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Technical Report

An Evaluation of Three-Way Control Single and Dual Bed Catalysts As Applied to Heavy-Duty Gasoline Engines

by

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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air, Noise and Radiation
U.S. Environmental Protection Agency

Table of Contents

I. Introduction

A test program to evaluate the applicability of three-way control (TWC) and dual-bed catalysts (TWC and Oxidation Catalysts) in combination with a closed-loop control stoichiometric (feedback) carburetor on a production 1978 IHC 404 CID heavy-duty gasoline engine was conducted at EPA's Office of Mobile Source Air Pollution control Laboratory (OMSAPC) Ann Arbor, Michigan. Testing was conducted according to the federal test procedure for the heavy-duty transient cycle.[1]

The test program consisted of forty-six cold-start tests, fifty-eight confirmatory hot-start tests run to insure accuracy and precision of the cold-start tests, and fourteen hot-start tests run to identify the effects of air/fuel ratio control points on NOx emissions. The effects of various combinations of catalysts, EGR, air/fuel ratio control points, carburetor response times and air pump capacity on emissions, fuel economy and engine power were examined.

This project and data developed through this project has been presented previously in an SAE paper jointly developed by EPA and Engelhard Industries. The paper was formally presented at the 1981 SAE international Congress and Exposition.[2]

This EPA Technical Report provides background for the SAE document. All individual test results are presented and an expanded review is done of the conduct of the test program and specific problem situations encountered in conducting the project. This report will only highlight results of this study. A more detailed analysis of results can be found in the SAE publication.

II. Discussion

A. Equipment

Tests were conducted by EPA with supportive expertise provided by Engelhard Industries, the supplier of all catalysts and oxygen sensors utilized in the test program. The feedback Carburetor and Logic Control Box were purchased by EPA from the Holley Carburetor Company.

The engine, an IHC 404 1978 production engine with a California calibration representative of 1979 technology, was loaned to EPA for testing purposes, through the cooperative efforts of the International Harvester Company. Technical specifications for equipment utilized in this program are described in Table 1.[2]

The Holley Model 2210 experimental feedback carburetor was a direct bolt on replacement of the original Model 2210 on the 1978 engine. A 10 Hz electric solenoid valve controlled both the idle

Table 1

Technical Specifications: TWC Catalyst Program

Engine: 1978 Production IHC 404 cubic inch V-8 heavy-duty truck engine

Three-Way Catalysts:	Two, 151-CID monolithic, 50 $grams/ft^3$ loading, Platinum-rhodium ratio of 5:1, (manufactured by Engelhard), Corning substrate of 300 $cells/in^2$.
Oxidation Catalysts:	Two, 113-CID monolithic, 50 $grams/ft^3$ loading, platinum-palladium ratio of 4:1, (manufactured by Engelhard), Corning substrate of 300 $cells/in^2$.
Feedback Carburetor:	Holley 2210 modified for experimental use by Holley Carburetor Co., Division of Colt Industries, for stoichiometric closed-loop control of idle and main-jets. Engelhard designed microswitch with throttle engagememt during the last approximate 9 degrees of throttle movement prior to wide open throttle. Microswitch activation provided a fixed 4.6 percent CO (A/F ratio = 12.9) enrichment (in place of the conventional power valve which provided upto 6.0 percent CO at wide open throttle on the 1978 production carburetor). Standard accelerator pump, choke and throttle deceleration positioner were retained.
Logic Box:	Holley Model 8 experimental-type designed and built with adjustable, - air/fuel ratio control point (350 mv to 800 mv) - response time (CRT) - AC gain (a gain parameter in the logic box) - wide open throttle (WOT) open-loop override - cold start open loop override*

* Provides an open-loop air/fuel ratio near stoichiometric from the carburetor jets so that the choke may provide enrichment.

