1.3
315	Closed Blowby Control System: Crankcase blowby recirculation through intake manifold adapter controlled by accelerator linkage, with air-fuel diffusion fans located in adapter ports.	Mixing of blowby gases prior to entering intake manifold.	2.1
317	Carburetor Modification with Vacuum Advance Disconnect: Combination air-fuel bypass from carburetor to intake manifold, based on intake vacuum and valve metered flow, combined with vacuum advance disconnect during acceleration.	Reduce combustion temperature and increase exhaust gas temperature for improved oxidation of unburned combustion byproducts.	1.2.4
322 (1)	Exhaust Gas Backpressure Valve: Backpressure flapper valve installed on end of exhaust pipe.	Apply backpressure on the exhaust system.	1.1.5
325	Air-Vapor Bleed to Intake Manifold: Water-alcohol-air-vapor bleed to intake manifold through adapter plate with air bleed during idle and crankcase blowby recirculation.	Leaner air-fuel mixture.	1.2.1
384	Air-Fuel Mixture Diffuser: Two-layer, conical wire screen air-fuel diffuser.	Improve air-fuel mixing and conditioning for combustion.	1.2.3
401	Air-Vapor Bleed to Intake Manifold: Metered water-alcohol-air vapor bleed to intake manifold from container.	Leaner air-fuel mixture.	1.2.1
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing: Exhaust gas recirculation combined with crankcase blowby recirculation to intake manifold with vacuum actuated valving and turbulent mixing.	Blowby control and lower combustion temperature.	4.0
418 (1)	Air Bleed to Intake Manifold: Air bleed to intake manifold through crankcase blowby recirculation line.	Lean air-fuel mixture.	1.2.1
425	Exhaust Gas Afterburner: Exhaust gas afterburner operating with rich air-fuel ratio and air injection.	Oxidize unburned byproducts of combustion.	1.1.3
427	Closed or Open Blowby Control System with Filter: Closed- or open-system crankcase blowby recirculation to intake manifold with blowby filtering.	Recirculate filtered blowby gases for combustion.	2.1/2.2

Table 4-1. DEVICES EVALUATED IN THE RETROFIT PROGRAM (CONCL)

DEVICE	DEVICE TITLE	PURPOSE	GROUP
430	Induction Modification: Conical screen insert between carburetor and intake manifold.	To diffuse air-fuel mixture.	1.2.3
433	Air-Vapor Bleed to Intake Manifold: Exhaust gas afterburner operating with lean air-fuel ratio and air injection.	Oxidize unburned byproducts of combustion.	1.2.1
440	Air-Fuel Mixture Deflection Plate: Shaped deflection plate insert between carburetor and intake manifold.	To diffuse air-fuel mixture.	1.2.3
457 (1)	Water Injection: Water-alcohol-air vapor injection to intake manifold.	Oxidize unburned byproducts of combustion.	1.4.2
458 (1)	Air Bleed to Intake Manifold: Air-vapor injection to intake manifold through positive ventilation line.	Oxidize unburned byproducts of combustion.	1.2.1
459 (1) (3)	LPG Conversion with Deceleration Unit: Liquified petroleum gas (LPG) carburetor conversion with deceleration throttle control device.	Decrease pollutants by use of lower reactivity, cleaner burning LPG; combined with delayed throttle closure during deceleration, to enhance combustion of residual fuel in the intake manifold.	1.4.1
460 (1) (3)	Compressed Natural Gas Dual-Fuel Conversion: Dual-fuel conversion enabling use of compressed natural gas or gasoline.	Decrease pollutants by use of lower reactivity, cleaner burning natural gas during high-emission-potential driving modes.	1.4.1
461 (1)	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation: Liquified petroleum gas conversion with exhaust reactor, exhaust gas recycle, and pulse air injection to reactor.	Decrease pollutants by use of lower reactivity, cleaner burning gaseous fuel combined with oxidation of combustion byproduct.	1.4.1
462 (1)	Air Bleed to Intake and Exhaust Manifolds: Air bleed to intake manifold through crankcase blowby recirculation line, with exhaust dilution by air bleed.	Lean air-fuel mixture.	1.2.1
463 (1)	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard: Replacement exhaust manifold.	Oxidize combustion byproducts in the exhaust system, while lowering combustion temperature to inhibit NOx.	1.1.2
464 (1)	Methanol Fuel Conversion with Catalytic Converter: Engine conversion for operation on methanol fuel, combined with exhaust gas oxidation by catalytic reaction, plus exhaust gas recirculation option.	Decrease pollutants by use of lower reactivity, cleaner burning fuel and catalytic oxidation of exhaust gas.	1.4.1
465 (1)	Fuel Additive: Bycosin fuel additive.	To enhance combustion efficiency.	1.4.2
466 (1) (3)	LPG-Gasoline Dual-Fuel Conversion: Dual-fuel conversion enabling use of liquified petroleum gas or gasoline.	Decrease pollutants by use of lower reactivity, cleaner burning natural gas during high-emission-potential driving modes.	1.4.1
467	Fuel Evaporation Control System: Fuel evaporation control by carbon canister storage.	Control fuel evaporation from fuel tank and carburetor.	3.0
468	Lean Thermal Reactor with Exhaust Gas Recirculation: Reactor air supplied by lean air fuel mixture with recirculation of oxidized exhaust gas.	Oxidize combustion byproducts and provide lower combustion temperatures, plus particulate control.	1.1.2
469 (1)	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control: Replacement exhaust manifold (thermal reactor) with recirculation of oxidized exhaust gas and particulate trapping.	Oxidize combustion byproducts and provide lower combustion temperatures, plus particulate control.	4.0

(1) Previously tested by EPA.
(2) Tested in retrofit program.
(3) Accredited for use in California. In the case of Device 459, accreditation does not refer to the deceleration control unit.
(4) System description data not available.

Table 4-2. AVERAGE PERCENTAGE EXHAUST EMISSION REDUCTION BY TEST PROCEDURE FOR DEVICES EVALUATED IN RETROFIT PROGRAM

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND NUMBER OF TESTS.

TEST TYPE	ITEM	DEVICE	DESCRIPTION	DATA SOURCE(3)	NO. OF TESTS	AVERAGE PERCENTAGE EMISSION REDUCTION(1) HC	CO	NO_x	FUEL CONSUMPTION PERCENTAGE CHANGE(2)
1972 FEDERAL TEST PROCEDURE (CVS)	Retrofit Program Test Data (Up to 18 Tests for Each Device):								
	1	1	Air Bleed to Intake Manifold	R	18	21.0	57.8	-4.8	4
	2	96	Catalytic Converter with Distributor Vacuum Advance Disconnect	R	17	68.4	62.6	47.8	-1
	3	175	Ignition Timing Modification with Lean Idle Adjustment	R	10	19.2	46.3	37.2	-10
	4	246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	R	15	12.1	30.9	47.6	7
	Retrofit Program Test Data (Up to 3 Tests for Each Device):								
	5	10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	R	2	36.7	28.7	53.6	0.5
	6	33	Carburetor Modification, Main Jet Differential Pressure	R	2	32.9	45.8	-43.4	13
	7	42	Air Bleed to Intake Manifold	R	2	23.2	45.3	2.6	7
	8	69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	R	3	32.4	29.2	24.4	0
	9	245	Variable Camshaft Timing	R	1	-35.9	-26.9	20.9	-10
	10	288	Carburetor Main Discharge Nozzle Modification	R	2	4.1	36.9	-18.7	-6
	11	295	Carburetor with Variable Venturi	R	1	-36.9	20.0	25.4	-10
	Developer and EPA Supplied Data:								
	12	23	Electronic Ignition Unit	E	1	2.9	-16.3	-56.0	No data available ↓
	13	24	Heavy Duty Positive Crankcase Control Valve with Air Bleed	E	(4)	3.9	12.6	7.4	
	14	52	LPG Conversion	E	18	81.1	85.2	64.9	
	15	95	Ignition Spark Modification	E	1	-26.7	-17.4	-31.3	
	16	100	Turbocharger	E	1	14.0	12.0	8.0	
	17	172	Intake Manifold Modification	E	1	-15.0	0.0	27.0	
	18	292	Catalytic Converter	E	1	21.2	-15.4	41.0	
	19	294	Exhaust Gas Recirculation with Carburetor Modification	E	1	-78.9	10.4	30.0	
	20	418	Air Bleed to Intake Manifold	E	(5)	8.2	39.4	1.9	
	21	460	Compressed Natural Gas Dual-Fuel Conversion	E	1	0.0	-19.0	-64.0	
	22	462	Air Bleed to Intake and Exhaust Manifolds	E	(6)	24.6	12.6	-30.0	
	23	465	Fuel Additive	E	1	12.3	9.9	8.2	
	24	466	LPG-Gasoline Dual-Fuel Conversion	E	6	19.0	70.0	29.0	
	No Baseline Given for the Following Devices: (12)								
	25	93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	E	6	(7)	(7)	(7)	
	26	459	LPG Conversion with Deceleration Unit	E	1	(7)	(7)	(7)	
	27	461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	E	1	(7)	(7)	(7)	
	28	463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	E	3	(7)	(7)	(7)	
	29	464	Methanol Fuel Conversion with Catalytic Converter	E	6	50.0	16.0	96.0	
	30	468	Lean Thermal Reactor with Exhaust Gas Recirculation	D	5	(7)	(7)	(7)	
EPA-9X7CVS (14)	1	469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	E	2	80.0	44.0	65.0	No data available

Table 4-2. AVERAGE PERCENTAGE EXHAUST EMISSION REDUCTION BY TEST PROCEDURE FOR DEVICES EVALUATED IN RETROFIT PROGRAM (CONCL)

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND NUMBER OF TESTS.

TEST TYPE	ITEM	DEVICE	DESCRIPTION	DATA SOURCE(3)	NO. OF TESTS	AVERAGE PERCENTAGE EMISSION REDUCTION(1) HC	CO	NO_x	FUEL CONSUMPTION PERCENTAGE CHANGE(2)
7-CYCLE 7-MODE COLD START	7-Cycle 7-Mode Cold Start Test Procedure:								
	1	36	Fuel Conditioning by Exposure to Electromagnetic Field	E	(8)	-12.5	-0.4	(7)	No data available
	2	57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	D	1	55.8	52.3	46.6	↑
	3	59	Three-Stage Exhaust Gas Control System	D	1	32.0	18.3	11.0	
	4	62	Catalytic Converter	E	1	44.0	14.5	7.0	
	5	164	Exhaust Gas Filter	D	1	10.0	2.0	0.1	
	6	182	Fuel and Oil Additives	D	(9)	26.2	30.5	24.0	
	7	244	Rich Thermal Reactor	D	(7)	83.0	67.0	(7)	
	8	315	Closed Blowby Control System	D	1	28.3	28.0	(7)	
	9	317	Carb Mod with Vac Adv Disconnect	D	3	32.0	22.0	35.0	
	10	322	Exhaust Gas Backpressure Valve	E	1	-71.3	6.9	-13.0	
	11	384	Air-Fuel Mixture Diffuser	D	1	40.2	19.6	29.4	
	12	401	Air-Vapor Bleed to Intake Manifold	D	1	25.0	34.1	-31.0	
	13	425	Exhaust Gas Afterburner	D	1(10)	97.0	97.0	(7)	
	14	430	Induction Modification	D	2	34.0	9.5	36.5	
	15	458	Air Bleed to Intake Manifold	E	(11)	-3.7	7.0	-8.1	
	No Baseline Given for the Following Devices: (12)								
	16	22	Electronic Fuel Injection	E	1	(7)	(7)	(7)	
	17	31	Thermal Reaction by Turbine Blower Air Injection	D	6	(7)	(7)	(7)	
	18	56	Crankcase Blowby and Idle Air Bleed Mod	D	3	(7)	(7)	(7)	
	19	160	Closed or Open Blowby Control System with Filter	D	1	(7)	(7)	(7)	
7-MODE HOT START	7-Cycle 7-Mode Hot Start Test:								
	1	170	Closed Blowby Control System	D	1	10.0	-31.0	47.0	
	2	279	Fuel Conditioner	D	1	3.4	24.5	4.3	
	3	296	Ignition Timing and Spark Modification	D	1	8.0	4.0	-4.0	
	4	325	Air-Vapor Bleed to Intake Manifold	D	7	29.7	32.1	10.0	
	5	427	Closed or Open Blowby Control System with Filter	D	2	5.5	48.6	0.5	
	6	433	Air-Vapor Bleed to Intake Manifold	D	7	29.7	32.1	10.0	
	No Baseline Given for the Following Device: (12)								
	7	165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation	D	1	(7)	(7)	(7)	
STEADY STATE	Steady State								
	1	308	Exhaust Gas Afterburner	D	3(13)	-17.0	-6.3	9.0	
	2	457	Water Injection	E	(13)	0.0	0.0	75(15)	
UNKNOWN	No Emission Data Provided by the Developer for the Following Devices:								
	1	259	Photocell-Controlled Ignition System	D	(7)	(7)	(7)	(7)	
	2	268	Capacitive Discharge Ignition	D	(7)	(7)	(7)	(7)	
	3	282	LP Gas Injection	D	(7)	(7)	(7)	(7)	
	4	408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	D	(7)	(7)	(7)	(7)	
	5	440	Air-Fuel Mixture Deflection Plate	D	(7)	(7)	(7)	(7)	
	No Emission Evaluation was Made on the Following Device:								
	6	467	Fuel Evaporation Control System	(7)	(7)	(7)	(7)	(7)	↓ No data available

(1) Negative signs indicate an emission increase.
(2) Measured during 1972 Federal Test Procedure for exhaust emissions. Negative signs indicate less miles per gallon.
(3) Data Source:
R = Retrofit Test Program
D = Developer Supplied Data
E = Environmental Protection Agency
(4) 6 baseline and 5 device tests for HC and CO; 3 baseline and 4 device tests for NOx.
(5) 16 baseline tests and 11 device tests on 3 cars.
(6) 10 baseline and 9 device tests for HC and CO, and 6 baseline and 6 device tests for NOx, on 2 cars.
(7) Unknown.
(8) 1 baseline and 11 device tests for HC and CO only.
(9) 4 tests for HC and CO; 1 test for NOx.
(10) HC and CO measured only.
(11) 1 baseline and 2 device tests on 1 car.
(12) See Volume II for emission levels with devices installed.
(13) Different steady state speeds.
(14) EPA Interim 9-Cycle, 7-Mode CVS Emission Test Procedure (refer to Volume II, Reference 16).
(15) NOx reduction reported for water-to-fuel ratio of 0.9:1. No appreciable effect reported for HC or CO.

Table 4-3. AVERAGE PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES EVALUATED IN RETROFIT PROGRAM - LISTED BY DEVICE CLASSIFICATION (1)

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND NUMBER OF TESTS.

DEVICE NO.	DESCRIPTION	AVERAGE EMISSION REDUCTION %			NO. OF TESTS	DATA SOURCE(2)	TEST TYPE
		HC	CO	NOx			
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS						
	Type 1.1 Exhaust Gas Control Systems:						
	1.1.1 Catalytic Converter						
62	Catalytic Converter	44.0	14.5	7.0	1	E	(3)
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	(9)	(9)	(9)	6	E	(4)
96	Catalytic Converter with Distributor Vacuum Advance Disconnect	68.4	62.6	47.8	17	R	(4)
292	Catalytic Converter	21.2	-15.4	41.0	1	E	(4)
	1.1.2 Thermal Reactor						
31	Thermal Reaction by Turbine Blower Air Injection	(9)	(9)	(9)	6	D	(3)
244	Rich Thermal Reactor	83.0	67.0	(10)	(10)	D	(3)
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	(9)	(9)	(9)	3	E	(4)
468	Lean Thermal Reactor with Exhaust Gas Recirculation	(9)	(9)	(9)	5	D	(4)
	1.1.3 Exhaust Gas Afterburner						
308	Exhaust Gas Afterburner	-17.0	-6.3	9.0	3	D	(6)
425	Exhaust Gas Afterburner	97.0	97.0	(10)	1(11)	D	(3)
	1.1.4 Exhaust Gas Filter						
164	Exhaust Gas Filter	10.0	2.0	0.1	1	D	(3)
	1.1.5 Exhaust Gas Backpressure						
322	Exhaust Gas Backpressure Valve	-71.3	6.9	-13.0	1	E	(3)
	Type 1.2 Induction Control Systems:						
	1.2.1 Air Bleed to Intake Manifold						
1	Air Bleed to Intake Manifold	21.0	57.8	-4.8	18	R	(4)
42	Air Bleed to Intake Manifold	23.2	45.3	2.6	2	R	(4)
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	55.8	52.3	46.6	1	D	(3)
325	Air-Vapor Bleed to Intake Manifold	29.7	32.1	10.0	7	D	(7)
401	Air-Vapor Bleed to Intake Manifold	25.0	34.1	-31.0	1	D	(3)
418	Air Bleed to Intake Manifold	8.2	39.4	1.9	(12)	E	(4)
433	Air-Vapor Bleed to Intake Manifold	29.7	32.1	10.0	7	D	(7)
458	Air Bleed to Intake Manifold	-3.7	7.0	-8.1	(13)	E	(3)
462	Air Bleed to Intake and Exhaust Manifolds	24.6	12.6	-30.0	(14)	E	(4)
	1.2.2 Exhaust Gas Recirculation						
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	36.7	28.7	53.6	2	R	(4)
245	Variable Camshaft Timing	-35.9	-26.9	20.9	1	R	(4)
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	12.1	30.9	47.6	15	R	(4)
294	Exhaust Gas Recirculation with Carburetor Modification	-78.9	10.4	30.0	1	E	(4)

Table 4-3. AVERAGE PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES EVALUATED IN RETROFIT PROGRAM - LISTED BY DEVICE CLASSIFICATION (1) (CONT)

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND NUMBER OF TESTS.

DEVICE NO.	DESCRIPTION	AVERAGE EMISSION REDUCTION % HC	CO	NOx	NO. OF TESTS	DATA SOURCE(2)	TEST TYPE
	1.2.3 Intake Manifold Modification						
172	Intake Manifold Modification	-15.0	0.0	27.0	1	E	(4)
384	Air-Fuel Mixture Diffuser	40.2	19.6	29.4	1	D	(3)
430	Induction Modification	34.0	9.5	36.5	2	D	(3)
440	Air-Fuel Mixture Deflection Plate	(10)	(10)	(10)	(8)	D	(8)
	1.2.4 Carburetor Modification						
33	Carburetor Modification, Main Jet Differential Pressure	32.9	45.8	-43.4	2	R	(4)
56	Crankcase Blowby and Idle Air Bleed Modification	(9)	(9)	(9)	3	D	(3)
288	Carburetor Main Discharge Nozzle Modification	4.1	36.9	-18.7	2	R	(4)
295	Carburetor with Variable Venturi	-36.9	20.0	25.4	1	R	(4)
317	Carburetor Modification with Vacuum Advance Disconnect	32.0	22.0	35.0	3	D	(3)
	1.2.5 Turbocharger						
100	Turbocharger	14.0	12.0	8.0	1	E	(4)
	1.2.6 Fuel Injection						
22	Electronic Fuel Injection	(9)	(9)	(9)	1	E	(3)
	Type 1.3 Ignition Control Systems:						
	1.3.1 Ignition Timing Modification						
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	32.4	29.2	24.4	3	R	(4)
175	Ignition Timing Modification with Lean Idle Adjustment	19.2	46.3	37.2	10	R	(4)
	1.3.2 Ignition Spark Modification						
23	Electronic Ignition Unit	2.9	-16.3	-56.0	1	E	(4)
95	Ignition Spark Modification	-26.7	-17.4	-31.3	1	E	(4)
259	Photocell-Controlled Ignition System	(10)	(10)	(10)	(8)	D	(8)
268	Capacitive Discharge Ignition	(10)	(10)	(10)	(8)	D	(8)
296	Ignition Timing and Spark Modification	8.0	4.0	-4.0	1	D	(7)
	Type 1.4 Fuel Modification:						
	1.4.1 Alternative Fuel Conversion						
52	LPG Conversion	81.1	85.2	64.9	18	E	(4)
459	LPG Conversion with Deceleration Unit	(9)	(9)	(9)	1	E	(4)
460	Compressed Natural Gas Dual-Fuel Conversion	0.0	-19.0	-64.0	1	E	(4)
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	(9)	(9)	(9)	1	E	(4)
464	Methanol Fuel Conversion with Catalytic Converter	(9)	(9)	(9)	6	E	(4)
466	LPG-Gasoline Dual-Fuel Conversion	19.0	70.0	29.0	6	E	(4)

Table 4-3. AVERAGE PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES EVALUATED IN RETROFIT PROGRAM - LISTED BY DEVICE CLASSIFICATION (1) (CONCL)

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND NUMBER OF TESTS.

DEVICE NO.	DESCRIPTION	AVERAGE EMISSION REDUCTION %			NO. OF TESTS	DATA SOURCE(2)	TEST TYPE
		HC	CO	NOx			
	1.4.2 Fuel Additive						
182	Fuel and Oil Additives	26.2	30.5	24.0	(15)	D	(3)
282	LP Gas Injection	(10)	(10)	(10)	(8)	D	(8)
457	Water Injection	0.0	0.0	75(18)	(6)	E	(6)
465	Fuel Additive	12.3	9.9	8.2	1	E	(4)
	1.4.3 Fuel Conditioner						
36	Fuel Conditioning by Exposure to Electromagnetic Field	-12.5	-0.4	(8)	(16)	E	(3)
279	Fuel Conditioner	3.4	24.5	4.3	1	D	(7)
	GROUP 2 CRANKCASE EMISSION CONTROL SYSTEMS						
	Type 2.1 Closed System:						
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed	3.9	12.6	7.4	(17)	E	(4)
170	Closed Blowby Control System	10.0	-31.0	47.0	1	D	(7)
315	Closed Blowby Control System	28.3	28.0	(9)	1	D	(3)
	Type 2.2 Open System:						
160	Closed or Open Blowby Control System with Filter	(9)	(9)	(9)	1	D	(3)
427	Closed or Open Blowby Control System with Filter	5.5	48.6	0.5	2	D	(7)
	GROUP 3 EVAPORATIVE EMISSION CONTROL SYSTEMS						
467	Fuel Evaporation Control System	(10)	(10)	(10)	(8)	(10)	(8)
	GROUP 4 EMISSION CONTROL COMBINATIONS						
59	Three-Stage Exhaust Gas Control System	32.0	18.3	11.0	1	D	(3)
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation	(9)	(9)	(9)	1	D	(7)
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	(10)	(10)	(10)	(8)	D	(8)
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	80.0	44.0	65.0	2	E	(5)

(1) Classification of retrofit system is shown in Table 1-1. Refer to Volume II for emission levels with and without device installed on test car.
(2) Data Source:
R = Retrofit Test Program
D = Developer Supplied Data
E = Environmental Protection Agency
(3) 7-cycle, 7-mode cold-start test procedure.
(4) 1972 Federal Test Procedure.
(5) EPA 9-Cycle, 7-Mode CVS Test Procedure.
(6) Different steady state speeds.
(7) 7-cycle, 7-mode hot-start test procedure.
(8) No test.
(9) No baseline data reported by test source.
(10) Unknown.
(11) HC and CO measured only.
(12) 16 baseline tests and 11 device tests on 3 cars.
(13) 1 baseline and 2 device tests on 1 car.
(14) 10 baseline and 9 device tests for HC and CO, and 6 baseline and 6 device tests for NOx, on 2 cars.
(15) 4 tests for HC and CO; 1 test for NOx.
(16) 1 baseline test and 11 device tests for HC and CO only.
(17) 6 baseline and 5 device tests for HC and CO; 3 baseline and 4 device tests for NOx.
(18) NOx reduction reported for water-to-fuel ratio of 0.9:1. No appreciable effect reported for HC or CO.

c. Air Bleed to Intake Manifold: Leaner air-fuel mixture is produced, decreasing CO, and to a lesser extent, HC, by oxidation.

d. Ignition Timing Modification: Ignition timing is retarded, by disconnecting the distributor vacuum advance at low speeds, to lower combustion temperature and NOx, with some post-combustion oxidation of HC.

