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STRATIFIED CHARGE ENGINES

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16. Abstract

This report reviews stratified charge concepts and engines, with emphasis on the important issues of exhaust emissions, fuel economy, and performance. Divided and open chamber designs are discussed. Potential improvements in exhaust emissions and fuel economy are considered in detail.

Significant engine programs discussed include those of the Ford, Texaco, and Honda companies. Other variations are described as information is available. Results of programs for the test and evaluation of newly developed and modified conventional engines, particularly engines in test vehicles, are provided.

A special addendum provides additional information current to March 1975, gleaned primarily from "Requests for Suspension of 1977 Emission Standards," filed by several of the automobile manufacturers.

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PREFACE

This work is part of a Department of Transportation study of automotive technology, production, and use aimed at providing decision-supporting information on automotive fuel consumption and pollution reduction. Stratified charge engine technology is reported through December 1974, with an addendum updating the information through March 1975.

This investigation, a subproject of the Automotive Energy Efficiency Project, was conducted in the Power and Propulsion Branch of the Mechanical Engineering Division of the Transportation Systems Center. The study was sponsored by the Department of Transportation, Office of the Secretary, Office of the Assistant Secretary for Systems Development and Technology.

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SUMMARY

The need to conserve petroleum resources and the increasingly stringent regulations to protect the environment have given strong impetus to the development of stratified charge engines for automotive application. Such engines show promise of better fuel economy and lower emissions than conventional spark ignition engines. Stratified charge engines are also attractive from the manufacturing viewpoint since the conventional internal combustion engine, with only minor modifications, can be used to implement most stratified charge concepts.

A stratified charge engine is a spark-ignition internal combustion engine using an overall lean fuel mixture, the mixture near the ignition source being richer than elsewhere in the cylinder. The fuel-rich mixture ignites and, in turn, easily ignites the remaining very lean charge. Complete combustion of the overall lean mixture is accomplished with greater thermodynamic efficiency than that attained with homogeneous combustion engines. Better fuel economies and lower emission levels are also achieved.

The stratified charge engine is the only foreseeable alternative to the catalytic converter for emission reduction and shows promise of being cheaper and more effective in meeting future, more stringent emission standards. Even so, major automobile manufacturers believe Federal relaxation of presently announced, 0.4 gm/mi NO_x emission level goals will be necessary before such alternate engine technologies can be used in production.

Major stratified charge engine development programs are being conducted by Ford, Texaco, and Honda. Ford and Texaco are concentrating on the open chamber type employing fuel injection. Honda's engine is a divided chamber type having a small auxiliary chamber for the fuel-rich charge, connected to the main chamber by a "torch" nozzle.

The improved efficiency of the overall lean mixture combustion of the stratified charge engine without emission controls results in better fuel economy than "uncontrolled" conventional engines.

Vehicles powered by the Ford Programmed Combustion Process (PROCO) and the Texaco Controlled Combustion System (TCCS) engines have demonstrated 25 percent improvement in fuel economy over 1968 pre-emission controlled engines; compound Vortex Controlled Combustion (CVCC) powered vehicles have shown about 4 percent improvement.

PROCO and TCCS engines have attained fuel economy improvements over comparable 1975 model year, conventional automobiles as indicated in Table S-1. A 1972 PROCO equipped Mercury Montego with a 351 CID V-8 has shown a 23 percent improvement over the standard 1975 Montego (1975 FTP); however, HC and CO emissions were high. A 1973 TCCS Plymouth Cricket with a 91 CID engine has demonstrated a fuel economy improvement (1975 FTP) of about 10 percent over a comparable, but standard, 1975 Datsun B210. (The TCCS Cricket was tested with low mileage on the catalyst.) The fuel economy of a CVCC powered Chevrolet Impala was 16 percent less than that of a 1975 Monte Carlo, making the CVCC Impala about equivalent to a 1974 production vehicle.

Vehicles powered with emission controlled TCCS, CVCC, and PROCO engines show ability to provide comparable performance to vehicles powered by conventional engines. In the case of a TCCS powered vehicle, a turbocharger is added to increase power. A PROCO powered vehicle would require an estimated 20 to 25 percent larger engine to provide the acceleration performance of a conventional engine.

Prototype. low mileage stratified charge engines, based on TCCS and PROCO concepts, and equipped with catalysts, have demonstrated the ability to meet statutory grams/per mile emission standards of 0.41 hydrocarbon (HC), 3.4 carbon monoxide (CO), and 0.4 nitric oxides (NO_x). CVCC concept engines have met these standards in a low mileage subcompact sized Honda and in a Vega, without a catalyst. The PROCO and TCCS engine test results are for low mileage vehicles because of catalyst durability problems.

The fuel economy of the CVCC and TCCS engines deteriorates about 25 to 30 percent when NO_x emissions are reduced to 0.5 gm/mi. PROCO fuel economy is essentially unaffected by reduction in NO_x emissions from 1.5 to 0.4 gm/mi; however, HC and CO emissions are high.

TABLE S-1. FUEL ECONOMY OF SELECTED CONVENTIONAL AND STRATIFIED CHARGE VEHICLES

	Emission-gm/mi			Economy	
	HC	CO	NO_x	MPG	% IMPROV.
TCCS 1973 Plymouth Cricket, 91-2					
1973 Certification Avg				20.6	
TCCS on 1975 FTP	1.07	.84	1.89	25.3*	+19% over 1973 Cricket
	0.36	1.15	0.38	20.1	- 2%
1975 Datsun B210 (low catalyst mileage)				23 in city; 31 highway	
PROCO 1972 Mercury Montego, 351-2					
1973 Torino Certification				9.0	
1974 Montego Certification				9.1	
1975 Montego Certification				11 urban; 16 highway	
1972 PROCO on 1975 FTP	3.54	28.2	.34	13.8	23% over 1975 Montego
	1.34	25.0	.96	13.2	
CVCC 1973 Impala, 350-2					
1973 Impala Certification				12.0	
(Honda)	1.5	19.3	2.4	10.5	
1974 Impala Certification				11.0	
1975 Monte Carlo Certification				13 urban; 18 highway	
1973 CVCC on 1975 FTP (Honda)	0.19	2.85	1.57	10.9	-16% from 1975 Monte Carlo

*TCCS at 1.89 NO_x shows 10% increase in mpg over 1975 Datsun B210.

NO_x emissions of the CVCC vehicles double as car weight doubles. This, with the poor fuel economy of the CVCC Impala, indicates that the CVCC concept is less attractive when applied to large cars.

Exhaust smoke and odor are not a problem with the CVCC. The PROCO and TCCS engines, however, do exhibit smoke and odor under full load, primarily due to fuel injector limitations.

United States automobile manufacturers are noncommital about investing in stratified charge engine lines because future NO_x level requirements have not been firmly set by the Government. General Motors advocates a 2.0 gm/mi NO_x level. Ford and Chrysler have expressed the opinion that the NO_x level of 0.4 gm/mi is too stringent, but have not suggested an alternate figure.

Incremental costs of a stratified charge engine to meet the 0.4 NO_x standards are estimated at $250 per large sized car over the costs of the 1974 baseline models.

1. INTRODUCTION

The need to conserve petroleum resources and the increasingly stringent regulations to protect the environment have given strong impetus to the development of stratified charge engines for automotive application. Such engines show promise of better fuel economy and lower emissions than conventional spark ignition engines. Stratified charge engines are also attractive from the manufacturing viewpoint since the conventional internal combustion engine, with only minor modifications, can be used to implement most stratified charge concepts.

The stratified charge concept was introduced by Sir Harold Ricardo over fifty years ago.[1*] Applied to the spark ignition internal combustion engine, the concept is implemented by having a much richer fuel-air mixture in the zone near the spark plug electrodes than elsewhere in the combustion volume. Common to all spark ignited stratified charge engine combustion processes is first, combustion in a fuel-rich zone near the ignition source, followed by completion of the burning in the fuel-lean region away from the ignition source. The more complete combustion in the overall lean mixture results in greater thermodynamic efficiency than attainable with homogeneous combustion engines.

In 1975, most cars manufactured and/or sold in the United States were equipped with an emission reducing system including a catalytic converter. The 1975 systems met 1975 emission standards while showing a 13.5 precent increase in fuel economy above 1974 model year cars.[2] However, these systems are expensive and may have technical difficulties in meeting future, more stringent fuel economy and emission requirements. In the near future, the stratified charge engine is the only possible major alternative to the catalytic converter system for emission reduction.

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[*] Superscripts refer to References.

The stratified charge engine is favorable over the diesel from a cost point of view; it achieves overall lean burn combustion without ignition difficulties characteristic of homogeneous spark ignition lean burn engines. Even so, according to General Motors, Ford and Chrysler corporations, some relaxation of presently announced future emission regulations will be required before alternative engine technologies can be used in production. These manufacturers have indicated, as cited in Appendix A, that Federal limitations of nitric oxide emission levels to not more than 0.4 gm/mi would prohibit the introduction of stratified charge engines.

1.1 STRATIFIED CHARGE ENGINE CONCEPTS

Two major methods of achieving charge stratification are indicated in Figure 1-1. The open chamber methods illustrated in Figures 1-1(a) and 1-1(b) use coordinated air swirl and fuel injection in a combustion chamber of conventional geometry. A cupped piston promotes controlled air movement. The most developed example of the open chamber type is the Ford Programmed Combustion Process (PROCO), illustrated in Figure 1-1(a). Fuel is injected in a controlled conical spray during the compression stroke but sufficiently early to permit vaporization. A rich combustible region is formed near the spark plug within an environment of excess air.

The Texaco Controlled Combustion System (TCCS) is illustrated in Figure 1-1(b). Fuel is injected into swirling air to establish a flame front immediately downstream from the injection nozzle. The flame front is formed along the downstream edge of the fuel-rich mixture zone near the ignition source. Stratification thus exists by having a rich mixture burning zone in a swirling air and gas environment.

A divided chamber stratified charge method is shown in Figure 1-1(c). The design depicted is the Honda Compound Vortex Controlled Combustion (CVCC) chamber consisting of a prechamber connected, through a nozzle, to the main combustion chamber. The rich fuel-air mixture in the prechamber is essentially physically separate from the lean fuel-air mixture in the main combustion chamber.

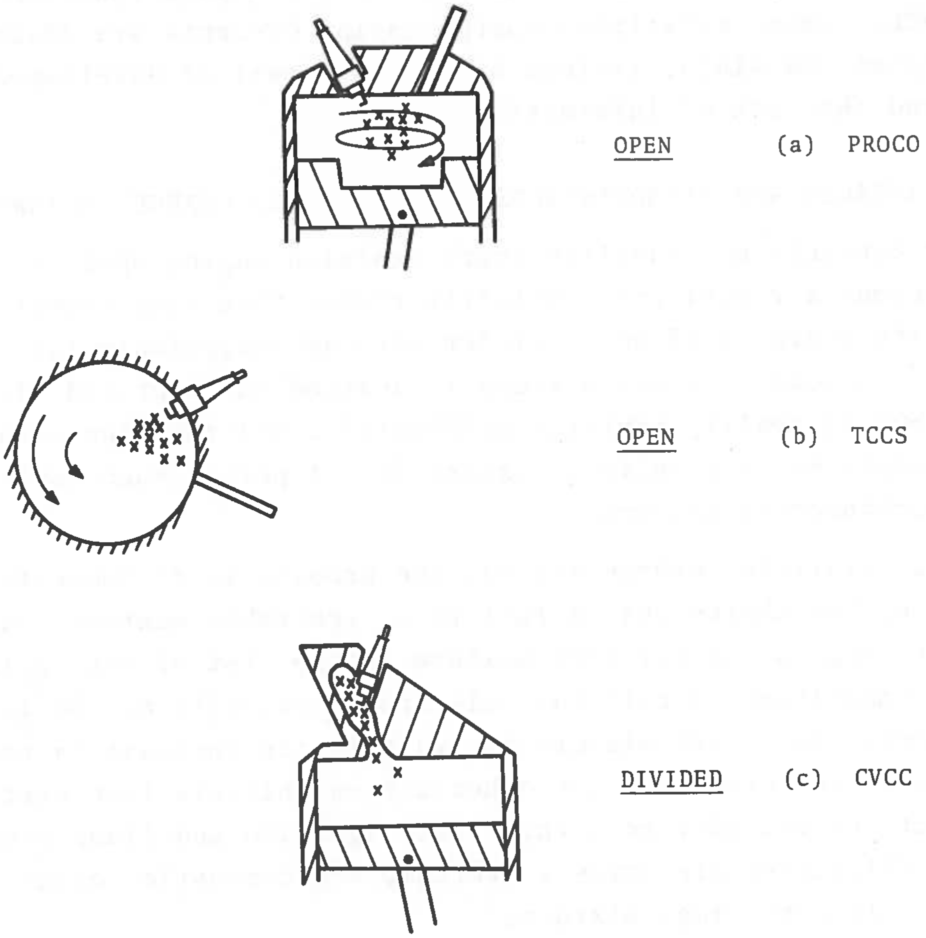


Figure 1-1. Methods of Charge Stratification

Prechamber volumes vary from about 4 to 12 percent of the total clearance volume.

A second type of divided chamber method, not illustrated, has a rich mixture chamber volume of about 65 to 85 percent of the total clearance volume. Physically, a partition with a connecting orifice is used to separate the combustion chamber into upper and lower chambers. A rich fuel-air mixture is supplied to the upper chamber, and only air to the lower chamber. This concept is used in the Newhall engine, described in Section 3.5. This report discusses in some detail those stratified charge engine concepts being intensively investigated and developed by automobile manufacturers. These include the Ford PROCO, Texaco TCCS, and the Honda CVCC. Other stratified charge engine concepts are discussed to the extent possible, limited by the low level of development effort and the lack of information.

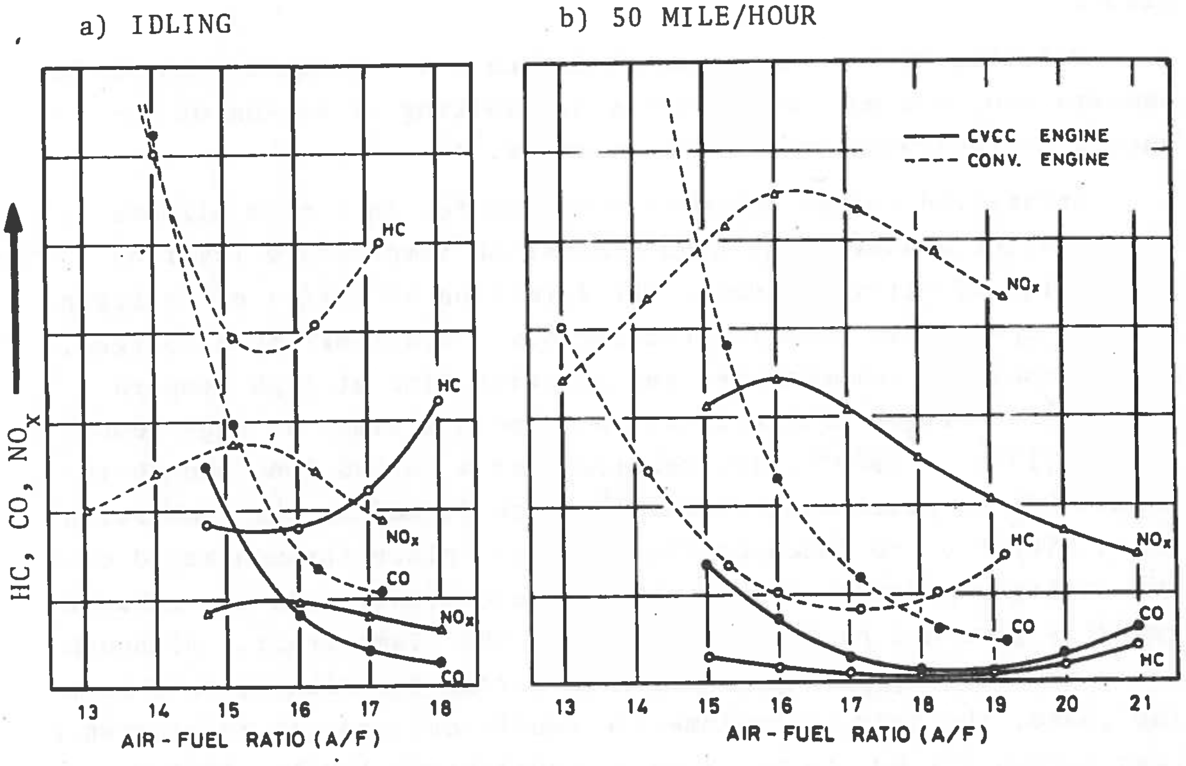
1.2 ADVANTAGES AND DISADVANTAGES OF STRATIFIED CHARGE ENGINES

The conventional gasoline spark ignition engine operates with a homogeneous air-fuel ratio slightly richer than stoichiometric to prevent the charging of any cylinder with an unignitable fuel-lean mixture.[3] A lean fuel-air mixture is desired for improved efficiency, but in reality ignition difficulties and the flame propagation mechanism in a uniform mixture do not permit much deviation from stoichiometric mixtures.

In a stratified charge engine, the problem is circumvented by stratifying the charge into a fuel-rich, ignitable mixture near the spark plug and an air-rich mixture in the rest of the cylinder. Mixture composition is critical only in the vicinity of the ignition source. Once that mixture is ignited, the increase in temperature and pressure cause the otherwise unignitable lean mixture throughout the cylinder to burn. Thus, ignition and flame propagation difficulties are largely overcome and combustion occurs in an overall lean air-fuel mixture.

1.2.1 Emission Control Considerations

The exhaust emissions produced by stratified charge engines are typically lower than for a conventional homogeneous charge engine due to the combustion process.[4] As an example, the exhaust emission trends for a Honda CVCC stratified charge engine, together with emission trends for a conventional engine of the same size[5] are shown in Figure 1-2. The curves shown are for idle conditions (a), and at a road load of 50 mph (b). Operation of the stratified charge engine is shown to be at overall leaner air-fuel ratios than conventional engines, and exhaust emissions are relatively lower than for the conventional engine.


a) IDLING

b) 50 MILE/HOUR

Source: Ref. 5

Figure 1-2. Comparison of Exhaust Emission of CVCC Engine with Conventional Engine

Figure reprinted with permission of A.R. Willems, SAE, Warrendale PA 15096.

Figure 1-3 qualitatively shows the influence of the air-fuel ratio (at the time of combustion) on exhaust emissions.[6] During the early part of combustion the three pollutants, HC, CO and NO_x are formed in the ignition zone with concentration levels as shown at the left of the figure. At the end of combustion, the pollution concentrations are reduced to levels shown on the right side of the figure.

Dilution of burning gases with excess air reduces combustion temperature, but not below levels prohibiting oxidation of unburned hydrocarbons and carbon monoxide.[6,7]

Stratified charge combustion originates in a rich mixture region which achieves the high combustion temperature favoring production of nitric oxides. The formation of oxides of nitrogen depends upon three interrelated factors: availability of oxygen, peak combustion temperature, and reaction time at high temperature.[6,8,9] Oxygen availability and exposure times at high temperatures (1300° – 2500°C) are required for a period long enough to permit NO_x to reach equilibrium.[10] Once formed in the combustion zone, little or no decomposition can take place through rapid cooling during expansion. Thus the NO_x concentration in the exhaust gases is governed by the conditions at the flame front. Although the combustion temperatures are high during the rich mixture burning phase, the near stoichiometric conditions are not in existence long enough for NO_x to build up to equilibrium levels; that is to say, the lack of oxygen counteracts the NO_x-favorable temperatures.

Both the prechamber and open chamber stratified charge engines have problems which affect their low emission capabilities. The major disadvantage of the prechamber stratified charge engine is combustion quenching during the lean burn phase.[5,6] The lean charge must be rich enough under all load conditions to propagate a flame with adequate velocity; otherwise, unburned HC will be present in the exhaust gases. The open chamber type engines have particulate problems due to the difficulty of controlling combustion by fuel injection rate. Carbon particles appear when combustion occurs in an overly rich mixture zone. Direct fuel injection requires coordination of air swirl and injection timing

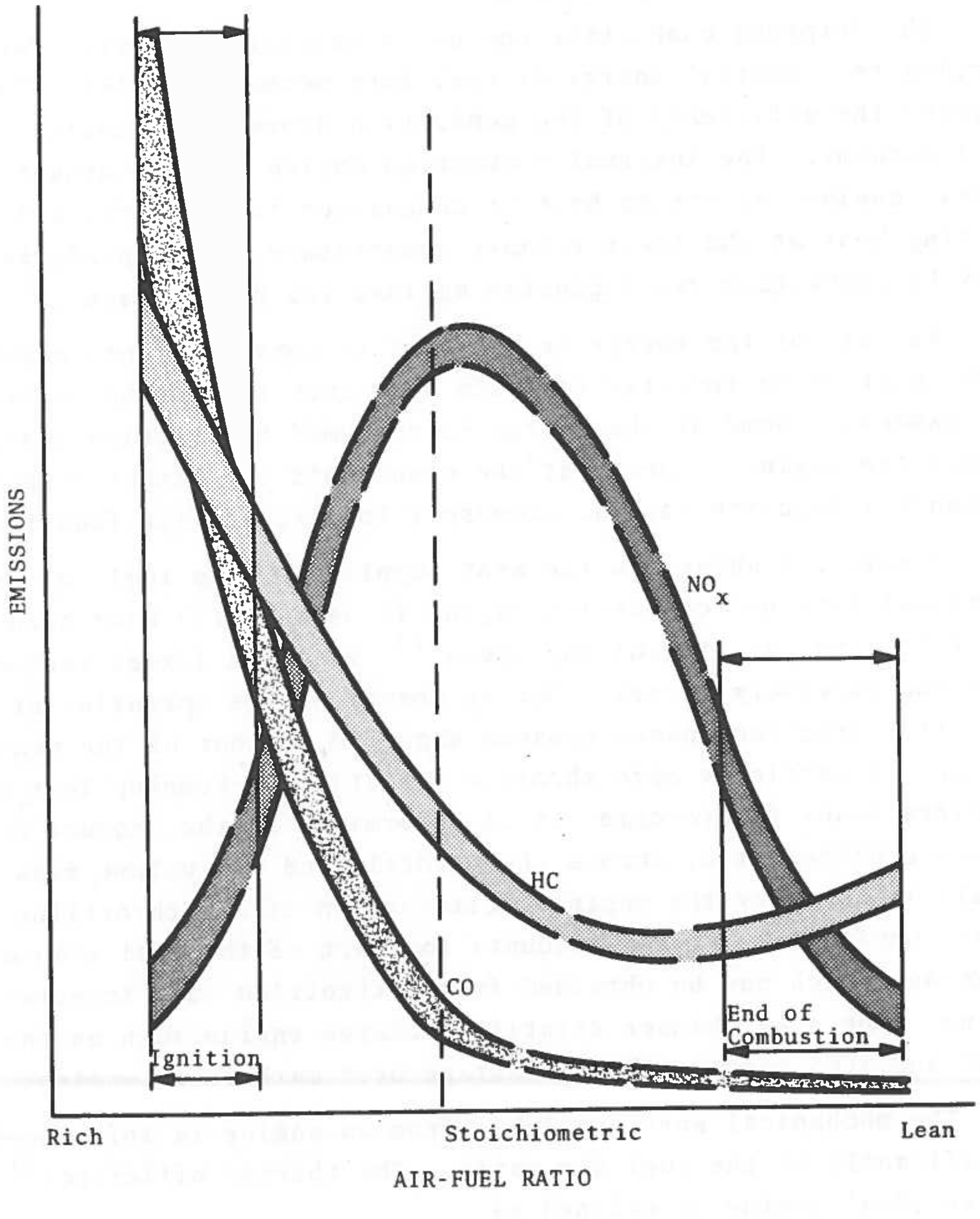


Figure 1-3. Effect of Stratified Charge Combustion on Emissions

for proper mixture formation, a problem shared by both stratified charge and diesel engines.