Table 1 (cont'd)

Technical Specifications: TWC Catalyst Program

Exhaust Gas Oxygen Sensor:	Standard production Robert Bosch part No. 0258001001.
Air Pump:	Each pump delivers 7.21-8.30 CFM @ 1000 pump RPM and 1.6 inches Hg backpressure, (IHC no. 446746-C92, 461369-C91).
EGR System:	Standard 1978 production.
Air Mixers:	Located between the TWC and oxidation catalysts.

and main jet circuits. Choke calibration and idle speed were standard (1978). The idle mixture screws were adjusted to provide approximately 50 percent duty cycle on the solenoid valve in order to achieve maximum control flexibility.

A throttle actuated microswitch deactivated the closed-loop control near the wide open throttle (WOT) position providing enrichment to about a 12.9 air/fuel ratio (4.6 percent CO) as a compromise for maximum horsepower, engine durability, and overall emissions. At all throttle positions between idle and the near WOT position the closed-loop control system was intended to provide stoichiometric air/fuel ratio conditions so that the TWC catalysts could function properly. It should be noted that when the microswitch was activated near WOT, resulting in an air/fuel ratio of 12.9, the TWC single-bed catalyst provided little overall conversion of HC, CO or NOx. However, since air was added between the two beds in the TWC dual-bed catalyst system the second bed or oxidation catalyst removed a large fraction of the HC and CO emissions.

The engine utilized a deceleration throttle positioner which opened the trottle slightly during deceleration (whenever the RPM exceeded 1800 at high manifold vacuums) in order to reduce misfiring and excessively rich mixtures.

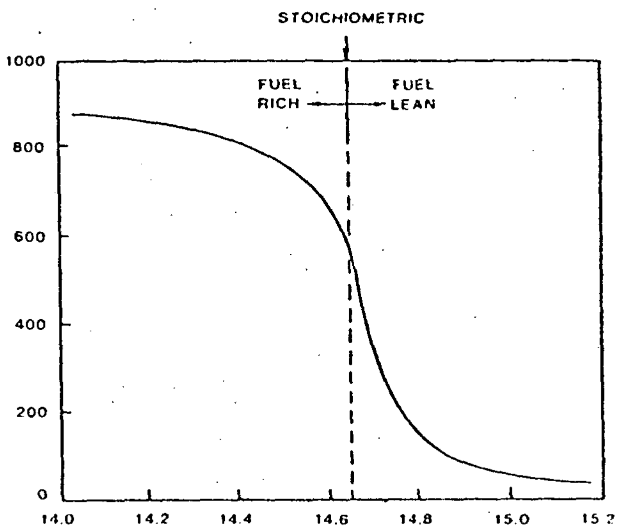
The Holley Model 8 logic box contained the adjustment features listed in Table 1. The millivolt control point established the operating point for the oxygen sensor output voltage and thereby determined the air/fuel ratio relative to the stoichiometric condition. This relationship is represented by Figure 1. The characteristic response time (CRT) determined the speed at which the air/fuel ratio cycled around the millivolt control point. A cold start override was controlled by a thermostatic switch in the engine coolant circuit which was set to activate the closed-loop system at 120°F.

The original 1978 production engine utilized air injection from one air pump into the exhaust ports of each cylinder bank. This air path was sealed for the conversion to the TWC catalyst system. The air pump was instead routed to the air mixer between the dual-beds as shown in Figure 2. The air pump was not used when the TWC single-bed catalysts were used alone. No attempt was made to divert air into exhaust ports upon cold start in order to reduce cold start HC and CO emissions (where the TWC catalyst initially acts as an oxidation catalyst). Doing so would surely decrease emissions, as demonstrated in the 1978 production version where the air, directed into the exhaust ports, had a very substantial effect on HC emissions.[2]

Tests were conducted in a standard EPA heavy-duty gasoline transient test cell. The cell utilized a double-ended dynamometer, water coolant system, electronic instrumentation an ambient

Figure 1.