4.1.1 Exhaust Emission Control Systems Group

To develop the data necessary to establish a reasonable level of confidence in the effectiveness indicated for devices in this group, a representative device from each of the four above types was selected for emission and driveability testing on test vehicle fleets located in Anaheim, California, and in Taylor, Michigan.

4.1.1.1 Percentage Exhaust Emission Reduction

The emission level of the car prior to device installation was referred to as the "baseline emissions," whereas the emission level with the device installed was the "retrofit emissions." The effectiveness of the device in controlling the car's emissions was then calculated for each pollutant in terms of percentage reduction. The formula used for this calculation is:

$$\text{Percentage Reduction} = \frac{\text{Baseline Emissions} - \text{Retrofit Emissions}}{\text{Baseline Emissions}} \times 100$$

Table 4-4 shows the percentage exhaust emission reductions obtained for the devices in these tests.

4.1.1.2 Statistical Analysis of Representative Exhaust Emission Control Device Test Results

Two kinds of statistical testing were used on the emission reduction data of devices tested in the retrofit program. One statistical test determined whether the replicate results and the results from the two cities could be combined. This was accomplished using Welch's approximate t solution for the Fisher-Behrens problem. The Fisher-Behrens problem is the testing of the hypothesis that the means of two normal populations are equal regardless of the size of their respective variances based on two samples, one drawn from each population. A brief description and a sample calculation of Welch's approximate solution of the Fisher-Behrens problem is presented in Volume III, Appendix H.[1]

The second statistical test considered whether the percentage emission reduction was different than zero for results of a given location or for location data combinations. This test used a normal student t test. Two sided 90 percent confidence limits were calculated for the mean percentage emission reductions.

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(1) Welch, B. L., Biometrika 34, 28-35, January 1947.

Table 4-4. PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES TESTED IN RETROFIT PROGRAM

CAR NO. AND LOCATION(1)	MAKE AND CID	TEST 1			TEST 2		
		HC	CO	NO_x	HC	CO	NO_x
Device 1: Air Bleed to Intake Manifold							
Anaheim							
1	65 Chev 194	17.7	-6.3	-50.5	(2)		
2	65 Ford 289	30.5	31.4	-10.6			
3	65 Ply 318	-8.2	60.6	16.6			
4	65 Chev 327	4.8	46.4	14.6			
5	65 Ford 390	20.8	41.4	0.0			
6	61 Chev 283	(3)	36.1	12.7			
17	65 Ford 390						
18	61 Chev 283						
19	65 VW 92	46.4	56.9	12.4			
Taylor							
8	65 Ford 289	41.0	89.3	24.9	3.1	77.9	-17.4
9	65 Ply 318	26.5	79.3	13.9	6.9	34.7	24.8
10	65 Chev 327	-29.0	93.1	-0.3	2.8	73.1	-18.8
11	65 Ford 390	23.6	74.0	-28.4	51.0	63.2	-57.5
12	61 Chev 283	46.0	50.4	3.6	1.9	52.6	-33.1
16	65 Chev 327						
20	65 VW 92	71.2	85.5	6.9			
Device 96: Catalytic Converter with Vacuum Advance Disconnect							
Anaheim							
1	65 Chev 194	85.1(4)	78.3	76.7	51.6(4)	77.4	15.7
2	65 Ford 289	92.2(4)	95.1	65.0	75.6(4)	63.2	41.1
3	65 Ply 318	34.1	12.1	68.8	65.9(4)	51.2	30.2
4	65 Chev 327	86.7(4)	99.2	38.0	75.1(4)	76.6	56.6
5	65 Ford 390	40.6	24.1	66.3	38.4	26.9	28.1
6	61 Chev 283	68.1(4)	32.9	34.6	48.7	4.1	11.6
Taylor							
8	65 Ford 289	66.6	67.4	51.7			
9	65 Ply 318	85.3	83.2	58.1			
10	65 Chev 327	70.8	77.6	61.7			
11	65 Ford 390	92.9(4)	99.5	57.6			
12	61 Chev 283	86.2(4)	95.8	50.0			
Device 246: Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect							
Anaheim							
1	65 Chev 194	(3)	12.4	60.0			
2	65 Ford 289	27.6	33.7	37.4			
3	65 Ply 318	-13.7	32.9	54.5			
4	65 Chev 327	2.8	23.4	36.9			
17	65 Ford 390	0.9	10.3	58.5			
18	61 Chev 283	(3)	-8.3	44.5			
19	65 VW 92	15.4	11.6	26.1			

Table 4-4. PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES TESTED IN RETROFIT PROGRAM (CONT)

CAR NO. AND LOCATION(1)	MAKE AND CID	TEST 1			TEST 2		
		HC	CO	NO_x	HC	CO	NO_x
Taylor							
8	65 Ford 289	(3)	(3)	(3)	-11.1	-4.2	57.7
9	65 Ply 318	8.3	58.4	47.6	-5.0	60.8	58.1
10	65 Chev 327	(3)	(3)	(3)	18.3	45.4	55.8
11	65 Ford 390	18.0	31.4	44.7	46.0	72.8	49.3
12	61 Chev 283	9.9	30.1	40.9	40.2	53.4	41.4
20	65 VW 92	9.4	-26.6	(3)			
Device 175: Ignition Timing Modification with Lean Idle Adjustment							
Anaheim							
1	65 Chev 194	14.1	11.4	43.6			
3	65 Ply 318	33.1	21.5	43.0			
4	65 Chev 327	4.8	8.1	14.9			
5	65 Ford 390	-21.0	-9.8	35.2			
6	61 Chev 283	(3)	(3)	(3)			
Taylor							
8	65 Ford 289	16.8	76.5	56.6			
9	65 Ply 318	26.5	78.7	42.5			
10	65 Chev 327	19.0	61.1	56.5			
11	65 Ford 390	24.5	74.7	3.0			
12	61 Chev 283	33.7	67.0	34.4			
16	65 Chev 327	40.0	73.4	42.8			
Device 10: Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect							
Anaheim							
4	65 Chev 327	45.9	39.0	55.5			
6	61 Chev 283	27.5	18.3	51.6			
Device 33: Carburetor Main Jet Differential Pressure Modification							
2	65 Ford 289	52.7	62.8	-121.6			
4	65 Chev 327	13.0	28.7	34.9			
Device 42: Air Bleed to Intake Manifold							
4	65 Chev 327	-7.6	50.0	-3.1			
5	65 Ford 390	54.0	40.9	8.3			

Table 4-4. PERCENTAGE EXHAUST EMISSION REDUCTION OF DEVICES TESTED IN RETROFIT PROGRAM (CONCL)

CAR NO. AND LOCATION(1)	MAKE AND CID	TEST 1			TEST 2		
		HC	CO	NO_x	HC	CO	NO_x
Device 69: Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification							
Anaheim							
3	65 Ply 318	39.2	30.1	32.1			
4	65 Chev 327	27.5	37.6	-5.6			
5	65 Ford 390	30.6	20.0	46.7			
Device 245: Variable Camshaft Timing							
6	61 Chev 283	-35.9	-26.9	20.9			
Device 288: Carburetor Main Discharge Nozzle Modification							
2	65 Ford 289	6.2	38.9	-1.8			
6	61 Chev 283	2.0	34.8	-35.6			
Device 295: Carburetor with Variable Venturi							
5	65 Ford 390	-36.9	20.0	25.4			

(1) Positive percentage denotes emission reduction from baseline and negative percentage denotes emission increase from baseline.
(2) All blank spaces and columns denote that no tests were performed, except for Note (3).
(3) Measured test data were invalid.
(4) Air pump installed and operating.

Although the absolute magnitude of the percentage reduction is subject to considerable error due to the small sample size of the retrofit test program, the mean values still represent the best known estimate of the true values. The statistical data provided by this analysis are shown in Table 4-5. A discussion of the emission reduction statistical confidence limits is presented in Volume III, paragraph 6.1.

4.1.1.3 Statistical Analysis Conclusions

Figure 4-1 shows the 90 percent confidence limits calculated for the emission reduction effectiveness of the four representative devices.

Device 96, the catalytic converter with distributor vacuum advance disconnect, shows a large percentage reduction for all three pollutants.

Device 175, the ignition timing modification system with lean idle mixture adjustment (which has been accredited by California for retrofit installation on 1955-65 model year cars), was effective for NOx control, with mean reduction levels centering on the 37 percent reduction level. The HC mean reduction level of this device was also statistically significant.

Since Device 175 is an ignition timing modification with lean carburetor idle mixture by adjustment, it is not likely that this device controls the overall CO during a CVS test to a significant degree. It is known that lean idle mixture will reduce the overall CO level to some extent, but not to the extent shown in the Taylor data (an average of 72 percent). By comparison, the Anaheim data showed a mean CO reduction of 8 percent. This CO reduction may be more representative for this device.

Table 4-5. MEAN PERCENTAGE EMISSION REDUCTION AND 90 PERCENT CONFIDENCE INTERVALS FOR EXHAUST EMISSION CONTROL RETROFIT SYSTEMS TESTED AT ANAHEIM, CALIFORNIA AND TAYLOR, MICHIGAN (1) (2)

Hydrocarbon Reduction (%)			Carbon Monoxide Reduction (%)			Oxides of Nitrogen Reduction (%)		
Test Data[3] Combination	Mean (n)	90% Confidence Limits	Test Data[3] Combination	Mean (n)	90% Confidence Limits	Test Data[3] Combination	Mean (n)	90% Confidence Limits
Device 1: AIR BLEED TO INTAKE MANIFOLD								
$A_1+T_1+T_2$	21.0(17)	10.4 to 31.6	A_1	38.1(7)	21.8 to 54.4	$A_1+T_1+T_2$	-4.8(18)	-14.9 to 5.4
			T_1+T_2	70.3(11)	60.4 to 80.2			
Device 96: CATALYTIC CONVERTER WITH VACUUM ADVANCE DISCONNECT								
A_1+A_2	63.5(12)	53.0 to 74.0	A_1+A_2	53.4(12)	36.5 to 70.4	A_1+T_1	57.1(11)	50.2 to 64.1
T_1	80.4(5)	69.7 to 91.0	T_1	84.7(5)	72.1 to 97.3	A_2	30.6(6)	16.9 to 44.2
Device 175: IGNITION TIMING MODIFICATION WITH LEAN IDLE ADJUSTMENT								
A_1+T_1	19.2(10)	8.9 to 29.3	A_1	7.8(4)	-7.6 to 23.1	A_1+T_1	37.3(10)	27.5 to 47.0
			T_1	71.9(6)	66.5 to 77.3			
Device 246: SPEED-CONTROLLED EXHAUST GAS RECIRCULATION AND VACUUM ADVANCE DISCONNECT								
$A_1+T_1+T_2$	12.1(13)	3.1 to 21.1	T_1+T_2	43.5(8)	27.3 to 59.7	$A_1+T_1+T_2$	47.6(15)	43.1 to 52.1
			A_1	16.6(7)	5.7 to 27.4			

(1) Negative reductions indicate an emission level increase from baseline

(2) Confidence intervals calculated from data presented in Table 6-1 (Volume III)

(3) A_1 = Anaheim Test 1 T_1 = Taylor Test 1

A_2 = Anaheim Test 2 T_2 = Taylor Test 2

(4) $A_1+T_1+T_2$ means that Anaheim Test 1, Taylor Tests 1 and 2 reduction data were combined as a single sample. See Volume III, Appendix H, for explanation of test data combinations as determined by Welch's approximate t solution of the Fisher-Behrens problem. (X) indicates total number of tests.

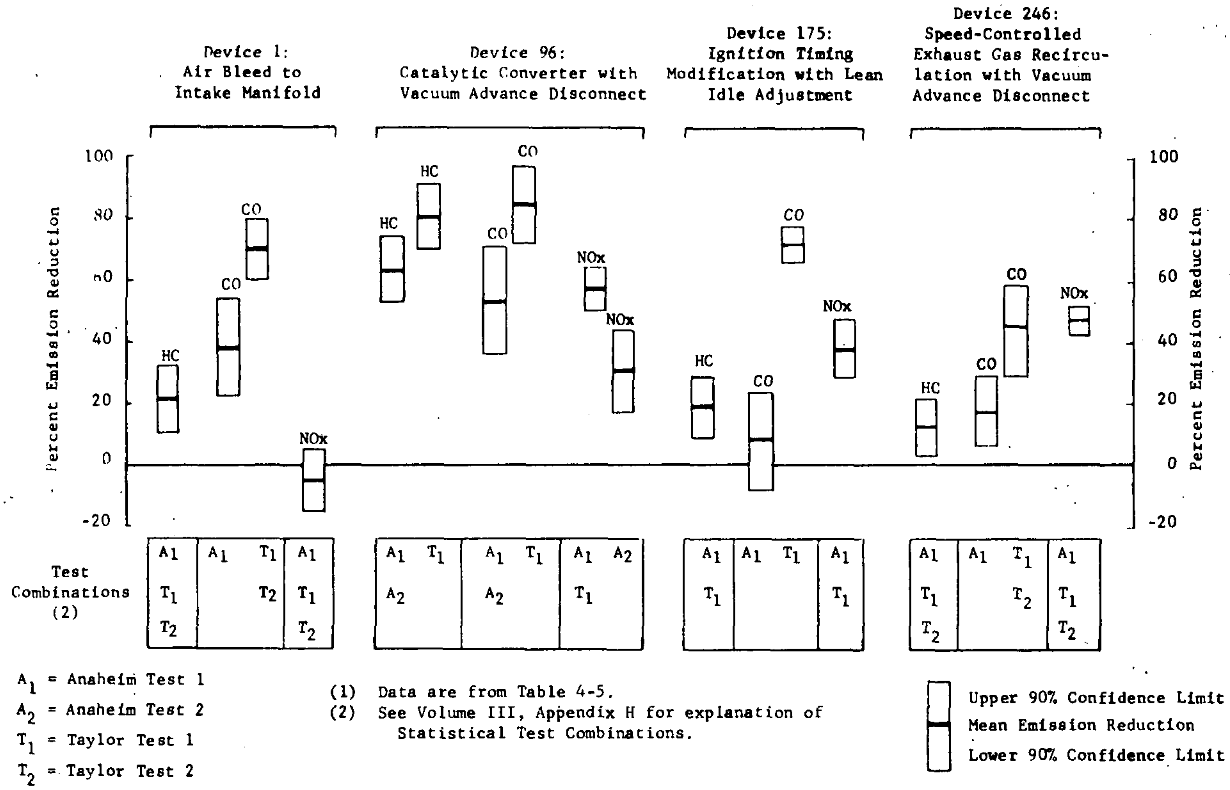

Figure 4-1. PERCENTAGE EXHAUST EMISSION REDUCTION MEANS AND 90% CONFIDENCE LIMITS FOR EXHAUST EMISSION CONTROL RETROFIT SYSTEMS TESTED AT ANAHEIM, CALIFORNIA, AND TAYLOR, MICHIGAN (1)

Device 246, the exhaust gas recirculation and vacuum disconnect system, is clearly an NOx control device. The CO reduction is also considerable with a pooled mean level of 31 percent for the Anaheim and Taylor test results. The HC reduction pooled mean was 12 percent.

Device 1, an air bleed to intake manifold type, is clearly a CO control device. The HC percentage reduction is also significantly different than zero to a lesser degree. The air bleed system does not control NOx, as its principle of operation leans the overall air-fuel mixture and lean mixtures generally will increase the NOx emission levels because of the availability of additional oxygen.

4.1.1.4 Screening and Developer Exhaust Emission Test Results

Table 4-2 identifies the retrofit devices that received up to three tests in the retrofit program, and the devices for which the developers provided test data.

The significant comparisons with devices tested on a vehicle basis are highlighted below for those devices with comparable types and numbers of tests.

Device 10, an exhaust gas recirculation system with vacuum advance disconnect, showed essentially the same CO and NOx emission reduction effectiveness as its fleet tested counterpart, Device 246.

In the air-bleed-to-intake-manifold category, Device 42 was directly analogous to Device 1 as a significant CO reducer, with some HC reduction effectiveness. Device 401, which also acts as an air bleed to the intake manifold, showed equivalent emission control characteristics. Device 325, an air-bleed-to-intake-manifold system with crankcase blowby recirculation, showed reductions equivalent to the air bleed systems evaluated in the test program (HC and CO reductions with essentially no change in NOx). Device 33, a carburetor main nozzle modification, showed significant emission reduction for HC and CO, but NOx increased 43 percent.

Device 69 followed the pattern of Device 175, as an ignition timing modification with lean idle mixture adjustment, in providing HC, CO, and NOx reduction.

Device 469, a rich thermal reactor combined with exhaust gas recirculation, showed equivalent emission reductions to the catalyst system (Device 96) tested on the vehicle fleet, with substantial reductions for all three exhaust pollutants.

Device 52 is representative of the gaseous fuel systems. The high air-fuel ratios which these systems enable make reductions of all three exhaust pollutants possible. It is generally agreed that HC emissions from gaseous fueled vehicles have less photochemical smog reactivity than those from gasoline fueled vehicles. No Federal reactivity scale has been defined to allow for quantitative correction of this difference between fuels. In California, a reactivity factor is being used in the test procedure for gaseous fuel system conversions.(1)

4.1.2 Crankcase Emission Control Systems Group

Crankcase control systems could reduce total vehicle HC emissions up to approximately 20 percent from an uncontrolled vehicle.(2) This type of retrofit device may indirectly affect exhaust emissions. This characteristic could be caused by the flow characteristics of the system. If the total flow of a blowby control system far exceeds the blowby flow rate produced by the engine, then it becomes a mixture leaning device, such as an air-bleed-to-intake-manifold system. The device still has an advantage over the air bleed in that crankcase blowby is being controlled and the crankcase is being purged with ventilation air.

No retrofit devices were tested in this group, since considerable data already exist on these devices, which have been in use on new cars in California since 1961 and nationally since 1963. Exhaust emission data were obtained on five devices in this category (Table 4-3).

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(1) "California Exhaust Emission Standards and Test Procedures for Motor Vehicles Modified to Use Liquid Petroleum Gas or Natural Gas Fuel," State of California Air Resources Board, 28 November 1969.

(2) "Control Techniques for Carbon Monoxide, Nitrogen Oxide, and Hydrocarbon Emissions from Mobile Sources," National Air Pollution Control Administration Publication No. AP-66, March 1970.

A potential problem could result from use of the air-bleed retrofit systems in combination with positive crankcase ventilation (PCV) and exhaust gas recirculation systems; this may cause excessively lean air-fuel carburetion. This could result from a combination of high ventilation airflow rates through the PCV valve and/or the additional air provided by an air-bleed system installed between the PCV valve and the intake manifold. High crankcase ventilation airflow rates occur on PCV equipped vehicles with low blowby flow rates. As the vehicle accumulates mileage blowby flow rates generally increase and ventilation airflow of the PCV system decreases. The possibility of excessive air ventilation decreases with age.

On the other hand, if an older used vehicle with a PCV system has a relatively rich fuel mixture, an air-bleed retrofit system could show some HC and CO emission reduction, provided that the air-bleed device flow rate is not excessive. In using the air-bleed approach for HC and CO control, criteria would have to be established to identify "lean" and "rich" cars and the allowable carburetor air-fuel mixture changes caused by the air-bleed system. Additional considerations on retrofit device vehicle applicability are presented in Section 6.

4.1.3 Fuel Evaporative Emission Control System Group

Carburetor and fuel tank evaporative emission control systems could reduce total vehicle hydrocarbon emission up to 20 percent from an uncontrolled vehicle. Without evaporative loss control, as much as 29 grams of fuel can evaporate during the hot soak period following shutdown of a hot engine. This type of system, like the blowby controls, may indirectly affect exhaust emissions.(1)

No evaporative control devices were found to be available for retrofit use or under development other than Device 165, a combination emission control system which incorporates gas tank and crankcase vapor controls.

Use of fuel evaporation emission control systems was initiated in 1970 on new motor vehicles sold in California and in 1971 on new vehicles sold nationally. Two fuel evaporative systems have been designed for production use. These are based on two different approaches to fuel vapor recovery. One system stores the fuel vapor in the crankcase and the other stores the vapor in a carbon canister during soaking periods (engine off). The vapors are purged from the crankcase or canister when the engine is running. The effectiveness of either system for reducing overall vehicle emissions should be equivalent.

4.2 DRIVEABILITY AND SAFETY

The driveability and safety of retrofit devices were evaluated as related factors in a device's overall effectiveness, because many driveability problems may also be safety problems.

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(1) Deeter, W.F., H.D. Daigh, and O.W. Wallin, Jr., "An Approach for Controlling Vehicle Emissions," SAE Paper 680400, May 1968.

