REPORT NO. DOT-TSC-OST-75-48.II

Reference copy

Highway Vehicle Retrofit Evaluation
Phase I
Analysis and Preliminary Evaluation Results

Volume II: Sections 4 through 13 and Appendix

M. G. HINTON et al

November 1975

Interim Report

Prepared for
U. S. DEPARTMENT OF TRANSPORTATION
Office of the Secretary
Office of the Assistant Secretary for Systems
Development and Technology
Office of Systems Engineering
Washington, D. C. 20590

Technical Report Documentation Page

1. Report No. DOT-TSC-OST-75-48.II	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle HIGHWAY VEHICLE RETROFIT EVALUATION -- PHASE I: ANALYSIS AND PRELIMINARY EVALUATION RESULTS Volume II: Sections 4 through 13 and Appendix		5. Report Date November 1975
		6. Performing Organization Code
7. Author(s) M.G. Hinton, J. Meltzer, T. Iura, L. Forrest, A. Burke, R. Kopa, W. Lee, K. Swan, F. Augustine, W. Smalley		8. Performing Organization Report No. DOT-TSC-OST-75-48.II
9. Performing Organization Name and Address The Aerospace Corporation* Environmental and Urban Division El Segundo CA 90245		10. Work Unit No. (TRAIS) OS614/R6506
		11. Contract or Grant No. F04701-74-C0075-2
12. Sponsoring Agency Name and Address U.S. Department of Transportation Office of the Secretary Office of the Asst. Sec. for Sys. Dev. & Tec. Office of Systems Engineering Washington DC 20590		13. Type of Report and Period Covered Interim Report May - October 1974
		14. Sponsoring Agency Code

15. Supplementary Notes

*Under contract to: U.S. Department of Transportation
Transportation Systems Center
Kendall Square
Cambridge MA 02142

16. Abstract

This report in two volumes presents an analysis and preliminary evaluation of selected used-car and light-truck fuel economy retrofit devices.

In particular, information is provided that depicts the performance characteristics of retrofit devices that have been brought to the attention of the Department of Transportation as having the potential to improve automotive fuel economy. The spectrum of devices includes carburetors, acoustic and mechanical atomizers, lean-bleed devices, vapor injectors, fuel modifications, inlet manifolds, drivetrain components, drag reduction techniques, driver aids, cooling fans, valve timing, tuneups, exhaust-related systems, engine oils, oil additives, and filters.

Included where possible, are analyses of the general operational principles of a given device and its possible effects on spark ignition engine operation in order to substantiate or explain the available test data.

17. Key Words Automotive retrofit devices, carburetors, induction-related systems, exhaust related systems, ignition systems, fuel modifications, drivetrain components, driver aids	18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	196	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report, prepared by The Aerospace Corporation for the U.S. Department of Transportation (DOT), Transportation Systems Center (TSC), as part of their Automotive Energy Efficiency Project, presents an analysis and preliminary evaluation of the potential of selected used car and light truck retrofit devices for reducing fuel consumption. A number of the more promising devices are recommended for experimental evaluation in a Phase II test program.

Over 20 representative classes of retrofit devices/concepts/techniques, including more than 130 specific items, were examined in the course of the study. A major portion of the analysis effort was directed to the evaluation of 16 advanced, novel, or new carburetors which had been brought to the attention of the Department of Transportation as having the potential to improve automotive fuel economy. The results of the carburetor analysis presented herein were also published in a separate interim report.[1]

In addition to carburetors, the spectrum of devices examined included: acoustic and mechanical atomizers; lean-bleed devices; vapor injectors; fuel modifications (additives, blends of water, alcohol, and gasoline); inlet manifolds; ignition systems; drivetrain components (radial tires, transmissions, overdrives); drag reduction techniques; driver aids; cooling fans; valve timing modifications; tuneups; compression ratio increases; exhaust-related systems (tuned exhaust systems, turbochargers, etc.); and engine oils, oil additives, and filters.

The preliminary evaluation results presented herein are necessarily based on and restricted to the results of the best comparative test data available for a given device or class of devices. In general, such comparative test data (before and after installation of a device in a vehicle), when available, are based on at most a few vehicles. Thus, it is not possible to extrapolate

(1) A Review of Proposed Automotive Carburetor Concepts for Improved Fuel Economy, The Aerospace Corporation, Report No. DOT-TSC-OST-74-41, March 1975.

such test data to the general vehicle population. Therefore, wherever possible, an analysis was made of the general operational principles of a given device and its possible effects on spark ignition engine operation in order to substantiate or explain test data results.

Appreciation is acknowledged for the guidance and assistance provided by Mr. Michael D. Koplow of the Department of Transportation, Transportation Systems Center, who served as DOT/TSC Technical Monitor for this study.

The following technical personnel of The Aerospace Corporation made valuable contributions to the study:

M. G. Hinton	W. B. Lee
F. E. Augustine	W. M. Smalley
A. F. Burke	K. B. Swan
L. Forrest	T. Iura
R. D. Kopa	J. Meltzer

CONTENTS

Volume I

CONTENTS (Continued)

CONTENTS (Continued)

Volume II

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Continued)

CONTENTS (Concluded)

ILLUSTRATIONS

Volume I

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Continued)

ILLUSTRATIONS (Concluded)

TABLES

Volume I

TABLES (Continued)

TABLES (Continued)

TABLES (Concluded)

SECTION 4

IGNITION SYSTEMS

The conventional ignition system used in present-day automobiles comprises a battery, switch, coil, resistor, distributor, spark plugs, and associated wiring. These components, functioning as a system, provide a spark of sufficient intensity and at the proper time to ignite the air/fuel mixture in the cylinders. The system has been relatively inexpensive, simple to maintain, and, until recently, generally regarded as entirely adequate. Public concern for fuel economy resulting from the fuel shortages experienced and the current high cost of gasoline has led to the marketing of a number of ignition system devices which are added to a conventional ignition system or in some cases replace existing components. Significant improvements in fuel economy and/or reduction in exhaust emissions are usually claimed to result from the use of these devices.

To obtain such benefits, these devices must necessarily modify some characteristic of the basic ignition system, which improves its performance. To provide a perspective for judging benefits that might be achieved by such modifications, the function, requirements, and limitations of a conventional 12-volt ignition system must first be described. Advanced electronic ignition systems which the automotive industry has applied in limited models and which are generally planned for broader application will be discussed next. Against this background, the claims of selected ignition devices can then be examined.

4.1 CONVENTIONAL 12-VOLT IGNITION SYSTEMS

A modern 12-volt ignition system is schematically shown in Figure 4-1. The switch turns on the system and, in its advanced position, energizes the starter. In some systems, the switch bypasses a resistor which otherwise limits current flow to the coil. The coil is a "pulse" transformer that steps up the 12-volt battery voltage to the thousands of volts necessary to

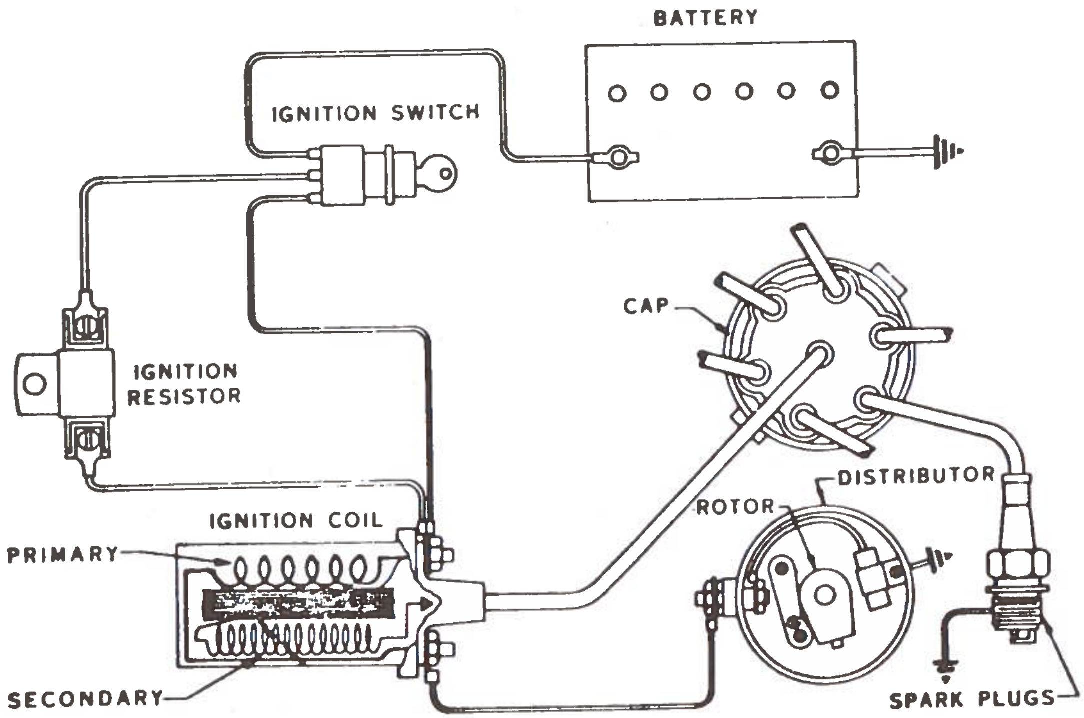


Figure 4-1. Present-Day 12-V Ignition System

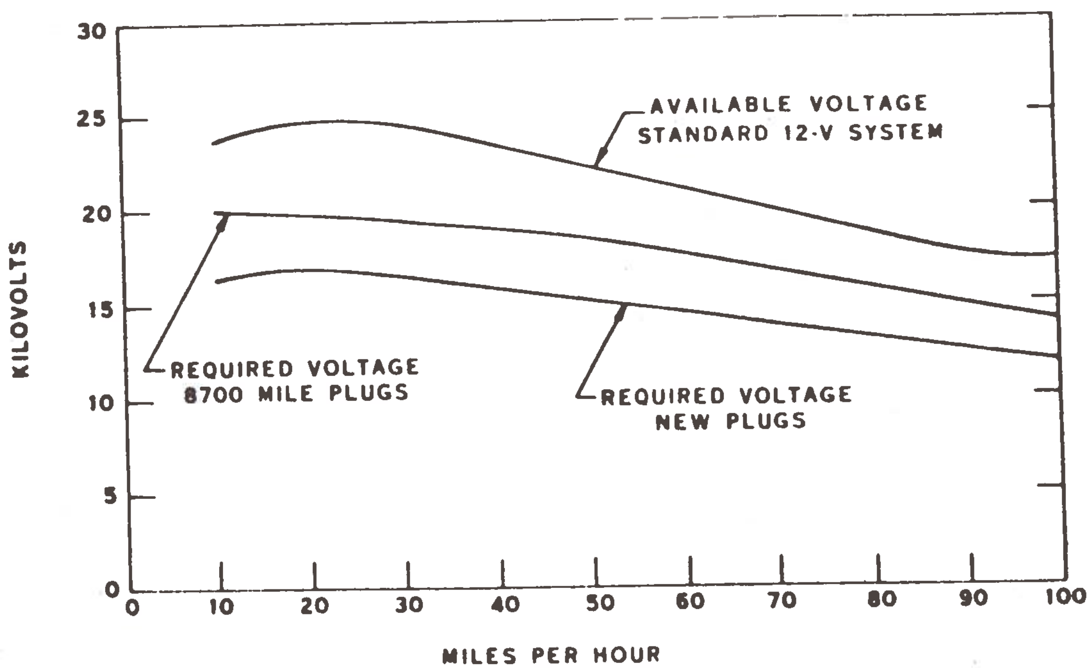


Figure 4-2. Typical Ignition Performance Curves

"jump" the spark plug gap. The distributor points interrupt the current flow through the primary windings in the coil to cause the magnetic field which had built up to suddenly collapse, thus producing a very high voltage output in the secondary circuit of the coil. The rotor distributes this high voltage to the appropriate spark plug. A centrifugal and vacuum advance mechanism within the distributor provides variable timing of this spark, consistent with engine speed and road-load conditions. The spark plugs ignite the air/fuel mixture in the cylinders.

The primary requirement of the ignition system is to provide at the proper time an available voltage to the spark plugs in each cylinder which is sufficient to produce a spark of the required intensity to ignite the air/fuel mixture. This available voltage must exceed the required voltage by some margin of reserve to account for "wear" factors such as deterioration of breaker points and spark plug electrodes, fouling of spark plugs, and cyclic variations in air/fuel mixture. The system also must satisfy cost, reliability, and life and service requirements. Figure 4-2 shows typical required and available voltages.

4.1.1 Factors Influencing Available Voltage

The main factors which influence available voltage in a given ignition system are:

a. Dwell Angle - the number of degrees of distributor shaft rotation during which the breaker points are closed in each successive firing. The greater the dwell angle, the longer the time to build up the magnetic field in the coil and thus the higher the output voltage.

b. Engine Speed - for a given dwell angle, the time that the points are closed is proportional to engine speed. Thus, with a conventional ignition system, the available voltage falls off at high rpm, particularly so in 8-cylinder engines which require eight firings per distributor shaft rotation.

c. Breaker Point Gap - increasing the gap has the effect of decreasing the dwell angle, since the points open sooner. The gap, however, must be sufficient to minimize arcing when the points break.

d. Contact Arcing - when an arc occurs between the contacts as they open, a part of the energy stored in the coil is lost in the arc. With less energy, the output of the coil is less. Arcing is most noticeable at low speeds because the contacts are opened slowly. If contacts are in reasonably good condition, arcing nearly disappears at speeds about 1000 rpm. As contacts deteriorate with extended use, arcing increases causing available voltage to drop. Contacts must be replaced periodically to maintain adequate available voltage.

e. High Voltage Leakage - this can occur in the spark plug lead wires or by a conductive coating which accumulates on the porcelain around the center electrode of the spark plug.

f. Battery Voltage - the higher the battery voltage, the higher the output voltage from the coil. Higher voltages in the primary circuit, however, increase the current flow across the breaker points which promotes early deterioration of the contacts.

4.1.2 Factors Influencing Required Voltage

The main factors which influence required voltage in a given ignition system are:

a. Compression Ratio - the resistance across the spark plug gap increases with pressure, thus requiring voltages to be higher at higher compression ratios.

b. Mixture Ratio - lean mixture ratios generally cause higher voltage requirements to produce a comparatively larger reaction to ensure that the flame fully develops. The quenching action of extremely rich mixtures imposes a similar requirement.

c. Spark Plug Configuration - a number of factors in the design of spark plugs affects the voltage requirements. Included are the diameter of the electrodes, gap spacings, projection depth, and heat range (conductive heat path). In addition, the location of the spark plug in the cylinder can affect voltage requirements because of nonhomogeneity of the mixture within the cylinder.

4.1.3 Designing a Conventional Ignition System

In the design of a conventional ignition system, a number of compromises must be made to provide the balance which best satisfies all of the system requirements. For example: increasing current flow across the breaker points increases available voltage at high engine rpm, but it also decreases the life of the contact points; increasing spark plug gap increases the intensity of the spark, but it also requires higher voltage to break down the gap resistance; increasing the heat range of the spark plug reduces the accumulation of deposits, but it also increases deterioration of the electrodes; increasing the slope of the breaker cam to make the points break faster benefits low-speed operation, but it also causes point bounce and erratic operation at high engine rpm.

4.1.4 Limitations of the Conventional Ignition System

The conventional ignition system is inexpensive, simple to maintain, and generally regarded as entirely adequate. There are faults, however, with the system which compromise its performance and require periodic service of the system to maintain its proper operation. These faults result primarily from limitations of the mechanically actuated breaker points.

Although contacts presently used are made of the best material commercially available, they deteriorate rapidly if worked at currents much above 4 amps. At this secondary current flow, the voltage output from the coil is just barely adequate at high engine speeds (4000 rpm). At low engine speeds, this current flow results in an excessive energy discharge which shortens the life of the spark plugs.

Mechanical actuation of the breaker points produces wear of the rubbing block which changes ignition timing and dwell angle. It also limits the speed at which the primary current can be interrupted. This affects the ability to fire partially fouled spark plugs, because it increases the voltage rise time and permits more time for bleed of the high-voltage energy.

4.2 ADVANCED IGNITION SYSTEMS

The automotive industry in recent years has given serious consideration to the use of advanced concepts which overcome some of the faults of a conventional system and permit greater flexibility in operation. These concepts include electronic inductive systems, capacitive discharge systems, and breakerless systems. While these improvements generally increase the system cost, they have been found necessary in order to meet current and projected exhaust emission requirements and to provide acceptable driveability and fuel economy. The need for such improvements relates to borderline misfire conditions resulting from lean mixture ratios at certain operating conditions and contributory effects from the exhaust gas recirculation required for NO_x control. Several of the 1975 model automobiles incorporate one or more of these advanced concepts.

4.2.1 Electronic Inductive Systems

Systems of this type incorporate an electronic package which controls the flow of current in the primary circuit. They are inductive like a conventional system and produce a high-voltage output from the coil by the interruption of current flow in the primary circuit. In these systems, however, the breaker points act only to control the transistor base current. With a current flow of approximately 1 amp across the breaker points, the transistors provide 7-10 amps of primary current to the coil which doubles the current flow permitted in a conventional system. This is the least costly of the electronic systems and provides the following advantages:

a. The low break current with minimal arcing ensures long life of the breaker points and helps cold starting.

b. Increased voltage output in the higher speed range is gained as a result of the increased current in the primary circuit.

c. The reduced current across the breaker points permits a smaller gap and lighter weight of the point assembly, thus increasing dwell angle and minimizing contact bounce.

It should be noted that the voltage rise time with this type system is about the same as a conventional system, and periodic maintenance is still required to adjust the breaker point gap which changes due to wear of the rubbing block.

4.2.2 Capacitive Discharge Systems

Capacitive discharge (CD) systems consist of a converter to increase the battery voltage, a storage element (capacitor), a switching element (silicon controlled rectifier or SCR), and an output transformer (coil).

As with the transistor system described previously, the breaker points are used to trigger a circuit, which in this case discharges the capacitor to cause the primary voltage in the coil to rise from 0 to about 400 volts in approximately 2 microseconds. This results in a sudden rise in the magnetic field to produce a high voltage output from the secondary winding of the coil. It should be noted that this is a reverse of the condition in a conventional system, where high voltage is induced by the sudden collapse of the magnetic field, and is the means by which a CD system achieves both a higher voltage level and much faster rise time than either the transistorized or conventional system. It also provides a further improvement in starting characteristics, extends the voltage level to a higher rpm, and (because of its shorter period of energy release) increases spark plug life.

Capacitive discharge systems have recently been improved by additional circuitry which provides a multiple-spark discharge (MSD). By monitoring coil decay, multiple sparks of equally high energy can be delivered to each cylinder over a period which covers 20 degrees of crankshaft rotation. The number of sparks per firing is variable and ranges from 16-20 at the idle rpm to 4-5 at the 2500-rpm level. Since the air/fuel mixture in a cylinder is not homogenous, the mixture ratio at the spark plug is variable at any given instant of time. Thus, the statistical probability of igniting very lean mixtures is considerably improved by this multiple-spark capability. Although data on spark plug life with this type system are limited, there is no apparent degradation, presumably because of its a.c. wave form characteristic.

4.2.3 Breakerless Systems

Breakerless systems are usually actuated by the rotation of the distributor shaft, but they use a magnetic or photoelectric pickup in place of the conventional breaker points. The pulse generated from the pickup mechanism is amplified and used to trigger the firing circuit. The advantages of this systems are:

a. Improved Firing Consistency - this results from the elimination of bounce which is inherent with mechanically actuated breaker points.

b. Increased Dwell Angle - elimination of the breaker point gap increases the time the points are closed, thereby extending the voltage level to a higher rpm.

c. Requires No Periodic Maintenance - mechanical and electrical wear are eliminated.

While fuel economy is one of the motivations which influenced the automotive industry to consider these advanced ignition systems, it does not necessarily follow that such systems would provide fuel economy benefits when retrofitted in existing vehicles which were originally designed to accommodate a conventional system.

4.3 POTENTIAL FOR FUEL ECONOMY IMPROVEMENTS IN RETROFIT APPLICATIONS

The fuel economy improvements provided by a retrofit ignition system device can vary considerably, since they are dependent upon the condition of the vehicle on which the device is installed.

In general, factory-equipped conventional ignition systems are designed to ensure consistent ignition under typical driving conditions, provided, of course, that the vehicle is properly maintained. Under these conditions, little, if any, improvement would be expected from its replacement with any "improved" ignition system. This general conclusion is supported by the results of a series of tests (Ref. 4-1). In these tests, performance of a conventional ignition system and an advanced ignition system of the capacitive-discharge type were compared with respect to engine power, fuel consumption, and exhaust emissions. No measurable difference in any of these engine characteristics was observed. Tests performed by the CARB on a number of ignition system devices also showed no significant difference in exhaust emissions or fuel economy from the baseline system. Data from these tests are presented in Table 4-1.

The potential for fuel economy improvement with "improved" ignition systems, therefore, lies primarily in applications where the vehicle has been poorly maintained or has been subjected to "unusual" driving conditions. In such cases, systems which provide and maintain a higher available

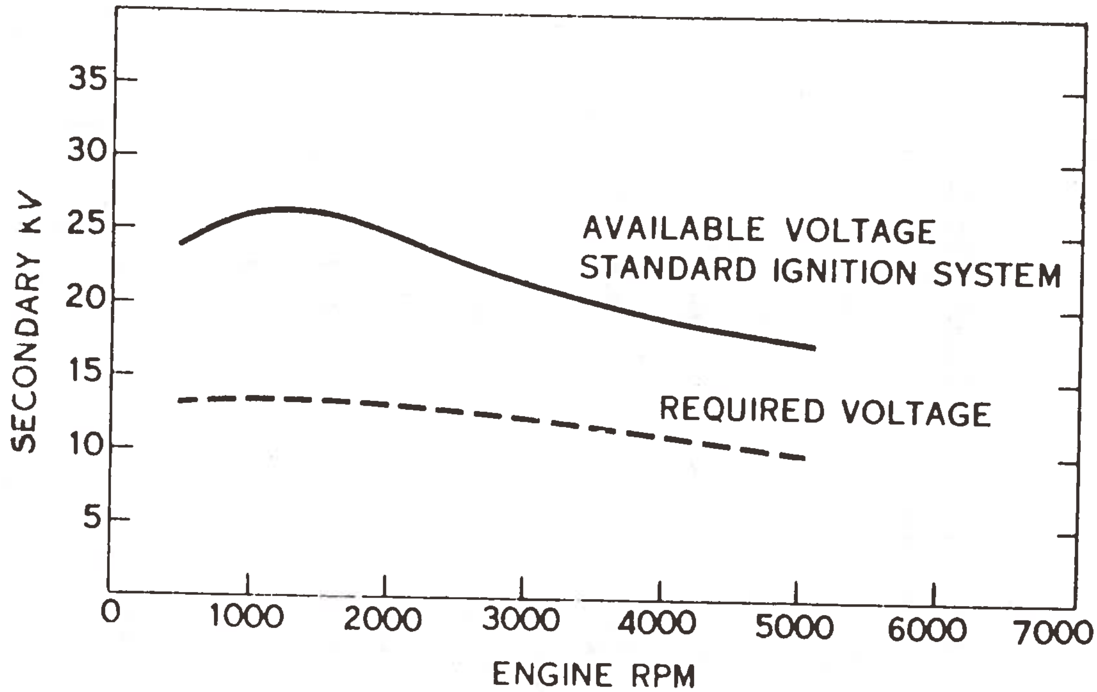
TABLE 4-1. SUMMARY OF CARB TESTS OF CD AND ELECTRONIC INDUCTIVE IGNITION SYSTEMS, HOT-START CVS PROCEDURE (Ref. 4-10 to 4-15)

Manufacturer	Trade Name	Exhaust Emissions HC	CO	NO_x	Fuel Consumption gm/test (MPG)
(Baseline)		4.07	23.21	5.50	1331
C. A. Jacobs	Jacobs (CD)	4.12	21.49	5.74	1303
(Baseline)		4.07	23.21	5.5	1331
Cragar Industries	Power Pack (CD)	4.14	17.6	5.77	1376
(Baseline)		4.07	23.21	5.5	1331
Firewell Products	Firewell (CD)	4.08	21.95	5.87	1362
(Baseline)		4.07	23.21	5.5	1331
American Ecologenics	CDS-84 (CD)	4.27	27.49	5.97	1338
(Baseline)		4.07	23.21	5.5	1331
Gulf and Western	Voltronix (EI)	3.86	17.12	5.47	--
(Baseline)		1.86	18.0	2.07	(12.68)
Tri-Star Corporation	Tiger (CD)	1.79	17.2	2.06	(12.71)
(Baseline)		1.86	17.47	1.90	(13.04)
Western Select	Sentry (EI)	1.79	15.3	1.90	(13.12)
(Baseline)		2.45	14.09	2.53	(13.56)
Air Quality Products	Pure-Power (CD)	2.51	15.3	2.53	(13.42)
(Baseline)		2.16	17.81	2.66	(11.16)
Gayload Electronics	Compu-Spark (CD)	1.62	18.04	1.82	(10.38)
(Baseline)		2.16	17.81	2.66	(11.16)
Synetic	Spitfire (EI)	2.06	17.59	2.43	(11.10)

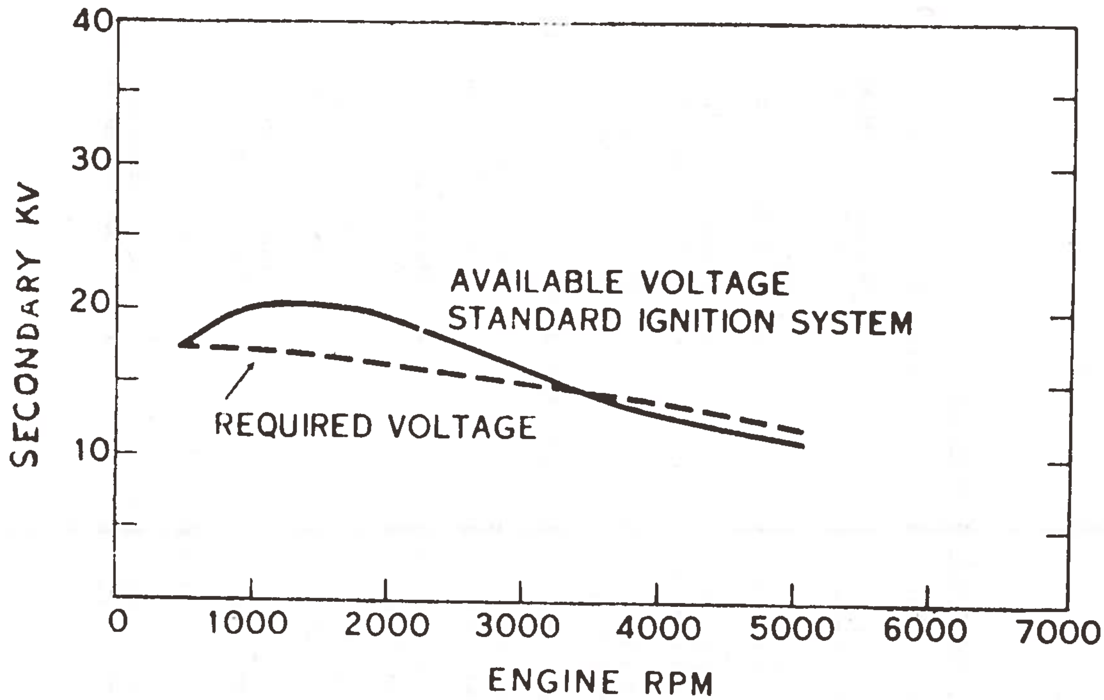
voltage level can significantly extend the period of time before misfire conditions would otherwise become prevalent. This is illustrated in Figure 4-3 which compares the changes in available voltage in a conventional ignition system resulting from lead fouling of the spark plug insulation after 8,000 to 10,000 miles of operation. Note that the change in available voltage in a conventional system places it in a potential misfire condition. In another series of tests under conditions which would promote spark plug fouling, it was observed that the onset of misfire occurred at 750 to 1,000 miles of driving with a conventional system as compared to 1,750 to 2,000 miles with an electronic system. These data were obtained from Ref. 4-1.

Obviously, a misfiring engine will have poorer performance and fuel economy and will emit more unburned hydrocarbons. Thus, to the extent that any of the retrofit systems improve this misfire condition, they can benefit fuel economy as well as other areas. The degree of improvement which they might provide, however, is dependent upon the voltage margin initially provided in the baseline vehicle, the severity of the driving conditions to which the owner subjects the vehicle, adherence to the recommended maintenance schedule, and the quality of the workmanship by the service agency. These, of course, are all variable and affect the potential for fuel economy improvement. For example, the manufacturer of one of the more promising devices performed a series of tests with a number of vehicles under several driving conditions. His results, which are presented in Table 4-2, showed a variation in fuel economy which ranged from a 6% loss to 78% gain.

To be meaningful, fuel economy claims for a device must be based on test results with a vehicle which is typical of the class on which it will be retrofitted. It is most doubtful that the claims for any of these retrofit devices have such a basis. Therefore, the evaluation of the ignition system devices which follows is necessarily limited to a qualitative judgment of the potential for fuel economy which these devices might provide.



a. New Spark Plugs



b. Used Spark Plugs (8-10,000 miles)

Figure 4-3. Effects of Lead Fouling on Available Voltage (Ref. 4-1)

TABLE 4-2. FUEL ECONOMY TESTS OF AUTOTRONIC CORPORATION MSD IGNITION SYSTEM, MANUFACTURER DATA (Ref. 4-16)

Test Vehicle and Configuration		MPG	% Improvement
(300 miles of city driving -- average trip 7-10 miles -- 100 miles of mountain roads)			
1973 Chevrolet	- Standard Ignition	10.7	29.9
1973 Chevrolet	- M. S. D. Ignition	13.9	
1974 Chevrolet	- Standard Ignition	9.3	21.5
1974 Chevrolet	- M. S. D. Ignition	11.3	
1969 Cadillac	- Standard Ignition	6.8	69.1
1969 Cadillac	- M. S. D. Ignition	11.5	
1974 Pontiac	- Standard Ignition	9.0	38.9
1974 Pontiac	- M. S. D. Ignition	12.5	
(500 - 1000 miles of highway driving -- 70 MPH -- average trip 200 miles)			
1973 Chevrolet	- Standard Ignition	13.4	30.6
1973 Chevrolet	- M. S. D. Ignition	17.5	
1974 Chevrolet	- Standard Ignition	11.9	37.8
1974 Chevrolet	- M. S. D. Ignition	16.4	
1969 Cadillac	- Standard Ignition	8.0	73.7
1969 Cadillac	- M. S. D. Ignition	13.9	
1974 Pontiac	- Standard Ignition	12.0	40.8
1974 Pontiac	- M. S. D. Ignition	16.9	
(Dynamometer tests -- 55 MPH constant speed)			
1973 Ford Galaxie	- Standard Ignition	14.56	10.6
1973 Ford Galaxie	- M. S. D. Ignition	16.11	

TABLE 4-2. FUEL ECONOMY TESTS OF AUTOTRONIC CORPORATION MSD IGNITION SYSTEM, MANUFACTURER DATA (Ref. 4-16) (Concluded)

Test Vehicle and Configuration		MPG	% Improvement
(Dynamometer tests -- 55 MPH constant speed) (Continued)			
1973 Mark IV Continental	- Standard Ignition	12.96	
1973 Mark IV Continental	- M. S. D. Ignition	13.72	5.9
1973 Chevrolet Impala	- Standard Ignition	17.11	
1973 Chevrolet Impala	- M. S. D. Ignition	17.45	2.0
(Dynamometer tests -- 35 MPH constant speed)			
1973 Ford Galaxie	- Standard Ignition	20.27	
1973 Ford Galaxie	- M. S. D. Ignition	21.38	5.5
1973 Mark IV Continental	- Standard Ignition	17.37	
1973 Mark IV Continental	- M. S. D. Ignition	18.83	8.4
1973 Chevrolet Impala	- Standard Ignition	19.33	
1973 Chevrolet Impala	- M. S. D. Ignition	19.58	1.3

("ENVIRONMENTAL PROTECTION AGENCY APPROVED TESTING LABORATORY" - 1973 CHEVROLET IMPALA)

Configuration	Test Conditions	Exhaust Emissions HC	CO	NO_x	MPG	% Improvement
Standard Ignition	Hot Start	3.41	93.6	4.08	11.30	
M. S. D. Ignition	Hot Start	3.99	108.1	3.93	10.65	-5.8
Standard Ignition	Cold Start	5.46	121.1	4.82	9.71	
M. S. D. Ignition	Cold Start	4.89	110.6	5.08	10.09	+3.9
Standard Ignition	50 MPH Fuel Economy Run				18.63	
M. S. D. Ignition	50 MPH Fuel Economy Run				20.06	+7.7

4.4 EVALUATION OF SELECTED IGNITION SYSTEM DEVICES

4.4.1 Capacitive Discharge Systems

Of the selected retrofit devices discussed, 11 are advanced electronic systems of the capacitive-discharge type. These systems characteristically maximize voltage level and rise time which significantly increases the margin in available voltage. Breaker contact deterioration is minimized by their low current flow, and, as a result of their short period of energy release, they also extend spark plug life. They would also be expected to provide consistent firing over a wider range of conditions and for a longer period of time than electronic or conventional inductive-type systems. Systems of this type, therefore, have the greatest potential for fuel economy benefits. All devices of this type offer about the same potential (Ref. 4-9). Some, however, include other features which further increase their potential. Table 4-3 lists these devices, identifies their special features, and comments briefly on additional benefits which these features might provide.

4.4.2 Electronic Inductive Systems

Five of the selected retrofit devices are advanced electronic systems of the inductive type. These systems provide some of the advantages of CD systems but usually to a lesser degree. Because of their inductive nature, voltage levels and rise times are not significantly different from a conventional system. Voltage dropoff with rpm, however, is extended, and breaker point deterioration is minimized by low current flow. Thus, systems of this type provide some potential for fuel economy benefits. Some of these systems also incorporate other improvements which further increase their potential benefit. These are identified with appropriate comments in Table 4-4 where devices of this type are listed.

4.4.3 Other Ignition System Devices

The remaining ignition system devices selected for evaluation are either conventional devices of an "improved" design which replace existing

TABLE 4-3. CAPACITIVE-DISCHARGE SYSTEMS

Manufacturer	Trade Name	Special Features	Comments
Autotronic Controls Corporation	MSD-2	Multiple spark discharge.	Most advanced CD system - provides multiple sparks during 20° of crank-shaft rotation - increases probability of firing lean mixtures.
Delta Products, Inc.	Mark Ten	None	Provides typical CD benefit potential.
Grant Industries, Inc.	Flamethrower	None	Provides typical CD benefit potential.
Clytronics Corporation	Clytronic Ignition System	Breakerless - special coil.	Triggered by pulse from an interrupted light source - eliminates deterioration due to wear of contact points and rubbing block - special coil maximizes primary and secondary inductance to permit increased voltage at higher RPMs.
Air Quality Products, Inc.	Pure-Power	None	Provides typical CD benefit potential.
Tri-Star Corporation	Tiger	None	Provides typical CD benefit potential.
Gaylord Electronics, Inc.	Compu-Spark	None	Provides typical CD benefit potential.
American Ecologenics Corporation	CDS-84	None	Provides typical CD benefit potential.
Firewell Products Corporation	Firewell	None	Provides typical CD benefit potential.
Cragar Industries, Inc.	Power Pack	None	Provides typical CD benefit potential.
C. A. Jacobs	Jacobs	None	Provides typical CD benefit potential.

TABLE 4-4. ELECTRONIC INDUCTIVE SYSTEMS

Manufacturer	Trade Name	Special Features	Comments
Hays Enterprises, Inc.	Magna-Pulse	Breakerless	Triggered by pulse from a magnetic pickup - eliminates deterioration due to "wear" of contact points and rubbing block.
Synetic	Spitfire	None	Provides typical electronic inductive system benefit potential.
Western Select	Sentry	Dwell Extender	Extending the dwell time provides more time to build up the magnetic field in the coil thus extending the voltage drop-off to higher RPMs.
General Products Division Gulf and Western Industries	Voltronix	None	Provides typical electronic inductive system benefit potential.
Corona Engineering	Corona	Breakerless - special coil.	Triggered by pulse from an interrupted light source - eliminates deterioration due to wear of contact points and rubbing block - special coil maximizes primary and secondary inductance to permit increased voltage at higher RPMs.

components in the system or are devices of an unconventional type which are added to the system and, by some obscure means, provide significant performance improvements.

Devices in the first category include "Magna Flash," Uhland Ignition System, "Azure Blue," and "Gas Energizer." In general, these devices provide only a nominal increase in voltage level and/or extension of spark duration. As such, their potential to provide fuel economy improvements is limited.

Devices in the second category include "Magic Ionizer," "Electronic Supercharger," and "Auto Saver." In general, these types of unconventional devices allude to some basic principle to explain the performance advantages which they claim. The details needed to understand how they alter performance, however, are usually avoided. Thus, from an engineering point of view, it is not possible to make a judgment on the potential benefit in fuel economy which these devices might provide.

The salient features and functions of these other ignition system devices are presented in Table 4-5.

4.5 RECOMMENDATIONS FOR TEST

It should be recognized that the actual fuel economy improvement from any retrofit ignition system device is highly dependent on the condition of the vehicle on which it is installed. Within this constraint, however, meaningful data can be obtained by imposing test conditions which encompass the range of expected conditions. This would, at least, provide some basis for judging its potential benefit in a typical retrofit application.

It is recommended that such a test be performed on the MSD Ignition System manufactured by the Autotronic Corporation.

TABLE 4-5. OTHER IGNITION SYSTEM DEVICES

Manufacturer	Trade Name	Salient Features	Function
Magna-Flash Manufacturing and Sales Company	Magna-Flash	"Improved" ignition coil.	Replaces and performs the same function of the standard coil.
Floyd M. Uhland	Uhland Ignition System	Dual coil - triple breaker points.	A voltage source is connected in parallel to first and second primary windings of two ignition coils. A current reversing, dual point assembly is connected to a circuit breaking single point assembly so that opening of the latter causes spark plug firing. Arc current developing across the contacts of the point assembly is reversed during alternate actuation thereby preventing unidirectional transfer and accumulation of deposits on the contact surface.
Azure Blue Corporation	Azure Blue Ignition Amplifier	Special type spark plug.	The device replaces the customary spark plug and compromises three sections: upper section with valve and perforations for purging the device chamber; center section is the combustion chamber with ignition contacts; lower section with high velocity jet opening. The operating principle of the device is to ignite a small amount of fuel-air mixture in the device chamber and to propel the high velocity flame front into the engine cylinger for improved combustion.
TRD International Tokyo, Japan	Auto Saver	Neon tube and resistance element.	The unit incorporates a neon tube and resistance and is connected in parallel with the primary circuit of the ignition coil. By reducing the time of counter-current flow when the breaker points open it is said to produce optimum ignition and combustion of fuel. In addition to fuel economy and operating advantages it is claimed that the device reduces exhaust emissions.

TABLE 4-5. OTHER IGNITION SYSTEM DEVICES (Concluded)

Manufacturer	Trade Name	Salient Features	Function
Magi Corporation	Ionizer	Interconnected inductive clips on leads in secondary circuit.	Induced voltage from the coil and firing cylinder lead wires is routed to form a corona across the spark plug electrodes and thus ionize the gases prior to ignition.
Warshowsky and Company	Electronic Supercharger	Special rotor in the distributor.	Induces voltage from the cylinder being fired and distributes it to the non-firing cylinders to ionize the gases prior to ignition.
Energy Innovations	Gas Energizer	Series added device in secondary circuit between coil and distributor.	Changes the inductance of the secondary circuit to slightly supress the discharge voltage and increase the current flow and spark duration.

4.6 REFERENCES FOR SECTION 4

4-1. J. C. Norris, "Delcotronic Transistor Controlled Magnetic Pulse Type Ignition Systems," SAE Trans., Vol. 72 (1963).

4-2. R. C. Teasel, et al., "Ignition Systems Can Effect Fuel Economy," SAE Trans., Vol. 74 (1966).

4-3. L. R. Hetzler and P. C. Kline, "Engineering C-D Ignition for Modern Engines," SAE Trans., Vol. 76 (1968).

4-4. P. C. Kline, "Some Factors to Consider in the Design and Application of Automotive Ignition Systems," SAE Trans., Vol. 79 (1970).