Oxygen Sensor Output Voltage (millivolts)



Air/fuel ratio

Typical curve of oxygen sensor output voltage vs. air/fuel ratio

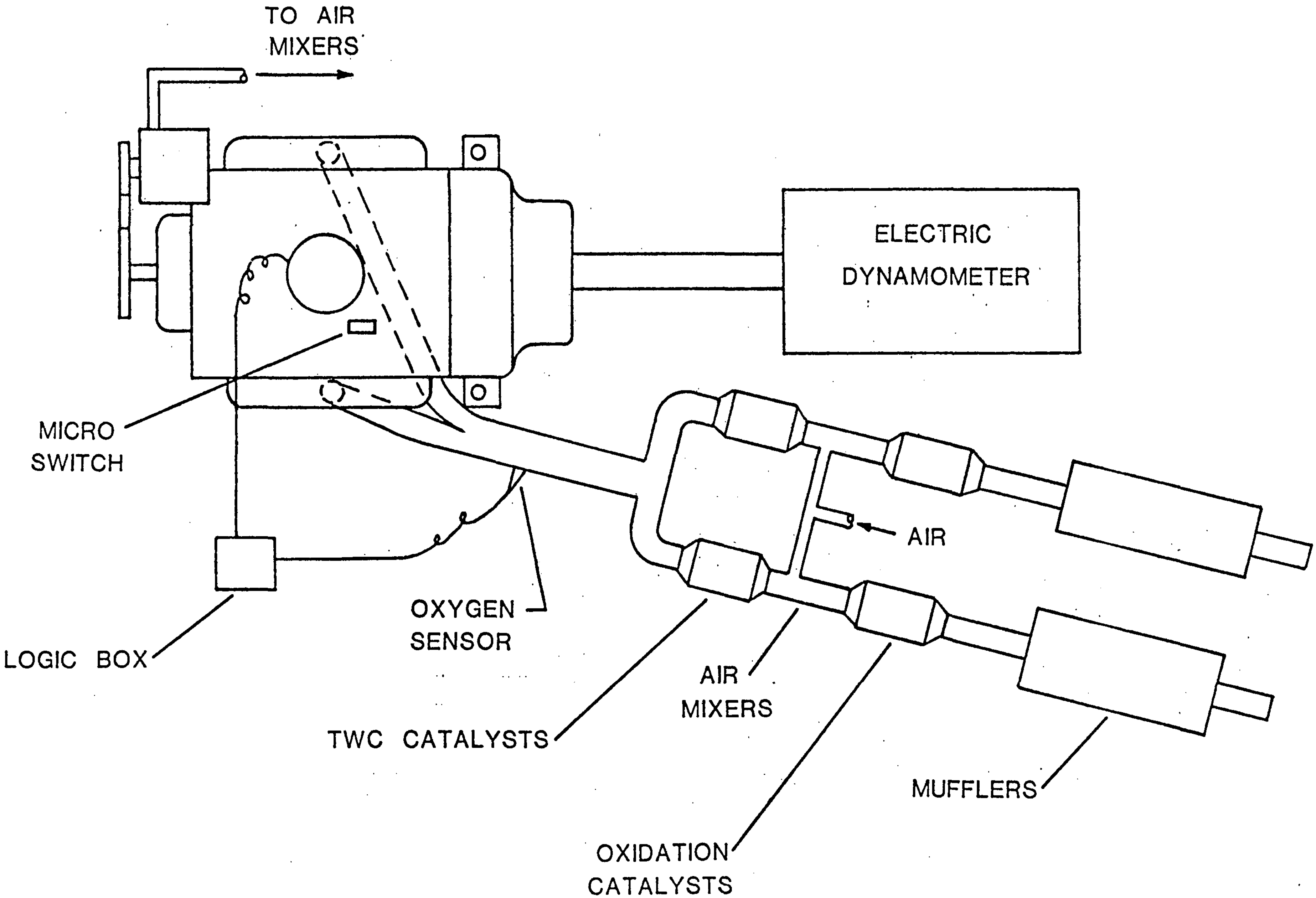


FIG. 2.- SCHEMATIC OF EXHAUST SYSTEM IN TEST CELL CONFIGURATION FOR DUAL BED CATALYST TESTING IN THIS PROGRAM

air handling/humidity conditioning system all of which serve as independent units for each test cell. Computer and CFV/CVS systems are shared between cells. A more complete description of test cell facilities can be found in EPA's 1972-1973 baseline engine report.[3]

Other equipment utilized in this test program was either standard 1978 production or fabricated to meet special requirements of the program.