1.2.2 Fuel Economy Improvements

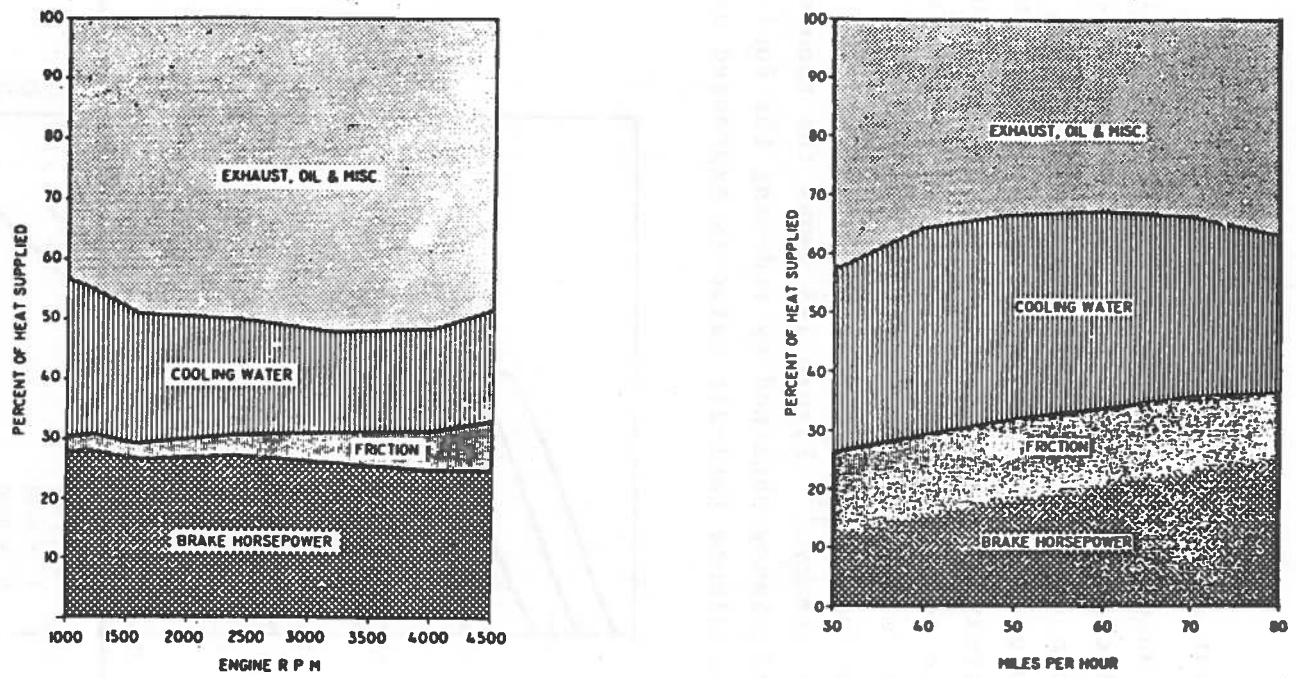
The internal combustion engine is basically a device for converting the chemical energy of fuel into mechanical work. The greater the efficiency of the combustion process the better the fuel economy. The internal combustion engine may be thought of as a heat engine, accepting heat at combustion temperatures and rejecting heat at the lower exhaust temperature, while producing net work by combustion gas expansion against the piston faces.[11]

Not all of the energy in the fuel is converted into mechanical work, part being rejected as waste heat into the cooling system and exhaust. Some of the energy is consumed by friction losses within the engine. Energy at the crankshaft is further reduced by mechanical friction losses, accessory losses, and air flow losses.

Figure 1-4 shows how the heat supplied by the fuel in a conventional internal combustion engine is used at (a) wide open throttle, and (b) at cruising speed.[12] Friction losses include air flow and accessory losses. During normal engine operation at part throttle, friction losses consume about 20 percent of the available energy. A partially open throttle results in a pumping loss which requires power to overcome; it is determined by the product of the pressure differential across the throttle and the volume flow rate of air ingested by the engine. Elimination of air throttling reduces pumping losses, and accounts for part of the fuel economy advantage which may be obtained from unthrottled fuel injected engine. The open chamber stratified charge engine such as the PROCO and TCCS possess this advantage over carbureted engines.

The mechanical work available from an engine is influenced significantly by the fuel-air ratio. The thermal efficiency[11] η_t for an ideal engine is defined as:

$$\eta_t = 1 - (1/r)^{k-1}$$



a) Heat Balance at Wide Open Throttle

b) Heat Balance at Cruising Speed

Figure 1-4. Engine Heat Balance

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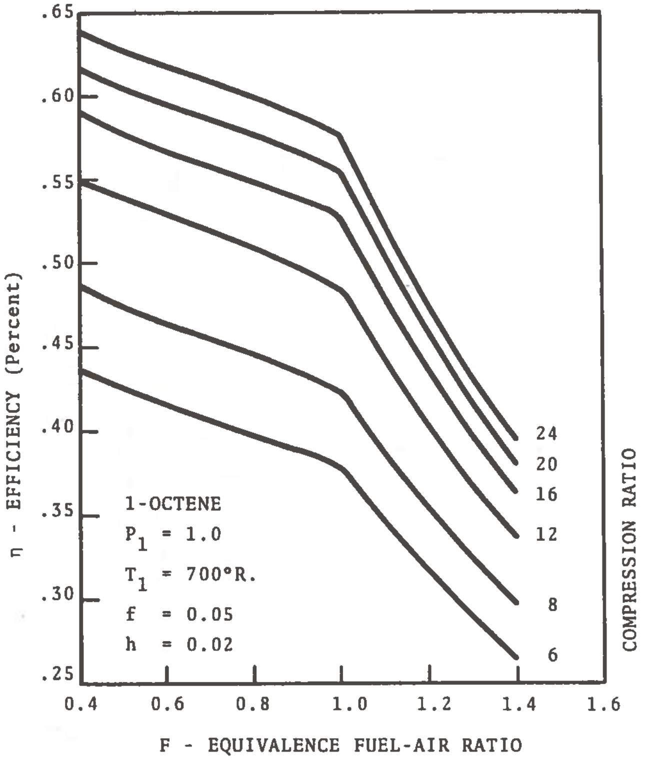
The theoretical power developed by such an engine is:

$$P = Q\eta_t$$

where Q is the heat energy supplied.

Considering an engine with a fixed compression ratio, r, the ideal thermal efficiency becomes a function of the ratio of specific heats, k. In a conventional spark ignition engine, high combustion temperatures result in molecular dissociation in the mixture and a relatively low value of k. A reduction in fuel-air ratio would reduce combustion temperatures and dissociation, thus increasing k. It follows from the preceding efficiency equation that reducing the fuel/air ratio, i.e., leaner charges, will increase engine efficiency.[13] Figure 1-5 shows the theoretical improvement in efficiency obtained by reducing the fuel-air ratio.[14] The equivalence fuel-air ratio is expressed as the



Source: Ref. 19

Figure 1-5. Efficiency Versus F (Equivalence Fuel-Air Ratio)

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fraction F, the actual fuel-air ratio divided by the stoichiometric fuel-air ratio. The conventional automobile engine operates at nearly stoichiometric conditions (F equal to unity). The stratified charge engine with an overall lean combustion process (F less than unity) can attain higher efficiencies as shown. Lower combustion temperature resulting from a reduced fuel-air ratio, also means less heat loss from the combustion chamber. Such losses normally show up as waste heat into the cooling system which reduces engine output.

The stratified charge concept provides fuel economy advantages in a spark ignition engine previously restricted to diesel engines. These advantages are reduced pumping losses and overall lean combustion. However, reduction in pumping losses is not applicable to carbureted stratified charge engines such as the Honda CVCC.

The efficiency of fuel-injected, open-chamber, stratified-charge engines may drop at increased load due to incomplete fuel utilization, and thus result in smoke formation. Consequently, a stratified charge engine automobile may require a larger size power plant than an equivalent, conventionally powered car, to avoid operation in the smoke region under high loads. Alternatively, the performance of the car may be derated by limiting the maximum fuel flow to the injectors.

1.2.3 Cost

There is little cost data available from U.S. auto manufacturers on converting to stratified charge engines. Manufacturers have indicated reluctance to commit themselves to alternate engines due to the issue of NO_x standards. Ford has labelled the PROCO as an "absolute dead loser" at 0.4 gm/mi NO_x levels.[15] Ford is evaluating the Honda CVCC for meeting a 2.0 gm/mi NO_x standard. At this NO_x level, Ford estimates a cost of $150 million for conversion of one engine line of 140 CID, and $160 million for a 400 CID engine line.

Honda introduced the CVCC powered Civic into the U.S. market for 1975. At that time they estimated that the list price of a

Honda CVCC Civic automobile would be \$100 to \$200 higher than a Civic with a conventional engine.[16]

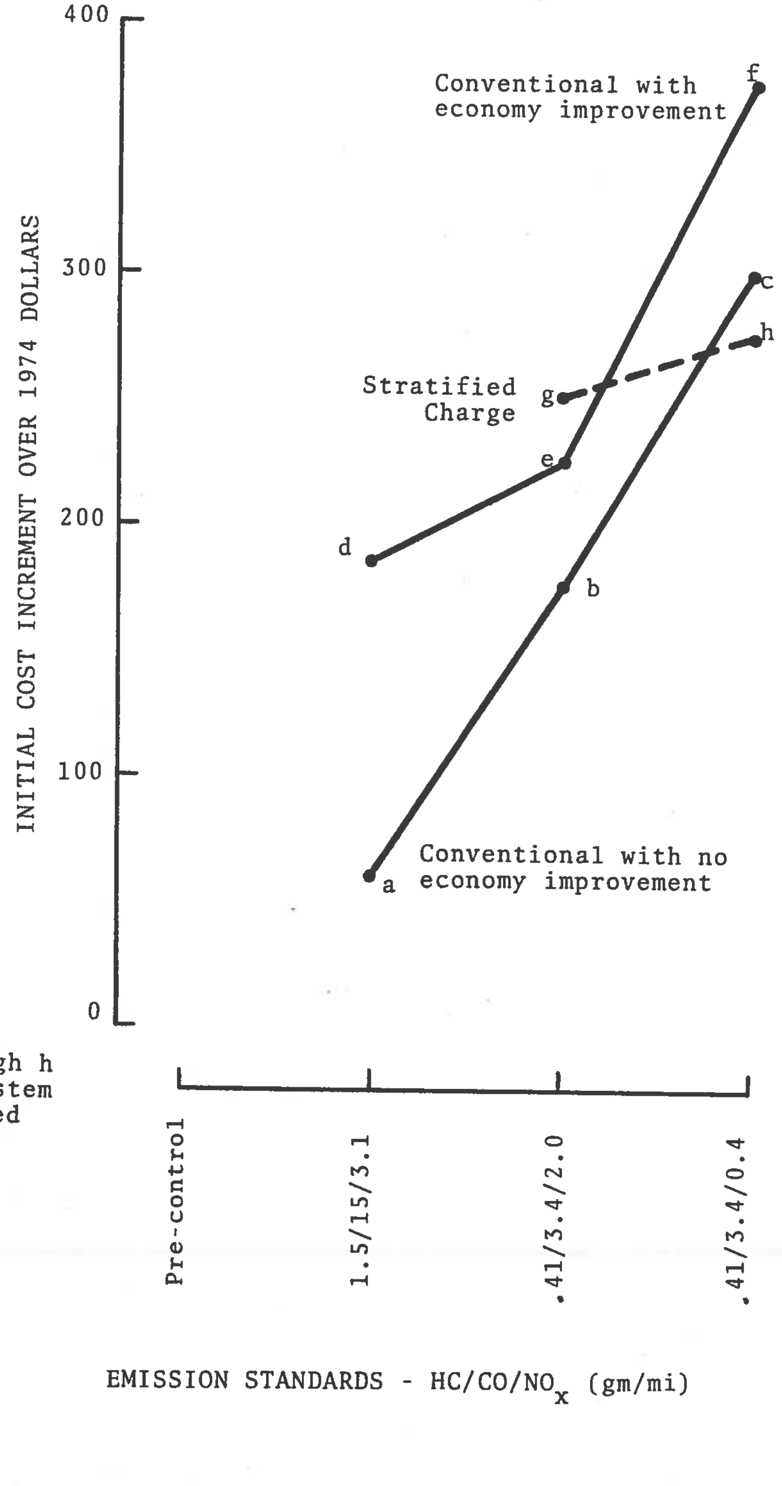
Figure 1-6 summarizes the first costs of alternate engine/ emission systems, above a 1974 baseline, for large size vehicles using either a conventional or stratified charge engine.[12,17] Three approaches to meeting the emission standards are treated:

(1) Line a-b-c shows the cost for conventional engine technology using a minimum cost approach and just meeting the emission standard;

(2) Line d-e-f shows estimates for higher cost technology, giving a possible 25 percent improvement in fuel economy,

(3) Line g-h shows the cost for stratified charge engines, also with a 25 percent improvement in fuel economy.

The cost data indicate that a stratified charge engine with catalyst (category h) for large size cars meeting .41/3.4/.4 gm/mi HC/CO/NO_x would be about \$100 less than a conventionally powered vehicle (g), both maintaining the same 25 percent improvement in fuel economy over a 1974 baseline. The least expensive conventional option (c), meeting emission levels of .41/3.4/.4 gm/mi, shows a decrease in fuel economy of 15 percent. The reader is cautioned not to interpret this data as assessment of the technological readiness of the emission systems, a matter considered in more detail in later sections of this report.



Note:
Letters a through h
identify the system
categories listed
in appendix B.

Source: Ref. 17

Figure 1-6. Incremental Initial Cost Increase over 1974 to Meet More Stringent Emission Levels

2. OPEN CHAMBER STRATIFIED CHARGE ENGINES

2.1 FORD PROGRAMMED COMBUSTION PROCESS (PROCO)

2.1.1 Introduction

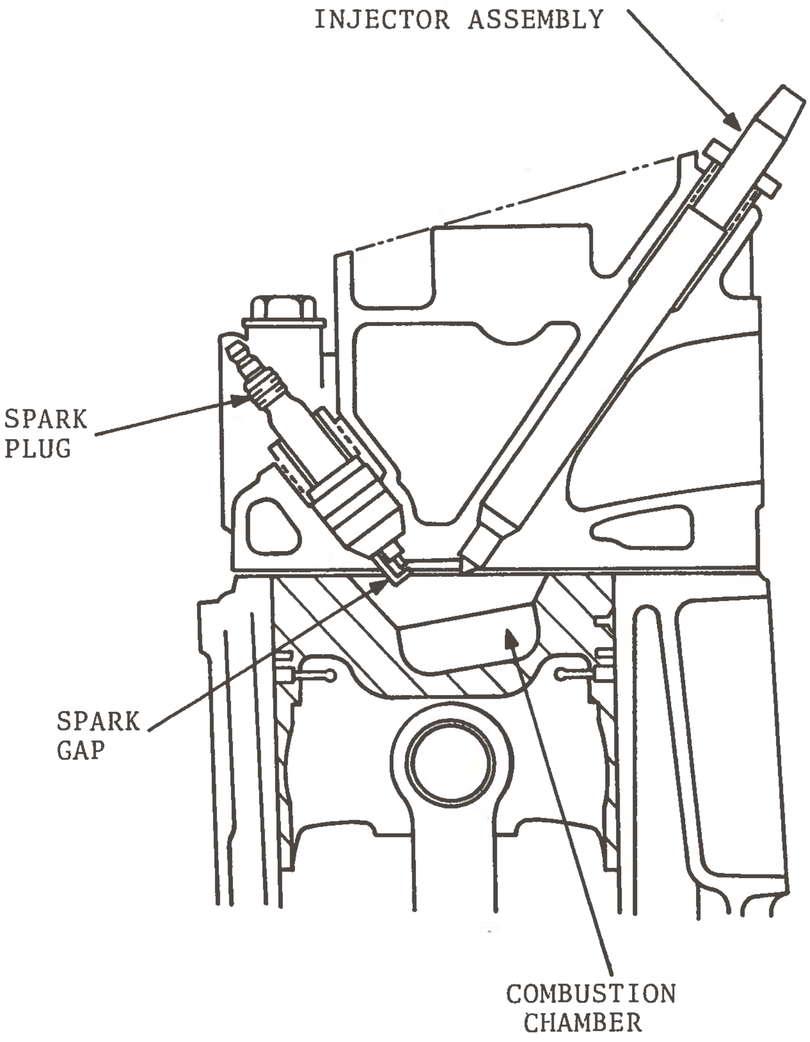
Ford has worked on stratified charge engine concepts since 1956. Initially, the Ford Combustion Process (FCP) was developed with the objective of improving fuel economy with engine power equal to that of a conventional engine.[18,9] A second generation FCP, the Ford Programmed Combustion Process (PROCO),[19] was developed to minimize exhaust emissions with minimum loss in fuel economy. The PROCO is essentially the same basic combustion system as the FCP, with additional emission control equipment which may include exhaust gas recirculation (EGR), improved carburetion, electronic ignition, and catalytic reactors.

Ford's development and test program has included tests on a PROCO-modified L-141 military engine installed in an M-151, 1/4-ton military vehicle. Fuel economy improvements were significant, but performance was reportedly inadequate for normal passenger car operation. Tests with a PROCO-equipped 1972 Montego adjusted for 0.4 gm/mi NO_x levels indicate that statutory 1978 emission standards could be met only on low mileage vehicles due to catalyst durability problems. An Arthur D. Little study concludes that PROCO shows promise of low emissions but has yet to attain the low levels of the Honda CVCC stratified charge engine.[20]

Ford indicates that with continued development success and a NO_x standard of 2.0 gm/mi, the PROCO could be in 1978 model year production automobiles.[21]

2.1.2 The PROCO Concept and Operation

Figure 2-1 shows a cross-sectional diagram of an engine embodying the PROCO concept.[19] A dished piston is used in the combustion chamber, providing a compression ratio of 11 to 1. A fuel injector, located near the top center of the cylinder bore, provides a low-penetrating, wide-angle, conical spray. In this form,



Source: Ref. 19

Figure 2-1. Typical Ford PROCO Engine

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the spray has a rich mixture at its center, surrounded by a leaner mixture and excess air. The spark plug is positioned with its gap just above the spray, near the bore center-line. The intake port configuration, not apparent from the diagram, is designed to impart a swirl to the air in the combustion chamber. Swirl rate is about 3-5 times greater than the crankshaft rpm.

At part load operation, air is throttled to maintain about 15.5:1 air-fuel ratio. Fuel is injected during the compression stroke, and combustion is initiated in a rich mixture zone in the vicinity of the spark plug electrodes. High air swirl rate maintains fast and near-complete combustion even with high EGR rates. The fast combustion process allows combustion event retard, resulting in lower peak temperatures and shorter exposure time at high temperature. The efficiency due to combustion event retard is compensated for by a high compression ratio.

2.1.3 PROCO Engine and Emission Characteristics

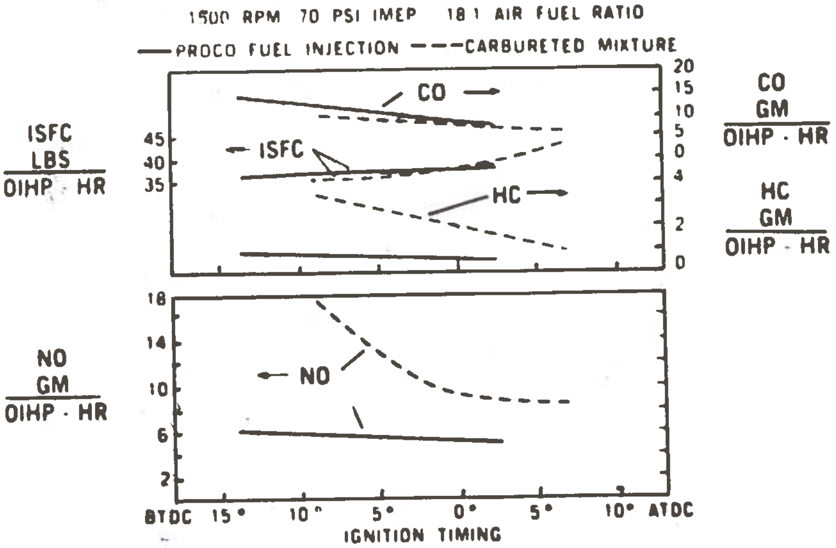
Exhaust emission characteristics of the PROCO system were studied by Ford on a single cylinder engine.[19] Parameters considered include injection timing, ignition timing, air-fuel ratio, and exhaust gas recirculation; the influence of an increase in squish area (area of the piston face less the open area of the dish) was also considered.

The single cylinder test engine was a Waukesha CFR, with 44 CID and an 11:1 compression ratio. The piston squish area was 65 percent of the piston face.

Figure 2-2 shows the emissions of the PROCO system without EGR and the emissions of the same engine operated with a conventional carburetor. Charge stratification results in a slight increase in carbon monoxide, with significant decreases in both nitric oxide and hydrocarbon emissions. For both carbureted and stratified charge operation, the air-fuel ratio was 18:1. Spark retard decreases emissions for both PROCO and carbureted systems.

Figures 2-3 through 2-7 show test results with EGR. Figures 2-3 through 2-6 are of particular interest since they show results obtained with a constant 15 percent EGR rate, and the effects of combustion control variables on emissions can be examined.

The effect of injection timing is indicated in Figure 2-3. Retarded injection timing reduces NO_x by causing a richer mixture to be present near the plug at the time of combustion. Fuel dispersion is reduced by retarded injection timing, producing a richer air-fuel mixture and tending to reduce NO_x formation. Hydrocarbon emissions decrease with injection retard due to shorter fuel



Source: Ref. 19

Figure 2-2. Comparison of Stratified Vs. Premixed Combustion in PROCO Engine Without EGR

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residence time. Conversely, CO emissions increase with short residence time since combustion is less complete during the final burning phase.

Ignition timing influence is shown in Figure 2-4. Rich first phase combustion is achieved through retarded ignition timing, thereby reducing NO_x. With ignition retard, hydrocarbons increase to a certain level due to lower fuel residence time, but then decrease due to the higher temperature in the expanding gases. Timing retard decreases carbon monoxides since longer fuel residence time results in leaner combustion in the primary burning phase.

Figure 2-5 shows the influence of the air-fuel ratio. Increasing the air-fuel ratio dilutes combustion, and slightly

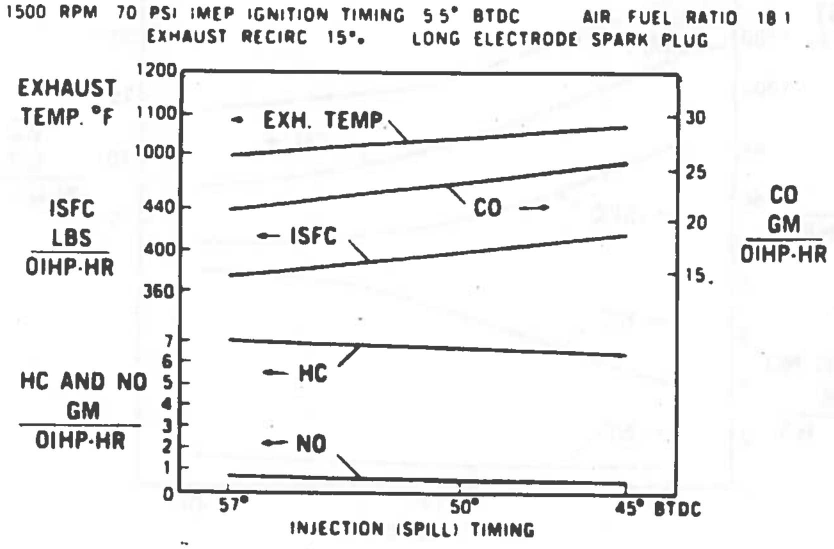

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Figure 2-3. Injection Timing Effects at One Load Point

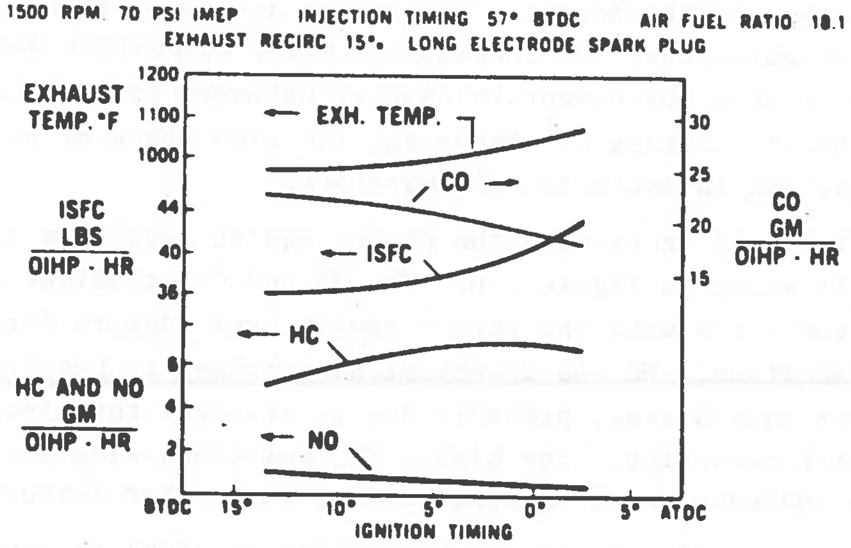

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Figure 2-4. Ignition Timing Effects at One Load Point

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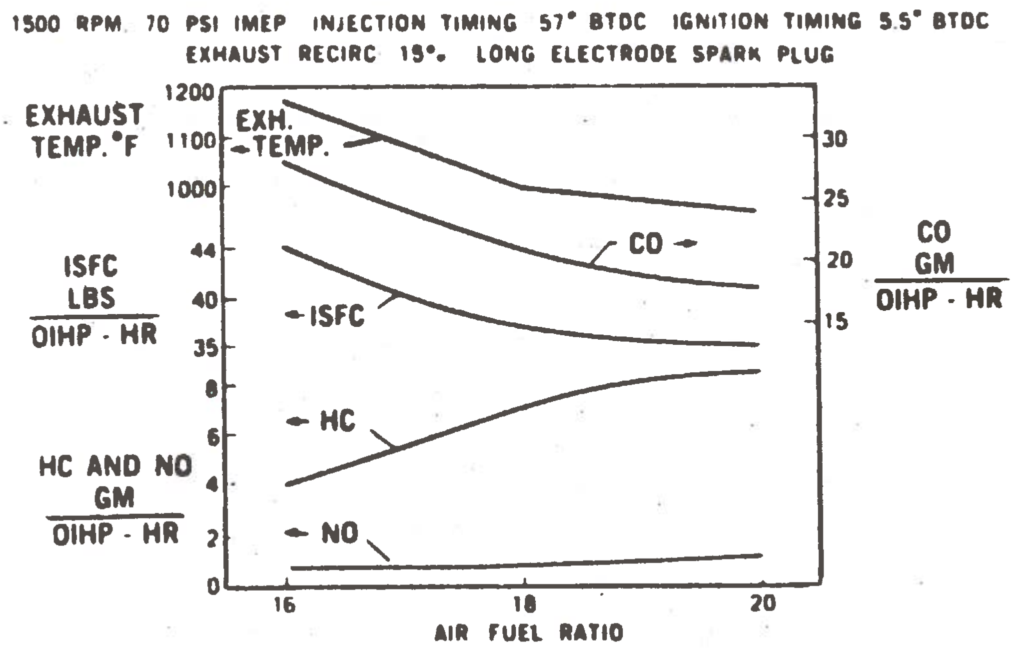

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Figure 2-5. Air-Fuel Ratio Effects at One Load Point

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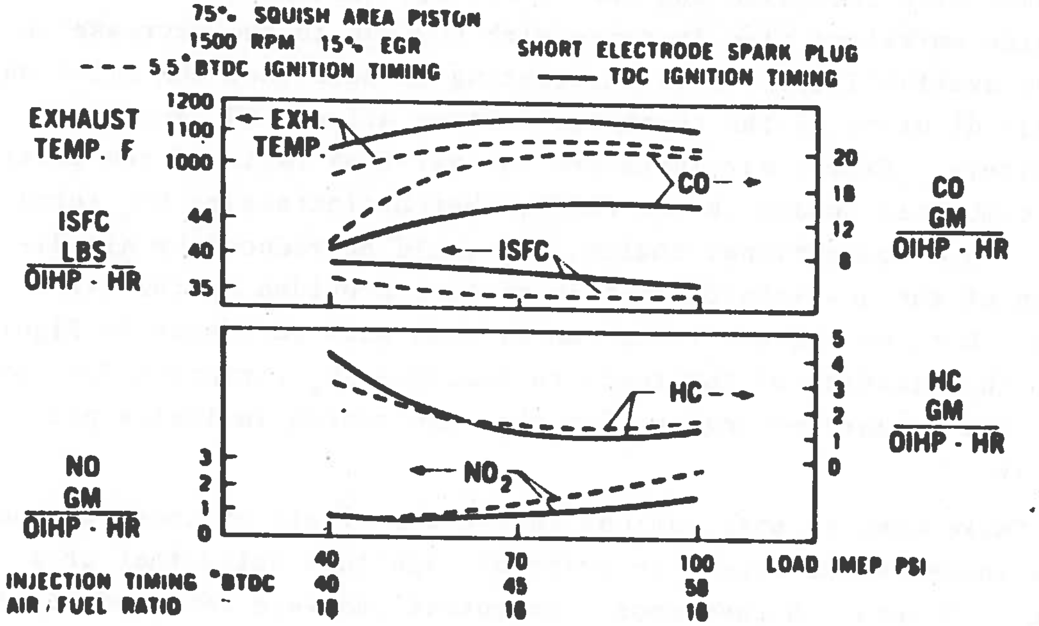
increases the NO_x since first phase burning occurs with a mixture ratio closer to stoichiometric. The excess air is a strong influence on HC emissions. HC increases, since combustion quenching takes place, with a consequent release of unburned hydrocarbons into the exhaust. Excess air leans out the rich phase of the combustion resulting in decreased CO emissions.

