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POTENTIAL OF SPARK IGNITION ENGINE,
ELECTRONIC ENGINE AND TRANSMISSION CONTROL

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FINAL REPORT

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PREFACE

This report, DOT-TSC-NHTSA-79-55, is one of four companion reports to DOT-TSC-NHTSA-79-52 "Potential of Spark Ignition Engine, 1979 Summary Source Document."* It was prepared under contract to DOT/TSC by Arthur D. Little, Inc. It provides an assessment of electronic control technology hardware for engine and transmission control in future automobiles and light trucks. It does not address control strategies. The latter are addressed in the companion report on "Potential of Spark Ignition Engine, Engine Design Concepts," DOT-TSC-NHTSA-79-56.

This report is a deliverable under PPA HS-027, "Support for Research and Analysis in Auto Fuel Economy and Related Areas."

*"Potential of Spark Ignition Engine, 1979 Summary Source Document," by T. Trella, R. Zub, and R. Colello, U.S. Department of Transportation, Transportation Systems Center, Report No. DOT-TSC-NHTSA-79-52, March, 1980.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
m ²	square meter	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
ac	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.46	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
teaspoon	teaspoons	5	milliliters	ml
tablespoon	tablespoons	15	milliliters	ml
fluid ounce	fluid ounces	30	milliliters	ml
cup	cups	0.24	liters	l
pint	pints	0.47	liters	l
quart	quarts	0.96	liters	l
gallon	gallons	3.8	liters	l
cubic foot	cubic feet	0.03	cubic meters	m ³
cubic yard	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	ac
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	st
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



* In U.S. units, the letter 'e' is used for exact conversions and is not included in tables. See NBS Mon. Publ. 284, Units of Weights and Measures, Price \$1.75, SO Catalog No. 11110/86.

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1. INTRODUCTION

1.1 BACKGROUND

Since before 1968, the manufacturers of spark ignition (S.I.) engines have been attempting to meet the increasingly stringent, federally-mandated automotive emission standards. With the coming of the energy crisis in 1974, it also became of national importance to improve transportation efficiency in general and the fuel efficiency of the automobile engine in particular. The oil consumption of the United States transportation sector accounts for approximately 55 percent of the total petroleum used, with the automotive sector accounting for 75 percent of that amount.¹

The initial attempts by automobile manufacturers to meet the emission constraints caused sharp declines in the fuel economy of a significant portion of the total automotive fleet. The primary reason was that prior to 1975, the techniques utilized to meet the emission standards were those that could be introduced into production with the least modifications to existing hardware. These included excessive retardation of spark timing, and leaner air-fuel (A/F) ratios, primarily for hydrocarbon (HC) and carbon monoxide (CO) control. Also included were lower compression ratios, higher surface-to-volume ratios in the combustion chamber, and relatively high levels of intake/exhaust valve overlap for charge dilution, all of which were primarily for the control of oxides of nitrogen (NOx). The specific problem with these initial attempts at emission control was that the conventional mechanical/pneumatic logic systems used to control these engine variables (spark, charge dilution, A/F ratio, etc.) were incapable of adjusting the amount of spark retard, charge dilution, or fuel to "best" levels under all dynamic engine conditions. More importantly, these systems were incapable of selectively imposing emission controls only during engine conditions that required it and to back off in favor of fuel efficiency under conditions where emission controls were not as critical. (This

is often referred to as optimal weighting). The net result of these non-optimal control strategies was a reduction of the overall efficiency and performance of S.I. engines.

Since 1975, with the introduction of the exhaust gas after-treatment device called the oxidation catalyst, a significant reversal in the trend of decreasing fuel efficiency was accomplished. The oxidation catalyst reduced hydrocarbon and carbon monoxide tailpipe emissions by oxidizing these constituents in the exhaust stream. This system, along with the development of the exhaust gas recirculation valve (EGR) for charge dilution, permitted engines to be introduced with more advanced timing, higher compression ratios, lower surface-to-volume ratios, and lower levels of intake/exhaust valve overlap. These factors resulted in an increase in engine efficiency that had previously been lost. This change to more efficient engine design was a result of greater flexibility in selectively imposing emission controls in an optimal way via external control devices (catalyst, EGR valves, etc.).

The next most significant emission control technology to be introduced has been that of electronic engine control systems. The continued downward trend in the cost per function provided by integrated electronic circuit technology has made for substantial increases in vehicle use of electronics for many complex control applications. The importance of this technology to emissions and fuel economy has been in its ability to control "key" engine variables (spark, EGR, A/F ratio, etc.) with a greater degree of accuracy, repeatability and speed. The intrinsic speed of response and the flexibility of "computing" non-linear control functions have given the engine control system the capability for following more optimal control trajectories under transient engine conditions. Important also, has been the ability to generate output control signals in response to a multitude of sensory inputs, performing sophisticated time-variant control strategies in an interactive computational sense.