4.2.1 Exhaust Emissions Control System Group

All of the devices tested belonged to the exhaust control retrofit group. The driveability tests were performed in accordance with the test procedures of the Automobile Manufacturers Association (AMA). These procedures include both cold and hot driving modes for determining the number of times required to start the vehicle, cranking time per start, rough idle, stall at idle, stall at various speed increments, backfire, detonation, surge, stretchiness, hesitation, and acceleration. These driveability characteristics were divided into two categories, critical and general; the former consisted of backfire and stall under both hot and cold driving modes, and the latter consisted of all other parameters. Backfire and stall were considered critical characteristics because of their possible adverse effect on the driver's safety and the vehicle's functional integrity. Each characteristic was measured in terms of either no problem; or trace, moderate, or heavy problems. Fuel consumption, measured during the emission tests, was an additional factor analyzed for impact on driveability and also was an input to the cost calculations.

Driveability characteristics were determined for the test vehicles with and without the retrofit devices installed. Additional tests were performed on four devices, including mountain, desert, and urban driving, to determine the effects of operating extremes on vehicle driveability with the devices installed. In the quantitative calculation of the driveability performance or index of a device, if there was no change in the driveability parameters with the retrofit device installed, as compared to the same vehicle without the device, the general Driveability Index was equal to zero. This was the best case (unless driveability was improved by the retrofit device), since the Driveability Index was calculated as a penalty index. For example, should an acceleration loss of three seconds be the only consequence of device installation the index would equal 1.25. This high of an index exceeds the acceptable limit level of 1.0 shown in the evaluation criteria of Table 1-2.

Test and analysis of the retrofit devices for their effect on safety was based on such factors as exhaust gas leakage, leakage of raw fuel, introduction of raw fuel to a source of ignition, engine failure or loss of power, and introduction of temperatures excessive for human or vehicle safety.

Table 4-6 presents the driveability results for the 11 devices tested. The general driveability and safety characteristics of the representative devices that received up to 18 tests are summarized in this table:

a. Air Bleed to Intake Manifold Devices: These devices have to be carefully tuned as part of the engine system, since they affect the air-fuel mixture. Too lean a mixture can cause rough idle, hesitation, surge, and slower acceleration. In the devices evaluated, traces of these problems were evident.

   There were no safety problems identified for the air bleed devices. Gasoline mileage improved 4 percent, while acceleration times were 10 percent slower on the average.

Table 4-6. DRIVEABILITY AND SAFETY CHARACTERISTICS FOR DEVICES TESTED IN RETROFIT PROGRAM

DEVICE NO.	DESCRIPTION	AVERAGE DRIVEABILITY INDEX	NO. OF TESTS	CRITICAL DRIVEABILITY CHARACTERISTICS(1)	GENERAL DRIVEABILITY CHARACTERISTICS(1)	SAFETY HAZARDS	AVERAGE CHANGE, % 0-60 ACCEL(2)	AVERAGE CHANGE, % GASOLINE MILEAGE(3)
	Up to 18 tests per device:							
1	Air Bleed to Intake Manifold	0.138	18	Less tendency to stall during cold start accel. modes (No. of occurrences insignificant)	More stall at idle and acceleration hesitation during cold modes	None	-10	4
96	Catalytic Converter with Distributor Vacuum Advance Disconnect	0.304	17	More stalls during cold acceleration modes (No. of occurrences insignificant)	• Longer starting times; more hesitation, and stretchiness during cold start modes • Idle was improved during cold and hot start modes • More detonation during hot start modes	Potential fire hazard(4)	-5	-1
175	Ignition Timing Modification with Lean Idle Adjustment	0.118	10	More stalls during cold start acceleration modes (No. of occurrences insignificant)	More stumble and hesitation during cold start modes	None	-6	-10
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	0.113	13	No effect	• More stumble, hesitation during cold start modes • Increased acceleration times	None(5)	-6	7
	Up to 3 Tests per Device:							
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	0.441	2	No effect	• More stumble and hesitation during cold start modes • Longer starting times during hot start modes	None(5)	-19	0.5
33	Carburetor Modification, Main Jet Differential Pressure	0.181	2	No effect	Longer starting times during hot start	Possible fire hazard(6)	-5	13
42	Air Bleed to Intake Manifold	0.116	2	More stalls during cold start acceleration modes (No. of occurrences significant; based on 2 tests only)	• Worse idle performance during cold start modes • Longer starting times during hot start modes • Less detonation during hot start modes	None	-3	7
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	0.087	3	More stalls during cold start acceleration modes (No. of occurrences insignificant)	More hestiation during cold start modes	None	-2	0
245	Variable Camshaft Timing	0.895	1	No effect	More stretchiness during cold start modes	None	-38	-10
288	Carburetor Main Discharge Nozzle Modification	-0.459	1	No effect	Shorter starting times and less stumble during cold start modes	None	17	-6(8)
295	Carburetor with Variable Venturi	3.261(7)	1	More stalls during cold start acceleration modes (No. of occurrences significant; based on one test only)	• Longer starting times, more stalls at idle during cold start modes • More hesitation during hot start modes • Shorter starting times during hot start modes	None	-12	-10

(1) Comments describe vehicle operation with device installed as compared to standard vehicle without device.
(2) Negative signs indicate acceleration degradation.
(3) Negative signs indicate less miles per gallon during 1972 Test Procedure emission test. See Appendix L, Volume III for fuel consumption.
(4) Potential fire hazard due to excessively high converter temperatures.
(5) Assumes good maintenance is practiced to prevent recirculated exhaust leakage.
(6) Potential fire hazard due to raw fuel syphoning to intake manifold.
(7) It is possible that this DI is invalid due to an inadvertent maladjustment of the ignition timing.
(8) Based on two measurements performed during emission tests using the 1972 Federal Test Procedure. Only one driveability test was valid.

b. Exhaust Gas Reactor Devices: The catalyst device evaluated in the retrofit program required no-lead fuel. Detonation was evident in some of the test vehicles. Acceleration times were about 5 percent slower with the device installed. Gasoline mileage decreased 1 percent on the average.

For safety considerations these devices have to be insulated or located such that their inherently high operating temperatures cannot injure operating or maintenance personnel, or cause thermal damage to vehicle structure and components.

c. Ignition Timing Modification: Electronic or mechanical control of ignition timing to retard the spark caused slower acceleration times of 6 percent. Gasoline mileage with these devices decreased by as much as 10 percent (Device 175).

These devices are characteristically only operative at idle and low- to mid-rpm ranges, where emissions are greatest and, therefore, do not affect normal cruising driveability. Some stumble and hesitation was observed during the cold start modes of operation.

There appear to be no safety problems, provided that all components are maintained satisfactorily.

d. Devices Incorporating Exhaust Gas Recirculation with Distributor Vacuum Advance Disconnect: Recirculated exhaust gas affects driveability slightly, because of the dilution it causes in the air-fuel mixture. When combined with retarded spark, as in the case of Device 246, this dilution caused acceleration times to be 6 percent slower. Gas mileage was improved by 7 percent on the average for Device 246.

No safety problems were evident in the devices examined; however, good maintenance would have to be practiced to ensure that the recirculated exhaust gas does not leak into the engine or passenger compartments and thereby introduce a safety problem.

4.2.2 Crankcase Emission Control System Group

These devices have acceptable driveability and safety characteristics, if installed and maintained satisfactorily. Since the devices evaluated are basically the same as the ones already in use on vehicles, driveability and safety tests were not conducted.

4.2.3 Fuel Evaporation Emission Control System Group

Although a device of this type was not found to be available for retrofit application, such devices should not present any driveability or safety problems. However, if not properly designed, fire or explosion hazards may occur.

4.3 RELIABILITY AND MAINTAINABILITY

Reliability and maintainability analyses were conducted on those devices for which sufficient system data were obtained or developed. These analyses were mainly limited by the completeness of functional and design information obtained from the developers. The evaluation indicated that reliability and maintainability of most of the devices could be improved by careful detailed design and production engineering, since the devices in general have not been designed to meet specific reliability, maintenance, or producibility objectives.

The results of the reliability analysis indicated that none of the retrofit devices evaluated would have a mean-miles-before-total-failure (MMBTF) of less than 50,000 miles if normal automotive design and fabrication standards are followed in their production design and manufacture.

4.3.1 Reliability and Maintainability Analysis Approach and Results

The approach used in the reliability and maintainability analyses was to compare device components with similar or identical conventional automotive components, and to estimate reliability and maintenance requirements based on the generally accepted characteristics of the comparable automotive components. It was assumed that the ultimate design of the device would reflect the same level of reliability and requirements for maintenance found in the similar automotive components. Thus, the reliability estimates and maintenance requirements determined for a given component (e.g., solenoid-actuated exhaust gas valve, vacuum hose, thermostatic switch) were relatively uniform for all devices incorporating similar components.

The criteria used in determining acceptable reliability and maintainability characteristics were those established by the California Health and Safety Code for retrofit device accreditation (refer to Table 1-2). These are as follows:

a. The reliability of a device shall provide an expected useful life of at least 50,000 miles of operation.

b. Maintenance shall not be required more than once each 12,000 miles and shall not cost more than $15 for labor and material each time.

4.3.1.1 Reliability and Corrective Maintenance Analysis Procedure

Corrective, or repair, maintenance requirements were analyzed along with reliability, to establish replacement parts costs and labor costs for repair. Corrective maintenance is defined as all maintenance and inspection action resulting from failure of a device totally or partially as a result of component failure. This type of maintenance is the opposite of preventive, or planned maintenance performed to keep a device in good working order.

To estimate reliability and corrective maintenance costs, a listing was made of all the components comprising each retrofit device, and the components were evaluated individually for reliability and maintainability characteristics on the basis of comparable counterparts in a conventional automotive system. For example, a solenoid actuator was considered similar to a starter solenoid, and a vacuum regulated actuator was considered similar to a vacuum advance unit. Using this comparative basis for evaluation, the following values were estimated for each component of the retrofit device:

a. Failure Interval: This was estimated in terms of the parameters, mean-miles-before-partial-failure (MMBPF) and mean-miles-before-total-failure (MMBTF). The MMBPF was the expected number of miles a device would be in operating condition (available to perform its function), based on the mean of all partial failures it might have during its service life, while the MMBTF was the total service life of a device based on all complete failures after which a device would have to be replaced as a unit.

b. Replacement Parts Cost: This cost was estimated on the basis of the cost of a comparable automotive part, considering the retail cost of device components given by the developer.

c. Labor for Corrective Maintenance: This was the labor associated with fixing each component failure and was based on the average California repair rate of $12.50 per hour.

Each retrofit device was individually evaluated for component failures. The failure intervals, replacement parts costs, and corrective maintenance actions estimated for the retrofit devices with sufficient data are tabulated in Table 4-7. In this table, the individual devices are listed according to general group classifications, and the corrective maintenance actions associated with a component failure are reduced to a list of 18 typical repair actions. Component material costs and labor hours associated with the repair actions for each device are listed in the appropriate matrix box. The MMBPF was estimated as the mean of the component replacement intervals. In most cases, replacement interval data were not available to distinguish total from partial failures; hence the MMBPF is the same as the MMBTF.

4.3.1.2 Reliability Analysis Results

The following observations are based on the reliability estimates shown in Table 4-7:

a. Almost any of the retrofit device components, if designed to normal automotive functional, cost, and production standards, may be expected to have a life of 50,000 miles or more, with reasonable preventive maintenance practices.

b. Systems which use valves, switches, and electrical sensors or contacts are prone to failure in proportion to the number of these components used. Generally, exhaust and induction control systems which incorporate electromechanical functions requiring valves, switches, and sensors, are more susceptible to reliability problems and consequently have greater need for preventive maintenance. MMBTF's estimated for these devices were usually 50,000 miles. Conversely, induction system modifications having no moving parts, such as carburetor jets and intake manifold inserts have high reliability (MMBTF equal to or greater than 75,000 miles), but generally involve some periodic inspection to verify that ignition and carburetion tuneup adjustments are maintained and that deposit buildup has not occurred.

Table 4-7. RELIABILITY AND CORRECTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM

DEVICE NO.	DEVICE DESCRIPTION	REPLACEMENT PARTS COST ($)/REPAIR LABOR HOURS																		FAILURE INTERVAL		PARTS COST ($)	LABOR HOURS
		CARBURETOR COMPONENT	IGNITION DEVICE/ HEATING ELEMENT/ HEAT EXCHANGER	CATALYST	SPRINGS/CABLES	POINTS/CONTACTS/ SENSOR	SPARK PLUGS	SWITCH	VALVE	TUBING/NOZZLES	HOUSING/CHAMBER/ CONTAINER	AIR PUMP	ELECTRONIC ASSEMBLY	HOSE	IGNITION COIL	ADAPTER	BACK PRESSURE/FLOW CONTROL VALVE	PCV VALVE	RETROFIT DEVICE	MEAN MILES BEFORE PARTIAL FAILURE (MMBPF) (1,000 MILES)	MEAN MILES BEFORE TOTAL FAILURE (MMBTF) (1,000 MILES)	AVERAGE COST OF REPAIR PARTS (C_{RP})	MEAN TIME TO REPAIR (MTTR) (1)
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS																						
	Type 1.1 Exhaust Gas Control Systems																						
	1.1.1 Catalytic Converter																						
62	Catalytic Converter	Insufficient Data																					
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	Insufficient Data																					
96	Catalytic Converter with Distributor Vacuum Advance Disconnect					15.00 / 1.05		5.00 / 1.10	12.00 / 1.35			50.00 / 1.60					3.00 / 0.90		125.00 / 4.00	50	50	35.00	1.67
292	Catalytic Converter			15.00 / 0.50							45.00 / 0.75								60.00 / 1.00	50	50	40.00	0.75
	1.1.2 Thermal Reactor																						
31	Thermal Reaction by Turbine Blower Air Injection									20.00 / 2.40		50.00 / 1.60							80.00 / 5.00	50	50	50.00	3.00
244	Rich Thermal Reactor																		275.00 / 8.00	75	75	275.00	8.00
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	Insufficient Data																					
468	Lean Thermal Reactor with Exhaust Gas Recirculation	Insufficient Data																					
	1.1.3 Exhaust Gas Afterburner																						
308	Exhaust Gas Afterburner		2.50 / 0.25		1.25 / 0.25						25.00 / 0.50				6.25 / 0.25				55.00 / 1.25	50	50	18.00	0.50
425	Exhaust Gas Afterburner		10.00 / 0.50								50.00 / 0.50	45.00 / 0.50							140.00 / 1.50	50	50	61.25	0.75
	1.1.4 Exhaust Gas Filter																						
164	Exhaust Gas Filter	Insufficient Data																					
	1.1.5 Exhaust Gas Backpressure																						
322	Exhaust Gas Backpressure Valve	Insufficient Data																					
	Type 1.2 Induction Control Systems																						
	1.2.1 Air Bleed to Intake Manifold																						
1	Air Bleed to Intake Manifold				2.00 / 0.75				12.50 / 1.00					2.00 / 0.25		8.00 / 0.50			48.00 / 1.25	75	75	14.50	0.75
42	Air Bleed to Intake Manifold																		10.00 / 1.00	75	75	10.00	1.00
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	1.50 / 0.40						4.00 / 1.25	2.50 / 1.35					1.00 / 0.25					41.00 / 1.75	50	50	10.00	1.00
325	Air-Vapor Bleed to Intake Manifold								3.00 / 0.30		15.00 / 0.60			2.00 / 0.25		7.50 / 0.60			40.00 / 1.25	50	50	13.50	0.60
401	Air-Vapor to Intake Manifold								2.50 / 0.35		15.00 / 0.75			2.50 / 0.30					33.00 / 1.00	50	50	13.25	0.60
418	Air Bleed to Intake Manifold	Insufficient Data																					
433	Air-Vapor Bleed to Intake Manifold								3.00 / 0.30		15.00 / 0.60			2.00 / 0.25		7.50 / 0.60			40.00 / 1.25	50	50	13.50	0.60
458	Air Bleed to Intake Manifold	Insufficient Data																					
462	Air Bleed to Intake Exhaust Manifolds	Insufficient Data																					

Table 4-7. RELIABILITY AND CORRECTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONT)

		REPLACEMENT PARTS COST ($)/REPAIR LABOR HOURS																		FAILURE INTERVAL		PARTS COST ($)	LABOR HOURS
DEVICE NO.	DEVICE DESCRIPTION	CARBURETOR COMPONENT	IGNITION DEVICE/ HEATING ELEMENT/ HEAT EXCHANGER	CATALYST	SPRINGS/CABLES	POINTS/CONTACTS/ SENSOR	SPARK PLUGS	SWITCH	VALVE	TUBING/NOZZLES	HOUSING/CHAMBER/ CONTAINER	AIR PUMP	ELECTRONIC ASSEMBLY	HOSE	IGNITION COIL	ADAPTER	BACK PRESSURE/ FLOW CONTROL VALVE	PCV VALVE	RETROFIT DEVICE	MEAN MILES BEFORE PARTIAL FAILURE (MMBPF) (1,000 MILES)	MEAN MILES BEFORE TOTAL FAILURE (MMBTF) (1,000 MILES)	AVERAGE COST OF REPAIR PARTS (C_{RP})	MEAN TIME TO REPAIR (MTTR) (1)
	1.2.2 Exhaust Gas Recirculation																						
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	3.50/0.60	4.50/0.60			2.50/0.45		2.00/0.30	8.00/0.50	1.50/0.15									55.00/1.25	50	50	11.00	0.55
245	Variable Camshaft Timing																		50.00/2.25	75	75	50.00	2.25
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect		10.00/0.50					15.00/0.75	15.00/0.75	3.00/1.09				2.00/0.25		6.00/0.50			61.00/2.25	75	75	16.00	0.87
	1.2.3 Intake Manifold Modification																						
172	Intake Manifold Modification																		60.00/1.50	75	75	60.00	1.50
384	Air-Fuel Mixture Diffuser	Insufficient Data																		75	75		
430	Induction Modification																		10.00/0.75	75	75	10.00	0.75
440	Air-Fuel Mixture Deflection Plate																		3.00/0.75	75	75	3.00	0.75
	1.2.4 Carburetor Modification																						
33	Carburetor Modification, Main Jet Differential Pressure																		8.65/1.00	75	75	8.65	1.00
56	Crankcase Blowby and Idle Air Bleed Modification	5.50/0.75	9.00/0.70					9.00/0.50						4.00/0.15					35.00/1.50	75	75	12.50	0.72
288	Carburetor Main Discharge Nozzle Modification																		25.00/1.25	75	75	25.00	1.25
294	Exhaust Gas Recirculation with Carburetor Modification	Insufficient Data																					
295	Carburetor with Variable Venturi																		70.00/0.75	75	75	70.00	0.75
317	Carburetor Modification with Vacuum Advance Disconnect																		13.95/0.75	75	75	13.95	0.75
	1.2.5 Turbocharger																						
100	Turbocharger	Insufficient Data																					
	1.2.6 Fuel Injection																						
22	Electronic Fuel Injection	Insufficient Data																					
	Type 1.3 Ignition Control Systems																						
	1.3.1 Ignition Timing Modification																						
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification								15.00/1.00				25.00/0.35	2.00/0.25					50.00/1.00	75	75	23.00	0.65
175	Ignition Timing Modification with Lean Idle Adjustment																		32.00/1.00	75	75	32.00	1.00
	1.3.2 Ignition Spark Modification																						
23	Electronic Ignition Unit	Insufficient Data																					
95	Ignition Spark Modification	Insufficient Data																					
259	Photocell-Controlled Ignition System																		50.00/0.75	75	75	50.00	0.75
268	Capacitive Discharge Ignition																		60.00/0.75	150	150	60.00	0.75
296	Ignition Timing and Spark Modification																		20.00/0.25	75	75	20.00	0.25

Table 4-7. RELIABILITY AND CORRECTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONCL)

DEVICE NO.	DEVICE DESCRIPTION	REPLACEMENT PARTS COST ($)/REPAIR LABOR HOURS: CARBURETOR COMPONENT	IGNITION DEVICE/ HEATING ELEMENT/ HEAT EXCHANGER	CATALYST	SPRINGS/CABLES	POINTS/CONTACTS/ SENSOR	SPARK PLUGS	SWITCH	VALVE	TUBING/NOZZLES	HOUSING/CHAMBER/ CONTAINER	AIR PUMP	ELECTRONIC ASSEMBLY	HOSE	IGNITION COIL	ADAPTER	BACK PRESSURE/ FLOW CONTROL VALVE	PCV VALVE	RETROFIT DEVICE	FAILURE INTERVAL: MEAN MILES BEFORE PARTIAL FAILURE (MMBPF) (1,000 MILES)	MEAN MILES BEFORE TOTAL FAILURE (MMBTF) (1,000 MILES)	PARTS COST ($): AVERAGE COST OF REPAIR PARTS (CRP)	LABOR HOURS: MEAN TIME TO REPAIR (MTTR) (1)
	Type 1.4 Fuel Modification																						
	1.4.1 Alternative Gas Conversion																						
52	LPG Conversion																		457.95 / 12.00	300	300	457.95	12
459	LPG Conversion with Deceleration Unit																		457.95 / 12.00	300	300	457.95	12
460	Compressed Natural Gas Dual-Fuel Conversion	Insufficient Data			(2)														451.14 / 12.00	100	300	(2)	(2)
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	Insufficient Data																	575.00 / 18.00	75	75	575.00	18
464	Methanol Fuel Conversion with Catalytic Converter	Insufficient Data																					
466	LPG-Gasoline Dual-Fuel Conversion				(2)														457.95 / 12.00	100	300	(2)	(2)
	1.4.2 Fuel Additive																						
182	Fuel and Oil Additive	Not Applicable																					
282	LP Gas Injection							5.00 / 0.50	20.00 / 0.75	5.50 / 0.50				12.00 / 1.25					80.00 / 3.00	50	50	24.50	1.20
457	Water Injection	Insufficient Data																					
465	Fuel Additive	Not Applicable																					
	1.4.3 Fuel Conditioner																						
36	Fuel Conditioning by Exposure to Electromagnetic Field	Insufficient Data																					
279	Fuel Conditioner																		10.00 / 0.50	50	50	10.00	0.50
	GROUP 2 CRANKCASE EMISSION CONTROL SYSTEMS																						
	Type 2.1 Closed Systems																						
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed																		24.40 / 0.75	100	100	24.40	0.75
170	Closed Blowby Control System																		17.00 / 1.75	100	100	17.00	1.75
315	Closed Blowby Control System								3.00 / 0.50					2.00 / 0.25					50.00 / 1.50	50	50	18.33	0.75
	Type 2.2 Open Systems																						
160	Closed or Open Blowby Control System with Filter								2.50 / 0.75					1.00 / 0.25		3.00 / 0.75			53.50 / 1.25	75	75	15.00	0.75
427	Closed or Open Blowby Control System with Filter								3.00 / 0.75					1.00 / 0.25		4.00 / 0.75			52.00 / 1.25	50	50	15.00	0.75
	GROUP 3 EVAPORATIVE EMISSION CONTROL SYSTEMS																						
467	Fuel Evaporative Control System	Insufficient Data																					
	GROUP 4 EMISSION CONTROL COMBINATIONS																						
59	Three-Stage Exhaust Gas Control System	Insufficient Data																					
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation		10.00 / 0.50				2.00 / 0.25		15.00 / 0.75	5.00 / 0.40				3.00 / 0.25	8.00 / 0.45	4.00 / 0.70	3.00 (3) / 0.15	3.00 / 0.25	175.00 / 5.00	50	50	19.50	0.75
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	9.00 / 0.75							12.00 / 0.75					5.00 / 0.50					20.00 / 1.25	50	50	11.50	0.81
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	Insufficient Data																					

LEGEND: $15.00 → [15.00 / 0.50] ← 0.50 Hr Labor to Replace
Replacement parts cost

NOTES: (1) Mean time for one repair action
(2) Cost and labor to replace Bowden cable depends on specific installation details. C_{RP} and MTTR depend on these estimates.
(3) Three control valves

c. Most retrofit emission control systems (except ignition control systems), tend to include multiple components which represent possible failure points. However, these components can usually be repaired without replacing the entire system.

d. Ignition control systems are usually transistorized devices. If designed properly, their MMBTF is greater than 75,000 miles, but failure occurs suddenly. These devices generally have to be replaced as a total unit upon failure as a whole or in part.

e. Those induction modifications that have no moving parts may generally be more reliable. Air-bleed and exhaust gas recirculation induction modifications are generally more failure prone, because they contain more moving parts.