4-5. R. J. Craver, et al., "Spark Plug Design Factors and Their Effect on Engine Performance," SAE Trans., Vol. 79 (1970).

4-6. T. Tanuma, et al., "Ignition Combustion and Exhaust Emissions of Lean Mixtures on Automotive Spark Ignition Engines," SAE Trans., Vol. 80 (1971).

4-7. R. R. Burgett, et al., "Measuring the Effect of Spark Plug and Ignition System Design on Engine Performance," SAE Trans., Vol. 81 (1972).

4-8. I. A. Harrington, et al., "A Study of Ignition System Effects on Power, Emissions, Lean Misfire Limit, and EGR Tolerance of a Single Cylinder Engine - Multiple Spark versus Conventional Single Spark Ignition," Paper presented at the Automobile Engineering Congress, February 1974.

4-9. Telephone conversation with A. Crum, Crager Industries, Los Angeles, California (September 18, 1974).

4-10. Evaluation Tests of C. A. Jacobs Capacitive Discharge Ignition System, Project M-262-A, California Air Resources Board (August 1973).

4-11. Evaluation Tests of Voltronix Transistorized Ignition System, Project M-262-B, California Air Resources Board (August 1973).

4-12. Evaluation Test of Cragar Industries, Inc. Power Pack Capacitive Discharge Ignition System, Project M-262-C, California Air Resources Board (August 1973).

4-13. Evaluation Tests of Firewell Capacitive Discharge Ignition System, Project M-262-D, California Air Resources Board (August 1973).

4-14. Evaluation Tests of American Ecologenics Corporation CDS 84 Capacitive Discharge Ignition System, Project M-262-E, California Air Resources Board (August 1973).

4-15. Evaluation Tests of Electronics and Capacitive Discharge Ignition Systems for Motor Vehicles, Project 238, California Air Resources Board (February 1974).

4-16. Study Report of Autotronic Corporation M. S. D. Ignition System, Story Marketing Company (March 19, 1974).

SECTION 5

EMISSION CONTROL RETROFIT SYSTEMS

Various retrofit systems have been developed for purposes of emission control, and some states are considering making their installation mandatory as part of an overall plan for meeting air quality goals. Although it was known in advance that these types of systems were considered to degrade vehicle fuel economy instead of enhancing it, they were examined in the present study in order to compare their emissions, fuel economy, and cost characteristics with similar characteristics of devices designed specifically for fuel economy improvement. Two basic groups of retrofit devices were examined: (a) those designed primarily for NO_x control (i.e., spark control by means of vacuum spark advance disconnect and exhaust gas recirculation devices) and (b) those designed primarily for HC and CO control (i.e., carburetor plus distributor retrofit systems and oxidation catalyst systems).

5.1 SPARK CONTROL RELATED DEVICES

5.1.1 Introduction

Vacuum spark advance disconnect (VSAD) and exhaust gas recirculation (EGR) are the two basic principles of operation employed in NO_x retrofit emission control devices. Both effectively lower the peak flame temperature in the combustion chamber and thus reduce the formation of oxides of nitrogen.

Spark-retard-type devices (VSAD) operate by controlling the vacuum to the distributor during some or all operating conditions. Retard of the basic timing is also required at the time of installation of many of the VSAD devices. A VSAD involves an increase in exhaust gas temperature and, usually, some increase in coolant temperature (Ref. 5-1). Various features have been incorporated in most of the VSAD-type devices to mitigate these effects.

Several VSAD-type devices were certified by the CARB as retrofit devices for the reduction of oxides of nitrogen for 1966-1970 (California) vehicles before the state law was repealed. Among these were the Carter Carburetor, Echlin Corporation, and Kar-Kit devices (Ref. 5-1). Two other VSAD-type devices manufactured by Air Quality Products and Contignitron, respectively, met the NO_x reduction requirement for certification of 42%, but they were not accredited because they exceeded the statutory installed cost limit of $35.

Although individual vehicles may very markedly, a staff report by the CARB (Ref. 5-2) indicates that the VSAD-type devices, as a class, can be expected to result in a fuel penalty of 6%-10%.

The three devices certified for use in California as NO_x retrofit devices are discussed briefly on the following pages.

5.1.2 The Carter Device

The VSAD-type device manufactured by the Carter Carburetor Division, ACF Industries, employs VSAD up to a predetermined speed and at low to moderate coolant temperatures. A speed control switch and an external temperature switch restore normal vacuum advance by actuating a solenoid valve in the distributor vacuum line.

The Carter System includes a solenoid valve installed in a vacuum line between the distributor vacuum advance mechanism and the manifold vacuum source to restore the vacuum spark advance at vehicle speeds above approximately 65 mph and/or engine coolant temperatures above approximately 225°F. A temperature switch is installed on the outside of the upper radiator hose to sense coolant temperature. An electronic speed-sensing switch signals the restoring of vacuum spark advance when vehicle speed reaches approximately 65 mph. This speed sensor measures engine rpm, thus requiring an adjustment for each vehicle installation to correspond to engine speed versus road speed for that vehicle.

Engine modifications and adjustments required at the time of installation include maximum basic timing advances of 2 degrees BTDC for small engines (141-224 CID) and TDC for engines ≥225 CID (this imposes an additional spark retard on most engines of up to 12 degrees or more). The carburetor vacuum source is plugged and the solenoid valve inserted between the distributor vacuum advance port and the intake manifold vacuum source.

Emissions reduction data on a test fleet of 23 vehicles tested by Carter in support of their application for accreditation in California indicated the following average percentage reductions over the hot-start CVS driving cycle: HC 30.6%, CO 51.7%, and NO_x 44.7%. The corresponding effect on fuel economy for this test fleet was not reported. However, comparative tests conducted by the CARB (Ref. 5-3) indicated fuel consumption penalties of 14.8% and 13.6% on the 2 vehicles tested.

The Carter device had a reported sales price of $23 and a total installed cost of $35 (Ref. 5-4).

5.1.3 The Echlin Device

The Echlin Manufacturing Company (Branford, Connecticut) device employs continuous VSAD at all vehicle speeds and engine coolant temperatures. This device includes a spacer plate between the carburetor and the intake manifold, a modulating valve, and two energy cells. The energy cells (acoustic) and modulating valve are contained in a small cylindrical shell which is mounted on the side of the air cleaner and connected to the space plate by a hose. Outside air is drawn through this system and (according to the manufacturer) is "highly energized" which results in better fuel atomization and air-fuel mixing. Engine modifications and adjustments at the time of installation include the following: vacuum advance disconnect, ignition timing set to 2 degrees BTDC, and idle CO set to 2%.

Emissions reduction data on a test fleet of 16 vehicles submitted by Echlin in support of their application for accreditation indicated the following average percentage reductions over the hot-start CVS driving cycle: HC 24.1%, CO 9.4%, and NO_x 41.6%. The fuel economy changes resulting from the installation of the Echlin device in the 16-car test fleet ranged from +9% to -19% with the average being -6.6%.

The Echlin device sold for $18, and the total installed cost was $35, the California statutory limit (Ref. 5-4).

5.1.4 The Kar-Kit Device

The Kar-Kit NO_x retrofit device, manufactured by Air Quality Products (Orange, California) is a basic VSAD kit. The manufacturer recommends that the kit only be used on vehicles intended to be used for in-town driving and not on vehicles intended for high-speed driving, since it makes no provision for restoring normal vacuum advance at high engine speeds or high coolant temperatures.

The kit includes two plugs to close off the ends of the vacuum advance line after it has been cut, a speedometer decal warning the driver not to exceed 60 miles per hour, and an instruction book warning of the hazards of high-speed use.

The kit had a suggested retail price of $5.98 and should, in the opinion of the CARB (Ref. 5-1 and 5-4), have cost less than $10 installed.

The Kar-Kit device has been reported (Ref. 5-5) to achieve an average NO_x reduction of 40%-45% and, similar to the other VSAD devices, to result in a 6%-10% fuel penalty.

5.2 EGR-TYPE DEVICES

Exhaust-gas-recirculation-type retrofit devices operate primarily by metering a quantity of exhaust gas from a connection to the engine exhaust system through a control valve to a tee connection with the PCV line leading to the intake manifold. Provision is also made for providing either full vacuum spark advance disconnect or vacuum advance delay under certain driving conditions.

Two EGR-type devices, the Dana and the STP, were accredited for use as a NO_x retrofit device in California. The STP device was the only NO_x retrofit device accredited in California for use on vehicles having an engine of less than 140 CID. This encompasses most imported vehicles.

The EGR-type devices have been reported by the CARB (Ref. 5-1) to result in a fuel penalty of up to 5%, although individual vehicle tests have shown a wide variation (+8% to -21%).

5.2.1 The STP Device

The STP Pollution Control Device, manufactured by the STP Corporation (Fort Lauderdale, Florida), is basically an EGR-type device which also uses short periods of vacuum spark advance delay.

The STP EGR system utilizes exhaust gas recirculation through a valve and metering means responsive to differentials of exhaust system pressure, intake manifold vacuum, and atmospheric pressure.

The control mechanism of the system is contained in a master EGR valve. The main metering valve plate, containing a small orifice, controls the flow of exhaust gases and additional air into the intake manifold. A smaller, secondary metering valve plate controls the flow of air into the master valve.

A vacuum advance delay valve is used in conjunction with the EGR valve assembly to provide variable spark retard simultaneously with exhaust gas recirculation when the engine is under load. The valve is designed to restore normal vacuum advance within 12 seconds during steady-cruise conditions.

No engine adjustments or modifications are required at the time of installation of the STP device other than to adjust the engine to the manufacturers original specifications.

The STP system was the only NO_x retrofit device accredited in California for use both on engines of less than 140 CID and larger engine sizes (>140 CID). Emissions reduction data reported by the CARB (Ref. 5-3) are presented in two categories: first, the average reductions for vehicles under 140 CID; and second, the average reductions for vehicles over 140 CID. The average emissions reduction in percent over the 1972 CVS hot-start driving cycle were as follows:

	HC	CO	NO_x
Less than 140 CID	-2.4*	5.5	44.5
Greater than 140 CID	16.6	19.5	54.6

*Indicates an increase.

Fuel economy changes varied widely among the certification test fleet vehicles (from +8% to -21%) with the overall average being a 5.6% penalty. This again is consistent with the CARB reports (Ref. 5-1 and 5-2) that the use of an EGR-type retrofit device can result in a fuel penalty of up to 5%.

5.2.2 The Dana Device

The Dana Retronox unit is an EGR-type device manufactured by the Perfect Circle Division of the Dana Corporation (Hagerstown, Indiana). Vacuum spark retard or delay is also utilized to reduce the formation of NO_x in certain driving regimes.

The original Retronox design includes an engine speed switch to control the ported carburetor vacuum used to activate the emission control systems. At a predetermined engine speed (1300 rpm), the speed switch allows ported carburetor vacuum to be applied to the distributor vacuum advance mechanism and to the EGR valve. This advances the spark timing and opens the EGR valve to admit exhaust gases to the intake manifold. When the engine speed drops below this value, the speed switch blocks off the vacuum to the distributor and the EGR valve, thereby retarding the spark timing and closing the EGR valve.

In the modified system, which is used on those vehicles equipped with a carburetor ported vacuum spark advance source, a vacuum delay valve performs a similar function to that of the engine speed switch. With the engine running and the throttle closed, no vacuum exists at the vacuum port located above the carburetor throttle plate; hence, the vacuum lines to the distributor and EGR valve are at atmospheric condition. As the throttle is opened, a vacuum is created at the port in the carburetor, and air is bled out of the system through a calibrated orifice in the vacuum delay valve. A period of approximately 10 seconds will elapse before the engine is operating at normal spark advance during a moderate acceleration. At wide-open throttle, no exhaust gas is recirculated to the engine.

Both versions of the Dana Retronox system were accredited for use as a NO_x retrofit device in California on vehicles with engine sizes greater than 140 CID. The suggested retail price of the kit was $25, and the installed cost was the California statutory limit of $35.

Comparative tests (hot-start CVS) reported by the CARB (Ref. 5-3) on four vehicles indicate no significant difference between the two versions of the Dana device in the reduction of hydrocarbons.

The modified design (with vacuum delay valve) appeared slightly more effective in the control of carbon monoxide and oxides of nitrogen. Reductions of hydrocarbon emissions were 4%, carbon monoxide 31% and 39%, and NO_x 45% and 50%, respectively, for the original and modified devices.

Measured fuel economy for the two versions of the Dana device, based on the results of the comparative tests, indicated an average fuel penalty of 3.4% for the speed-switch version and a 2.6% penalty for the vacuum-delay-valve version. This is consistent with the CARB reports (Ref. 5-1 and 5-2) that the EGR-type devices can be expected to result in a fuel penalty of up to 5%.

5.3 CARBURETOR PLUS DISTRIBUTOR RETROFIT DEVICES

Two basic engine modifications employed by the auto makers in meeting Federal exhaust emissions standards for the control of HC and CO have been the leaning of air-fuel ratios and the modification of ignition (spark) timing. The modification of these parameters as a retrofit technique on pre-controlled (pre-1968) vehicles will also result in the reduction of exhaust emissions. However, because 1968 and newer vehicles have utilized these modifications to some extent, this retrofit technique is considered to be applicable primarily to precontrolled vehicles.

Basically, this retrofit approach consists of three adjustments; i.e., increased idle speed to reduce HC on deceleration, a lean idle mixture (14:1) to reduce HC and CO at idle and part throttle, and vacuum spark advance disconnect during some driving modes. Engine overheating protection is provided by a temperature-sensing device which restores the normal spark advance if high coolant temperatures occur.

Some fuel economy penalty will result from the use of VSAD but will be partially (but not completely) offset by the leaner idle setting.

5.3.1 The General Motors System

The General Motors emission control system was developed as a retrofit system for most 1955 to 1967 model used cars with engine displacements over 140 CID (Ref. 5-6). The basic elements of the system include the following:

a. Increased idle speed - set to 600 rpm in drive for cars with automatic transmissions and to 700 rpm in neutral for cars with manual transmissions.

b. Leaner idle mixtures - set either by the use of an exhaust gas analyzer (14:1 A/F or 1.5% CO) or by the speed drop method from best lean idle (40 rpm drop for 2- and 4-barrel carburetors, 20 rpm drop for single-barrel carburetors).

c. Ignition timing - set to the manufacturer's specification with the vacuum hose disconnected and plugged.

d. Vacuum advance - inoperative during normal driving operation; a thermal vacuum switch, installed at the radiator inlet, restores full vacuum advance above 205°F coolant temperature for overtemperature protection.

e. Carburetor idle speed and mixture adjustment screws - sealed to assure proper settings between tuneups with a plastic adhesive compound supplied with the kit.

The installed cost of the General Motors system has been estimated to be $20 with device-related maintenance (annual adjustment of the idle air-fuel ratio) estimated to be about $5 (Ref. 5-7).

Low mileage EPA tests of this sytem indicate average emissions reductions of 25% for HC, 9% for CO, and 23% for NO_x from a tuned baseline. Durability data developed by General Motors over 25,000 miles without maintenance show no deterioration in the reduction of HC and NO_x

but do show approximately a 20% deterioration in the reduction of CO (Ref. 5-7). This deterioration in CO reduction was attributable to an increase in idle enrichment, thus pointing up the need for annual maintenance to ensure that the installed idle speed and mixture ratio are maintained.

As previously noted, the use of VSAD results in some loss in fuel economy while the leaner idle setting somewhat compensates for this. In the case of the General Motors device, a fuel economy reduction of approximately 2% (Ref. 5-7) is associated with this system.

5.4 CATALYST SYSTEMS

Oxidation catalysts have been shown to be an effective retrofit system for the reduction of HC and CO emissions (Ref. 5-8 and 5-9). The catalytic converter may be in the form of either small pellets of aluminum oxide or a monolithic, honeycomb-type aluminum oxide substrate coated with catalytic material. The most effective catalyst material has been found to be a combination of platinum and palladium. The pellet-type catalyst is held in place within the container by two metal screens while the monolithic type is integrally mounted within the container. The complete converter is mounted in the vehicle exhaust system just below the exhaust manifold. One converter is used on a 4- or 6-cylinder engine and two are used on a V-8 engine.

For a V-8 installation requiring two converters, the installed cost of the converters is estimated at $70-$85. To assure satisfactory emission reductions, an air pump must also be installed (if the vehicle is not already so equipped) to inject auxiliary air into the converters to ensure that an oxidizing atmosphere exists. The installed cost of the air pump could add an additional $85 to the system cost.

The oxidation catalyst would be applicable only to those vehicles whose engines are capable of operating on lead-free fuel without knocking or suffering valve damage.

A brief review of California and New York test fleet results on vehicles equipped with catalyst systems is presented in the following paragraphs.

5.4.1 California Test Fleet

The California test fleet (Ref. 5-8, 5-10, 5-11, and 5-12) comprised 100 vehicles (1966-1972 model year) equipped with the Universal Oil Products (UOP) Mini-Verter containing 170-180 grams of pellet catalyst per converter. One converter was used for each 6-cylinder engine and two for a V-8.

The 100-car fleet was divided into Groups A, B, and C as follows: Group A consisted of 11 vehicles with factory-installed air pumps, Group B consisted of 29 vehicles without air pumps, and Group C consisted of 60 vehicles to which air pumps were added. This latter group is considered to be the most likely candidate for a retrofit system.

The latest test results on this fleet (Ref. 5-8) are given for the Group C vehicles only (with retrofit air pump). The Group A vehicles (factory-installed air pumps) were reported to show good emissions reductions but were stated to be representative of only a small segment of the vehicle population. The Group B vehicles (no air pump) showed poor emissions reductions because of the lack of an air pump.

The average hydrocarbon emissions reduction for the Group C vehicles at 0 miles was 69%. The average HC reduction for 39 vehicles which had been rebaselined after 16 months (17,360 miles) was 43%. The carbon monoxide reduction was 67% at 0 miles and 45% after 17,360 miles. It was further stated that both the HC and CO reductions appeared to have stabilized at the 45% reduction level. NO_x emissions were not reported since they were not significantly affected by this system.

Fuel economy measurements made on 20 Group C vehicles after 16 months of operation showed an average mileage of 11.8 miles per gallon with the converters and 12.1 miles per gallon without the converters. This represents a 2.5% fuel economy penalty as measured over the 1972 CVS cold-start driving cycle.

5.4.2 New York City Test Fleet

The New York City test fleet consisted of five 1971 Plymouth Fury Police Department vehicles. These vehicles were equipped with the Engelhard PTX-423 monolithic catalytic converter and secondary air pump. In addition, it was reported (Ref. 5-9) that the manufacturer required that the vehicles be equipped with specially hardened cylinder heads so as not to void the vehicle warranties. The manufacturer also supplied electronic ignition systems for evaluation, and new carburetors were installed. The five vehicles were emission tested every 4,000 miles for the duration of the test program using the 1972 cold-start test procedure.

Initial average reductions for the 5 test vehicles were 72% for HC and 75% for CO. Emission reductions were found to deteriorate with mileage. After 25,000 miles, the average reductions were 38% for HC and 52% for CO. All emissions reductions were referenced to the baseline values run at the conclusion of the test.

Fuel consumption was calculated from the CVS emissions for four of the test vehicles at the conclusion of the test. The vehicles averaged 15.52 miles per gallon without the catalyst and 15.19 miles per gallon with the catalyst. This represents a 2.1% fuel economy penalty which was not considered significant (Ref. 5-9).

5.5 SUMMARY

The results of the evaluation indicate that all of the retrofit emission devices have a negative effect on fuel economy. The spark control (VSAD) and exhaust gas recirculation (EGR) devices show consistent and effective reduction of NO_x (45%-53%) with a lower effectiveness in the reduction of CO and HC (5%-25%). The VSAD-type devices show the largest fuel penalty of all the systems evaluated at 6%-10%. The EGR devices, with a 53% reduction in NO_x, and a 3%-5% fuel penalty, are more effective than the VSAD type from both an NO_x reduction and fuel economy point of view.

The carburetor plus distributor retrofit systems, consisting of idle rpm and lean idle air-fuel ratio adjustment combined with vacuum spark advance disconnect, are applicable primarily only to the precontrolled cars (1955-1967). They are the least expensive of the systems evaluated ($20 installed) but are less effective in emissions reduction (25% HC, 9% CO, and 23% NO_x). However, only a small fuel penalty of approximately 2% is incurred with the use of this device.

The oxidation catalyst was found to be the most effective retrofit system for the reduction of HC and CO. The emission reduction is as high as 50%-70% at low mileage and levels out to about 45% at extended mileage. NO_x reductions are essentially not affected by the catalyst system. Fleet testing by the State of California and the City of New York indicates the retrofit catalyst has a fuel penalty of up to 2%. Although this would appear to be a viable system in terms of emission reductions of HC and CO combined with a small fuel penalty, the cost of the system is quite high ($70 for a V-8). In order to achieve the indicated level of HC and CO reduction, the vehicle must also be equipped with an air pump to supply additional air to the catalyst to ensure that an oxidizing atmosphere is present. If the vehicle is not already equipped with an air pump, this must also be added, increasing the total installed cost to $155.

5.6 REFERENCES FOR SECTION 5

5-1. 1966-1970 NO_x Control Program, CARB Fact Sheet No. 14, California Air Resources Board (January 29, 1974).

5-2. Staff Report on Comparative Effects of NO_x Retrofit Control Devices, Report No. 73-8-2a, California Air Resources Board (April 18, 1973).

5-3. Applications for Accreditation of an NO_x Control Device, California Air Resources Board.

5-4. Los Angeles Times, Los Angeles, July 29, 1974.

5-5. Summary of NO_x Retrofit Devices, California Air Resources Board.

5-6. G. W. Niepoth, et al., "Exhaust Emission Control for Used Cars," SAE Paper 710069, January 1971.

5-7. The Clean Air Act and Transportation Controls, An EPA White Paper, Environmental Protection Agency, Washington, D.C. (August 1973).

5-8. Status Report on Catalytic Device Equipped Test Fleets, Report No. 74-11-4, California Air Resources Board (12 June 1974).

5-9. An Evaluation of Catalytic Converters in Light Duty Vehicles, Test Report No. 8, Bureau of Motor Vehicle Pollution Control, Department of Air Resources, New York, New York.

5-10. Report on Emissions from Vehicles Equipped with U.O.P.'s Catalytic Device, California Air Resources Board (18 July 1973).

5-11. Fifth Progress Report, Project CO State Fleet Equipped with U.O.P. Device, California Air Resources Board (17 August 1973).

5-12. Report on Emissions from Vehicles Equipped with U.O.P.'s Catalytic Device, California Air Resources Board (November 1973).

SECTION 6

DRIVETRAIN COMPONENTS

In the study of drivetrain components, two general areas were examined for retrofit application:

a. Radial tires
b. Transmission/overdrive/rear axle ratio modifications

These two areas are discussed under separate headings on the following pages.

6.1 RADIAL TIRES

6.1.1 Introduction

This discussion concerns the fuel economy gains to be expected from the use of radial tires on passenger cars. The distinguishing features of radial tires are briefly described, followed by a presentation of the results of vehicle driving tests in which two types of radial tires were comparatively tested versus the other general types of tire construction. The significance of these data to the question of general use in urban driving patterns is discussed.

6.1.2 Differences Between Radials and Other Tire Constructions

Until recent years, the standard tire construction for automotive use was the bias ply. This refers to layers of rubber-coated cord which extend diagonally from bead to bead. Each layer of cord comprises a ply. The cord angle, defined as the angle between the cord and meridional (radial) plane of the tire at the tread center line of the crown, is approximately 60 degrees. There are normally two or four plies in automotive bias ply tires, with the adjacent plies laid up at an opposite angle or bias. The belted-bias tire contains the basic two-ply body (or bias) cords of the bias-ply tire, plus two or more belt plies between the tread rubber and the tire body. These belt plies extend across the full width of the crown (ground contact) area of the tire. The belt ply cord angle is approximately 60 degrees, while that of the body ply is about 56 degrees. The belted-bias construction became the predominant original equipment tire on American passenger cars starting in about 1969.

The key difference with the radial tire is the orientation of the body ply cords. These are in the radial plane, perpendicular to the tread centerline; that is, the cord angle is essentially 0 degrees. The belt ply cords are similar to those of the belted-bias construction but with a somewhat larger cord angle (typically about 70 degrees). This construction produces a flexible sidewall which tends to act independently of the belt and results in a substantial reduction of the hysteresis (or flexing) losses of the polymer material of the tire. This hysteresis loss is by far the major contributor to the tire rolling losses, so that the radial tire has an intrinsic advantage over the other two tire constructions in this respect. Radial tires are expected to be original equipment on about 75% of the domestic 1975 model year cars.

In all these tire constructions, the body ply cords are usually of rayon, nylon, or polyester, while the belt ply cords are typically steel, fiberglass, or rayon.

Representative rolling resistance coefficients of these three tire constructions are shown in Figure 6-1, which was taken from Ref. 6-1.

6.1.3 Experimental Confirmation of Improved Fuel Economy

The lower rolling resistance of radial tires described in the preceding paragraphs implies an improved fuel economy but does not of itself quantify the magnitude of the improvement to be expected. A carefully designed experiment (described in Ref. 6-2) has supplied information in this regard. This test compared the following four tire constructions:

a. HR78-15: 2-ply steel belt with 2-ply radial rayon body
b. HR78-15: 4-ply rayon belt with 2-ply radial rayon body
c. H78-15: 2-ply glass belt with 2-ply polyester bias body
d. 8.55-15: 4-ply nylon bias ply

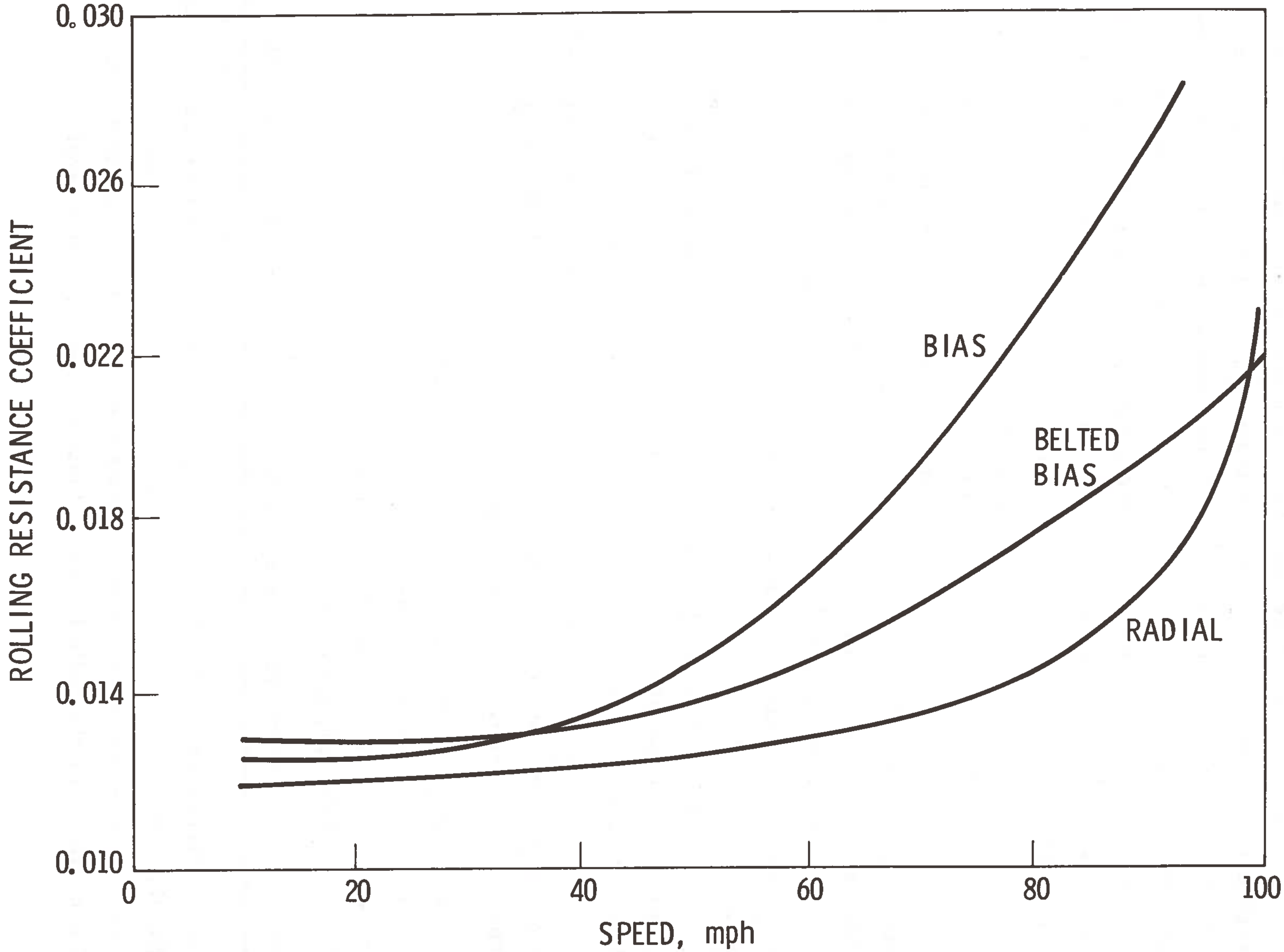


Figure 6-1. Tire Construction Effects

These tires were new, broken in for approximately 70 miles at 50 mph prior to the tests. They were tested on 5 vehicles, which were new, identically equipped, and tuned 1971 Oldsmobile Delta 88s. Each vehicle was broken in for 1500 miles and then tuned. A separate driver was assigned to each car, and this car/driver combination was held constant. Each of the above types of tires was tested on each of four cars. The fifth or control car used only one set of tires (type a above).

The tests consisted of constant-speed driving on an 8.5-mile oval track at speeds of 35, 50, and 75 mph. A measured volume of fuel in an auxiliary tank was consumed to completion in each test, after which the vehicle coasted to a stop. The total distance traveled, including coast-down, was recorded, and the fuel economy was calculated. This auxiliary fuel tank (with its separate fuel pump) was activated by the driver at the beginning of the test run while the vehicle was at lap speed. All cars were adjusted to the same total weight for each test.

The test series lasted three weeks. Each week of four test days comprised the set of tests at a single vehicle speed. Each test day consisted of testing one set of tires on each of the five vehicles.

The test results are summarized in Figures 6-2 through 6-5. On the basis of 100, the tire constructions were rated as follows for overall fuel economy over the three speeds evaluated:

a.	Steel-belted radial	106
b.	Rayon-belted radial	103
c.	Polyester/glass-belted bias	99
d.	Four-ply nylon bias	100

The differences between the radials and the other two tires are statistically significant at the 95% confidence level, while the belted-bias and the bias ply tires are statistically equal. The control group of steel-belted radials is also statistically equivalent to this same tire construction tested on the four different cars. Thus, the steel-belted radials show an overall 6% improvement in fuel economy over the belted-bias or bias-ply tires and an overall 3%

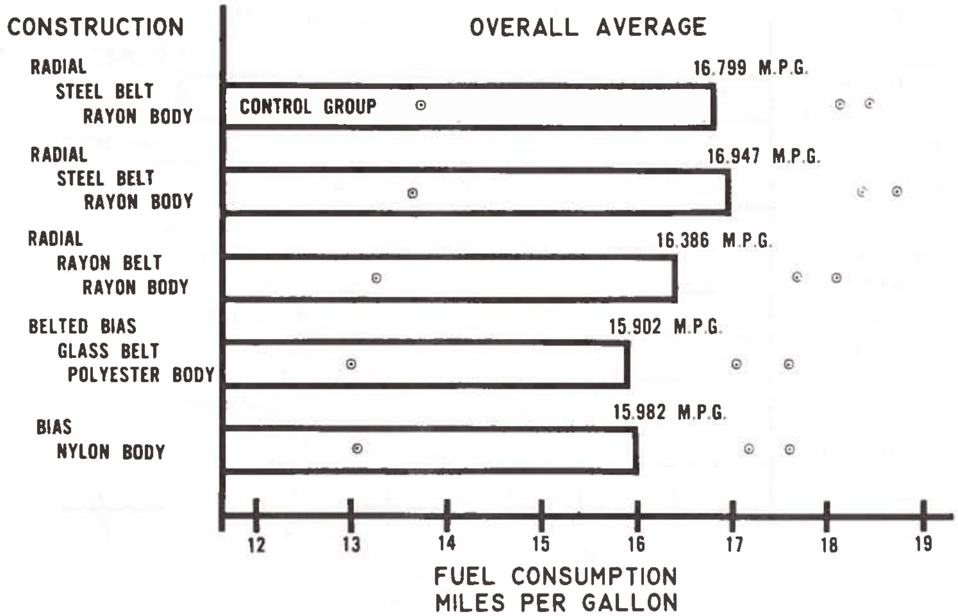


Figure 6-2. Effect of Tire Construction on Fuel Consumption - Overall Average (Ref. 6-2)

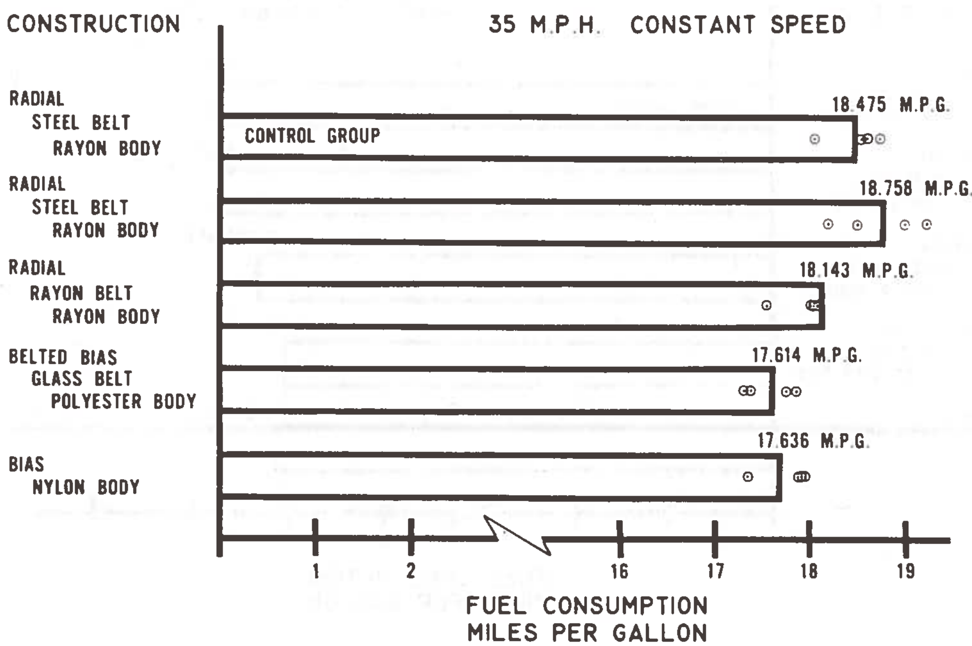


Figure 6-3. Effect of Tire Construction on Fuel Consumption - 35 mph Constant Speed (Ref. 6-2)

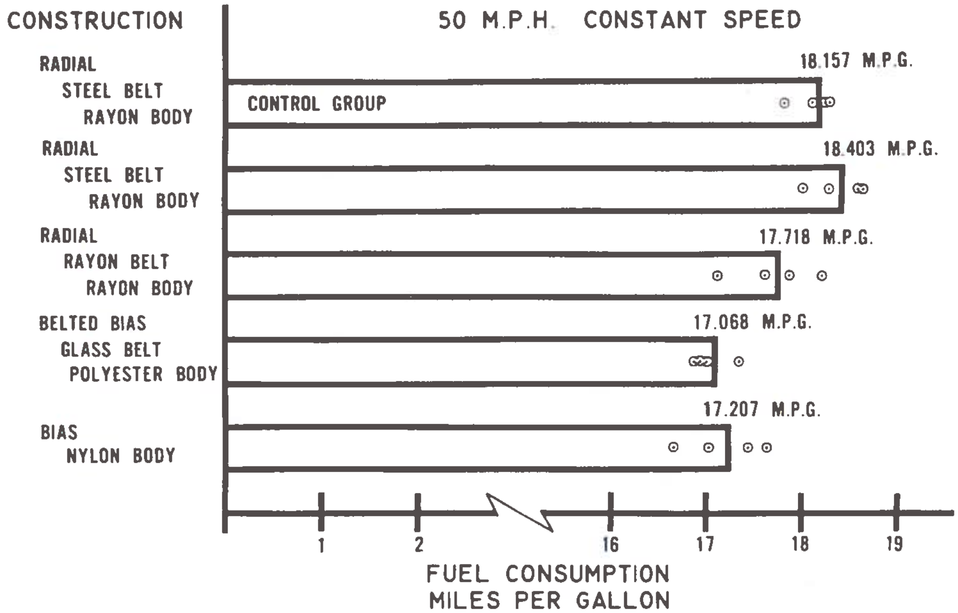


Figure 6-4. Effect of Tire Construction on Fuel Consumption - 50 mph Constant Speed (Ref. 6-2)

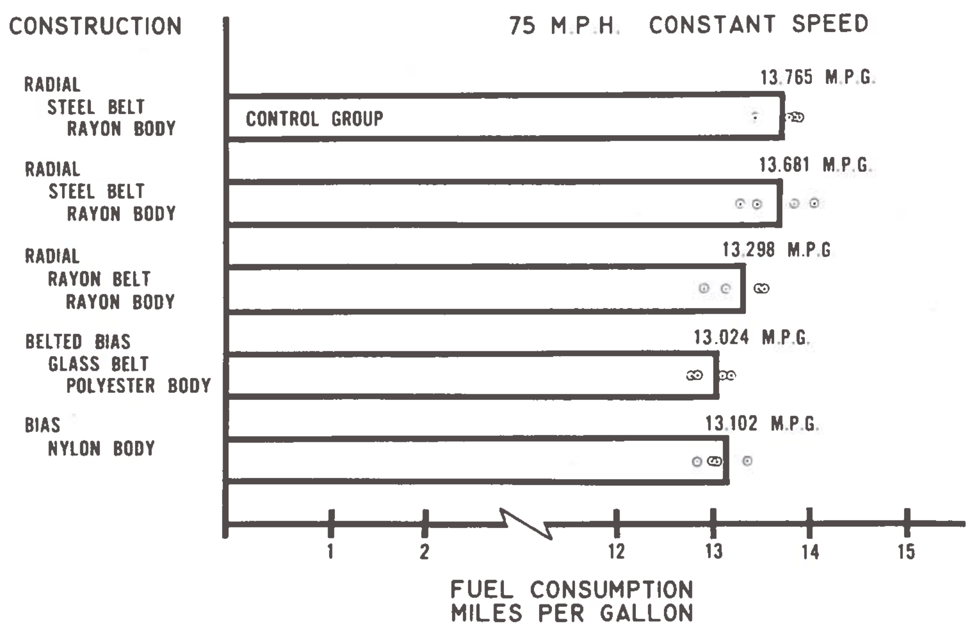


Figure 6-5. Effect of Tire Construction on Fuel Consumption - 75 mph Constant Speed (Ref. 6-2)

improvement over the rayon-belted radials. The numerical results varied with the vehicle speed, but this relative ranking was unchanged for all speeds tested. At the three speeds tested (35, 50, and 75 mph), the increases in fuel economy of the steel-belted radials versus the bias-ply tire were 6.4%, 7.0%, and 4.4%, respectively.

6.1.4 Summary

The data presented herein offer quantitative evidence of the increased fuel economy attainable by the use of radial tires. These data are for a specific set of conditions of tire size and type, vehicle, and speed. As described earlier, however, the decreased rolling resistance of radial tires is an intrinsic property, so that their use on any passenger car is clearly beneficial to fuel economy. It is difficult to estimate an overall improvement for their general use in various driving cycles, but the effects of decreased rolling resistance are significant at all speeds and especially at the low to moderate speeds characteristic of much urban and rush-hour freeway driving. The effects of inertia forces (uneven driving habits) are significant, as well as other parameters such as inflation pressure, road surface, etc. Road surfaces are fairly well standardized in most driving patterns, however, and abnormally low inflation pressures (detrimental to rolling resistance) are readily apparent to every driver and easily corrected. There is thus good reason to expect an overall fuel economy increase across the nation of some 2% to 5% if the use of radial tires became almost universal. The deterrent to their use at present is price; there is a very substantial increase over that for the other tires. Current price quotations from two large tire retailers for the tire types and sizes used in the tests are as follows (all prices are per tire plus tax):

a. Radial, steel-belted rayon body, $60 to $70 each
b. Belted bias, polyglass belt, polyester body, $27 to $37 each
c. Bias nylon ply body, $17 to $27 each

While this price differential represents an obstacle to the selection of radials, their longer useful lifetime alone (~twice the mileage of conventional tires) can compensate for their additional cost. Thus, any savings in fuel cost due to improved fuel economy in general represents an additional benefit.