The effects of increasing the piston squish area from 66 to 75 percent is shown in Figure 2-6. The HC and CO emissions are reduced at light loads with the larger squish area due to more thorough combustion. HC and CO emissions increase at heavier loads with a larger squish area, probably due to stronger turbulence and increased wall quenching. The higher NO_x emissions with the larger squish area indicate more thorough mixing and faster combustion.

The influence of exhaust gas recirculation (EGR) is shown in Figure 2-7. EGR reduces NO_x significantly by reducing flame temperature without increasing oxygen availability. HC emissions



Source: Ref. 19

Figure 2-6. Squish Area Effects Across the Part-Load Range

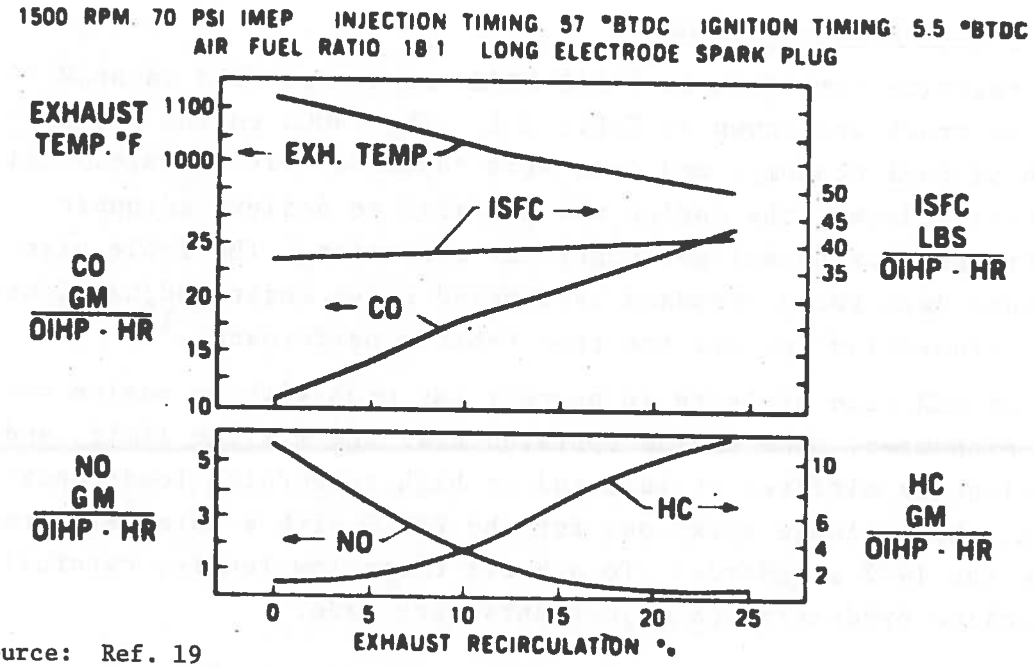


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Figure 2-7. Exhaust Recirculation Effects at One Load Point

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increase with increased EGR due to mid-air quenching. Carbon monoxide emissions also increase with EGR due to the decrease in oxygen availability. It is interesting to note that EGR dilution and air dilution of the combustion charge affects NO_x emissions oppositely. Excess air increases the air-fuel ratio of the initial rich combustion phase in the PROCO, thereby increasing NO_x formation. In a conventional engine, NO_x would be reduced by air dilution of the near-stoichiometric mixture provided by the carburetor. Both of these effects can be seen with reference to Figure 1-3. The addition of EGR tends to decrease NO_x formation for both PROCO and carbureted engines for the same reason indicated previously.

Smoke density observations during the single cylinder engine tests showed smoke levels an order of magnitude below that of a diesel. However, higher smoke concentrations were reported at high loads and high EGR rates.

2.1.4 PROCO Vehicle Tests

M-151 PROCO Emissions

Emission data from an L-141 PROCO engine mounted in an M-151 1/4-ton truck are shown in Table 2-1. The PROCO engine was set for best fuel economy, and data were taken at zero mileage. Set for best economy, the engine was not able to achieve adequate performance for normal passenger car operation. The table also includes data for a standard carbureted L-141 engine adjusted with rich carburetion for off the road vehicle performance.[19]

An EGR rate of 14 to 16 percent was used with an engine coolant heat exchanger. The engine operated near the misfire limit, and occasionally misfired at idle and at high speed/high load conditions. Low mileage emissions for the PROCO with a catalyst were below the 1977 standards. To achieve these low levels, carefully controlled predetermined adjustments were made.

TABLE 2-1. FORD VEHICLE EMISSION DATA

M-151 VEHICLE	EMISSIONS, g/mi			ECONOMY, mpg*	NO. TESTS AVERAGED	TEST FACILITY
	HC	CO	NO_x			
CVS/CH						
CARBURETED	4.55	41.60	4.40	17.2	3	FORD
PROCO, W/O CATALYST	2.60	13.45	0.32	21.7	1	FORD
PROCO, WITH CATALYST	0.35	1.01	0.35	21.3**	2	FORD
PROCO, WITH CATALYST	0.37	0.93	0.33	NOT MEASURED	14	EPA
1972 CVS TEST PROCEDURE						
CARBUR, W/O EMISSION CONTROL	5.65	46.24	4.47	16.6	3	FORD
STRATIFIED, BEST ECONOMY	4.96	7.75	3.85	23.8	2	FORD
PROCO, W/O CATALYST	3.10	13.75	0.33	21.2	1	FORD
PROCO, WITH CATALYST	0.54	1.18	0.37	19.6	4	FORD

*FUEL ECONOMY COMPUTED FROM THE MASS EMISSION DATA

**20.4 MPG MEASURED WITH A BURETTE

Source: Ref. 19

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PROCO Fuel Economy

The L-141 PROCO/M-151 vehicle with catalyst under low mileage conditions attained a 23.8 percent improvement in fuel economy over the richly carbureted L-141 engine. The carbureted vehicle was nonemission controlled, and carburetor adjusted for good off-road capability.

M-151 PROCO Performance

The L-141 installed in the M-151 was derated in power by the EGR system. This was necessary to facilitate assessment of

NO_x emission potential. As a result, the vehicle was not able to successfully negotiate all the portions of the emission tests used. A 20 to 25 percent larger engine was estimated as necessary to provide enough power for the required accelerations with full EGR.[19]

351 and 141 CID Vehicles Emissions

The development work on the L-141, funded by USATAC*, was terminated in 1973. A revised PROCO plan to achieve NO_x emissions of 2.0 gm/mi instead of 0.4 gm/mi was continued. The program included the conversion of several 351-CID V-8 engines and a 141-CID engine to PROCO operation.[21]

A 1972 Montego was converted to PROCO operation and initially adjusted to meet 0.4 NO_x standards. The results shown in Table 2-2 show that the 1977 emission levels can be achieved on low mileage vehicles, but increased HC and CO emissions resulted by 26,000 miles, apparently from catalyst degradation. In a recent discussion with DOT/EPA, Ford reconfirmed this technical point.[22]

TABLE 2-2. EMISSIONS AND FUEL ECONOMY - 351 CID PROCO

Measurement	Catalyst Mileage	Emissions (gm/mi)			Fuel Economy** MPG
		HC	CO	NO_x	
At the start	10	.16	.25	.32	13.9
At 26,000 miles, after repair and readjustment	26,195	.79	1.16	.37	12.75
At 26,000 miles, after application of part load back pressure system and 240°F thermostat	26,400	.47	1.11	.35	13.2

**Tank mileage for 26,000 miles: 12.7 MPG

Note: Vehicle: 1972 Montego, 110T772
4500# inertia weight
1975 CVS-CH Test Results

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*U.S. Army Tank Automotive Command.

The installation of a part load back pressure system and a 240°F thermostat resulted in a substantial reduction in HC.

Before returning the vehicle for continued durability tests, two new Engelhard PTX catalysts were installed and the vehicle recalibrated for 2.0 NO_x levels. The emission results are shown in Table 2-3. Based on the data in Tables 2-1 and 2-2 Ford indicated that the simple recalibration from the 0.4 gm/mi to the 2.0 gm/mi NO_x level did little to affect the fuel economy. Table 2-4 summarizes the effect of changing the EGR flow rate from 25 to 15 percent on the emissions and fuel economy of the same vehicle.[6]

TABLE 2-3. EMISSIONS AND FUEL ECONOMY - 1.5 NO_x CALIBRATION

Vehicle Mileage	Catalyst Mileage	Emissions gm/mi			Fuel Economy MPG
		HC	CO	NO_x	
28,180	Without Catalyst	1.32	18.2	1.01	14.0
28,309	92	0.13	0.33	1.19	13.2
33,890	5,673	0.23	0.47	1.25	13.4

Note: Vehicle: 1972 Montego, 110T722
4500# inertia weight
1975 CVS-CH Test Results

TABLE 2-4. 351 CID PROCO EMISSIONS AND FUEL ECONOMY

NO_x Design Level (gm/mi)	EGR	Emissions, (gm/mi)			Fuel Economy* MPG	Remarks
	%	HC	CO	NO_x		
0.4	25	3.54	28.2	.34	13.8	no catalyst
1.5	15	1.34	25.0	.96	13.2	no catalyst

* Based on carbon balance

Note: Vehicle: 1972 Montego, 110T722
(1975 Test Procedure)

Next, the vehicle was reoptimized to improve fuel economy at 2.0 gm/mi NO_x. This included changing the rear axle ratio from 3.25:1 to 2.75:1. Improvements in fuel economy were attained, with increased HC and CO emissions. Selected results are shown in Table 2-5 for tests conducted without a catalyst;[21] no data are available for tests conducted with a catalyst.

TABLE 2-5. EMISSIONS AND FUEL ECONOMY - 351 CID PROCO VEHICLE

Vehicle Description	Emissions (gm/mi)			Fuel Economy MPG
	HC	CO	NO_x	
3.25:1 axle ratio, constant initial injection & spark timing, exhaust back-pressure control	1.82	25.9	1.48	13.5
2.75 axle ratio, constant initial injection & spark timing, exhaust back-pressure control	2.11	34.1	1.35	13.8
Same as above increased EGR rate and richened A/F calibration	1.98	26.9	1.37	14.5
Same as above with revised injection timing	2.70	16.1	1.93	15.1

Note: 1972 Montego, 110T721
#4500 Inertia Weight

Investigation of combustion chamber geometry has shown that increased squish area and narrower spray angles produce minor fuel economy improvement and reduce HC and CO emissions; NO_x levels remain the same. Table 2-6 shows test results on a 141 CID PROCO with such modifications. Squish area change in a PROCO engine has unique effects on HC emission as discussed in Section 2.3. This mechanism is currently being investigated at the Ford Motor

Company and at the Massachusetts Institute of Technology. The PROCO fuel injection system is also being studied, in order to solve design and cost of manufacturing problems. These problems are important because of the injection spray geometry and air turbulence interaction which has a strong influence on the combustion process.

TABLE 2-6. EMISSIONS AND FUEL ECONOMY - NEW COMBUSTION CHAMBER GEOMETRY

Vehicle Description	CVS-CH Exhaust Emissions (gm/mi)			Fuel Economy MPG
	HC	CO	NO_x	
Without catalyst without EGR	0.26	5.24	1.64	20.2

Note: 1971 Capri 110T715
2500# Inertia Weight
141 CID PROCO Vehicle

Large CID PROCO Fuel Economy

According to a recent Arthur D. Little (ADL) study, the PROCO engine shows promise of low emissions, although it has not yet achieved levels of Honda engines.[20] ADL scaled an engine map from a 430 CID Ford Combustion Process (FCP) engine, the PROCO precursor, and predicted a fuel economy improvement of 20 percent for a 400 CID FCP engine on the Federal Driving Cycle. Actual road test results of a 430 CID FCP engine installed in a luxury class vehicle showed a 30.8 percent average mile-per-gallon improvement for steady-state tests conducted for the range of 30-70 mph at 10 mph increments.[18] The FCP engine does not have an emission control system. ADL factored in results of emission controls and reported an 18 percent fuel economy improvement for both standard and compact size vehicles.

Ford's fuel economy data, taken from Table 2-4 at NO_x levels of 0.4 and 1 gm/mi, are shown in comparison with EPA certification data of equivalent sized vehicles in Table 2-7. Each certification vehicle listed had a 351 CID V-8 engine with a 2 barrel carburetor, and met applicable emission requirements for the years indicated. The PROCO-powered Montego on the 1975 Federal Test Procedure (FTP) shows about 23 percent improvement in fuel economy over the 1975 certification Montego on the EPA urban driving cycle. Although the PROCO engine does not meet the 1975 HC and CO levels, catalytic exhaust gas treatment can be used to reduce HC and CO levels as indicated in Tables 2-2 and 2-3. Ford, however, claimed that catalyst durability was a major problem,[22] and did not report any tests with a catalyst equipped Montego.

TABLE 2-7. FUEL ECONOMY DATA

Vehicle Description	Emissions (gm/mi)			Fuel Economy	Improv. (Percent)
	HC	CO	NO_x	MPG	
1973 Torino Certification	-	-	-	9.0	
1974 Montego Certification	-	-	-	9.1	
1975 Montego Certification	-	-	-	11 urban 16 Hwy.	
1972 PROCO on 1975 FTP	3.54 1.34	28.2 25.0	.34 .96	13.8	+23 above 1975 Montego Urban

Note: PROCO '72 Mercury Montego - 351-2bbl.

Ford indicated that with continued success in their development program, and at a NO_x level fixed at about 2.0 gm/mi, the PROCO engines could be introduced into limited production by the 1978 model year.[21] The company claims an improvement in fuel economy of up to 25 percent at the higher NO_x level.[23]

Large PROCO Vehicle Performance

No quantitative data is readily available to evaluate the performance of the larger PROCO vehicles. Individuals who have driven a PROCO vehicle comparable to those covered by this report, have indicated that PROCO vehicles are under-powered as compared to their conventional counterparts.

2.2 TEXACO CONTROLLED COMBUSTION SYSTEM (TCCS)

2.2.1 Introduction

The Texaco Controlled Combustion Process (TCCS), with roots back to 1946, has been increasingly investigated as an internal combustion engine concept to provide multifuel capability, better fuel economy, and reduced emissions.[24,25] The U.S. Army Tank-Automotive Command (USATAC) has sponsored the application of the concept to the L-141 engine in an M-151 1/4-ton military utility vehicle.[26,27] Texaco has also converted and tested a 1973 Plymouth Cricket,[28] incorporating catalytic converters for HC and CO reduction. White Engines, Inc., producers of the modified engines for the USATAC program, is currently developing the LIS-183 TCCS engine, which is designed for reduced emissions and improved power output.

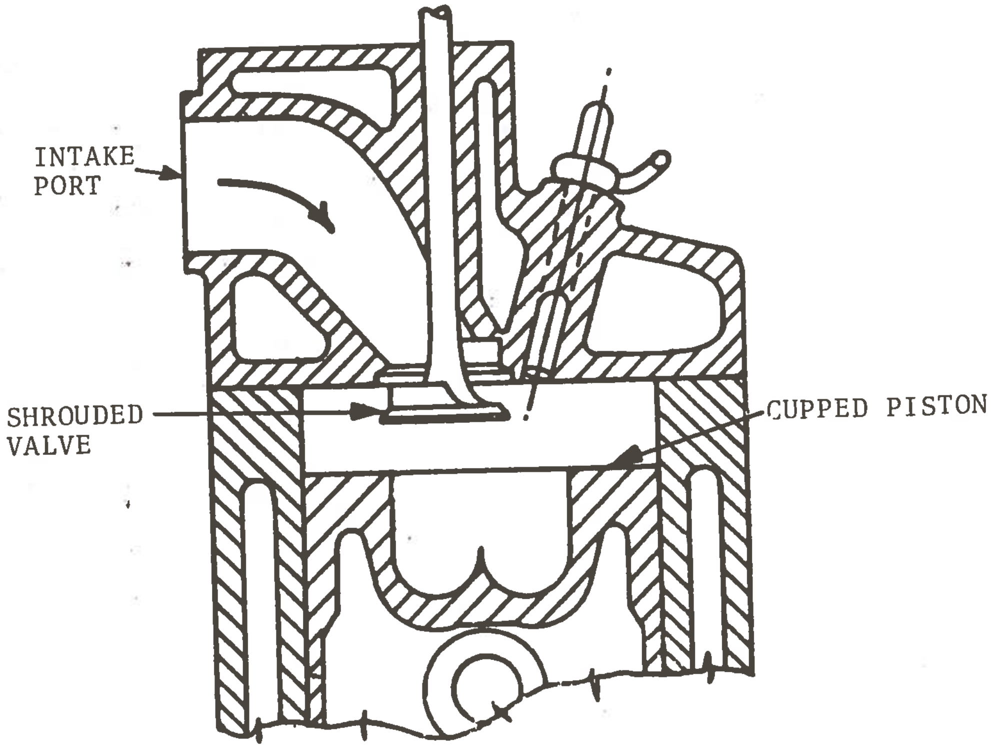
The TCCS powered military M-151 vehicle has shown significant advantages over its conventional counterpart. Fuel economy advantages ranged from 59 to 6 percent, depending on whether the TCCS engine was non-emission-controlled or controlled for a NO_x level of 0.4 gm/mi. The reduced power of the naturally aspirated TCCS engine can be increased by turbocharging;[27] turbocharging has an additional benefit of reducing visible smoke.

Although the TCCS engine was not specifically intended for use in an automobile, a 1973 Cricket passenger car was converted to TCCS operation. An improvement in fuel economy of about 10 percent was determined over a comparably sized 1975 Datsun B210.

The following paragraphs describe emission, fuel economy, and performance results of engine and vehicle tests incorporating TCCS L-141 engines, turbocharged L-141 engines, and standard L-141 engines. Test results are also described for a TCCS powered 1973 Plymouth Cricket against certification data for a comparable Cricket, and also data for a comparable, but later (1975) Datsun.

2.2.2 Texaco Controlled Combustion System (TCCS)

A diagram of a TCCS combustion chamber is shown in Figure 2-8. The intake and exhaust ports are located on one side of the



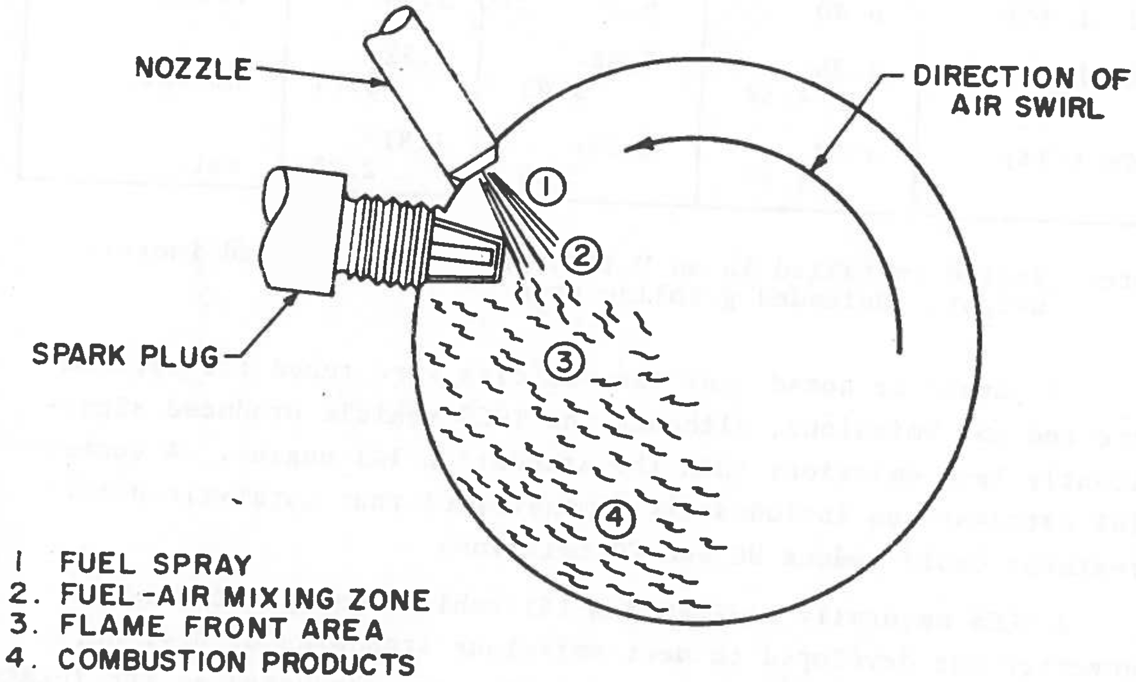
Source: Ref. 6

Figure 2-8. Texaco TCCS Engine

cylinder head, and injector nozzle and spark in a common plane on the opposite side.[25,29] The shrouded valve and intake port passage geometry impart a swirl to the intake air about the cylinder axis. (Fuel is injected into this swirl air.) The cupped piston increases the swirl rate during the compression stroke as the piston approaches TDC by displacing swirling air from the large diameter cylinder bore into the smaller diameter piston cup. The cup's toroidal shaped bottom maintains and reinforces the swirling motion.

The combustion process itself is illustrated in Figure 2-9. Fuel is injected near the end of the compression stroke into

Region 1 immediately upstream of the spark plug so that a fuel-rich mixture exists at the ignition source. Downstream from the mixing zone (Region 2) a flame front (Region 3) is established. Additional mixture supplied to the flame front is burned as rapidly as it it is formed. Combustion exhaust (Region 4) is carried downstream with the swirling air and gases. With this process, fuel ignition presents no problems, and lean overall air-fuel mixture operation is attained.



Source: Ref. 6

Figure 2-9. Texaco Controlled Combustion System

2.2.3 TCCS Vehicle Emissions

The design and fabrication of the L-141 4-cylinder unit followed testing of a TCCS single cylinder engine. Vehicle testing was initiated in 1967. A naturally aspirated and a turbocharged version of the TCCS engine were constructed. Although emission control was not an objective, measurements were made by the National Air Pollution Control Administration (NAPCA). The then proposed FA4-S3 driving cycle was simulated on a dynamometer with a turbocharged version of the L-141 TCCS installed in the M-151 vehicle (3000 lb. inertia weight). Data obtained using constant-volume-sampling are shown in Table 2-8 for both the standard L-141 and the TCCS version.[6,25]

TABLE 2-8. EMISSIONS FROM A TURBOCHARGED TCCS L-141 ENGINE

Configuration	Emissions (gm/mi)			Remarks
	HC	CO	NO_x	
Std. L-141	6.40	76.22	3.39	uncontrolled
TCCS L-141	3.85-4.58	9.08-9.62	1.52-1.74	no cat.
TCCS L-141	1.74-1.97	2.29-2.69	1.81-2.23	cat.

Note: Engine installed in an M-151 vehicle, 3000 pound inertia weight. Unleaded gasoline used.

It should be noted that the vehicles were tuned for performance and not emissions, although the TCCS vehicle produced significantly less emissions than the standard L-141 engine. A commercial catalyst was included; it demonstrated that catalytic aftertreatment could reduce HC and CO emissions.