In summary, all retrofit devices evaluated are considered to have acceptable reliability characteristics if conventional automotive design standards are applied to the production models and if good preventive maintenance practices are followed during their service life.

4.3.1.3 Maintainability Analysis Procedure

The method for estimating retrofit maintainability requirements was similar to the method used for reliability. Maintainability was analyzed in terms of the preventive maintenance required to keep a device in satisfactory operating condition on a planned, scheduled basis.

Each retrofit device was examined for probable preventive maintenance requirements by considering it comparable to a conventional automotive counterpart. Using this approach, it was reasonable to conclude that an air filter should be changed every 12,000 miles, or a valve assembly cleaned and reset every 25,000 miles. For each retrofit device examined the following information was determined by the engineering evaluation team:

a. Preventive maintenance action - description.

b. Maintenance interval - quantified by the mean-miles-before-maintenance (MMBM) interval.

c. Labor associated with the preventive maintenance action - listed as mean-time-to-maintain (MTTM), in hours.

d. Material and parts cost for the maintenance action (C_{MP}), in dollars.

Table 4-8 lists retrofit devices by group classification and the preventive maintenance actions, associated intervals, and costs. In this table, the preventive maintenance actions were condensed to 18 typical actions encompassing the maintenance required for all individual devices. Maintenance intervals (MMBM), associated labor time (MTTM), and maintenance parts cost were entered for the preventive maintenance actions applicable to each device. If the preventive maintenance of a device required an engine tuneup parameter adjustment, then the time for this adjustment was included in the device maintenance time. The labor and parts costs for complete engine tuneup are excluded from the estimates because the retrofit contract requirements specifically excluded tuneup as a retrofit method.

Table 4-8. PREVENTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM

DEVICE NO.	DESCRIPTION	REPLACE CATALYST	AIR, EGR, BLOWBY FILTER	OIL/FUEL/ INJECTANT	UNIT	CLEAN AND REPLACE UNIT/COMPONENT	CLEAN PARTS/ ORIFICES/VALVES	FUEL FILTERS	LINES	CHECK SWITCH OPERATION (WITH METER)	VALVE ACTUATION	VOLTAGE	CHECK & ADJUST IGNITION TIMING/ DWELL	CARBURETION	VALVE SETTING	SWITCH SETTING	INSPECT (VISUAL) PLUGS & POINTS	LINES & HOSES	PIPES & CHAMBERS	MEAN-MILES-BEFORE-MAINTENANCE (MMBM) (1,000 MILES)	COST MAINTENANCE PARTS (C_{MP}) $	MEAN-TIME-TO-MAINTAIN (MTTM), HRS
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS:																					
	Type 1.1 Exhaust Gas Control Systems:																					
	1.1.1 Catalytic Converter																					
62	Catalytic Converter	Insufficient Data																				
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	Insufficient Data																				
96	Catalytic Converter with Distributor Vacuum Advance Disconnect	25(1)/.30	12/.25																	8.33	(1) 16.25	0.27
292	Catalytic Converter		12/.25																	12	2.50	0.25
	1.1.2 Thermal Reactor																					
31	Thermal Reaction by Turbine Blower Air Injection		12/.25																	12	3.00	.25
244	Rich Thermal Reactor		12/.25																	12	1.25	0.25
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard		12/.25																	12	1.25	0.25
468	Lean Thermal Reactor with Exhaust Gas Recirculation	Insufficient Data																				
	1.1.3 Exhaust Gas Afterburner																					
308	Exhaust Gas Afterburner												12/.35				12/.30		12/.15	12	3.00	0.80
425	Exhaust Gas Afterburner														12/.25		12/.10		12/.10	12	1.50	0.45
	1.1.4 Exhaust Gas Filter																					
164	Exhaust Gas Filter	Insufficient Data																				
	1.1.5 Exhaust Gas Backpressure																					
322	Exhaust Gas Backpressure Valve	Insufficient Data																				
	Type 1.2 Induction Control Systems:																					
	1.2.1 Air Bleed to Intake Manifold																					
1	Air Bleed to Intake Manifold		12/.10								12/.10							12/.10		12	2.50	0.30
42	Air Bleed to Intake Manifold							X			12/.10							12/.10		12	0	0.20
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect		12/.10							12/.15	12/.15									12	2.50	0.40
325	Air-Vapor Bleed to Intake Manifold		X	2.5/.25			2.5/.25													2.5	2.30	0.50
401	Air-Vapor Bleed to Intake Manifold			2.5/.25			2.5/.25								X					2.5	2.50	0.50
418	Air Bleed to Intake Manifold	Insufficient Data																				
433	Air-Vapor Bleed to Intake Manifold		X	2.5/.25			2.5/.25													2.5	2.30	0.50
458	Air Bleed to Intake Manifold	Insufficient Data																				
462	Air Bleed to Intake and Exhaust Manifolds	Insufficient Data					X	X														

Table 4-8. PREVENTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONT)

DEVICE NO.	DESCRIPTION	REPLACE CATALYST	AIR, EGR, BLOWBY FILTER	OIL/FUEL/ INJECTANT	UNIT	CLEAN & REPLACE UNIT/COMPONENT	CLEAN PARTS/ ORIFICES/VALVES	FUEL FILTERS	LINES	CHECK SWITCH OPERATION (WITH METER)	VALVE ACTUATION	VOLTAGE	CHECK & ADJUST IGNITION TIMING/ DWELL	CARBURETION	VALVE SETTING	SWITCH SETTING	INSPECT (VISUAL) PLUGS & POINTS	LINES & HOSES	PIPES & CHAMBERS	MEAN-MILES-BEFORE-MAINTENANCE (MMBM) (1,000 MILES)	COST MAINTENANCE PARTS (C_{MP}) $	MEAN-TIME-TO-MAINTAIN (MTTM), HRS
	1.2.2 Exhaust Gas Recirculation																					
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect						12/.15		12/.05	12/.10	12/.15			12/.05						12	1.25	0.50
245	Variable Camshaft Timing												25/.50							25	0	0.50
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect						6/.10		6/.10		6/.10			6/.10		6/.10				6	1.25	0.50
	1.2.3 Intake Manifold Modification																					
172	Intake Manifold Modification	Not Required																		.	0	0
384	Air-Fuel Mixture Diffuser				X															25	0	0.08
430	Induction Modification					25/.08														25	0	0.08
440	Air-Fuel Mixture Deflection Plate					25/.08														25	0	0.08
	1.2.4 Carburetor Modification																					
33	Carburetor Modification, Main Jet Differential Pressure	Not Required																			0	0
56	Crankcase Blowby and Idle Air Bleed Modification						12/.10			12/.05				12/.10				12/.05		12	2.00	0.30
288	Carburetor Main Discharge Nozzle Modification	Not Required																			0	0
294	Exhaust Gas Recirculation with Carburetor Modification	Insufficient Data																				
295	Carburetor with Variable Venturi						12/.25							12/.25						12	0	0.50
317	Carburetor Modification with Vacuum Advance Disconnect						12/.10							12/.10						12	0	0.20
	1.2.5 Turbocharger																					
100	Turbocharger	Insufficient Data																				
	1.2.6 Fuel Injection																					
22	Electronic Fuel Injection	Insufficient Data																X				
	Type 1.3 Ignition Control Systems:																					
	1.3.1 Ignition Timing Modification																					
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification		12/.05								12/.05		12/.10		12/.05	12/.05				12	0	0.30
175	Ignition Timing Modification with Lean Idle Adjustment																	X				
	1.3.2 Ignition Spark Modification																					
23	Electronic Ignition Unit	Insufficient Data																				
95	Ignition Spark Modification	Insufficient Data																				
259	Photocell-Controlled Ignition System												25/.25				25/.25			25	0	0.50
268	Capacitive Discharge Ignition	Not Required																			0	0
296	Ignition Timing and Spark Modification	Not Required																			0	0

Table 4-8. PREVENTIVE MAINTENANCE ESTIMATES OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONCL)

DEVICE NO.	DESCRIPTION	REPLACE CATALYST	AIR, EGR, BLOWBY FILTER	OIL/FUEL/ INJECTANT	UNIT	CLEAN & REPLACE UNIT/COMPONENT	CLEAN PARTS/ ORIFICES/VALVES	FUEL FILTERS	LINES	CHECK SWITCH OPERATION (WITH METER)	VALVE ACTUATION	VOLTAGE	CHECK & ADJUST IGNITION TIMING/ DWELL	CARBURETION	VALVE SETTING	SWITCH SETTING	INSPECT (VISUAL) PLUGS & POINTS	LINES & HOSES	PIPES & CHAMBERS	MEAN-MILES-BEFORE-MAINTENANCE (MMBM) (1,000 MILES)	COST MAINTENANCE PARTS (C_{MP}) $	MEAN-TIME-TO-MAINTAIN (MTTM), HRS
	Type 1.4 Fuel Modification:																					
	1.4.1 Alternative Gas Conversion																					
52	LPG Conversion							25/.25												25	2.00	0.25
459	LPG Conversion with Deceleration Unit							25/.25												25	2.00	0.25
460	Compressed Natural Gas Dual-fuel Conv.	Insufficient Data																		300		
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation							25/.25												25	2.00	0.25
464	Methanol Fuel Conversion with Catalytic Converter	Insufficient Data																				
466	LPG-Gasoline Dual-Fuel Conversion							25/.25												25	2.00	0.25
	1.4.2 Fuel Additive																					
182	Fuel and Oil Additive	Replace Additive - Every Tank Full																			0	
282	LP Gas Injection						12/.50			12/.10	12/.10									12	0	0.70
457	Water Injection	Insufficient Data																				
465	Fuel Additive	Replace Additive																			0	
	1.4.3 Fuel Conditioner																					
36	Fuel Conditioning by Exposure to Electromagnetic Field	Insufficient Data																				
279	Fuel Conditioner	Not Required																			0	0
	GROUP 2 CRANKCASE EMISSION CONTROL SYSTEMS																					
	Type 2.1 Closed System:																					
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed						25/.25													25	0	0.25
170	Closed Blowby Control System					12/.15								12/.10						12	0	0.25
315	Closed Blowby Control System					25/.30	25/.10							25/.25	25/.10					25	0	0.75
	Type 2.2 Open System:																					
160	Closed or Open Blowby Control System with Filter		12/.25																	12	3.00	0.25
427	Closed or Open Blowby Control System with Filter		15(2)/.25		10/.25	5/.25														5	(2) 3.00	0.46
	GROUP 3 EVAPORATIVE EMISSION CONTROL SYSTEMS																					
467	Fuel Evaporation Control System							12/.25												12	1.00	.25
	GROUP 4 EMISSION CONTROL COMBINATIONS																					
59	Three-Stage Exhaust Gas Control System	Insufficient Data																				
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation		12/.15				12/.10	12/.10	X								12/.10	12/.05		12	2.50	0.50
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing						12/.25				12/.25									12	2.00	0.50
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	Insufficient Data																				

LEGEND:

X — Possible maintenance action required.

Maintenance Interval in Thousands of Miles → Code 12/.5 ← Preventive Maintenance Labor-Hours

NOTES: (1) $16.25 is the cost of replacement catalyst for an 8-cylinder engine every 25,000 miles; the average C_{MP} for use in the evaluation methodology is $5.42.

(2) $3.00 is the estimated cost of filter replacement every 15,000 miles; the average C_{MP} for use in the evaluation methodology is $1.00.

4.3.1.4 Maintainability Analysis Results

The following observations were made for the comparative maintenance estimates shown in Table 4-8:

a. Most of the retrofit devices examined in this program have preventive maintenance intervals (MMBM) equal to or greater than 12,000 miles. The exceptions are the alcohol-water injection systems (Devices 325, 401, and 433) which require refill and metering valve adjustment or cleaning about every 2,500 miles. Also, Device 246 requires cleaning of the EGR valve every 6,000 miles.

b. Approximately 75 percent of the devices require 0.5 hour or less to maintain. The associated costs for maintenance parts are less than $3.00 for most of these devices.

   The catalyst system (Device 96) requires a new change of catalyst at 25,000-mile intervals at a cost of $20 for an 8-cylinder engine and $15 for a 6-cylinder engine.

c. Maintenance requirements generally increase with the number of filters, valves, electrical switches and hoses incorporated in the retrofit system.

d. Solid-state ignition modification systems reportedly require no preventive maintenance.

In summary, most of the retrofit devices examined appear to have reasonable periodic maintenance requirements and maintenance intervals of no less than 12,000 miles.

4.3.2 Effect of Retrofit Device Installation on Vehicle Reliability and Maintainability

The possibility of increased maintenance and decreased reliability in a motor vehicle as a result of a retrofit device use can be as unacceptable as the reliability and maintenance characteristics of the device itself. Accordingly, each device was examined for its impact on the reliability and maintenance of the vehicle on which it might be installed. The observations presented below are of a general nature based on past experience with emission control systems. The durability tests that will be reported in Volume VI should provide some actual data to substantiate these observations. The following observations were made:

a. The devices using ignition spark retard as an approach for emission control may cause engine overheating. A majority of these types of devices have coolant temperature sensors which restore spark advance if overheating occurs. The possibility of exhaust valve damage and the adverse effects of long-term exposure of other related engine components to increased engine heat must be considered with these devices.

b. Exhaust gas recirculation devices may pose two problems: (1) recirculation may provide a troublesome source of induction system contamination, and (2) the carburetion system may require more frequent tuning to provide satisfactory driveability.

c. Recirculation of crankcase gases to the carburetor base and air inlet (closed systems) contaminates the carburetor and may contribute to increased carburetor maintenance requirements.

d. Use of catalytic reactors, thermal reactors, and exhaust gas reactor manifolds has potential problems of increased exhaust backpressure and higher temperature; this may result in hotter valve operation.

e. Capacitive discharge ignition systems may require more frequent replacement of the high voltage wires and coil used in conventional ignition systems, because of increased susceptibility of conventional system components to deterioration.

4.3.3 Retrofit Emission Inspection Requirements

An inspection program is recommended as a necessary part of any program of vehicle emission control incorporating retrofit devices. Each of the 65 retrofit systems evaluated have specific inspection and maintenance requirements which control their installation and use. Although these requirements may vary from one device to the next, they all have in common the objective of reducing vehicle emissions.

Vehicles equipped with an exhaust control device should receive an emission test to verify satisfactory device operation in terms of actual emission reduction. This test is required because of the many variables that used cars and installation personnel can introduce to make a retrofit device ineffective.

The retrofit crankcase blowby control device should be inspected for correct functional operation to the device manufacturer's specifications. There is no information on inspection requirements for retrofit fuel evaporative control systems.

4.3.3.1 Retrofit Program Inspection and Maintenance Requirements

To achieve maximum effectiveness of the retrofit device installation, each used vehicle within the jurisdiction of a retrofit program should be inspected and adjusted for minimum emissions at the time of retrofit device initial installation. Also periodic inspections of the device operation and engine tuneup should be conducted. A Northrop Corporation study concluded that vehicles experience degradation in exhaust pollutants as they accumulate mileage and age.(1) Lower levels of emissions are achievable when vehicles are serviced and adjustments made to engine, carburetor, and ignition systems.

Most of the retrofit devices evaluated were found to require maintenance usually at a frequency of 12,000 miles. Depending on the driving habits of individual motorists, this would require servicing the device periodically at an interval of once every 12-24 months. The recommended interval and maintenance procedure would be dependent on the respective device and manufacturer. Requirements for defective or worn parts replacement, along with the procedures, must be defined by the retrofit manufacturer based on reliability and maintainability analyses conducted prior to State and/or Federal certification.

4.3.3.2 Emission Inspection Criteria

Inspection criteria should be established to identify those retrofit devices and systems that have failed or are marginal in performance, and thus require repair. Prior to instituting an inspection program, sufficient empirical data on the certified devices and systems should be gathered to define and relate failures and performance levels to specific corrective actions. The minimum emission and inspection criteria must include the following:

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(1) Northrop Corporation Electro-Mechanical Division in association with Olson Laboratories, Inc., "Mandatory Vehicle Emission Inspection and Maintenance," Part B, Test Program Final Report, Contract ARB 1522 (California Air Resources Board), Northrop Report No. 71Y240A (two parts), 10 December 1971.

a. Exhaust Control Device Emission Criteria: Exhaust emission inspection of retrofit devices would require measuring HC, CO, and NOx levels. Emission limits for inspection would be established for the controlled pollutants. In selecting a retrofit device inspection procedure, careful consideration should be given to the compatibility of the procedure for application to new model vehicles for continued use after uncontrolled vehicles phase out.

For those retrofit devices and systems that perform as a function of engine speed, such as in the case of some ignition timing modification and exhaust gas recirculation types, the desired test procedure must simulate different road speeds to provide complete evaluation of the installed retrofit system. Conversely, if the exhaust control technique is independent of road-load conditions, then an idle test may be sufficient. A fundamental requirement of any inspection procedure, however, is that it provide a means of verifying that the emission reduction potential of a retrofit device is being attained within an acceptable tolerance.

b. Crankcase Blowby Device Inspection Criteria: Retrofit crankcase emission control systems would be subjected to an operational check and a visual component inspection. These devices may be inspected using crankcase vacuum or pressure as a means of establishing failure levels. A crankcase vacuum measurement at idle would provide an objective performance test that is more effective than a physical inspection of the system. This would include measuring the crankcase vacuum or pressure and comparing it to a rejection level. For the "open" crankcase systems, the inspection criteria would require a crankcase vacuum measurement which would assure the inspector that no blowby outflow to the atmosphere is occurring. The "closed" or "sealed" crankcase systems criteria could allow some crankcase pressure because all crankcase openings are closed to the atmosphere.

Past experience at Olson Laboratories has shown that a crankcase pressure of approximately 3 inches of water is acceptable for closed systems without any adverse effect on car operation or crankcase system performance. Most closed systems are designed to operate from 1 to 2 inches of water crankcase vacuum on a vehicle with average blowby flow rates.

Detailed procedures for inspecting and measuring the performance of crankcase systems are given in California documents.[(1)(2)]

c. Fuel Evaporative System Inspection Criteria: Retrofit fuel evaporative emission control systems would have to be subjected to visual inspection for correct operation and fuel leaks. The pressure/vacuum safety relief system could be inspected with pressure gage instrumentation.

Quality audits of the vehicle population could be performed using the 1972 Federal Test Procedure for evaporative emissions.

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(1) "California Test Procedure and Criteria for Motor Vehicle Crankcase Emission Control," California Air Resources Board, 16 August 1966.

(2) Handbook, Pollution Control Device Installation and Inspection, HPH 82.1, California Highway Patrol, April 1971.

4.3.3.3 Feasibility of Retrofit Inspection and Maintenance

A network of inspection and maintenance facilities to assure that installed devices and systems are operating as intended would maximize achievement of the emission reduction goals and objectives of a retrofit program. Although the feasibility analysis relative to an inspection and maintenance program for retrofit systems is beyond the scope of this present study, the factors and tasks that should be considered in such an analysis include the following:

a. Instrumentation and Equipment Required: This task would identify those instruments, equipment, tools, and fixtures required to inspect and service the retrofit device and systems as installed on the affected vehicles. Initial acquisition costs, service contracts and warranties, operating and maintenance manuals, spare parts lists, and other items related to these hardware requirements would be defined.

   Typical instruments would include HC, CO, and NOx analyzers. Equipment would include chassis dynamometers, diagnositic consoles, and vehicle lifts, if applicable to the selected inspection procedure. Tools and fixtures may include vacuum and pressure gauges.

   Other requirements are documented test and inspection procedures, service and repair procedures for the devices, and any data handling procedures and/or computerized programs.

b. Technical Personnel Qualifications and Training: The technical personnel may be categorized into inspection types and maintenance types. Depending on the facility configuration, the inspection and maintenance technician may be one and the same. Personnel qualifications and training requirements are dependent on inspection procedures and associated instrumentation relative to a specific retrofit technique.

   The physical installation of the devices evaluated require normal automotive mechanic skills. However, most auto mechanics are not presently capable of properly adjusting a retrofit device and related engine tuneup parameters for low emissions without some additional training. Technician upgrading with training programs would be required for a successful and effective retrofit program.

c. Facilities Requirements: Facilities may be privately owned and operated, and regulated through State licensing. They may also be State owned and operated, or State owned and privately operated. Each alternative arrangement has its merits in view of the State, private industry, and the general motorist.

   Inspections may be performed at State facilities with maintenance performed by the private sector. Alternatively both inspections and maintenance may be performed at private facilities. The economic, social, and political implications of each arrangement should be evaluated.