B. Procedure

All testing activities conducted through this program follow OMSAPC standard procedures for heavy-duty gasoline transient testing. Specific procedures can be found in the Code of Federal Regulations, 40 CFR, Part 86, Subpart N.

Briefly, with the engine and emission control system set up for the configuration to be tested, one heavy-duty transient cold-start test and three confirmatory hot-start tests (individual hot-start portions of the cold-start transient tests) were run. A twenty minute soak was conducted between each test. As each sample was collected it was analyzed by EPA technicians on in-house analyzer A009. Raw emission figures were turned in for computer processing upon completion of the test sequence for each version. Processing was usually complete by the following day with the configuration not being changed until confirmatory emission results and satisfactory cycle performance were obtained. Upon analysis of emission results the subsequent configuration to be tested was determined and testing scheduled.

In the instances where major version changes, such as carburetor substitution occured, or where major engine repairs were conducted the engine was analyzed with a Sun 2001 Diagnostic Computer to insure proper tune prior to testing.

C. Engine History

This engine was initially utilized in an EPA program to determine engine emission sensitivity to the 1984 heavy-duty transient test cycle. Data developed through the sensitivity program was presented through SAE publication.[4] The engine was also utilized in a 1979 test program involving the application of various oxidation catalyst and air pump configurations. Data developed in this program was utilized in the development of the 1984 heavy-duty gaseous emission regulations.[1] The data was not published separately. Testing of the TWC/feedback carburetor system begain on January 17, 1980 at EPA's MVEL. Initial baseline and early catalyst testing was conducted in test cell D103W. Due to other priority testing requirements the engine was moved, at approximately mid-program (6-26-80), to test cell D104E where the test program was completed on December 19, 1980. The engine was removed from the test cell on December 23, 1980.

D. Problems

A number of minor problems inherent with test programs of this nature were encountered. These included thermocouple failure, air handling limitations and resulting high cell temperature problems, torque cell failures, computer downtime, analyzer downtime, logic control box missettings and various miscalibrations. These did not seriously disrupt the program. A number of more serious situations however did delay program completion.

During the soak portion of the cold-start test conducted on May 29, 1980 a fuel regulator failure (a test cell component) resulted in engine flooding and raw fuel collection in the cylinders. As the system was dismantled to dispell the fuel four of the eight spark plugs were broken. The test configuration was resumed with replacement of the fuel regulator and all eight spark plugs. The problem of engine modification from the baseline configuration (new spark plugs), and potential subsequent data variation was noted and testing resumed.

A NOx correlation testing program on another engine required the IHC engine to be move to a new test cell midway through testing (from test cell D103W to cell D104E). The NOx study was designed to determine the difference in bag versus continuous NOx measurement during transient heavy-duty gasoline engine emission tests. Cell D103W is physically located next to diesel cell D102 which is equipped with a continuous NOx measurement capability. Locating the NOx correlation engine in cell D103W allowed, with minor modification (creation of a passageway through the common wall separating the two cells), simultaneous normal bag sampling and continuous NOx sampling to occur.

The transfer of the TWC test engine to another testing cell was not felt to have been a significant problem since the same physical parameters or limits apply to all test cells and since each test must be compared to the cycle performance specifications. Any parameter exceeding its stated limits (temperature, humidity etc.) or not passing the cycle performance specifications is susceptible to being voided regardless of where the test was run. It of course, would have been of preference not to have moved the engine.

In mid-July a knock was detected in the engine that corresponded to a noticable emission increase. An engine check discovered a misgapped spark plug. The plug was regapped and testing continued with emissions returning to near expected levels. However, by mid-August the knock had intensified and engine analysis indicated a broken piston. Probably the forementioned misgapped plug was closed by a piece of the broken piston that had since disintegrated with continued engine use. It was further determined that arching was occuring from several plug wire boots and that the oxygen sensor had lost some of its low temperature sensitivity through damage from either the piston failure or spark plug misfiring. The piston, oxygen sensor (aged at Engelhard), plug wires and plug boots were replaced.