A TCCS naturally aspirated M-151 vehicle using a catalytic converter was developed to meet emissions standards of 0.41 HC, 3.4 CO, and 0.40 NO_x.[27] Emission tests were conducted at the Texaco Research Center and at the Environmental Protection Agency, Ann Arbor, using the 1975 Federal Test Procedure.[27] Results are summarized in Table 2-9. The emissions were below the then statutory 1975 levels of 0.41 HC, 3.4 CO and 0.40 NO_x. The Texaco test results were obtained at the culmination of 2200 miles of vehicle testing after which the vehicle was turned over to EPA for testing.

Catalytic treatment of exhaust gases was chosen because the TCCS exhaust temperatures were too low for a thermal reactor. NO_x control was achieved by a combination of ignition and injection

TABLE 2-9. EMISSIONS OF A NATURALLY ASPIRATED TCCS L-141 ENGINE

Lab	Emissions (gm/mi)			Fuel Economy MPG
	HC	CO	NO_x	
Texaco	0.25	1.17	0.33	-
"	0.28	0.62	0.32	-
"	0.30	0.79	0.29	-
EPA	0.40	0.26	0.30	15.3
"	0.33	0.15	0.31	16.1
"	0.37	0.30	0.31	15.8

Source: Ref. 27

Note: Engine installed in an M-151 vehicle.

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timing retard, and water-cooled exhaust gas recirculation (EGR). The EGR system employed a mechanical control valve which was calibrated for 30 percent and a 15 percent EGR rate at low and high loads, respectively. In summary the emission system consisted of:

1. A high turbulence swirl catalytic reactor type exhaust manifold (Alumina on Inconel mesh).
2. A noble metal catalyst at the outlet of the swirl reactor (Commerically available noble metals).
3. A final catalyst inserted in the muffler case (Texaco non-noble metal).
4. Two position EGR system.
5. Intake air throttling valve.
6. Exhaust back pressure control valve.

The naturally aspirated TCCS M-151 vehicle was also subjected to a 50,000 mile chassis dynamometer durability test. The complete maintenance and mass emissions records are contained in reference 27. Maintenance work required included replacement of four catalysts, ignition system modifications, and cleaning of the EGR system. These problem areas were not related to the TCCS combustion concept, but rather to durability of add-on emissions control hardware. Engine components were reportedly in excellent condition at the completion of the durability tests.

The improved power of the turbocharged, uncontrolled TCCS L-141 powered M-151 vehicle made it a promising contender for a low emission vehicle with adequate power to offset the loss in performance of the TCCS naturally-aspirated low emission M-151.

Emission control was similar to the naturally aspirated vehicle in that it employed catalytic aftertreatment of the exhaust gases plus EGR. HC and CO emissions were somewhat reduced due to the addition of the turbocharger, and the use of only two catalytic reactors was necessary. The emission controls included:

1. A noble metal catalyst at the turbocharger outlet.
2. A finishing reactor in place of the muffler (non-noble metal).
3. Double-walled exhaust manifold.
4. Modulated EGR.
5. Intake air throttling.

The emissions and performance of the turbocharged L-141 TCCS powered vehicle as functions of emission controls are shown in Table 2-10. Modifications to achieve low NO_x emission included fuel injection and ignition retard (combustion event retard), increasing EGR up to 22 percent at low load, and the addition of two catalyst sections.

Emission tests were conducted on vehicles using four fuels. The engine was operated on gasoline, jet fuel (JP-4), CITE fuel, and No. 2 diesel fuel, in each case with 11 percent EGR, no catalyst and 8 degrees combustion event retard. Results indicated that all the fuels produced equivalent NO_x emissions. The heavier fuels produced lower hydrocarbon and higher carbon monoxide levels.[27]

TABLE 2-10. TURBOCHARGED TCCS ENGINE TEST RESULTS

Degree of Emission Control	Emissions (gm/mi)			Fuel Economy mpg(ℓ/100 km) Weight
	HC	CO	NO_x	
No emission controls	3.13	7.00	1.46	24.3 (9.7)
8° combustion event retard	3.24	6.43	1.29	22.4 (10.5)
8° combustion event retard plus 11% low load EGR; no EGR at full load	3.60	6.69	0.84	20.5 (11.5)
8° combustion event retard, 16% low load EGR, plus 2 catalyst sections; no EGR at full load	0.22	1.29	0.66	19.4 (12.1)
Full emission controls 13° combustion event retard, 22% low load EGR, 2 catalyst sections; 11% EGR at full load	0.35	1.41	0.35	16.2 (14.5)

Fuel: gasoline Source: Ref. 27
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Plymouth Cricket

Texaco equipped a Plymouth Cricket having an automatic transmission with the controlled combustion, TCCS system including EGR, two oxidation catalysts, and air throttling at low load.[6] Emission test data are given in Table 2-11. The best fuel economy without EGR was 25.3 mpg, which is 23 percent greater than the 20.6 mpg of the average 1973 model year Cricket, certified at 2500 pounds inertia weight. Fuel consumption was determined by weight.

Figure 2-10 shows the effects of reducing NO_x emission levels on fuel consumption for the TCCS powered M-151 utility vehicle and for the Plymouth Cricket.[6] At a NO_x level of 4.0 gm/mi there is essentially no fuel economy penalty. Fuel consumption for both vehicles increases exponentially as NO_x levels are reduced below

1 gm/mi. At the statuatory 1978 NO_x emission level of 0.40 gm/mi the fuel economy penalty is approximately 35 percent.

TABLE 2-11. TCCS PLYMOUTH CRICKET EMISSIONS

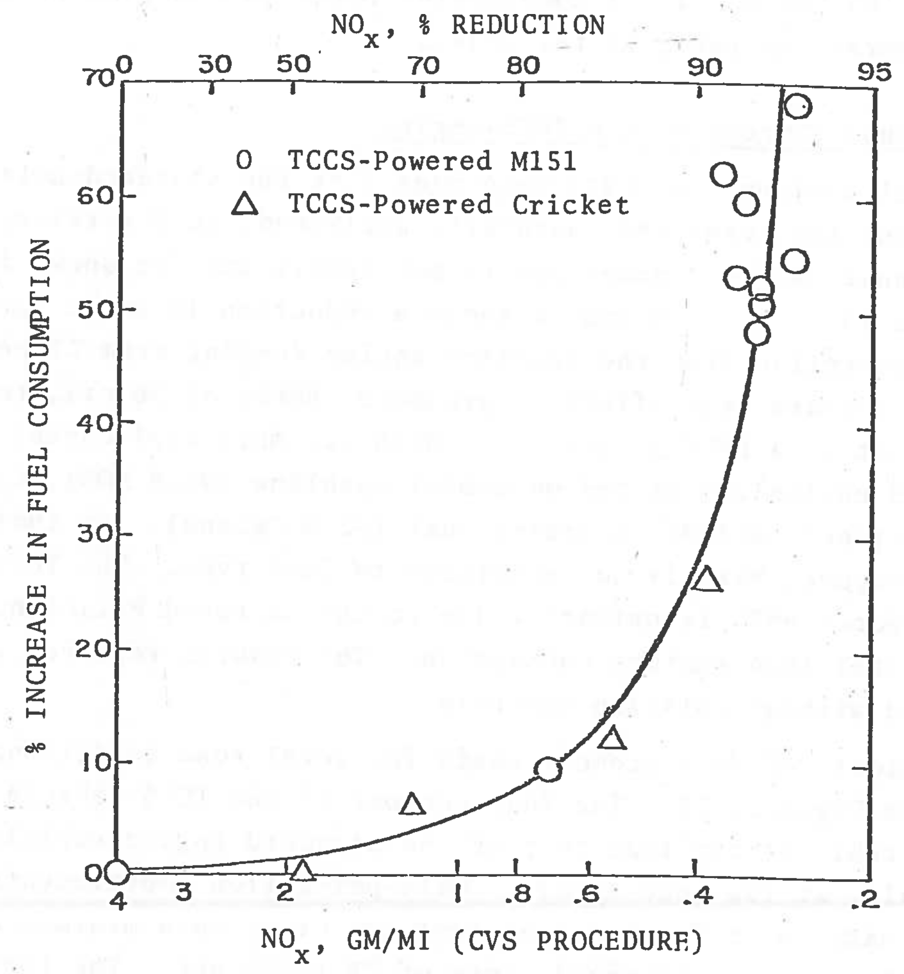
Degree of Emission Control	NO_x gm/mi	Fuel Economy MPG	Max. HP at Rear Wheels at 3000 Engine RPM
Best Economy no EGR	1.89	25.3	33.2
Combustion retard	1.2	23.8	31.6
Combustion retard plus exhaust back pressure increase	0.99	22.5	28.8
Combustion retard and moderate EGR	0.55	22.6	26.0
Combustion retard, increased EGR	0.38	20.1	23.2

Note: Engine naturally aspirated.

Smoke and odor were reported as obvious exhaust constituents from the TCCS engine under high load; turbocharging reduced both. The smoke condition was attributed to injection system fuel control, and odor to the combustion process being somewhat similar to that of the diesel engine. Smoke density was significantly reduced after catalytic treatment of the exhaust gas.

White Engine

The TCCS engine concept is currently undergoing development in a 183 CID engine by White Engine, Inc. The U.S. Army Tank Automotive Command is funding the development of the LIS-183 engine specifically designed to accomodate the TCCS stratified charge concept. The new engine has a longer stroke than the L-141 to promote air swirl. This will result in better control of the fuel stratification and, therefore, the combustion process.



Source: Ref. 28

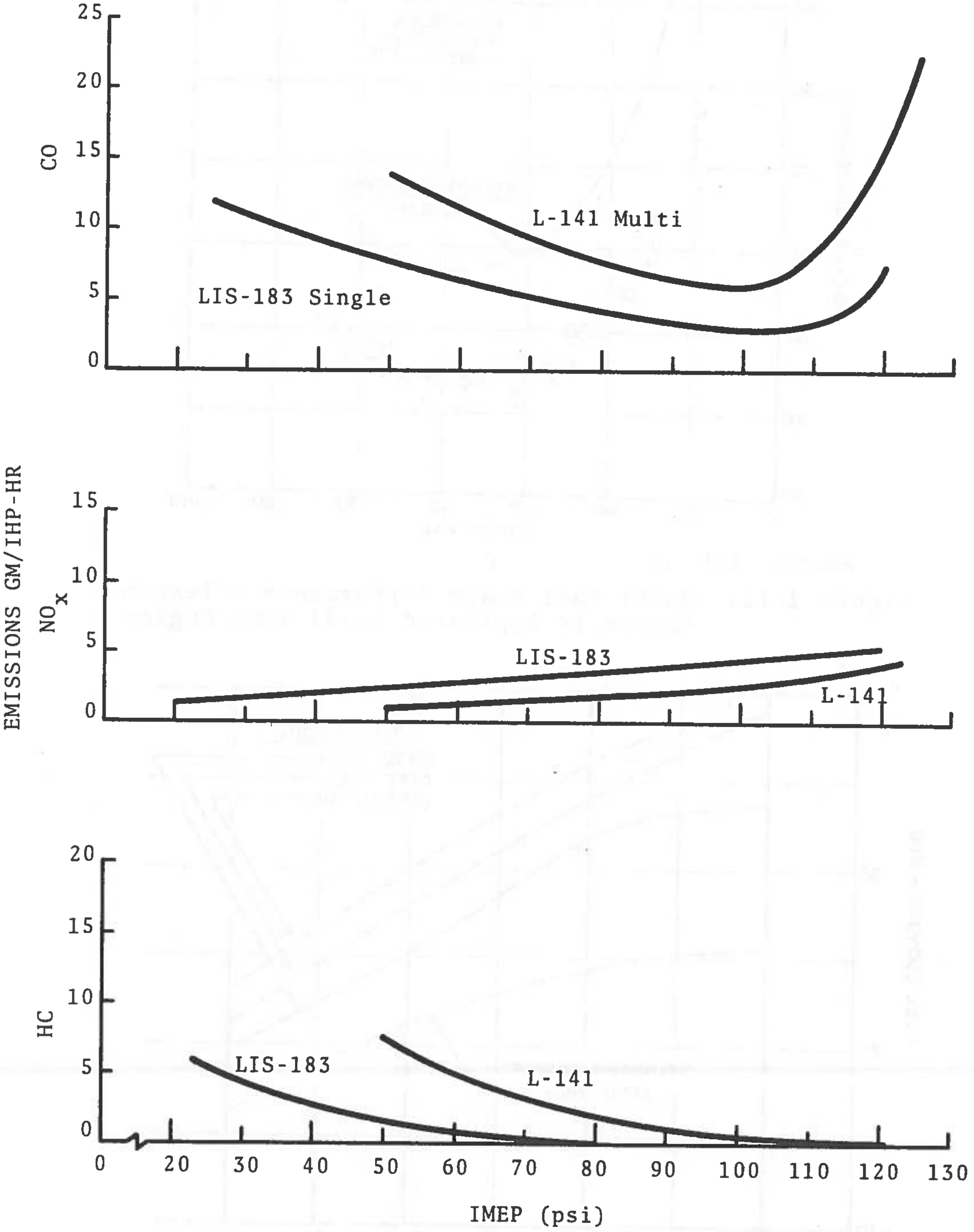
Figure 2-10. Fuel Consumption at Various NO$_x$ Levels for TCCS Engines

Engine power, economy, and emissions data are not yet available on a multicylinder version of the LIS-183. However, emissions data are available for a single cylinder development version. Figure 2-11 shows emissions as a function of indicated mean effective pressure (IMEP) for both the LIS-183 single cylinder engine, and the TCCS L-141 naturally aspirated multicylinder engine. The new engine design shows promise for lower emissions than the TCCS L-141, since measured specific emissions are lower. Additionally, the LIS-183 has an 11.7:1 compression ratio in contrast to the 10:1 compression ratio of the L-141.

2.2.4 Fuel Economy of the TCCS Engine

Fuel consumption tests were made with the standard L-141 engine and the converted, naturally aspirated, TCCS version. Brake performance curves[26] under equivalent conditions are shown in Figure 2-12. The TCCS engine shows a reduction in brake specific fuel consumption from the standard engine ranging from 27 percent at a brake mean effective pressure (BMEP) of 30 psi, to about 24 percent at a BMEP of 100 psi. With its multifuel capability, the TCCS engine was tested on combat gasoline (92.6 RON), CITE fuel (38.0 Cetane), and No. 3 diesel fuel (52.6 Cetane). As indicated in the figure, BSFC is not sensitive to fuel type. The TCCS version reduced BSFC is primarily due to the improved efficiency of the overall lean mixture combustion. The results reported were obtained without emission controls.

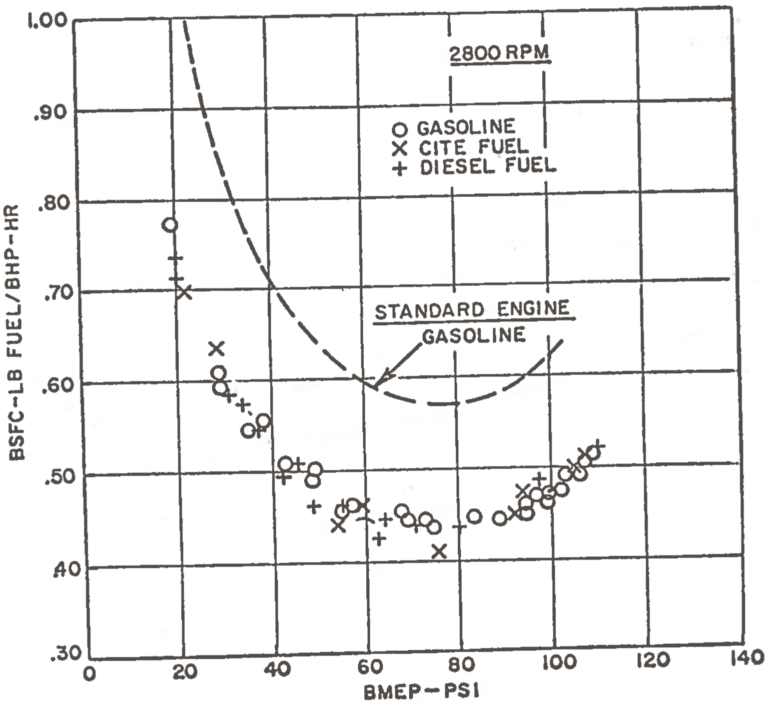
Results of fuel economy tests for level road conditions are shown in Figure 2-13. The fuel economy of the TCCS vehicle is considerably better than that of the standard-engine vehicle, especially at low road speeds. Mile-per-gallon improvements range from a maximum of 38 on diesel fuel and CITE, to a minimum of 22 on gasoline, over the speed range of 25 to 50 mph. The total improvements over the standard engine performance range from 18 to 52 percent, and from 18 to 31 percent on gasoline. The curves for different fuels are each directly related to its fuel heating values per gallon, and correlate with the brake specific fuel consumption trends indicated in Figure 2-12.



Source: Ref. 30

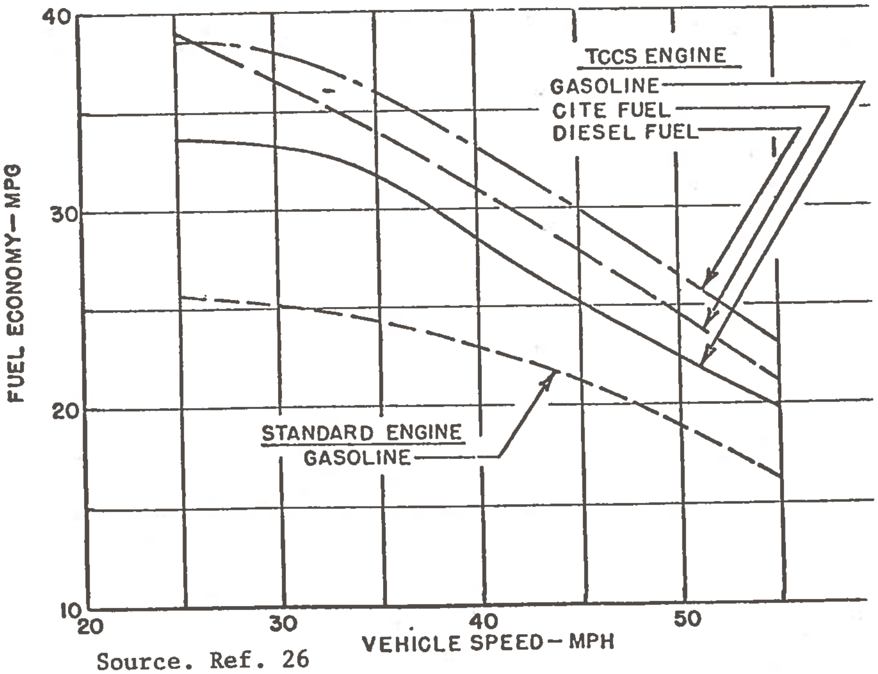
NOTE: Engine Speed - 2800 RPM

Figure 2-11. Emissions Versus Loads for LIS-183 and L-141



Source: Ref. 26

Figure 2-12. Multi-fuel Brake Performance - Texaco Naturally Aspirated L-141 TCCS Engine



Source. Ref. 26

Figure 2-13. Level Road Fuel Economy - M-151 Light Duty Vehicle Texaco Naturally Aspirated L-141 TCCS Engine

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In Table 2-12 a comparison is made between the carbureted L-141 engine and the turbocharged TCCS L-141 engine powered vehicles. The fuel economy of the turbocharged TCCS vehicle is nearly 50 percent better than that of the carbureted conventional vehicle, both without emission controls. Maximum emission controls penalize the fuel economy of the TCCS vehicle by 33 percent; however, a fuel economy advantage over the standard, carbureted M-151 vehicle is maintained.[27]

TABLE 2-12. TURBOCHARGED TCCS ENGINE-POWERED M-151 VEHICLE EMISSIONS AND FUEL ECONOMY WITH AND WITHOUT EMISSION CONTROLS

Vehicle Description	Emissions (gm/mi)			Fuel Economy, mpg (ℓ/100 km) Weight
	HC	CO	NOx	
Full emission controls	0.35	1.41	0.35	16.2 (14.5)
No emission controls	3.13	7.00	1.45	24.3 (9.7)
Carbureted L-141 engine	4.50	73.18	3.22	15.3 (15.4)

Source: Ref. 27

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A determination of the effect of EGR on fuel economy of the naturally aspirated TCCS 141 was obtained by comparing mpg results from tests using 15 percent and 30 percent EGR.[27] The results, based on carbon balance, are shown in Table 2-13. The NO_x emissions were reduced by a factor of 2 and the miles-per-gallon reduced 28 percent by doubling the EGR rate. The fuel economy of a standard carbureted M-151 vehicle with emission levels approximately ten times those of the emission controlled vehicle was typically 13 to 14 mpg. Again note the M-151 was tuned for off road performance (carburetor rich). However, the data demonstrates the potential for improving fuel economy at low emissions.

The TCCS Cricket fuel economy[30] is compared to the 1973 certification Cricket fuel economy[31] in Table 2-14. At a NO_x level of 2.0, the TCCS fuel economy is about 19 percent better than that of the standard 1973 certification vehicle; it would be worse at

TABLE 2-13. EGR, FUEL ECONOMY AND EMISSIONS FOR THE TCCS L-141 ENGINE

EGR %	Emissions (gm/mi)			Fuel Economy, MPG
	HC	CO	NO_x	
15	0.50	0.14	0.70	21.9
30	0.37	0.24	0.31	15.7

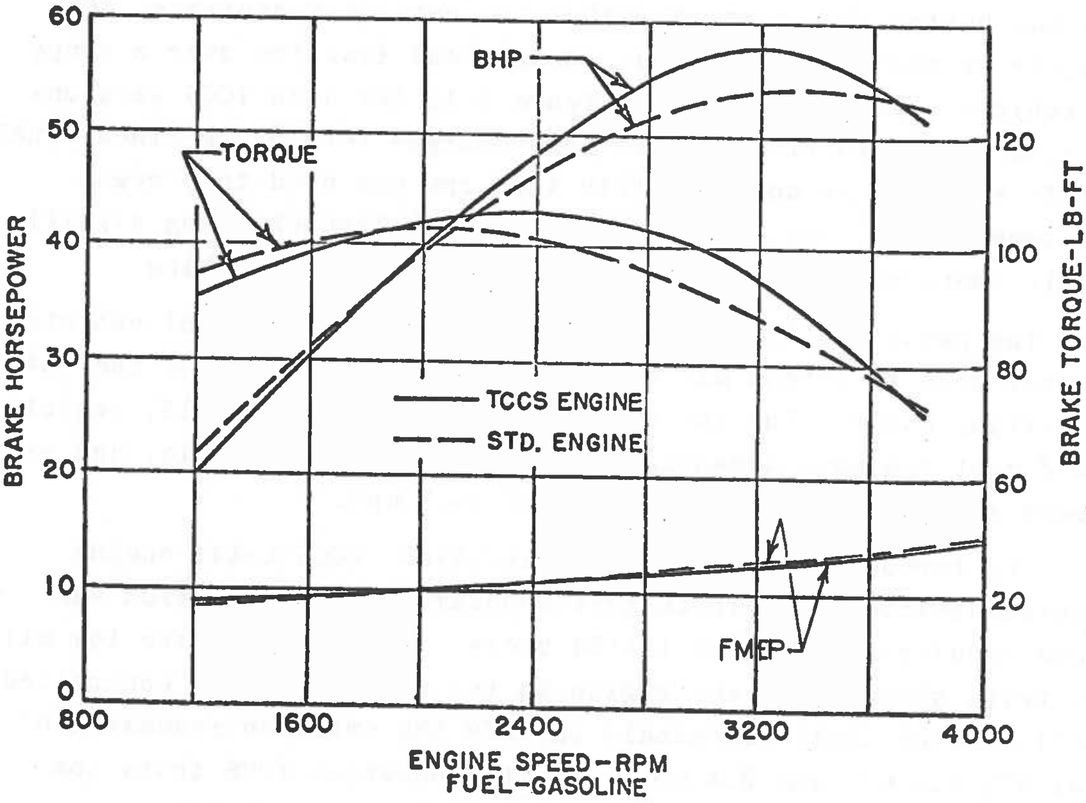
0.4 NO_x. There is no data available for later model Crickets, but data on a 1975 Datsun B210 is listed[32] as representative of a comparable late model car. The Datsun and the TCCS Cricket are both equipped with automatic transmissions and are in the same inertia weight (2500 lb) class. The Datsun, however, has a 7 percent smaller CID. The TCCS Cricket at a 2.0 NO_x level shows a 10 percent improvement in fuel economy over the Datsun on the urban driving cycle.

TABLE 2-14. FUEL ECONOMY OF THE TCCS '73 PLYMOUTH CRICKET (91 CID)

Vehicle Description	HC	CO	NO_x	MPG
1973 Certification AVE	-	-	-	20.6
TCCS on 1975 FTP	1.07	.84	1.89	25.3
	0.36	1.15	0.38	20.1
1975 Datsun B210				23 urban, 31 highway

2.2.5 TCCS Vehicle Performance

Brake horsepower (BHP) and brake torque curves for the naturally aspirated TCCS L-141 and standard L-141 engines[27] are shown in Figure 2-14. The curves are plotted as a function of engine RPM at full load operation on gasoline. There was no engine emission control in either case. It can be seen that the TCCS engine develops higher BHP than the standard engine in the mid speed range of 2000-3600 rpm, but less BHP in both the low and high speed ranges. The friction mean effective pressure (FMEP) curve shows that engine friction characteristics were unchanged by the



Source: Ref. 26

Figure 2-14. Full Load Brake Performance - Texaco Naturally Aspirated L-141 TCCS Engine Operating on Gasoline

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modification. The high speed power loss was primarily due to injection limitations imposed to limit engine exhaust smoke.