4.4 INITIAL AND RECURRING COSTS

4.4.1 Initial Costs

Initial costs are those incurred initially by the vehicle owner in purchasing a retrofit device and having it installed as an operating part of the total vehicle. The initial costs consist of the material costs and labor costs necessary to provide a complete retrofit device installation. Material costs include the basic device itself and the accessories that are necessary for a complete installation. Labor costs include the time required to accomplish installation, and then to test or adjust the device for operation.

The number of hours for installation, test, and adjustment was determined by estimating the time required to perform each installation step of the related procedures (see paragraph 4.5 for installation requirements). The total time was compared to the estimate provided by the developer to determine whether there was any significant difference between the two. The labor cost was determined by multiplying the standard California hourly rate of $12.50 by the number of hours. The estimated retail cost of the material was taken from the developer's source material, unless this retail cost was considered unrealistic. In the latter case, a cost estimate based on historical cost data for similar items was used.

As part of device installation, most developers required that the engine be "well tuned"; however, in the retrofit program, the effect and cost of periodic tuneup was specifically excluded, in accordance with the contract. Tuneup related costs were included only if the developer's installation specified a tuneup related part or adjustment on which device performance depended. In this case, the contract exclusion of tuneup was not considered applicable, since that exclusion was for engine tuneup when used by itself as a retrofit approach.

4.4.2 Recurring Costs

Recurring costs are those resulting from the upkeep and operation of a retrofit device during its service life. These costs include retrofit repair, maintenance, and the cost of increased or decreased fuel consumption. The recurring costs are measured in dollars per mile driven and consist of a summation of the following factors:

a. <u>Repair Costs per Mile Driven:</u> These costs include material and labor costs associated with the repair of failed retrofit components. Mathematically they are calculated from the mean-time-to-repair (MTTR) in hours, mean-miles-before-partial-failure (MMBPF), average costs of repair parts (C_{RP}), and repair labor rate (L_C) in dollars per hour.

b. <u>Preventive Maintenance Costs:</u> These costs include material and labor costs associated with preventative maintenance which is performed on a planned, scheduled basis to keep the device in satisfactory operating condition. Mathematically these costs are calculated from the mean-miles-before-maintenance (MMBM), the mean-time-to-maintain (MTTM) in hours, the cost of maintenance parts (C_{MP}), and the maintenance labor rate (L_C) in dollars per hour.

c. <u>Fuel Consumption Cost:</u> This cost reflects the increased or decreased fuel consumption resulting from retrofit device operation as a part of the vehicular system. This cost, in dollars per mile driven, is computed from the fuel consumption with the device installed (in gallons per mile), fuel consumption without the device installed, and fuel cost in dollars per gallon.

Calculation of total recurring costs resulting from the retrofit installation were based on the figures determined for MMBPF, MTTR, MMBM, MTTM, C_{RP}, and C_{MP} from the reliability and maintainability data listed in Tables 4-7 and 4-8. The recurring cost data were calculated using the equations outlined in Section 3 of Volume III.

4.4.3 Initial and Recurring Cost Results

The initial and recurring costs calculated for each device are shown in Table 4-9. The fuel consumption costs were included in the recurring cost calculations for the devices which were tested in the retrofit program. It was not possible to include fuel consumption for those devices which were not tested, because most developers did not submit fuel consumption data and those who did reported improvements in economy which were questionable. The sensitivity analysis summarized in paragraph 3.4 showed that fuel consumption change due to a device installation was the most sensitive factor influencing recurring costs.

4.5 INSTALLATION AND SKILL LEVEL REQUIREMENTS

The initial step in defining the installation procedure for each retrofit device was to obtain or develop installation data. This information had been specifically requested from the developers, and much of the information they provided included installation procedures on a step-by-step basis. In many cases, no procedures were provided but illustrations of installations were available. Step-by-step procedures were then developed by comparing the vehicle with and without the device and determining a logical installation procedure. In cases where a device was one of those tested in the retrofit program, the actual installation procedure was used for comparison purposes. A list of required material was prepared based on the installation requirements. The tools, equipment, instruments, and facilities required to perform the installation, test, and adjustment procedures were similarly identified.

Table 4-10 presents a summary of the significant installation and adjustment requirements for the retrofit devices studied.

If an emission inspection is required after device installation, then the automotive mechanic's capability would have to be upgraded to include training in the technique of emission measurements and adjustments with the appropriate instrumentation. Paragraph 4.3.3 reviews the inspection requirements for effective retrofit installations, including instrumentation and facilities.

The implementation of a retrofit emission control strategy requires quality control of device installations and recurring maintenance and inspections. Such quality control would require the regulation of garages and mechanic personnel to verify their capability to install, adjust, maintain, inspect, and repair the approved devices.

Table 4-9. INITIAL AND RECURRING COSTS OF DEVICES EVALUATED IN RETROFIT PROGRAM

DEVICE No.	DESCRIPTION	INITIAL COST TO CAR OWNER ($)(1)	RECURRING COST TO CAR OWNER ($/100 mi)(4)
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS		
	Type 1.1 Exhaust Gas Control Systems:		
	1.1.1 Catalytic Converter		
62	Catalytic Converter	(3)	(3)
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	(3)	(3)
96	Catalytic Converter with Distributor Vacuum Advance Disconnect	175(5)	0.171(2)
292	Catalytic Converter	73	0.047
	1.1.2 Thermal Reactor		
31	Thermal Reaction by Turbine Blower Air Injection	143	0.051
244	Rich Thermal Reactor	375(5)	0.036
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	(3)	(3)
468	Lean Thermal Reactor with Exhaust Gas Recirculation	(3)	(3)
	1.1.3 Exhaust Gas Afterburner		
308	Exhaust Gas Afterburner	71	0.108
425	Exhaust Gas Afterburner	159	0.059
	1.1.4 Exhaust Gas Filter		
164	Exhaust Gas Filter	103	0.025
	1.1.5 Exhaust Gas Backpressure		
322	Exhaust Gas Backpressure Valve	(3)	(3)
	Type 1.2 Induction Control Systems:		
	1.2.1 Air Bleed to Intake Manifold		
1	Air Bleed to Intake Manifold	64	0.022(2)
42	Air Bleed to Intake Manifold	23	-0.191(2)
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	63	0.062
325	Air-Vapor Bleed to Intake Manifold	56	0.342
401	Air-Vapor Bleed to Intake Manifold	46	0.350
418	Air Bleed to Intake Manifold	(3)	(3)
433	Air-Vapor Bleed to Intake Manifold	56	0.342
458	Air Bleed to Intake Manifold	(3)	(3)
462	Air Bleed to Intake and Exhaust Manifold	(3)	(3)
	1.2.2 Exhaust Gas Recirculation		
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	71	0.062(2)
245	Variable Camshaft Timing	78	0.259(2)
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	89	-0.040(2)
294	Exhaust Gas Recirculation with Carburetor Modification	(3)	(3)
	1.2.3 Intake Manifold Modification		
172	Intake Manifold Modification	79	0.0
384	Air-Fuel Mixture Diffuser	(3)	(3)
430	Induction Modification	19	0.004
440	Air-Fuel Mixture Deflection Plate	12	0.004
	1.2.4 Carburetor Modification		
33	Carburetor Modification, Main Jet Differential Pressure	21	-0.257(2)
56	Crankcase Blowby and Idle Air Bleed Modification	54	0.048
288	Carburetor Main Discharge Nozzle Modification	41	0.144(2)
295	Carburetor with Variable Venturi	79	0.430(2)
317	Carburetor Modification with Vacuum Advance Disconnect	23	0.021
	1.2.5 Turbocharger		
100	Turbocharger	(3)	(3)

Table 4-9. INITIAL AND RECURRING COSTS OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONCL)

DEVICE NO.	DESCRIPTION	INITIAL COST TO CAR OWNER ($)(1)	RECURRING COST TO CAR OWNER ($/100 mi)(4)
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS (Cont)		
	1.2.6 Fuel Injection		
22	Electronic Fuel Injection	(3)	(3)
	Type 1.3 Ignition Control Systems		
	1.3.1 Ignition Timing Modification		
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	63	0.069(2)
175	Ignition Timing Modification with Lean Idle Adjustment	45	0.332(2)
	1.3.2 Ignition Spark Modification		
23	Electronic Ignition Unit	(3)	(3)
95	Ignition Spark Modification	(3)	(3)
259	Photocell-Controlled Ignition System	59	0.025
268	Capacitive Discharge Ignition	69	0.0
296	Ignition Timing and Spark Modification	23	0.0
	Type 1.4 Fuel Modification		
	1.4.1 Alternative Gas Conversion		
52	LPG Conversion	608	0.021
459	LPG Conversion with Deceleration Unit	608	0.021
460	Compressed Natural Gas Dual-Fuel Conversion	601	(3)
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	(3)	(3)
464	Methanol Fuel Conversion with Catalytic Converter	(3)	(3)
466	LPG-Gasoline Dual-Fuel Conversion	(3)	(3)
	1.4.2 Fuel Additive		
182	Fuel and Oil Additives	1	0.293
282	LP Gas Injection	118	0.073
457	Water Injection	(3)	(3)
465	Fuel Additive	(3)	(3)
	1.4.3 Fuel Conditioner		
36	Fuel Conditioning by Exposure to Electromagnetic Field	(3)	(3)
279	Fuel Conditioner	16	0.0
	GROUP 2 CRANKCASE EMISSION CONTROL SYSTEMS		
	Type 2.1 Closed Systems		
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed	34	0.013
170	Closed Blowby Control System	39	0.026
315	Closed Blowby Control System	69	0.038
427	Closed or Open Blowby Control System with Filter	68	0.135
	Type 2.2 Open Systems		
160	Closed or Open Blowby Control System with Filter	69	0.051
	GROUP 3 EVAPORATIVE EMISSION CONTROL SYSTEMS		
467	Fuel Evaporation Control System	137	(3)
	GROUP 4 EMISSION CONTROL COMBINATIONS		
59	Three-Stage Exhaust Gas Control System	(3)	(3)
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation	238	0.073
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	36	0.067
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	400	(3)

(1) Estimated retail costs of material and labor excluding engine tuneup costs not related to device installation.
(2) Device tested in retrofit program.
(3) Insufficient data on which to base cost estimate.
(4) Recurring costs include fuel consumption change as measured during 1972 Federal Test Procedure for emissions. For devices not tested in retrofit program, recurring costs do not include fuel consumption effects, as fuel data from the retrofit developers were incomplete generally.
(5) For 8-cylinder engine.

Table 4-10. INSTALLATION AND SKILL LEVEL REQUIREMENTS SUMMARY

Device Number	Installation	Most Complex Adjustment or Test Characteristic	Minimum Skill Level
EXHAUST GAS CONTROL SYSTEMS			
31	Drill and tap holes in exhaust manifold, install turbine blower, connect air injection nozzles.	Adjust air flow to exhaust system for optimum emission oxidation.	Automotive Mechanic
62	Install the converter in place of the standard vehicle muffler. Install air pump to supply auxiliary air to the converter. Connect bypass to system to provide converter overtemperature protection.	Adjust air flow volume to converter for optimum oxidation of emissions.	Automotive Mechanic
93	Install converter in exhaust system. Install engine valve timing modification. Install auxiliary air pump and heavy duty ignition system. Connect air pump to converter.	Adjust carburetor for lean air-fuel mixture. Use exhaust analyzer.	Automotive Mechanic
96	Install catalytic converters, air pump, and overheat protection device.	Test overtemperature alarm circuit during vehicle acceleration and deceleration.	Automotive Mechanic
164	Remove the presently installed exhaust system from the manifold and replace with the exhaust filtering system.	Test for increased backpressure in the exhaust system.	Automotive Mechanic
244	Replace standard exhaust manifold with exhaust reactor manifold and install air pump.	Adjust carburetor to air-fuel ratio of 11.0:1. Use exhaust analyzer for optimum oxidation of emissions.	Automotive Mechanic
292	Install catalyst exhaust gas purifier in exhaust line.	Adjust carburetor for best lean idle setting. Use exhaust analyzer for optimum emissions reduction.	Automotive Mechanic
308	Install afterburner in exhaust line, replace ignition points with dual ignition points, install second coil, hook up afterburner electrically.	Adjust carburetor air-fuel idle setting to manufacturer's specifications. Measure available spark voltage to unit with engine analyzer.	Automotive Mechanic
322	Install spring-controlled flapper valve (hinge up) to the end of the tail pipe.	Insufficient information for adjustment of device.	Automotive Mechanic
425	Install afterburner unit in exhaust line, install air pump, and electronic control box.	Adjust carburetor idel air-fuel mixture to 11.5:1. Use exhaust analyzer.	Automotive Mechanic
463	Remove vehicle exhaust manifold and replace with the Thermal Reactor. For V-8 engines, a reactor is installed on each cylinder bank. Connect reactors to vehicle exhaust system. Connect EGR diaphragm valve to the vacuum advance line. Connect EGR valve inlet to exhaust system. EGR valve outlet is connected to the carburetor above the throttle plate.	Adjust exhaust recycle gas to 12 percent of engine intake air. Adjust air flow to converter for optimum emission reduction - use exhaust analyzer.	Automotive Mechanic
468	Insufficient data.	Adjust spark advance for low emissions and acceptable driveability.	Automotive Mechanic
INDUCTION CONTROL SYSTEMS			
1	Install adapter plate between carburetor and intake manifold, mount valve body assembly in engine compartment, and connect valve body to adapter plate.	Balance idle air-fuel mixture screws to obtain smoothest idle at recommended speed. Adjust for combustion efficiency of 75-80 percent. Unscrew device counterweight for 1-3" Hg vacuum reduction in intake manifold vacuum. Readjust counterweight to increase combustion efficiency above 85 percent.(1)	Automotive Mechanic
10	Install adapter plate between carburetor and intake manifold. Replace inner venturi in carburetor with vaporizer. Connect recirculating tube from exhaust to adapter plate. Install thermostatic vacuum switch.	Adjust carburetor for best idle air fuel mixture using exhaust analyzer. Adjust engine idle rpm with tachometer.	Automotive Mechanic
22	Insufficient data.	Insufficient information for device adjustment.	Insufficient Info.
33	Drill holes in top of carburetor fuel bowl and in intake manifold. Connect these holes with hose that includes a vacuum adjustment valve.	Adjust device valve during steady cruise until noting a drop in engine rpm. Close valve slightly and lock.	Automotive Mechanic
42	Drill holes in intake manifold and air filter casing. Install connectors and hook up device with hose.	Adjust the device valve with a CO exhaust analyzer.	Automotive Mechanic
56	Replace idle mixture screws with special screws, install adapter plate between carburetor and intake manifold, mount vacuum switch and heater assembly on carburetor, connect hoses and wiring.	Test vacuum switch and heater elements for function. Adjust carburetor idle air-fuel mixture for best lean operation. Adjust idle rpm with tachometer.	Automotive Mechanic
57	Install adapter plate between carburetor and intake manifold. Install vacuum disconnect switch and vacuum hoses.	Automatic transmissions - adjust idle 50 rpm over manufacturer's recommendation. Standard transmissions - adjust idle 75 rpm over manufacturer's recommendations. Adjust carburetor idle mixture to 86 percent combustion efficiency, or at 0.9 to 1.2 percent carbon monoxide. Idle 2200 rpm adjust plate air to 87 ±1 percent combustion efficiency or 1.2 ±0.1 percent carbon monoxide.(1)	Automotive Mechanic
100	Install turbocharger in new exhaust system. Turbocharger intake air is ducted from standard air cleaner, outlet air is ducted to carburetor venturi inlet. Install electric fuel pump for high boost operation.	Insufficient information.	Automotive Mechanic
172	Remove intake manifold from engine and insert device into manifold. Reinstall manifold. Install leaner primary jets in carburetor.	Adjust engine idle rpm to manufacturer's specifications, and adjust carburetor for best lean idle mixture.	Automotive Mechanic

Table 4-10. INSTALLATION AND SKILL LEVEL REQUIREMENTS SUMMARY (CONT)

Device Number	Installation	Most Complex Adjustment or Test Characteristic	Minimum Skill Level
INDUCTION CONTROL SYSTEMS (Cont)			
245	Replace valve cam timing sprocket with a new variable cam sprocket.	Adjust basic ignition timing to manufacturer's specifications. Adjust carburetor idle air-fuel mixture for lean operation using exhaust analyzer.	Automotive Mechanic
246	Install adapter plate between carburetor and intake manifold. Connect recirculating tube from exhaust to vacuum-operated shutoff valve to adapter plate. Install solenoid valve. Replace speedometer cable with new one having switch installed.	Adjust carburetor for best lean idle setting. Use exhaust analyzer for optimum emissions reduction.	Automotive Mechanic
288	Remove venturi assembly from carburetor and install device into assembly. Reassemble into carburetor.	Adjust idle rpm and adjust carburetor for best idle air-fuel mixture with exhaust analyzer.	Automotive Mechanic
294	Insufficient information for installation of the device.	Insufficient information for adjustment of device.	Insufficient Info.
295	Remove carburetor and replace with new variable venturi carburetor.	Adjust throttle linkage to carburetor. Readjust idle rpm and idle air-fuel mixture for best lean operation.	Automotive Mechanic
317	Replace carburetor primary metering jet, insert capillary tube in carburetor cover, connect evaporation chamber to PCV valve.	Readjust basic ignition with electronic engine analyzer. Set carburetor air-fuel mixture to 15:1. Reset carburetor choke 1 division (rich) from factory specifications.	Automotive Mechanic
325/ 433	Mount a fluid reservoir in the engine compartment, install adapter plate between carburetor and intake manifold, replace idle adjusting screws with special screws, and connect hose from reservoir to adapter plate.	Readjust idle rpm and idle air-fuel mixture. Observe with engine running that device is aerating and that all connections are secure.	Automotive Mechanic
384	Remove carburetor and install device in intake manifold. Replace carburetor.	Adjust carburetor idle air-fuel mixture. Use multimeter to check for device "shorts."	Automotive Mechanic
401	Mount fluid reservoir in engine compartment, insert T-fitting in PCV hose, connect reservoir to T-fitting.	Adjust idle rpm. Adjust valve for flow of air through device intake.	Automotive Mechanic
418	Insert the device in the crankcase ventilation return line between the PCV valve and intake manifold.	Adjust carburetor idle air-fuel mixture. Use exhaust analyzer.	Automotive Mechanic
430	Remove carburetor and install device in intake manifold. Replace carburetor.	Adjust idle automatic transmission to 620 rpm. Standard transmissions to 700 rpm. Adjust carburetor to minimum HC and CO level on exhaust analyzer. Adjust automatic choke to lean value.	Automotive Mechanic
440	Install device between carburetor and intake manifold.	Adjust engine idle rpm and carburetor air-fuel mixture. Use exhaust analyzer.	Automotive Mechanic
458	Install fluid reservoir on fender wall. Insert vapor metering T-valve in crankcase ventilation return line between PCV valve and intake manifold. Connect reservoir outlet tube to the T-valve. Fill reservoir with fluid.	Adjust carburetor idle air-fuel mixture. Use exhaust analyzer.	Automotive Mechanic
462	Connect exhaust scavenger to the tapped holes in the exhaust manifold. Install the crankcase scavenger in the positive crankcase line. Remove the interior part of the PCV valve.	Insufficient information for adjustment of the device.	Automotive Mechanic
IGNITION CONTROL SYSTEMS			
23	Insufficient information for installation of the device.	Insufficient information for adjustment of the device.	Insufficient Info.
69	Install the spark retard device, solenoid valve in vacuum advance line, and replace idle adjust screws.	Adjust ignition timing control for low speed engine performance. Adjust carburetor air-fuel for minimum emission levels at idle rpm and trim adjustment at 1,600 rpm.	Automotive Mechanic
95	Install device on spark plug wires near distributor.	Check ignition system with electronic engine analyzer.	Automotive Mechanic
175	Install control unit in engine compartment, hook up wiring and vacuum hose to distributor and coil.	Adjust engine idle rpm and idle air-fuel mixture (exhaust analyzer). Adjust unit for proper solenoid switch operation with engine analyzer.	Automotive Mechanic
259	Replace points and condenser in distributor with photocell and shadow disc. Install amplifier coil in engine compartment. Make wiring connections.	Adjust basic ignition timing and test spark voltages with electronic engine analyzer.	Automotive Mechanic
268	Install unit in engine compartment and connect wires.	Readjust spark plug gap and adjust basic ignition timing with electronic engine analyzer.	Automotive Mechanic
296	Install unit in engine compartment and connect wiring.	Test spark voltages with electronic engine analyzer.	Automotive Mechanic
FUEL MODIFICATION SYSTEMS			
36	Install the device in the fuel line between the fuel pump and the carburetor. Connect terminals (electrical) to 12-volt dc supply.	Insufficient information.	Automotive Mechanic
52	Install converter and fuel filter plus vacuum fuel lock unit. Connect heater water to converter. Connect vacuum fuel lock to intake manifold. Install Type C carburetor adapter and carburetor on intake manifold. Install 160°F thermostat in engine cooling system. Install 35-gallon LPG tank set, wire braid hoses, fuel gage, and remote fill line.	Adjust idle air-fuel mixture. Test for leaks. Adjust power mixture at wide open throttle.	Automotive Mechanic

Table 4-10. INSTALLATION AND SKILL LEVEL REQUIREMENTS SUMMARY (CONCL)

Device Number	Installation	Most Complex Adjustment or Test Characteristic	Minimum Skill Level
FUEL MODIFICATION SYSTEMS (Cont)			
182	Fuel additive; no installation required.	Check condition of fuel filter. Replace as necessary.	Vehicle owner
279	Mount the device in the engine compartment and connect it into the fuel line between fuel pump and carburetor. Connect electrical wiring.	Check system for electrical leaks, or shorts.	Automotive Mechanic
282	Mount LPG tank in trunk of car, mount regulating valve assembly, connect with copper tubing from tank to valve to intake.	Adjust setting of regulating valve to minimize ignition spark knock (pinging). Check system for leaks.	Automotive Mechanic
457	Insufficient information.	Insufficient information	Insufficient Info.
459	Insufficient information.	Adjust fuel flow valve and air flow valve drag linkage.	Automotive Mechanic
460	Install pressure regulators on left front side of engine compartment. Install mixer on carburetor. Install connector and fuel filter plus vacuum fuel lock unit. Connect heater water to converter. Connect vacuum fuel lock to intake manifold. Install 160°F thermostat in engine cooling system. Install CNG tanks, fuel lines, solenoid valves and Bowden control cable.	Adjust final pressure for light load operation. Adjust mixer idle screw to lean drop-off point.	Automotive Mechanic
461	Insufficient information.	Insufficient information.	Insufficient Info.
464	Install carburetor modification kit for conversion of gasoline fuel to methanol. Install converter close as possible to exhaust manifold. Install air pump and connect air supply to converter.	Adjust carburetor for air-methanol (fuel) mixture.	Automotive Mechanic
465	Fuel additive; no installation required.	Insufficient information available for preparation of additive-treated fuel.	Insufficient Info.
466	Install converter and fuel filter plus vacuum fuel lock unit. Connect heater water to converter. Connect vacuum fuel lock to intake manifold. Install Type C carburetor adapter and carburetor on intake manifold. Install 160°F thermostat in engine cooling system. Install tank set, hoses, fuel gage and remote fill line.	Adjust idle air-fuel mixture. Test for leaks. Adjust power mixture at wide open throttle.	Automotive Mechanic
CRANKCASE EMISSION CONTROL SYSTEMS			
24	Replace PCV valve with variable jet valve. Install separator unit in blowby line between variable jet valve and the crankcase.	Check crankcase pressure (or vacuum) after installing device.	Automotive Mechanic
160	Mount filter unit in engine compartment, install hose adapter fittings, and connect hoses.	Readjust carburetor for best lean idle air-fuel mixture. Set idle rpm to manufacturer's specifications.	Automotive Mechanic
170	Replace PCV valve with a special valve, connect hoses, plug and seal all outlets to the crankcase.	Adjust device metering valve to obtain 4-5" Hg vacuum at idle rpm. Readjust carburetor to obtain best idle rpm and idle air-fuel mixture. Use exhaust analyzer.	Automotive Mechanic
315	Replace PCV valve with an adjustable flow control valve. Connect control valve linkage to accelerator pedal linkage. Replace oil fill cap. Install adapter plate between carburetor and intake manifold.	Adjust control valve to maintain vacuum of 0.5 inch Hg at valve cover. Readjust carburetor for best idle air-fuel mixture - use exhaust analyzer. Set idle rpm.	Automotive Mechanic
427	Mount the filter unit in the engine compartment, replace PCV valve with special part, connect to filter unit.	Adjust carburetor for best lean operation. Use exhaust analyzer. Set idle rpm.	Automotive Mechanic
EVAPORATIVE EMISSION CONTROL SYSTEMS			
467	Replace existing gas tank with a sealed gas tank; install vapor separator, carbon canister, connecting tubing, three-way check valve, check valve, and miscellaneous hoses, clamps, and connectors.	Insufficient Information	Automotive Mechanic
COMBINATIONS			
59	Insufficient Information	Insufficient Information	Insufficient Info.
165	Install afterburner in exhaust line, connect afterburner to intake, connect fuel tank emission accumulator to intake, connect crankcase emission to intake, install high voltage coil, glo plug, flow control valves, filter.	Regulate the flow of exhaust gases through the afterburner and the heat exchanger. Adjust to give best overall engine performance.	Automotive Mechanic
408	Install an adapter plate between the carburetor and intake manifold. Correct recirculating line from exhaust line to adapter plate. Connect PCV valve to adapter plate. Replace oil filter cap with check valve oil-fill cap.	Adjust acceleration valve for minimum exhaust gas inlet at 21" Hg vacuum at idle. Adjust deceleration valve to open at 25" Hg vacuum during deceleration.	Automotive Mechanic
469	Insufficient information.	Insufficient information.	Insufficient Info.