In late September while running consecutive hot-start tests to determine NOx emission levels at various millivolt set points (determinant of air/fuel ratio) and ignition failure resulted in a complete burnout of the TWC catalysts. The ignition failure was caused by a short (insulation melt) in the primary lead to the coil. EPA technician responsiveness resulted in damage being confined to the TWC catalysts and oxygen sensor.

To insure that the oxidation catalysts were not damaged the complete dual-bed system and oxygen sensor were replaced. The replacement catalysts, supplied by Engelhard, were loaded identically to those destroyed in the burn out. The catalysts were aged by running a seris of cold-start tests with forced cool-downs over a two day period. A total of approximately eight break-in hours of testing were run.

All tests determined to have been affected by any of the forementioned problems were voided and those versions rerun.

III. Results

A description of configurations tested as well as emission and fuel economy figures can be found for cold-start tests in Table 2.* The most favorable emission results were obtained in the dual-bed configuration (Figure 2) with EGR (version 45c). The HC level of 0.68 g/Bhp-hr, CO level of 3.60 g/Bhp-hr and NOx level of 0.74 g/Bhp-hr are well below the 1984 heavy-duty emission standards of 1.3 g/Bhp-hr for HC, 15.5 g/Bhp-hr for CO and the statutory NOx standard of 1.7 g/Bhp-hr. The NOx standard is not part of the 1984 regulation but is being developed as a separate rulemaking. These test levels represent conversion efficiencies of approximately 73 percent for HC, 91 percent for CO and 86 percent for NOx as compared to the stock single exhaust configuration (version 00). Emission values for version 13 (version 45 without EGR), version 21 (version 45 with a fast carburetor response) and version 23 (version 45 with a slow carburetor response) also meet these standards.

The need to test both single and dual-bed configurations was required since before testing it could not be determined if the dual-bed configuration would be required to meet the HC and CO emission standards.

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* A considerable number of confirmatory hot start tests were run to verify the cold start data but the test results were not used further in the anlaysis. This hot start data is given in Appendix A.

Table 2

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	Emissions CO (g/BHP-hr)	Emissions NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
00	1978 production engine, 1978 EGR, air pump with air to exhaust ports, standard carburetor, conventional single exhaust.	2.55 2.48	40.85 42.13	6.00 4.66	0.671* 0.674*
09	1978 production engine, 1978 EGR, air pump with air to exhaust ports, standard carburetor, fabricated single exhaust split into dual exhausts, straight pipes representing dummy catalysts, no air mixers.	2.65 2.65	54.11 50.65	5.56 5.07	0.663* 0.689*
10	1978 production engine, 1978 EGR, air pump with air to exhaust ports, standard carburetor, fabricated exhaust, single exhaust split into dual exhausts, two dummy TWC catalysts, straight pipes representing dummy oxidation catalysts, no air mixers.	2.31 3.05 3.01	65.25 72.82 74.23	4.68 4.54 4.42	0.732 0.701* 0.713*
11	1978 production engine, no EGR, one air pump, air to air mixers between the two dummy TWC and two dummy oxidation catalysts, feedback carburetor, open-loop at wide open throttle and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	3.58 4.63 4.57 4.49	50.96 58.00 57.70 48.93	7.81 8.41 8.23 7.94	0.692 0.655** 0.642** 0.648**

* Test conducted after installation of new piston and catalysts.

** Test conducted after installation of new piston.

Table 2 (cont'd)

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
12	Version 11, except the system is completely closed-loop.	4.24	51.05	7.85	0.685
13	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.84 0.49 0.97 0.77	5.74 2.96 3.11 5.38	1.04 0.94 1.78 1.62	0.686 0.708 0.673 0.724
15	1978 production engine, no EGR, no air pump, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricated exhaust.	0.76	21.35	0.70	0.682
16	Version 15 except the system is completely closed-loop.	0.89	18.53	0.71	0.693
17	Version 15 with the carburetor response in the slow position.	1.25	20.12	1.67	0.686
18	Version 15 except the system is completely closed-loop with the carburetor response in the slow position.	1.41	17.08	1.37	0.672
19	1978 production engine, no EGR, no air pump, two TWC catalysts, no oxidation catalysts, feed-	1.27 1.46	25.27 22.15	1.41 1.64	0.712 0.698