The net effect of this new technology, as it is shown in this study, has been to greatly improve the precision of control of the homogeneous-charge, spark-ignited engines. This improved control enables the fuel efficiency to be maximized for a given mechanical hardware configuration and emission constraint. The study details the automobile manufacturer's current progress with this technology and the potential fuel economy improvements which exist via advance applications of electronic engine controls.

1.2 OBJECTIVE AND SCOPE

It is the objective of this report to identify, evaluate, and document the characteristics and functions of significant electronic engine and powertrain control systems. Important considerations in the assessment are the powertrain variables controlled, the technology utilized, and the fuel economy gains achieved. A detailed analysis, by engine class and control system technology, is made in order to quantify specific advantages of various electronic systems and their capability to achieve increased engine efficiency and vehicle fuel economy. An attempt is made to identify the minimum technology required to move from the 1978 emission standards of 1.5 HC/15.0 CO/2.0 NO_x to the 1981 emission standard of .41 HC/3.1 CO/1.0 NO_x with no fuel economy losses. This 1981 standard and the level of technology required to achieve it represent a baseline from which an analysis of further potential fuel economy gains via electronic control systems is made.

1.3 METHOD OF APPROACH

Before it is possible to fully understand the capabilities of an electronic control system, it is necessary to review what is being controlled and why. In section 2 of this study, an overview is presented of all major engine subsystems with particular emphasis on their functional relationship to emissions and fuel economy. Also included is a discussion of advanced emission control concepts presently under develop-

ment by automobile manufacturers and how the full potential of these concepts may be realized via electronic controls. Section 3 of this study presents the details of presently produced (although in limited test fleet numbers) electronic engine/emission control systems introduced by foreign and domestic manufacturers. A comparison of the fuel economies of these test fleets to the conventionally equipped cars of equivalent engine/vehicle class is given. This demonstrates actual performance of electronic systems to date. Section 4 of this study attempts to define what technologies outlined in Section 2 are required to meet the 1981 emission standards (as stated by the Clean Air Act Amendment of 1977) with no fuel economy losses. From this, a projection of fuel economy improvements into the 1980's is presented. The remaining concepts outlined in Section 2 form the technology base.

2. ENGINE/POWERTRAIN/EMISSION CONTROL CONCEPTS

Each engine/powertrain or emission control subsystem discussed in this section has a direct functional relationship to the control of one or more presently regulated exhaust emission species (HC, CO or NOx) with a negative, neutral or positive effect on overall powertrain efficiency. In this section, each control subsystem is reviewed as to its effect on emissions and fuel economy with particular emphasis given to electronic controllability. The following list outlines the subsystems and advance concepts covered:

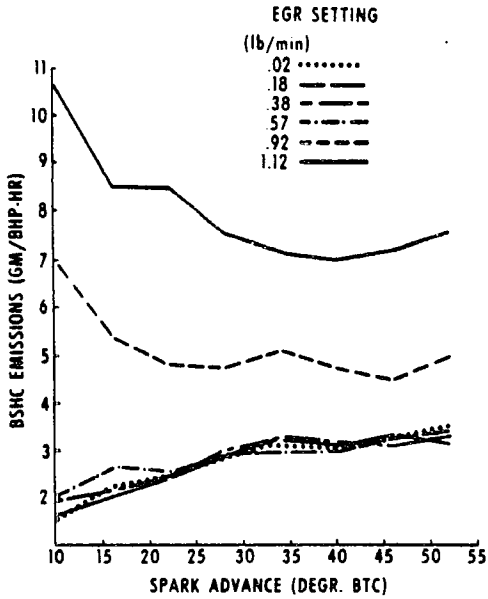
1. Ignition Systems,
2. EGR Systems,
3. Fuel Delivery Systems (Carburetor, Fuel Injection),
4. Catalyst and Secondary Air Systems,
5. Feedback Control Systems,
6. Transmission Control, and
7. Advance Concepts in Calibration.