(1) "Combustion efficiency" refers to the calibration used on some engine analyzers for adjusting the air-fuel ratio.

In general, the emission reduction benefit of a retrofit device on an assured basis would require some form of emission test following installation and upon repair action to the device. These requirements for quality control predicate a qualified mechanic skill level, knowledgeable in retrofit device operating principles and in the use of equipment and instrumentation capable of verifying that a device is functioning properly. The management of a regulated quality control system further predicates qualified inspection personnel to train and certify mechanics for participation in a retrofit program.

The type of quality control program required to implement and sustain use of retrofit devices is illustrated by that used in California for the installation, adjustment, servicing, inspection, and certification of vehicle pollution control equipment.(1) This California program prescribes specific inspection requirements to be followed in the certification of emission controlled vehicles upon change of ownership. Inspection stations are licensed by the State, and a Class A pollution control device installer certification is required of inspection personnel. A Class A installer has to be experienced in major automotive tuneup, with optional instruction from an approved school. Applicants must pass an examination before certification is granted. Quality controls of equivalent stringency are considered essential requirements of any program based on use of retrofitted vehicle emission control devices as a means of achieving air quality standards.

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(1) Handbook for Pollution Control Device Installation and Inspection, HPH 82.1 California Highway Patrol, April 1971.

SECTION 5

PERFORMANCE ANALYSIS

By means of the methodology described in Section 3, an analytical evaluation was made of those devices for which sufficient data were developed through engineering analysis and test. The objective was to determine the relative index ratings of the devices in terms of their effectiveness in reducing vehicle emissions, effect on vehicle performance, and costs to the vehicle owner.

Data for the evaluation were obtained through the data survey or by test. These were reviewed for acceptance in the engineering analysis of the retrofit devices. The completeness of data provided by the retrofit data survey varied widely. The emission test data provided by the developers were nearly always supported by a test report from a recognized independent test facility. Reliability, maintainability, and cost data were evaluated for reasonableness, and supplemented or complemented by analysis when sufficient system information was available. Driveability data were for the most part incomplete, because of the lack of data on baseline vehicle driveability. Fuel consumption data were generally not provided. Therefore, driveability and fuel consumption evaluation was made only on those devices tested in the retrofit program.

Eleven devices were tested for emission reduction, fuel consumption, and driveability. Four of these devices were selected for more extensive emission, fuel consumption, and driveability testing to obtain data samples from a variety of used cars in two different geographic areas of the U.S., as described in Section 4. Table 5-1 summarizes all of the available performance data of the devices that were tested and the devices that received an engineering evaluation based on data supplied by the developer.

5.1 CRITERIA INDEX

The Criteria Index measures the ability of a device to meet legal constraints and specified limits that could be imposed for critical performance parameters. Values for the various Criteria Index factors were assigned 1 or 0 depending on whether or not the evaluation criteria presented in Table 1-2 were satisfied. In all cases, inadequate data supplied by the developers prevented complete Criteria Index evaluations of the devices. As a result, the Criteria Index could be established only for some devices. Certain devices were found to have a value of 0 for at least one of the criteria index factors. In these cases the Criteria Index was also 0, since this index is the product of the individual factors.

In the retrofit test program, CVS tests were conducted under the 1972 Federal Test Procedure, for which no used car emission standards had been established at the time of this study. Therefore, the emission standard criteria of the Criteria Index could not be applied to the 1972 CVS test data, and the Criteria Index could not be established for these cases.

Table 5-1. PERFORMANCE SUMMARY OF DEVICES EVALUATED IN RETROFIT PROGRAM

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND THE NUMBER OF TESTS.

DEVICE NO.	DESCRIPTION	CRITERIA INDEX	NUMBER OF TESTS	AVERAGE EMISSION INDEX PER UNIT(2) REDUCTION	AVERAGE DRIVEABILITY INDEX RATING POINTS	COST INDEX $/100 MILES(3)	PERFORMANCE INDEX(4)	COST EFFECTIVENESS INDEX, UNIT REDUCTION $/100 MILES	INITIAL COST FOR INSTALLATION $	TEST TYPE	(16) DATA SOURCE
	Devices with up to 18 Tests in Retrofit Program (1972 Federal Test Procedure):										
1	Air Bleed to Intake Manifold	(1)	18	0.247	0.138	0.063	0.103	3.92	64	1972 FEDERAL TEST PROCEDURE (CVS)	R
96(5)	Catalytic Converter with Distributor Vacuum Advance Disconnect	0	17	0.596	0.304	0.521	0.163	1.14	175		R
175	Ignition Timing Modification with Lean Idle Adjustment	0	10	0.343	0.118	0.391	0.067	0.88	45		R
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	0	15	0.302	0.113	0.079	0.134	3.82	89		R
	Devices with up to 3 Tests in Retrofit Program (1972 Federal Test Procedure):										
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	(1)	2	0.396	0.441	0.204	0.105	1.94	71		R
33	Carburetor Modification, Main Jet Differential Pressure	0	2	0.118	0.181	-0.229	0.174	-0.51 (18)	21		R
42	Air Bleed to Intake Manifold	(1)	2	0.237	0.116	-0.161	0.165	-1.47 (18)	23		R
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	(1)	3	0.287	0.087	0.152	0.110	1.89	63		R
245	Variable Camshaft Timing	0	1	-0.139	0.895	0.364	-0.312	-0.38 (19)	78		R
288	Carburetor Main Discharge Nozzle Modification	0	2	0.074	-0.459	0.198	0.054	0.37	41		R
295	Carburetor with Variable Venturi	0	1	0.028	3.261(20)	0.536	-0.603	0.05	79		R
	Devices Evaluated Based on Developer and EPA Data:										
23	Electronic Ignition Unit	0	1	-0.231	(10)(6)	(10)	(10)(7)	(10)	(10)		E
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed	(1)	(8)	0.079	(10)	0.047	(10)	1.68	34		E
52	LPG Conversion	0	18	0.771	(10)	0.224	(10)	3.44	608		E
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	(1)	6	(10)	(10)	(10)	(10)	(10)	(10)		E
95	Ignition Spark Modification	0	1	-0.251	(10)	(10)	(10)	(10)	(10)		E
100	Turbocharger	(1)	1	0.113	(10)	(10)	(10)	(10)	(10)		E
172	Intake Manifold Modification	0	1	0.040	(10)	0.105	(10)	0.38	79		E
292	Catalytic Converter	0	1	0.156	(10)	0.192	(10)	0.81	73		E
294	Exhaust Gas Recirculation with Carburetor Modification	0	1	-0.128	(10)	(10)	(10)	(10)	(10)		E
418	Air Bleed to Intake Manifold	(1)	(9)	0.165	(10)	(10)	(10)	(10)	(10)		E
459	LPG Conversion with Deceleration Unit	(1)	1	(10)	(10)	0.224	(10)	(10)	608		E
460	Compressed Natural Gas Dual-Fuel Conversion	0	1	-0.277	(10)	(10)	(10)	(10)	601		E
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	(1)	1	(10)	(10)	(10)	(10)	(10)	(10)		E
462	Air Bleed to Intake and Exhaust Manifold	0	(21)	0.024	(10)	(10)	(10)	(10)	(10)		E
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	(1)	3	(10)	(10)	(10)	(10)	(10)	(10)		E
464	Methanol Fuel Conversion with Catalytic Converter	(1)	6	(10)	(10)	(10)	(10)	(10)	(10)		E
465	Fuel Additive	(1)	1	0.101	(10)	(10)	(10)	(10)	(10)		E
466	LPG-Gasoline Dual-Fuel Conversion	(1)	6	0.393	(10)	(10)	(10)	(10)	(10)		E
468	Lean Thermal Reactor with Exhaust Gas Recirculation	(1)	5	(10)	(10)	(10)	(10)	(10)	(10)		D
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	(1)	2	0.630	(10)	(10)	(10)	(10)	400	EPA 9X7 CVS (17)	E
22	Electronic Fuel Injection	(1)	1	(10)	(10)	(10)	(10)	(10)	(10)	7-CYCLE 7-MODE COLD START	E
31	Thermal Reaction by Turbine Blower Air Injection	0	6	(10)	(10)	0.337	(10)	(10)	143		D
36	Fuel Conditioning by Exposure to Electromagnetic Field	0	(11)	-0.065(13)	(10)	(10)	(10)	(10)	(10)		E
56	Crankcase Blowby and Idle Air Bleed Modification	0	3	(10)	(10)	0.120	(10)	(10)	54		D
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	0	1	0.516	(10)	0.188	(10)	2.74	63		D
59	Three-Stage Exhaust Gas Control System	0	1	0.204	(10)	(10)	(10)	(10)	(10)		D
62	Catalytic Converter	0	1	0.218	(10)	(10)	(10)	(10)	(10)		E
160	Closed or Open Blowby Control System with Filter	(1)	1	(10)	(10)	0.143	(10)	(10)	69		D
164	Exhaust Gas Filter	0	1	0.040	(10)	0.205	(10)	0.19	103		D
182	Fuel and Oil Additives	0	(12)	0.269	(10)	(10)	(10)	(10)	1		D
244	Rich Thermal Reactor	0	(10)	0.750(13)	(10)	0.536	(10)	1.39	375		D
315	Closed Blowby Control System	0	1(13)	0.281	(10)	0.175	(10)	(10)	69		D
317	Carb Mod with Vac Adv Disconnect	0	3	0.297	(10)	0.052	(10)	5.71	23		D

Table 5-1. PERFORMANCE SUMMARY OF DEVICES EVALUATED IN RETROFIT PROGRAM (CONCL)

NOTE: THE RELIABILITY OF THE DATA SHOWN DEPENDS ON THE TYPE OF TEST PROCEDURE AND THE NUMBER OF TESTS.

DEVICE NO.	DESCRIPTION	CRITERIA INDEX	NUMBER OF TESTS	AVERAGE EMISSION INDEX PER UNIT(2) REDUCTION	AVERAGE DRIVEABILITY INDEX RATING POINTS	COST INDEX $/100 MILES(3)	PERFORMANCE INDEX(4)	COST EFFECTIVENESS INDEX UNIT REDUCTION $/100 MILES	INITIAL COST FOR INSTALLATION $	TEST TYPE	(16) DATA SOURCE
322	Exhaust Gas Backpressure Valve	0	1	-0.258	(10)	(10)	(10)	(10)	(10)	7-CYCLE 7-MODE COLD START (CONT)	E
384	Air-Fuel Mixture Diffuser	0	1	0.297	(10)	(10)	(10)	(10)	(10)		D
401	Air-Vapor Bleed to Intake Manifold	0	1	0.094	(10)	0.442	(10)	0.21	46		D
425	Exhaust Gas Afterburner	0	1(13)	0.970	(10)	0.377	(10)	2.57	159		D
430	Induction Modification	0	2	0.267	(10)	0.030	(10)	8.90	19		D
458	Air Bleed to Intake Manifold	0	(15)	-0.016	(10)	(10)	(10)	(10)	(10)		E
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation	0	1	(10)	(10)	0.549	(10)	(10)	238	7-CYCLE 7-MODE HOT START	D
170	Closed Blowby Control System	0	1	0.087	(10)	0.065	(10)	1.34	39		D
279	Fuel Conditioner	0	1	0.107	(10)	0.033	(10)	3.24	16		D
296	Ignition Timing and Spark Modification	(1)	1	0.027	(10)	0.031	(10)	0.87	23		D
325	Air-Vapor Bleed to Intake Manifold	0	7	0.239	(10)	0.454	(10)	0.53	56		D
427	Closed or Open Blowby Control System with Filter	(1)	2	0.182	(10)	0.271	(10)	0.67	68		D
433	Air-Vapor Bleed to Intake Manifold	0	7	0.239	(10)	0.454	(10)	0.53	56		D
308	Exhaust Gas Afterburner	0	3(14)	-0.047	(10)	0.250	(10)	-0.19(19)	71	STEADY STATE	D
457	Water Injection	(1)	(14)	0.250	(10)	(10)	(10)	(10)	(10)		E
259	Photocell-Controlled Ignition System	(1)	(10)	(10)	(10)	0.104	(10)	(10)	59	NO TEST DATA	D
268	Capacitive Discharge Ignition	(1)	(10)	(10)	(10)	0.046	(10)	(10)	69		D
282	LP Gas Injection	0	(10)	(10)	(10)	0.309	(10)	(10)	118		D
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	0	(10)	(10)	(10)	0.139	(10)	(10)	36		D
440	Air-Fuel Mixture Deflector Plate	(1)	(10)	(10)	(10)	0.020	(10)	(10)	12		D
467	Fuel Evaporation Control System	0	(10)	(10)	(10)	(10)	(10)	(10)	137		(10)

(1) Criteria Index not totally determined due to lack of emission standards and/or missing data. See Volume III, Table 5-1, for results of individual Criteria Index parameter evaluations.

(2) Negative sign indicates emission increase from baseline.

(3) Negative sign indicates cost saving due to more miles per gallon with device installed.

(4) Negative sign indicates driveability plus cost indexes exceed emission index ($C_1 = 4$, $C_2 = 1$, $C_3 = 2$, see paragraph 3.2)

(5) No lead gasoline at $0.38/gallon. For the other devices, gasoline cost calculated on basis of $0.35/gallon.

(6) No acceptable driveability test data supplied by the developer or EPA. Driveability Index not determinable for this or subsequent devices.

(7) PI not determinable due to lack of DI's for this and subsequent devices.

(8) 6 baseline and 5 device tests for HC and CO; 3 baseline and 4 device tests for NOx.

(9) 16 baseline tests and 11 device tests on 3 cars.

(10) Unknown

(11) 1 baseline test, and 11 device tests for HC and CO only.

(12) 4 tests for HC and CO; 1 test for NOx.

(13) HC and CO only.

(14) Different steady state speeds.

(15) 1 baseline and 2 device tests on 1 car.

(16) R - Retrofit Test Program
D - Developer Supplied Data
E - Environmental Protection Agency (data references are presented in Volume II).

(17) EPA Interim 9-Cycle, 7-Mode CVS Emission Test Procedure (refer to Volume II, Reference 16).

(18) In this case, negative values are due to increase in miles per gallon of fuel.

(19) In this case, negative values are due to increased emissions above baseline.

(20) Validity of this driveability test doubtful (see Table 4-6).

(21) 10 baseline and 9 device tests for HC and CO, and 6 baseline and 6 device tests for NOx, on 2 cars.

Section 3 of Volume III presents a discussion of the individual Criteria Index factors.

5.2 PERFORMANCE INDEX

The Performance Index (PI) measures the relative performance rating of the devices and enables a further quantitative refinement beyond the Criteria Index, which is a qualitative evaluation. The devices are listed in Table 5-1 in terms of emission reduction, driveability, and cost indexes. The negative values shown in Table 5-1 for the Emission Index indicate an overall increase in the emission levels as a result of device installation. The highest positive numerical Emission Index value represents the greatest ability to control (or reduce) emissions. The percentage reductions for the individual pollutants achieved by each device are listed in Table 4-2.

Note that all reported emission indexes were not obtained using the same testing procedures, nor the same number of tests. This should be kept in mind when judging the relative significance of the data.

The Driveability Index, an indication of a penalty, becomes numerically smaller as the driveability penalty becomes less. Negative values indicate an improvement in vehicle driveability with the device installed. The devices are relatively worse as their index values increase. The developers of devices that were not tested in the retrofit program were generally unable to provide driveability data because of the lack of information on their own test vehicles prior to device installation.

The Cost Index combines those parameters which determine the initial costs of a device and the recurring costs. The initial costs are measured in terms of device retail cost and installation cost amortized over the device lifetime. The recurring costs, such as maintenance and gasoline mileage changes, are added expenses for keeping the retrofit device in operation after installation.

Negative values for the Cost Index represent a cost savings attributable to increased gasoline mileage. Devices are rated relatively worse as their Cost Index values increase, since increased cost is a penalty.

The Performance Index provides the overall performance rating of devices for which Emission, Driveability, and Cost Indexes could be calculated. The set of weighting factors used in this analysis rate emissions twice as important as cost and cost is rated twice as important as driveability. Other weighting factors may be used as described in paragraph 3.4 and Table 6-13 of Volume III.

5.3 COST EFFECTIVENESS INDEX

The Cost Effectiveness Index (CEI) is intended to provide additional information to complement the Performance Index. Should two or more devices have essentially the same Performance Index, the one with the highest Cost Effectiveness Index would be preferred. Cost Effectiveness is usually defined as the rate of the desired results or the desired output versus the required cost input. In this discussion, the CEI is defined as the ratio of the Emission Index to the Cost Index.

A thorough comparative analysis of devices by the evaluator should incorporate and review the absolute Emission and Cost Indexes along with the Performance and Cost Effectiveness Indexes. The reason for this is that the pure CEI ratio (by itself) will not reveal the difference between two devices that have different absolute Emission and Cost Indexes. The evaluator must question the merits of a device to fit his requirements. He must ask "How much emission reduction do I need to fit my requirements, and how much money will it cost for that reduction?" Once he has these questions answered, he may then compare devices by reviewing the PI.

Negative values for the Cost Effectiveness Index are obtained for two reasons:

a. A cost savings was achieved due to better fuel economy. This is indicated by a negative Cost Index.

b. An overall increase in emissions was achieved. This is indicated by a negative Emission Index.

The first case is clearly favorable, while the second case would mean spending money to increase emissions.

For positive Cost Effectiveness Index values, the higher numbers indicate the larger emission reductions per dollar.

5.4 FEASIBILITY

The feasibility and infeasibility of a retrofit device, within the context of this study, can only be determined with respect to the device's applicability for use as a retrofit method for controlling vehicle emissions. A device may be rated infeasible for emission control without infringing upon its use for other applications. For example, some devices, while being claimed as emission reduction devices, actually are devices for enhancing some engine performance parameter that only indirectly or insignificantly reduces emissions. Any additional claims made for a device by the developer are not considered here, because the findings of this study pertain only to a device's use as a retrofit method to control vehicle emissions effectively and without unacceptable vehicle performance and cost penalties.

To determine which devices are feasible and which are not, the evaluation criteria presented in Table 1-2 can be applied. These criteria can be changed to fit the specific requirements of the particular air quality control agency. In effect, the evaluation criteria determine the feasibility or infeasibility of a device. Those devices that passed the evaluation criteria levels would be the feasible retrofit systems and the rest may be infeasible to some degree.

It should be mentioned that most of the devices evaluated in this study are prototype systems. In some cases, sound engineering and manufacturing techniques may remove the reasons for device infeasibility.

SECTION 6

RETROFIT DEVICE DEVELOPMENT STATUS AND VEHICLE APPLICABILITY

Ultimately, the feasibility of a retrofit device for control of used car emissions depends on its development status and the extent to which it is applicable to the vehicle population which must be controlled. A device may theoretically and experimentally indicate substantial emission reduction effectiveness at an acceptable cost and yet require too long a period of development to be producible for mass application. Developmental requirements may be compounded by accreditation requirements. In a rigorously regulated accreditation program, in which specific and perhaps severe accreditation criteria have to be met, it may take more than a year for a device to meet the criteria and be put on the market. This would assume, in most cases, that the device was ready for mass production at the time the accreditation was begun. For example, although accreditation criteria for used car exhaust control emission and fuel evaporative loss control devices were initiated in California in 1968, only two exhaust control devices for gasoline-fueled vehicles had been accepted under these criteria as of this report. These were accepted in late 1971 and early 1972. Special incentives, such as State-financed accreditation programs, could possibly accelerate and shorten the time required for accreditation and marketing of a device.