Table 2 (cont'd)

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
	back carburetor, open-loop at WoT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.				
20	Version 19 except the system is completely closed-loop.	1.30	17.07	1.53	0.699
21	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricted exhaust.	0.71	4.11	2.07	0.698
23	Version 21 with the carburetor response time in the slow position.	0.70	3.19	1.55	0.714
24	Version 21 except the system is completely closed-loop with the carburetor response in the slow position.	0.79	3.05	2.05	0.736
26	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, completely closed-loop, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.87	3.22	1.93	0.738

Table 2 (cont'd)

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
27	1978 production engine, no EGR, two air pumps, air to air mixers between the two TWC catalysts and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricated exhaust.	0.90	4.00	1.90	0.728
35	1978 production engine, EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor resonse, 350 millivolt control point, fabricated exhaust.	0.81	3.59	3.11	0.737
37	1978 production engine, EGR, no pump, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 350 millivolt control point, fabricated exhaust.	0.94 0.75	9.72 17.98	3.01 3.26	0.704 0.741*
41	Version 35 without EGR.	0.62	3.28	3.89	0.691
43	Version 19 at the 350 millivolt control point.	1.20 0.78	20.47 28.79	4.25 3.69	0.643** 0.711*

* Test conducted after installation of new piston and catalysts.

** Test conducted after installation of new piston.

Table 2 (cont'd)

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
45a.	1978 production engine, EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.84 0.75 0.43 0.53	2.95 3.39 2.73 3.75	1.13 1.94 1.42 1.44	0.713 0.649** 0.714* 0.750*
45c.	Version 45 at the 710 millivolt control point.	0.68	3.60	0.74	0.704*
45f.	Version 45 at the 630 millivolt control point.	0.56	3.29	0.71	0.737*
45m.	Version 45 at the 630 millivolt control point.	0.65	3.33	3.78	0.748*
49	1978 production engine, EGR, one air pump, air to air mixers between the two dummy TWC and two dummy oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust, (version 11 with EGR).	4.35 5.29	51.98 46.06	5.36 4.69	0.669 0.688*
53	Version 49 at the 350 millivolt control point.	4.47	41.37	5.89	0.682

* Test conducted after installation of new piston and catalysts.

** Test conducted after installation of new piston.

Table 2 (cont'd)

IHC 404 Cold Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
55	Version 49 without EGR at the 350 millivolt control point.	4.44 4.87	47.87 39.21	8.33 7.74	0.760 0.659*

* Test conducted after installation of new piston and catalysts.

In the single bed catalyst configurations (TWC catalysts only) version 15-20, 37 and 43 approximate the HC and NOx standards but fall short of CO standards by some 25 percent. For this reason further discussion will be confined to dual-bed system configurations. The reader is referred to the SAE document as referenced for further analysis of single bed configurations.[2]

The effect of EGR on NOx emissions can be seen in the dualbed configurations at the 350 millivolt (MV) control point with EGR (version 35) as compared to the similar configuration without EGR (version 41.) Here an approximate 20 percent decrease in NOx emissions and a corresponding 6 percent decrease in fuel economy can be seen. The NOx levels however, 3.11 g/Bhp-hr for version 35 and 3.89 g/Bhp-hr for version 41 both exceed the proposed NOx standard.

Configurations at the 530 millivolt control point that meet the proposed standard indicated a 9 percent increase in NOx emissions with actual NOx levels of 1.48 g/Bhp-hr with EGR (version 45, 4 test average) and 1.35 g/Bhp-hr without EGR (version 13, 4 test average). These averages are misleading however since some of the version 45 tests were conducted after installation of a new piston and catalysts (discussed in section D). The only version 45 test conducted before piston and catalysts change yielded a NOx value of 1.13 g/Bhp-hr or a 17 percent reduction in NOx emissions. In general, the application of EGR resulted in significant NOx emissions reduction.