2.1 IGNITION SYSTEMS

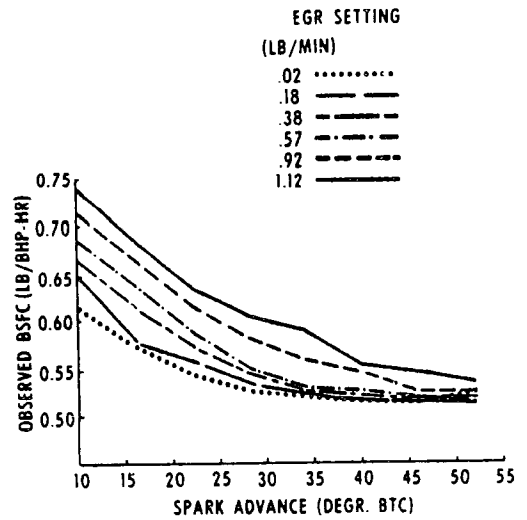
It is known that both NOx (oxides of nitrogen) and HC (hydrocarbon) exhaust emissions of spark ignited engines are significantly affected by ignition timing. In general, (see Figure 2-1) these emission species decrease substantially with increasing spark timing retard. Spark timing retard is relative to the most efficient operating spark advance which is defined as minimum spark advance for best torque (MBT). Specifically, the chemical mechanization for NOx reduction via spark retard is one of lowering peak cycle flame temperature (to less than 4000°F) during combustion. This method achieves substantial reductions in NOx due to the exponential functional dependence of NOx formation on peak cycle temperature. Ignition timing retard also causes an associated increase in exhaust gas temperature, which in turn, enhances the oxidation of unburned hydrocarbon species in the exhaust stream.

In the early years of emission control, manufacturers relied on simple variations in basic timing, centrifugal advance

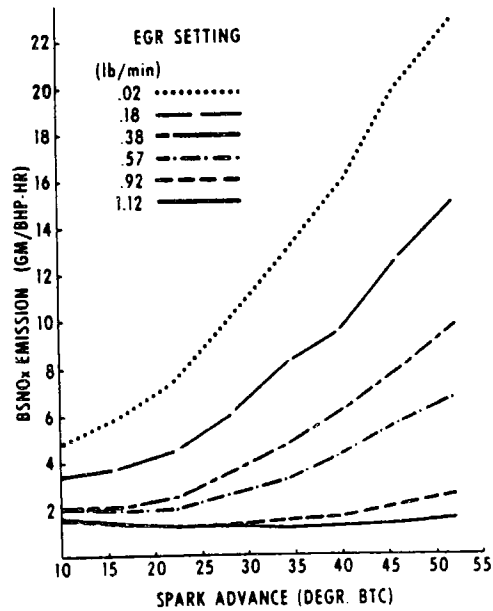
1200 RPM - 17 TO 1 A/F - 86 LB. FT. TORQUE
305 CU. IN. V-8 ENGINE



1200 RPM - 17 TO 1 A/F - 86 LB. FT. TORQUE
305 CU. IN. V-8 ENGINE



1200 RPM - 17 TO 1 A/F - 86 LB. FT. TORQUE
305 CU. IN. V-8 ENGINE

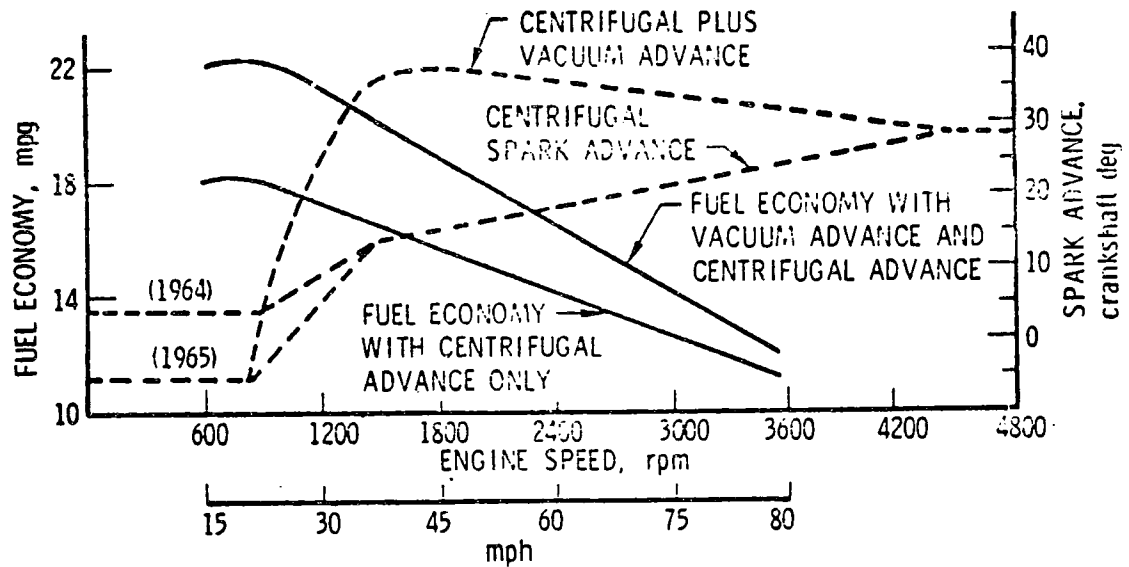


Source: Reference 2.