6.2 TRANSMISSION/OVERDRIVE/REAR AXLE RATIO MODIFICATIONS

6.2.1 Introduction

In the early 1950s, many American automobiles were factory equipped with an overdrive. Benefits, such as better fuel economy, longer engine life, and extended clutch life, resulted to a certain extent, depending primarily on the driving habits of the particular car owner and on the type of driving duty of the automobile. Because of small market demand, the Big-Three auto makers discontinued production of the overdrive in the early 1960's, and American Motors followed suit in the late 1960's.

The function of the overdrive was to decrease the speed-ratio between the engine output shaft and the car driving wheels, in a manner similar to an additional higher gear shift in the transmission box or a lower gear ratio in the rear axle differential. For a given car speed, the engine ran slower, the engine friction and pumping losses were reduced, and the fuel economy was improved. Recent emphasis on fuel economy has brought a renewed interest in overdrive and in modification of the transmission or differential gear ratio.

6.2.2 Background

The brake specific fuel consumption (BSFC) of an internal combustion engine, as a function of engine operating parameters (speed and torque), is usually presented in the form of an engine performance map. Figure 6-6 (Ref. 6-3) shows a performance map of a typical U.S. passenger-car engine as installed in the automobile. Also shown is the power requirement of the automobile at level-road operation as the function of piston speed, which is directly proportional to engine rpm and to the car speed. As indicated in the figure, the lowest brake specific fuel consumption occurs at the combination of moderate piston speed of 1000 ft/min corresponding to an engine speed of

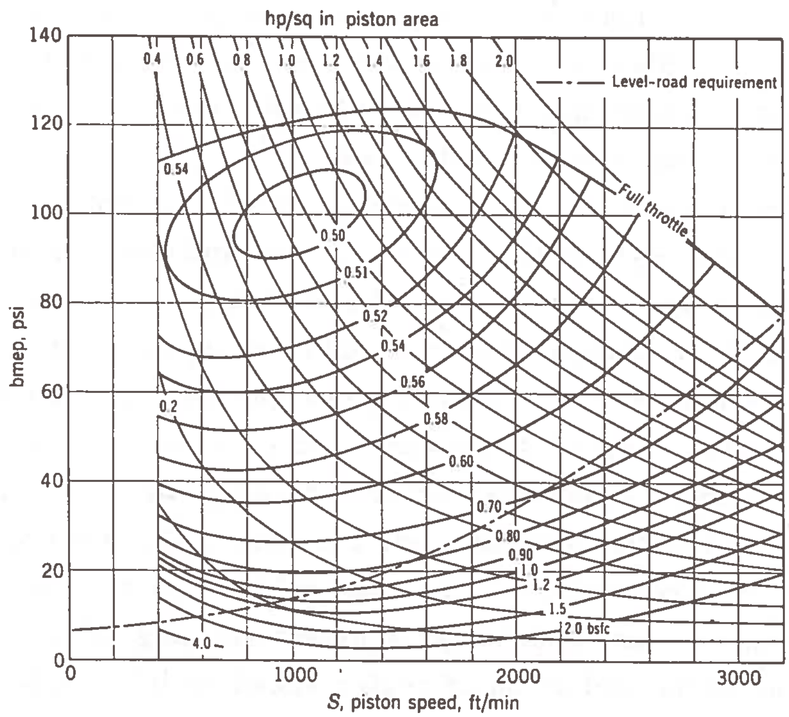


Figure 6-6. Performance Map of a Typical U.S. Passenger-Car Engine as Installed (Ref. 6-3)

about 1800 rpm, and of high brake mean effective pressure (BMEP) in the engine cylinder corresponding to high torque output.

When the gear ratio between the engine output shaft and the driving wheels is changed, then, at constant car speed, the operating condition of the engine will change along a constant specific power curve, as shown in the figure by the constant hp/in.^{2} lines. Any reduction of engine speed from road-load condition will result in the reduction of brake specific fuel consumption. This is shown in Figure 6-7 which is a crossplot of several points from Figure 6-6. For example, for 30% reduction of engine speed from road-load conditions, generally about 20% reduction of brake specific fuel consumption or 20% fuel economy improvement will result.

The above statement, strictly speaking, applies to cars with manual transmissions (Ref. 6-4). Automatic transmissions with torque convertor have an efficiency which is less than 100% and is, furthermore, considerably reduced if the torque convertor operates at a low speed ratio. As indicated in Figure 6-8 (Ref. 6-5), the high torque required for driving the car wheels produces a reduced speed ratio and efficiency of the torque convertor. At steady-speed horizontal highway driving, the power requirement of the automobile is relatively small and, therefore, the incurred losses in the torque convertor are tolerable. In stop-and-go city driving, however, the torque convertor power losses may substantially negate the fuel economy improvement, due to the reduction of engine speed from a road-load condition.

The results of the road test of an automobile equipped with an overdrive are shown in Figure 6-9 (Ref. 6-6). The fuel economy (mpg) is plotted as the function of car steady speed on a level road. From 20% to 28% fuel economy gains due to overdrive operation were recorded.

The reduction of engine speed at road-load conditions (e.g. by means of an overdrive unit) may have a significant effect on exhaust emissions. While the concentration of some pollutants (e.g., NO_x) may increase due to higher BMEP at reduced engine speed, the emission on a specific mass basis may be reduced. One specific example is shown in Figure 6-10 (Ref. 6-7). The relative specific mass emission (gr/hp-hr)

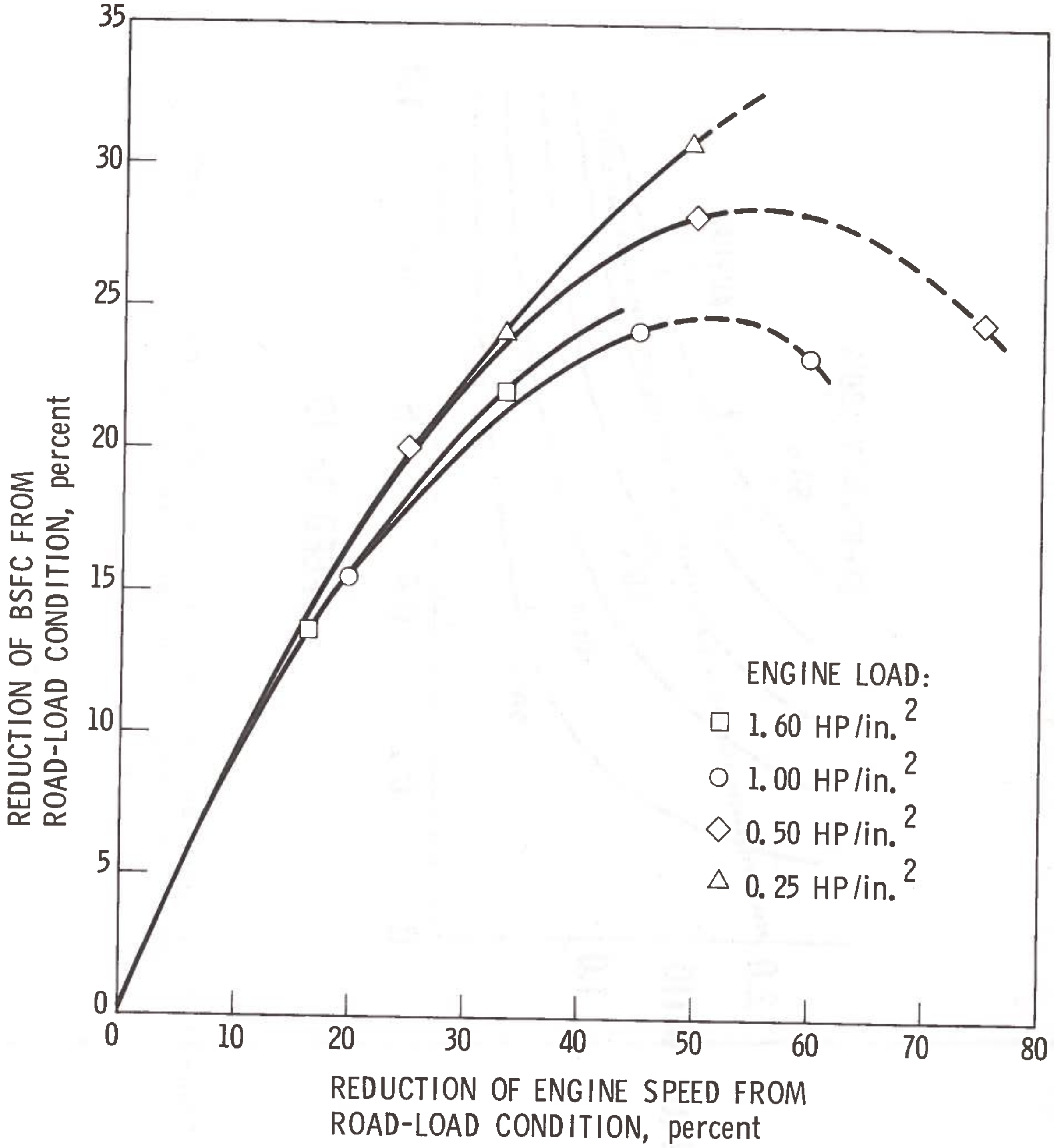


Figure 6-7. Effect of the Reduction of Engine Speed from Road-Load Condition on the Brake Specific Fuel Consumption

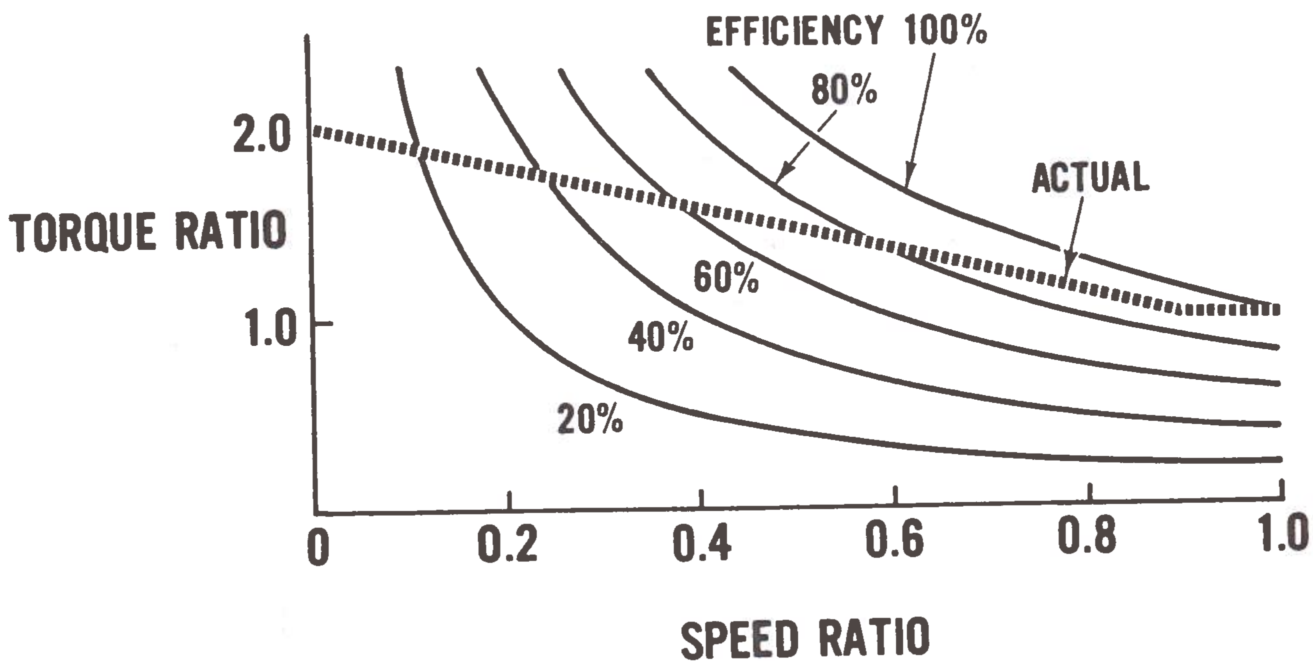


Figure 6-8. Torque Convertor Efficiency as a Function of Transmission Speed Ratio and Torque Ratio (Ref. 6-5)

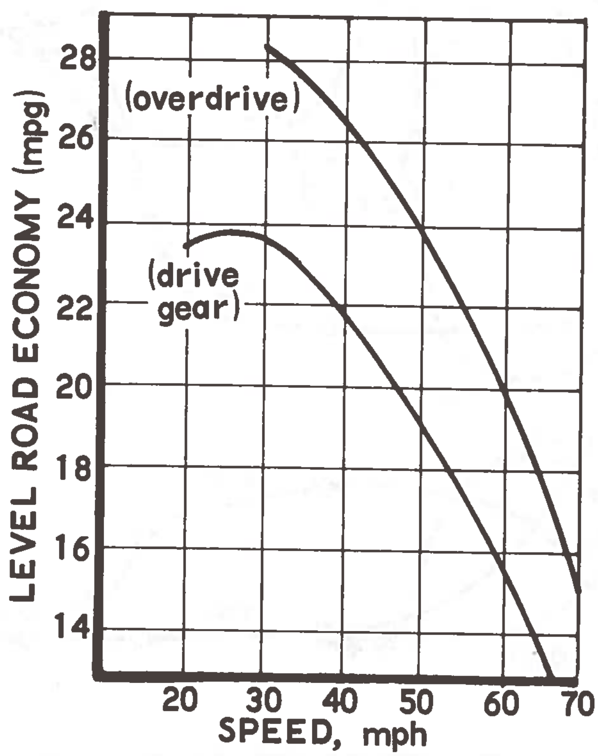


Figure 6-9. Effect of 30% Overdrive on Fuel Economy of a Passenger Car (Ref. 6-6)

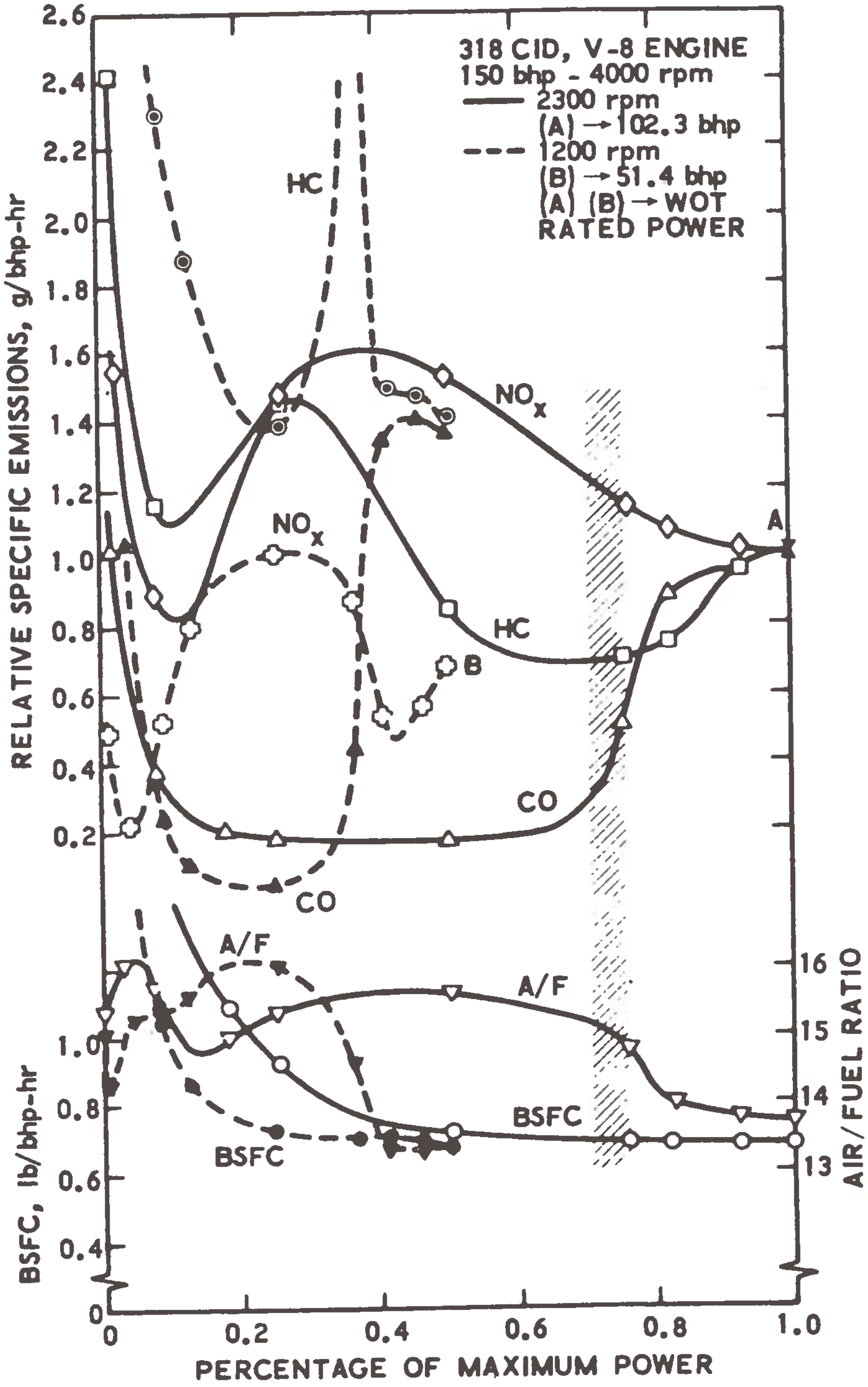


Figure 6-10. Relative Specific Mass Emissions of a Heavy-Duty Spark Ignition Engine (Ref. 6-7)

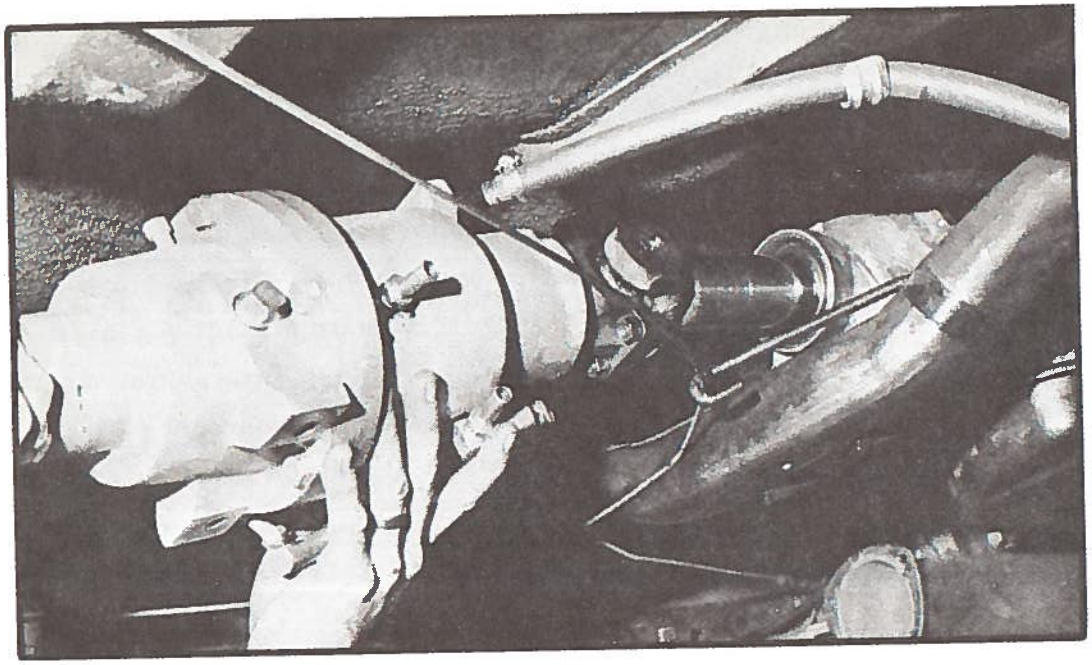
of exhaust NO_x, HC, and CO is plotted as a function of percent maximum power of a 318 CID, V-8 engine. In the case of NO_x, specific mass emissions were substantially reduced (up to 50% of maximum power) by operating at 1200 rpm instead of 2300 rpm. The HC and CO emissions do not exhibit the same trend and are higher than the 2300 rpm values at various power settings. Many factors, including specific engine type, carburetor calibration, EGR flow rates, and driving patterns, are important variables in determining the true impact of reduced rpm on exhaust emissions. In the absence of additional statistical data, no conclusive assessment of the quantitative effect of reduced engine rpm at road load conditions can be made at this time.

6.2.3 Physical Systems

6.2.3.1 Hone Overdrive

The retrofit overdrive unit produced by the Hone Manufacturing Company (Santa Fe Springs, California) is shown in Figure 6-11. This unit is applicable to all light-duty vehicles and consists of a planetary, fully synchromesh gear system which permits engagement and disengagement of the gears under normal operational conditions. When engaged by a separate stick shift, the Hone overdrive reduces the engine-to-drive-wheel speed ratio by 30%. The company does not advertise specifically how much fuel economy improvement the unit will provide; however, it claims that the unit will pay for itself in fuel savings in about two years of average use of the automobile. The retail price is $385, and installation cost is estimated from $100 to $150. When installed on vehicles of a gross weight exceeding 7,500 lb, the overdrive unit may have a tendency to overheat. For such cases, the Hone Company markets a heavy-duty retrofit cooling system, priced at $96.

For Willys Jeeps and International Harvester Scouts, the retrofit overdrive units are listed in the J. C. Whitney parts catalog at $200. The company producing these units is reportedly out of business.



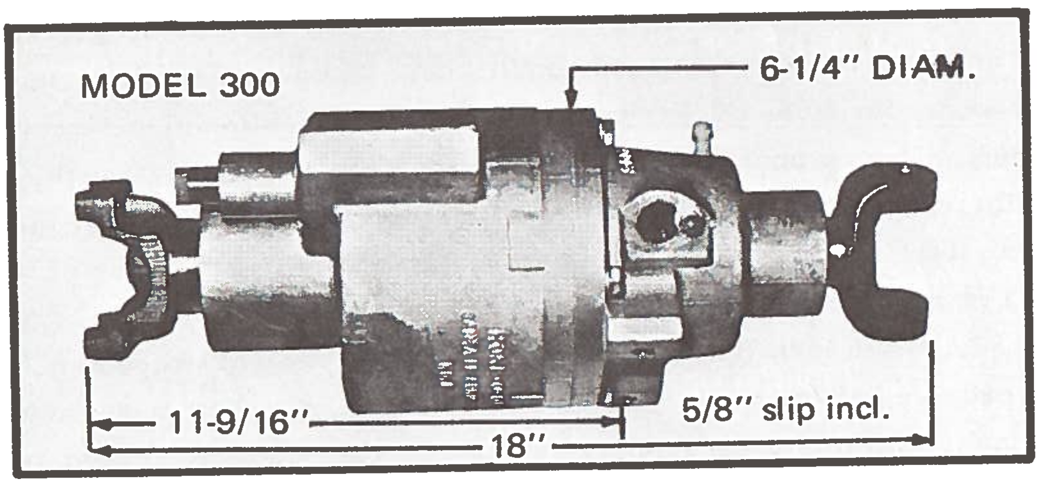


Figure 6-11. Hone Overdrive Assembly for Passenger Cars (Company Advertisement)

6.2.3.2 Ring and Pinion Sets

In several automotive parts catalogs, retrofit ring-and-pinion gear sets for cars and trucks are listed. These sets fit most of the standard rear axle differential housings and are available in various gear ratios from 3.89 to 6.14. The prices range from $45 to $80. Installation cost is approximately $60. Although the sets with listed gear ratios are intended for high-speed or drag racing, special gear ratios are also available upon request.

The installation of a lower gear ratio would improve the fuel economy in the same way as the use of an overdrive, but without the benefit of the ability to downshift for better driving performance in the city traffic.

6.2.3.3 Special Automatic Transmissions

For heavy trucks and vans, the Detroit Diesel Allison Division of General Motors Corporation is marketing "pre-programmed" four- and five-range automatic transmissions.

The proper operating gear range for the type of road, load, and speed conditions is selected automatically, and the shift to higher gear range for better fuel economy is performed quickly and automatically. The effect of this transmission on the fuel economy of large trucks was evaluated by the United States Auto Club in tests conducted at the GM Proving Grounds. In simulated city and rural delivery operation, about 11% fuel economy improvement on large van-type trucks equipped with the Allison automatic transmission, as compared to the same vehicles equipped with a manual transmission, was recorded. The company, however, does not plan mass production of this type of automatic transmission for use in passenger cars.

6.2.4 Summary

The reduction of engine speed by means of an overdrive, lower gear ratio in the differential, or by a multi-range transmission offers the potential for improvement of the automotive fuel economy. Generally, the improvement is most pronounced at steady cruising speeds and diminishes in stop-and-go operation, particularly when the aforementioned devices are used in combination with a torque convertor. In Table 6-1, three approaches to

TABLE 6-1. SUMMARY OF DRIVE TRAINS

Device	Hone Overdrive	Ring & Pinion Gear Sets	Allison Multi-range Automatic transmission
Degree of Fuel Economy (Miles Per Gallon) Improvement	N. I. *	N. I.	11% - 14% *
Retrofit Device or "Kit" Content and Physical Characteristics	See Figure 6-11	one replacement ring and pinion set	automatic transmission with torque convertor, 4 or 5 speed ranges, programmed shift
Compatibility with Mass Production	yes	yes	yes
Potential Availability in Quantity in Near Future	N. I.	N. I.	N. I.
Applicable Vehicle or Engine Models (Gasoline and Diesel)	gasoline and diesel l. d. vehicles	gasoline and diesel vehicles	gasoline and diesel heavy duty vehicles
Attendant Installation Requirements (including Necessary Facilities)	service garage equipment	service garage equipment	service garage equipment
Installation Time Requirement	8 hr.	4 hr.	N. I.
Cost to Consumer for Device for Installation	$395 $120	$45 - $80 $60	$1037 - $4626 N. I.
Special Maintenance Requirements	none	none	N. I.
Effect on HC, CO, and NO_x Emissions (if any)	N. I.	N. I.	N. I.
Effect on Vehicle Power and Acceleration Performance (if any)	negative	negative	N. I.
Type of Data Available	N. I.	N. I.	road tests
Source and Reliability of the Data Base	N. I.	N. I.	evaluation by U.S. Auto Club
Theoretical Background	see under 6.2.2	see under 6.2.2	see under 6.2.2
Remarks	* estimated improvement capability 5% - 15%		* as compared to same vehicles with a manual transmission

N. I. = no information

modification of the drive train are listed. The least expensive is the one which involves only a change of ring-and-pinion gear set in the rear-axle differential. In principle, the same effect on fuel economy as with the installation of an overdrive could be realized. However, because of the adverse effects on vehicle driveability in city traffic, this approach would be limited to a relatively moderate change of the rear-axle gear ratio and therefore result in a relatively modest improvement in the fuel economy. An assessment of the cost/benefit ratio would be possible only on the basis of a statistical evaluation of various car makes, models, rear-axle gear ratios, and driving patterns.

A more expensive approach is to retrofit an automobile with an overdrive. Since the overdrive can be downshifted for better vehicle driveability in city traffic, it offers a more advantageous compromise between fuel economy and vehicle driveability. It is, however, substantially more costly than the retrofit ring-and-pinion set, and, as in the former case, statistical test data for assessment of the cost/benefit ratio are completely lacking.

A promising system appears to be the multi-range automatic transmission with torque convertor lockup. The road tests of heavy trucks equipped with this automatic transmission indicate well over 10% fuel economy gains, as well as better driveability, in comparison to the same vehicles equipped with a manual transmission. However, at present, such special automatic transmissions are not available for light-duty vehicles, and their merits in application to passenger cars cannot be assessed at this time.

On the basis of the presently quoted retail prices, the costs of retrofitting passenger cars with an overdrive or with a special automatic transmission appear relatively high for the fuel economy gains.

6.3 REFERENCES FOR SECTION 6

6-1. J. D. Walter, Energy Losses in Tires, Firestone Tire & Rubber Company, California Institute of Technology Seminar Series on Energy Consumption in Private Transportation, December 4, 1973.

6-2. W. Bezbatchenko, "The Effect of Tire Construction on Fuel Economy," The General Tire and Rubber Company, SAE Paper 740067.

6-3. C. F. Taylor, The Internal Combustion Engine in Theory and Practice, Vols. I and II, The MIT Press, Cambridge, Massachusetts (1968).

6-4. "Automobile Fuel Economy," Motor Vehicle Manufacturers Association of the United States, Inc. (21 September 1973).

6-5. C. Marks, General Motors Corporation, "Which Way to Achieve Better Fuel Economy?" Paper presented at the Seminar on "Energy Consumption of Private Vehicles, Present and Possible," the California Institute of Technology, December 1973.

6-6. E. F. Obert, Internal Combustion Engines, 3rd ed., International Textbook Company, Scranton, Pennsylvania (1968).

6-7. Characterization and Control of Emissions from Heavy Duty Diesel and Gasoline Fueled Engines, Final Report, EPA-LAG-0129 (D), Fuels Combustion Research Group, Bureau of Mines, Washington, D. C. (December 1972).

SECTION 7

VEHICLE DRAG

7.1 INTRODUCTION

This section examines the possibility of achieving a significant overall reduction in fuel consumption by means of applying retrofit aerodynamic aids to passenger cars to reduce air drag. Traditionally, aerodynamic design factors for passenger cars have usually yielded to styling considerations, so that there may be worthwhile room for aerodynamic improvement for many present day cars. The theoretical basis for the importance of air resistance to automotive performance and fuel economy is considered first, and test data are then presented which demonstrate improved aerodynamic effectiveness of some retrofit aids.

7.2 THEORETICAL BACKGROUND

The brake horsepower developed by a vehicle engine is used to overcome five types of motion-resisting forces or losses: rolling resistance, air resistance, vehicle inertia forces (both translatory and rotational), grade resistance, and power-train losses. In typical non-steady-state city driving, the relative magnitudes of these forces are continually varying with changes in vehicle speed and terrain. For the purpose of this discussion, it is not necessary to include grade resistance at this time; that is, a level surface is assumed. Since the intent is to focus upon the effect of drag in the aerodynamic resistance, to do this properly, one must concurrently treat the other two motion-resisting forces of rolling resistance and vehicle inertia.

From basic theory of fluid mechanics, the aerodynamic force which resists vehicle motion is expressed in the form

$$F_A = \frac{C_d A_f \rho v^2}{2g_c}$$

where

F_A = aerodynamic force, lb_f

C_d = overall drag coefficient, dimensionless

A_f = projected frontal area of vehicle, ft^2

ρ = air density, lb_m/ft^3

v = component of relative air velocity parallel to longitudinal axis of vehicle, ft/sec. For the usual performance analysis case of zero wind, this becomes equivalent to vehicle road speed.

g_c = gravitational conversion constant, 32.2 lb_m ft/sec^2 lb_f

The drag coefficient C_d, as used for automotive applications, is something of a catchall term in that the total aerodynamic resistance comprises three sources. First is the form drag resistance which is a function of the aerodynamic shape of the total exterior surface of the vehicle. Of particular importance is the shape of the rear of the body, as this determines the extent of turbulence in the wake. The second contribution is skin friction or the air friction on the outside surface of the body. The third factor is air flow through the vehicle for purposes of cooling or ventilating. This factor can be either resistance-increasing or resistance-decreasing, depending on the function, location, and aerodynamic nature of the flow paths. It is thus seen that the exact value of drag coefficient is specific for each vehicle; a typical range for passenger cars is 0.4 to 0.55 (Ref. 7-2). Typical frontal areas on present-day passenger cars are 18-25 ft^2.

Rolling resistance F_R is expressed in the form

$$F_R = fW$$

where f is the coefficient of rolling resistance, and W is vehicle weight. The coefficient f is a very complex function of tire material, construction, inflation pressure, size, road surface, vehicle speed, and other variables.

Inertia resistance F_I is the force required to accelerate the vehicle mass, including the rotational acceleration of the wheels, power train, and rotating engine components. The contribution of the rotational inertia of these components is accounted for by means of a mass factor, as indicated below

$$F_I = \frac{\gamma ma}{g_c}$$

where

γ = mass factor, dimensionless

m = vehicle mass, lb_m

a = vehicle acceleration, ft/sec^2

The mass factor is commonly expressed in terms of the total crankshaft-to-drivewheel gear reduction ratio. For automatic transmissions in "drive" at normal speeds, or manual transmissions in direct drive, γ is equal to approximately 1.07 for many passenger cars.

Figure 7-1 presents the relative effect of aerodynamic drag (compared to the total of aerodynamic plus rolling resistance) for two classes of vehicles. The first, denoted Class A, is a 3000-lb car with radial tires. The second, denoted Class B, is a 4500-lb car with belted-bias tires, representative of a large portion of the standard size cars presently on the road. The numerical results are of necessity approximate, but serve to illustrate the key features underlying this discussion. The first important result concerns the relative magnitude of the rolling versus air resistance forces (neglecting inertia forces temporarily). It is seen that, at low speeds, the rolling resistance is the more important. At a speed of about 38 mph for Class A and about 46 mph for Class B, the two forces become equivalent. At a vehicle speed of 70 mph, the air resistance force becomes approximately three times the rolling resistance for Class A vehicles and approximately twice the rolling resistance for Class B vehicles. The difference between the two classes shown

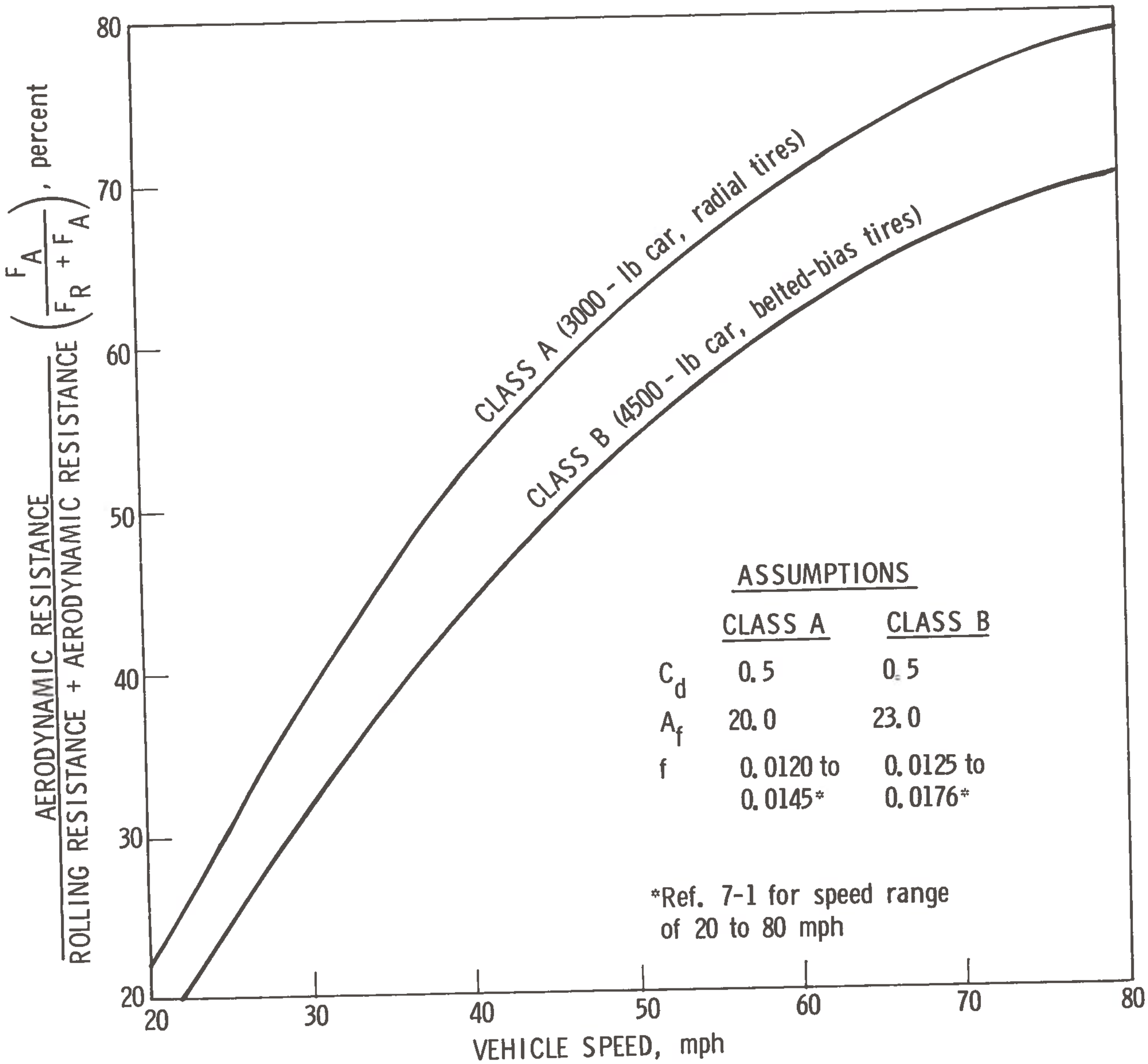


Figure 7-1. Relative Effect of Aerodynamic Resistance (Ref. 7-1)

in Figure 7-1 is attributable partly to the higher rolling resistance of belted-bias versus radial tires, but is mostly due to the greater weight of the Class B vehicle, since rolling resistance is proportional to vehicle weight, while air resistance is not. There is an effect on air resistance of weight, due to the greater frontal area which normally accompanies a significant weight increase, but this frontal area increase is nearly always much less than proportional to the weight increase. The drag coefficient may increase, decrease, or remain essentially unchanged as a result of the larger vehicle size. These data emphasize the importance of aerodynamic design to a passenger car. Clearly, any reduction in drag coefficient will have a nearly comparable improvement in the high-speed, steady-state horsepower (and hence, fuel) requirement and an appreciable effect at intermediate speeds (30-60 mph). There is one factor which significantly curtails, but does not eliminate, the seemingly easy gains in fuel economy, due to drag reduction, which one might infer from the above discussion.

This is the statutory 55-mph speed limit. Inspection of Figure 7-1 shows that the most significant percentage reduction in tractive force requirement (and consequently in engine horsepower and, hence, fuel consumption) due to a decrease in air resistance occurs at high speeds, such as 70 mph. This regime of maximum improvement is thereby ruled out. It would be self-defeating to advocate higher speed limits to accommodate this feature, unless the net gain would outweigh the inherent decrease in fuel consumption due to the 55-mph speed limit. This, in all probability, will not be the case. That is, a car with any proposed retrofit drag reduction device will probably still have a somewhat poorer fuel economy at 70 mph than that same vehicle will have at 55 mph without the device and will, of course, have a poorer fuel economy at 70 mph than that same car at 55 mph, with the drag reduction device.

7.3 EXPERIMENTAL RESULTS

Herein are briefly described some published results which offer quantitative indication that significant drag reductions may in fact be achieved on a retrofit basis. These results are reported in the popular automotive press, Ref. 7-3 and 7-4. These articles describe simple aerodynamic modifications made to two different small passenger cars (1974 Pinto Runabout and 1973 Datsun 240Z). The effects of these changes were observed by means of fuel consumption tests performed at a constant indicated speed of 70 mph on an oval driving track. Distance measurements were supplied by a fifth wheel, and fuel flow was measured by an onboard flow meter. The aerodynamic aids investigated covered four potential improvement areas:

a. Air flow deflector surface located at the extreme aft end of the body on the upper trunk deck

b. Front deflector plate to divert undercar air flow

c. Blocking off grill air bypass and part of cooling air

d. Streamlined fairing over headlamp sockets

Figure 7-2 illustrates such aerodynamic aids as mounted on the Datsun 240Z.

The article of Ref. 7-3 describes the tests on the Pinto. This car had the base 2-liter engine and automatic transmission. The rear flow deflector surface was a 6-in. wide aluminum sheet bolted to the trailing edge of the deck lid and extending the width of the vehicle. It was tested both in the horizontal position and inclined up from the deck at an angle of 30 degrees from the horizontal. The front deflector, also of aluminum sheet stock, extended vertically down from the bumper to 2 in. above the ground and covered the width of the vehicle to the outside of the front tires. The front grill air inlet was blocked off to match radiator width. Streamline aids consisted of a convex cover mounted over the headlamps. All these aids were made for the occasion and do not represent commercially available after-market parts.