The performance of the non-emission-controlled naturally aspirated TCCS vehicle was compared to two standard M-151 vehicles.[25] Chassis dynamometer tests were conducted to determine full load rear wheel traction. Traction performance of the TCCS vehicle essentially matches that of one of the standard vehicles, but is slightly below the performance of the other. Figure 2-15 shows that the TCCS vehicle has less tractive force than the average traction of the two standard vehicles over a speed range of 25 to 55 mph.

The performance of the turbocharged version of the TCCS vehicle was better than that of either the naturally aspirated TCCS vehicle or the standard M-151. Rear wheel traction over a range of vehicle speeds is shown in Figure 2-16 for both TCCS versions at wide open throttle. In the turbocharged version, a linear fuel cutoff starting at approximately 1000 rpm was used to prevent overspeeding the engine at 2800-3000 rpm. Turbocharging significantly improved high speed acceleration and hill climbing.

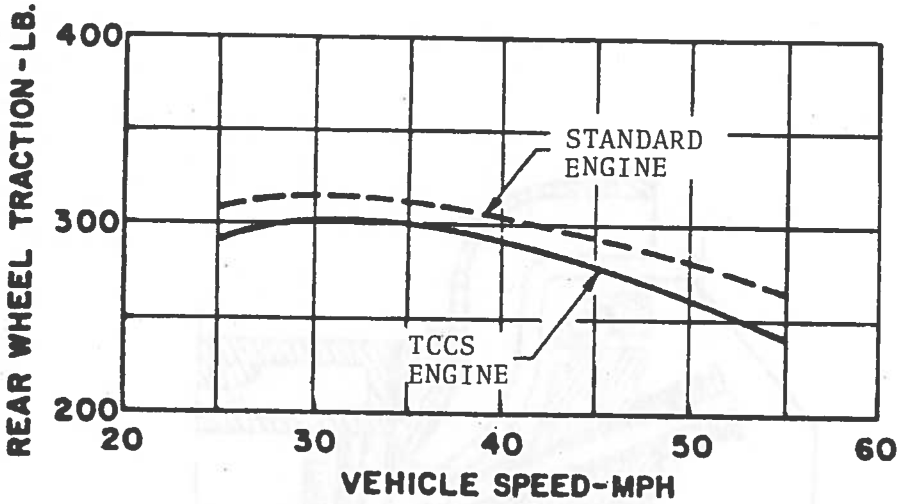
The naturally aspirated TCCS M-151 emission control vehicle was not able to attain all the required accelerations of the LA4-S4 driving cycle. The non-emission-controlled TCCS M-151 vehicle could meet the most demanding accelerations of the cycle, and exceeded the maximum required speed of 56.7 mph.

The turbocharged, emission-controlled TCCS L-141 engine powered vehicle was able to meet smoothly all acceleration and speed requirements of the LA4-S4 cycle. A series of five low mileage tests showed that the engine in its fully emission controlled configuration could repeatedly satisfy the emission standards of 0.41 HC, 3.4 CO, and 0.4 NO_x. The turbocharged TCCS tests comprised approximately 1300 vehicle miles.

2.3 BAUDRY STRATIFIED CHARGE ENGINE (IFP)

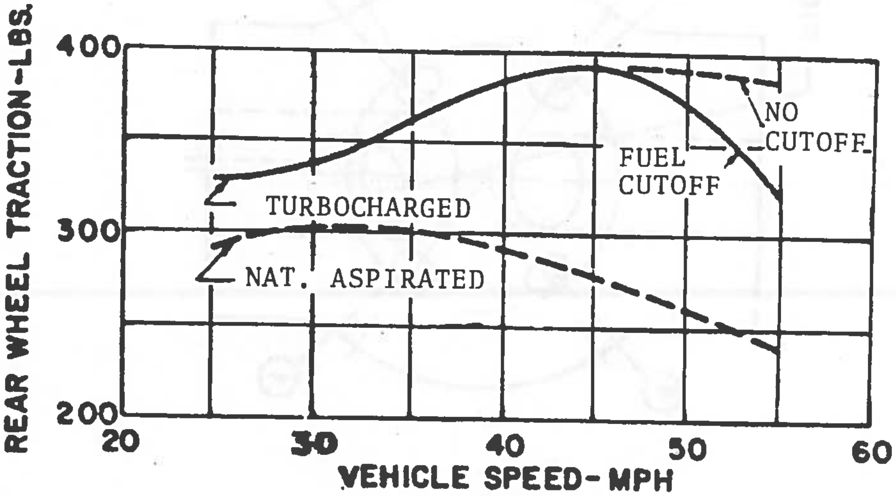
The IFP Process (Institut Francais du Pétrole) provides a method of charge stratification in which the mixture feed is separated into two streams with very different fuel-air ratios.[33] Figure 2-17 is a sectional diagram of the Baudry engine which is based on the IFP Process.

As seen in Figure 2-17 a small diameter tube, directed toward the spark plug, brings a relatively rich mixture into the immediate vicinity of the intake valve. A conventional intake manifold is used to supply the cylinder with either air or a lean air-fuel mixture. This arrangement avoids the use of either a prechamber



Source: Ref. 25

Figure 2-15. Wide Open Throttle Traction, Naturally Aspirated TCCS M-151



Source: Ref. 25

Figure 2-16. Wide Open Throttle Traction, Turbocharged TCCS M-151

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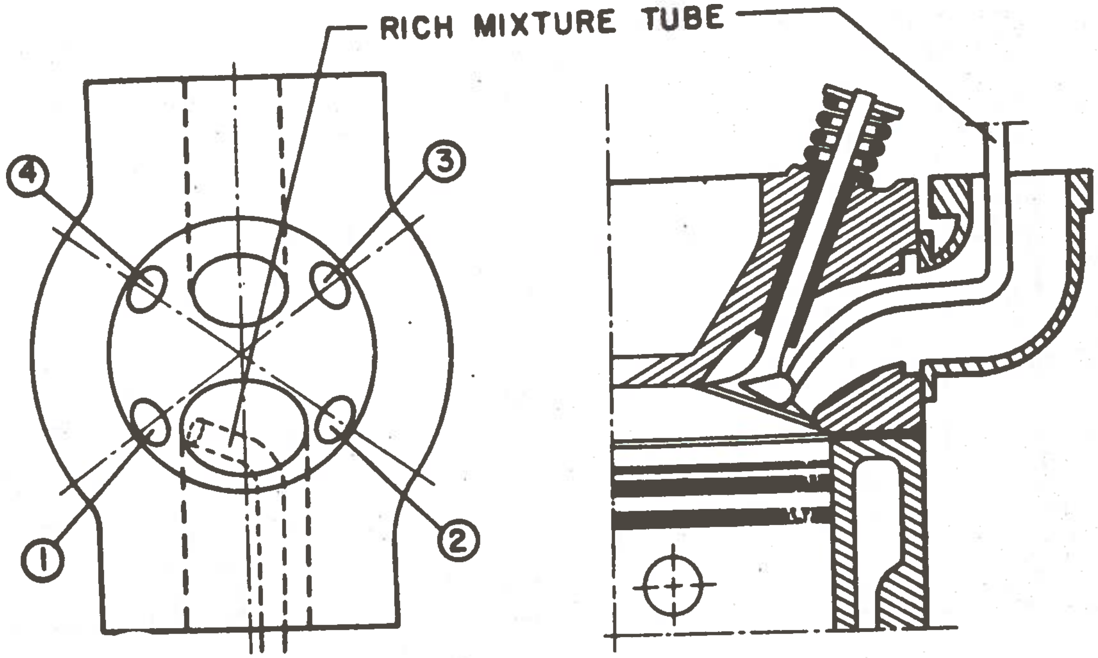


Source: Ref. 6

Figure 2-17. Baudry Stratified Charge Engine or fuel injection for charge stratification, and hence is very simple. Since the initial intake stratification is maintained during the compression stroke, local enrichment is maintained in the vicinity of the spark plug.

The IFP Process was applied to a 4-cylinder engine having a compression ratio of 8.5, and a bore and stroke of 7.8 cm and 10 cm, respectively. Overall equivalence ratios as low as 0.55 were reported at full throttle. No emissions data were given. The lowest permissible equivalence ratio with the normal carbureted engine (lean limit) was reported to be 0.85.

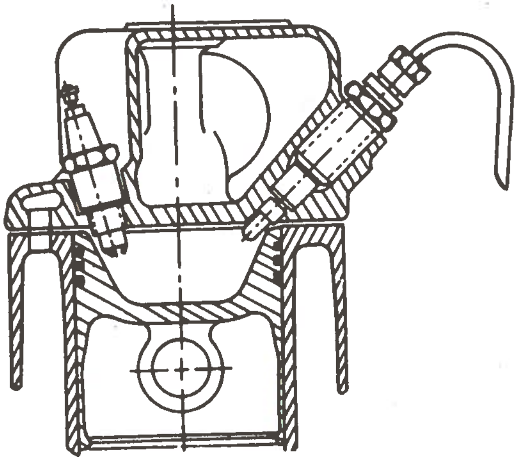
Single cylinder engine tests indicated that the IFP Process broadens the range of fuel-air ratios over which minimum emissions can be obtained under steady-state conditions. Extensive emissions data on the Baudry IFP Process are not available for evaluation.

2.4 HESSELMAN STRATIFIED CHARGE ENGINE

The Hesselman engine, devised some 40 years ago, as a possible economical alternative to the gasoline engine operates on fuel oil.[6,34] The engine configuration is shown schematically in Figure 2-18. The fuel injector and spark plug are located on opposite sides of the cylinder head, symmetrical to the deeply cupped piston. A shrouded intake valve is employed to establish air rotation (swirl) during the induction stroke.

During engine operation, the end of the injection timing for all loads was fixed at 25 to 30 degrees before the end of the combustion stroke. A short injection duration was provided during idling and at light loads, while at full loads injection began about 30 degrees before fuel cutoff. The amount of fuel injected was controlled by a linkage mechanism connecting the fuel pump injector rack to manifold vacuum. Air throttling was found to be necessary if the engine was run below a given speed, and at slow speeds below a given load.

There is no recent developmental work reported in the literature on the Hesselman Engine.



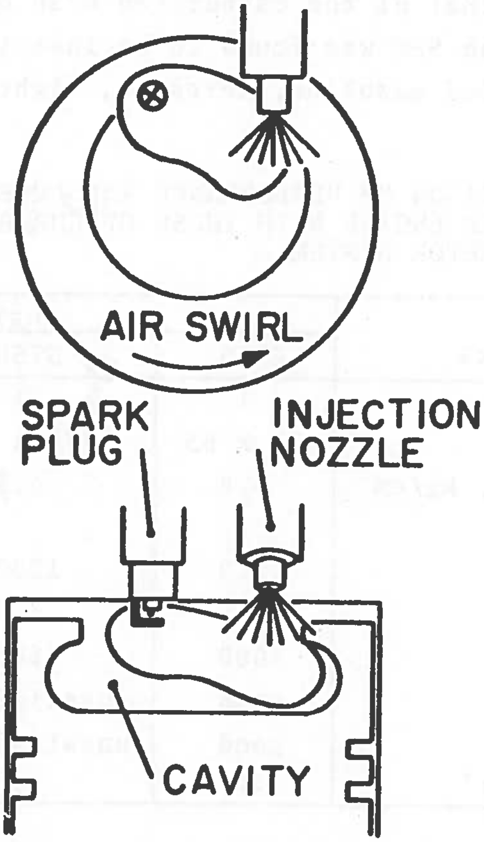
Source: Ref. 6

Figure 2-18. Hesselmann Stratified Charge Engine

2.5 MITSUBISHI COMBUSTION PROCESS (MCP)

The Mitsubishi Combustion Process (MCP) is a stratified charge concept employing swirling air and direct cylinder fuel injection.[29,35] Mitsubishi Heavy Industries, Ltd., produces a variety of single cylinder small farm and industrial engines in the range of 141 cc (8.6 CID) to 511 cc (31.2 CID) displacements, and the MCP is being developed for the same applications.

Figure 2-19 is a schematic diagram of the basic MCP engine. Fuel is injected toward the top of the cupped piston and directed into the swirling air. The swirling air carries the evaporating fuel droplets to the spark plug, while the piston cavity prevents excessive fuel droplet diffusion.



Source: Ref. 35

Figure 2-19. Mitsubishi Combustion Process Engine

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Successful prototype engines have been operated in field applications. Engine tests have indicated hydrocarbon emissions are a problem at idle and light loads due to unburned fuel in the lean mixture zone. Nitric oxides increase at high load due to mixture homogenization. A comparison of the emission levels and performance of standard Mitsubishi G750, carbureted small industrial engines and those of a stratified charge, MCP-352-A engine are given in Table 2-15. The emission tests were taken under worst case conditions for HC and NO_x; carbon monoxide concentration is low under all operating conditions due to the overall lean air-fuel ratio and strong turbulence. Fuel consumption was reportedly decreased to approximately 1/2 that of the conventional engines. For the MCP-352-A engine, the minimum specific fuel consumption (SFC) was 20 percent less than that of the carbureted G750 on dynamometer performance tests. The SFC was found to be insensitive to fuel type. Those tested included gasoline, kerosene, light oil, and diesel fuel.

TABLE 2-15. COMPARISON OF PERFORMANCE AND EMISSION CHARACTERISTICS FOR MCP ENGINE WITH THOSE OF CURRENT ENGINES WITH CARBURETOR SYSTEM

Characteristics	Engine		
	G750	G750*	MCP-352-A
Cylinder No.	1	1	1
Bore X stroke, mm	75 x 65	75 x 65	80 x 70
BMEP (at 2000 rpm), kg/cm^2	6.8	6.5	7.2
Emission level**			
HC, ppm	1500	1300	600
CO, %	8.5	4.0	0.1
NO,ppm	1000	1500	800
Startability	good	unsatisfactory	good
Acceleration	good	unsatisfactory	good
Noise level, dB(A)t†	97	97	96

Source: Ref. 35

*Second G750 engine is improved to reduce emission level.

**The operating conditions for emission level are HC, CO at idling, and NO at full load of 2000 rpm.

† The noise level is at rated power.

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The MCP engine reportedly reduces exhaust emissions and fuel consumption, while providing sure starts at temperatures as low as -22°F. The MCP performance is comparable to that of its conventional engine counterpart.

The MCP engine concept is similar to the Witzky stratified charge principle, described in the next section.

2.6 WITZKY SWIRL STRATIFIED COMBUSTION PROCESS

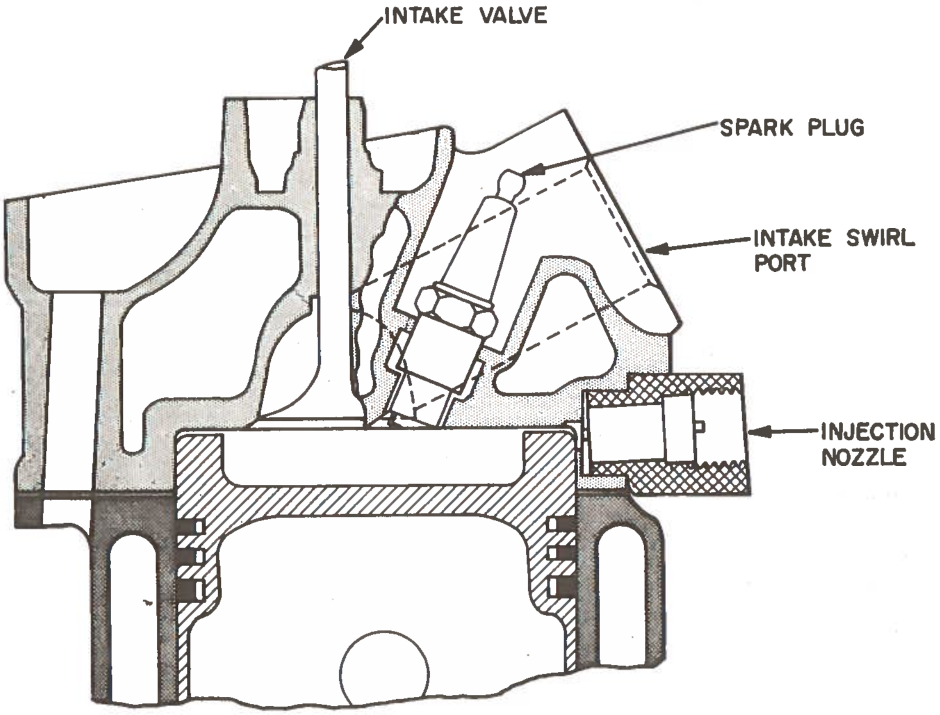
The Witzky stratified charge process was conceived and developed at Southwest Research Institute over a decade ago.[34] The process is basically an unthrottled Otto cycle process with direct cylinder injection against an air swirl within the cylinder.

Figure 2-20 is a cross sectional diagram of a Witzky stratified charge engine. The fuel charge is concentrated around a centrally located spark by the swirling air motion. Each intake port passage is provided with a swirl inducing vane which is hinged for deployment at low speed and power where stratification becomes critical.[36]

Witzky suggested the stratification method was similar to the settling of tea leaves in the center of a cup of tea which has been stirred and allowed to settle.[37] Fuel is injected into the cylinder against an air swirl; the heavier-than-air fuel droplets form a fuel rich region in the center, and a surrounding, leaner mixture toward the periphery of the combustion chamber. The intake air is unthrottled and at low speeds it is necessary to concentrate the fuel charge around the spark plug by deploying swirl deflecting vanes. Thus there is an ignitable air-fuel mixture around the spark plug even at low loads and engine speeds.

The Witzky process has been applied to a 215 CID Buick V-8 engine and an L-141 Jeep engine. On the Buick engine, four of the eight cylinders were converted to stratified charge operation, and four were left conventionally carbureted. When operating on four stratified charge cylinders, the engine's brake specific fuel consumption at 1000 rpm was about 42 percent less than that of the engine when operating on four conventionally carbureted cylinders. A 7 percent increase in maximum output in comparison to that of the carbureted engine was reported. The stratified charge version operated successfully on 91 and 60-octane gasoline and on JP-4 fuel. The compression ratio was 12:1. Good acceleration, smoothness of operation, and low noise levels were reported.

The L-141 engine test results confirmed the smoothness of the combustion process and demonstrated additional multifuel capabilities. No emissions data were reported.



Source: Ref. 36

Figure 2-20. Witzky Stratified Charge Engine

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3. DIVIDED CHAMBER STRATIFIED CHARGE ENGINES

3.1 HONDA COMPOUND VORTEX CONTROLLED COMBUSTION SYSTEM (CVCC)

3.1.1 Introduction

Honda Motor Co., Ltd., began research work on a prechamber type stratified charge engine in the mid 1960's. Their objectives were to develop a low emissions engine, without such add-on devices as catalytic converters, which could be mass produced within a reasonable time. Honda has succeeded in meeting these objectives by producing CVCC Honda Civic automobiles which pass the original 1975 Federal emission standards (0.41 HC/3.4 CO/3.1 NO_x). EPA tested three Honda CVCC Civic vehicles which passed original 1975 emission standards (0.41 HC/3.4 CO/3.1 NO_x); these were noted to have the lowest emissions of any gasoline fueled automobile without exhaust treatment ever tested by the EPA. There was no smoke, odor or noise problems reported. Tests on a CVCC-converted Vega with an air pump and EGR indicated the CVCC can meet the original 1975 Federal emission standards but not the statutory NO_x standards announced for 1978.

A CVCC powered Impala had emission levels below the original 1975 limits and, in comparison to a Honda CVCC Civic of less than half its weight, had comparable HC and CO levels but nearly double the NO_x level.

Fuel economy for a CVCC Civic was reduced nearly 25 percent when reducing NO_x levels from 1.15 gm/mi to just under 0.4 gm/mi. Engine power was also reduced. Honda also reported that fuel economy of the CVCC Civic was 10 percent less than that of the conventionally powered Civic vehicle. EPA fuel economy tests of CVCC Hondas on the 1972 FTP was 20 percent lower than the average for 1973 certification vehicles in the same weight class. These results are discussed in greater detail in the following sections.

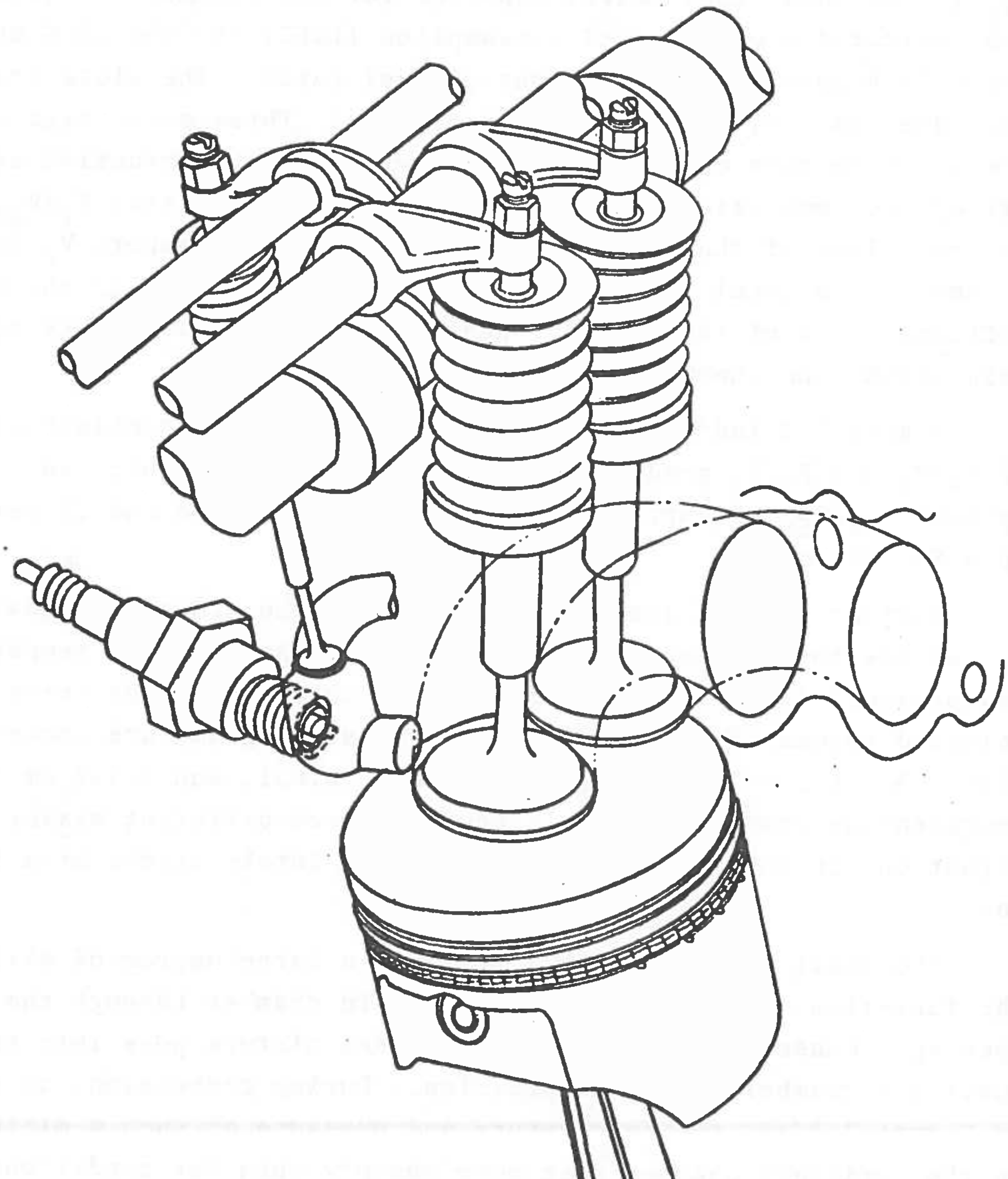
3.1.2 The CVCC Concept

The basic construction of a CVCC engine is shown in Figure 3-1. The engine has an auxiliary small combustion chamber, including a spark plug, located where the spark plug would be in a conventional engine. A "torch" opening connects the auxiliary chamber with the main combustion chamber. A carburetor supplies a fuel-rich mixture to the auxiliary chamber through a separate intake passage and prechamber intake valve. A fuel-lean mixture is supplied to the main chamber through a conventional intake manifold.

During the intake stroke a rich mixture is drawn into the auxiliary chamber while a fairly lean mixture is taken into the main chamber. The torch opening allows a controlled amount of rich mixture to enter into the main chamber during the intake stroke. When the compression stroke starts, a portion of the rich mixture in the main chamber is returned to the auxiliary chamber so that a fairly rich mixture of ignitable quality is maintained there. Upon ignition by the spark plug in the small chamber, combustion proceeds through the torch opening into the main chamber.

3.1.3 Engine and Emission Characteristics

Honda has conducted a complete stratified charge engine development program including theoretical analysis and prototype testing.[5,38] The CVCC engine used during the program was a 4-cylinder, 1950 cc (111.9 CID) water cooled engine with an 8:1 compression ratio. Such an engine is typical of that used to power the CVCC Civic vehicle. The CVCC emission characteristics in comparison to those of a conventional engine were shown in Figure 1-2 as a function of fuel-air ratio and for conditions of idle and 50 mph load. The CVCC engine, operated with a lean overall air-fuel ratio, had significantly lower emissions under either operating condition. Note that both engines were operated at the same indicated specific fuel consumption (ISFC). The curves indicate that by controlling the CVCC's air-fuel ratio according to varied operating loads, the emissions may be reduced considerably below those of the conventional engine.