FIGURE 2-1. ENGINE MAPPING DATA, BSFC, BSFC AND BSNO_x VERSUS SPARK ADVANCE AT FIXED EGR VALUE SETTINGS

and vacuum advance for HC and NOx control. Figure 2-2 indicates the typical relationship of spark timing, fuel economy and engine speed. As can be seen, ignition timing retardation has a highly negative impact on fuel economy. During this time period (1968-1974), the advances in ignition systems were made primarily in the area of improved ignition or spark quality via electronic (solid-state) ignition circuitry. The emphasis was on eliminating the emissions and fuel economy degradation effects (up to 35 percent and 14 percent respectively) of contact triggered systems which suffer from contact point erosion, arcing, metal transfer and wear. Also, due to the leaner air/fuel mixture of the carburetors (for HC and CO control), severe misfires and slow burns could be eliminated only with increases in spark duration, spark energy and spark reliability. These developments led to the introduction of General Motor's High Energy Ignition (HEI) system, Ford's Dura Spark module, and Chrysler's Lean-Burn ignition system. As indicated, these electronic systems improved the quality, instantaneous reliability and long term durability of ignition, but the "when to fire" function or control law was still implemented via vacuum and centrifugal advance mechanisms.

Vacuum advance is implemented by the distributor vacuum unit, which consists of a spring-loaded diaphragm and a vacuum chamber. Vacuum is usually applied through a carburetor ported vacuum system where the vacuum signal is provided by a small port located in the carburetor body slightly above the closed position of the throttle plate. The position of the port, relative to the throttle plate, determines the vacuum advance versus throttle position profile. Centrifugal advance is implemented via a mass-spring system attached to the distributor shaft. The higher the distributor shaft rotation speed (proportional to engine speed), the further the mass moves radially against the spring force, resulting in increased spark advance. In addition, most engines include temperature switches which apply more vacuum (thus more spark advance) at idle under



Source: Reference 1.

FIGURE 2-2. EFFECTS OF CENTRIFUGAL AND VACUUM SPARK ADVANCE ON PERFORMANCE

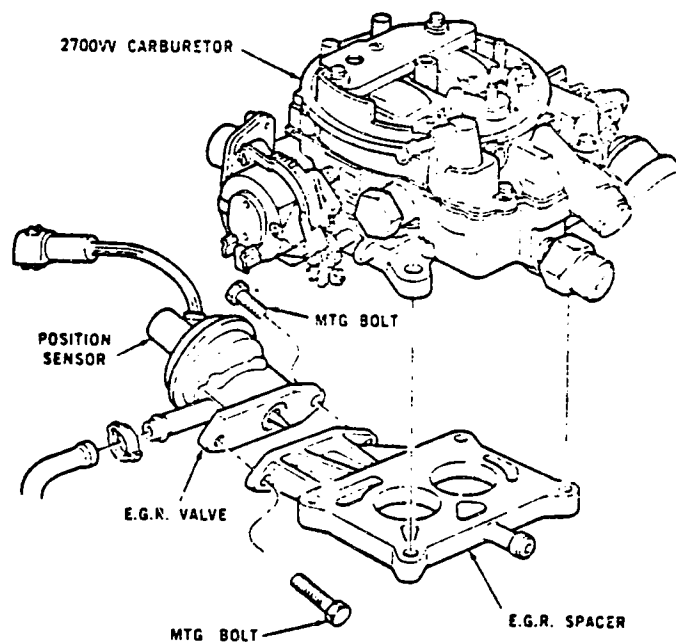
cold or overtemperature engine conditions. Except for incidences of a spark delay valves in some vacuum lines, this mechanical/pneumatic system defines the production ignition control system on most automobiles through 1977.