The reported fuel economy at 70 mph with all the above aids was 17.7 mpg versus 15.4 for the unmodified car, for an improvement of

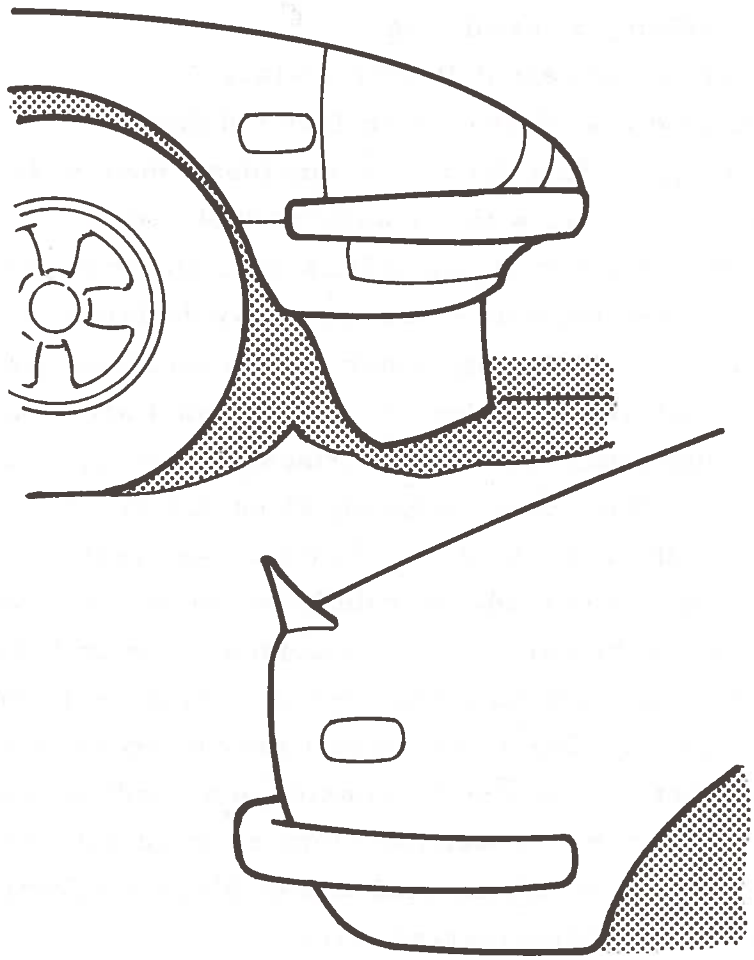


Figure 7-2. Illustration of Aerodynamic Aids on the Datsun 240Z

15%. As indicated in the bar chart of Figure 7-3, the fuel economy gains in mpg for the aerodynamic aids tested individually were reported to be:

Front (under car) deflector	0.9
Front deflector plus grill air inlet reduction	1.4
Headlamp streamlining	0.1
Horizontal rear deflector surface	0.2
Angled rear deflector surface (30 deg)	1.1

The procedure for the Datsun (described in the article of Ref. 7-4) was very similar, with the addition that commercially available after-market parts were tested, as well as specially made deflectors. However, the after-market deflectors were probably designed primarily to increase the dynamic tire loading rather than to decrease overall drag resistance. They offered much less air flow contact area than did the specially made aluminum sheet metal surfaces. The specially made deflector for the front end was 8 in. deep, allowing about 3.5 in. of ground clearance, and extended the width of the vehicle. Two after-market front deflectors were also tested. The specially made rear deflector plate was about 7 in. high, extending the width of the car, and was mounted at the trailing edge of the trunk deck. Three different mounting angles from the horizontal were tested; 25, 30, and 50 degrees. One after-market rear deflector surface was evaluated. The front grill blockoff consisted of a cardboard panel which covered all the grill opening above the bumper, about half the total air inlet area. Streamline aids again consisted of plexiglass headlamp covers, but these were commercial after-market parts.

The testing of Ref. 7-4 was concerned with dynamic tire loading effects in addition to air drag reduction. The former is a very important consideration which must always be taken into account whenever retrofit aerodynamic aids are evaluated. It was of particular interest in this case, since the stock Datsun 240Z has a somewhat high front-end lift at high speeds. The reported test results are summarized in Table 7-1 and in the graphs of Figure 7-4.

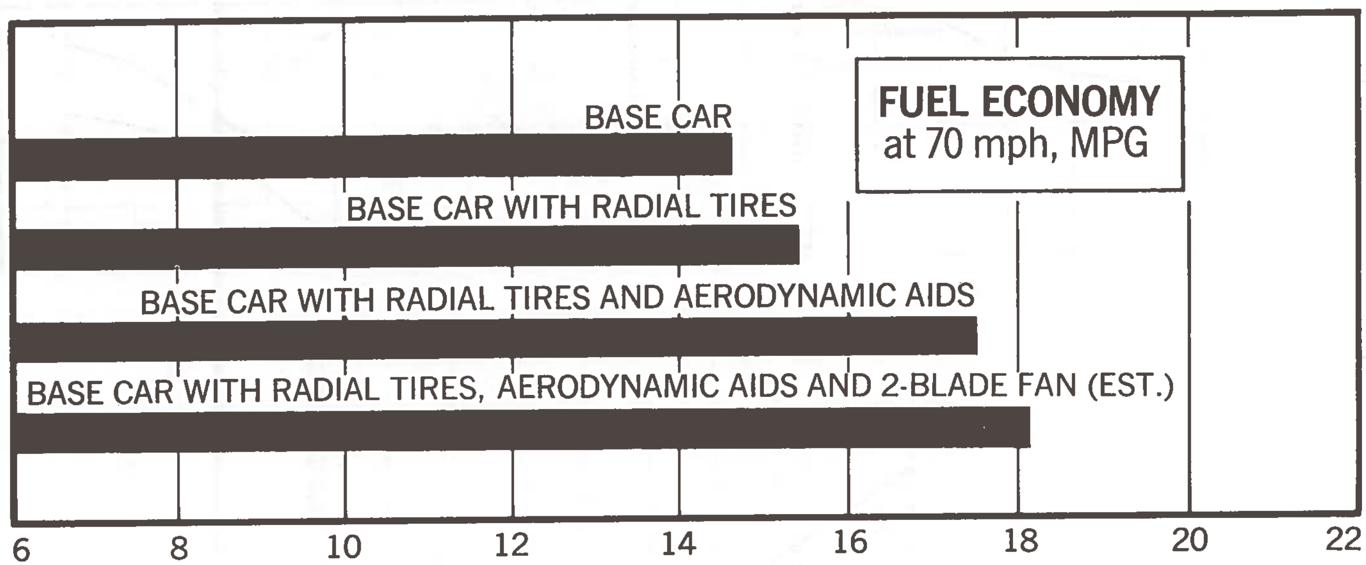


Figure 7-3. Results of Pinto Fuel Economy Tests (Ref. 7-3)

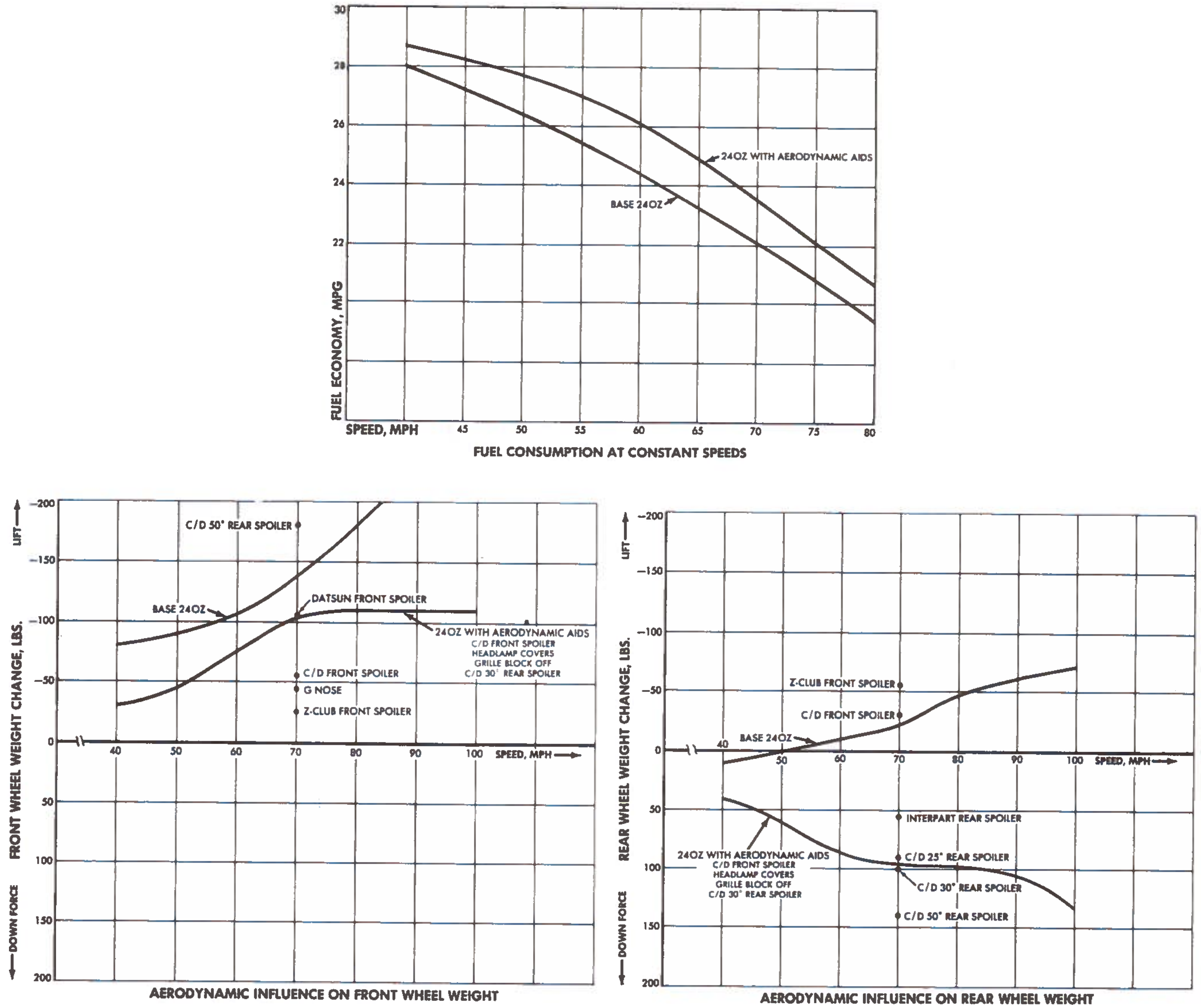


Figure 7-4. Test Results for Datsun 240Z (Ref. 7-4)

TABLE 7-1. SUMMARY OF DATSUN DEVICES AND TEST RESULTS

Device	Increase in Fuel Economy at 70 mph, mpg (≈ 22 mpg for Unmodified Car)	Decrease in Dynamic Lifting Force from Stock Car, lb
Front Deflectors		
Datsun after-market part	0	35 (Front end)
Z Club after-market part	0.4	105 (Front end)
Specially made	0.8	85 (Front end)
Rear Deflectors		
Interpart after-market part	0.2	75 (Rear end)
Specially made, 50 deg	-0.6	160 (Rear end, but -40 front end)
30 deg	0.2	120 (Rear end)
25 deg	0.2	110 (Rear end)
Streamlined headlamp covers (Interpart after-market part)	0.2	0
Grill blockoff plus Z Club front deflector	0.8	Not given
Grill blockoff plus specially made front deflector	0	Not given
Composite: specially made front and rear (30 deg) deflectors, grill blockoff, headlamp covers	1.2 (≈ 5%)	≈ 35 (Front end) ≈ 115 (Rear end)

The fuel consumption curves of Figure 7-4 indicate an increase in fuel economy at 40 mph of approximately 0.8 mpg. This represents about a 3% increase over the indicated 28 mpg fuel economy for the unmodified car at 40 mph.

In addition, Datsun offers a retrofit nose configuration that provides a more streamlined contour, sealed headlamp openings, and reduced air inlet area. This device, tested by itself at 70 mph, showed a reported gain in fuel economy of 1.2 mpg and a 95-lb decrease in front-end lift. The retrofit package costs $625 in this country.

An apparent anomaly exists in the above data in that the Z Club front deflector was more efficient in drag reduction when combined with the partially blocked grill than was the specially made deflector plate, while the latter had the lower drag when tested individually. A possible explanation is that the Z Club device is canted forward about 45 degrees (like a locomotive cow catcher), while the specially made deflector was nearly vertical with a slight wedge shape in the overhead view. The Z Club deflector thus tends to divert its air flow directly into the restricted air inlet, possibly providing an aerodynamically more efficient radiator inlet flow process.

The overall fuel economy gains reported for the Datsun are lower than those for the Pinto, in accordance with the more streamlined basic contour (both fore and aft) of the former which leaves less room for improvement.

To summarize this discussion of experimental results, direct comparative figures are given concerning the effects on high speed fuel economy of relatively simple aerodynamic aids to two vehicles typical of a large number of present-day small passenger cars. The results indicate that significant gains in high speed fuel economy can be attained by this approach for many of these cars. Most of the aerodynamic aids tested were specially fabricated for the tests, but all could be made without difficulty as standardized after-market parts.

7.4 SUMMARY

This section has demonstrated the importance of air drag to passenger car performance and has shown the possibility of significant gains in high speed fuel economy due to drag reduction on a retrofit basis for many passenger cars. These gains will be reduced in magnitude by factors relating to the impact of urban driving patterns, but there should still be a worthwhile increase in overall fuel economy achievable by this general approach to air drag reduction.

7.4 REFERENCES FOR SECTION 7

7-1. J. D. Walter, Energy Losses in Tires, Firestone Tire & Rubber Company, California Institute of Technology Seminar Series on Energy Consumption in Private Transportation (December 4, 1973).

7-2. R. G. S. White, "A Method of Estimating Automotive Drag Coefficients," SAE Paper 690189. International Automotive Engineering Congress, Detroit, Michigan, January 1969.

7-3. D. Sherman, Car and Driver Magazine, p. 44 (March 1974).

7-4. D. Sherman, Car and Driver Magazine, p. 39 (May 1974).

SECTION 8

AUXILIARIES AND ACCESSORIES

Two significant classes of auxiliary and/or accessory equipment have been postulated to improve fuel economy: driver aids and cooling system improvements, particularly flexible cooling fans.

8.1 DRIVER AIDS

As discussed in Sections 3 and 6.2, a number of inherent fuel consumption characteristics of the vehicle/engine system principally determine vehicle fuel economy values (for a given engine/vehicle combination) and constrain the ability to improve fuel economy. Some of these include:

a. High speed driving. Constant speed fuel economy decreases steadily and significantly as vehicle speed increases (see Figure 6-9).

b. Carburetor enrichment at full load. High speed operation or rapid accelerations requiring high engine power result in an enriched air-fuel ratio and decreased fuel economy (see Figure 3-3).

c. Cold engine operation. Choking during cold engine operation results in a rich mixture and decreased fuel economy (see Figure 3-3 and Section 3.1.1.2.4).

d. Carburetor enrichment during acceleration. An accelerator pump provides additional fuel during acceleration (see Section 3.1.1.2.4).

e. Increased engine efficiency at high loads. Operating at higher BMEP and reduced RPM for a given vehicle speed increases engine efficiency and improves fuel economy (see Figures 6-7 and 6-9).

Of these, the driver of the vehicle has some measure of control over items 1, 2, and 4, which encompass control of vehicle speed and acceleration rate.

One method of improving fuel economy in any automobile is to develop conservative driving habits; i.e., avoiding jackrabbit starts or anything else that requires rapid accelerations or decelerations. No doubt most drivers have some tendency to use excessive acceleration to a greater or lesser degree, and it is understandable considering the power available in modern American automobiles.

There are now a number of devices on the market which, if used diligently, could aid most drivers in improving their fuel economy habits. These devices include manifold vacuum gauges, accelerometers, miles-per-gallon meters, and cruise control devices.

Engine manifold vacuum gauges provide a direct indicator of engine throttle setting and, in turn, the torque output of the engine. According to Ref. 8-1, there are at least 11 of these devices on the market. They are dial gauges calibrated in inches of mercury and mount on the auto dashboard. Some of the gauges also have sectors of the face marked off into zones which are labeled according to the quality of fuel economy at those particular levels of vacuum. For example, these zones might be labeled "poor," "economy zone," "deceleration," and "idle." Those gauges which are both calibrated in inches of mercury and labeled qualitatively are probably the most help to the average motorist.

The Autotronic Controls Corporation of El Paso, Texas, is preparing to market a device called the "Electronic Fuel Pacer." When it comes on the market in 1975, it will sell for about $40. This device measures velocities and changes in velocity. Using analog circuitry, it computes accelerations and, forming the product of acceleration and velocity, it computes the horsepower-to-weight ratio of the automobile. This function is useful in indicating fuel economy, since it is sensitive to both acceleration and velocity. At low velocities, higher accelerations are in the acceptable range for fuel economy, whereas, at high velocities, only small accelerations are permissible. The instrument uses colored lights to indicate acceptable, marginal, and unacceptable zones for fuel economy. The corresponding colors are green, amber, and red, respectively. Uneconomical levels of deceleration are indicated by a red light also. For this instrument, the range of the green light includes hp/wt ratios from -0.007 to +0.003. The amber light ranges from +0.003 to +0.007. Above +0.007 and below -0.007, the red light comes on. The levels of "economical" accelerations are quite low and were set somewhat arbitrarily based on data from the Department of Transportation, according to Autotronic representatives. Since this instrument reads zero when acceleration is zero, it has no means of flagging uneconomical operation in steady-state conditions, such as high-speed cruising or hill climbing at wide-open throttle.

A miles-per-gallon meter is being manufactured by Space-Kom, Inc., of Goleta, California. It is marketed nationally through Sears and J. C. Whitney and sells for about $30 to $35. The miles-per-gallon meter measures fuel flow rate and divides by speed which yields miles per gallon. The virtue of this type of device is obvious; it reads out directly in terms of the function to be maximized. Some have questioned the accuracy of the flow meters used in these devices and their response time due to the fuel reservoir in the carburetor. However, a spokesman for Space-Kom maintains the accuracy of the device is within 3%-4% and the response is fast enough that the indicator needle must be damped to be readable.

There are at least two electronic cruise controls on the market; the Annunecionics Pacesetter retails at $99.95 and one is advertised in the J. C. Whitney catalog for $19.95. The reason for the great difference in price is not clear.

The Pacesetter consists of a throttle servo which mounts in the engine compartment on the air cleaner, a solid-state electronic controller which mounts under the dashboard, and the necessary mounting and linkage hardware. Once engaged, this device maintains the automobile at whatever speed is set into the controller via the dial speed control. Speed settings may be altered without disengaging the control. To disengage the control, a light tap on the brake is all that is necessary. Benefits in fuel economy accrue if the driver restricts his cruise speed to about 55 mph. The actual percentage savings available depends on the particular driving cycle and the amount of time spent in cruise operation.

No data have been found which indicate how effective any of the driver aids discussed above might be in improving fuel economy. It might be possible to establish some limits on the effectiveness of these devices using a computer simulation of the recently established Society of Automotive Engineers (SAE) urban, suburban, and interstate driving cycles which are to be used as standards in evaluating fuel economy. These cycles are described in Ref. 8-2. In each of these cycles, a route is divided into distance segments, and, for each of these segments, an initial speed, an acceleration, and a final speed are specified. A fuel economy comparison for a particular driver aid might be made by first simulating a particular automobile with specified fuel consumption and horsepower characteristics in the baseline cycle and recording the average fuel consumption. Next, the cycle would be altered such that accelerations are limited to those which have been assumed to be economical. For instance, those values described earlier for the Autotronic Fuel Pacer might be used. The distance segments should remain the same. With the accelerations thus limited, the time to reach the steady-state velocity in each segment would be longer. In some cases, velocity might not be reached; in this event, the initial velocity for the next segment would be altered to match the end conditions of the previous segment. The average fuel consumption for such a cycle would be computed and compared to that for the baseline cycle.

Table 8-1 summarizes evaluation factors considered for these devices. Installation and maintenance requirements are minimal. There

TABLE 8-1. EVALUATION SUMMARY FOR DRIVER AIDS

1. Degree of Fuel Economy	Undetermined
2. Kit Content	Dashboard-mounted instruments with necessary linkages to the engine compartment for control or sensing
3. Mass Producibility	No problems anticipated
4. Availability	All devices for sale nationally
5. Applicable Models	No known limitations
6. Installation Time and Cost	0.5-1 hr; \$8-\$15 (mechanic desirable)
7. Maintenance	Periodical check for sensible operation; if bad, send back to factory for adjustment
8. Effect on HC, CO, and NO_x	Second-order reductions due to efficient operation
9. Effect on Vehicle Power and Driveability	None
10. Types of Data Available	Manufacturer's brochures, magazine articles
11. Reliability of Data Base	Only advertising brochures are available

would be no effects on power and driveability, since these devices do not directly modify engine performance. For a fixed driving cycle, such as the 1972 FTP, there would be no effect on exhaust emissions. However, if a driving cycle were modified by these devices such that the total amount of fuel consumed were reduced, then total emissions would be affected.

It would appear that these devices have a potential for reducing fuel consumption and that the optimum driver aid might be a device combining cruise control with either a vacuum gauge or an accelerometer that indicates economical acceleration ranges. The Autotronic Electronic Fuel Pacer, a representative vacuum gauge, a miles-per-gallon meter, and an electronic cruise control could be evaluated in a road test program using the SAE standard driving cycles. From this testing, some idea of the potential for fuel economy could be gained, and the relative merits of the various driver aids could be evaluated. However, such a test program would have to be rather extensive in terms of numbers of vehicles and numbers of different drivers in order to establish reasonable confidence in fuel economy improvement levels.

8.2 IMPROVED COOLING SYSTEMS

8.2.1 Introduction

Approximately 25% to 30% of the total energy used by the automobile engine is lost as heat transferred to the metal cylinder block (Ref. 8-3). This heat must be removed from the engine to prevent damage from excessive temperature. This is accomplished through the use of a circulating water cooling system whereby water is pumped through a cooling jacket surrounding the cylinders and back through a radiator where the heat is transferred from the cooling water to the ambient air.

8.2.2 Water Pump

Centrifugal pumps are currently used in cooling systems because their flow rate is proportional to engine speed. The water pump is driven directly by a belt attached to the engine crankshaft pulley with the pump speed increasing in direct proportion to the engine speed. Since the thermal load on the cooling system also increases with engine speed, the demand and availability of the water circulating capacity of the water pump are in balance. The power required to drive the conventional centrifugal water pump is shown in Figure 8-1. Future automotive systems could reduce this power loss through the use of other techniques, including the use of passive cooling systems.

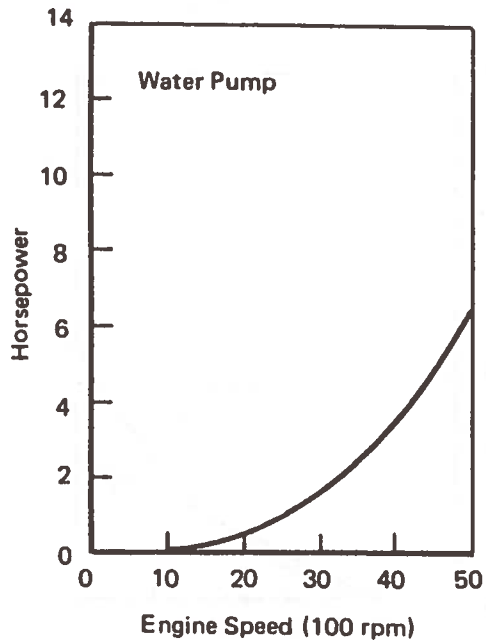


Figure 8-1. Water Pump Power Requirements (Ref. 8-3)

8.2.3 Cooling Fan

The primary function of the cooling fan is to draw cool air in through the radiator and blow it back over the engine during periods when there is insufficient ram air supplied by the forward motion of the vehicle. At low speeds, the fan is needed to provide adequate cooling. At speeds above approximately 50 mph, there is sufficient ram pressure to provide the necessary air coolant flow across the radiator, and the fan is actually not needed. Thus, the power used by the fan above approximately 2000 rpm represents excessive power consumption that provides a potential area for increased fuel economy.

One alternative retrofit scheme for reducing fan power at high engine speeds involves the use of four blades which have variable pitch control. These fan blades will decamber with increasing speed, thus requiring less power at high speeds. A comparison of the conventional and flex-fan power requirements is shown in Figure 8-2, where it will be noted that essentially no difference in power requirements occurs until the engine speed exceeds

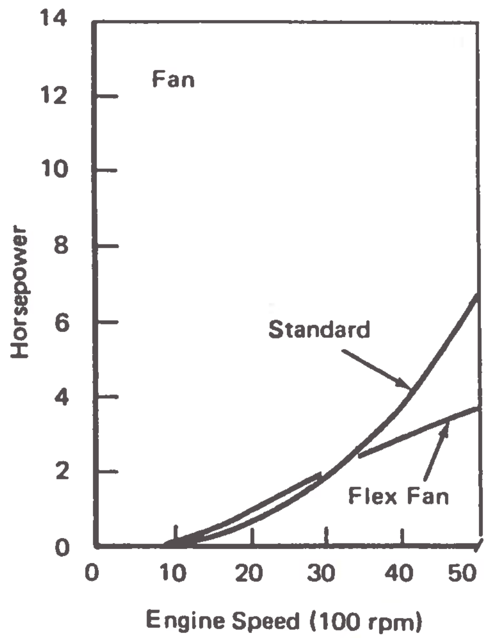


Figure 8-2. Fan Power Requirements (Ref. 8-3)

approximately 3000 rpm (84 mph). The maximum difference is seen to be about 3 hp at 5000 rpm. From this it is estimated that the use of a retrofit flex-fan would provide a maximum fuel savings of 3% only at engine speeds well above the normal driving range.

A more significant reduction in fan horsepower at high speeds is possible by the use of a viscous clutch fan drive. The viscous clutch provides maximum fan performance at low speeds and reduces noise and horsepower consumption at higher engine speeds by lowering the fan-to-engine speed ratio. The viscous clutch fan drive usually has a temperature sensitive control which senses the temperature of the cooling system and varies the fan-to-engine speed ratio according to actual cooling requirements. The range of operation of a typical temperature modulation viscous clutch and fan is shown in Figure 8-3. The upper limit on the temperature modulation range is the performance curve for a non-temperature modulated clutch (clutch locked out). The power savings of a viscous drive fan, extensively used on cars equipped with factory-installed air conditioning, are not large compared

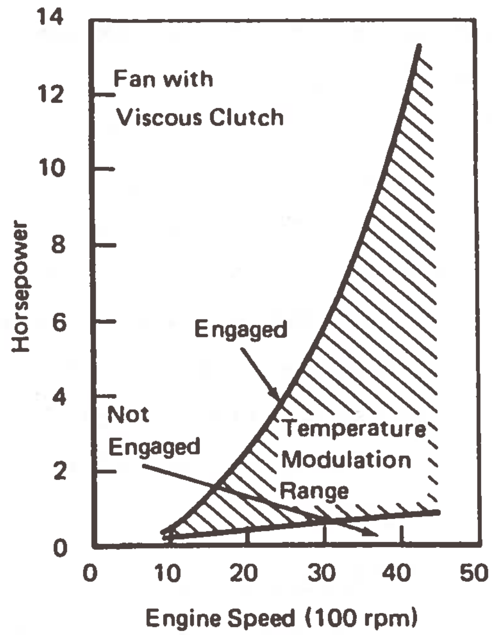


Figure 8-3. Viscous Fan Power Requirements (Ref. 8-3)

to a flex-fan at low engine speeds. It is expected that road-load fuel economy at 70 mph would be approximately 1% better than with the flex-fan (Ref. 8-4).

8.2.4 Summary

The two power-consuming portions of the cooling system are the water pump and the cooling fan. The power required to drive the water pump cannot be significantly reduced without reducing the coolant circulation rate. Certain options are available, however, in reducing the power output of the cooling fan. These include the use of a flex-fan, which will decamber at high engine speeds when ram air provides the required air flow across the radiator and engine, thereby reducing the power requirements; and the use of a viscous clutch drive on the fan. The viscous clutch provides maximum fan performance at low speeds and reduces the power consumption at higher speeds by lowering the fan-to-engine speed ratio. The viscous clutch drive is currently in use on vehicles equipped with factory-installed air conditioning. Because these two techniques for reducing fan power requirements are effective only at the higher engine speeds, their use is not expected to result in any significant improvement in fuel economy during urban driving (e.g., Federal Driving Cycle). The use of a flex-fan could result in a possible fuel economy gain of up to a maximum of 3% at high speeds (i.e., 80-85 mph). The viscous clutch fan drive has been estimated to result in a 1% fuel economy gain over the flex-fan at 70 mph. In summary, it would appear that the use of these devices would be of only marginal benefit during normal driving conditions and they are not, therefore, recommended for inclusion in the test phase of the program.

8.3 REFERENCES FOR SECTION 8

8-1. F. Gerle, "Vacuum Very Much!" Super Stock Magazine, p. 22 (June 1974).

8-2. SAE Paper J1082, "Fuel Economy Measurement - Road Test Procedure," April 1974.

8-3. A Study of Technological Improvements in Automobile Fuel Consumption, Vol. II, Arthur D. Little, Inc. (February 1974).

8-4. A Study of Technological Improvements to Automobile Fuel Consumption, Southwest Research Institute (January 1974).

SECTION 9

OPERATIONAL AND ADJUSTMENT TECHNIQUES

Three specific areas of retrofit-related operational and/or adjustment techniques pertaining to spark-ignition engine operation were examined for their effect on fuel economy: valve timing effects, tuneups, and compression ratio.

9.1 VALVE TIMING

9.1.1 Introduction

High-power, high-speed retrofit camshafts have been marketed for racing and sports cars for many years. Recently some manufacturers have advertised retrofit camshafts or camshaft timing devices which improve engine performance and also reduce the exhaust emissions and fuel consumption of the automobile. Fuel economy improvements up to 25% have been claimed but without the support of reliable test data.

Published research reports of studies of the effect of valve timing on exhaust emissions from automotive engines indicate substantial reduction of exhaust NO_x emission is obtainable with the change of valve timing accompanied by a relatively small effect on specific fuel consumption. At present, no test data are available to indicate to what extent the change in valve timing may contribute to the resulting fuel economy improvement when other retrofit devices, such as the tuned exhaust system and special inlet manifolds, are installed on the engine.

9.1.2 Background

Traditionally, the major objective of cam design for the timed actuation of the engine valve system is to provide the highest volumetric efficiency and the least charge dilution (by residual gases in the engine cylinder) over the entire operating range of the engine. Fulfillment of this objective results in good engine performance and fuel economy.

However, a change in valve timing from the optimal setting has a significant effect on exhaust emissions, particularly on the emission of NO_x. Generally, any change in timing of the inlet valve or of the exhaust valve, or of both (from the optimal timing), will result in an increase of the charge dilution by a larger amount of residual gases trapped in the engine cylinder. This increase of residual gases (or exhaust gases) in the engine cylinder by means of a change in valve timing is called internal exhaust gas recirculation, as opposed to external exhaust gas recirculation (EGR).

Figure 9-1 (Ref. 9-1) shows the effect of cam advance and retard on manifold vacuum and fuel consumption at engine constant speed, load, MBT spark advance, and air-fuel ratio. Fuel consumption increased slightly as the cam was advanced and decreased slightly as the cam was retarded. When the cam is advanced and the exhaust valves opened before the end of the expansion stroke, cylinder pressure is relieved, resulting in loss of power and a correponding increase in fuel consumption. When the cam is retarded, the exhaust valve opens later at the end of the expansion stroke, and therefore more work is extracted from the charge. The gain is, however, relatively small (about 6% at 1600 rpm) and diminishes rapidly with increasing engine speed.

Table 9-1 (Ref. 9-2) presents the results of a cold-start test, conducted according to California 1970 Standard Test Procedure, obtained on a 1968 vehicle (with a V-8, 350 CID engine, and automatic transmission) equipped with a variable cam timing system. At constant volume sampling, the specific mass NO_x emission was reduced by 48%, HC by 19.8%, and CO by 11.3%. However, the fuel economy during road testing was reduced on the average by 6.5%.

In a similar study (Ref. 9-3), over 90% reduction of specific mass NO_x emission was recorded during steady-state car operation. The fuel consumption was not significantly changed from the baseline value, which was relatively high due to rich setting of the carburetor (A/F = 13:1).

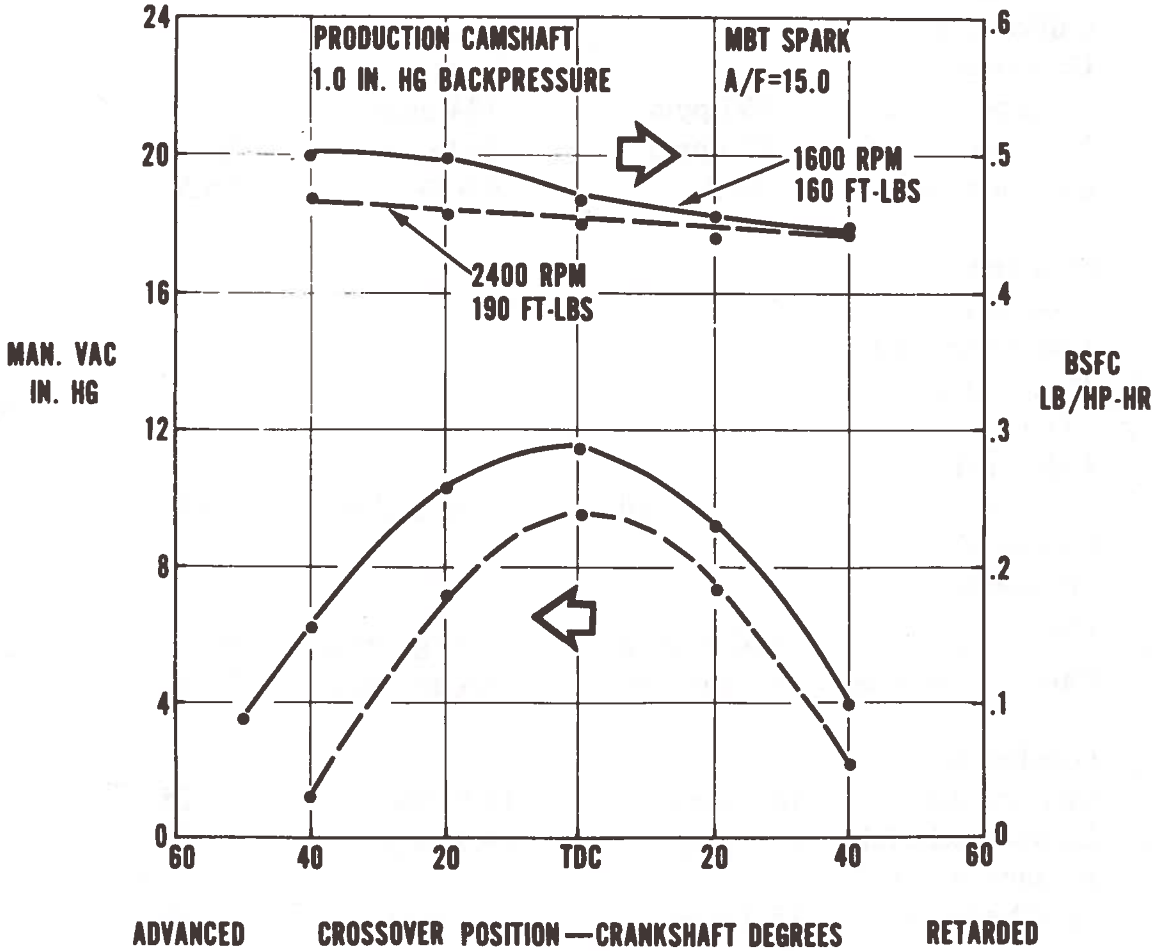


Figure 9-1. Effect of Cam Advance and Retard on Brake Specific Fuel Consumption and Manifold Vacuum (Ref. 9-1)

TABLE 9-1. EMMISSIONS AND FUEL ECONOMY TEST RESULTS OF CAR EQUIPPED WITH THE EATON, YALE & TOWNE CAM ADVANCE SYSTEM (Ref. 9-2)

Test Description	Result Without Cam Advance at 16:1 A/F Ratio	Result With Cam Advance at 16:1 A/F Ratio	Percentage Difference*
Cold Start 1970 California Test:			
Unburned hydrocarbons	197 ppm	134 ppm	32
Nitric oxide	1010 ppm	363 ppm	64
Carbon monoxide	1.02%	0.85%	16.5
Cold Start, Constant Volume Sampler Mass Emissions Test:			
Unburned hydrocarbons	4.19 gm/mile	3.36 gm/mile	19.8
Oxides of nitrogen ($N0 + N0_2$)	4.63 gm/mile	2.39 gm/mile	48
Carbon monoxide	32.0 gm/mile	28.4 gm/mile	11.3
Gasoline Mileage:			
City schedule	14.1 mpg	13.5 mpg	4.25
Highway schedule	16.2 mpg	14.9 mpg	8.03
Average of city and highway	15.2 mpg	14.2 mpg	6.58
Fuel usage for Nine Federal Cycles	N.A.	3.90 lb** Indolene 30	N.A.

*The percentage difference is defined as:

$$\frac{\text{Result Without Cam Advance} - \text{Result With Cam Advance}}{\text{Result Without Cam Advance}}$$

**Not from the same test runs.

9.1.3 Physical Systems

The variable cam timing system developed by Eaton, Yale & Towne, Inc., is shown in Figure 9-2 (Ref. 9-2). The timing servomechanism is an assembly which replaces the camshaft timing chain sprocket in the chaincase. The actuating power comes from pressurized engine oil routed from a groove in the front journal of the camshaft (which registers with the oil gallery) through the nose of the cam and into the servo unit. The principal elements of the servo are a splined sprocket ring, an axial motion piston which carries the control valve body, the spool-type control valve, the mounting plate which fastens to the camshaft, and a pair of three-lead helical ball spline rings.

In operation, a control shoe, which is positioned by the input signal, is in rubbing contact with the control valve. When the control shoe position is changed, it moves the valve relative to the piston valve body, admitting oil to the piston chamber from the high pressure supply when the motion is toward the front of the engine or dumping oil from the piston chamber when the motion is toward the rear of the engine. This dumping and filling process causes the piston to follow the control shoe with good fidelity, since the stroke of the control valve with respect to the piston is small compared to the total piston stroke. The axial motion of the piston is transmitted to the helical ball splines, and changes in the piston position cause angular phase changes between the chain-driven sprocket ring and the camshaft. The overall effect is that the axial position of the control shoe, which works at a low force level, controls the angular phasing between the camshaft and the chain-driven sprocket ring.

When the control shoe, and consequently the piston, are toward the rear of the engine, the camshaft is at basic timing. When the control shoe is shifted toward the front of the engine, the piston follows and causes the cam to advance. The control shoe position is, in turn, controlled by a calibrated vacuum motor and linkage arrangement. The vacuum motor is actuated by the carburetor ported vacuum. This signal is fairly well suited for control of cam advance, since it is zero at idle and very light load, high through the mid-load region, and very low at full throttle. The resultant cam advance versus load curve is shown in Figure 9-3.