Source: Ref. 16

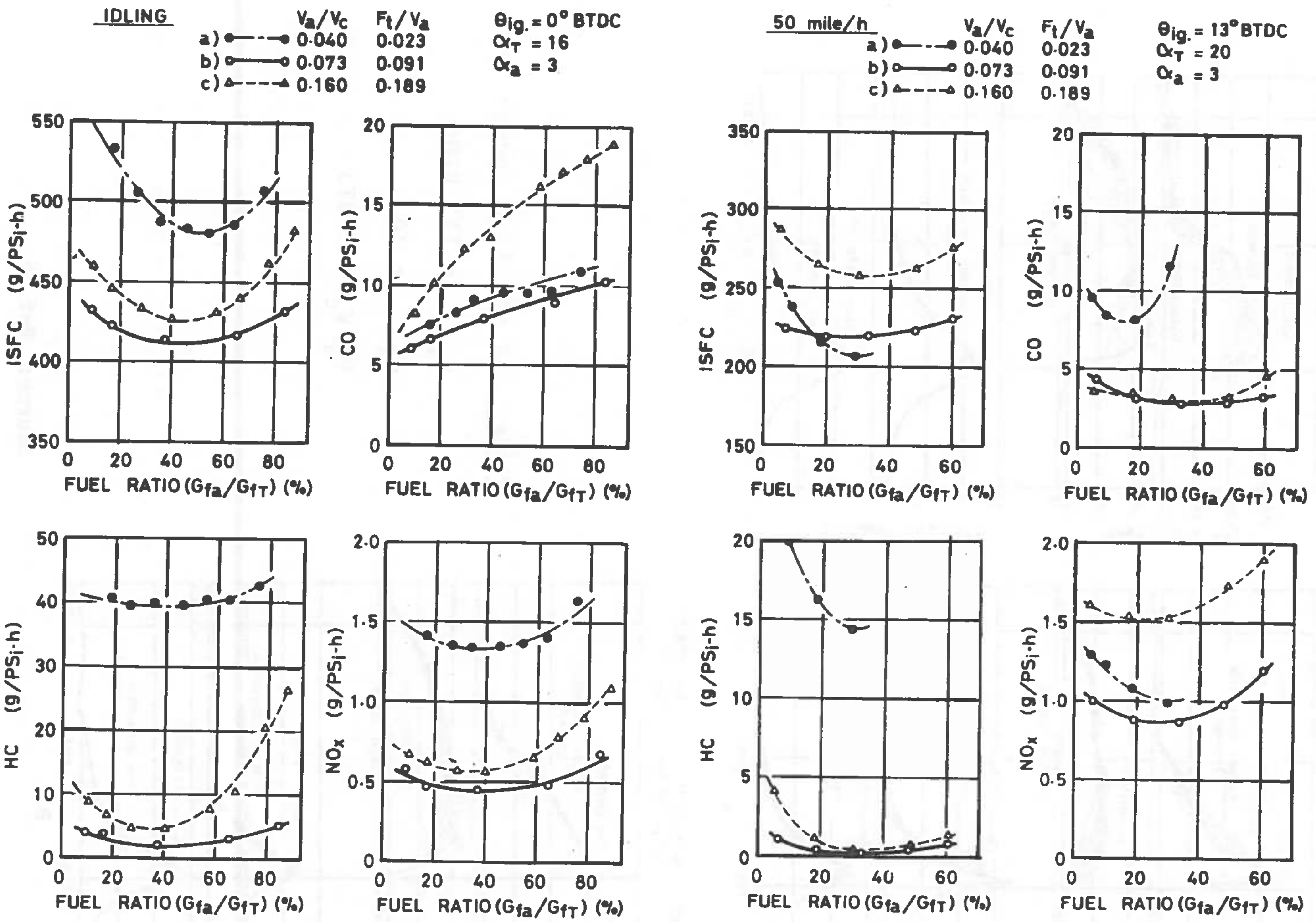
Figure 3-1. Honda CVCC Engine Schematic

An important parameter is fuel ratio (G_{fa}/G_{ft}). G_{fa} is the weight of fuel supplied to the auxiliary combustion chamber, and G_{ft} is the total fuel weight supplied for the cylinder. Emissions and indicated specific fuel consumption (ISFC) for the CVCC are shown in Figure 3-2 as functions of fuel ratio. The plots are for (A) idle and (B) 50 mph load conditions. Three parametric curves are given in each case, a parameter-set being a combination of a set of the combustion chamber ratio, V_a/V_c, and a ratio F_t/V_a. V_a is the volume of the small auxiliary combustion chamber; V_c is the volume of the total combustion chamber volume; and F_t is the cross sectional area of the "torch" opening between the auxiliary and the main combustion chambers.

Figure 3-2 indicates that there is an optimum combination of V_a/V_c and F_t/V_a producing lowest emissions (case b); the optimum G_{fa}/G_{ft} is approximately 40 percent at idle and 25 percent at a 50 mph load.

Further insight into the influence of the cross sectional area F_t of the torch passage can be gained by examining the temperature and pressure diagrams of the combustion chambers at the three selected values of the ratio F_t/V_a. These diagrams are shown in Figure 3-3 for values of F_t/V_a of 0.023, 0.091, and 0.189 cm^{-1}, representing cases which would produce three different mixing situations in the main chamber during the intake stroke at a 50 mph load.

The small value of F_t/V_a produces a large degree of mixing of the fuel-rich mixture drawn into the main chamber through the torch opening. Consequently, a relatively lean mixture goes into the auxiliary chamber during compression. During combustion, as shown in Figure 3-3(a), the temperature and pressure of such a mixture in the auxiliary chamber rise more sharply than for conditions of a larger F_t/V_a as shown in Figure 3-3(c). The temperature in the main combustion chamber for the small value of F_t/F_a is relatively low in all cases, which results in less oxidation of hydrocarbons, as indicated in Figure 3-2(a) and (b) for the small F_t/V_a case.



Source: Ref. 5

Figure 3-2. ISFC and Emissions of a CVCC Engine
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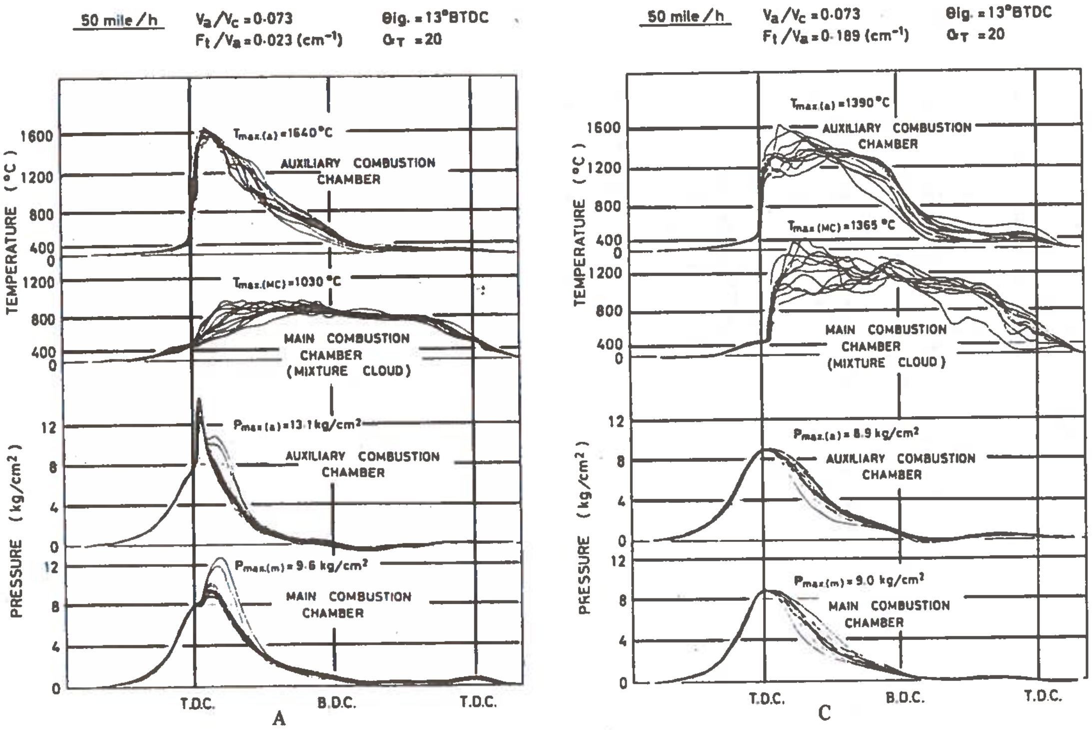
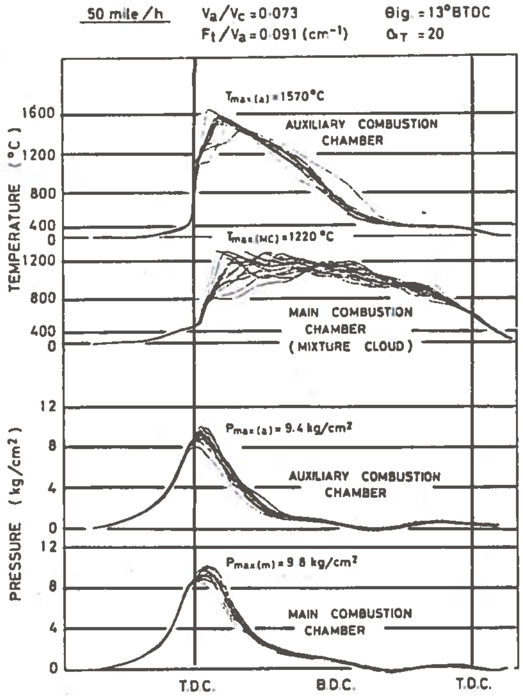


A C



B

Note: 50 mph load condition

θ_{ig} = 13° BTDC

d_T = 20

V_a/V_c = 0.073

Source: Ref. 5

Figure 3-3. Temperature and Pressure Diagrams of the CVCC Engine

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At F_t/V_a of 0.091 as shown in Figure 3-3(b) there is a proper degree of mixing, and the auxiliary combusiton chamber is richer. The ignition is more positive with smooth pressure rise in both chambers. A high gas temperature is maintained in the main chamber until near the end of the exhaust stroke, thereby promoting oxidation of hycrocarbons. A large value of F_t/V_a as shown in Figure 3-3(c) results in relatively slow ignition and unstable combustion in the main chamber. Rapid fluctuations are noted in both temperature and pressure from cycle to cycle.

Honda has correlated these experimental results with theoretical predicted figures using an analytical mixture formation model they have developed.

3.1.4 CVCC Vehicle Emissions

Emissions data are available for five CVCC powered vehicles: a 2-liter (119 CID) 4-cylinder engine in the Honda Civic, a 2.3-liter Ford Pinto, a 140 CID 4-cylinder GM Vega, a 350 CID V-8 Chevrolet Impala, and a 400 CID Ford Torino. The latter four engines were essentially refitted with Honda CVCC heads to make the conversions. Additional emissions data on Honda powered vehicles has been gathered by the EPA.

Table 3-1 shows the emissions data for a 2000 lb inertia weight CVCC Civic measured by Honda on the 1975 FTP.[16] All vehicles were tested at low mileage. EPA tests of three CVCC Civics are summarized in Table 3-2 for the 1975 FTP at 2000 lb inertia weight.[8] The three Civic vehicles tested by EPA passed the original 1975 Federal emission standards (0.41 HC/3.4 CO/3.1 NO_x) and were noted to have the lowest emissions of any gasoline fueled automobile, without exhaust gas treatment, ever tested by EPA. The 50,000 mile car (#2034) ran through the durability test with normal maintenance. There were no smoke, odor or noise problems associated with the CVCC Hondas tested by the EPA.

Honda is developing a low NO_x version of the CVCC by addition of EGR and improving and optimizing cylinder head and prechamber geometry, fuel-air ratio control, and combustion duration.[4] Test results of low mileage engines, embodying such modifications and

TABLE 3-1. HONDA EMISSIONS DATA FOR CVCC CIVIC

Configuration	HC	CO	NO_x	No. of Vehicles	MPG
CVCC Civic manual	0.23	2.41	0.95	25	22
CVCC Civic	0.23	2.60	1.15	3	21

Note: 2000 lb I.W. (1975 FTP).

TABLE 3-2. EPA EMISSIONS DATA FOR CVCC CIVIC

Configuration	HC	CO	NO_x	MPG	Remarks
a. car 3652 low mileage	0.18	2.12	0.89	22.1	5 tests
b. car 3606 low mileage	0.23	2.00	1.03	20.7	1 test
average of a & b	0.21	2.06	0.96	21.4	
c. car 2034 50,000 mi	0.24	1.75	0.65	21.3	4 tests

Note: 2000 lb I.W. (1975 FTP).

installed in a Honda Civic car with manual transmission, are shown in Table 3-3. The first vehicle listed, having no catalyst or EGR, achieved a NO_x level reduction of a factor of two in comparison with vehicle emissions of the unimproved vehicles in Table 3-1. The same degree of hydrocarbons and carbon monoxide reduction was maintained without EGR. When EGR was added, the NO_x level was reduced from 0.43 gm/mi to 0.24 gm/mi but the fuel economy fell about 18 percent below that of the unimproved CVCC Civic vehicles shown in Table 3-1.

TABLE 3-3. EFFECTS OF EGR ON NO_x EMISSIONS OF LOW MILEAGE IMPROVED CVCC HONDA CIVIC

Configuration	HC	CO	NO_x	MPG
No catalyst No EGR	0.25	2.5	0.43	not reported
No catalyst with EGR	0.28	3.1	0.24	18.1

The emissions data for the 2500 lb inertia weight conventional and CVCC Vega 140 CID engine are shown in Table 3-4. The CVCC engines were not equipped with EGR, catalysts, or air pumps. The conventional Vega engine was set up to meet the 1972 California emissions specifications with an air pump and EGR.[16] The data indicate that the CVCC GM-Vega can meet the original 1975 Federal emission standards, but not the statuatory 1978 NO_x standards.

TABLE 3-4. EMISSIONS FOR CONVENTIONAL AND CVCC VEGA

Configuration	HC	CO	NO_x	MPG
Conventional	2.13	10.6	3.8	17.2
CVCC	0.26	2.9	1.18	17.9

Note: 140 CID at 2500 lb I.W.

In addition to the Vega engine, Honda has developed a CVCC version of the Chevrolet 350 CID V-8 engine. The engine has been installed and tested in a 5000 lb inertia weight Chevrolet Impala with a 3-speed automatic transmission. The emissions are listed in Table 3-5 as measured by Honda.[16] and General Motors. The GM results are an average of a 5 car test.[4] Test results indicate the CVCC powered Impala had emission levels below the original 1975 limits. In the 5 GM tests the NO_x emissions range from 1.5 to 2.0 gm/mi.

The effect of vehicle weight on NO_x emissions with the CVCC engine is indicated in Table 3-6. The CVCC powered Impala at 5000 lb inertia weight is compared to the 2000 lb inertia weight Honda

TABLE 3-5. EMISSIONS FOR CONVENTIONAL AND CVCC 1973 IMPALA

Configuration	HC	CO	NO_x	MPG	Source
Conventional	1.56	19.33	2.42	10.5	Honda
CVCC	0.19	2.85	1.57	10.9	Honda
CVCC	0.23	2.9	1.7	11.2	GM (5 tests)

Note: 350 CID V-8 at 5000 lb inertia weight.

TABLE 3-6. EMISSIONS FOR CVCC HONDA AND CVCC IMPALA

Configuration	HC	CO	NO_x	MPG
Honda	0.21	2.06	0.96	21.4
Impala	0.23	2.9	1.7	11.2 (5 tests)

Note: CVCC Honda 2000 lb I.W.
CVCC Impala 5000 lb I.W.

CVCC Civic. The NO_x emissions for the Impala are nearly double those for the Honda, while the HC and CO emissions remain roughly comparable.

The effect of NO_x control on fuel economy for Honda CVCC powered Civic vehicles is shown in Table 3-7. As NO_x emissions are reduced to below 0.4 gm/mi, fuel economy is reduced by nearly 25 percent. NO_x reduction was achieved by EGR and ignition timing retard. The EGR reduces peak combustion temperatures in the pre-chamber, thus minimizing oxides of nitrogen. However, flame speed is also reduced, resulting in a loss of engine power. The CVCC process is relatively inefficient because its low turbulence ratios result in low-flame-speed combustion.

Ford, under an agreement with Honda, is developing a CVCC powered Ford vehicle to meet a 2.0 gm/mi NO_x level with a catalyst.

TABLE 3-7. HONDA CVCC FUEL ECONOMY AT VARIOUS NO_x LEVELS

	HC	CO	NO_x	MPG
All tests Honda CVCC 2000 lb I.W.	0.23	2.2	1.15	25.2
	0.17	2.3	0.90	23.0
	0.25	2.0	0.47	20.4
	0.33	3.0	0.38	19.0
	0.29	2.7	0.30	18.0

Ford constructed a single-cylinder prechamber engine which was tested at one load and speed to determine if the concept has inherent emission advantages over conventional carbureted engines.[39] The tests indicated that at NO_x levels below 1.5 gm/ihp-hr, the developmental prechamber engine used less fuel with EGR than the conventional engine with EGR.

A 2.3 liter 1974 Pinto and a 400 CID V-8, EGR equipped Torino prechamber engine were constructed and tested to meet 2.0 NO_x levels.[40] Initial test results are given in Table 3-8. HC and CO emission levels were above target values of 0.41 and 3.4 gm/mi, respectively. Improved engine versions are being prepared for dynamometer testing. Prechamber engines being developed jointly by Honda and Ford reportedly have not been able to attain a 0.4 gm/mi NO_x level.

TABLE 3-8. EMISSIONS FROM 1974 PINTO AND 1974 TORINO CVCC VEHICLES

Vehicle Description	HC	CO	NO_x	MPG
2.3L Pinto, no EGR Manual, 3000 lb I.W.	2.86	14.96	1.70	20.8
400 CID Torino, with EGR Automatic, 5000 lb I.W.	0.68	4.77	2.04	9.6

Note: CVS-CH

No performance data were available on the CVCC Ford Pinto and Torino vehicles. Prechamber engines were installed in five 1973 Galaxies equipped with automatic transmissions, but complete test results were not available. Preliminary test results indicate lower performance but a 4 percent improvement in fuel economy as compared to a 1973 conventional Galaxie.

3.1.5 Fuel Economy

Honda has reportedly indicated that the CVCC powered Civic fuel economy is 10 percent less than that of the conventionally powered Civic vehicle.[8] EPA tests indicate that the average fuel economy (20.4 mpg) of three CVCC Honda vehicles tested according to the 1972 FTP was 20 percent lower than the average for 1973 certification vehicles (25.5 mpg) in the same weight class.

Comparison of the GM CVCC Vega conversion showed a fuel economy improvement of 9 percent for the best Vega listed in Table 3-4. The fuel economy improvement of the CVCC Impala was marginal according to Honda's data listed in Table 3-5. The fuel economy data of the CVCC Impala is listed in Table 3-9 with results from EPA certification tests[31,32,41] of comparable conventional powered vehicles. The CVCC Impala with emission controls to meet 1975 standards (from Table 3-5) shows a poorer fuel economy than the 1975 certification vehicle. A reduction in NO_x emissions to 0.4 gm/mi would result in even further degradation of fuel economy. For the CVCC Honda Civic, Table 3-7 shows a fuel economy penalty of approximately 25 percent to achieve 0.4 NO_x levels.

3.1.6 Performance

No driving problems were encountered in testing the CVCC Honda Civic. The CVCC Impala did not develop any problems in negotiating the 1975 FTP or with steady-state driving when tested by the EPA.

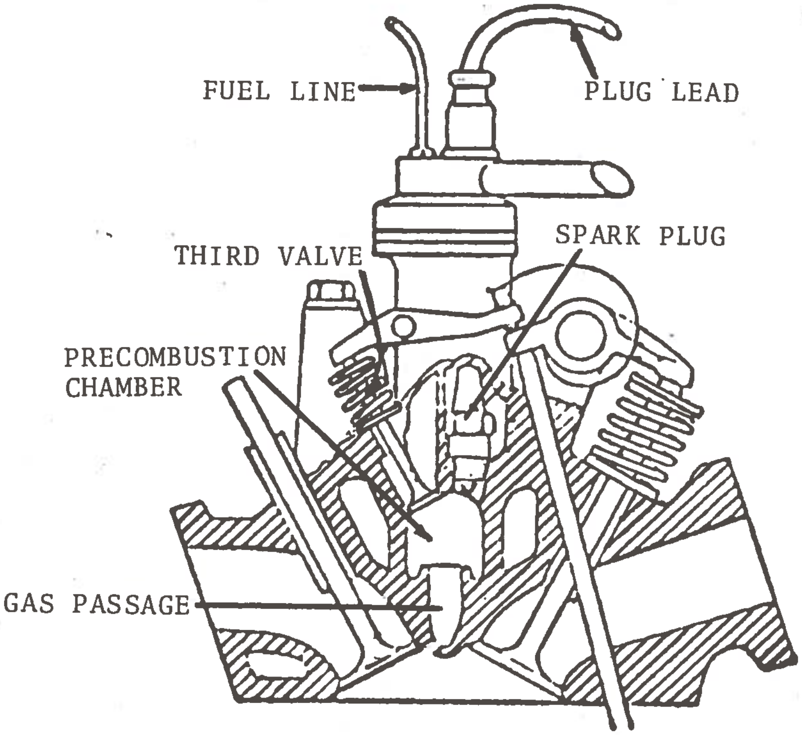
TABLE 3-9. COMPARATIVE FUEL ECONOMY AND EMISSIONS DATA

Vehicle Description	Emissions gm/mi			Fuel Economy MPG	% IMPROV.
	HC	CO	NO_x		
1973 Impala Certification (Honda)	1.5	2.85	1.57	12.0 10.5	
1974 Impala Certification				11.0	
1975 Monte Carlo Certification				13 urban; 18 highway	
1973 CVCC Impala on 1975 FTP (Honda)	0.19	2.85	1.57	10.9	-16% from 1975 Monte Carlo on urban cycle

3.2 HEINTZ RAM-STRATICHARGE ENGINE

The basic design of the Heintz engine[29] is illustrated in Figure 3-4. A small prechamber is located above the main chamber, as in the Honda CVCC engine. However, the forechamber geometry is more complex, having a cup-like design and a recessed spark plug. The intake manifold supplies unthrottled air to the main chamber and make-up air through a fixed orifice into the prechamber intake manifold located above the prechamber's small valve. The fuel injection supplies fuel to the prechamber only for up to about 40 percent engine load. At increased loads, additional fuel is supplied by a second injector into the main cylinder intake manifold.

The Heintz stratified charge concept employs a maximum air-fuel ratio of approximately 30 to adequately control exhaust hydrocarbons. Engine tests were performed on a 1957 Chrysler Imperial 392 CID V-8 with a design objective of reducing exhaust hydrocarbons below 2 percent of the level of the conventional engine. Successful operation on propane, butane, gasoline, kerosene, and up to 40 cetane diesel fuel was reported. The maximum brake mean effective pressure of the naturally aspirated Heintz engine was 23 percent less than that from the original Chrysler engine. This



Source: Ref. 6

Figure 3-4. Heintz Ram-Straticharge Engine.

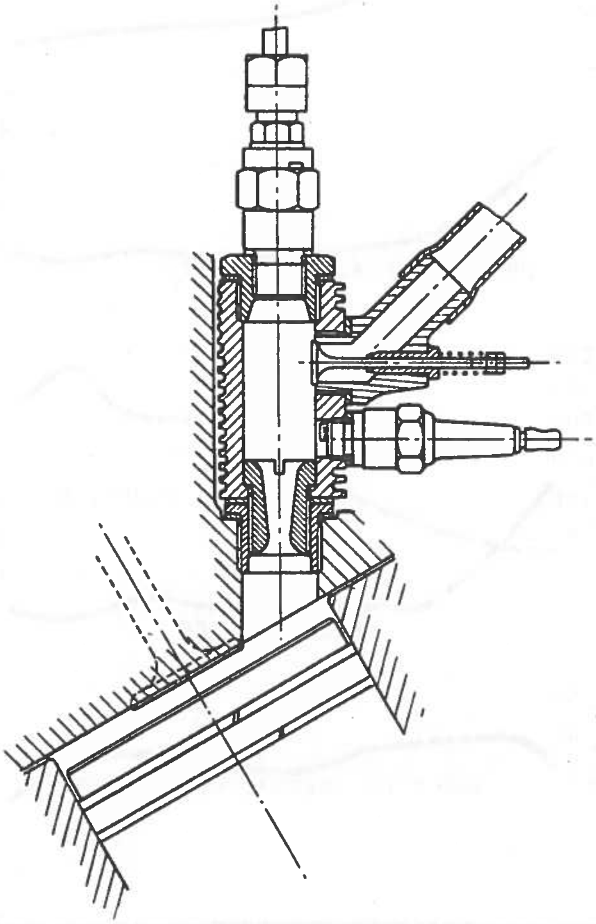
represents a reduction in power, primarily due to a reduction in compression ratio from 9.25:1 to 7.7:1.

There have been no recent developments to the Heintz engine reported in the literature.