In recent years, dynamometer studies^{2,3,4} have indicated a much more complicated and non-linear functional dependence for spark advance than the simple control capabilities of centrifugal and vacuum advance systems. It has been shown (see Figure 2-3) that for maximum fuel efficiency within given emission and drivability constraints, optimal spark advance is a highly non-linear function of many variables, some of which are engine speed, derivative of engine speed, intake manifold pressure or engine load, throttle position, derivative of throttle position, intake air temperature, EGR rate, barometric pressure, and A/F ratio (lean or stoichiometric operation). It is obvious that with such complicated interactions among many dynamic variables that a cost effective control method would be to concentrate the "computation" of the control laws into one central electronic module with a multitude of sensory inputs. Chrysler's Lean-Burn system, General Motor's MISAR system and Ford's EEC-I system (discussed in detail in Section 3.) are examples of this control philosophy for spark advance. The electronic and sensory technology required to accomplish this control is defined in Section 3. It is apparent that once a general-purpose central "computer" and sensory system has been justified cost-effectively for improved spark control (as in the case of MISAR and EEC-I), it should be possible to incorporate added functions with the cost increase being primarily memory. As dynamometer studies like Rishavy, Auiler and Dohner,^(2,3,4) et al., continue to define optional spark advance trajectories and control laws, it will become apparent that on-board centralized electronic computers will be the accepted method of implementation. The following sections (2.2-2.8) outline how additional emission control devices may be integrated into the electronic control system.

2.2 EXHAUST GAS RECIRCULATION (EGR) SYSTEMS

EGR is a technique by which the charge inducted into the combustion chamber is diluted by the recirculation of gases from the exhaust stream into the intake manifold (see Figure 2-4). There is usually a single point of entry just under the carburetor for homogenous mixing with incoming air and fuel. The dilution of the intake charge with these residual gases reduces the combustion temperature and therefore the NO_x formation rates. Before the external EGR valve was introduced, charge dilution was accomplished via modifications of intake/exhaust valve timing. Valve overlap (inlet and exhaust valve opening times overlap) was an effective way of introducing EGR dilution internally by exposing the exhaust system to the low pressure intake system for a longer period of time. Exhaust gases would return to the cylinder through the exhaust valve. Unfortunately, excessive valve overlap degrades overall volumetric (breathing) efficiency, low-speed torque and idle characteristics. These reasons, along with the fact that NO_x reduction is only required when the engine is under load, indicate that a system which can modulate charge dilution selectively, better serves the requirements of NO_x abatement. The external EGR valve is such a system.

The EGR valve system usually consists of a pintel attached to a spring-loaded diaphragm and a vacuum chamber. The vacuum (or control signal) to the chamber can be modulated several ways. These systems are ported vacuum-modulated, intake vacuum-modulated, venturi vacuum-modulated, exhaust backpressure-modulated, or throttle position-modulated.¹ All of these systems are presently in production and in each case the control signal and therefore EGR flow rate are modulated roughly in proportion to the engine load. In addition, some provision is made to eliminate EGR during idle, closed throttle deceleration, and wide open throttle. Also, most EGR systems incorporate an engine coolant temperature lock-out mechanism which eliminates EGR for improved vehicle driveability during engine warm-up when NO_x formation rates are low. Dynamometer



EGR mixes with air and fuel from the carburetor at the entrance to the intake manifold.