The air/fuel ratio (millivolt control point) effect on emissions is principally related to NOx. The stoichiometric point is located at approximately the 530 MV control point with rich air/fuel ratios at higher MV control points and lean air/fuel ratios at lower MV control points. Tests indicate a MV control point independence in dual-bed configurations with regard to HC and CO control. The NOx relationship is demonstrated by the series of hot-start tests (version 45) run at various MV control points (Table 3). Here, a requirement for richer than stoichiometric air/fuel ratios to meet the proposed NOx standard is indicated. This engine would have to run at approximately the 550 MV control point to meet the NOx standard of 1.7 g/Bhp-hr (air/fuel ration about 0.2 rich of stoichiometric.)

The critical response time (CRT) determines the speed at which the air/fuel ratio cycles around the MV control point from full rich to full lean. A fast CRT of 0.2 seconds, a medium CRT of 2.8 seconds and a slow CRT of 5.6 seconds were evaluated. The slow response time, according to closed-loop theory, produces the tightest control under steady state conditions but not necessarily under transient conditions. This is represented by the following test data. Versions 21 and 23 represent individual cold-start tests while version 13 is the simple mean of four cold-start tests.

Table 3

IHC 404 Hot Start Tests*

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
45a.	1978 production engine, EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WoT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.30 0.30	0.61 0.81	2.02 1.97	0.693 0.665
45b.	Version 45 at the 740 millivolt control point.	0.43	0.89	0.93	0.689
45c.	Version 45 at the 710 millivolt control point.	0.42	0.94	0.92	0.689
45d.	Version 45 at the 685 millivolt control point.	0.40	1.07	1.18	0.687
45e.	Version 45 at the 655 millivolt control point.	0.36	0.84	1.00	0.658
45f.	Version 45 at the 630 millivolt control point.	0.33	0.74	1.21	0.678
45g.	Version 45 at the 605 millivolt control point.	0.39	0.82	1.63	0.608
45h.	Version 45 at the 575 millivolt control point.	0.31	0.64	1.54	0.675
45i.	Version 45 at the 550 millivolt control point.	0.38	0.69	1.88	0.684
45j.	Version 45 at the 495 millivolt control point.	0.38	1.02	2.28	0.647
45k.	Version 45 at the 440 millivolt control point.	0.32	0.77	3.01	0.653

* All tests conducted after installation of new piston.

Table 3 (cont'd)

IHC 404 Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
45l.	Version 45 at the 385 millivolt control point.	0.27	0.56	3.45	0.667
45m.	Version 45 at the 350 millivolt control point.	0.24	0.55	3.85	0.633

Version	CRT (sec.)	Emission g/Bhp-hr HC	CO	NOx	lb. fuel/Bhp-hr BSFC
23	5.6	0.70	3.19	1.55	0.714
13	2.8	0.77	4.30	1.29	0.698
21	0.2	0.71	4.11	2.07	0.698

Upon analysis of individual cold-start tests for version 13 (Table 2) and the Los Angeles Freeway (LAF) portion of the transient test as presented in the referenced SAE document it was determined that the best balance of emissions and fuel economy was obtained with the 2.8 second CRT. This is further exemplified by the near normal oxygen sensor voltage trace as indicated in the same SAE document.[2]

The effect of open-loop at WOT on emissions is presented by the comparisn of two dual-bed, 530 MV control point configurations both without EGR; the open-loop at WOT version 13 and the same configuration in the completely closed-loop mode version 26. Version 13 figures represent the simple mean of four cold-start tests.

Version	WOT-Mode	Emission g/Bhp-hr HC	CO	NOx	lb. fuel/Bhp-hr BSFC
13	open	0.77	4.30	1.29	0.690
26	closed	0.87	3.22	1.93	0.738

Although open-loop enrichment may result in higher emissions (CO) it was found necessary to run open-loop at WOT in order to maintain maximum engine horsepower levels required by heavy-duty vehicles.

Maximum horsepower levels were determined from WOT map tests run to establish speed-load parameters for the computer driven transient tests. Results indicate an average horsepower value of 167 for the standard 1978 production engine (version 10). The average in the dual-bed, open-loop at WOT configuration (version 45) is 162 horsepower, representing a 3 percent loss in maximum horsepower. The corresponding completely closed-loop configuration (version 46) resulted in an average horsepower of 148 an 11 percent drop from standard 1978 production. Due to this horsepower loss subsequent testing was concentrated in the open-loop at WOT mode.[2] Actual emission testing was not conducted on version 46; mapping was done for horsepower determination only.