3.3 BRODERSON DIVIDED CHAMBER ENGINE

The University of Rochester has carried out research during the last two decades to develop the Broderson divided combustion chamber engine.[8] The original Broderson design provided for a swirl prechamber located at the top of the main combustion chamber.[29]

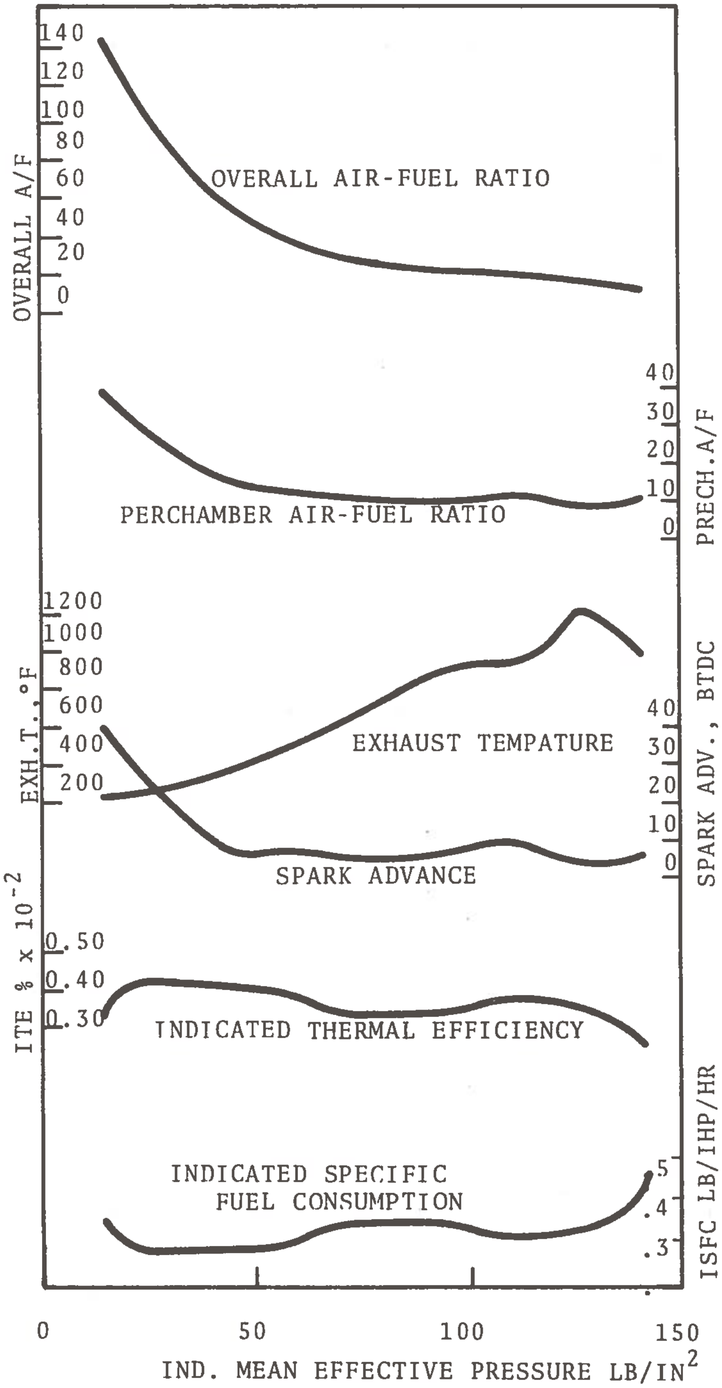
A CFR research engine of 37.33 CID was converted by the University of Rochester to use the Broderson concept. The original Broderson design was modified to use a cylindrical prechamber as shown in Figure 3-5. A "nozzle" connected the prechamber with the main chamber. The compression ratio was 12:1 and the prechamber volume was 17.2 percent of the total clearance volume. A fuel injector supplied the prechamber, while a carburetor provided with a finely adjustable needle valve supplied a lean homogeneous air-fuel mixture to the main chamber. An auxiliary inlet valve was provided for air-scavenging the prechamber.



Source: Ref. 8

Figure 3-5. Broderson Engine Combustion Chamber Cross Section

Test results obtained at 1200 rpm are shown in Figure 3-6. Engine load changes were made by changing only the amount of fuel supplied to the engine, since the carburetor was mounted with its throttle valve locked wide open. At light loads injected fuel was supplied to the prechamber and only unthrottled air to the main chamber.



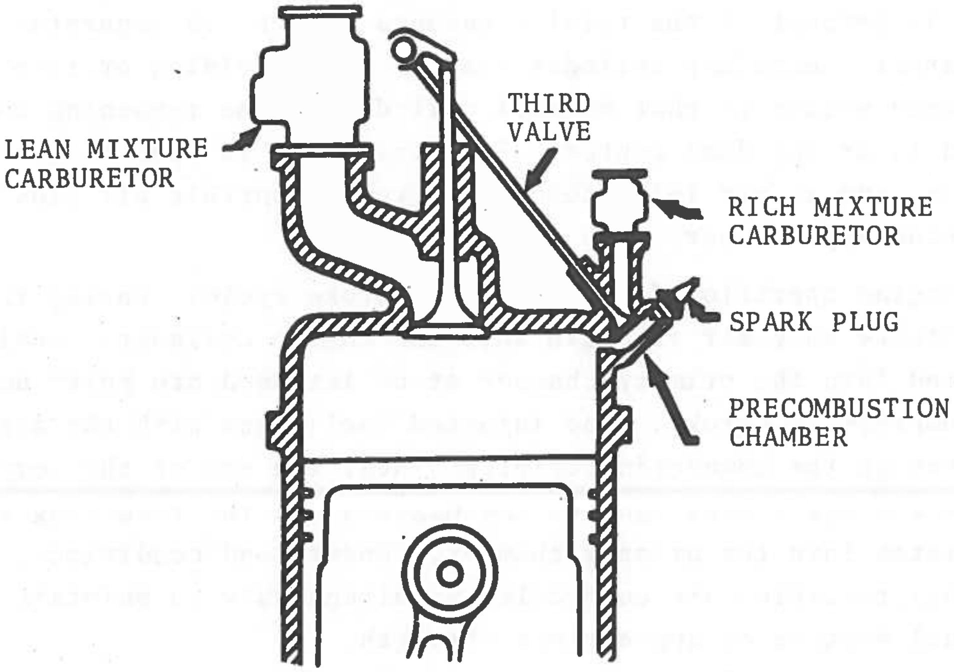
Source: Ref. 8

Figure 3-6. Broderson Engine Performance Curves at 1200 RPM and Compression Ratio 12:1

The data in Figure 3-6 indicate average air-fuel ratios as high as 140 were reached for very light loads. Thermal efficiency of 42 percent and an indicated specific fuel consumption (IFSC) of 0.29 lbs/ihp-hr were attained at 25 psi indicated mean effective pressure. No emissions data were taken but it was estimated that the engine would produce comparable emission levels to the Honda CVCC.

3.4 NILOV JET IGNITION ENGINE

The Nilov engine consists of a large main combustion chamber in communication with a small prechamber,[6] as shown in Figure 3-7. The prechamber uses a rich-mixture carburetor and the main cylinder uses a lean-mixture carburetor. The Nilov engine has the disadvantage of throttled operation, a disadvantage shared by all carbureted engines.



Source: **Ref. 6**

Figure 3-7. Nilov Engine

During the induction stroke the prechamber valve is opened late, so that a rich charge is compressed at the spark plug on the compression stroke. After ignition, a flame jet issues from the horizontal orifice connecting the prechamber to the main cylinder, igniting the leaner mixture in the main cylinder.

No emissions or fuel economy data are readily available.

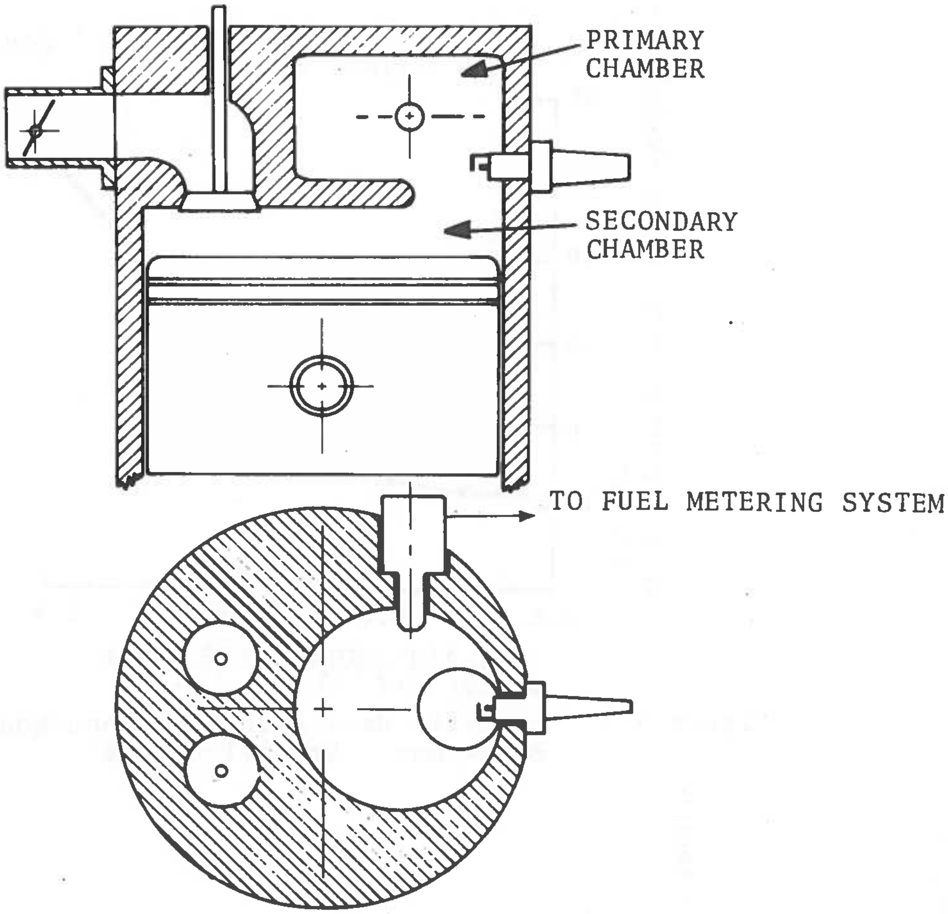
3.5 NEWHALL PRECHAMBER ENGINE

The Newhall Engine has been developed at the University of Wisconsin for fundamental research on emission control.[43] The concept entails a combustion process which simultaneously reduces hydrocarbon, carbon monoxide, and nitric oxide engine emissions. The engine employs divided chamber construction, a primary chamber charged with an air-fuel mixture and a secondary one charged with air.[8]

A diagram of the combustion chamber of the Newhall engine is shown in Figure 3-8. The primary combustion chamber, comprising 65 to 85 percent of the total clearance volume, is separated from the larger secondary cylinder chamber by a dividing orifice. Clearance volume is that overall cylinder volume remaining when the piston is at top dead center. Fuel injection is used in the primary chamber, and an air inlet throttling valve controls air flow into the secondary chamber.

Engine operation follows a four stroke cycle. During the intake stroke only air is drawn into the engine cylinder. Fuel is injected into the primary chamber at an intermediate point during the compression stroke. The injected fuel mixes with the air passing through the connecting orifice. Near the end of the compression stroke the spark plug ignites the mixture and the resulting flame propagates into the primary chamber. Under load conditions, air and fuel throttles are controlled simultaneously to maintain an air-fuel mixture of appropriate strength.

Engine tests[43] were reported for a converted CFR engine of 37.33 CID having a compression ratio of 8:1. No comparison was made between emissions of the Newhall and conventional engines.



Source: Ref. 43

Figure 3-8. Newhall Prechamber Engine

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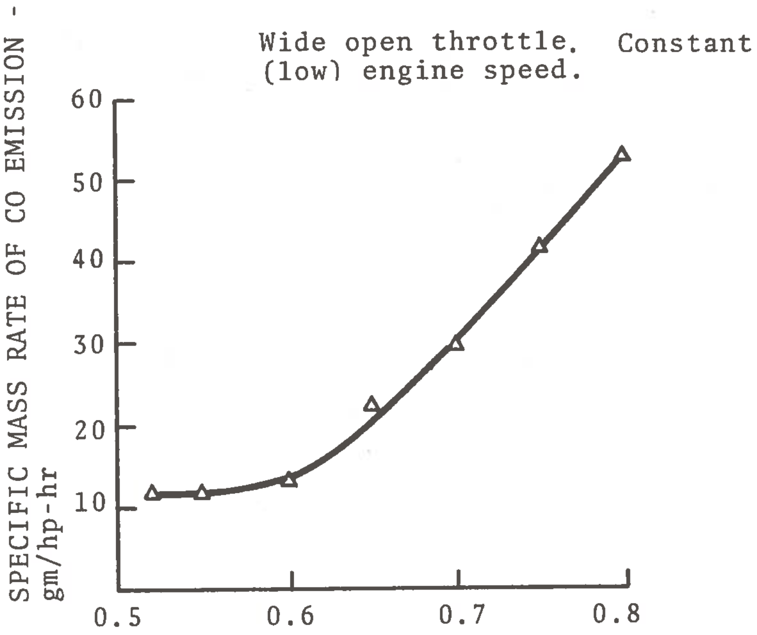
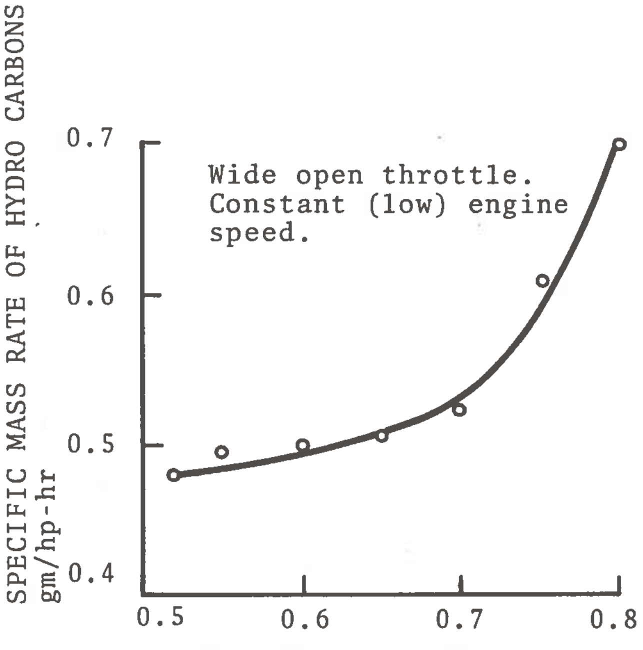
Specific mass emissions of carbon monoxide, hydrocarbons, and nitric oxide are shown in Figures 3-9 through 3-11 at wide open throttle for a single relatively low engine speed (not specified). Indicated specific fuel consumption (ISFC) is shown in Figure 3-12. For part throttle operation there was little evident change in HC and CO emissions, but the NO_x concentration decreased. The fuel consumption is comparable to that of conventional engines for fuel-air equivalence ratios less than 0.7. Fuel consumption increases rapidly for richer equivalence ratios since heat release occurs late during the expansion stroke, decreasing engine efficiency.



FUEL-AIR EQUIVALENCE RATIO

Source: Ref. 43

Figure 3-9. Specific Mass Rate of Carbon Monoxide Emissions - Newhall Engine



FUEL-AIR EQUIVALENCE RATIO

Source: Ref. 43

Figure 3-10. Specific Mass Rate of Hydrocarbon Emissions - Newhall Engine

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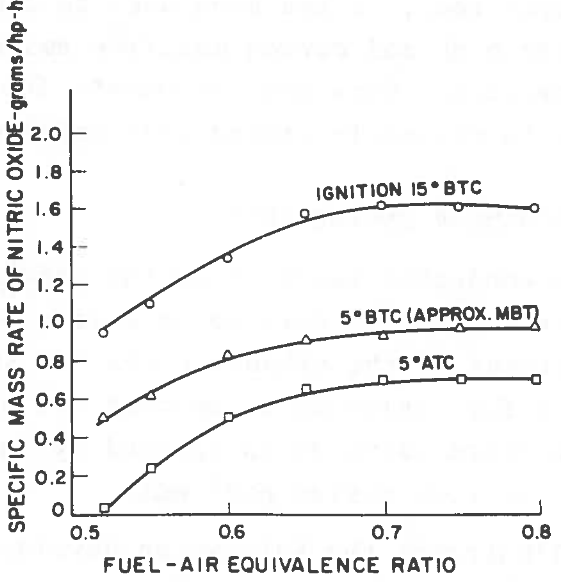
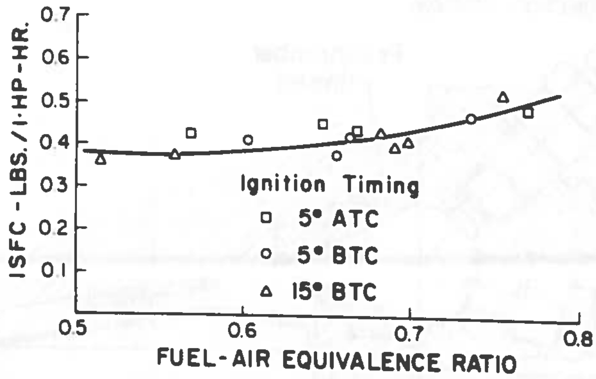


Source: Ref. 43

Figure 3-11. Specific Mass Rate of Nitric Oxide Emissions - Newhall Engine



Source: Ref. 43

Figure 3-12. Measured Values of Indicated Specific Fuel Consumption - Newhall Engine

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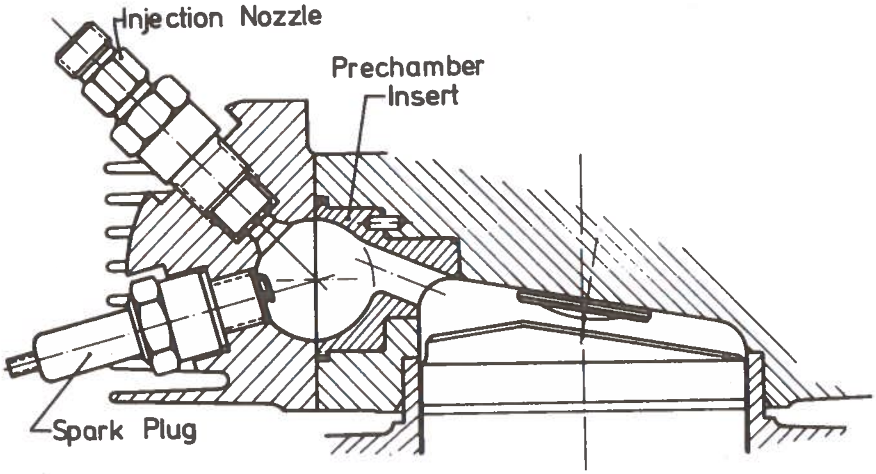
The Newhall Engine was not designed for any particular application. As a research tool, it has been used to demonstrate that nitric oxide, hydrocarbons and carbon monoxide emissions can be simultaneously controlled. Data are inadequate for assessing the concept in relation to presently stated 1978 emission standards.

3.6 VOLKSWAGEN PRECHAMBER ENGINE (PCI)

Volkswagen has conducted research on the prechambered stratified charge engine concept to develop an engine not requiring catalytic aftertreatment of the exhaust gases. A stratified charge engine with a fuel injected prechamber was selected for development since a third valve on an opposed cylinder overhead valve engine raises serious design problems.

Figure 3-13 illustrates the Volkswagen development engine's combustion chamber. A spherical prechamber constituting 25 to 30 percent of the compression volume is connected to the main cylinder by a relatively large flow passage. The injection nozzle is positioned upstream from the spark plug with respect to the direction of the swirling incoming air to avoid overenrichment at the spark plug. A carburetor is used to provide a homogeneous air-fuel mixture for the main chamber.



Source: Ref. 43

Figure 3-13. Second-Generation PCI Engine Combustion Chamber with Spherical Unscavenged Prechamber

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Load regulation of Volkswagen's PCI engine is primarily accomplished by adjusting the strength of the mixture introduced into the main cylinder. Mixture preparation by swirl action eliminates the need for fuel injection timing in the prechamber, with the end of injection held constant.

Emissions data from a 1.6-liter air-cooled engine and a 2.0-liter water-cooled Volkswagen PCI engine are listed in Table 3-10. The larger engine employed an exhaust thermal reactor. Although emission levels are low, they do not meet the 1978 statutory emission levels.

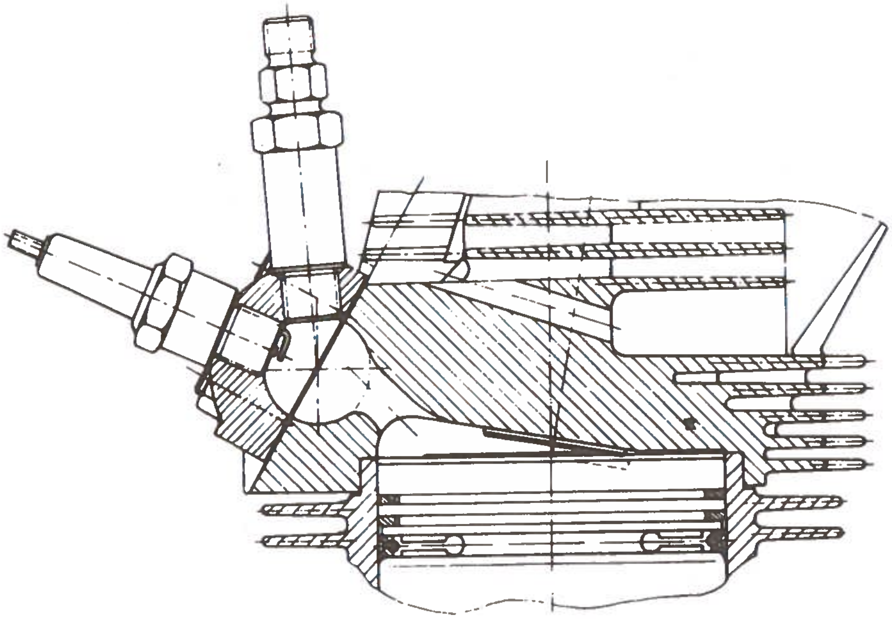
TABLE 3-10. VOLKSWAGEN LARGE VOLUME PRECHAMBER ENGINE EMISSIONS

Engine	Exhaust Emissions, gm/mi			Engine Specifications
	HC	CO	NO_x	
1.6-Liter Air-Cooled	2.0	5.0	0.9	8.4:1 compression ratio, prechamber volume 28% of total clearance volume, conventional exhaust manifold, direct prechamber fuel injection
2.0-Liter Water-Cooled	1.0	4.0	1.0	9:1 compression ratio, prechamber volume 28% of total clearance volume, simple exhaust manifold reactor, direct prechamber fuel injection

Note: Exhaust Emissions for CVS-CH.

A third generation, 1.6-liter PCI engine has recently been reported.[44] It features a double fuel injection system and a spherical prechamber with a volume some 20 percent of the total compression volume. Figure 3-14 illustrates the design of the third generation engine.

Engine dynamometer tests indicate the specific fuel consumption of the engine differs only slightly from that of the production VW engine. At wide open throttle, the peak torque value of the third generation PCI engine is 3 percent less, but somewhat flatter, than that of the production engine.



Source: Ref. 44

Figure 3-14. Third-Generation PCI Engine Combustion Chamber

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The engine was installed in a VW Beetle and tested on a chassis dynamometer in accordance with the 1975 CVS procedure, at 2250 pounds inertia weight. Exhaust emissions with no exhaust gas aftertreatment are listed in Table 3-11. The emissions are comparable to the previously reported emissions from the injected/carbureted version shown in Figure 3-9. Reportedly, the hydrocarbon and carbon monoxide emissions may be minimized by modifying the exhaust system to incorporate a lean reactor. Road behavior and engine noise were comparable to a standard production Beetle.

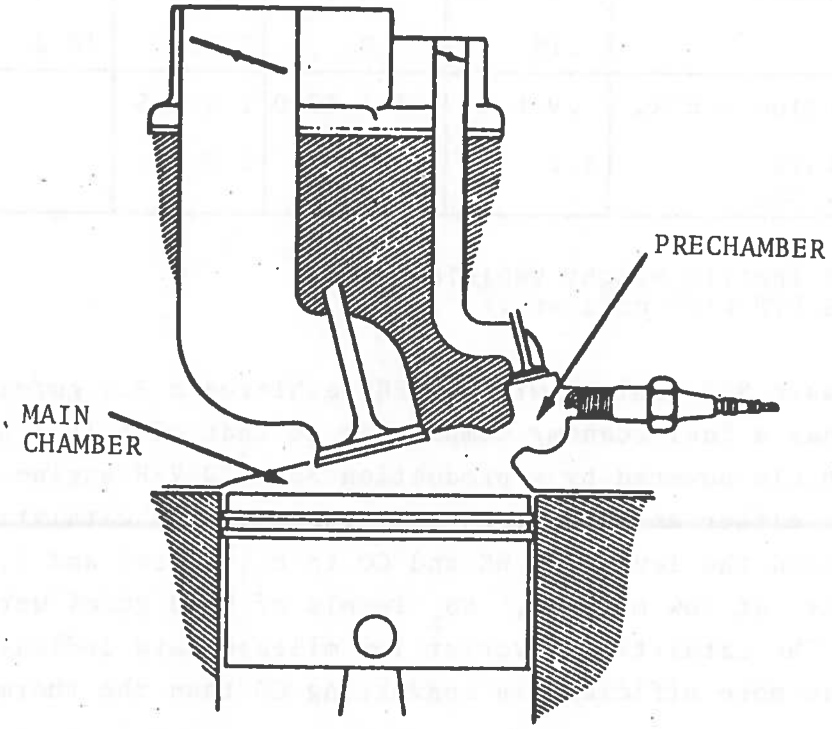
TABLE 3-11. EMISSIONS FROM THIRD-GENERATION, 1.6-LITER PCI VOLKSWAGEN ENGINE

Emission	Amount
HC	2.1-2.5 gm/mile
CO	4.4-8 gm/mile
NO_x	0.75-0.96 gm/mile
Fuel Economy	22-26 miles/gal (calculated from emissions)

3.7 GENERAL MOTORS STRATIFIED CHARGE ENGINE (SCE)

The prechambered stratified charge engine (SCE) is being considered by General Motors as an alternate engine to achieve low emissions. GM indicates that progress in the development of alternate engines is inhibited by the announced 1978 0.4 NO_x-level requirement. The company is, however, conducting evaluation tests of the SCE to define its emission potentials.[45]

A 350 CID V-8 engine has been converted to SCE operation as diagramed in Figure 3-15. The design and operation are similar to the Honda CVCC. A dual carburetor supplies the prechamber with a rich fuel-air mixture and the main chamber with a lean fuel-air mixture. The intake manifold features an early fuel evaporation system (EFE).