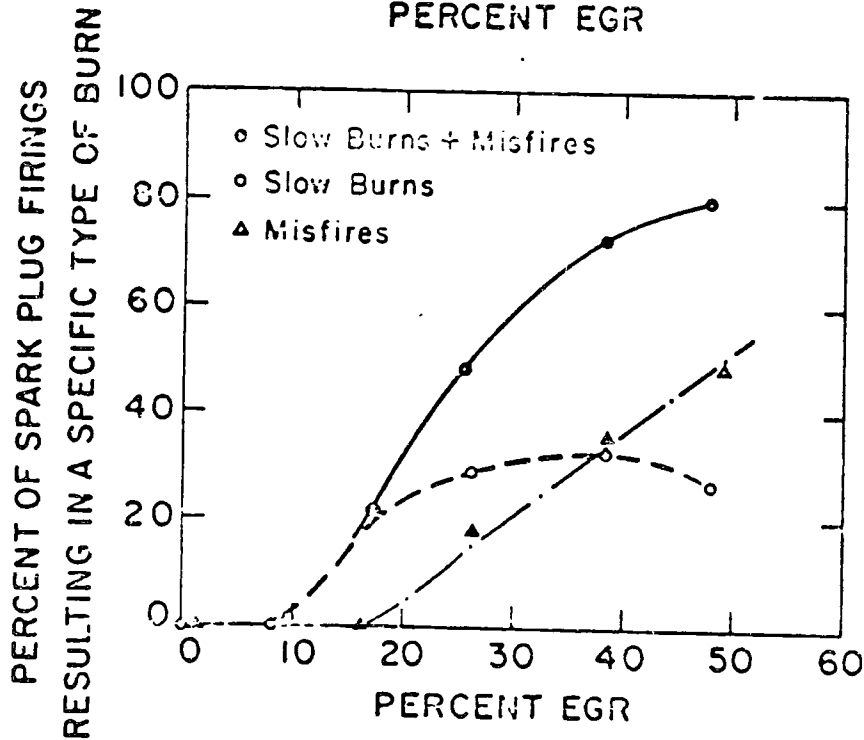
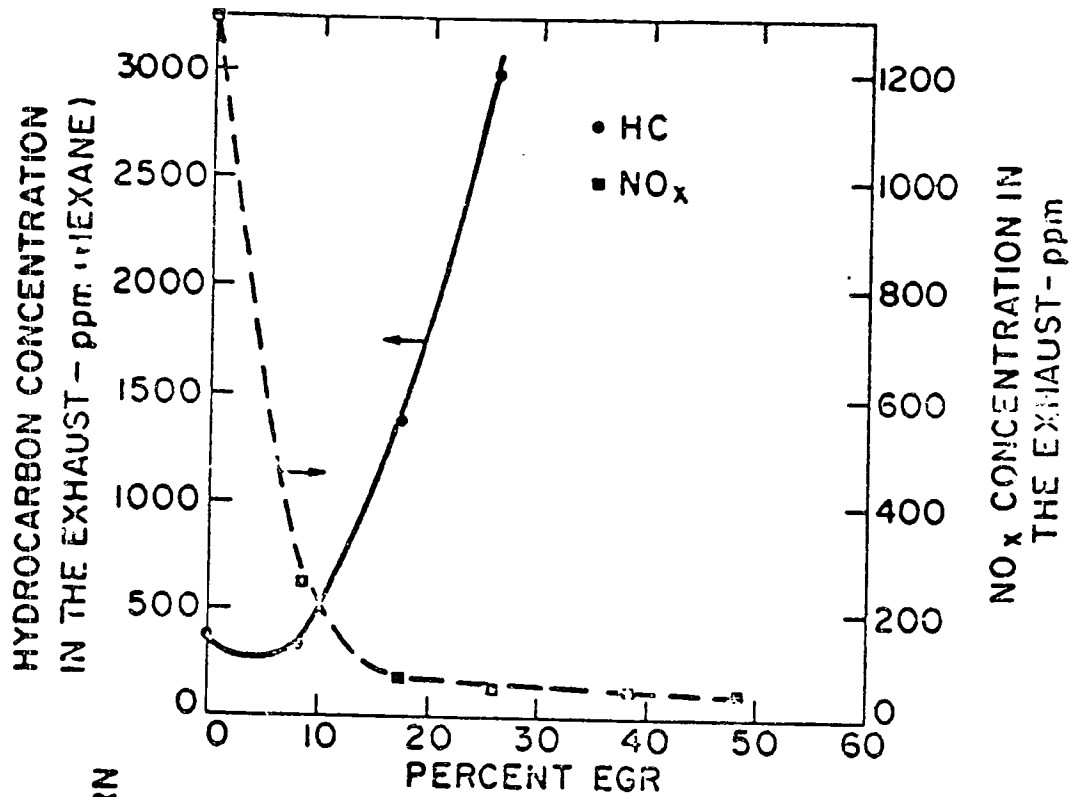
Source: Reference 5.

FIGURE 2-4. EGR VALVE AND POSITION SENSOR ASSEMBLY MOUNTING

studies indicate that the accuracy requirements for the EGR control system are on the order of 3 to 5 percent due to the sensitivity of misfires, slow burns and hydrocarbon formation to inappropriately high EGR levels. The problems associated with today's EGR systems are numerous and relate specifically to the inability of the system to meet this accuracy requirement under dynamic engine conditions. Some of these problems are listed here:

- a) Under transient conditions, intake manifold vacuum and load do not hold a linear relationship.
- b) EGR flow affects manifold vacuum, thereby causing positive feedback in this typically "open-loop" control system.
- c) Dynamic response of EGR valves degrade over time due to wear and clogging with corrosive elements contained in the exhaust gas.
- d) EGR valves typically are not sonic flow valves, therefore mass flow through the system at a given control vacuum varies as a function of the delta pressure across the valve.
- e) Single point entry under the throttle plate does not deliver homogenous mixtures to the combustion chamber. Maldistribution through the intake manifold is excessive (± 15 percent) and is known to vary with engine load.

In systems terminology, the net result of these issues is that poor control of EGR, both initially and over 50,000 miles, requires emissions compensation from other control variables, namely spark advance and A/F ratio. More spark retard is required to compensate for hydrocarbon formation (see Figure 2-5) either because of inappropriately high EGR levels or to compensate for increasing NO_x formation as the dynamic performance of the valve degrades with mileage. Also, the A/F ratio is calibrated richer to eliminate misfires and slow burns associated with poor EGR control and EGR maldistribution. These compensations inevitably lead to losses in fuel economy.