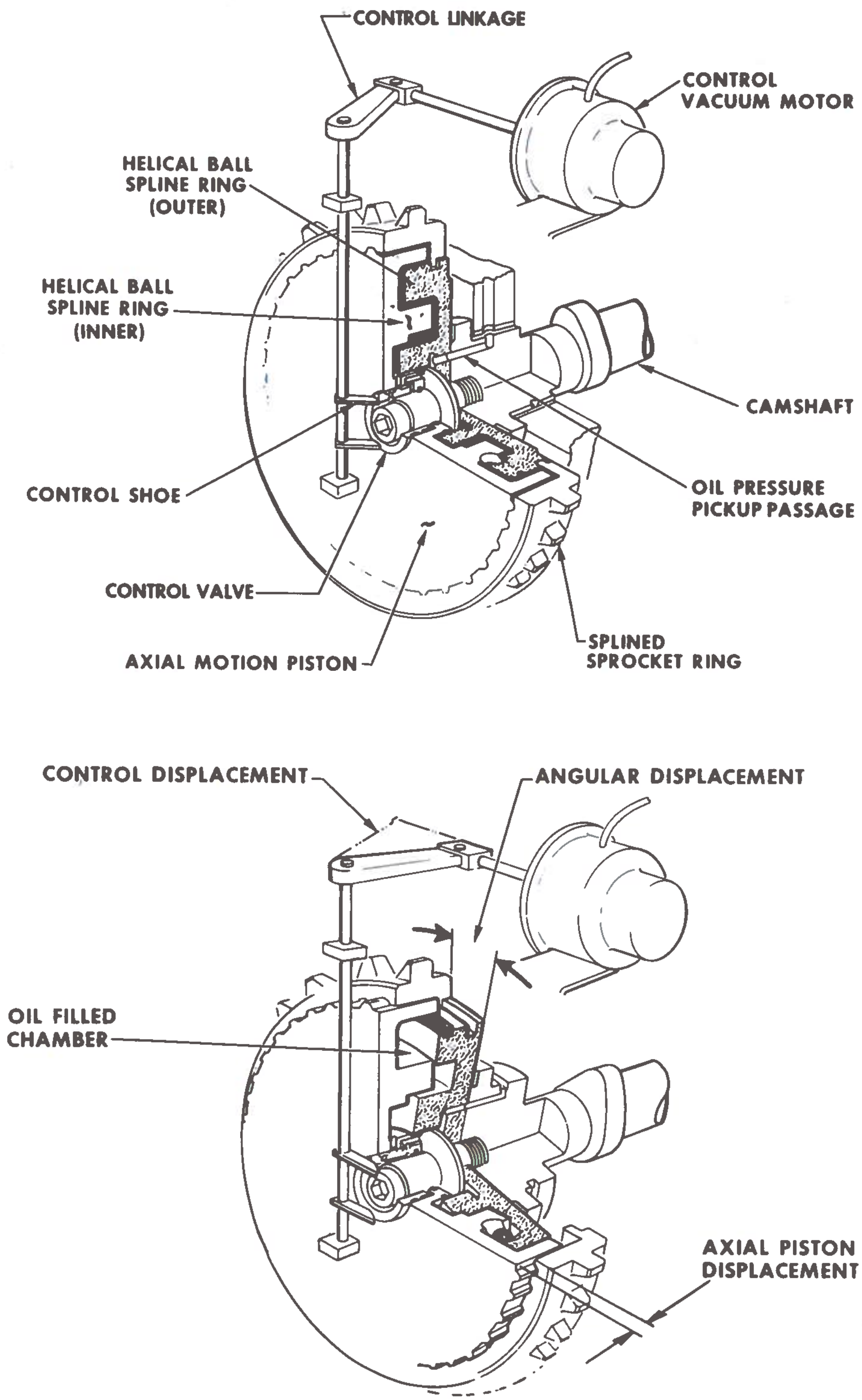


Figure 9-2. Eaton, Yale & Towne Cam Advance Servomechanism and Control: Basic Timing and Advanced Timing (Ref. 9-2)

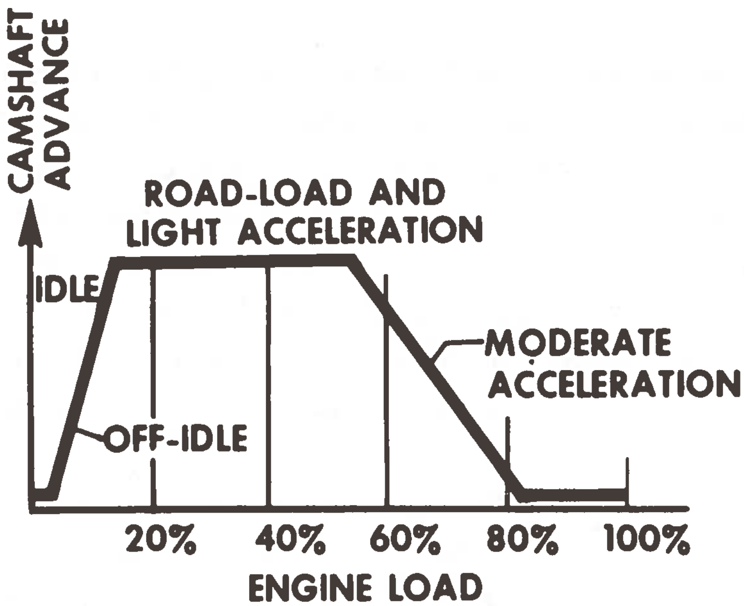


Figure 9-3. Cam Advance as a Function of Engine Load Characteristic (Ref. 9-2)

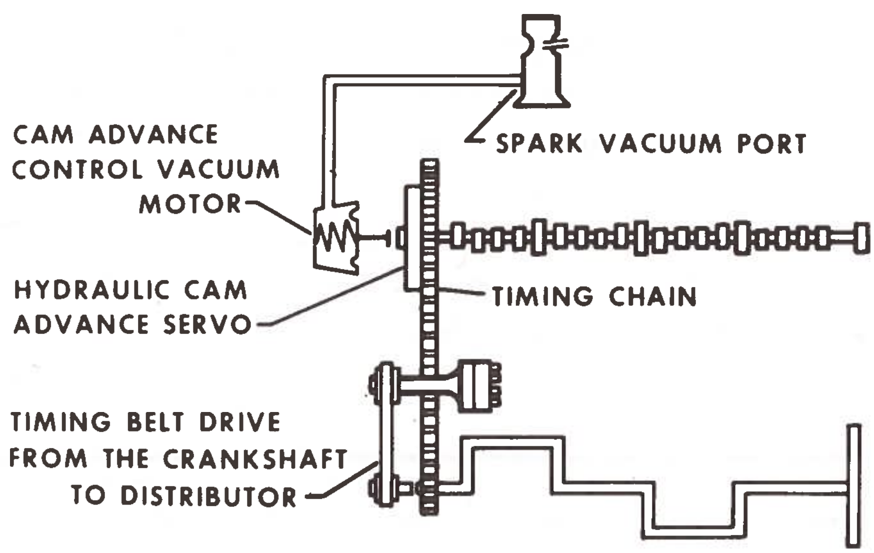


Figure 9-4. Schematic of Cam Advance Control and Ignition Distributor Drive System (Ref. 9-2)

In typical engine practice, the ignition distributor is driven by a gear on the camshaft, and any changes in camshaft timing alter ignition timing by the same amount. This timing variation is not acceptable, and there are two general solutions to the problem. One is to add a mechanism to correct the spark timing by measuring the amount of cam advance and retarding the distributor the same amount. This is quite feasible and has been tested successfully. The other method, which is to alter the distributor drive so that it is driven by the crankshaft through a 2:1 speed reducer, is more straightforward, as shown in Figure 9-4.

The Eaton, Yale & Towne variable cam timing device has been tested by The National Air Pollution Control Administration (NAPCA)(Ref. 9-4). The device has been found very effective in exhaust NO_x control, but no effect on fuel economy was reported. Thus far, this device has not been available on the automotive market.

Similar development work has been underway at General Motors Corporation (Ref. 9-3). The company, however, does not plan at present to put the variable timing camshaft in production.

For a limited period, two variable camshaft timing devices have been available on the automotive market, one produced by the Vari-Cam Corporation of San Diego, California, and the other by Ollie Morris Equipment Corporation of Santa Ana, California.

The Vari-Cam device was tested by NAPCA (Ref. 9-5). It was found moderately effective in reducing exhaust emissions (NO_x and HC) without adversely affecting the vehicle driveability. No effect on fuel economy was reported. The Vari-Cam device retails for $75, and the installation cost is estimated to be $65.

The Cam-A-Go variable cam timing device by Ollie Morris Equipment Corporation is manually actuated and has been marketed for drag-racing cars. No test data on the effects on fuel economy and exhaust emissions have been reported.

Several other variable camshaft devices or special camshafts have been reported or advertised. The Gas Stretcher camshaft by Crower

Cams and Equipment Company, Chula Vista, California, has been marketed as a retrofit camshaft for light-duty vehicles for from $90 to $125. Over 20% fuel economy improvement has been claimed. No test data in support of these claims were published. Recently this device was banned from sale by the California Air Resources Board because of adverse effects on exhaust emissions.

9.1.4 Summary of Valve Timing Devices

Various claims of substantial fuel economy improvements obtainable with retrofit high-performance camshafts or with variable cam timing devices have been made in several magazines and parts catalogs. However, these claims are not supported by reliable test data or by technical publications of research work conducted on engines with variable cam timing. The camshaft timing which determines the valve timing has in certain cases, particularly in the low range of engine speed, a limited effect on fuel economy. Improvements up to 6% were recorded when, for example, the valve timing was retarded 40 degrees at 1600 rpm. However, tests on automobiles made according to Standard Cycle Test Procedures revealed negative or insignificant effects on the fuel economy.

Table 9-2 presents the summary of valve timing devices surveyed. The General Motors Variable Valve Timing Camshaft has been developed for controlling the exhaust emission of NO_x. This approach is based on the fact that valve overlap influences internal exhaust gas recirculation which in turn affects the emission of NO_x. Therefore, the valve overlap rather than the timing of the whole camshaft is being varied in this case. Very strong reduction (90%) of NO_x has been recorded with no effect on the fuel economy of the engine. However, this device would be relatively costly to produce and install as a retrofit system.

The Eaton, Yale & Towne cam timing device does not require replacement of the camshaft. It mounts in place of the stock camshaft sprocket wheel and can be installed without disassembling the engine. It is, however, less effective for exhaust NO_x control than the GM device. No positive effect on fuel economy has been observed.

TABLE 9-2. SUMMARY OF VALVE TIMING DEVICES

Device	G. M. C. Variable Valve Timing	Eaton Yale & Town Variable Cam Timing	CAM-A-GO Variable Cam Timing	Crower Gas Stretcher Cam	VARI-CAM Device	Ule Electronic Camshaft
Degree of Fuel Economy (Miles Per Gallon) Improvement	negligible	negative*	N. I.	21% *	N. I.	N. I.
Retrofit Device or "Kit" Content and Physical Characteristics	multipiece camshaft having the capability of rotating the intake cams relative to exhaust cams	See Figure 9-2	timing chain replaced by a movable gear for change of timing	retrofit high-performance camshaft with special shape of cam lobes	N. I.	valves actuated by high pressure hydraulic system which is electronically controlled
Compatibility with Mass Production	yes	yes	yes	yes	N. I.	N. I.
Potential Availability in Quantity in Near Future	N. I.	N. I.	N. I.	N. I.	N. I.	N. I.
Applicable Vehicle or Engine Models (Gasoline and Diesel)	gasoline l. d. vehicles	gasoline l. d. vehicles	gasoline l. d. vehicles	gasoline l. d. vehicles	gasoline l. d. vehicles	gasoline l. d. vehicles
Attendant Installation Requirements (including Necessary Facilities)	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment
Installation Time Requirement	N. I.	N. I.	N. I.	N. I.	N. I.	N. I.
Cost to Consumer for Device for Installation	N. I.	N. I.	\$200 - \$240 N. I.	\$90 - \$125 N. I.	\$75 N. I.	N. I.
Special Maintenance Requirements	N. I.	N. I.	none	none	N. I.	N. I.
Effect on HC, CO, and NO_x Emissions (if any)	90% reduction of NO_x	50% NO_x and 20% HC reduction	N. I.	N. I.	moderate reduction of HC, CO and NO_x	N. I.
Effect on Vehicle Power and Acceleration Performance (if any)	rough idling	minimal	power improvement claimed	power improvement claimed	power improvement claimed	N. I.
Type of Data Available	steady state	70 FTP - test cold start	N. I.	road test	68 FTP cold and hot start CVS	N. I.
Source and Reliability of the Data Base	SAE Paper #740102	SAE Paper #700673	N. I.	company test	NAPCA	Description by the inventor
Theoretical Background	see Section 9.1.2	see Section 9.1.2	see Section 9.1.2	see Section 9.1.2	see Section 9.1.2	N. I.
Remarks		* slight improvement at steady state, negative in cycle test		* reported by Competition Specialties Inc.		

N. I. = no information

The Ule electronic camshaft represents a complete departure from mechanical actuation of the engine valves. This electronically controlled hydraulic system, which replaces the conventional camshaft, pushrods, and rocker arms, is in the experimental stage, and no performance data are available as yet. If successful, this system would offer versatile control of the valve timing.

The following three devices are or have been available on the automotive specialty market as high-performance retrofit components.

The CAM-A-GO variable valve timing appears to be the best developed device on the market. It is used for power augmentation of drag-racing engines. However, no data on fuel economy and exhaust emission effects have been presented.

The moderately priced VARI-CAM device has been tested by NAPCA and found moderately effective in reducing the exhaust emissions, but no effect on fuel economy has been reported. This device is still marketed.

The Crower Gas Stretcher Camshaft has been advertised as a power booster and fuel economy device. This is not a variable valve timing device but a high-performance camshaft with fixed change of timing from the conventional camshafts. No official test data have been presented, and the device, because of adverse effect on exhaust emission, is presently banned from installation on passenger automobiles.

9.2 ENGINE TUNEUPS

As described in detail in Section 4, the conventional ignition system has a usable lifetime which is limited by the wearout and/or malfunction of key components (e.g., points, spark plugs, etc.). Also, cylinder misfire can occur due to deposits on the spark plugs (e.g., lead deposits). In addition, the air-fuel ratio of the charge can be adversely affected by carburetor problems such as gum or other deposits, improper float adjustments, or improper idle air-fuel ratio adjustments, etc.

These types of component and/or adjustment malfunctions are recognized by the auto industry to be the inevitable result of prolonged vehicle operation with conventional ignition and carburetion systems. The exact time interval (or vehicle mileage) which transpires before vehicle fuel economy is seriously affected would be expected to vary somewhat according to driving conditions, quality of gasoline used, etc. However, the auto industry has for years recommended that the engine be tuned up (set timing; replace points, plugs, condenser; clean carburetor) at 10,000- to 12,000-mile intervals (on the average) to retain vehicle performance and economy. With the advent of the use of unleaded gasoline (to reduce combustion chamber and spark plug deposits) and high-energy ignition systems, the recommended tuneup interval has in most cases been extended to 20,000 miles or more.

The quantification of average fuel economy losses due to ignition and carburetion degradation would require the collection of data from many cars tested at specified time intervals in order to fully document fuel economy improvement resulting from engine tuneups. This type of data is generally unavailable today. However, such information for one car tested at various operating speeds is shown in Table 9-3 (Ref. 9-6). In this case, approximately 10% fuel economy improvement was obtained over normal driving speed ranges. In another study (Ref. 9-7), it was shown that a spark plug misfiring half the time at 60 mph reduced fuel economy by 7.3 percent.

TABLE 9-3. COMPARISON OF MILEAGE FOR ONE CAR, BEFORE AND AFTER TUNING (Ref. 9-6)

Operating Speed, Miles Per Hour	Miles Per Gallon		Improvement After Tuning	
	Before Tuning (Car #2)	After Tuning (Car #2A)	Miles Per Gallon	Percent
30	19.30	21.33	2.03	10.52
40	18.89	21.33	2.44	12.92
50	17.29	18.94	1.65	9.54
60	15.67	17.40	1.73	11.04
70	13.32	15.36	2.04	15.32

Thus, engine tuneups at prescribed intervals should be an effective way of reducing national automotive fuel consumption. The number of vehicles which should be tested to quantify the approximate range of fuel savings is felt to be too extensive to include in the Phase II testing portion of this program.

9.3 ENGINE COMPRESSION RATIO

Increasing the engine compression ratio (CR) is a well-established technique for reducing engine fuel consumption by virtue of the increased thermal efficiency accompanying the CR increase. As noted in Ref. 9-8, increasing the weighted average CR from 8.35 to 9.35 would improve fuel economy approximately 5 %.

On a retrofit basis, a CR increase could be accomplished by shaving the head or by piston replacement; either method would be expensive, requiring some degree of engine teardown. However, higher octane gasoline would be required (to prevent knocking) and the emissions of HC and NO_x could be increased somewhat.

Therefore, retrofit to increase engine compression ratio is not recommended as a method for improving fuel economy.

9.4 REFERENCES FOR SECTION 9

9-1. M. A. Freeman and R. C. Nicholson, "Valve Timing for Control of Oxides of Nitrogen (NO_x)," SAE Paper No. 720121, SAE Congress, Detroit, Michigan, January 1972.

9-2. G. B. K. Meacham, "Variable Cam Timing as an Emission Control Tool," SAE Paper No. 700673, SAE Meeting, Los Angeles, California, August 1970.

9-3. C. A. Schiele, S. F. DeNagel and J. E. Bennetherm, "Design and Development of A Variable Valve Timing (VVT) Camshaft," SAE Paper No. 740102, SAE Congress, Detroit, Michigan, February 1974.

9-4. J. C. Thomson, An Evaluation of a Variable Cam Timing Technique as a Control Method for Oxides of Nitrogen, Division of Motor Vehicle Research and Development, National Air Pollution Control Administration, Department of Health, Education, and Welfare, Washington, D.C. (October 1970).

9-5. J. C. Thomson, Exhaust Emissions on an Uncontrolled Passenger Car Using Variable Cam Timing, Division of Motor Vehicle Research and Development, National Air Pollution Control Administration, Department of Health, Education, and Welfare, Washington, D.C. (August 1970).

9-6. The Effect of Speed on Automobile Gasoline Consumption Rates, U.S. Department of Transportation, Federal Highway Administration, Office of Highway Planning, Highway Statistics Division (October 1973).

9-7. E. S. Starkman and C. Marks, "Conservation and Efficient Use of Energy," statement to U.S. Congress, Select Committee on Small Business, Washington, D. C., General Motors Corporation, July 10, 1973.

9-8. An Assessment of the Effects of Lead Additives in Gasoline on Emission Control Systems Which Might Be Used to Meet the 1975-76 Motor Vehicle Emission Standards, Report No. TOR-0172(2787)-2, The Aerospace Corporation, El Segundo, California (15 November 1971).

SECTION 10

EXHAUST-RELATED SYSTEMS

10.1 INTRODUCTION

In spark ignition internal combustion engine operation, approximately 30% of the total heat energy of the fuel is converted to useful work on the piston, about 30% of the total energy is removed by the cooling water, and the remaining 40% is lost in the exhaust gases. The energy lost in the exhaust gases can be partially recovered by passing the exhaust gases through a turbine, by operating the engine on a "more-complete-expansion cycle," by utilizing the kinetic energy of the exhaust gases in a tuned exhaust system, or by transferring the heat energy of the exhaust gases to a steam boiler for operation of an auxiliary steam turbine. This latter method is used in some large internal combustion engine power plant installations.

Furthermore, lowering the exhaust backpressure results in reduced engine pumping work (required for the expulsion of burned gases from the engine cylinder); therefore, a higher engine efficiency and improved fuel economy could be realized if practical means for substantially reducing the exhaust backpressure were available.

Since the early developments of the spark ignition and diesel engines, most possibilities have been investigated. Thus far, only the application of turbochargers, principally for power output augmentation, has found a widespread use in several categories of diesel and gas engines and to some extent in sports and racing car engines. Recently, however, tuned exhaust systems (headers) for power and/ or fuel economy improvement of light-duty passenger cars and trucks are being offered as retrofit exhaust systems on the automotive specialty market.

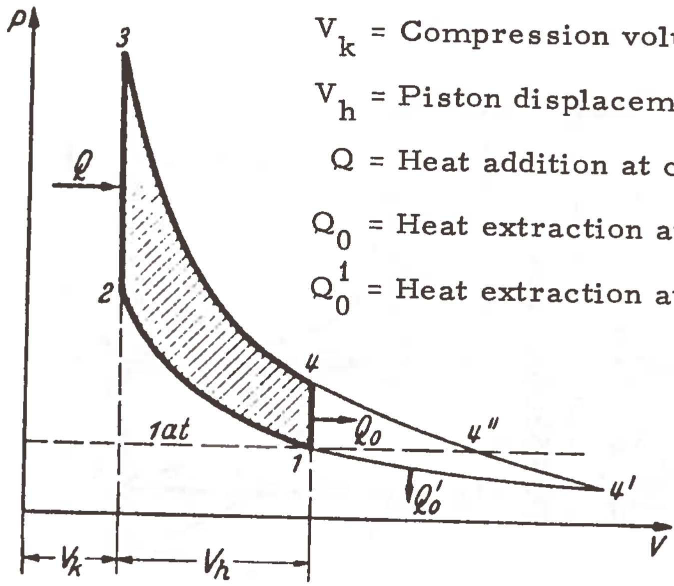
The basic principles involved in the operation of several exhaust-related systems are discussed in the following paragraphs, followed by a description of the physical and performance characteristics of specific devices available for retrofit.

10.2 BACKGROUND

A considerable number of theoretical and experimental studies of various phenomena associated with the transient flow regime in gasoline and diesel engine exhaust systems have been published in the past. The many aspects investigated include basic studies of matching engine and turbocharger characteristics; evaluation of the application of a turbocharger to a passenger car engine for improvement of exhaust emissions and fuel economy; experimental studies of the effect of exhaust backpressure on engine performance, efficiency, and exhaust emissions; and theoretical and experimental studies of the effects of tuned exhaust systems on engine power and fuel economy. A comprehensive listing of pertinent references is presented in the bibliography of Ref. 10-1.

10.2.1 Backpressure Effects

Figure 10-1 (Ref. 10-2) illustrates the theoretical work available from an idealized "constant-volume" fuel-air cycle, as the shaded area between the points 1-2-3-4 in the pressure-volume diagram. If the expansion process were continued from point 4 (normally the beginning of the exhaust stroke) to point 4'' (at ambient pressure), additional work proportional to the area 4-4''-1 could be gained. Furthermore, if the expansion could be continued adiabatically to point 4', which corresponds to expanding the gases down to the ambient temperature, and then compressed back isothermally to point 1 (initial state), additional work proportional to the area 4-4'-1 could be gained. The work proportional to area 4-4''-1 can be partially recovered in an exhaust turbine or in an engine operating on a "more-complete-expansion cycle." In the 4-cycle more-complete-expansion engine, the compression pressure, and hence the maximum cylinder pressure, is controlled by late closing of the inlet valve, which gives an effective compression ratio lower than the expansion ratio. The advantage of this cycle is the possibility of an efficiency higher than could be obtained with an expansion ratio equal to the compression ratio. The disadvantage is a mean



V_k = Compression volume

V_h = Piston displacement volume

Q = Heat addition at constant volume

Q_0 = Heat extraction at constant volume

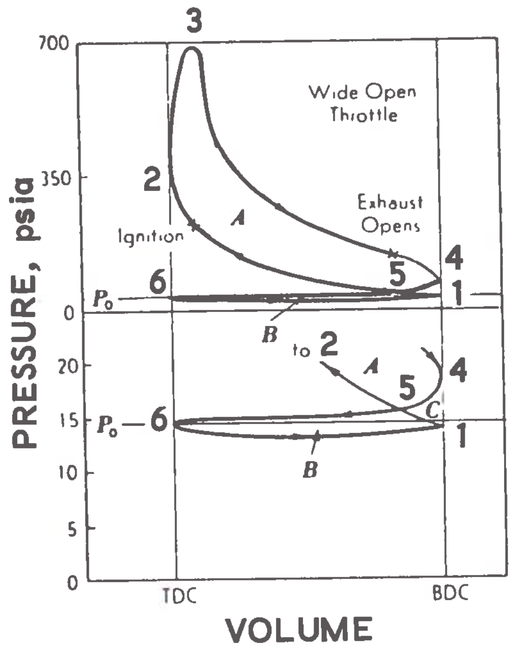
Q_0^1 = Heat extraction at constant temperature

Figure 10-1. Pressure-Volume Diagram of an Idealized "Constant-Volume" Fuel-Air Cycle (Ref. 10-2)

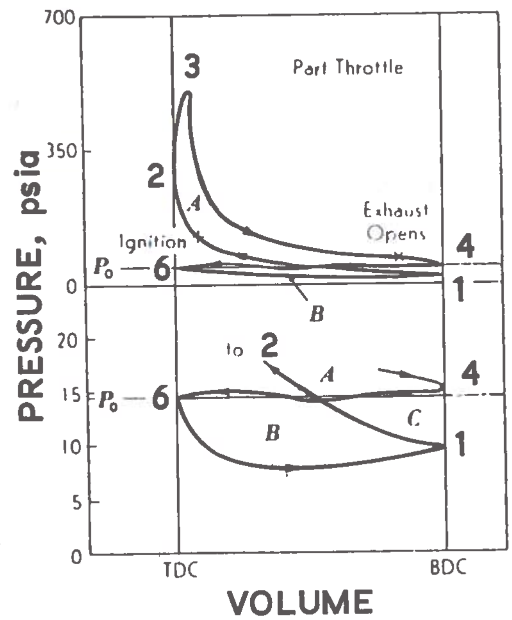
effective pressure lower than in the conventional arrangement with the same maximum pressure.

The more-complete-expansion cycle is more advantageous for engines that are not frequently operated at light loads. In light load operation the mean cylinder pressure during the latter part of the expansion stroke tends to be near to, or even lower than, the friction mean pressure. Under such circumstances the more-complete-expansion portion of the cycle could involve a net loss rather than a gain (Ref. 10-1). The work proportional to area 4-4'-1 could be theoretically recovered in a turbine with an exhaust cooler (condenser) and vacuum system, as in the steam turbine power plant installations.

Figure 10-2 (Ref. 10-3) shows an actual pressure-volume indicator diagram of a spark ignition 4-stroke engine. In distinction to the idealized cycle in Figure 10-1, the indicator diagram shows another area between the points 5, 6, and 1 which represents the pumping work of the engine. (For clarity, the negative work is shown in a larger scale in the lower part of the figure.) The boundary 5 to 6 of this area is determined by the backpressure of the gases during the exhaust stroke. For a given intake manifold pressure



(a)
Positive Work

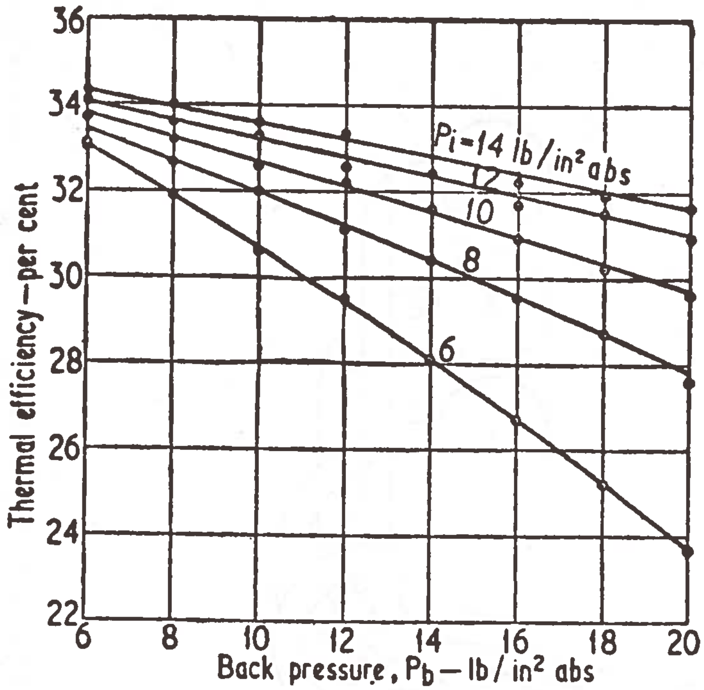


(b)
Negative (Pumping) Work

Figure 10-2. Indicator Diagram of a Spark Ignition 4-Stroke Engine Working Cycle (Ref. 10-3)

(boundary 1 to 6), it is evident that the higher the exhaust back pressure the higher will be the boundary 5-6 and consequently the larger the area 5-6-1 representing the negative (pumping) work of the engine. The increased negative (pumping) work at part throttle conditions shown in Figure 10-2(b) is due to the decreased intake manifold pressure.

The effect of exhaust backpressure and inlet manifold pressure on the thermal efficiency of a spark ignition four-stroke engine are shown in Figure 10-3 (Ref. 10-4). As indicated, the reduction in thermal efficiency of the engine caused by increasing the exhaust backpressure is greater when the engine is operated at low inlet manifold pressures, corresponding to light engine loads and high speeds.



P_i = inlet manifold pressure

Figure 10-3. Thermal Efficiency of the Automotive Engine as a Function of Exhaust Backpressure (Ref. 10-4)

10.2.2 Tuned Exhaust Systems

One way to utilize the exhaust gas energy to reduce the exhaust backpressure, and therefore to increase the power and improve the fuel economy of the engine, is by means of a dynamically tuned exhaust system. In principle, such a system consists of a number of pipes equal to the number of cylinders, each one connected to the exhaust port of the individual cylinder of the engine. Generally, the discharge ends of the pipes are merged into a common collector which is connected to the remaining exhaust system consisting of exhaust pipe, muffler, and tail pipe. The combination of tuned exhaust pipes with a collector-diffuser has been successfully applied to racing V-8 engines as exemplified by the Ford racing engine shown schematically in Figure 10-4.

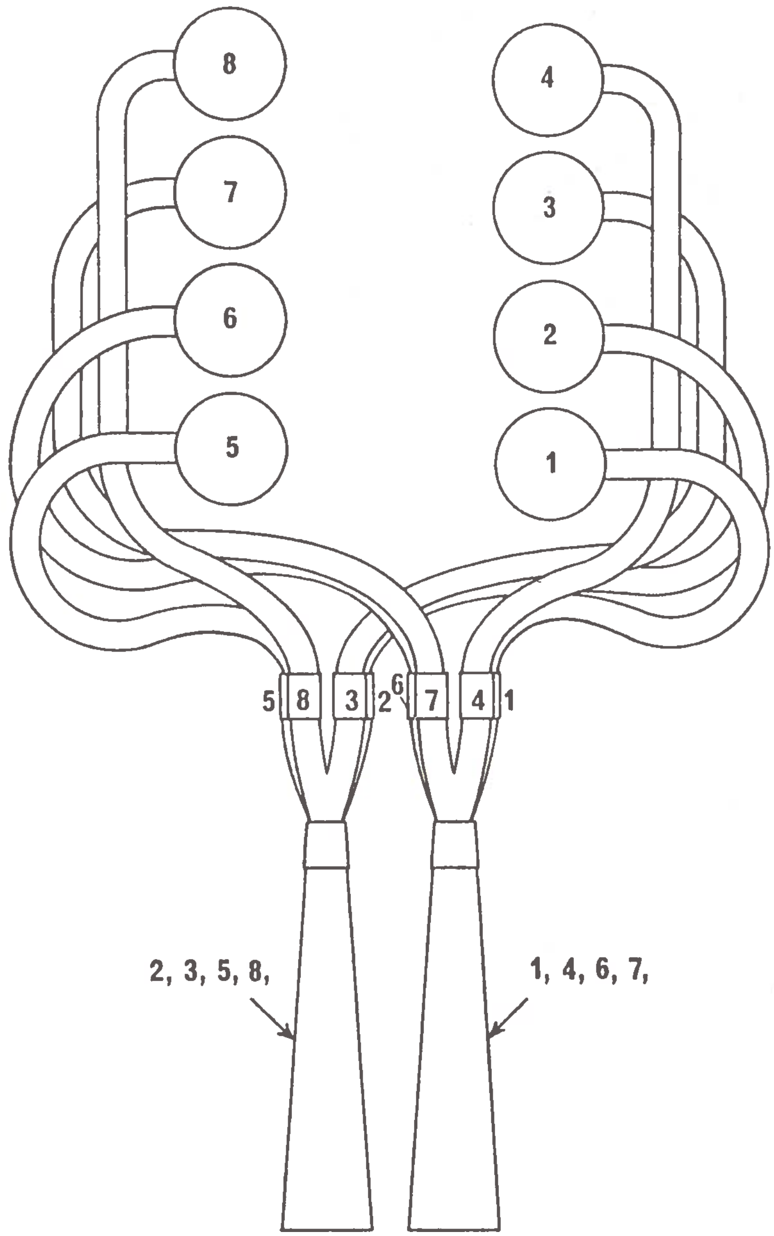


Figure 10-4. Tuned Exhaust System with Diffuser-Type Collectors for a Racing V-8 Engine (Ref. 10-4)

As described in Ref. 10-5, the engine exhaust interactions with a tuned exhaust system are as follows: a pressure wave created in the exhaust pipe at the beginning of the opening of the exhaust valve and the discharge of the exhaust gases propagates through the exhaust pipe with a sonic velocity and is reflected at the open end of the exhaust pipe as a suction wave which propagates back toward the still-open exhaust valve. Upon arrival at the exhaust valve, the suction wave exerts an evacuating effect on the gases still contained inside the engine cylinder. If the exhaust pipe is tuned (has a correct length), the reflected suction wave will arrive just before the closing of the exhaust valve and exert a scavenging effect on the gases remaining in the engine cylinder.

Figure 10-5 (Ref. 10-4) presents the experimentally determined effect of engine speed on the timing of arrival of the reflected suction wave at the exhaust valve. The experiments were carried out on a single-cylinder engine with a 5-ft 2-in. long pipe attached to the exhaust port. At 1000 rpm, a waveform was recorded that shows two positive and two negative pressure amplitudes during the opening of the exhaust valve (between BDC and TDC). The resulting effect on exhaust scavenging is minimal because, during the valve overlap at TDC, almost atmospheric pressure persists. However, some benefit in reduction of engine pumping work may result, since the total magnitude of negative pressure is larger than that of the positive pressure. At 2000 rpm, some benefit may also result because the negative pressure occurs at the most effective crank angle position of the piston. Nevertheless, no scavenging benefits can be expected due to the positive pressure prevailing at TDC. At 3000 rpm, both reduced pumping work and scavenging benefits result due to the negative pressure amplitude extending from the last half of the exhaust stroke well beyond TDC. At 4000 and 5000 rpm, no benefit in the reduction of engine pumping work can be expected; however, an effective scavenging of the exhaust gases results due to the negative pressure amplitude extending well over the valve overlap period.

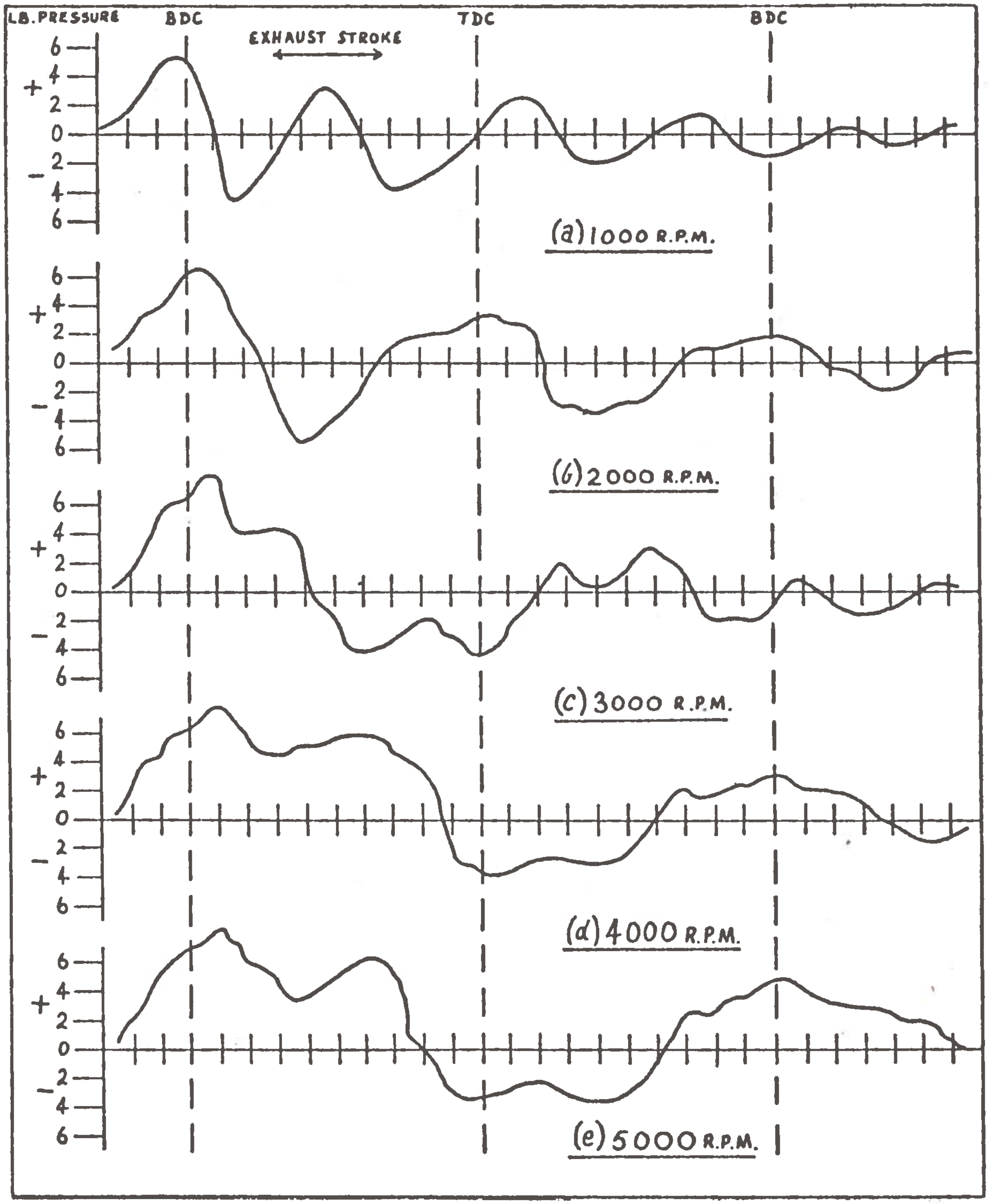


Figure 10-5. Effect of Engine Speed on Pressure Variation at the Exhaust Port of a Single-Cylinder Engine with Tuned Exhaust Pipe (Ref. 10-4)

These results (Figure 10-5) characterize the nearly ideal performance of the tuned exhaust system for a single-cylinder engine: at high engine speeds, an increase in power output is obtained due to better cylinder scavenging (better volumetric efficiency); at medium and low engine speeds, better fuel economy due to reduced engine pumping work losses can be realized. It should be pointed out, however, that in multi-cylinder engines, where the tuned exhaust pipes are merged into a common collector, an interference occurs which can strongly influence the basic characteristics shown in Figure 10-5.

The exhaust scavenging effect of a tuned exhaust system can be further amplified by attaching a conical diverging pipe (diffuser) to the open end of the cylindrical exhaust pipe connected to the engine exhaust port. This phenomenon was discovered by Kadenacy and analyzed by several investigators in the 1930's (Refs. 10-2 and 10-6). Appreciable power increase and lower fuel consumption on two-stroke engines have been reported.

The effect of such a diffuser can be described as follows. A pressure wave propagating through the cylindrical exhaust pipe at sonic velocity becomes supersonic upon entering the diffuser. Because of the atmospheric backpressure outside the diffuser, this wave instantly becomes a shock wave. For a short period, the shock wave remains quasi-stationary inside the diffuser and effectively blocks off any reverse flow toward the engine exhaust valve. In other words, the shock wave acts as an "acoustic check valve." Therefore, a stronger suppression is generated at the engine exhaust port.