6.1 VEHICLE APPLICABILITY OF RETROFIT DEVICES

The retrofit study program was focused on the evaluation of those devices designed for use on "uncontrolled" vehicles. These vehicles are considered those which have no exhaust or fuel evaporative controls, but may have crankcase blowby controls. As shown in Table 6-1, the uncontrolled vehicle population varies nationally in terms of model year depending on whether a car was sold new in or outside California. Exhaust controls were required on new cars sold in California beginning in 1966 and on new cars sold nationally in 1968. These controls are for CO and HC only. NOx controls will not be required Federally until 1973, but were required on new cars in California beginning in 1971.(1) Crankcase blowby controls have been in effect since 1961 in California and since 1963 nationally; and fuel evaporative controls were required in California and nationally in 1970 and 1971, respectively.

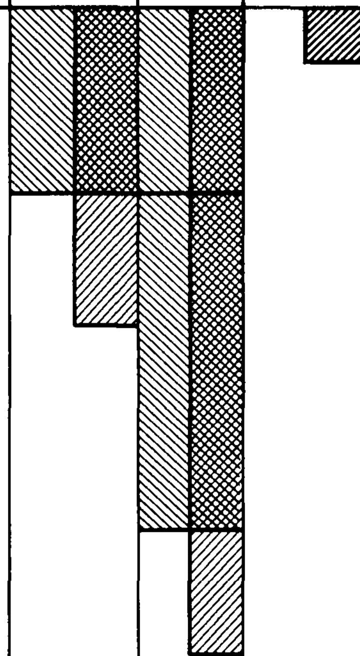
6.1.1 <u>Pre-1968 Model Vehicles</u>

Since approximately 10 percent of the nation's cars are located in California, it is evident that the retrofit controls for exhaust systems documented in this study

(1) The 1973 national emission standard for NOx was specified in Federal Register Volume 36, No. 128, Part II, dated 2 July 1971. The California NOx standard for 1971 was specified in the California Health and Safety Code, Chapter 4, Article 2, Paragraph 39101.5.

Table 6-1. LIGHT-DUTY VEHICLE POPULATION AND TYPE OF EMISSION CONTROL (1)

ITEM	MODEL YEAR	AGE		PERCENT OF TOTAL	VEHICLE QUANTITY (MILLIONS)	DEGREE OF CONTROL			
		YEARS	MILEAGE (1)			EXHAUST	BLOW-BY	EVAPOR-ATION	PERCENT TOTAL
1	1970	1.5	13,100	9	8.5				
2	1969	2.5	22,500	12	11.0				32
3	1968	3.5	31,900	11	10.2				
4	1967	4.5	41,300	10	9.3				
5	1966	5.5	50,700	9	8.5				
6	1965	6.5	60,100	9	8.5				42
7	1964	7.5	69,500	7	6.8				
8	1963	8.5	78,900	7	6.8				
9	1962	9.5	88,300	6	6.0				
10	1961	10.5	97,700	5	4.9				
11	1960	11.5	107,100	4	4.3				
12	1959	12.5	116,500	3	3.4				
13	1958	13.5	125,900	3	3.4				26
14	1957	14.5	135,300	1	1.7				
15	1956	15.5	144,700	1	1.7				
16	1955–	16.5+	154,100+	3	3.4				



(1) Based on an average of 9,400 miles per year.

Federal control coverage

California control coverage

would be applicable to 90 percent of the pre-1968 light duty vehicle fleet. This would represent about 60 percent of the light duty vehicles in the nation. Blowby controls, however, would be applicable to only 90 percent of the pre-1963 vehicles, or less than 25 percent of the vehicle population. A fuel evaporative loss control system would be applicable to 90 percent of the pre-1971 vehicles. Thus, the exhaust control systems and the fuel evaporative loss control systems are the principal methods for retrofit to pre-1968 and pre-1971 vehicles.

6.1.2 Post-1968 Vehicles

The applicability of exhaust control retrofit devices to vehicles already equipped with exhaust controls depends on the type of control incorporated in the vehicles when produced. The factory installed control devices used on post-1965 vehicles in California and on post-1967 nationally fall into two categories: engine modification and air injection.

The engine modification systems include many functional changes such as lean carburetion, ignition timing retard at idle speed, combustion chamber redesign, and manifold redesign. Several of the engine modification systems incorporate one or more of the design principles on which the retrofit devices are based.

The air injection system incorporates some of the features of the engine modification system. It includes an air pump that injects air into the exhaust manifold to more completely oxidize the hydrocarbons and carbon monoxide.

To specifically determine the applicability of each retrofit device or generic group to these production-controlled vehicles, a detailed study and test program would have to be performed. The functional characteristics of each original equipment modification of each auto manufacturer would have to be compared to the retrofit device characteristics and a cost effectiveness determination made. In general, it can be stated that not all of the retrofit devices would be feasible or practical for additional emission reduction of vehicles already controlled. Those retrofit devices which appear to be reasonably feasible for retrofit to controlled vehicles (1968 through 1971 for all of U.S. and 1966 through 1971 for California vehicles) are discussed below.

6.1.2.1 Catalytic Reactors, Thermal Reactors, and Exhaust Gas Afterburners

In most cases, catalytic reactors, thermal reactors, and exhaust gas afterburners could be retrofitted to 1968-1971 model cars which already have some form of exhaust control, to provide further control of CO and HC. Installation requirements and costs would be similar to those of the pre-1968 vehicles evaluated in the retrofit study program.

The main difference in cost would be whether the vehicle is already equipped with an air injection pump, or if it has lean carburetion. The 1968-1971 model vehicles which are already equipped with exhaust control systems generally have lean air fuel carburetion, which might provide sufficient air. Some of the newer developments in catalysts will reportedly convert HC, CO, and NOx when carburetor mixtures are near stoichiometric. The catalyst systems generally, however, need external air injection into the reactor for maximum effectiveness, as do the thermal reactors and afterburners. Since the latter, in addition, usually require rich air-fuel carburetion to support the oxidation process, they would not generally be compatible with vehicles incorporating lean carburetion. Catalytic systems, therefore, would be the most likely candidate in this group for retrofit to controlled vehicles. The cost versus effectiveness of this approach would have to be determined.

6.1.2.2 Exhaust Gas Recirculation

Exhaust gas recirculation (EGR) systems recirculate exhaust gases to the induction system and dilute the air-fuel mixture delivered by the carburetor, with resultingly lower combustion temperature and inhibition of NOx formation. These systems can be retrofitted to cars already equipped with exhaust controls for CO and HC. The installation requirements and costs would be quite similar to those evaluated in the retrofit program for pre-1968 cars. On cars which are factory equipped with exhaust emission control systems with relatively lean carburetor mixtures, the addition of an EGR system may present some driveability problems if the rate of exhaust gas recirculation is excessive.(1)

6.1.2.3 Distributor Vacuum Advance Disconnect

The distributor vacuum advance disconnect system provides a means of lowering HC and NOx emissions at part throttle operation. This approach would probably be the most cost effective to install on vehicles already equipped with HC and CO exhaust control systems. However, this system may degrade part-throttle driveability operation and fuel consumption. Wide open throttle performance would not be affected, because in this mode of operation there is no manifold vacuum to operate the distributor vacuum advance unit anyway.(1)

6.1.2.4 Air Bleed to the Intake Manifold

Air bleed systems can be retrofitted to vehicles already equipped with HC and CO exhaust control systems. However, it is possible that these retrofit devices could cause serious problems by overleaning the carburetor mixture, since the 1968-71 vehicles equipped with exhaust control systems already have a lean main circuit carburetor mixture. The air bleed system, in metering additional air, may cause excessive leaning. This is particularly true in part throttle operation (10-18 inches of mercury manifold vacuum), because the air-bleed-to-carburetor-mixture flow ratio in the manifold may be excessive. This condition could lead to surging problems during cruise mode operations and could also result in lean misfire. Air bleed systems may also increase NOx slightly because of the increased availability of oxygen in the combustion chamber.

As higher engine loads are required (less than 10 inches of mercury manifold vacuum), the air-bleed-to-carburetor-mixture flow ratio becomes less. Therefore, the air bleed systems should not affect driveability or engine performance at heavy engine loads.

6.1.2.5 Gaseous Fuel Conversions

Most light duty vehicles could be converted to run on liquefied petroleum gas or compressed natural gas, if the initial costs were not so high and if the supply of these fuels was adequate. Gaseous fuels enable the CO, HC, and NOx reduction advantages provided by high air-fuel ratios. In addition, it is generally agreed that the

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(1) California recently passed a law requiring NOx control systems on 1966-70 model vehicles, as specified in California Air Resources Board Resolution 71-110, 17 November 1971.

HC emission byproducts from gaseous fueled vehicles are of lower photochemical smog reactivity than those from gasoline fueled vehicles; however, no Federal reactivity scale has been defined to allow quantitative correction for this factor.

The reduction in recurring vehicle maintenance costs that use of gaseous fuel systems has indicated, could offset their high initial costs, possibly within a 50,000-mile service life. Since the natural gas and oil industry is not presently geared to supply the quantity of fuel that would be needed to support widespread conversions, the application of these conversions appears to be limited to fleet vehicles through the 1970's.(1)

6.1.2.6 Evaporative Emission Control Systems

Fuel evaporative control systems control the hydrocarbons which would otherwise evaporate from the fuel tank and carburetor vents of a car. Most of the evaporation losses come from the carburetor external vents, and controls for this would be relatively difficult to retrofit. Fuel tank evaporation control systems would be easier to retrofit than carburetor vents.

Evaporative control system retrofitting may produce some serious safety hazards. An example would be a fuel tank evaporation control system installed in the trunk of a car. Any leaks could cause excessive fumes, which could enter the passenger compartment. Installation of these systems would require careful design to avoid these hazards.

No retrofit evaporative control systems were supplied for evaluation in the retrofit study program.

6.2 RETROFIT DEVICE DEVELOPMENT STATUS AND APPLICABILITY SUMMARY

Table 6-2 summarizes the development, manufacturing, and marketing status of devices evaluated in the retrofit study, as well as the estimated uncontrolled vehicle applicability. The table columns are defined as follows:

a. Development Status: This column defines the development status of the device in that it indicates that a prototype (P) was developed and tested on a vehicle, or that the device is in a production (PR) configuration. Also of importance is whether or not the developer has applied for a patent (DPP) - Patent Pending, or has an existing patent (DP) on his device.

b. Estimated Applicability to Uncontrolled Used Cars: The percentage of the uncontrolled used car population which could be retrofitted with the device is represented by this column. Values are estimated from retrofit developer inputs.

(1) "Emission Reduction Using Gaseous Fuels for Vehicular Propulsion," Final Report on EPA Contract 70-69 by the Institute of Gas Technology, June 1971.

Table 6-2. DEVELOPMENT STATUS AND APPLICABILITY OF DEVICES EVALUATED IN RETROFIT PROGRAM

DEVICE NO.	DESCRIPTION	DEVELOPMENT STATUS (1)	ESTIMATED APPLICABILITY TO UNCONTROLLED USED CARS (%)
	GROUP 1 EXHAUST EMISSION CONTROL SYSTEMS		
	Exhaust Gas Control Systems - Type 1.1		
62	Catalytic Converter	P	No data
93	Catalytic Converter with Exhaust Gas Recirculation, Spark Modification, and Lean Idle Mixture	P	No data
96	Catalytic Converter with Distributor Vacuum Advance Disconnect	P/DP	90
292	Catalytic Converter	PR/DP	90
31	Thermal Reactor by Turbine Blower Air Injection	P	No data
244	Rich Thermal Reactor	P/DP	80
463	Rich Thermal Reactor with Exhaust Gas Recirculation and Spark Retard	P	No data
468	Lean Thermal Reactor with Exhaust Gas Recirculation	P	No data
308	Exhaust Gas Afterburner	P/DP	90
425	Exhaust Gas Afterburner	PR/DP	90
164	Exhuast Gas Filter	P	90
322	Exhaust Gas Backpressure Valve	P	No data
	Induction Control Systems - Type 1.2		
1	Air Bleed to Intake Manifold	PR	90
42	Air Bleed to Intake Manifold	PR	90
57	Air Bleed with Exhaust Gas Recirculation and Vacuum Advance Disconnect	P	90
325	Air-Vapor Bleed to Intake Manifold	PR	90
401	Air-Vapor Bleed to Intake Manifold	PR	90
418	Air Bleed to Intake Manifold	P	90
433	Air-Vapor Bleed to Intake Manifold	PR	90
458	Air Bleed to Intake Manifold	P	No data
462	Air Bleed to Intake and Exhaust Manifolds	P	No data
10	Throttle-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	PR	90
245	Variable Camshaft Timing	PR	90
246	Speed-Controlled Exhaust Gas Recirculation with Vacuum Advance Disconnect	P	90
294	Exhaust Gas Recirculation with Carburetor Modification	P	No data
172	Intake Manifold Modification	P/DP	90
384	Air-Fuel Mixture Diffuser	P	90
430	Induction Modification	P	90
440	Air-Fuel Mixture Deflection Plate	P/DP	90
33	Carburetor Modification, Main Jet Differential Pressure	P	90
56	Crankcase Blowby and Idle Air Bleed Modification	P/DPP	90
288	Carburetor Main Discharge Nozzle Modification	P	90
295	Carburetor with Variable Venturi	PR	90
317	Carburetor Modification with Vacuum Advance Disconnect	P/DPP	90
100	Turbocharger	P	No data
22	Electronic Fuel Injection	P	No data
	Ignition Control Systems - Type 1.3		
69	Electronic-Controlled Vacuum Advance Disconnect and Carburetor Lean Idle Modification	P	90
175	Ignition Timing Modification with Lean Idle Adjustment	PR	90
23	Electronic Ignition Unit	P	No data
95	Ignition Spark Modification	PR/DPP	100
259	Photocell-Controlled Ignition System	P	90
268	Capacitive Discharge Ignition	PR	90
296	Ignition Timing and Spark Modification	P/DPP	90
	Fuel Modification - Type 1.4		
52	LPG conversion	PR/DP	No data
182	Fuel and Oil Additives	PR	No data
465	Fuel Additive	P	No data
36	Fuel Conditioning by Exposure to Electromagnetic Field	P	No data
279	Fuel Conditioner	PR/DPP	100
282	LP Gas Injection	PR/DP/DPP	90
457	Water Injection	No data	No data
459	LPG Conversion with Deceleration Unit	PR/DP	No data
460	Compressed Natural Gas Dual-Fuel Conversion	PR	No data
461	LPG Conversion with Exhaust Reactor Pulse Air Injection and Exhaust Gas Recirculation	No data	No data
464	Methanol Fuel Conversion with Catalytic Converter	P	No data
466	LPG-Gasoline Dual-Fuel Conversion	PR/DP	No data
	GROUP 2 CRANKCASE EMISSION CONTROL SYSTEMS		
24	Heavy Duty Positive Crankcase Control Valve with Air Bleed	PR	No data
160	Closed or Open Blowby Control System with Filter	PR	90
170	Closed Blowby Control System	PR/DP	90
315	Closed Blowby Control System	PR/DP	90
427	Closed or Open Blowby Control System with Filter	PR	90
	GROUP 3 EVAPORATIVE EMISSION CONTROL SYSTEMS		
467	Fuel evaporation control system	(2)	No data
	GROUP 4 EMISSION CONTROL COMBINATIONS		
59	Three-Stage Exhaust Gas Control System	P	90
165	Exhaust Gas Afterburner/Recirculation with Blowby and Fuel Evaporation Recirculation	P	75
408	Exhaust Gas and Blowby Recirculation with Intake Vacuum Control and Turbulent Mixing	P/DP	90
469	Rich Thermal Reactor with Exhaust Gas Recirculation and Particulate Control	P	No data

(1) P = PROTOTYPE
PR = PRODUCTION
DP = DEVICE PATENTED
DPP = DEVICE PATENT PENDING

(2) No retrofit device of this type was found to exist except in combination with another device (refer to paragraph 4.1.3).

SECTION 7

GUIDELINES FOR SELECTING AND IMPLEMENTING RETROFIT METHODS

The determination that certain retrofit methods are feasible for use in controlling used car emissions is only the starting point for applying these methods. Carefully planned effort is required on the part of agencies responsible for air quality to define the requirements for retrofit methods and the standards or criteria they must meet in their respective regions. Equally well planned and managed effort is required to select those devices offering the optimum solution to a region's air quality control requirements and then to manage the everyday affairs of an operational retrofit program.

The evaluation methodology developed in the retrofit study is a basic tool that can be used by air quality control agencies to screen and select optimum retrofit devices to meet their requirements. In addition to using this methodology, there are a number of other steps which have to be planned for and accomplished in implementing a retrofit program. The basic approach for selecting and implementing a retrofit method of control may be summarized in the following steps:

a. Define the emission reduction that would be required from the used car population.

b. Define the characteristics of the used vehicle population to which retrofit methods would be applicable.

c. Identify feasible retrofit methods for application to that vehicle population.

d. Determine which retrofit methods are most cost effective for the desired level of emission control, giving due consideration to facilities and labor requirements for implementing the retrofit program.

e. Define the retrofit device accreditation program.

f. Conduct the cost effectiveness studies required to verify the retrofit program approach as being the most appropriate method of emission control.

g. Prepare an implementation plan.

h. Initiate and maintain the implementation plan.

7.1 DEFINING THE REQUIRED EMISSION REDUCTION

The State implementation plans required by the Clean Air Amendments Act of 1970 should be the means for identifying used car emission control requirements. The air pollution caused by the used car population would have to be sufficiently detrimental to human health or welfare to justify a retrofit program. The control of air quality is more complex than mere control of the motor vehicle population, but those pollutants predominantly caused by vehicles can be identified and the impact on human health and welfare assessed.

7.2 DEFINING THE RETROFIT VEHICLE POPULATION

The vehicle population to be controlled is a decisive factor in the type of retrofit method to be implemented. The uncontrolled vehicle population has to be of sufficient size and density to justify the program. Vehicle population surveys should be conducted in air quality control regions where population densities and the meteorological conditions of air basins are known to influence the air pollution problems caused by vehicles. These surveys should be designed to establish the vehicle population profile in terms of vehicle model year, engine displacement, and ownership. Further, the survey should establish the vehicle owner attitudes and preferences concerning retrofit controls, their costs, and the means of implementing such controls.

7.3 IDENTIFYING CANDIDATE RETROFIT METHODS

Retrofit methods offering the type and level of control required by the air pollution problem of the region under study should be identified. All candidate methods should be identified on the basis of the following performance parameters:

a. Emission reduction effectiveness

b. Effect on safety, driveability, and vehicle performance including fuel consumption changes

c. Reliability and maintainability

d. Development status

e. Initial and recurring cost

Each parameter should be given a quantitative value that represents the minimum criteria that a device has to meet in order to be identified as a candidate for use. These criteria will provide a means of screening devices on an initial basis prior to indepth evaluation.

The feasibility of a retrofit control system can be determined by comparing its performance to a set of evaluation criteria. Table 1-2 lists the evaluation criteria used in this study and may be changed to fit the requirements of the evaluator. A device would be considered feasible if it can meet the evaluation criteria.

7.4 DETERMINING COST EFFECTIVE RETROFIT METHODS

Each device identified as a candidate should be evaluated by means of the formal analytical evaluation methodology developed through the retrofit study. This evaluation methodology provides a systematic means of objectively evaluating alternative devices in terms of their relative effectiveness and costs and performance. The methodology can be exercised either by computer or by manual means. A sample manual exercise of the evaluation methodology is shown in Appendix A.

7.5 DEFINING THE CERTIFICATION PROGRAM

An essential element in approving a particular device or devices for use in a State or region is the accreditation program that demonstrates that the device actually performs in the manner in which it was intended. If the air quality control agency does not have significant statistical confidence in a device then an accreditation program of adequate size should be conducted by the developer. Such elements as sample size, reliability, durability, maintainability, and effectiveness should be addressed in the design of the accreditation test program. The accreditation plan must include several key elements such as:

a. General provisions for retrofit systems

b. Emission level standards

c. Accreditation procedures

d. Test procedures

e. Compliance to standards.

7.6 COST EFFECTIVENESS STUDIES OF ALTERNATIVE PROGRAMS

The cost effectiveness of a retrofit device program for the uncontrolled vehicle population must be evaluated in order to decide whether the retrofit method of control is the most effective when all alternative methods are taken into consideration. Alternative methods for used car control such as periodic vehicle inspection and maintenance must be weighed against the retrofit approach to determine which is the most cost effective for a particular region.

7.7 PREPARING AN IMPLEMENTATION PLAN

A detailed plan is required by which to control the accreditation of feasible devices for use, to control the installation, and to control the long term maintenance and continuing effectiveness of the installed devices.

An accreditation program for the certification of retrofit emission control systems for used vehicles must be rigorously planned and managed if the retrofit systems are to be effective in reducing vehicle air pollution.

The overall implementation plan should specify how and when the selected retrofit method will be incorporated on the uncontrolled vehicle population, and what means will be used to ensure long-term maintenance and effectiveness of the device.

7.8 IMPLEMENTING THE PLAN

A formally chartered agency should be assigned the responsibility for implementing and maintaining the control plan. This responsibility includes such requirements as:

a. Training of retrofit installation, maintenance, and repair personnel.

b. Establishment of periodic inspection requirements or surveillance techniques.

c. Overall program administration within the air quality control regions of concern.

The effective implementation and management of a sound retrofit plan is of paramount importance, if the calculated reduction in vehicle emissions is to be realized. This is the enforcement phase of the program, wherein the several millions of uncontrolled vehicles are brought under control by the enforcement agency. As indicated by the three requirements listed above, this phase implies controlling the developers, the vehicle repair personnel, and the many vehicle owners. A task of such a magnitude requires that the preparation described in the previous steps be adequate and sound.

Of further consideration in the establishment and implementation of a viable retrofit program is that the above steps not only consider the present time and circumstances, but that all the predictable variations that could occur in the future years be recognized and accommodated in the program. A continuing program should be instituted which provides a periodic evaluation of the air quality problem and the effectiveness of the program.

APPENDIX A — SAMPLE METHODOLOGY CALCULATIONS

APPENDIX A

SAMPLE PERFORMANCE EVALUATION METHODOLOGY CALCULATION

A retrofit system was randomly selected to demonstrate the use of the evaluation methodology developed in the retrofit study.