Source: 53

Figure 3-15. General Motors Stratified Charge Engine (SCE)

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The SCE, without exhaust gas aftertreatment, has been tested with a thermal reactor, and with a catalytic converter. The engine was provided with additional spark advance while cold to compensate for lower flame speeds. Results with the three systems are listed in Table 3-12.

TABLE 3-12. GM 350 CID V-8 SCE EMISSIONS

Vehicle Description	HC gm/mi	CO gm/mi	NO_x gm/mi	MPG
SCE System No. EGR Range (2) Tests	.7-1.0	4.3-4.6	1.6-1.7	9.5-11.1
Average	.9	4.5	1.7	10.3
SCE System W/Reactor Range (5) Tests	.20-.33	2.9-3.3	1.4-1.6	9.2-10.2
Average	.26	3.0	1.5	9.8
SCE System W/Converter Range (3) Tests	.17-.20	.8-1.0	1.4-1.5	9.8-10.4
Average	.19	.9	1.5	10.2
1974 Production W/EGR, AIR	.9-1.8	18.1-32.9	1.6-2.5	
Average 4 Cars 2 tests ea. car	1.2	25.2	1.9	

Note: 5000 Inertia Weight Vehicle
1975 FTP with cold start.

The basic SCE vehicle without EGR achieved a 2.0 gm/mi NO_x level and has a fuel economy comparable to that of a 1974 production vehicle powered by a production 350 CID V-8 engine. Addition of either an exhaust thermal reactor or a catalytic converter reduced the levels of HC and CO to below 0.41 and 3.4 gm/mi, respectively, at low mileage. No_x levels of 0.40 gm/mi were not attained. The catalytic converter low mileage data indicate the converter is more efficient in converting CO than the thermal reactor.

GM reports that SCE engines tested with exhaust gas aftertreatment appear to have minimum NO_x levels between 1.0 and 2.0 gm/mi.[46] This can be seen in Table 3-12. The stratified charge system without EGR achieved significantly lower CO levels that the 1974 production car which has both air injection and EGR. Exhaust gas aftertreatment devices were tested for effectiveness in reducing emissions below 0.41 gm/mi and 3.4 gm/mi, respectively. Success at low mileage was reported for cars with either a reactor or catalytic converter. The durability of these systems has not been determined.

The reduction of NO_x by addition of EGR was explored on a 350 CID V-8 SCE in a 4,000 pound inertia weight vehicle. Emission results for the basic system described at the beginning of this Section, with and without EGR,[47] are shown in Table 3-13. At the lowest NO_x level using EGR, 0.43 gm/mi, HC and CO emissions had increased approximately twofold over the basic SCE, with a 6.4 percent reduction in fuel economy (calculated). No test results were given for EGR together with exhaust gas aftertreatment.

TABLE 3-13. EFFECT OF EGR ON NO_x EMISSIONS FROM THE GM SCE 350 CID V-8

Vehicle Description	HC gm/mi	CO gm/mi	NO_x gm/mi	MPG
Basic System (No EGR)				
Range (2)	1.0-1.3	3.9-4.3	1.3-1.4	12.2-12.7
Average	1.2	4.1	1.4	12.5
Basic System Plus EGR				
Range (3)	2.0-3.2	6.1-11.2	.43	11.4-12.0
Average	2.8	8.1	.43	11.7

Note: 4000 Pounds Inertia Weight Vehicle
1975 FTP with cold start.

GM is continuing the development of a small stratified charge Vega engine which first operated early in 1974. No emissions test data are available.[47]

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APPENDIX A
SUPPORTING STATEMENTS FOR U.S. AUTO MANUTACTURERS BEING NON-COMMITTAL ABOUT STRATIFIED CHARGE ENGINES DUE TO EMISSION LEVELS

A.1 GM[47]

"Our data thus indicate that the 1975 interim standards are, in general, more stringent than necessary to achieve air quality goals in most areas of the country with a wide margin of safety. NO_x is the one exception, and our data suggest a level of 1.4 gpm for California and a few additional cities and 2.0 for the nation would be an adequate level of control for model years beginning in 1978.

"Stabilizing the NO_x standard at that level would remove a large barrier to the development of a wider range of alternative power plants, including the diesel and stratified charge engines that show promise of delivering improved fuel economy at those less stringent emission levels without the use of aftertreatment devices."

A.2 FORD[23]

"Our work is almost finished now and we're more optimistic than ever about stratified-charge engines. These engines have two rather important characteristics: they can meet current emission standards, and they can deliver a fuel-economy improvement of up to 25 percent, compared with current engines.

"One thing they can't do: they can't meet the present 1978 NO_x standard of four-tenths grams per mile. The experts contend that the present standard is too stringent, must be changed, and will be changed, but we can't spend hundreds of millions of dollars to build a product that couldn't be sold under existing law."

A.3 CHRYSLER[48]

"The biggest fuel-wasting regulation of all — emissions standard for NO_x — looms on the horizon.

"EPA and independent scientific groups agree that the original NO_x standard of 0.4 grams per mile is more stringent than necessary to protect health. Unless Congress establishes a more realistic permanent standard it will come into effect in the 1978 model year. Experimental systems we are testing to meet that standard show fuel economy penalties of 20 to 30 percent."

APPENDIX B
SYSTEM CATEGORY CONFIGURATIONS AND ACRONYMS

Configurations

(a) EM, AIR, EGR, QHI

(b) OXCAT, AIR, EGR, QHI, HEI

(c) DCAT, AIR, EGR, QHI, HEI

(d) OXCAT, AIR, PEGR, EFE, HEI

(e) OXCAT, MAIR, PEGR, SEFE, HEI

(f) DCAT, MAIR, PEGR, SEFE, HEI, CC

(g) SCE, OXCAT

(h) SCE, OXCAT, PEGR, CC

Definitions/Acronyms

AIR = Air Injection

BMEP = Brake Mean Effective Pressure

CC = Charcoal Exhaust Storage

CO = Carbon Monoxide

CVCC = Compound Vortex Controlled Combustion

CVS-(CH) = Constant Volume Sampling - (Cold Hot)

DCAT = Dual Catalyst

EFE = Early Fuel Evaporation

EGR = Exhaust Gas Recirculation

EM = Engine Modifications

EPA = Environmental Protection Agency

FCP = Ford Combustion Process

FDC = Federal Driving Cycle

FTP = Federal Test Procedure

HC = Hydrocarbons

HEI = High Energy Ignition

IMEP = Indicated Mean Effective Pressure

ISFC = Indicated Specific Fuel Consumption

MAIR = Modulated Air Injection

NO_x = Nitrogen Oxides

OXCAT = Oxidation Catalyst

PEGR = Proportional Exhaust Gas Recirculation

PROCO = Programmed Combustion

QHI = Quick Heat Manifold

SC = Stratified Charge Engine

SEFE = Super Early Fuel Evaporation

SFC = Specific Fuel Consumption

TCCS = Texaco Controlled Combustion System

APPENDIX C
ADDENDUM — TO MARCH 1975

C.1 INTRODUCTION

This addendum discusses information available through March 1975. The scope of this addendum includes only the submissions of Chrysler,[49] Ford,[50,51] and General Motors.[52] No additional information from GM supplemented the main body of the text of this Stratified Charge Engine Report, which included data through December 1974.

C.2 CHRYSLER-TEXACO (TCCS) ENGINE

Chrysler did not report additional quantitative results from their TCCS Plymouth Cricket vehicles.[49] However, the fully emission controlled vehicle (see Table 2-11) reportedly was able to follow the FTP driving cycle, but with no spare power.

A design study of a 360 CID V-8 TCCS engine was terminated in favor of a smaller displacement engine. Chrysler conducted a joint feasibility study with Texaco and Ricardo for the conversion of a 198 CID six-cylinder engine to TCCS operation. Although the concept was judged as feasible, no design work was undertaken.

Preliminary cost estimates made by Chrysler for a full-size TCCS car indicate it would cost more than a conventional engine with a dual-bed catalyst system. No cost figures were available.

C.3 FORD-PRECHAMBER AND PROCO ENGINES

Ford has continued the development of the 2.3L and 400 CID prechamber engines. Their preliminary emission results are reported in Table 3-8. The 2.3L engine is being developed to meet the objectives of 25 mpg in the Ford City/Suburban driving cycle in a 3000 lb inertia weight vehicle. Emission level objectives with a catalyst are 0.41 gm/mi HC, 3.4 gm/mi CO, and 2.0 gm/mi NO_x. The 400 CID prechamber engine is being designed to meet the same emission objectives while maintaining 1973 model year fuel economy for 5000 lb inertia weight vehicles. Table C-1 presents emission data and fuel economy from these programs.[50]

TABLE C-1. EMISSIONS AND FUEL ECONOMY OF CVCC 2.3L and 400 CID ENGINES

Engine	OBJECTIVE			CVS-CH Emissions			MPG*	
	HC	CO	NO_x	HC	CO	NO_x	CVS-CH	City/Sub (Ford)
2.3L, 3000 lb. IW	1.5	15	3.1	1.3	8.5	1.8	22.2	-
400 CID	1.5	15	3.1	0.91	7.0	2.9	-	14.0
2.3L, 3000 lb. IW	.9	9.0	2.0	0.77	9.2	1.8	20.5	-
400 CID	.9	9.0	2.0	0.56	4.8	1.8	-	13.0
2.3L, 300 lb IW	.4	3.4	2.0	0.58	4.9	1.4	18.5	-
400 CID	.4	3.4	2.0	0.22	2.3	1.7	-	12.3
400 CID Baseline 1973 Galaxie (Production)	3.4	39.0	3.0	1.6	15.4	2.4	-	11.6

*A dash indicates no data given.

Ford indicates that the emission potential of the 2.3L CVCC type engine is not fully developed and that the above results for that engine are preliminary. The 400 CID engines show HC and CO emissions below the objectives, but NO_x control is marginal without EGR. EGR for the 400 CID engine is being developed. Ford indicates that EGR would reduce fuel economy, or reduce HC and CO control, and that a catalytic converter would probably be required.

The 400 CID CVCC vehicle, without EGR and calibrated at the lowest emission level, shows a fuel economy improvement of 6 percent over the 1973 baseline Galaxie, and an improvement of 20 percent at the 3.1 gm/mi NO_x level.

In the PROCO development program, the 351 CID durability test (see Table 2-3) has been completed. The fuel injection system and engine were not serviced during the 50,000 mile durability test. The PROCO engine installed in a 1972 Montego, was equipped with an oxidation catalyst and EGR. A catalyst change was required at about 30,000 miles.

PROCO developments included the conversion of a 400 CID engine installed in a Mark IV Continental. The vehicle was equipped with a 4-speed automatic transmission having a lock-up torque converter with an overdrive in 4th gear. The vehicle was prepared for the major purpose of demonstrating the maximum fuel economy potential of current technology. The Mark IV achieved CVS-CH fuel economy of 14.1 mpg; driveability and combustion harshness, however, made vehicle performance unacceptable.

Ford indicated that major efforts are continuing to adapt the PROCO concept to the 400 CID engine. Through a contractual agreement with American Bosch (AMBAC) Corporation, a reduced cost, production-feasible gasoline injection system is being developed. Production costs and unit price quotations from AMBAC will be obtained. Additionally, injection component design investigations are being carried out by Robert Bosch and Nippondenso. In a study to determine the emission and fuel economy tradeoffs with PROCO, three identical cars were equipped with 400 CID PROCO engines and tested at three emission calibrations.[50] The results are shown in Table C-2.

Vehicle calibrations for these tests were made primarily by EGR and air-fuel mixture adjustments, and changing the injection spray angles. The Torino was calibrated to obtain the highest fuel economy by increasing the air-fuel mixture from 16.2:1 to 17.5:1, and removing the exhaust back pressure control. At this calibration level, the Torino meets Ford feedgas objectives for emission standards of 0.4/3.4/2.0 gm/mi and 0.4/3.4/1.5 gm/mi, respectively. The fuel economy of the Torino is about 10 percent higher than the Montego calibrated at 2.0 gm/mi NO_x.

TABLE C-2. PROCO 400 CID EMISSIONS

Vehicle	HC gm/mi	CO gm/mi	NO_x gm/mi	MPG
Montego (90° Inj. Spray Angle)	1.41	18.0	1.16	12.6
Montego (60° Inj. Spray Angle)	1.51	12.7	1.71	13.1
Torino (100° Inj. Spray Angle)	2.10	8.06	1.50	14.4

Note: 5000 Pounds Inertia Weight
2.75 Axle Ratio no Catalysts.

From a supplementary study conducted by Ford,[3] 4000 mile feedgas emissions and fuel economy are presented in Table C-3 for the 2.3L Pinto at 3000 lb inertia weight, and the 400 CID Torino at 5000 lb inertia weight. The data include conventional, CVCC, and PROCO powered vehicles tested by Ford. These data are plotted in Figure C-1 for the 400 CID vehicle. The Ford data show that for all emission configurations fuel economy decreases as progressively lower emission standards are met. The data for the 2.3L Pinto are plotted in Figure C-2. The 2.3L conventional engine, calibrated at 0.41/3.4/2.0 gm/mi $HC/CO/NO_x$, lost 22.7 percent in fuel economy from the 1.5/15/3.1 emission calibration, while the catalyst equipped PROCO dropped 12.9 percent in fuel economy.

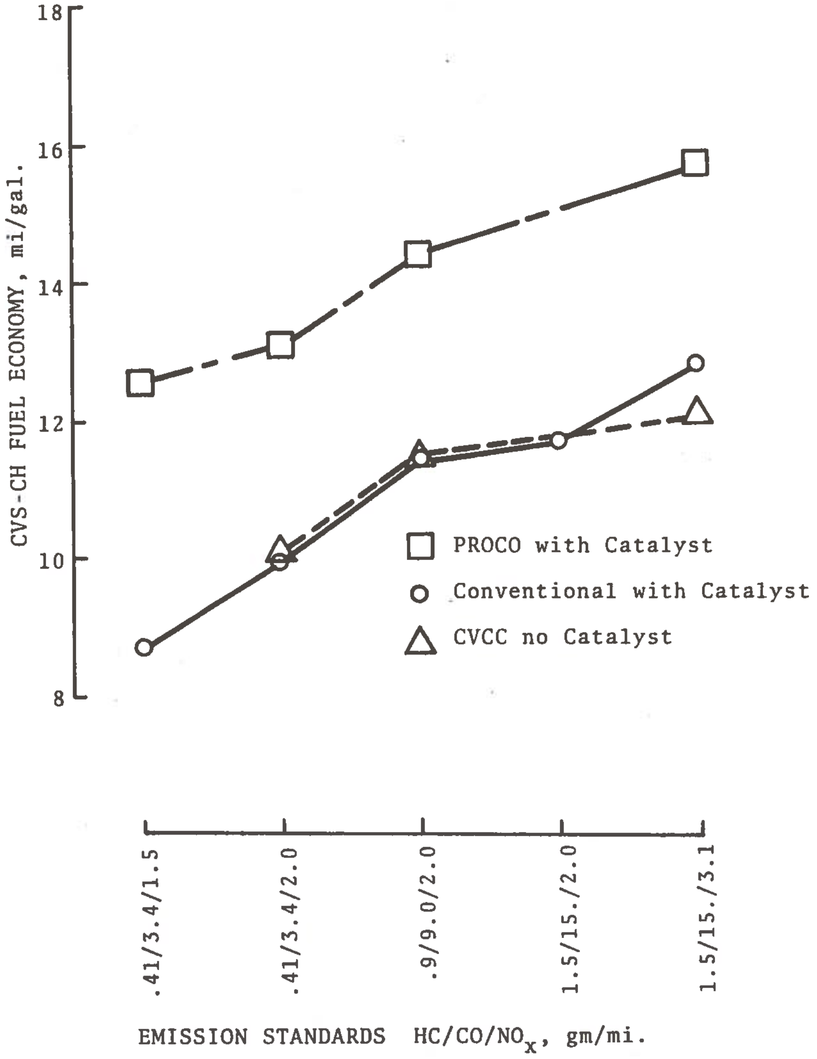
The catalyst equipped 400 CID conventional engine, meeting feedgas objectives for emissions of 0.4/3.4/2.0 gm/mi, had a 22.3 percent lower fuel economy than when calibrated at 1.5/15/3.1. The 400 CID catalyst-equipped PROCO fuel economy was reduced by 16.6 percent between these emission levels. The non-catalyst CVCC 2.3L and 400 CID vehicle fuel economies were reduced by 13.3 percent and 16.6 percent, respectively, where $HC/CO/NO_x$ emissions were reduced from 1.5/15/3.1 gm/mi to .41/3.4/2.0 gm/mi.

TABLE C-3. EMISSIONS AND FUEL ECONOMY OF CVCC AND PROCO VEHICLES

Configuration	Emission Std. (gm/mi)			4000 mi Feedgas Obj. (gm/mi)			Feedgas Emissions (gm/mi)			CVS-CH Fuel Economy * MPG
	HC	CO	NO_x	HC	CO	NOx	HC	CO	NO_x	
CVCC 2.3L NC	1.5	15.	3.1	1.0	10.0	2.5	1.18	7.72	1.85	21.0(3)
PROCO 2.3L				3.7	40.0	2.5	2.0	5.9	1.91	27.2(2)
PROCO 2.3L NC				1.02	10.0	2.5	0.82	5.2	2.3	23.9(4)
CVCC 400 CID NC				1.0	10.0	2.5	0.91	6.98	2.89	12.0(2)
PROCO 400 CID				3.7	40.0	2.5	3.7	4.1	2.5	15.7(1)
Conventional 2.3L				3.2	36.0	2.5	1.44	13.09	2.33	21.6(3)
Conventional 400 CID				3.1	36.0	2.5	2.21	7.42	2.24	12.8(3)
PROCO 2.3L NC	1.5	15.	2.0	1.02	10.0	1.6	1.0	7.8	1.7	
Conventional 2.3L				3.2	36.0	1.6	1.68	13.0	1.73	20.8(5)
Conventional 400				3.2	36.0	1.6	2.17	8.22	1.55	11.7(2)
CVCC 2.3L NC	.9	9.0	2.0	0.7	7.0	1.6	0.77	9.19	1.79	20.5(3)
PROCO 2.3L				2.2	40.0	1.6	1.96	9.2	1.49	26.4(2)
PROCO 2.3L NC				0.57	5.9	1.6	0.45	54.	1.91	23.0(2)
CVCC 400 CID NC				0.7	7.0	1.6	0.63	5.31	1.74	11.5(2)
PROCO 400 CID				2.2	40.0	1.6	2.1	8.1	1.5	14.4(2)
Conventional 2.3L				2.0	36.0	1.6	0.93	12.3	1.4	19.8(3)
Conventional 400 CID				2.0	36.0	1.6	1.89	8.14	1.74	11.5(3)
CVCC 2.3L NC	.41	3.4	2.0	0.3	3.0	1.6	0.52	3.9	1.37	18.2
PROCO 2.3L				1.1	14.0	1.6	1.0	7.8	1.7	23.7(2)
CVCC 400 CID NC				0.3	3.0	1.6	0.18	2.51	1.76	10.0(6)
CVCC 400 CID				0.8	11.0	1.6	0.63	5.31	1.74	11.5(2)
PROCO 400 CID				1.1	14.0	1.6	1.51	12.7	1.71	13.1(1)
Conventional 2.3L				0.8	11.0	1.6	0.77	15.7	1.62	16.7(3)
Conventional 400 CID				0.8	11.0	1.6	0.66	18.2	1.67	9.94(4)
PROCO 400 CID	.41	3.4	1.5	1.1	14.0	1.23	1.41	18.0	1.16	12.6
Conventional 2.3L				0.8	11.0	1.2	0.62	11.9	1.33	16.34(3)
Conventional 400 CID				0.8	11.0	1.2	0.84	9.6	1.3	8.7(6)
CVCC 400 CID				0.8	11.0	1.2	0.34	3.68	1.16	9.63(2)

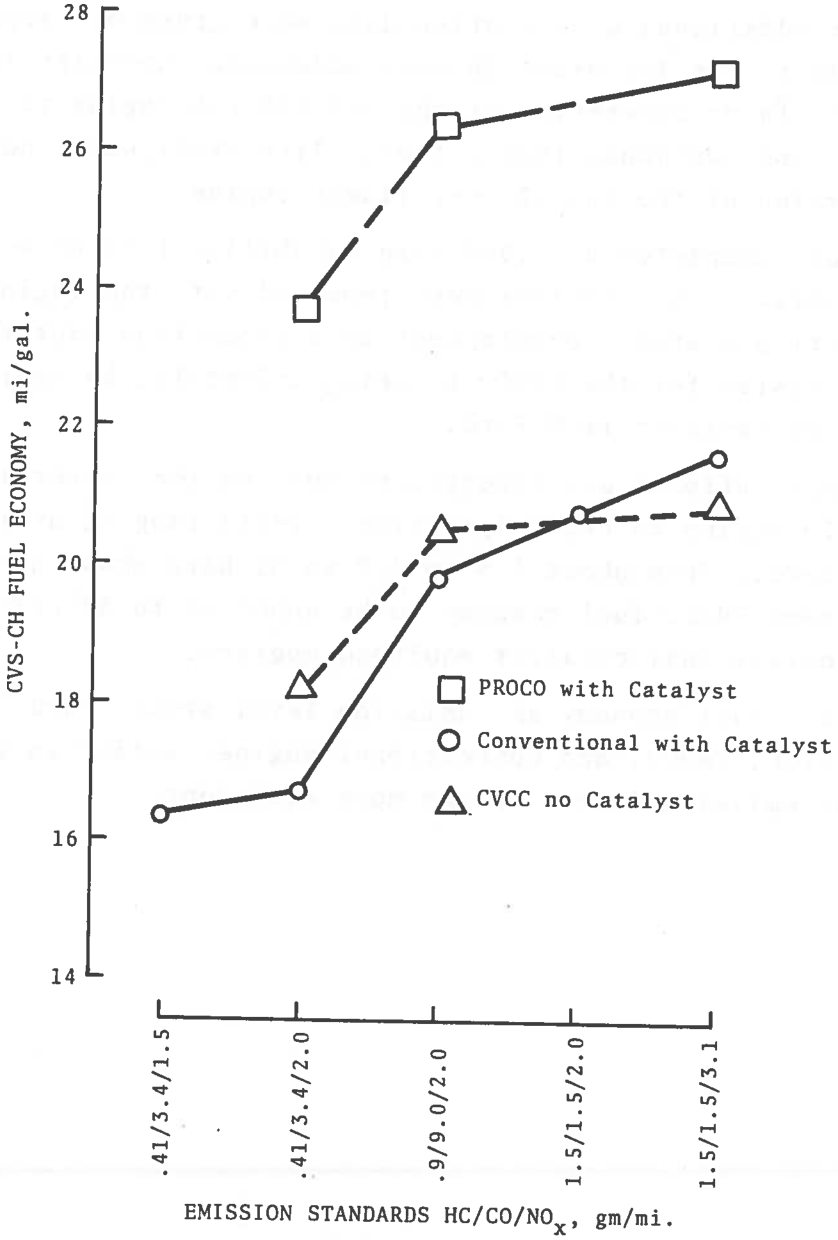
*Numbers in brackets indicate number of fuel economy tests used to obtain average shown.

NOTES:
1. NC = No catalyst
2. 2.3L Vehicles tested at 3000 lbs I.W., 3.4:1 Axle Ratio
3. 400 CID Vehicles tested at 5000 lbs I.W., 2.75:1 Axle Ratio



NOTE: 400 CID ENGINE
2.75 REAR AXLE RATIO
5000 # I.W.

Figure C-1. Torino Fuel Economy Vs Emission Standard



NOTE: 2.3L Engine
3.4 Rear Axle Ratio
3000# I.W.

Figure C-2. Pinto Fuel Economy Vs Emission Standard

C.4. SUMMARY

In summary:

No additional quantitative data were given by Chrysler or General Motors for inclusion in this addendum. Chrysler indicated they do not favor conversion of the 360 CID V-8 engine to TCCS operation and mentioned that a feasibility study was conducted on the conversion of the 198 CID 6-cylinder engine.

Ford completed a 50,000 mile durability test on a PROCO 351 CID Montego. No problems were reported with the engine or fuel injection system. Development of a production prototype fuel injection system for the PROCO is being undertaken by American Bosch, under contract from Ford.

Major efforts are reported by Ford on the conversion of the 400 CID engine to PROCO operation. Tests ranging over NO_x emission levels from about 1.5 to 2.0 gm/mi have shown the catalyst equipped PROCO fuel economy to be about 25 to 32 percent over that of conventional catalyst equipped engines.

In a fuel economy and emission level study, Ford indicated that the CVCC, PROCO, and conventional engines suffer in fuel economy as emission levels become more stringent.