10.3 DESCRIPTION OF EXHAUST-RELATED SYSTEMS

10.3.1 Tuned Exhaust Systems

Several domestic manufacturers offer tuned exhaust systems for retrofitting of passenger cars, pickups, and vans. The Hooker Headers are described here to represent the general class. Figure 10-6 (Ref. 10-7) shows the components of the Hooker Adjustable Headers. The kit allows the car owner to assemble an "adjustable" header system. For example, when

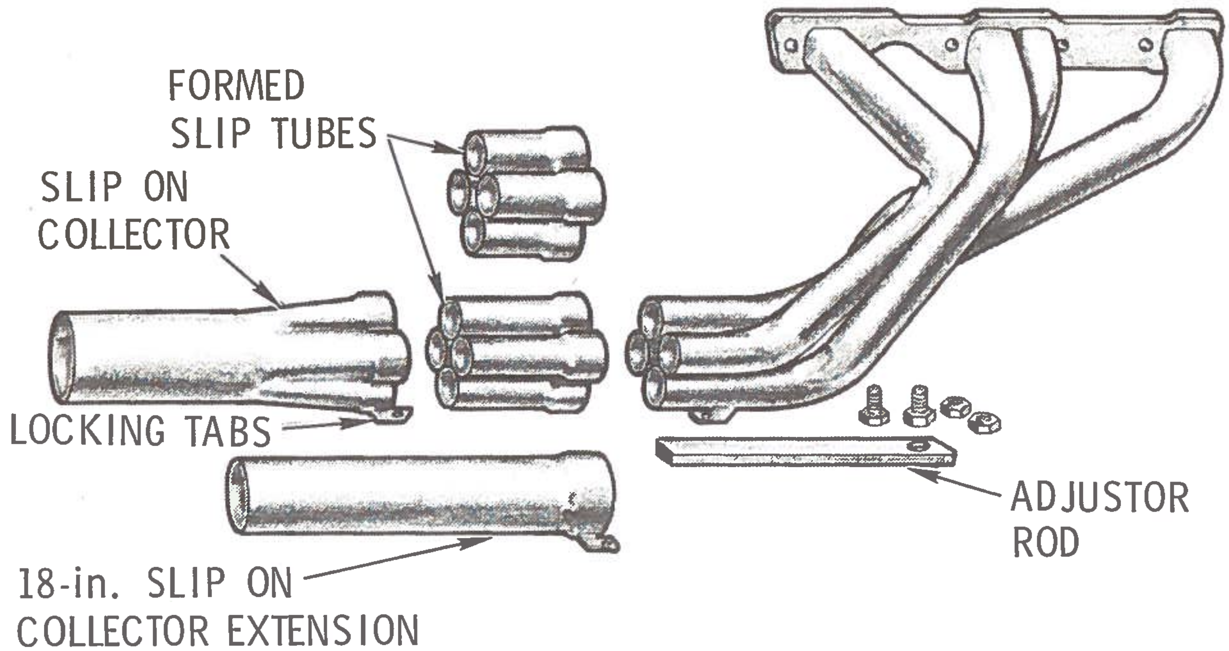


Figure 10-6. Hooker Adjustable Header Kit (Ref. 10-7)

used on a racing car, the length of the primary tubes can be adjusted by insertion of slip-tubes upstream of the collector. Quick tuning can be accomplished to suit the track conditions. For best performance at high engine speed, the slip-tubes can be shortened or completely removed. Conversely, for high torque at lower engine speed, longer slip-tubes can be inserted upstream of the collector. An assembled header is shown in Figure 10-7.

10.3.1.1 Fuel Economy

Table 10-1 (Ref. 10-8) presents the effect of Hooker Headers on fuel economy. This series of tests was performed at Automotive Environmental Systems, Inc., in Westminster, California. The fuel economy improvement depends, as expected, on the engine speed. The gain of 14.4% recorded on a Chevrolet Vega at 50 mph dropped to 4.5% at 60 mph. Unfortunately, in the reference cited, it is not stated to what specific rpm range the headers were tuned. On a Chevrolet pickup, on the other hand, a 5.1% fuel economy gain at 50 mph increased to a 6.8% gain at 60 mph. Nevertheless, on the Federal Driving Cycle, the gain for both automobiles was nearly 6%.

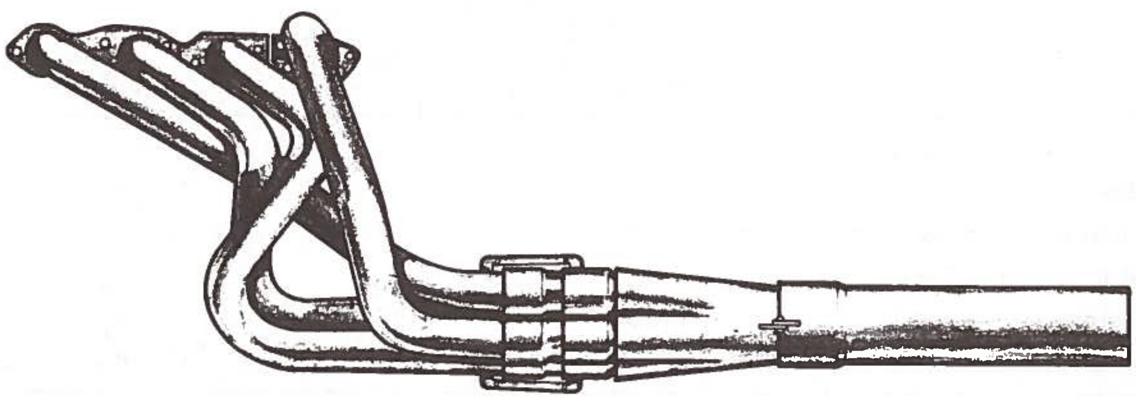


Figure 10-7. Hooker Adjustable Header Assembled (Ref. 10-7)

TABLE 10-1. EFFECT OF HOOKER HEADERS ON FUEL ECONOMY, EXHAUST EMISSIONS, AND EXHAUST NOISE (Ref. 10-8)

Noise Data, dBA

	California Drive By	SEMA 25-Ft Static	Proposed 1-Ft Static
1973 Chevrolet Vega:			
Stock	77.0	72.5	90.5
Headers and Exhaust System	75.5	70.0	96.0
1974 Chevrolet Pickup:			
Stock	75.5	72.0	92.0
Headers and Exhaust System	76.5	69.0	93.5

Mileage Comparison, mpg

	Federal Driving Cycle	Steady 50 mph	Steady 60 mph
1973 Chevrolet Vega:			
Stock	20.70	30.87	28.61
Headers and Exhaust System	21.87 (+5.7%)	35.32 (+14.4%)	29.34 (+4.5%)
1974 Chevrolet Pickup:			
Stock	11.62	16.17	15.48
Headers and Exhaust System	11.70 (+6.2%)	16.91 (+5.1%)	16.48 (+6.3%)

Emission Data, gm/mi

	CVS Federal Driving Cycle (Approx. test driving time: 23 min.)		
	HC	CO	NO_x
1973 Chevrolet Vega:			
Stock	1.830	52.015	2.194
Headers and Exhaust System	1.722 (-5.9%)	34.454 (-33.8%)	2.803 (+28%)
1974 Chevrolet Pickup:			
Stock	1.773	26.405	3.409
Headers and Exhaust System	1.849 (+4.6%)	24.777 (-6.2%)	3.480 (+2.3%)

Note: Figures in parentheses indicate percentage of increase or decrease.

Table 10-2 (Ref. 10-9) presents the results obtained from a series of tests conducted at the Edelbrock Equipment Company. The test car, a 1974 Chevelle Laguna equipped with a 454 CID V-8 engine, was operated on a chassis dynamometer. The emissions were evaluated by the hot-start CVS method and the fuel economy by direct fuel measurement in an independent series of seven-mode tests. The test data indicate about 5% fuel economy gain when the car was fitted with Hooker Headers. This gain increased to about 10% when, in addition to the headers, the Edelbrock Torker inlet manifold was installed in place of the factory standard inlet manifold. However, in town and highway driving tests, the data indicate almost 17% fuel economy gain.

TABLE 10-2. EFFECT OF HOOKER HEADERS AND HEADERS WITH EDELBROCK MANIFOLD ON FUEL ECONOMY AND EXHAUST EMISSIONS (Ref. 10-9)

Test Phase	Gas Mileage			Emissions (CVS Method, Hot Start)		
	Dyno	Town	Highway	CO	HC	NO_x
1. Stock as received	9.4	10.2	11.6	17.64	1.15	4.68
2. Hooker headers w/AIR fittings	9.9	10.7	12.0	15.32	1.17	4.13
3. Edelbrock Torker 2-0 Rochester Q-Jet	10.4	12.0	13.6	10.59	1.09	3.74
4. Edelbrock Torker 2-0 Holley 6619 4-bbl	10.3	11.9	13.5	10.01	1.09	3.92

Subsequent replacement of the stock Quadra-Jet Carburetor by the high-performance Holley Carburetor did not result in any improvement of gas mileage or exhaust emissions.

The above test data, while promising, represent only a few tests of automobile engines retrofitted with tuned exhaust systems. Because of the lack of statistical data, no conclusive statement can be made in respect to the general effectiveness of these exhaust systems. This is particularly true of the town and highway driving data in Table 10-2, since driver habits and characteristics can have a large effect on fuel economy.

10.3.1.2 Emissions

Table 10-1 also presents the effect of tuned Hooker Headers on exhaust emissions from a Chevrolet Vega and a Chevrolet Pickup. For both automobiles, a slight reduction -- about 5% of exhaust HC, 34% of CO on the Vega, and 6% of CO on the Chevrolet Pickup -- was recorded. However, in the absence of official test results on several automobiles, the latter results cannot be interpreted as indicative of the emission effects resulting from tuned exhaust systems. It is noteworthy that, for both automobiles, some increase in exhaust NO_x was recorded. This could be the result of the reduction of residual exhaust gases in the engine cylinders (reduced internal EGR) as effected by better cylinder scavenging due to the tuned exhaust system.

Table 10-2 (Ref. 10-9) presents the emission results obtained on a 1974 Chevelle Laguna with a 454 CID engine. A slight reduction of about 13% CO and 11% of NO_x but no reduction of HC emission was obtained after installation of Hooker Headers. When, in addition to Hooker Headers, the conventional inlet manifold was replaced by an Edelbrock Torker 2-0 manifold, 40% CO, 6% HC, and 20% NO_x reductions were recorded. Communication with the Edelbrock Company revealed that the above emission results were obtained by a CVS method with a hot-start rather than the cold-start as specified by law.

10.3.1.3 Cost and Maintenance

Besides Hooker Header Industries, several other companies manufacture tuned exhaust systems: Cyclone Automotive Products, Jardine Headers Company, Hedman Headers Company, Cragar Industries, Inc., etc. Moreover, in some distributor catalogs (e.g., J.C. Whitney &Co.), tuned headers of unidentified make are listed for most of the domestic and foreign cars. Depending on engine type and size, the price of a complete set of headers ranges from \$60 to \$110. The installation cost depends on the accessibility inside the engine compartment and is estimated between \$25 and \$75. On a large-scale, mass-production basis, the tuned headers could be produced and marketed for a lower cost than the conventional cast iron exhaust manifolds. However, the tuned headers are made of relatively light steel tubing and may be less durable because of the greater susceptibility to corrosion and to thermal cracking. Therefore, the manufacturers generally recommend coating the headers with a high-temperature-resistant paint once a year.

10.3.2 Dual Exhaust Systems

Dual exhaust systems are essentially two independent single exhaust systems connected to the exhaust manifold or manifolds of an automotive engine. The retrofit dual exhaust systems are advertised in several magazines and replacement parts catalogs as means to improve the fuel economy of the automobile. Typical suppliers include Hooker, Cyclone, Cragar, Spearco, and other unidentified makes listed in the automotive parts catalogs.

10.3.2.1 Fuel Economy

Test data were not obtained to substantiate claims made as to fuel economy gains resulting from installation of dual exhaust systems in place of a single exhaust system. Meaningful data on the influence of backpressure on air consumption and performance are available from the work of Bolt, et al. (Ref. 10-10), and this data can be used to estimate the expected effects of such dual systems, as described below.

The engine used in this project was a 1971 Ford 351 in.^{3} displacement W-series engine with the factory-installed 2-venturi Autolite carburetor and standard distributor. Nominal compression ratio for this engine is 8.9:1; the mean measured value was 8.5:1.

The engine conditions used in testing were selected to represent the normal range of steady-state automobile engine operation. The values used were the 15 possible combinations of speed and manifold pressure given below:

Engine Speeds, rpm	Absolute Inlet Manifold Pressure, in. Hg
1000	17
1500	21
2000	26
2500	
3000	

At the beginning of each test run, the engine was set at selected values of speed, absolute inlet manifold pressure, and exhaust backpressure. A speed-controlled dynamometer maintained engine speed, while the throttle and exhaust system valves were adjusted in turn to obtain the desired values.

As shown in Figure 10-8, the bhp was reduced as backpressure was increased, for all conditions tested. The experimental points are represented well by straight lines. The slopes of these lines become more negative as speed increases.

Since the throttle required minor adjustments to maintain constant manifold pressure as the backpressure was changed, there were corresponding variations in air consumption (Figure 10-9) and fuel flow rate. The fuel flow variations were reported in Ref. 10-10 for the 2000 rpm case only, and are shown, together with air consumption variations, in Figures 10-10 and 10-11. Figure 10-12 repeats the 2000 rpm bhp results of Figure 10-8 and denotes the corresponding fuel consumption (bsfc) resulting from the fuel flow of Figure 10-11. The resulting relative changes in bhp and fuel economy (1/bsfc) are compared in Figure 10-13 for the 2000 rpm test condition. As can be noted, the trends as a function of exhaust backpressure are similar and have nearly the same slope. Although definitive fuel flow information

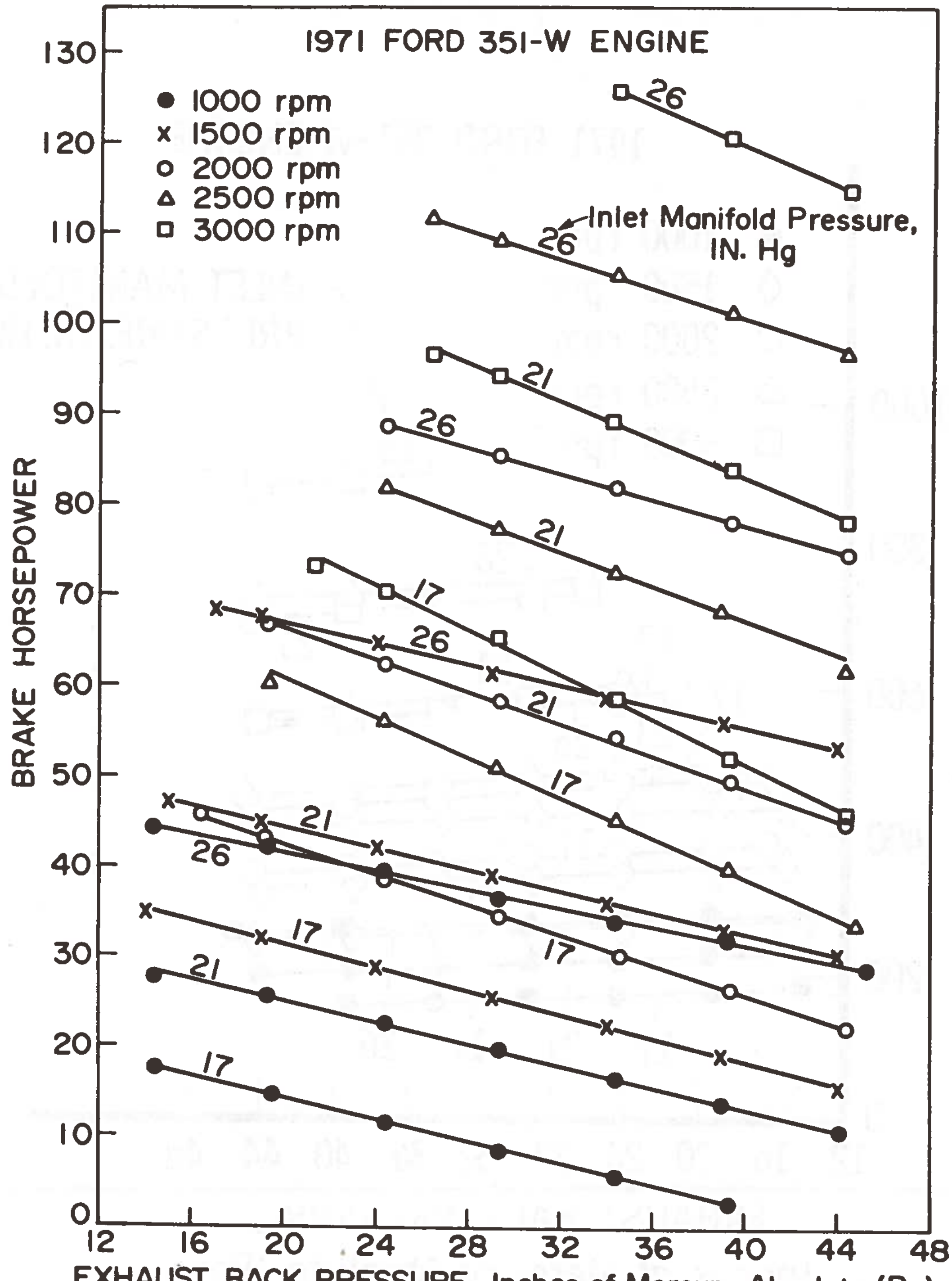


Figure 10-8. BHP as a Function of Exhaust Backpressure for Various Speeds and Absolute Inlet Manifold Pressures (Ref. 10-10)

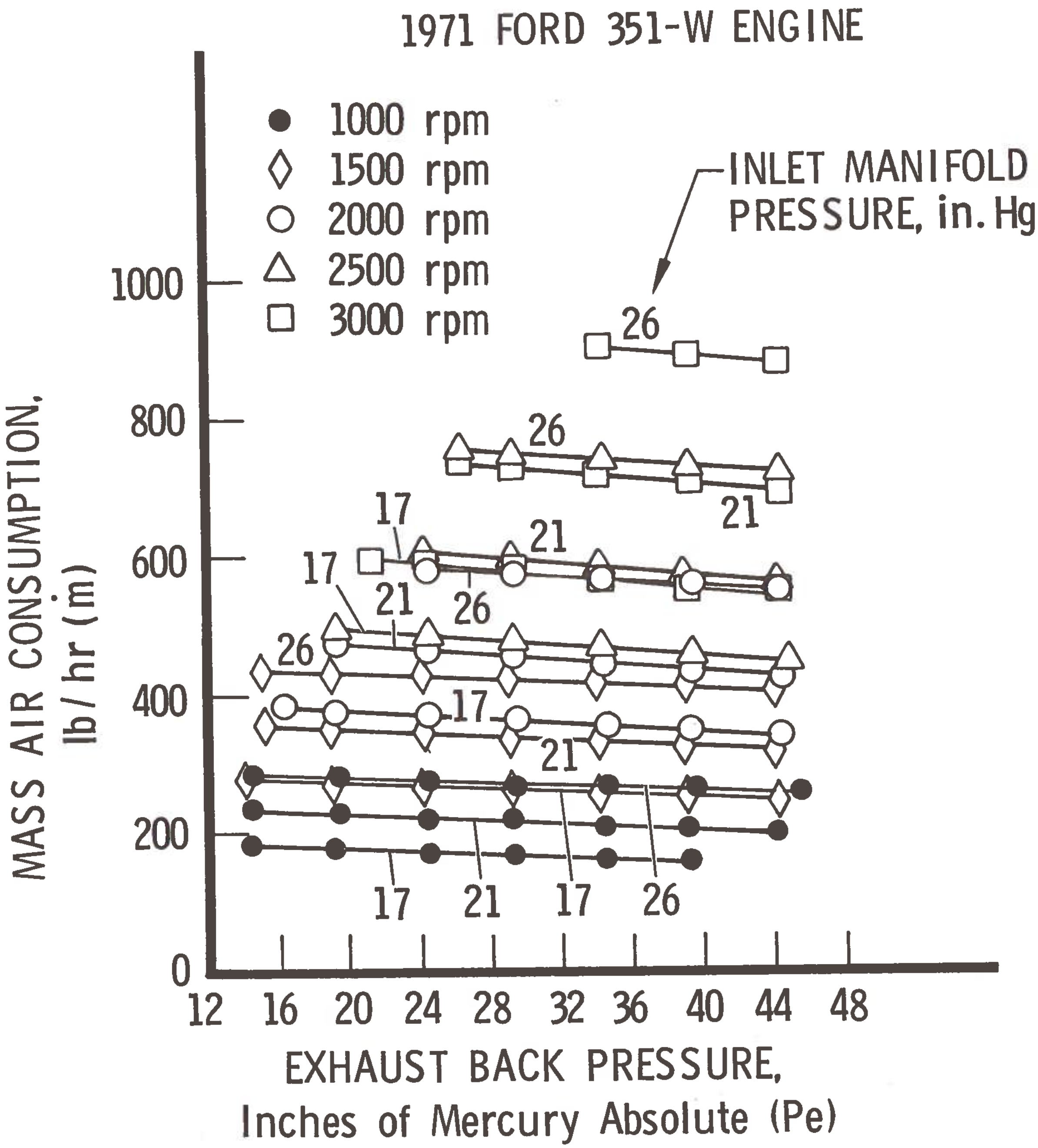


Figure 10-9. Mass Air Consumption as a Function of Exhaust Backpressure for Various Speeds and Absolute Inlet Manifold Pressures (Ref. 10-10)

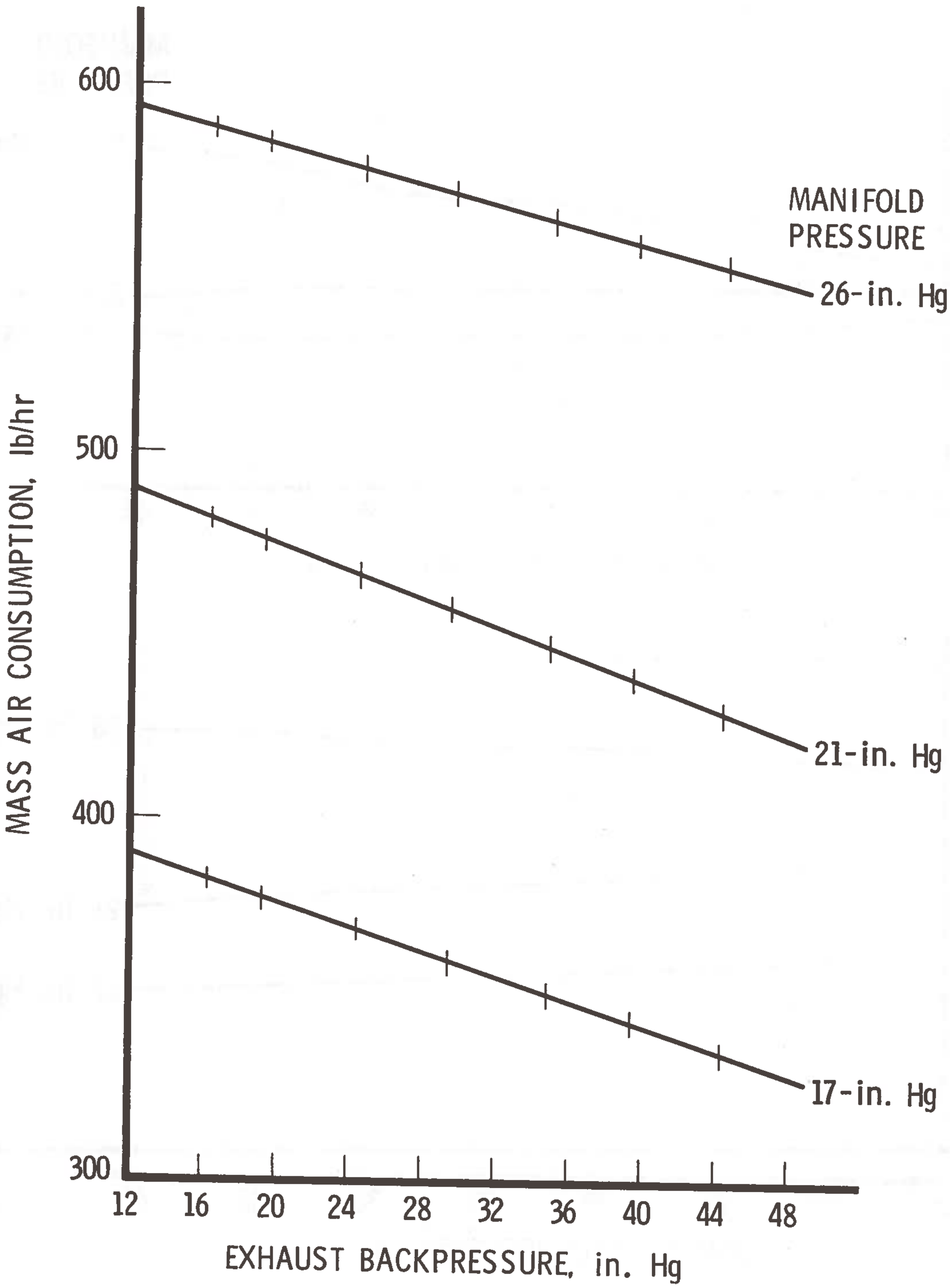


Figure 10-10. Air Consumption as a Function of Exhaust Backpressure at 2000 rpm (Ref. 10-10)

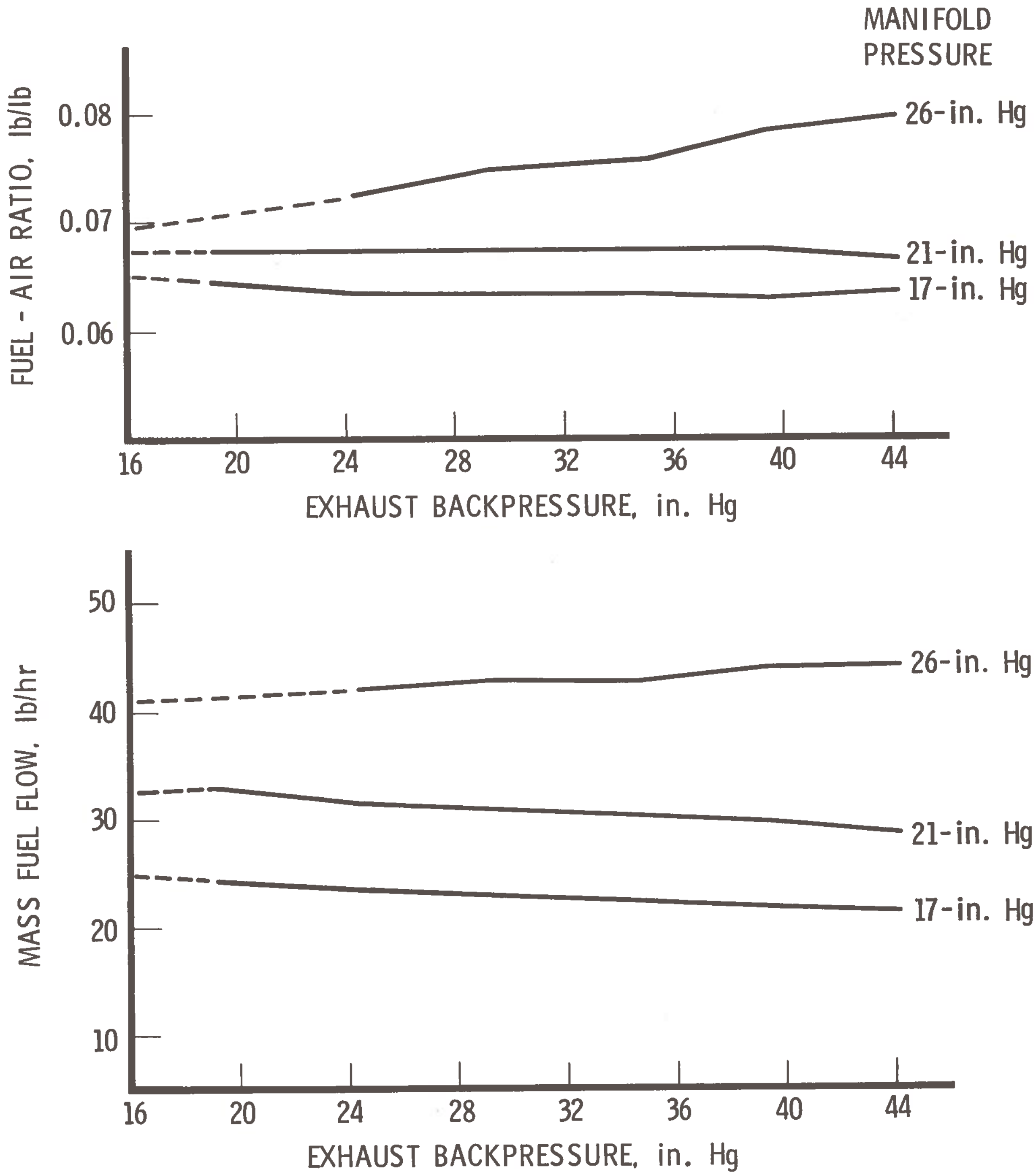


Figure 10-11. Fuel-Air Ratio and Fuel Flow as a Function of Exhaust Backpressure at 2000 rpm (Ref. 10-10)

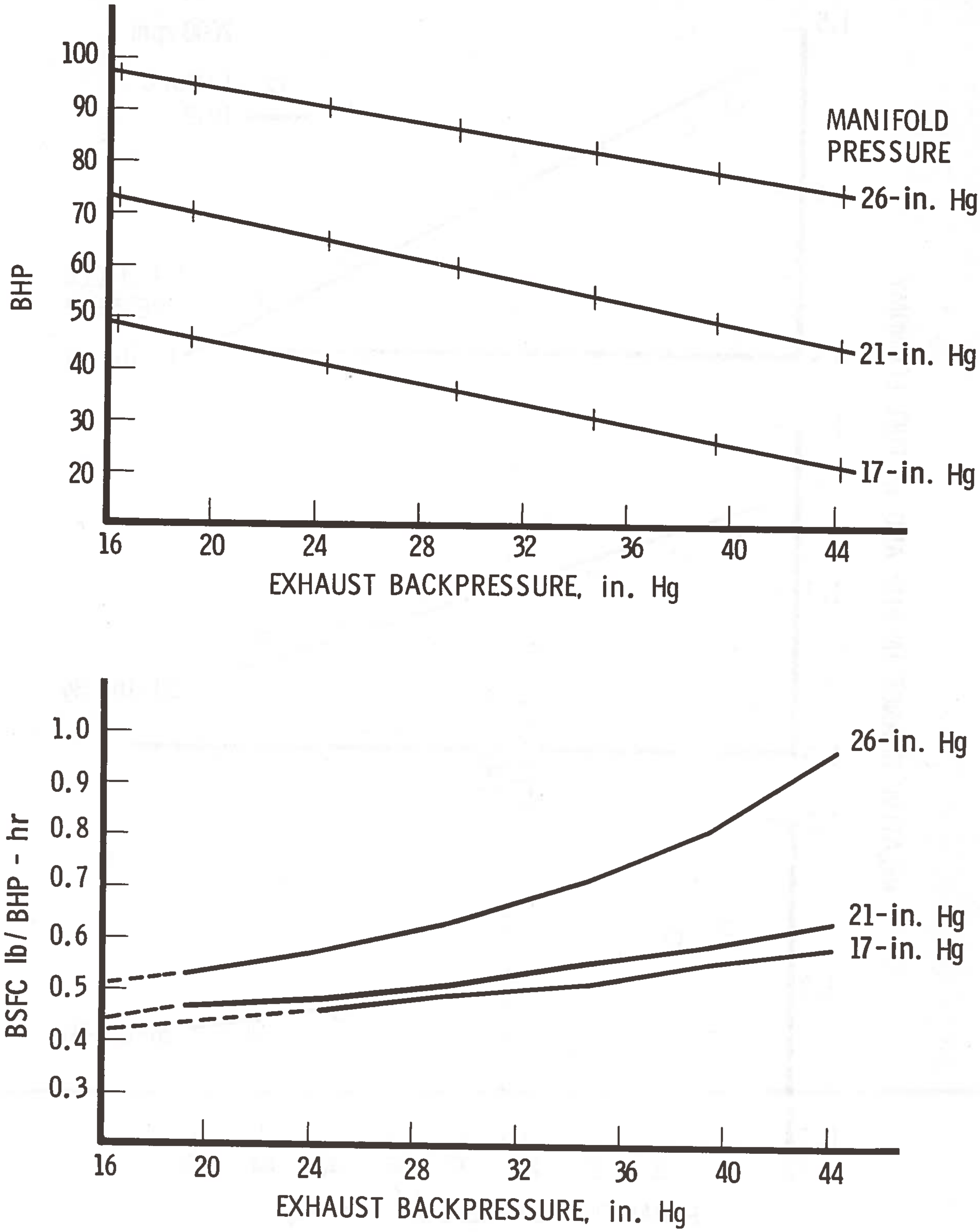


Figure 10-12. BHP and BSFC as a Function of Exhaust Backpressure at 2000 rpm (Ref. 10-10)

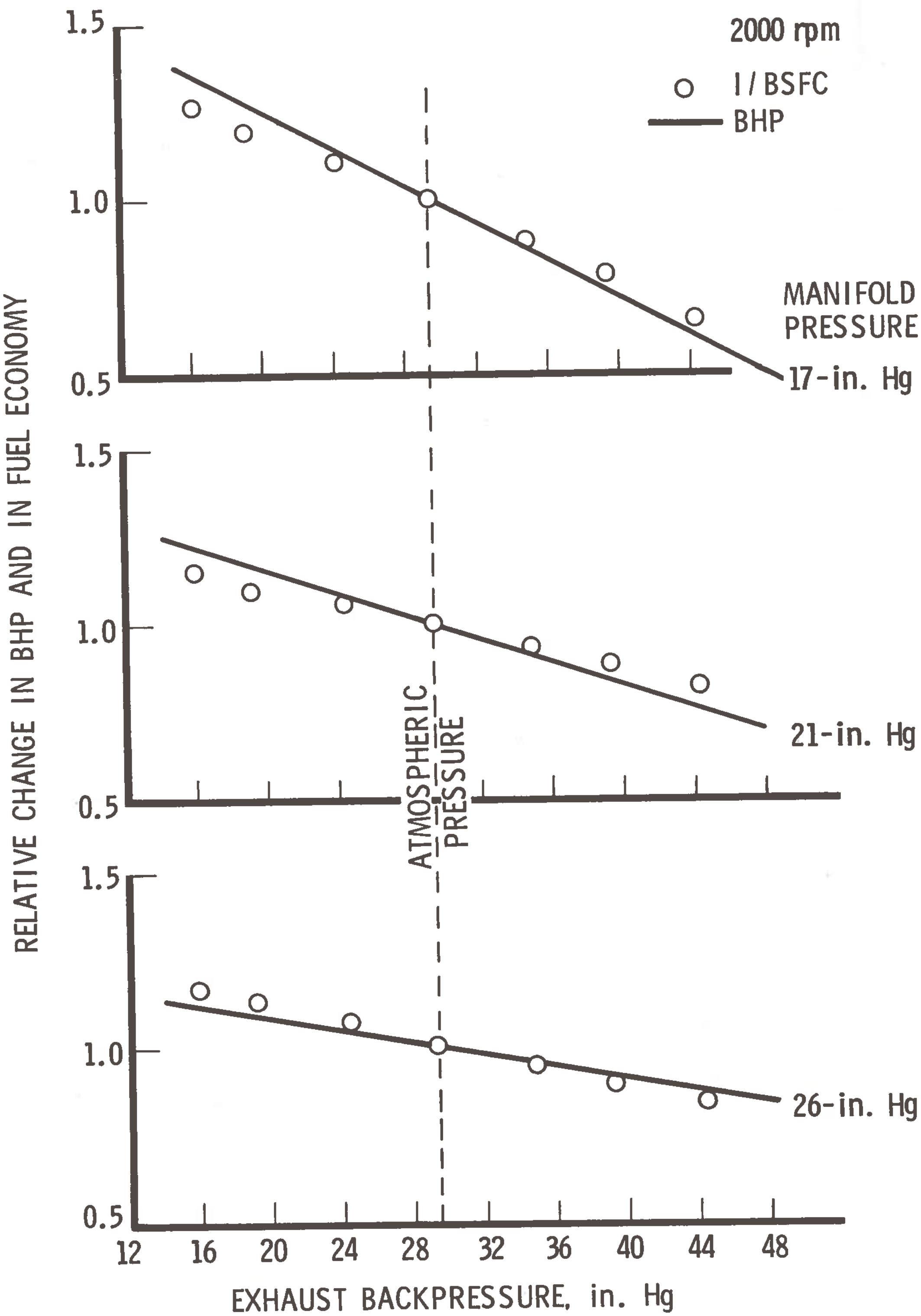


Figure 10-13. Relative Changes in BHP and Fuel Economy as a Function of Exhaust Backpressure at 2000 rpm

for the other test conditions is not available in Ref. 10-11, the similar slopes of the air flow and bhp lines of Figures 10-8 and 10-9 suggest that similar results are obtained at the other test conditions.

Based on an analysis of carburetor-engine-vehicle performance at road-load conditions reported by Harrington and Bolt (Ref. 10-11), the 2000 rpm test condition is consistent with vehicle speed operation in the 50 to 55 mph range at manifold pressures in the 14- to 15-in. Hg range. From data reported by Schaldenbrand and Struck (Ref. 10-12), Figure 10-14, a standard muffler system would have a pressure drop of approximately 10 in. of water (or approximately 0.74-in. Hg) at this road-load condition. Using the slope of the 17-in. Hg manifold pressure line of Figure 10-12 for illustrative purposes, decreasing the backpressure by 1-in. Hg results in a fuel economy increase of approximately 2.3%. Thus, completely eliminating the standard muffler backpressure at this road-load condition would result in a fuel economy increase of approximately 2%, based on the foregoing analysis.

Since the pressure drop through the exhaust system varies approximately as the square of the mass flow rate, installing a dual exhaust system could reduce the backpressure approximately 75%. However, under normal driving conditions, this would not have a large effect on fuel economy, as noted above.

10.3.2.2 Emissions

Figure 10-15 (Ref. 10-10) shows that an increase in exhaust backpressure results in a noticeable decrease of the concentration of the exhaust HC and NO_x. However, on a specific-mass-emission basis, this effect is significant only on engines with a large valve-timing overlap (Ref. 10-13). The specific mass emission of CO, on the other hand, will significantly increase with an increase in exhaust backpressure, as can be inferred from Figures 10-8 and 10-15.