Source: Reference 6.

FIGURE 2-5. THE VARIATION IN THE HYDROCARBON AND NO_x EXHAUST EMISSION LEVELS AND THE AVERAGE STATISTICAL OCCURRENCE OF VARIOUS BURN TYPES AS A FUNCTION OF THE AMOUNT OF EGR, MONITORING CYLINDER 7 OF A 400 CID PRODUCTION ENGINE

Ford Motor Company was the first to introduce electronic control of EGR. This control is part of the EEC-I system introduced with the Lincoln Versailles model (details are discussed in Section 3. of this report) for 1978. This system demonstrates the ability of an electronic control system to eliminate some of the issues mentioned previously. The EGR valve in this system is a sonic flow valve and therefore flow rate is proportional to valve position (independent of downstream pressure). The valve is controlled in a closed-loop manner about a feedback position sensor on the pintel shaft; the feedback gain in the electronic module is a function of error in position which compensates for changes in the dynamic response of the EGR valve actuator with mileage. This also insures that if the valve needs more control signal (in this system the control is via air pressure) to get to a commanded flow rate (position), it receives it, thus compensating for partial clogging of the valve stem. The electronic control system in this case is microprocessor-based and therefore has the ability to decouple the effect of EGR flow on manifold vacuum which eliminates the positive feedback problem often referred to as EGR surge. The same computational algorithm used for decoupling the effect of EGR can be used for computing engine load, although a direct reading of engine torque would be more accurate. The benefit of the more precise and interactive control of EGR is the relaxing of the conservative calibrations of spark advance and A/F ratio resulting in improved fuel economy (~3 percent) with no loss in emission control.

Besides providing NOx abatement, an additional benefit, is that EGR has been shown¹ to be an effective engine knock suppressant, specifically for A/F ratio operations rich of stoichiometry. Therefore, the engine compression ratio can be increased, resulting in increased fuel efficiency. Unfortunately, the problem of EGR maldistribution due to the characteristics of the intake manifolds and to non-homogenous mixing with air and fuel is left unresolved. Electronics have demonstrated the accuracy and repeatability of control under transient engine conditions but electronics alone cannot compensate for poor

fluid or mechanical delivery systems. Perhaps a computer-controlled variable-valve timing system could selectively (only when required) deliver precise amounts of EGR to each cylinder internally (via variable valve overlap), yielding additional gains in fuel economy which often follows improved accuracy of control.

One last point to note is that the Ford system (ref. section 3.0) indicates that adding control of EGR to the electronic control system for spark is cost effective because the sensory inputs required for spark control are identical to those utilized in the determination of the required EGR flow rate. That is, (see Figure 2-6) the commanded EGR valve position is a function of engine speed, manifold pressure, barometric pressure, inlet air temperature, coolant temperature and the derivative of engine speed. This integrated systems-approach to emission control will become the prominent strategy in the 1980's.

2.3 FUEL DELIVERY SYSTEMS

The fuel systems used in automobile engines today are either carburetor-based or of the manifold fuel injection type. In both cases, the fuel systems attempt to deliver the proper amount of fuel to be mixed with incoming air for efficient combustion in the engine cylinders. This precise air/fuel ratio control is required over a wide range of engine speeds, loads, EGR rates, and inlet air densities. Other fuel systems envisioned for future introduction are throttle-body fuel injection and direct-cylinder fuel injection. In this section, the relative merits of each fuel delivery system and potential for electronic controls are discussed. Initially however, there is a need to illustrate the importance of the air/fuel mixture preparation on exhaust emissions. Figure 2-7⁷ presents a graph of relative exhaust emissions versus air/fuel ratio in the combustion chamber that is typical for spark ignition engines. As indicated, the air/fuel ratio has a significant impact on NO_x, HC and CO formations.

The rate of NO_x formation depends strongly on air/fuel ratio and peak flame combustion temperature. NO_x levels are