The data required to exercise the sample calculation are presented in Table A-1. (The device is not identified for this sample calculation.) These data are from Appendix E of Volume III. For the sample calculation, several references are made to the equations in Section 3 of Volume III. The determination of the parameters for the three indexes (Criteria, Performance, and Cost Effectiveness) is in the order of natural flow. For example, the Driveability Index must be calculated to provide an input to the Criteria Index and is later used in the calculation of the Performance Index.

1.0 CRITERIA INDEX

The development of the Criteria Index is presented in paragraph 3.1 of Volume III. The purpose of the Criteria Index is to identify any weak characteristics of a particular device. For this sample calculation the assumed evaluation criteria that a device should meet are listed in Table 1-2 (these values could vary for different States or agencies according to their particular requirements).

1.1 EMISSION STANDARDS FACTOR

Using the assumed standards of 4.5 gm/mi for HC, 46.7 gm/mi for CO, and 3.0 gm/mi for NOx, the evaluator compares the retrofit emission values as follows:

	Assumed Standards (gms/mile)	Retrofit Test Emissions (gm/mile)	Difference Between Stds & Retrofit (gms/mile)
HC	4.50	6.17	-1.67
CO	46.70	89.83	-43.13
NOx	3.00	1.88	1.12

HC and CO levels are greater than the assumed standards. This causes the emission standards factor to receive a rating of "0". The negative values indicate emission levels are above standards.

Table A-1. INPUT DATA FOR SAMPLE CALCULATION USING EVALUATION METHODOLOGY

1. Emission Data (Gm/Mile):

	HC	CO	NOx
Baseline:	4.54	70.78	2.39
Retrofit:	6.17	89.83	1.88

2. Safety Factor: This device received a safety factor of 1.

3. Driveability Test Data:

Test	Parameter	Baseline	Retrofit	Retrofit-Baseline
Cold	Stall at Idle	1	0	0-1 = -1
	Stumble	2	6	6-2 = 4
	Stretchiness	0	10	10-0 = 10
	Start time, sec	0.5	0.5	0.5(1)-0.5(1) = 0
	Attempts	1	1	
Hot	Stretchiness	0	12	12-0 = 12
	Start time, sec	0.5	0.5	0.5(1)-0.5(1) = 0
	Attempts	1	1	
	Avg Acceleration Time, sec	17.3	23.9	23.9-17.3 = 6.6

4. Installation and Recurring Cost Data:

Retrofit kit cost = \$50.00
Installation time = 2.25 hours
Labor rate = \$12.50/hour

MTTR = 0 hrs (1)	L_C = \$12.50/hour
MMBPF = 75,000 miles (1)	C_{RP} = 0 (1)
MMBTF = 75,000 miles (1)	C_{MP} = 0 (2)
MTTM = 0.50 hrs	σD = 0.0661 gal/mile
MMBM = 25,000 miles	σB = 0.0594 gal/mile
	G_c = \$0.35

NOTES: (1) For this device the engineering evaluation showed that the mean miles before partial failure (MMBPF) and the mean miles before total failure (MMBTF) are both 75,000 miles. Therefore, no labor (MTTR) and repair parts cost (C_{RP}) are required.

(2) No maintenance parts required for scheduled maintenance.

5. Reliability Data:

Mean-miles-before-total-failure (MMBTF) = 75,000 miles.

6. Maintainability:

Mean-miles-before-maintenance (MMBM) = 25,000

1.2 EMISSION BASELINE FACTOR

The emission baseline factor prevents HC, CO, and NOx pollutant level increase from baseline levels with the device installed. An experimental error is allowed due to variations in test repeatability (10 percent used in this study) before the emission baseline factor is set equal to zero. The per unit reductions for the three pollutants are obtained using Eqs. (3.3), (3.4) and (3.5) from Section 3, Volume III and the data from Table A-1:

$$\text{HC Reduction, } (R)_{HC} = \frac{E_{BHC} - E_{DHC}}{E_{BHC}} = \frac{4.54 - 6.17}{4.54} = -0.36 \text{ per unit} \quad \text{(A.1)}$$

$$\text{CO Reduction, } (R)_{CO} = \frac{E_{BCO} - E_{DCO}}{E_{BCO}} = \frac{70.78 - 89.83}{70.78} = -0.27 \text{ per unit} \quad \text{(A.2)}$$

$$\text{NOx Reduction, } (R)_{NOx} = \frac{E_{BNOx} - E_{DNOx}}{E_{BNOx}} = \frac{2.39 - 1.88}{2.39} = 0.21 \text{ per unit} \quad \text{(A.3)}$$

The negative values indicate an emission increase above baseline levels. HC and CO increased by more than 0.10 (10 percent). Therefore, the emission baseline factor is zero.

1.3 SAFETY FACTOR

The safety factor was determined by an engineering evaluation of the device. Any potential dangers were identifed with respect to design, installation, or modes of operation. This device received a safety factor of 1 (Table A-1).

1.4 CRITICAL DRIVEABILITY FACTOR

In the Driveability Index (DI), the sum of the "without device" driving problems is subtracted from the sum of the "with device" driving problems to arrive at a driveability variation ΔD, for each parameter:

$$\Delta D = D_{\text{with device}} - D_{\text{without device}}$$

There are five driveability test parameters that are considered to be critical. These critical driveability parameters, if they exist, have an adverse effect on the safety and, therefore, the acceptability of the device being evaluated. These critical driveability parameters are:

	Parameter	Test	ΔD
a.	Stall on acceleration	Cold Start driveaway test	0
b.	Backfire	Cold Start driveaway test	0
c.	Stall at idle	Hot Start driveaway test	0
d.	Stall on acceleration	Hot Start driveaway test	0
e.	Backfire	Hot Start driveaway test	0

Since there were no critical driveability changes for this device, the critical driveability factor is one.

1.5 GENERAL DRIVEABILITY FACTOR

The criterion for the general driveability factor requires that the Driveability Index be no greater than 1.0. Therefore, it is necessary to calculate the Driveability Index at this point. As defined in Eq. (3.7), Section 3, Volume III, the Driveability Index equation is:

$$DI = (S_2) \Big[\big(\alpha_1 \Delta D_{RI} + \alpha_2 \Delta D_{STI} + \alpha_3 \Delta D_{STM} + \alpha_4 \Delta D_H + \alpha_5 \Delta D_D + \alpha_6 \Delta D_S + \alpha_7 \Delta D_{SU}\big)_{cold} + \big(\alpha_8 \Delta D_{RI} + \alpha_9 \Delta D_{STM} + \alpha_{10} \Delta D_H + \alpha_{11} \Delta D_D + \alpha_{12} \Delta D_S + \alpha_{13} \Delta D_{SU}\big)_{hot} + \big(\alpha_{14} \Delta D_{TN}\big)_{cold} + \big(\alpha_{15} \Delta D_{TN}\big)_{hot} + \alpha_{16} \Delta D_A \Big] \bullet \left[\frac{1}{\alpha_1 + \alpha_2 + \ldots + \alpha_{16}} \right] \quad (A.4)$$

Where: S_2 = 1/3 (Scaling factor)

The nine parameters measured during the cold driveability test and the hot driveability test were:

ΔD_{RI} = Rough Idle (Cold start and hot start test)

ΔD_{STM} = Stumble (Cold start and hot start test)

ΔD_H = Hesitation (Cold start and hot start test)

ΔD_D = Detonation (Cold start and hot start test)

ΔD_S = Stretchiness (Cold start and hot start test)

ΔD_{SU} = Surge (Cold start and hot start test)

ΔD_{TN} = Average cranking time (T) times number of engine start attempts (N) (Cold start and hot start test)

ΔD_{STI} = Stall at Idle (Cold test only)

ΔD_A = Acceleration from 0-60 mph, in seconds (Hot start only)

Additionally, the weighting coefficients (α_i) used in this study were:

Cold Driveability							Hot Driveability								
Rough Idle	Stall Idle	Stumble	Hesitation	Detonation	Stretchiness	Surge	Rough Idle	Stumble	Hesitation	Detonation	Stretchiness	Surge	Start Cold	Start Hot	Acceleration
$\alpha 1$	$\alpha 2$	$\alpha 3$	$\alpha 4$	$\alpha 5$	$\alpha 6$	$\alpha 7$	$\alpha 8$	$\alpha 9$	$\alpha 10$	$\alpha 11$	$\alpha 12$	$\alpha 13$	$\alpha 14$	$\alpha 15$	$\alpha 16$
0.3333	1.6666	0.0083	0.0083	0.5	0.0083	0.0083	2.0	0.1	0.1	0.1	0.05	0.05	1.0	1.0	5.0

Substituting the driveability test data from Table A-1 into Eq. (A.4) we obtain:

Parameter	Cold Driveaway	Hot Driveaway
ΔD_{STI}	= 0-1 = -1	
ΔD_{STM}	= 6-2 = 4	
ΔD_S	= 10-0 = 10	= 12-0 = 12
ΔD_{TN}	= 0.5(1)-0.5(1) = 0	= 0.5(1)-0.5(1) = 0

Acceleration: $\Delta D_A = 23.9 - 17.3 = 6.6$

All other driveability parameters were zero.

Substituting the above values in the Driveability Index equation, we obtain:

$$DI = 1/3 \Big[\big(0.3333(0) + 1.6667(-1) + 0.0083(4) + 0.0083(0) + 0.5(0) + 0.0083(10) + 0.0083(0) \big)_{Cold} + \big(2.0(0) + 0.1(0) + 0.1(0) + 0.1(0) + 0.05(12) + 0.05(0) \big)_{Hot} + 1.0(0) + 1.0(0) + 5.0(6.6) \Big] \left[\frac{1}{11.933} \right] = 0.895 \tag{A.5}$$

Since the calculated general driveability (DI) is less than 1, the criterion is satisfied and the general driveability factor is set to one.

1.6 INSTALLATION COST FACTOR

The installation cost includes retail cost of the device, labor cost to install it, and any special adaptive parts that may be needed. From Table A-1, the installation cost is:

(Retrofit kit cost) plus (installation cost)

$$\$50.00 + 2.25 \text{ hrs } (\$12.50/\text{hr}) = \$78.13 \tag{A.6}$$

With an installation cost of less than the $85.00 criterion, the installation cost factor is equal to one.

1.7 THE RECURRING COST FACTOR

The recurring cost of the device takes into account all of those incremental costs due to the continued operation of the retrofit device. It includes the cost of periodic maintenance of the device, repairs for failed parts, total replacement if required, and any incremental losses in fuel economy. The recurring cost is given by the equation:

$$C_{Recur} = \left(\frac{MTTR}{MMBPF} + \frac{MTTM}{MMBM}\right) L_C + \frac{C_{RP}}{MMBPF} + \frac{C_{MP}}{MMBM} + (\sigma_D - \sigma_B)\, G_C \tag{A.7}$$

Where:

MTTR = Mean-time-to-repair, hours

MMBPF = Mean-miles-before-partial-failure, miles

MTTM = Mean-time-to-maintain, hours

MMBM = Mean-miles-before-maintenance, miles

L_C = Labor rate, dollars per hour

C_{RP} = Average cost of repairs, dollars per repair

C_{MP} = Average cost of maintenance parts, dollars per maintenance action

σ_D = Fuel consumed with device installed, gallons per mile

σ_B = Fuel consumed without device installed (baseline), gallons per mile

G_C = Fuel cost, dollars/gallon

Substituting the values from Table A-1 into Eq. (A.7):

$$C_{Recur} = \left(\frac{0}{75,000} + \frac{0.50}{25,000}\right)\left(\frac{\text{hours}}{\text{mile}}\right)\left(\frac{\$12.50}{\text{hour}}\right) + \frac{0}{75,000} + \frac{0}{25,000}\left(\frac{\$}{\text{miles}}\right)$$

$$+ (0.0661 - 0.0594)\left(\frac{\text{gal}}{\text{mile}}\right)\left(\frac{\$0.35}{\text{gal}}\right) = \$0.00259/\text{mile} \qquad \text{(A.8)}$$

The assumed recurring cost criterion is $0.00125/per mile and the limit is exceeded. Therefore, the recurring cost factor is zero.

1.8 RELIABILITY FACTOR

From Table A-1, the MMBTF is 75,000 miles, which meets the minimum reliability criterion. The reliability factor is one.

1.9 MAINTAINABILITY FACTOR

The MMBM given in Table A-1 is 25,000 miles and is greater than the minimum maintainability criterion of 12,000 miles. Therefore, the maintainability factor is one.

1.10 AVAILABILITY FACTOR

The availability factor reflects the inconvenience to the car owner and is the ratio of the total miles of service life before device failure to the total hours for failure repair and periodic maintenance of the device. The value for the availability factor is given by the following equation:

$$\text{Availability, } A = \frac{\text{MMBPF}}{\text{MTTR} + \left(\frac{\text{MMBPF}}{\text{MMBM}}\right)(\text{MTTM})} \text{ Miles per Repair and Maintenance Hour} \qquad \text{(A.9)}$$

Where:

MMBPF = Mean-miles-before-partial-failure

MMBM = Mean-miles-before-maintenance

MTTR = Mean-time-to-repair, hours

MTTM = Mean-time-to-maintain, hours

Substituting values:

$$A = \frac{50,000}{0 + \left(\frac{50,000}{25,000}\right)(0.5)} = 50,000 \text{ miles/repair and maintenance hour} \qquad \text{(A.10)}$$

This far exceeds the minimum criterion of 12,000 miles per repair hour so the availability factor is equal to one.

1.11 CRITERIA INDEX ANALYSIS

A summary of the Criteria Index Factor is as follows:

	Criterion Factor	Does the Device Pass the Evaluation Criteria?
a. Emission standards factor	0	No
b. Emission baseline factor	0	No
c. Safety factor	1	Yes
d. Critical driveability factor	1	Yes
e. General driveability factor	1	Yes
f. Installation cost factor	1	Yes
g. Recurring cost factor	0	No
h. Reliability factor	1	Yes
i. Maintainability factor	1	Yes
j. Availability factor	1	Yes

The Criteria Index results show that the device does not meet the emission standards, emission baseline, and recurring cost factors. This presents a warning to the evaluator selecting a particular retrofit device to give these factors closer attention. At this point the evaluator may exclude a particular device from further evaluation as a retrofit emission control system.

The reader is cautioned to note that the device used for this example was randomly selected and installed on one test vehicle. Several tests should be conducted on each device being evaluated to establish mean values and statistical validity. The results shown here are not conclusive.

2.0 PERFORMANCE INDEX

The Performance Index (PI) is represented by a summation equation designed to obtain a quantitative rating of the devices under evaluation. This equation measures the relative performance ratings of the device, and allows an objective evaluation even if it does not pass State or regional evaluation criteria index requirements.

The general form of the Performance Index (PI) is given by the following equation:

$$\text{Performance Index, PI} = \frac{C_1\begin{pmatrix}\text{Emission}\\ \text{Index, Per}\\ \text{Unit of}\\ \text{Reduction}\end{pmatrix} - C_2\begin{pmatrix}\text{Drive-}\\ \text{ability}\\ \text{Index}\\ \text{Points}\end{pmatrix} - C_3\begin{pmatrix}\text{Cost}\\ \text{Index}\\ \text{\$/100 miles}\end{pmatrix}}{C_1 + C_2 + C_3} \qquad (A.11)$$

For this example, the weighting coefficients C_1, C_2, and C_3 are 4, 1, and 2, as defined in paragraph 3.4 of Volume III.

2.1 EMISSION INDEX

The emission index (EI) provides the per unit reduction of vehicle emission reduction with the retrofit device installed from the baseline emission level of the vehicle without the device installed. For each pollutant, this per unit reduction is expressed by the following equation:

$$EI = \frac{S_1}{\beta_{HC} + \beta_{CO} + \beta_{NO}} \left[\beta_{HC} \left(\frac{E_{BHC} - E_{DHC}}{E_{BHC}} \right) + \beta_{C_0} \left(\frac{E_{BCO} - E_{DCO}}{E_{BCO}} \right) + \beta_{NO} \left(\frac{E_{BNO} - E_{DNO}}{E_{BNO}} \right) \right] \quad (A.12)$$

Where "S_1" is a scale factor. It is "1" for the emission term.

Equal weighting is assumed for the emission weighting coefficients. Therefore,

$$\beta_{HC} = \beta_{CO} = \beta_{NO} = 1.$$

Substituting the baseline and retrofit emission levels values given in Table A-1:

$$EI = 1/3 \left[(1) \left(\frac{4.54 - 6.17}{4.54} \right) + (1) \left(\frac{70.78 - 89.83}{70.78} \right) + (1) \left(\frac{2.39 - 1.88}{2.39} \right) \right]$$

$$= -0.139 \quad (A.13)$$

2.2 DRIVEABILITY TERM

The driveability term (DI) was calculated in determining the general driveability factor of the criteria index and the result was 0.895 See Eq. (A.5).

2.3 COST INDEX

The Cost Index (CI) combines those parameters which determine the initial costs of a device and the recurring costs. The Initial Cost (C_{DI}) is amortized over the expected life (in miles) of the device.

$$\frac{C_{DI}}{MMBTF} \quad \text{dollars per mile} \quad (A.14)$$

Where C_{DI} = initial cost for parts and installation and MMBTF = mean-miles-before-total-failure.

The Cost Index (CI) is:

$$CI = S_3 \left[\frac{C_{DI}}{MMBTF} + C_{Recurr} \right] \quad \text{dollars per 100 miles}$$

Where S_3 = Scaling factor = 100

Substituting the values given in Table A-2 and from Eqs. (A.6) and (A.8):

$$CI = 100 \left[\frac{\$78.13}{75{,}000 \text{ miles}} + \frac{\$0.00259}{\text{mile}} \right] = \$0.364/100 \text{ miles} \tag{A.15}$$

2.4 PERFORMANCE INDEX CALCULATION

Substituting equation results Eq. (A.13) for the EI, Eq. (A.5) for the DI, and Eq. (A.15) for the CI into Eq. (A.11) we obtain:

$$PI = \frac{1}{4+1+2} [4(-0.139) - 1(0.895) - 2(0.364)] = -0.312 \tag{A.16}$$

In general, the negative sign indicates that the cost and/or driveability penalties are greater than any emission benefits. In this example, the emission index increase was also a penalty.

3.0 COST EFFECTIVENESS INDEX

The Cost Effectiveness Index (CEI) is obtained by dividing the Emission Index by the Cost Index. Using the results of Eqs. (A.13) and (A.15):

$$CEI = \frac{EI}{CI} = \frac{-0.139}{0.364} = -0.382 \ \frac{\text{Unit Reduction}}{\$/100 \text{ Miles}} \tag{A.17}$$

Negative EI means increased emission levels above baseline as a result of device installation. For this example, the CEI indicates that money was spent to increase emissions, a clearly unfavorable situation.

APPENDIX B

RETROFIT SYSTEM DESCRIPTION INDEX

NOTE: This appendix correlates the retrofit devices evaluated with the respective Volume II paragraphs in which the devices are described.

RETROFIT SYSTEM DESCRIPTION INDEX

DEVICE NO.	VOL. II		DEVICE NO.	VOL. II		DEVICE NO.	VOL. II	
	PARA.	PAGE		PARA.	PAGE		PARA.	PAGE
1	4.1.1	4-3	170	7.1.2	7-7	401	4.1.5	4-39
10	4.2.1	4-50	172	4.3.1	4-80	408	9.3	9-15
22	4.6.1	4-141	175	5.1.2	5-12	418	4.1.6	4-43
23	5.2.1	5-22	182	6.2.1	6-61	425	3.3.2	3-79
24	7.1.1	7-3	244	3.2.1	3-31	427	7.2.2	7-27
31	3.2.4	3-64	245	4.2.2	4-58	430	4.3.2	4-86
33	4.4.1	4-104	246	4.2.3	4-67	433	4.1.4	4-30
36	6.3.1	6-76	259	5.2.3	5-25	440	4.3.3	4-91
42	4.1.2	4-14	268	5.2.4	5-32	457	6.2.4	6-73
52	6.1.1	6-5	279	6.3.2	6-78	458	4.1.7	4-45
56	4.4.2	4-112	282	6.2.3	6-67	459	6.1.3	6-35
57	4.1.3	4-22	288	4.4.3	4-117	460	6.1.6	6-47
59	9.1	9-1	292	3.1.2	3-19	461	6.1.4	6-40
62	3.1.3	3-26	294	4.2.4	4-79	462	4.1.8	4-46
69	5.1.1	5-3	295	4.4.4	4-123	463	3.2.2	3-51
93	3.1.4	3-29	296	5.2.5	5-36	464	6.1.5	6-43
95	5.2.2	5-23	308	3.3.1	3-73	465	6.2.2	6-66
96	3.1.1	3-3	315	7.1.3	7-15	466	6.1.2	6-31
100	4.5.1	4-139	317	4.4.5	4-132	467	8.1	8-3
160	7.2.1	7-21	322	3.5.1	3-95	468	3.2.3	3-58
164	3.4.1	3-89	325	4.1.4	4-30	469	9.4	9-21
165	9.2	9-5	384	4.3.4	4-97			

APPENDIX C

TABLES OF CONTENTS

FOR

VOLUMES II, III, IV, V, AND VI

The tables of contents from Volumes II, III, IV, V, and VI are presented in this appendix to provide an overview of the subject matter of this report and to aid the reader in locating subjects of interest.

VOLUME II

CONTENTS

VOLUME II

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

CONTENTS (CONTINUED)

ILLUSTRATIONS

ILLUSTRATIONS (CONTINUED)

VOLUME II

ILLUSTRATIONS (CONTINUED)

ILLUSTRATIONS (CONTINUED)

ILLUSTRATIONS (CONTINUED)

VOLUME II

TABLES

TABLES (CONTINUED)

TABLES (CONTINUED)

TABLES (CONTINUED)

TABLES (CONTINUED)

TABLES (CONTINUED)

TABLES (CONTINUED)

VOLUME II

TABLES (CONTINUED)

VOLUME III

TABLE OF CONTENTS

VOLUME III

CONTENTS (CONTINUED)

VOLUME III

CONTENTS (CONTINUED)

ILLUSTRATIONS

VOLUME III

TABLES

VOLUME IV

CONTENTS

VOLUME IV

CONTENTS (CONTINUED)

ILLUSTRATIONS

TABLES

VOLUME V

CONTENTS

VOLUME VI

CONTENTS

(1) Missing page numbers were not established at the time of printing of this volume; Volume VI to be published shortly.