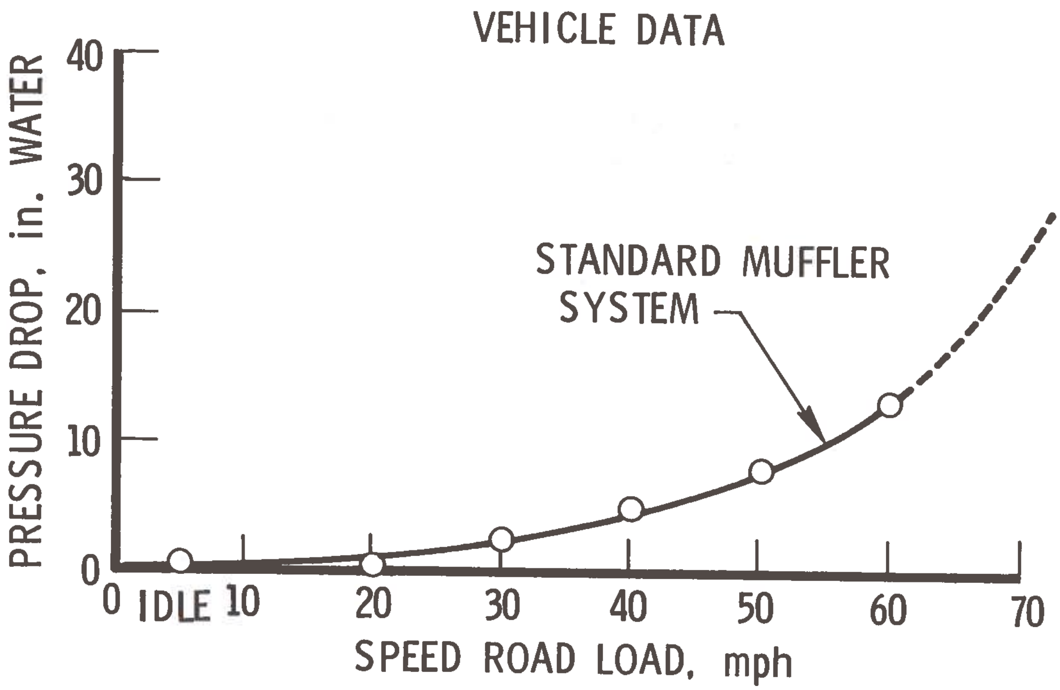


Figure 10-14. Exhaust System Pressure Drop as a Function of Car Speed at Road-Load Operating Conditions (Ref. 10-12)

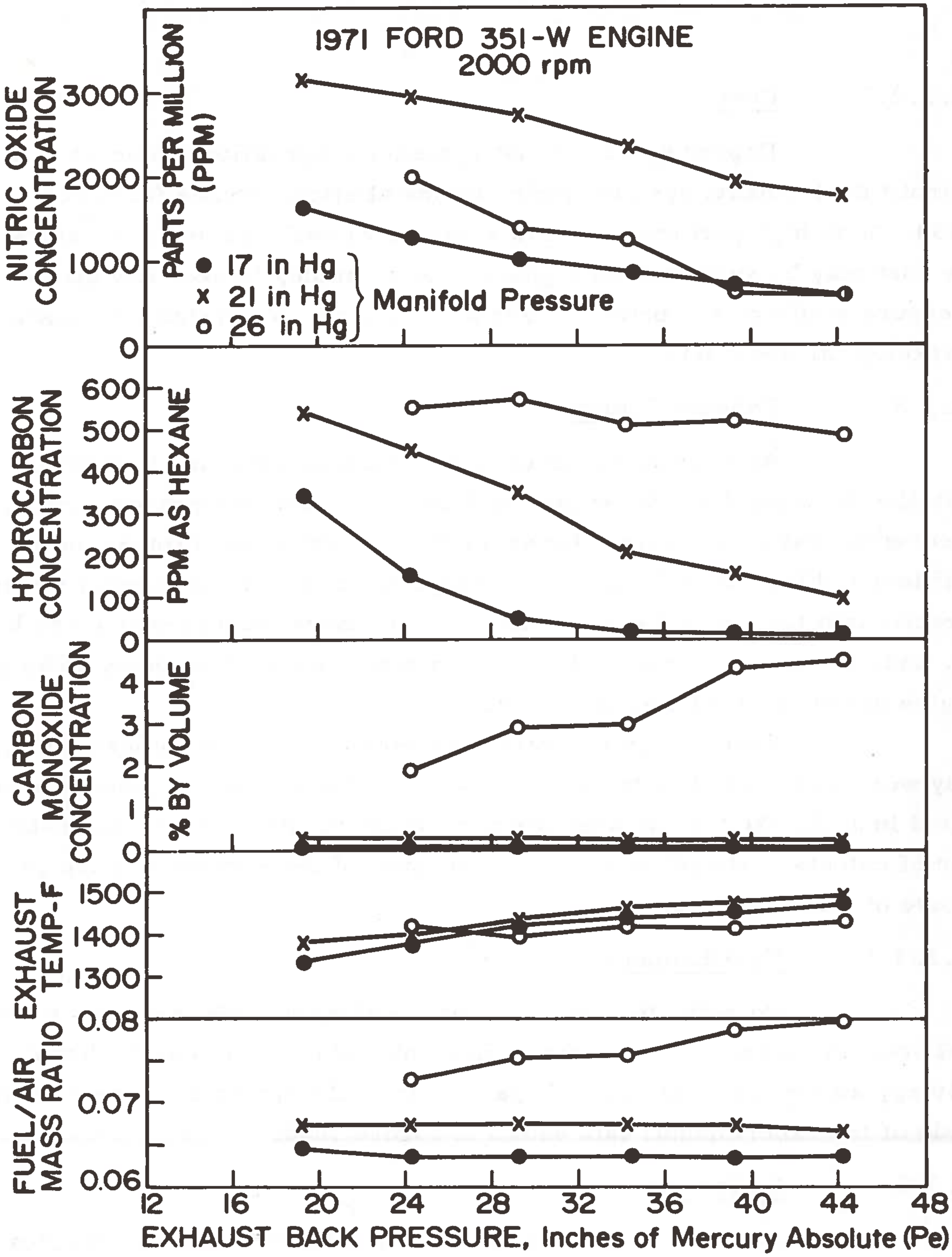


Figure 10-15. Effect of Exhaust Backpressure on Exhaust Emissions of an Automotive Engine (Ref. 10-10)

10.3.2.3 Cost

Depending on exhaust system configuration, the cost of a retrofit dual exhaust system, including installation, ranges from $65 to $130. With high performance (low resistance) mufflers and resonators, the cost may be substantially higher. For example, Hooker low back-pressure mufflers are priced at $48 as compared to conventional mufflers marketed for about $15.

10.3.3 Exhaust Cutouts

An exhaust cutout consists of a manually operated bypass valve installed between the exhaust manifold and the remaining exhaust system. By opening the valve, the driver bypasses the exhaust system (including the muffler) and lets the exhaust gases escape from the engine exhaust manifold directly into the atmosphere. This way, no exhaust backpressure can build up, and, therefore, some modest gain in power and fuel economy at high engine speed and load may be realized.

Exhaust cutouts were marketed for hot-rod enthusiasts before they were superseded by the tuned exhaust systems; however, they are still listed in J. C. Whitney automotive parts catalog. At present, the installation of cutouts is illegal in California because of the excessive noise caused by use of these devices.

10.3.3.1 Fuel Economy

No reliable test data substantiating the effect of cutouts on fuel economy have been presented. In combined city and open highway driving, an average fuel economy gain of 1% to 2% can be estimated on the basis of the experimental data shown in Figure 10-8.

10.3.3.2 Emissions

As discussed under "Dual Exhaust Systems," no significant effect on the specific mass emission of HC and NO_x due to reduced back-pressure (by means of exhaust cutout) is to be expected. Only a modest reduction of CO specific mass emission, proportional to the eventual power increase at high engine speeds when an exhaust cutout is used, may be realized.

10.3.3.3 Cost and Maintenance

Two makes of exhaust cutouts are listed in the J. C. Whitney catalog, one retailing for $2.98 and the other for $5.98. The units are manufactured of heavy gauge steel and cast iron, respectively, and no special maintenance is indicated.

10.3.4 Turbochargers

The turbocharger consists of a turbine driven by the engine exhaust gases connected to the shaft of a compressor which supplies air to the engine. Turbochargers are designed to be installed either upstream from the carburetor or between the carburetor and the inlet manifold. For a brief period, a turbocharger was offered as optional equipment on 1961 Corvairs and 1962 and 1963 Oldsmobile cars. In the automotive after-market, turbochargers are sold as retrofit systems for racing and high performance cars, generally to boost the maximum power of the engine. Usually, the operational characteristics are matched to augment engine torque over the range of 40% to 100% of the maximum allowable speed of the engine. Because of the increased tendency of the engine to knock, a rich air/fuel mixture at high loads is usually supplied. A properly retrofitted, tuned, turbocharged engine may provide as much as a 25% increase in maximum power output relative to the unmodified stock engine.

Turbochargers for internal combustion engines are manufactured by the Airesearch Industrial Division of the Garrett Corporation, Los Angeles, California; by Rajay Industries, Long Beach, California; and by Schwitzer Corporation, Division of Wallis Murray Company, Indianapolis, Indiana.

Airesearch, the largest manufacturer of turbochargers, markets a world-wide line of units for application to aircraft and automotive gasoline engines and to stationary, industrial, agricultural, and marine diesel engines. Over 300,000 units in five basic models for engines from 60-hp to 700-hp rating are manufactured yearly. A performance chart, supplied by the company, facilitates the selection of the proper model and dimensional configuration of the turbocharger for a particular engine.

Several independent companies produce turbocharger installation kits designed for popular car models (VW, Pinto, Vega, and Mustang). Some specialized firms also perform the installation on other makes and models of automobiles.

10.3.4.1 Fuel Economy

The effect of a turbocharger on fuel economy for a passenger car was investigated (Ref. 10-14). It was found that turbocharging resulted in a 2% to 3% decrease in fuel economy. However, when a turbocharged spark ignition engine was compared to a larger displacement, naturally aspirated engine of equal power output, an 18% to 24% better fuel economy was obtained with a turbocharged engine (Ref. 10-14).

In the case of retrofitting a passenger car gasoline engine with a turbocharger, some benefits in fuel economy might be obtained if the turbocharger characteristics are matched to the medium speed range of the engine, and maximum power in the high speed range is sacrificed. However, data on fuel economy for this type of matching of the turbocharger-engine system characteristics are not available to date.

10.3.4.2 Emissions

The exhaust emission data presented in Table 10-3 (Ref. 10-14) indicate that the turbocharging may increase the exhaust HC emission. This could be caused by a magnified mixture distribution problem or by the turbocharger oil leakage into the turbine housing. The increased NO_x emission is explained in Ref. 10-14 as the effect of higher inlet air temperature due to compression in the turbocharger. It should be noted that the brake specific emissions presented in Table 10-3 were determined according to the EPA 13-mode test procedure applicable to heavy-duty diesel engines. Therefore, these results cannot be directly compared with emission data obtained on similar engines by the standard CVS tests.

TABLE 10-3. THE EFFECT OF A TURBOCHARGER ON EMISSIONS FROM A 350 CID AUTOMOTIVE ENGINE (Ref. 10-14)

13-Mode Cycle Emissions, gm/bhp-h*				
	Without EGR		With EGR	
Emissions	Baseline	Turbocharged	Baseline	Turbocharged
HC	0.039	0.097	0.076	0.12
CO	1.220	1.120	1.380	1.19
NO_x	7.940	9.090	2.930	3.40

*EPA test procedure applicable to heavy-duty diesel engines

10.3.4.3 Cost and Maintenance

Turbochargers can be purchased in a kit form or installed by a specialized firm. The cost of the kit is approximately $600, and installation charges are about $200. When installed, the unit is connected to the engine lubricating system and requires no further maintenance.

10.3.5 Other Exhaust Devices

A few other exhaust devices have been advertised on the automotive specialty market with claims of improving engine power or fuel economy. These include tailpipe end attachments, some called exhaust ejectors and others exhaust boosters. They are not considered in detail herein, since they obviously would have a lesser effect on exhaust backpressure than the devices discussed previously.

10.4 SUMMARY OF EXHAUST-RELATED DEVICES

The prospect of making use of the relatively large amount of energy contained in the exhaust gases of internal combustion engines is gaining in importance as the shortage of fuels becomes a serious factor in the world-wide economy. Some of the devices applicable to automotive exhaust systems, as known today, are reported to substantially improve the fuel economy. However, statistical data covering an adequate cross-section of engine makes and of operating conditions are lacking. Until such data are available, no conclusive statement about the effectiveness of some of the promising devices can be made.

Table 10-4 presents the summary of the exhaust-related devices surveyed. Although some of the devices (e.g., tuned exhaust systems and dual exhaust systems) are also manufactured by several other smaller companies not listed in this table, their products are generally similar with respect to performance characteristics, price range, and installation requirements. The devices which only reduce the exhaust backpressure, such as the dual exhaust systems and exhaust cutouts, are the least expensive and easiest to install. However, they have relatively little effect on the fuel economy of the automobile and no effect on exhaust emissions. Although they could be made readily available in large quantities and their cost further reduced on a mass production basis, they do not appear to be feasible retrofit measures from a cost/benefit consideration.

The devices which make use of the energy contained in the exhaust gases through an expansion process (turbochargers) or through gas dynamical effects (tuned exhaust systems) are more complex and more costly to manufacture and to install as retrofit systems. The turbochargers, even though well developed and in mass production, are high priced and require considerable time and skill to install. At present, the installation kits are available only for a few compact automobiles. As indicated in Table 10-4, the effect of turbocharging on exhaust HC and NO_x is negative. If a turbocharger is installed on an existing engine as retrofit system, even with characteristics matched for best fuel economy, relatively little gain is to be expected. If, however, the existing engine were exchanged for one of about 30% smaller CID, then the installation of a turbocharger on the smaller engine would result in the same maximum power capacity as the original engine. Since the smaller engine would be operated on a high load level and consequently at better efficiency, an overall fuel saving gain of about 20% could be realized.

TABLE 10-4. SUMMARY OF EXHAUST-RELATED SYSTEMS

Device	Hooker Headers (Tuned Exhaust Systems)	Cyclone Headers	Hooker Headers & Edelbrock Manifolds	Hooker Dual Exhaust Systems	Exhaust Cutout	Airesearch Turbocharger	Wallis Murray Turbocharger	Rajay Turbocharger
Degree of Fuel Economy (Miles Per Gallon) Improvement	5% - 14% * 6% - 17% ** - 22% ***	15% *	10% - 17% *	N. I.	N. I.	3% negative * 18%-24% pos. **	N. I.	5% - 6% * 9% - 13% **
Retrofit Device or "Kit" Content and Physical Characteristics	see Figure 10-6	individual cylinder exhaust pipes merged to common collector	see Figure 10-6 and Figure 10-7	two independent exhaust systems connected to exhaust manifolds	by-pass valve installed between the exhaust manifold and the exhaust system	exhaust turbine and turbo-compressor plus controls and hardware	N. I.	exhaust turbine and turbo-compressor, plus installation kit
Compatibility with Mass Production	yes	yes	yes	yes	yes	yes	yes	yes
Potential Availability in Quantity in Near Future	N. I.	18,000 units per year	N. I.	N. I.	N. I.	350,000 units/year	180,000 units per year	24,000 units per year
Applicable Vehicle or Engine Models (Gasoline and Diesel)	R. V. - vehicles, compacts, trucks, vans	gasoline l. d. vehicles	gasoline l. d. vehicles	gasoline and diesel l. d. vehicles	gasoline and diesel l. d. vehicles	gasoline and diesel vehicles 1)	gasoline and diesel vehicles 1)	gasoline *** l. d. vehicles
Attendant Installation Requirements (including Necessary Facilities)	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment	service garage equipment
Installation Time Requirement	3 - 8 hr.	3 - 8 hr.	6 - 10 hr.	1/2 - 1 hr.	1/2 - 1 1/2 hr.	16 hr	N. I.	6 - 8 hr.
Cost to Consumer for Device for Installation	$75 - $230 $45 - $120	$60 - $140 $45 - $120	$300 - $400 $ 90 - $150	$70 - $130 $ 8 - $ 15	$3 - $6 $8 - $25	$600 $200	N. I.	$585 - $620 $ 90 - $120
Special Maintenance Requirements	none	none	none	none	none	none	none	none
Effect on HC, CO, and NO_x Emissions (if any)	HC, CO, moderate reduction	N. I.	40% CO, 20% NO_x reduction *	none	none	negative on HC and NO_x	N. I.	N. I.
Effect on Vehicle Power and Acceleration Performance (if any)	25% power increase claimed	20% power increase claimed	power increase claimed	power increase claimed *	power increase claimed *	40% torque, 30% max. power increase	N. I.	12% - 24% faster acceleration
Type of Data Available	CVS - test hot start	single road test	CVS - test hot start	N. I.	N. I.	steady state engine-dyno test data	N. I.	statement in advertisement catalog
Source and Reliability of the Data Base	company test no statistical data	pamphlet released by company	company test no statistical data	N. I.	N. I.	company pamphlet and SAE paper	N. I.	N. I.
Theoretical Background	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2	see heading 10.2.2
Remarks	* Vega ** Chev. pickup *** R. V. pickup	* advertisement in magazines, no test data	* company test no official test data	* advertisement in magazines, no test data	*advertisement in parts catalog no test data	*on engines of equal displacement ** on engines of equal power		* V-6 Capri ** V-6 Mustang *** for few compacts only

N. I. = no information

1) Installation kits available only for few compact cars

The most promising exhaust-related devices from a cost/benefit point of view appear to be the tuned exhaust systems (headers). The tuned exhaust systems as advertised in several auto-parts catalogs and marketed by a number of well-known firms (as well as some unidentified manufacturers) are moderately priced and required no special skills to install. They are available for most of the popular domestic and foregin automobiles, and, because of the growing demand, their production is steadily increasing. Up to 25% power increase and 5% to 20% fuel economy gains have been claimed for certain cars retrofitted with tuned exhaust systems. However, no statistical test data obtained by official test laboratories have been presented. At this writing, it is not known to what extent the currently marketed tuned exhaust systems are optimized for their capability to improve the fuel economy of the automotive engine. According to some manufacturer statements, these systems were developed primarily for improvement of the engine power and performance. On the basis of this information and the theoretical background available, it can be inferred that the commercially obtainable tuned exhaust stystems probably do not realize the full potential improvement in fuel economy.

No adverse effects of tuned exhaust systems on exhaust emissions, noise, engine performance, and maintenance are indicated.

10.5 REFERENCES FOR SECTION 10

10-1. C. F. Taylor, The Internal-Combustion Engine in Theory and Practice, Vol. 1 and 2, The M. I. T. Press, Cambridge, Massachusetts (1968).

10-2. E. Schmidt, Thermodynamik, 4th ed., Springer-Verlag, Berlin, Germany (1950).

10-3. E. F. Obert, Internal Combustion Engines, 3rd ed., International Textbook Company, Scranton, Pennsylvania (1968).

10-4. P. H. Smith and J. C. Morrison, The Scientific Design of Exhaust and Intake Systems, Robert Bentley, Inc., Cambridge, Massachusetts (1968).

10-5. E. Jenny, Berechnungen und Modellversuche über Druckwellen grosser Amplituden in Auspuff-Leitungen, Ph.D. thesis, Swiss Institute of Technology, Zurich (1949).

10-6. P. H. Schweitzer, C. W. Van Overbek, and L. Manson, "The Kadenacy Effect," Engineering 160, 241-299 (1945).

10-7. Hooker Makes Horsepower, Sophisticated, High Performance Exhaust Systems, List Price and Applications, Hooker, (March 1, 1974).

10-8. C. J. Baker, "The Great Header Emission, Mileage & Noise Flap," Hot Rod Magazine, p. 35 (May 1974).

10-9. N. Mayersohn, "The Impossible Dream," Car Craft 22 (4) (April 1974).

10-10. J. A. Bolt, et al., "The Influence of the Exhaust Back-Pressure of a Piston Engine on Air Consumption, Performance, and Emissions," SAE Paper No. 730195, SAE Congress, Detroit, Michigan, January 1973.

10-11. D. L. Harrington and J. A. Bolt, "Analysis and Digital Simulation of Carburetor Metering," SAE Paper No. 700082, January 1970.

10-12. H. Schaldenbrand and J. H. Struck, "Development and Evaluation of Automobile Exhaust Catalytic Converter Systems," SAE Paper No. 486-E, March 1962.

10-13. J. D. Benson and R. F. Stebar, "Effects of Charge Dilution on Nitric Oxide Emission from a Single-Cylinder Engine," SAE Paper No. 710008, SAE Congress, Detroit, Michigan, January 1971.

10-14. J. F. Schweikert and J. H. Johnson, "A Turbocharged Spark Ignition Engine with Low Exhaust Emissions and Improved Fuel Economy," SAE Paper No. 730633, Chicago, Illinois, June 1973.

SECTION 11

MISCELLANEOUS TECHNIQUES/DEVICES

Under the category of miscellaneous techniques/devices for fuel economy improvement, two general areas were examined. The first area included engine oils, additives, and filters for which specific fuel economy improvement claims have been made. The second area deals with removal of or tampering with emission control systems by individuals in an attempt to improve fuel economy.

11.1 ENGINE OILS, OIL ADDITIVES, AND FILTERS

11.1.1 Engine Oils (Key Oil)

The sales literature on engine oils and engine oil additives is replete with claims of superior product performance with respect to lubricity, anti-wear, anti-corrosion, and other properties. A number of oil products also claim to provide improved engine performance as well as benefits in fuel economy. One of these, Key Oil, manufactured by Key Oils & Lubricants, Inc., Santa Fe Springs, California, is sold specifically as an engine oil rather than as an oil additive.

The manufacturer states that they purchase 100% paraffin base oil from eastern or mid-continent refineries and further process the oil in such a manner as to impart to it certain superior attributes including improved wetting and lubricating qualities, very high film strength which prevents metal-to-metal contact and reduces piston blowby by 90%, plus very high resistance to breakdown. These attributes lead to the following claims for this motor oil:

a. Significantly reduced friction losses leading to increases in fuel economy of 20% or more

b. Reduced wear and extended engine life

c. Sharply reduced blowby, resulting in greater engine power and reduced oil contamination

d. Oil lifetimes of more than 50,000 miles without breakdown

e. Reduced oxidation and corrosion

In addition, a wide range of viscosity index is achieved (10W - 30W, 20W - 50W), probably by use of the same viscosity-improver additives that are normally contained in premium lubricants.

The available evidence to support these claims is meager, consisting only of testimonials from two sources: an article in the May 1974 issue of Motor Trend magazine (Ref. 11-1) and a verbal testimonial from H. Gregory, Plant Engineer for Hughes, Fullerton, California (Ref. 11-2). Motor Trend magazine reported an increase of 13% in fuel economy in a Chevrolet Vega driving on their standard 73-mile test loop in Los Angeles (including both surface street and freeway driving). In addition to the Key motor oil used, the transmission lubricant was changed to a Key Oils gear lubricant product for which low friction properties are also claimed. Thus, the fuel economy benefits reported may include possible effects due to the gear oil.

A telephone conversation with H. Gregory, Production Plant Engineer and General Foreman at the Hughes facility in Fullerton (Ref. 11-2), revealed they are enthusiastic users of Key Oils products. The Hughes plant has been using Key industrial oils with great success since April 1974. Gregory claims that tooling life has been increased tenfold, and savings in the cost of tooling coolants "run into the thousands." Prior to using the Key lubricants, the water soluble oil used in tooling coolants had to be changed every 24 hours because of oil breakdown. The Key coolant products have not been changed since they were adopted at Hughes in April 1974. Hughes planned also to use Key motor oil in their transportation fleet of new leased vehicles, beginning in 1975. Gregory has been using the oil in his personal automobile and believes it has improved his mileage.

Key motor oil is priced at $1.75 a quart and is available through several distributorships in Southern California. Presently, the bulk of the company's business is with medium to large users such as Hughes and diesel truck operators. Present plant capacity is 12,000-16,000 gallons per day, although the present operational level is not that high (Ref. 11-3).

Table 11-1 provides a summary evaluation of the Key Oil product. The manufacturer recommends and sells an engine flush (probably a detergent compound) to be used before changing to the Key motor oil. The purpose of this procedure, it is said, is to remove as much friction-producing material as possible to allow the low-friction Key oil to operate under optimum conditions. The process involves about one-half hour labor and two oil filter changes. The manufacturer suggests that subsequent oil changes are not really necessary; only periodic changes of filters with the addition of one quart of new oil at about 5,000 mile intervals are required.

With such little information available, it is difficult to assess the merit of this product. The composition of the oil is proprietary, and the manufacturer is unwilling to discuss any details of the process except to state that it involves further refinement of the base oil stock. The Motor Trend article (Ref. 11-1) adds that the product is a petroleum-based oil that has been re-refined "to remove all the resins, tars, varnish, and other friction and dirt-causing elements that are normally left in other oils." It is noted, however, that all modern lubricants undergo extensive refinement to remove such objectionable components. Indeed, the refining may be so thorough as to remove hydrocarbon fractions that are desirable for effective lubrication. For this reason, the refined oil is frequently tempered or seasoned by the addition of chemicals that provide the desired properties (Ref. 11-4). Some of the properties ascribed to Key oil, such as anti-wear, oiliness, and high film strength, are achieved in other oil products by the use of additive agents which combine with or adhere to metals to form surface films with lubrication qualities exceeding the capability of the base oil (Ref. 11-5). These additives are further discussed under the next heading.

The manufacturer's claims for fuel economy improvement by the use of this product must be discounted. A 20% improvement in fuel economy corresponds roughly to a 3.5% improvement in engine thermal efficiency, which is equal to about half the total loss due to mechanical friction in the engine. Other sources (Ref. 11-6 and 11-7) suggest that advanced oil formulations might contribute fuel economy gains of from 6% to 10% or less.

TABLE 11-1. EVALUATION SUMMARY, KEY OIL

1.	Degree of Fuel Economy Improvement	Manufacturer claims 20% or more. This evaluation not quantified; may be negligible
2.	Kit Content	Motor oil; Cost: $1.75 per quart
3.	Mass Producibility	12,000-16,000 gal/day
4.	Availability	Southern California
5.	Applicable Models	All motor vehicles
6.	Installation Requirements	Initially, use of engine flush for 4 hr. and change of filter before using Key oil.
7.	Installation Time and Cost	0.5 hr. - $7.50
8.	Maintenance Requirements	Change oil filter periodically
9.	Effect on HC, CO, and NO_x	None
10.	Effect on Vehicle Power, Acceleration	Increased power due to decreased blowby
11.	Types of Data Available	Testimonials only
12.	Reliability of Data Base	Poor

Lacking authoritative test verification of the benefits provided by the Key oil product, it is not recommended for test as a device with high potential for fuel economy gains.

11.1.2 Engine Oil Additives (Hilton Hy-Per-Lube)

One engine oil additive was investigated during the course of this study. Hilton Hy-Per-Lube is manufactured by the Hilton Products Co., Seattle, Washington. This product is designed to be added to the conventional motor oil every oil change, one quart to every four quarts of the base motor oil. The claims for this additive are essentially the same as those for the Key oil product; that is, improved fuel economy (7%-11%), better piston ring seal for improved power, and reduced tendency for oil breakdown, foam out, etc.

There are no available data on the performance or composition of Hy-Per-Lube. The known features of the product are summarized in Table 11-2.

As discussed earlier, the use of additives in motor oils for the purpose of achieving desired properties is common practice in the manufacture of premium lubricants. Such additives include corrosion inhibitors; detergent-dispersants; anti-foam, oiliness, anti-wear, and extreme pressure agents; etc. Improved friction and wear characteristics are achieved through the use of various chemical compounds which act to form films which adhere to or combine with the metal surfaces and enhance boundary lubrication. A description of these agents and their function may be found in Ref. 11-5 and 11-8, among many other sources.

Hilton Hy-Per-Lube may be a formulation of an extreme pressure agent combined with a number of other common oil additives. This idea is reinforced somewhat by the background of the manufacturer (Ref. 11-9). The primary business of Hilton Products is the manufacture of high-speed electric drives for large valves used in industrial plants, such as paper mills. The Hy-Per-Lube was originally developed by Hilton as a special lubricant for these drives which undergo severe stresses. The apparent success of the lubricant encouraged its marketing as an automobile engine lubricant. In addition to these products, Hilton now markets hydraulic oils which are being used in large cranes at the Seattle waterfront.

TABLE 11-2. EVALUATION SUMMARY, HILTON HY-PER-LUBE

1.	Degree of Fuel Economy Improvement	Manufacturer claims 7%-11%. This evaluation not quantified; may be negligible
2.	Kit Content	Oil additive; cost: $3 per quart
3.	Mass Producibility	No identified limitations
4.	Availability	Pacific Northwest
5.	Applicable Models	All motor vehicles
6.	Installation Requirements	No special requirements
7.	Installation Time and Cost	Part of regular oil change, no charge
8.	Maintenance Requirements	None
9.	Effect on HC, CO, and NO_x	None
10.	Effects on Vehicle Power, Acceleration	Manufacturer claims power boost. Confirming data not available.
11.	Types of Data Available	None
12.	Reliability of Data Base	-

This product is not recommended for test as a device with high potential for fuel economy gains.

11.1.3 Oil Filters (GEM)

The Griswold Electromechanical (GEM) automotive filter is an innovation in the oil filter market that is being developed by the Special Equipment Company (SECO) of Pasadena, California. The system is an electromechanical oil purifier. It is a combination electrostatic separator and a conventional mechanical filter that is designed to substitute for the standard automobile oil filter package. The device is an adaptation of a principle utilized for some years in portable filtering equipment used to purify hydraulic oils in various machinery. This equipment has been manufactured by SECO; one notable use was for reclaiming turbine oils in USAF Titan II rocket launch vehicles. The filtration principle has been patented by its inventor, Edward A. Griswold.

The manufacturer makes no specific claims about the magnitude of fuel economy improvement that the device will achieve. Their claims are expressed in terms of the oil cleanliness that can be maintained, and one may infer from this that reduced friction due to the absence of particulate matter in the oil circulating in the engine will provide a worthwhile benefit. They claim that the GEM system has nearly 100% filtration efficiency for particulate matter ranging from molecular size to 100 micrometers. On this basis, an indefinite lifetime is claimed for the engine oil (500,000 miles) and, by inference, a comparable lifetime for the engine. SECO has plans to extend this filter system to other automotive functions such as filtering carburetor air, passenger compartment air, lube oil, and exhaust both before and after passage through catalytic mufflers.

The filtration action of the GEM filter combines electrostatic and mechanical separation. The filtration element is planned to be the same size as conventional automotive oil filters and would be installed similarly. An exact description of the automotive filter element is not available. In lieu of this, the inventor provided a description of its patented antecedent. A patent drawing of this device is presented in Figure 11-1. The electrodes for

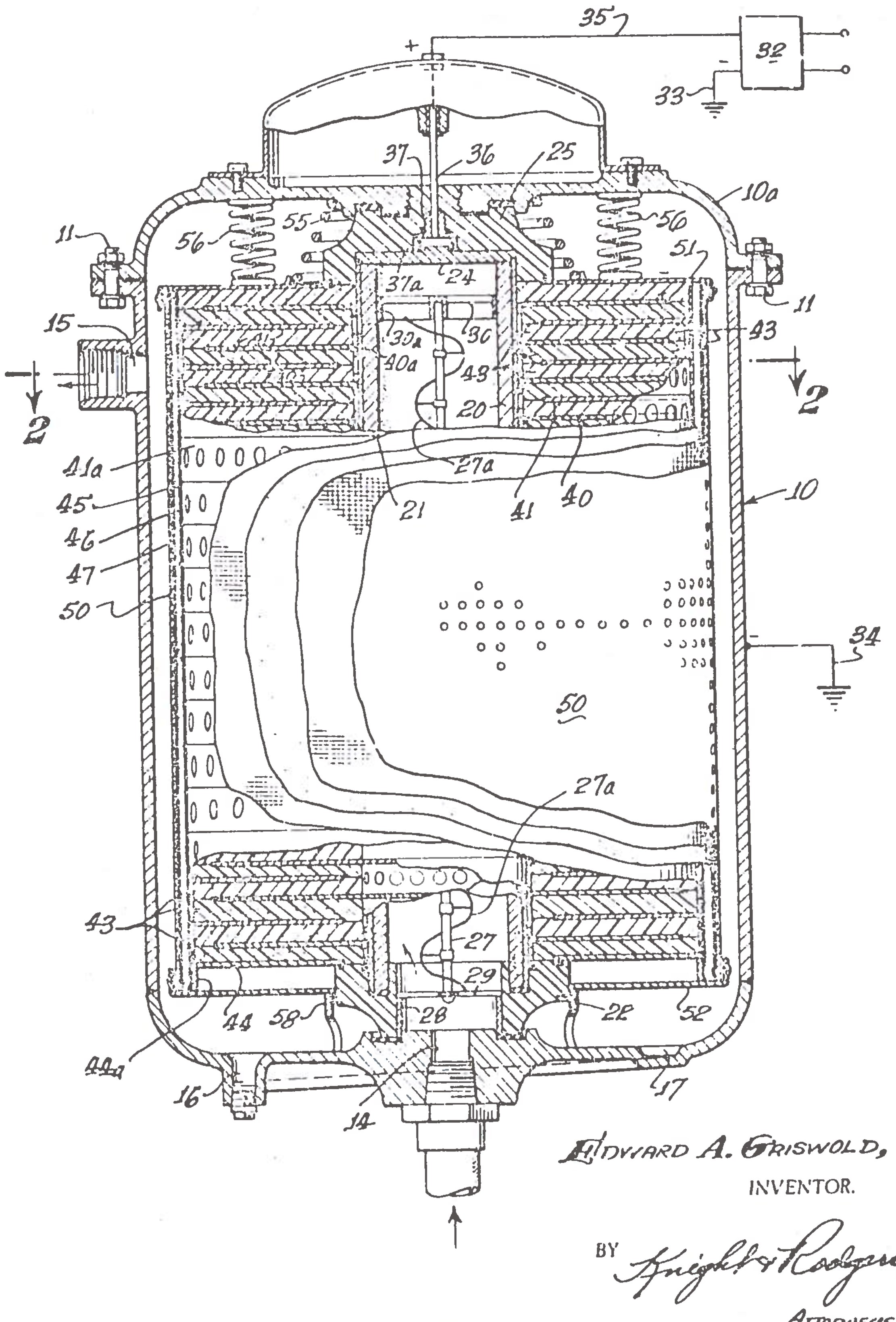


Figure 11-1. GEM Filter Patent Drawing

the electrostatic portion of the device consist of a central wire and tube assembly which also serves as an entrance tube for the incoming fluid. The fluid passes through this tube, depositing some of its particulate load on the tube surface. The fluid passes out of the central tube radially through holes in the tube surface and through the porous mechanical filter element. These elements are held in a matrix between metal plates alternately fixed to the inner tube and outer shell of the filter element. The plates are oppositely charged and act as additional electrostatic separators. After passage of the oil radially through this filter matrix, it passes through a third filtering element consisting of a cylindrical mechanical filter bonded on the inside of the outer shell. It exits the element through the holes in the outer shell and flows between this shell and the filter casing to the oil return line.

The operation of the electrostatic filter is described as follows in literature provided by the inventor: "The charging mechanism of the GEM is contact electrification. The particles moving with the fluid between charged plates in the presence of an electrical field migrate to the collection plates due to electrophoresis. This phenomenon is due to natural surface charges on the particles resulting from the chemical structure of the particle; i.e., charged atoms or groups of atoms. When the particles contact the charged plates, they may either stick to the plate or rebound. The smaller particles (< 0.1 µm) tend to stick, held by molecular attractive forces (Van der Waals forces). The larger particles may rebound, carrying with them a charge of the same sign as the plate they contacted. As these charged particles continue to flow, they are attracted to particles of the opposite charge and tend to flocculate. The flocked particles become large enough to be collected by the porous mechanical matrix and by the cylindrical filter element surrounding the electrode matrix. In a closed system, such as an automotive lubricating system, multiple passes through the filter are available for cleaning, thereby enhancing collection efficiency."

The inventor states (Ref. 11-10) that the pressure drop through this device is low in the beginning and remains low. He also states that cleaning is only infrequently required and may be accomplished by backflushing or rapping. It is not clear how these characteristics are maintained over the asserted long life of the filter.

The only available test information on this system consists of records, submitted by the inventor, of tests run by the U. S. Air Force on Titan II turbine oil. The military specifications only required filtering down to the 5-10 μm size range so that no data on filtering efficiency below 5 μm were obtained. Above 5 μm, efficiency exceeded 99% after one hour of filtering and approached very close to 100% after three hours. The inventor claims to have a demonstration setup in which he filters a rouge powder with a mean particle size of less than 1 μm. Initially, after addition of the rouge, the oil is extremely murky, but it is clarified by the electromechanical filter in a very brief time. Quantitative efficiency data on this experiment were not provided.

A summary of information on this product is given in Table 11-3. The inventor claims that the GEM automotive oil filter is now ready for production but does not reveal specific marketing plans. The item is readily mass produced and will sell in a price range $10 to $100 depending on the production rate. Installation time and cost are very low, involving only a filter replacement and an electrical connection with the coil. Maintenance would involve periodic inspection and cleaning; the period and method were not specified.

In summary, this device is offered as a technique for cleaning motor oils to a high degree of purity as a means of achieving long engine life by reduced wear. No specific claims on fuel economy improvements are made, although some benefits are inferred to accrue by virtue of reduced engine friction achieved by the removal of oil particulates. No information on engine performance with this device is provided. The filtration principles utilized have been demonstrated in non-automotive applications; however, the sub-micron filtering capability claimed by the inventor is not substantiated by available data.

This device is not considered to have a high potential for fuel economy improvement. Accordingly, it is not recommended for test evaluation

TABLE 11-3. EVALUATION SUMMARY, GEM FILTER

1.	Degree of Fuel Economy Improvement	No claims; probably negligible
2.	Kit Content	Filter element containing electrodes and mechanical filter element, lead from Hi Voltage Coil and Diode; Cost: $100 (low production rates)
3.	Mass Producibility	High rates possible
4.	Availability	Not yet in production
5.	Applicable Models	No limitations
6.	Installation Requirements	Either car owner or mechanic can accomplish by following instructions
7.	Installation Time & Cost	0.5 hr., $5-$10
8.	Maintenance Requirements	Periodic inspection & cleaning
9.	Effect on HC, CO, and NO_x Emissions	None
10.	Effect on Vehicle Power, Acceleration	None
11.	Types of Data Available	No independent tests, manufacturer's information only. Little quantitative data
12.	Reliability of Data Base	Unknown

11.2 REMOVAL OF EMISSION CONTROL DEVICES

11.2.1 Introduction

Numerous control techniques have been employed to reduce automotive exhaust emissions. A brief description of these emission control techniques is presented to provide an insight into their operation and the effect on fuel economy.

There are two key vehicle design factors that have been modified by the automakers to achieve lower exhaust emissions: spark timing and carburetion (air-fuel ratio). Additionally, there have been compression ratio reductions made to allow for the use of low-octane low-lead fuel and to reduce NO_x formation. These compression ratio reductions have reduced fuel economy by an average of 3.5% (Ref. 11-11).

Retarding of the spark advance from its optimum setting for best fuel economy can reduce exhaust emissions within the cylinder and outside of the cylinder. With retarded timing, the combustion is initiated later, and the piston is further down the cylinder during the main portion of the combustion event. This results in reduced exposure to the high temperatures which are conducive to high oxides of nitrogen (NO_x) formation.

Retarded timing also results in increased exhaust temperature because of the reduced expansion of the burned gases which result when the combustion is initiated later in the cycle. The high exhaust temperature promotes the further oxidation (combustion) of hydrocarbon (HC) and carbon monoxide (CO) in the exhaust system.

The carburetion required for minimum emission depends on the type of control technique being used on the engine. The high oxygen availability of leaner mixtures results not only in low HC and CO emissions but also in optimum fuel economy. Most current vehicles operate on the lean side of the stoichiometric mixture to meet the emission standards. Alteration of carburetion on such vehicles can result in reduced economy and higher emissions.

Some systems, however, utilize control approaches in which rich carburetion is used to provide high HC and CO emissions to the exhaust manifold. These pollutants are then burned in the exhaust with the help of additional air pumped into the exhaust ports. The high concentration of combustibles (HC and CO) is required to provide sufficient "fuel" to the exhaust manifold so that the temperatures generated are high enough for near-complete combustion. This type of thermal after-treatment approach can be more effective than the lean carburetion approach as far as emissions are concerned, but fuel economy suffers. An additional emissions benefit of the rich carburetion approach is that it results in lower NO_x emissions due to the lower availability of oxygen during the combustion in the cylinder.

Air pumps are sometimes employed to facilitate HC and CO reductions in the exhaust of both lean- and rich-burning engines by increasing the oxygen availability. Air pumps do not significantly affect fuel consumption because the power required to drive the pump is quite low. For example, at 3000 rpm the required power ranges from approximately 0.5 HP at 5-in. Hg backpressure to approximately 1.0 HP at 15-in. Hg backpressure.

Exhaust gas recirculation (EGR) reduces NO_x emissions by reducing the oxygen concentration and flame temperature during the combustion event. EGR can affect economy in several ways. With moderate, well-controlled EGR rates, economy can be improved slightly because the recirculated exhaust gas reduces the amount of throttling required to run the engine and allows more spark advance to be used. Because EGR reduces the octane requirement of an engine, a well-controlled system can allow higher compression ratios. Most EGR systems on current cars, however, do not take advantage of the octane-improving properties of recirculated exhaust gas nor are they well controlled.

If EGR rates are not properly controlled, or if they are excessive, then fuel economy can suffer. High EGR rates slow down combustion and occasionally cause misfire. These phenomena in themselves reduce efficiency, but even more loss can be incurred if richer carburetion is used to help clear up the poor combustion quality.

Current (1973-74) automobiles incorporate the above mentioned emission control techniques in a variety of ways. Most models incorporate some spark retard, EGR, carburetion enleanment, and low compression ratio in order to meet the emission standards.

In order to quantify the fuel economy and emissions change which would result from disconnecting the emission controls, a test program was undertaken by the Environmental Protection Agency involving 1973 and 1974 model year vehicles. These model years were selected since they require a greater degree of emission control than earlier models and have shown the greatest change in fuel economy from uncontrolled vehicles (10%-11% lower on a sales-weighted average). Therefore, successful re-optimization of these vehicles for best fuel economy by modifying the emission control system would be expected to result in greater improvements than should be possible for 1972 and earlier models.

11.2.2 Test Program

A total of ten 1973-1974 vehicles, representative of the full range of typical vehicle weights encountered in the existing vehicle population, were selected for the test program. Seven of the ten vehicles were tuned to manufacturers specifications (including new points, plugs, condenser, rotor, and air cleaner) prior to baseline testing by EPA. Following the baseline tests, the vehicles were modified by EPA and by one or more of eight garages with instructions to make whatever changes were believed necessary to improve fuel economy. Some vehicles were submitted to more than one garage, resulting in a total of 13 garage "tampering" episodes. The other three vehicles were baseline tested in the "as received" condition prior to garage modifications or tuneups to automakers' specifications by EPA.