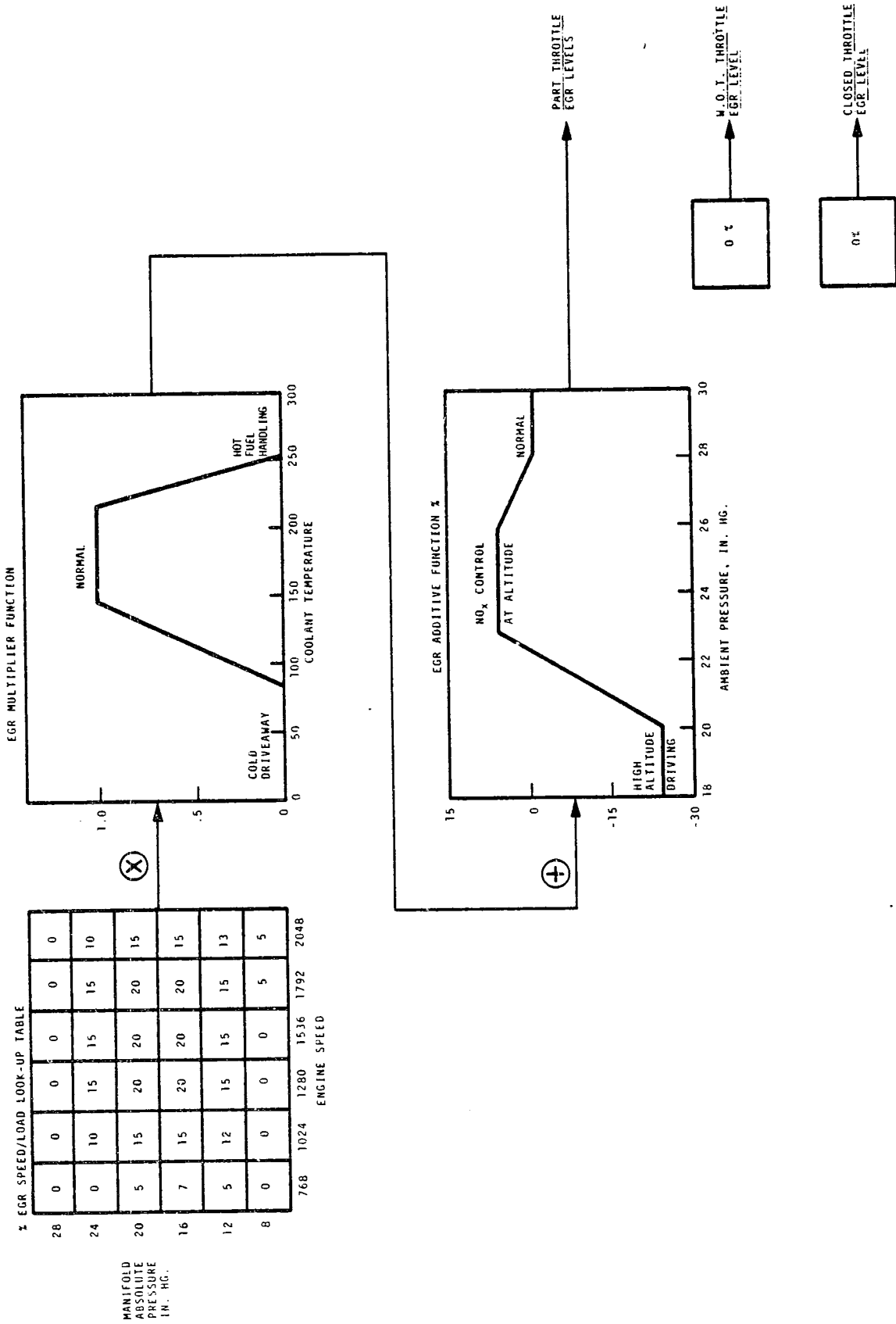
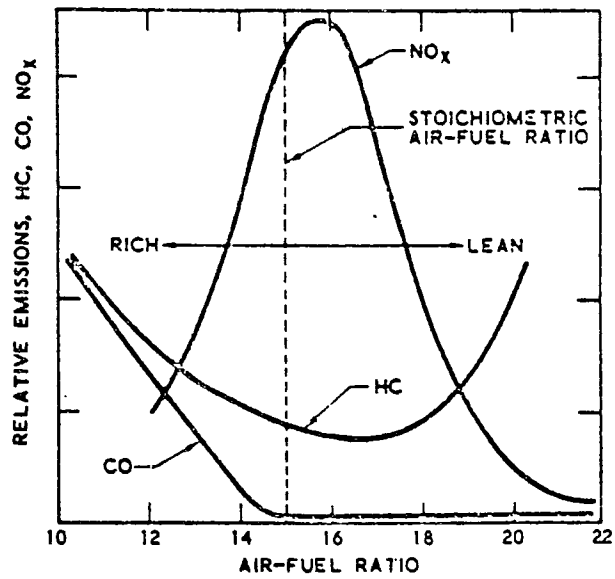


FIGURE 2-6. EXAMPLE OF A TYPICAL OPTIMIZED EGR CALIBRATION



Source: Reference 1.

FIGURE 2-7. EFFECT OF AIR/FUEL RATIO ON EMISSION LEVELS; SPARK-IGNITION ENGINE