Modifications performed on the test vehicles by EPA consisted of the adjustment of ignition and fuel system parameters without modification or replacement of parts and disconnecting specific emission control devices that are external to the basic engine system.

Garage modifications included both adjustments of ignition and fuel system parameters (i.e., timing and air-fuel ratio) in addition to disconnection, removal, or alteration of engine and/or emission control system components. The most frequently encountered alterations included changes in basic timing, idle air-fuel ratio, EGR disconnect, and the restoration of full vacuum advance.

11.2.3 Test Results

The results of the test program are summarized in Table 11-4 for the baseline tuned vehicles. It will be noted that the EPA modifications resulted in a 7% average fuel economy improvement while the modifications by 8 different garages in 13 different cases resulted in an average decrease of 3.5% in fuel economy (mpg). Accompanying these changes in fuel economy, it will also be noted that significant increases in emissions resulted from the modifications, and, with one exception, the average emission levels of the modified vehicles exceeded the Federal standards for 1973-74.

Three of the ten vehicles, baseline tested in the "as received" condition, were modified by the garages or given a tuneup to automakers' specifications by the EPA. Results of the testing on these vehicles are shown in Table 11-5. Of interest here is the fact that the EPA tuneup to automakers' specifications resulted in an average fuel economy increase of 9% compared to the "as received" condition, while the garage modifications were less successful, showing only a 4% increase. In general, the EPA tuneup also resulted in better emission reduction (or smaller increase) than did the garage modifications.

11.2.4 Conclusions

This study indicated that when modifications are made to the 1973-74 vehicles (equipped with the more stringent emission controls) by skilled engineers and technicians who have detailed knowledge of automotive emission control systems as well as access to sophisticated test equipment, average fuel economy improvements of approximately 7% can be obtained. However, emissions of air pollutants (HC, CO, and NO_x) increase an average of approximately 66%, 21%, and 126%, respectively, through such adjustment.

This study also suggests that independent garages in most cases (70%) perform modifications in which fuel economy losses result. The average change in fuel economy for 13 cases of garage tampering was a reduction of 3.5%. Only 4 cases out of 13 achieved even minor improved fuel economy.

TABLE 11-4. EFFECTS OF EMISSION CONTROL MODIFICATIONS ON FUEL ECONOMY AND EMISSIONS (REF. 11-11)

	Average Emissions, gm/mi*			Percent Change from Baseline Tuneup			Fuel Economy	
	HC	CO	NO_x	HC	CO	NO_x	MPG	% Change
Baseline (tuned)	2.57	30.7	2.00	--	--	--	14.2	--
Garage Modified	3.58	58.2	3.25	39.3	89.5	63.0	13.7	-3.5
EPA Modified	4.23	37.1	4.31	64.7	21.0	116.0	15.2	+7.0

*1972 CVS Federal Test Procedure

TABLE 11-5. EFFECTS OF MODIFICATIONS ON THREE "AS RECEIVED" VEHICLES* (REF. 11-11)

	Percent Change from "As Received"			
	HC	CO	NO_x	Fuel Economy
Garage Modified				
** '73 Fury Wagon	-85.6	0.7	71.4	9.3
*** '73 Vega	29.6	25.2	11.2	6.4
'74 Nova	0	25.2	-62.6	-2.9
EPA Tuneup to Mfrs' Spec				
** '73 Fury Wagon	-92.5	-67.4	14.8	18.2
*** '73 Vega	17.6	12.6	-35.5	11.5
'74 Nova	21.5	39.6	-63.2	-1.9

*Only one emission test on each car, as compared to replicate tests for other cars in test program.

**Fouled plug in number 4 cylinder replaced.

***New air cleaner and spark plugs installed as part of garage modification.

11.3 REFERENCES FOR SECTION 11

11-1. "Super Vega," Motor Trend Magazine, p. 63 (May 1974).

11-2. Telephone conversation from H. Gregory, Plant Engineer, Hughes Aircraft Company, Fullerton, California (September 4, 1974).

11-3. Telephone conversation from C. Hollingshead, Key Oil Co., (August 24, 1974).

11-4. Obert, The Internal Combustion Engine, International Textbook Company (February 1970).

11-5. B. Holliday and R. L. Jengten, Lubricating Oil Additives: How They Act, Battelle Memorial Institute (October 1967).

11-6. Discussion with D. Hittler, American Motors Corporation (August 23, 1974).

11-7. The Aerospace Corporation discussion with R. L. Jentgen, Battelle Memorial Institute (August 30, 1974).

11-8. R. L. Jengten, "Lubricant Additives," Product Engineering (August 30, 1965).

11-9. Telephone conversation from H. Hilton, Hilton Products Co., Seattle, Washington (September 5, 1974).

11-10. Telephone conversaion from E. A. Griswold, Special Equipment Co., Pasadena, California (September 10, 1974).

11-11. A Study of Fuel Economy Changes Resulting from Tampering with Emission Controls, Test and Evaluation Branch, Emission Control Technology Division, Office of Mobile Source Air Pollution Control, Environmental Protection Agency, Washington, D. C. (January 1974).

SECTION 12

COMPARISON AND PRELIMINARY EVALUATION OF CONCEPTS/DEVICES

This section presents the rationale for and the results of a comparison and preliminary evaluation of the retrofit concepts/devices considered in this study. This evaluation was based both on (a) the type and level of confirmatory data available for each concept/device, and (b) the theoretical basis for expecting fuel economy improvement due to the general operating principles of the concept/device.

In the evaluation process, a discrete number of screening comparisons were made. First, each class of retrofit device was rated as to its potential for fuel economy improvement. Second, those devices which were considered to have the potential for 5% or more improvement were rated as to whether or not additional confirmatory testing was required. Third, those devices deemed to require additional testing were then compared against a matrix of constraint factors. And finally, a number of devices were selected as appropriate for inclusion in the Phase II testing program, based on the results of the first three evaluation steps. The following pages present the details of this evaluation process, based on the information presented in Sections 3 through 11.

12.1 FUEL ECONOMY IMPROVEMENT POTENTIAL

Table 12-1 presents the results of rating each device or device class as to fuel economy improvement potential. To facilitate the rating process, an arbitrary four-part rating scale was utilized:

a. Negative (decreased fuel economy)
b. Negligible (from no change to 4% improved fuel economy)
c. Modest (from 5% to 14% improved fuel economy)
d. Substantial (15% or greater improved fuel economy)

The rationale for the selected ratings shown in Table 12-1 are briefly delineated for each concept/device or class of devices.

TABLE 12-1. COMPARISON OF CONCEPTS/DEVICES FOR FUEL ECONOMY POTENTIAL

CLASS/DEVICE	FUEL ECONOMY IMPROVEMENT POTENTIAL*			
	NEGATIVE - TO 0%	NEGLIGIBLE 0 TO 4%	MODEST 5 TO 14%	SUBSTANTIAL 15% AND ABOVE
CARBURETORS (selected ones)			X	
ATOMIZERS		SCREENS	ACOUSTIC (PCA)	
LEAN-BLEED SYSTEMS		X	SOME PRE-CONTROLLED CARS COULD HAVE MODEST INCREASE	
VAPOR INJECTORS		X		
FUEL MODIFICATIONS				
FUEL ADDITIVES		X		
FUEL MIXTURES		X		
INLET MANIFOLDS		OFFENHAUSER DATA	EDELBROCK DATA	
PRESSURE REGULATORS		X		
FUEL PRE-AGITATOR	X			
IGNITION SYSTEMS				
CAPACITIVE DISCHARGE		ON MAINTAINED VEHICLES	ON CARS WITH LEAN AIR-FUEL RATIOS	
ELECTRONIC INDUCTIVE		ON MAINTAINED VEHICLES	ON CARS WITH LEAN AIR-FUEL RATIOS	
OTHERS		X		

* Based on present state of the art and available data

TABLE 12-1. COMPARISON OF CONCEPTS/DEVICES FOR FUEL ECONOMY POTENTIAL (Continued)

CLASS/DEVICE	FUEL ECONOMY IMPROVEMENT POTENTIAL*			
	NEGATIVE - TO 0%	NEGLIGIBLE 0 TO 4%	MODEST 5 TO 14%	SUBSTANTIAL 15% AND ABOVE
EMISSION CONTROL RETROFITS	X			
DRIVETRAIN				
TIRES			RADIAL TIRES	
TRANSMISSIONS			TRUCK AUTOMATIC TRANSMISSIONS	
REAR AXLE GEAR RATIOS			X	HIGHWAY DRIVING
OVERDRIVE UNITS			X	HIGHWAY DRIVING
DRAG REDUCTION DEVICES		X	HIGHWAY DRIVING	
DRIVER AIDS		←	INDETERMINATE	→
FLEXIBLE COOLING FANS		X		
VALVE TIMING		X		
TUNEUPS			X	
COMPRESSION RATIO INCREASE			X - NOT RECOMMENDED	

* Based on present state of the art and available data

TABLE 12-1. COMPARISON OF CONCEPTS/DEVICES FOR FUEL ECONOMY POTENTIAL (Concluded)

	FUEL ECONOMY IMPROVEMENT POTENTIAL*			
	NEGATIVE - TO 0%	NEGLIGIBLE 0 TO 4%	MODEST 5 TO 14%	SUBSTANTIAL 15% AND ABOVE
TUNED EXHAUST SYSTEMS			X	
DUAL EXHAUST SYSTEMS		X		
EXHAUST CUTOUT			X - NOT RECOMMENDED ILLEGAL IN SOME STATES	
TURBOCHARGERS	X - WITH SAME ENG			WITH REDUCED ENG CID
ENGINE OIL			MAY BE POSSIBLE	
ENGINE OIL ADDITIVES			MAY BE POSSIBLE	
ENGINE OIL FILTER		X**		
TAMPERING WITH ECSs	← X →	← X →		
SUGGESTED COMBINATIONS				
INLET MANIFOLD AND TUNED EXHAUST			X	POSSIBLE
CARBURETOR PLUS CD IGNITION - MSD, IN PARTICULAR			X - LEAN AIR FUEL RATIOS	

* Based on present state of the art and available data

** Prevents performance degradation over lifetime

12.1.1 Carburetors

Based on the evaluation of carburetor concepts presented in Section 3, it is estimated that carburetors permitting "lean" operation (A/F = 18 to 20) have the potential to improve fuel economy in the order of 5% due to lean operation alone. In addition, improvements to reduce choked operation requirements and/or to improve atomization or vaporization during engine warmup could further improve fuel economy. Finally, the ability to advance spark timing at the same NO_x emission level would afford still further fuel economy potential.

On this basis, the Electrosonic, Ultrasonic, Dresserator, and Ethyl carburetors (or systems) have been rated in the "modest" column. Of course, there is some evidence that somewhat greater improvements may be possible on cars controlled to very low NO_x levels.

12.1.2 Atomizers

As noted previously in Section 3, it is estimated that screens or the other mechanical atomizing devices examined would not appreciably improve fuel economy. On this basis, they are shown in the "negligible" column. On the other hand, acoustic atomizers are judged to have the potential for "modest" improvements, insofar as they would be used in conjunction with leaner operation and also with regard to their potential for reducing choking requirements during engine warmup. The Post Carburetor Atomizer (PCA) device examined in this study is also used as the atomizer in the Electrosonic carburetor mentioned above.

12.1.3 Lean-Bleed Systems

Lean-bleed systems, or devices which admit or "bleed" additional air (through the PCV line or with the intake manifold) during idle, deceleration, or low-speed operation, are estimated to provide fuel economy improvements in the "negligible" range. However, the degree of fuel economy improvement would be related to the nominal air-fuel ratio setting of the particular vehicle. For example, some older cars (e.g., pre-controlled) may have richer carburetor settings and could therefore have improvements which might extend into the "modest" range.

12.1.4 Vapor Injectors

Vapor injectors, or devices which admit additional air which is drawn through a fluid (water-alcohol mixtures, in general) to result in an ingested vapor, are estimated to provide fuel economy improvements in the "negligible" category. Neither the amount of air or fluid ingested is sufficient in quantity or quality so as to measurably influence either the air-fuel ratio of the mixture or the combustion process.

12.1.5 Fuel Modifications

As noted in Section 3, modern major brand gasolines already incorporate detergent and/or dispersant additives. The available data on the other gasoline additives examined herein indicated that they would have a "negligible" effect on fuel economy when compared to such existing modern gasolines.

With regard to fuel mixtures, a number of combinations were considered: gasoline/alcohol, gasoline/water, and gasoline/water/alcohol. In each case, the available vehicle fuel economy data have shown no more than "negligible" increases, while there are some instances of fuel economy decreases due to rough engine operation, misfiring, etc. Although there are some engine dynamometer test data to indicate the potential for "modest" increases (with gasoline/water mixtures), at the present state of development for retrofit application it is estimated that such fuel mixtures should be rated as "negligible."

12.1.6 Inlet Manifolds

The available data on inlet manifolds with reduced cross-sectional areas to obtain high flow velocities with improved fuel distribution present a somewhat mixed picture. Offenhauser data indicate fuel economy improvements in the "negligible" range (3% to 4%) while Edelbrock data indicate "modest" to "substantial" improvements (9% on CVS tests, 16% to 18%

in dynamometer and street driving). Because of the possible strong effects of the inlet manifold on fuel economy during cold-start, warmup, and low-speed operation, it is estimated at this time that inlet manifold retrofits have the potential for "modest" fuel economy improvements.

12.1.7 Pressure Regulators

Pressure regulators, which are advertised to prevent excess fuel pressure from blowing the needle valve in the float bowl off its seat, are estimated to result in "negligible" improvements in fuel economy. This estimate is based on University of Michigan tests of one such device.

12.1.8 Fuel Pre-Agitator

One device, a tube with tiny brass baffles which fits inside the fuel line, was found to decrease fuel economy in tests at the University of Michigan.

12.1.9 Ignition Systems

As discussed in detail in Section 4, the conventional ignition system is entirely adequate for purposes of combustion-initiation unless or until the system components (plugs, points, etc.) wear out or are otherwise affected by operational constraints (plug deposits, etc.). Therefore, for vehicles which are well maintained and have tuneups at recommended intervals (before incipient malfunction), it is estimated that both capacitive discharge (CD) and electronic inductive ignition systems would result in "negligible" improvements in fuel economy. However, recognizing that many owners do not properly maintain their vehicles, the longer service life capability of CD and electronic inductive ignition systems suggest that "modest" improvements would result from their use. This would be particularly true for vehicles with lean air-fuel ratio settings which would be more prone to cylinder misfire with deterioration of ignition system voltage. Therefore, on an overall basis, such ignition systems are rated in the "modest" category.

In the "others" category, some ignition systems merely replace existing components of the conventional system and are estimated to result in a very limited or "negligible" fuel economy improvement potential. There are, in addition, some "unconventional" systems, sometimes called "ignition bridges," which are added to conventional ignition systems with claims of improved performance. Analysis of their effects on fuel economy has not been possible, but University of Michigan tests of one such device indicates it should be placed in the "negligible" rating column.

12.1.10 Emission Control Retrofit Systems

Retrofit systems designed for emission control were known to have possibly adverse effects on fuel economy, but they were examined in this study in order to place their characteristics in perspective with those of devices claimed to improve fuel economy. NO_x control systems such as vacuum-spark-advance-disconnect (VSAD) and EGR have fuel economy penalties ranging from 3% to 10%. Carburetor plus distributor retrofits for HC and CO control have a small fuel economy penalty (~2%). Oxidation catalyst retrofits (for HC and CO control) can result in fuel economy penalties up to 2%.

12.1.11 Drivetrain Components

Radial tires, in particular the steel-belted variety, are estimated to have the potential for "modest" improvements in fuel economy. The actual improvement realized may vary with the type of driving conditions and tire age.

In the area of transmissions, special 4- and 5-speed range automatic transmissions tested in large van-type trucks by the U.S. Auto Club demonstrated ~11% fuel economy improvement when compared to manual transmission equipped vehicles. However, this type of transmission is not planned for production for passenger car use.

Of course, engine speed (rpm) reduction at a given vehicle speed (mph), as effected by changing the rear axle gear ratio or by adding an overdrive unit, is well known to result in reduced fuel consumption. In highway driving operation, both techniques can result in "substantial" fuel economy improvements. When city traffic driving is taken into account, however, such fuel economy improvements are estimated to be reduced to the "modest" category. In addition, merely changing the rear axle gear ratio will result in reduced acceleration performance and hill-climbing ability. The overdrive unit permits down-shifting to normal gear ratios for better acceleration in city traffic driving.

12.1.12 Drag Reduction Devices

Any reduction in aerodynamic drag would, of course, be beneficial with regard to reducing fuel consumption in that power (and fuel) required to overcome drag is reduced. However, the magnitude of the benefit is dependent on the vehicle speed. For example, at low speeds, the rolling resistance is much higher than aerodynamic drag; at ~40 mph, the two forces are nearly equal; at ~70 mph, the air drag is 2 to 3 times higher than the rolling resistance. It is estimated that drag reduction devices could result in "modest" fuel economy improvements during highway driving, but that their effect would be "negligible" in city traffic or low-speed driving.

12.1.13 Driver Aids

The effects of driver aids such as vacuum gages, miles-per-gallon meters, cruise controls, etc. are felt to be indeterminant with respect to fuel economy improvement. Some drivers might have "negligible" improvements while other very careful drivers may be able to achieve "substantial" improvements if the device enables them to change their driving habits from the "hot rod" category to that of totally fuel economy oriented.

12.1.14 Flexible Cooling Fans

Based on the analysis of power requirements presented in Section 8, the use of flexible cooling fans should result in essentially no change in fuel economy over normal driving speed ranges.

12.1.15 Valve Timing

Although claims are made of fuel economy improvements with retrofit camshafts or variable-cam timing devices, the data from available vehicle tests indicate negative or insignificant effects on fuel economy.

12.1.16 Engine Tuneups

Engine tuneups are recognized as a requirement in order to avoid fuel economy degradation which results from ignition system wearout, carburetor deposits, etc. Statistical data to quantify average fuel economy improvements from tuneups are not available. Data from one car test indicated ~10% fuel economy improvements over the 30- to 70-mph speed range after a tuneup. On this basis, tuneups are rated in the "modest" category, although it is recognized that the amount of improvement obtained for a given car would be a function of its relative state of maintenance and mileage since it was last tuned.

12.1.17 Compression Ratio Increase

Although "modest" fuel economy improvements can be realized by increasing the engine compression ratio (by shaving the head or by replacing the pistons), it is not recommended because it would require higher octane gasoline and the emissions of HC and NO_x could be increased somewhat.

12.1.18 Tuned Exhaust Systems

Based on limited test data, tuned exhaust systems are estimated to have the potential for "modest" improvements in fuel economy. This is due to the combination of reduced exhaust backpressure (and pumping losses) and improved cylinder scavenging effects.

12.1.19 Dual Exhaust Systems

Dual exhaust systems are estimated to result in "negligible" (1% or less) fuel economy gains; backpressure reductions are not significant.

12.1.20 Exhaust Cutouts

Exhaust cutouts, which afford maximum backpressure reductions, are estimated to result in "modest" fuel economy gains at high speed and load conditions. However, this approach is not recommended, as it is illegal in some states because of noise effects.

12.1.21 Turbochargers

Exhaust-gas-driven turbochargers are estimated to result in small (2% to 3%) fuel economy losses when added to a stock engine in a vehicle. If the engine were also replaced with one ~30% smaller in displacement, then a "substantial" improvement in fuel economy could be projected. However, this would be a very expensive method of retrofitting.

12.1.22 Engine Oil and Oil Additives

It is difficult to support the fuel economy improvement claims of up to 20% as made by manufacturers or users of the engine oil and additive examined in this study. For example, a 20% improvement in fuel economy corresponds roughly to a 3.5% improvement in engine thermal efficiency, a quantity equal to about half the total loss due to mechanical friction in the engine. Other sources have postulated that improved oil formulations could contribute to as much as 6% to 10% fuel economy improvements. On this basis, it is estimated that "modest" improvements "may" be possible with improved engine oils or additives.

12.1.23 Engine Oil Filter

The advanced engine oil filter examined in this study is estimated to result in minimal effects on fuel economy, regardless of its efficiency as an oil filter. While it certainly could prevent performance degradation due to wearout of parts dependent on lubrication (cylinders, cylinder walls, etc.) and could extend engine operating life on that basis, its fuel economy improvement impact would thus be limited to those factors affected by lubricated component wear rate, which is judged to be indeterminant for purposes of the present study.

12.1.24 Tampering with Emission Control Systems

It has been suggested that some vehicle owners might have their emission control systems altered or tampered with in an effort to improve fuel economy, even though this may be prohibited by law. EPA conducted a 10-car program (1973 and 1974 model years) to examine possible effects. When such adjustments were made by private garages, there was an average decrease in fuel economy of ~3-1/2%. Only 4 out of 13 cases achieved even minor improvements in fuel economy.

12.1.25 Suggested Device Combinations

a. Inlet Manifold and Tuned Exhaust

The combination of these devices suggests that they might exhibit the greatest combined effect on engine "breathing" (induction, scavenging, exhaust) and thus might possibly achieve "substantial" fuel economy improvements.

b. Carburetor plus CD Ignition

The combination of these devices suggests that they might exhibit the greatest combined effect on air-fuel ratio, charge preparation, and combustion, particularly for vehicles with lean air-fuel ratio settings.

12.2 CONFIRMATORY TESTING REQUIREMENT

Table 12-2 summarizes the results of evaluating whether or not there is a substantial need for additional or confirmatory testing during Phase II of the present program. Only those devices or device classes rated in the "modest" and "substantial" categories in Table 12-1 are included in the summary.

12.2.1 "No Additional Testing Required" Category

The available technical data, test data, and/or theoretical background information were considered adequate so as to negate a requirement for testing in the present program for:

a. Overdrive units

b. Rear axle ratio changes

c. Turbocharger plus smaller engine installations

d. Radial tires

e. Multi-speed-range automatic transmissions with lockup clutches

TABLE 12-2. COMPARISON OF CONCEPTS/DEVICES FOR CONFIRMATORY TESTING REQUIREMENT

	TESTING REQUIRED	
	YES	NO
SUBSTANTIAL (>15% improvement)		
OVERDRIVES (highway driving)		X
AXLE RATIO CHANGE (highway driving)		X
TURBOCHARGER WITH SMALLER CID ENGINE		X
INLET MANIFOLD AND TUNED EXHAUST COMBINATION	X	
MODEST (5 to 14% improvement)		
SELECTED CARBURETORS	X	
ELECTROSONIC		
ULTRASONIC		
DRESSERATOR		
ACOUSTIC ATOMIZER (PCA)	X	
INLET MANIFOLDS	X	
OFFENHAUSER		
EDLEBROCK		
CD IGNITION SYSTEM	X	
MSD		
RADIAL TIRES		X
AUTOMATIC TRUCK TRANSMISSIONS		X
DRAG REDUCTION DEVICES	X	
DRIVER AIDS	X	
TUNEUPS		X
TUNED EXHAUST SYSTEM	X	
SELECTED CARBURETOR PLUS MSD OR PCA PLUS MSD	X	
OIL/OIL ADDITIVES	X	

In the case of tuneups, it is recognized that there is a lack of fleet test data to adequately quantize overall effects on vehicle fuel economy on a statistical basis. However, it is felt that the beneficial effects of tuneups are sufficiently well recognized and that a test program which would be adequate for this purpose would be sufficiently large (in number of vehicles required) as to be beyond the scope of the present Phase II test program.

12.2.2 "Additional Testing Required" Category

In the case of all other devices listed in the "yes" column of Table 12-2, it is considered that the test data base is incomplete and inadequate for purposes of adequately quantifying the relative impact of each device or device class on fuel economy improvement potential. Indeed, in most cases the devices or classes were rated to have the potential for fuel economy improvement primarily based on their postulated operational features alone. In those cases where available test data were promising, the data were incomplete and/or inadequate with respect to "controlled test" requirements.

12.3 OTHER EVALUATION FACTORS

A final comparison was made of the devices requiring confirmatory testing (from Table 12-2) in order to identify any other factors which might constrain the use of the device or constrain the testing of the device in the present Phase II test program. Table 12-3 summarizes the results of this comparison.

The area of "side effects" included such factors as deleterious effects on exhaust emissions, increased maintenance requirements, and possible deleterious effects on vehicle power and acceleration performance. As noted in Table 12-3, such side effects were not evident for the devices considered, at least to the degree that they would obviously prevent the use of any device if actually found to sufficiently improve fuel economy.

In the area of "availability," the factors examined included compatibility with mass production and potential availability in the near future (at least for confirmatory testing). As can be seen in the table, all devices (or classes) were considered to be available except for the

TABLE 12-3. COMPARISON OF CONCEPTS/DEVICES FOR OTHER EVALUATION FACTORS

	SIDE EFFECTS	AVAILABILITY	COST IMPACT	OTHERS
INLET MANIFOLD AND TUNED EXHAUST COMBINATION	NONE EVIDENT	AVAILABLE FOR PURCHASE	$175 TO $390 PLUS 5 TO 14 hr	NONE EVIDENT
SELECTED CARBURETORS				
ELECTROSONIC	NONE EVIDENT	SHOULD BE AVAILABLE	INSTALLATION COSTS ONLY	NONE EVIDENT
ULTRASONIC	NONE EVIDENT	SHOULD BE AVAILABLE	INSTALLATION COSTS ONLY	NONE EVIDENT
DRESSERATOR	NONE EVIDENT	AVAILABILITY UNCERTAIN	INSTALLATION COSTS ONLY	NONE EVIDENT
ACOUSTIC ATOMIZER (PCA)	NONE EVIDENT	SHOULD BE AVAILABLE	$55 HARDWARE 1 hr INSTALLATION	NONE EVIDENT
INLET MANIFOLDS				
OFFENHAUSER	NONE EVIDENT	AVAILABLE	$100 TO $160, 2 TO 6 hrs INST	NONE EVIDENT
EDELBROCK	NONE EVIDENT	AVAILABLE	$135 TO $165, 2 TO 6 hrs INST	NONE EVIDENT
OIL/OIL ADDITIVES(1)	NONE EVIDENT	AVAILABLE	MINOR	MAY REQUIRE(1) EXTENSIVE TESTS
MSD IGNITION SYSTEM	NONE EVIDENT	AVAILABLE	$70	NONE EVIDENT
DRAG REDUCTION DEVICES (1)	NONE EVIDENT	AVAILABILITY OF MEANINGFUL DEVICES UNCERTAIN	UNKNOWN	MAY REQUIRE (1) EXTENSIVE SEPARATE EFFORT
DRIVER AIDS (1)	NONE EVIDENT	AVAILABLE	$10 TO $100 ea	REQUIRES A(1) COMPREHENSIVE TESTING PROG
TUNED EXHAUST SYSTEM HOOKER HEADER	NONE EVIDENT	AVAILABLE	$75 TO $230, 3 TO 8 hrs INST	NONE EVIDENT
SELECTED CARBURETOR PLUS MSD	NONE EVIDENT	SEE CARBURETORS	$70 PLUS INST	NONE EVIDENT
OR PCA PLUS MDS	NONE EVIDENT	AVAILABLE	$125 PLUS INST	NONE EVIDENT

(1) Not recommended for current test program

Dresserator carburetor and drag reduction devices. In the case of the Dresserator carburetor, the models built and tested to date by Dresser Industries have been special prototype models built for proof-of-principle testing only. A few models more suitable for possible retrofit applications are currently in fabrication. If initial tests by Dresser are satisfactory to them, Dresser has indicated their possible availability to DOT for testing in the Phase II test program.

In the case of drag reduction devices, there are a number of such devices readily available on the special parts market, but they are predominantly made for small and/or sports cars. Thus the availability of such devices to fit a spectrum of full-, intermediate-, and compact-size passenger cars is rated to be somewhat uncertain.

In the "cost impact" column of Table 12-3 are listed hardware costs and installation requirements (in hours) where known. In the case of the carburetors shown, it is anticipated that they would be obtained "on loan" from the manufacturer and returned after testing.

As noted in the "others" column of Table 12-3, the evaluation of oil/oil additives, drag reduction devices, and driver aids disclosed factors which indicated they would not be suitable candidates for the Phase II test program. In the case of special engine oils and/or oil additives, it was felt that simple vehicle comparative tests (with and without the oil or additive) would not be adequate to determine true fuel economy effects or possible adverse effects on parts lubrication, parts wear, etc. Such an evaluation should include extensive dynamometer tests, including mileage accumulation tests, which is beyond the scope of the present test program.

As noted previously, the proliferation of passenger car sizes, models, and body shapes would require extensive vehicle tests over closely controlled test tracks and test conditions (wind effects, etc.) in order to properly evaluate the effects of drag reduction devices on fuel economy. Again, these types of tests are not within the scope of the planned Phase II test program.

Similarly, an adequate evaluation of the effects of various driver aids (vacuum gages, miles-per-gallon meters, etc.) on vehicle fuel economy would also require many vehicles and many drivers to arrive at a statistically meaningful answer as to fuel economy improvement potential; therefore, evaluation of driver aids is not within the scope of the Phase II effort.

12.4 RECOMMENDED DEVICES FOR PHASE II TESTING

Table 12-4 summarizes the devices recommended for testing in the Phase II test program. These devices are those which were (a) considered to have the potential for fuel economy improvement of 5% or more (Table 12-1), (b) required additional confirmatory testing to adequately establish their fuel economy improvement potential (Table 12-2), and (c) were available and within the scope of the planned Phase II testing effort insofar as tests with and without the device were considered sufficient to establish their relative merit.

TABLE 12-4. RECOMMENDED DEVICES FOR NEAR-TERM TESTING

- Dresserator Carburetor
- Electrosonic Fuel System*
- Acoustic Atomizer (PCA)
- Inlet Manifold (Offenhauser or Edelbrock)
- MSD Ignition System
- Tuned Exhaust System (Hooker Header)

- Combinations of Devices
  - Inlet Manifold and Tuned Exhaust
  - Carburetor and MSD (or PCA and MSD)

*Ultrasonic Fuel System is similar to Electrosonic; not necessary to test both at this time.

SECTION 13

VERIFICATION TEST PLANNING

This section presents the results of an initial assessment of the basic elements of the Phase II test program and an overview of the combinations of devices and tests which are recommended for the Phase II program. Possible test types, test organizations, and applicable test procedures are examined for their impact on Phase II testing requirements and program scope.

13.1 POSSIBLE TEST TYPES

Engine dynamometer, chassis dynamometer, and test track test modes are the three basic test types which were considered to be appropriate for fuel economy determination for the degree of accuracy required in this program.

In the engine dynamometer case, only fully warmed-up, steady state, engine tests for fuel economy were felt to be appropriate. Both road-load and WOT fuel economies are easily obtained by this test method.

Chassis dynamometer tests offer several distinct advantages over engine dynamometer tests. They enable determination of exhaust emissions by the Federal Test Procedure (1975 CVS), and fuel economy can be calculated by the carbon balance technique from the CVS emissions results; fuel economy can also be determined by running the Highway Driving Cycle on the dynamometer, and by weighing the fuel used at various steady-state driving speeds.

Test tracks also offer the possibility of obtaining warmed-up, steady-state, vehicle fuel economy values. However, such tests have been significantly affected by such factors as wind conditions, track conditions, etc. Ordinarily several replicate test runs are necessary to determine an average fuel economy value for a given vehicle speed.

Other test types, such as city, suburban, or city-suburban routes which are a portion of normal traffic patterns, were considered to be inappropriate for comparison testing of the type contemplated for Phase II purposes. These kinds of "route" or "traffic pattern" tests can be significantly affected by the other vehicles on the roadway, the individual test drivers, and general speed and stop-and-start effects due to traffic flow. Many tests would be required on such routes to develop meaningful fuel economy values because of the many uncontrolled test variables present.

13.2 POSSIBLE TEST ORGANIZATIONS

13.2.1 Engine Dynamometer Testing

It was known that the University of Michigan had the capability to perform engine dynamometer testing in their Automotive Engineering Laboratory. Indeed, the University of Michigan had previously tested several fuel economy retrofit devices on a 350 CID Chevrolet engine, and their test data have been reported throughout this report, as appropriate.

Discussions with Professor David E. Cole indicated that additional dynamometer testing could be accommodated at the Automotive Engineering Laboratory as a part of the Phase II test activities. Therefore, no further engine dynamometer testing facilities were contacted.

13.2.2 Chassis Dynamometer Testing

There are approximately 10 to 12 private or commercial emission testing laboratories in the United States which have the capability to perform emission tests per the Federal CVS procedure. Fuel economy determination from both the CVS emission test and the Federal Highway Driving Cycle (dynamometer test with single CVS bag) are also made at these same facilities.

Of particular interest in the current program are Automotive Research Associates (ARA) located in San Antonio, Texas, and Olson Laboratories with facilities in Santa Ana, California; Livonia, Michigan; and other locations. The location of ARA in San Antonio could facilitate testing of several devices manufactured by Autotronics Controls Corp. of El Paso (Electrosonic carburetor, MSD ignition, and PCA atomizer). The Santa Ana location of Olson is very close to the Dresser Industries facility in Santa Ana, and the Livonia location is reasonably close to the University of Michigan and the general Detroit area.

If conventional test track testing were desired, the Ontario Motor Speedway in Ontario, California, has such test facilities.

13.3 TEST PROCEDURES

13.3.1 Engine Dynamometer Tests

In case of engine dynamometer fuel economy tests, the series of test conditions denoted in Table 13-1 were felt to be adequate. A baseline test would first be run at various road-load and WOT conditions with the engine set to factory specifications in the areas of carburetion, ignition system, and spark timing. Next, these test conditions would be repeated with the test device installed but with the engine still set to factory specifications. The difference in fuel economy between these two test series at each test point or condition would be attributed to the device being tested.

Next, the engine-with-device tests would be repeated with the engine reset to the device manufacturer's instructions, if any. This generally involves only resetting the spark advance. The difference in fuel economy measurements between this series of test points and the previous series would be attributed to the difference in engine parameter settings.

Finally, a re-baseline test would be run without the device installed to verify the baseline data and to assure no basic change in engine operating characteristics had occurred during the overall test series.

13.3.2 Chassis Dynamometer Tests

Table 13-2 delineates a similar test sequence that would be desirable to use for chassis dynamometer testing purposes. In each case where a 1975 FTP test is indicated, results include CVS emissions, fuel economy calculated from CVS emissions, and fuel economy calculated from a Highway Driving Cycle test run immediately after CVS emissions test. In addition, steady-state speed settings could be added to each test sequence if necessary or desirable (not shown).

TABLE 13-1. TEST PROCEDURES FOR ENGINE DYNAMOMETER TESTS (FUEL ECONOMY ONLY)

- Baseline Test (without device)
  - Engine Set to Factory Specifications
    - Carburetor
    - Ignition system
    - Timing
    - 25, 35, 45, 55, and 70 mph steady-state conditions
    - 25 and 55 mph WOT conditions
- Engine with Device
  - Engine Set to Factory Specifications
    - Same steady-state and WOT conditions
- Engine with Device
  - Engine Set to Device Manufacturer's Instructions (where appropriate)
    - Generally involves only ignition timing advance
    - Same steady-state and WOT conditions
- Re-Baseline Test (without device)
  - Same as Baseline Test to Verify Baseline Data and to Assure No Change in Engine Operating Characteristics

TABLE 13-2. TEST PROCEDURES FOR CHASSIS DYNAMOMETER TESTS (EMISSIONS AND FUEL ECONOMY)

- Baseline 1975 FTP Test (without device)
  - Vehicle as Received
- Check Fuel and Ignition System for Conformance to Factory Specifications
  - If Out-of-Spec. Re-Tune (timing and idle air-fuel ratio only)
    - No parts changes
  - Run Re-Baseline 1975 FTP Test (without device)
- Perform Engine Tuneup
  - Parts Changes as Required (points, plugs, condenser, etc.)
  - Run Tuned-Engine 1975 FTP Test (without device)
- Add Test Device
  - Fuel and Ignition System Set to Factory Specifications
  - Run Device-Added 1975 FTP Test
- Test Device Added
  - Reset to Device Manufacturer's Specifications (where appropriate)
  - Run Device-Added 1975 FTP Test

The first test is of the vehicle as received for testing and without the test device. The second test is performed for vehicles out-of-specification with regard to factory settings. Comparison of second and first test results will indicate the fuel economy change due to conformance with factory specifications.

The third test is performed after an engine tuneup; the differences between Test 3 results and Tests 1 and 2 indicate fuel economy improvements due to tuneup only and to parts changes with nominal factory settings.

In a fourth test, the test device is added (with the engine tuned to factory requirements). The difference in fuel economy between Test 4 and Test 3 would be attributed to the test device alone.

In a fifth test, the engine would be reset to the device manufacturer's specifications. The difference in fuel economy between Test 5 and Test 4 would be attributed to the difference in engine settings. The difference between Test 5 and Test 3 would be attributed to the combined effect of the device and the change in engine settings.

13.3.3 Test Tracks

Table 13-3 delineates a similar sequence of tests if steady-state testing on a track were desired. However, because of possible variations in test track conditions plus the increased number of tests that would be required to compensate for wind conditions, etc., such tests are not recommended for inclusion in the Phase II program.

13.4 RECOMMENDED TESTS

Table 13-4 lists those combinations of devices/test type/test organization which are recommended to be included in the Phase II test program. The devices shown differ slightly from those shown in Table 12-4 for the following reasons:

a. The PCA acoustic atomizer was found to be available for one type of engine only and thus unavailable for screening tests as noted below. It was therefore dropped from consideration at this time.

b. The Electrosonic Fuel System was not available from Autotronics in a timely manner. Therefore the Ultrasonic Fuel System was selected and the Electrosonic dropped from consideration at this time.

In one portion of the program it is recommended that the MSD ignition system, Edelbrock and Offenhauser inlet manifolds, Hooker and Hedman tuned exhaust systems, and a combination of one inlet manifold plus one tuned exhaust system be tested on an engine dynamometer at the University of Michigan Automotive Engineering Laboratory per the basic test procedures summaried in Table 13-1.

TABLE 13-3. TEST PROCEDURES FOR STEADY-STATE TESTS ON A TEST TRACK

- Baseline Tests of Vehicle without Device
  - Engine Tuned to Factory Specifications
- Tests of Vehicle with Device
  - Engine Tuned to Factory Specifications
- Tests of Vehicle with Device
  - Engine Tuned to Device Manufacturer's Specifications (where appropriate)
- In All Cases
  - Engine Warmed Up Prior to Test
  - Test Speeds of 25, 45, 55, and 70 mph

Because of geographic location, it is recommended that the Ultrasonic Fuel System (and the car on which the Ultrasonic will be installed) be tested on a chassis dynamometer by Olson Laboratories in Livonia, Michigan. At a minimum, tests with and without the Ultrasonic System would be performed.

In a similar manner, it is recommended that the Dresserator System be tested at the Olson test facility in Anaheim (geographical proximity to the Dresser facility). In addition, it is further recommended that those devices which look promising based on the engine dynamometer screening tests performed at the University of Michigan be further tested by the CVS method on a chassis dynamometer at the Olson test facility, either at Anaheim, California or Livonia, Michigan, depending upon scheduling availability and parts and test vehicle availability.

These specific test devices, test types, and test facilities will be further examined and a definitive test plan and schedule developed as the initial activity of the Phase II program.

TABLE 13-4. RECOMMENDED TESTS

- University of Michigan
  - Engine Dynamometer
    - MSD
    - Hooker and Hedman tuned exhaust systems
    - Inlet manifolds (Edelbrock and Offenhauser)
    - Tuned exhaust plus inlet manifold
- Olson (CVS Tests), Livonia, Michigan
  - Ultrasonic Fuel System
    - As installed
    - Set to factory specifications
  - Ultrasonic Car
    - Factory carburetor and factory settings
- Olson (CVS Tests), Anaheim, California
  - Dresserator System (on Dresser Car)
    - As installed
    - Set to factory specifications
  - Dresser Car
    - Factory carburetor and settings
- Olson (CVS Tests), Livonia, Michigan
  - Promising Devices from University of Michigan Screening Tests

APPENDIX

REPORT OF INVENTIONS

A diligent review of the work performed under this contract has revealed no innovation, discovery, improvement or invention.