The effect of air pump capacity is demonstrated by a comparison of a dual-bed, 530 MV control point, fast CRT configuration without EGR and one air pump (version 21) and the same configuration with two air pumps (version 27). Full air from both air pumps was directed to the air mixers. Indicated figures represent one cold-start test for each version.

Version	Airpump No.	Emission g/Bhp-hr HC	CO	NOx	lb. fuel/Bhp-hr BSFC
21	1	0.71	4.11	2.07	0.698
27	2	0.90	4.00	1.90	0.728

Since a reduction in fuel economy was shown with two air pumps and further since several other configurations produced CO emissions under the 4 g/Bhp-hr level achieved with two air pumps, all subsequent testing was conducted in the single air pump mode.

In analyzing the fuel consumption figures, given in pounds of fuel/Bhp-hr or Brake Specific Fuel Consumption (BSFC), considerable variation for any given version is indicated. Thus it is difficult to determine fuel economy trends for the various versions. Table 4 indicates BSFC for baseline configurations and the dual-bed closed-loop system with and without EGR.[2]

Although slight fuel economy differences can be found between individual versions, no significant fuel consumption differences can be identified between baseline and closed-loop configurations with and without EGR, between single vs. dual-bed catalyst modes or between open vs. closed-loop at WOT modes.

Due to the experimental nature of this program several test runs were accepted as valid that exceeded various cycle performance specifications. High engine idle rates that occur during the early portions of the transient cold-start test were considered the primary cause of this situation. This problem could not be corrected by either software or hardware adjustments due to time and equipment constraints. Since the problem was limited to the first sample bag overall emission effects were not considered significant enough to void marginal tests.

A problem observed with the preferred feedback system was intermittent engine hesitation on strong accelerations. This occurred even with a warm engine and intensified with the addition of EGR. The problem, which occured around the stoichiometric air/fuel ratio, is generally controlled with the rich mixtures typical of current heavy-duty engines. It is theorized that the problem could be best corrected through manufacturing design changes.

The SAE publication should be referred to for a more complete discussion of results of the test project.[2]

IV. Conclusions

The results of this test program indicated that at low mileage a TWC dual-bed catalyst system with a closed-loop stoichiometric carburetor can yield emissions substantially below the 1984 HC and CO standards and the statutory NOx standard for heavy-duty gasoline engines.

Table 4

Heavy-Duty Transient Test
Fuel Consumption 2/

Configuration		Fuel Consumption (Lbs. Fuel/BHP-hr)
1978 Production Engine (See Table II)		0.671 1 run
Version 00		0.674 1 run
Version 9		0.663 1 run
		0.689 1 run
Version 10		0.732 1 run
		0.713 1 run
		0.701 1 run
	Avg. of above	0.692 (7 runs)
Same Engine with Closed-Loop System		0.705 Avg. 17 runs (of various versions)
With EGR		St'd. Dev. = 0.032
Same Engine with Closed-Loop System		0.697 Avg. 16 runs (of various versions)
Without EGR		St'd Dev. = 0.032

Engine-out HC and CO emissions were sufficiently high however, that the TWC single-bed catalyst alone could not be utilized. Dual-bed catalysts were required and were able to produce high conversion efficiencies. A number of key improvements to the air/fuel preparation and distribution as well as improved quality of combustion in the engine are required to alleviate the problem of hesitation upon acceleration. These improvements are considered feasible since they have been accomplished with light-duty passenger car engines.

Improved air/fuel distribution is also very important in order to achieve maximum engine horsepower at the leanest possible (but still net rich) air/fuel ratios. Maximum horsepower with the closed-loop carburetor and catalysts was approximately 3 percent below the maximum horsepower of the 1978 production engine. With implementation of the above improvements this loss should approach zero.

Brake specific fuel consumption was essentially the same (within data scatter) as obtained with the 1978 production engine.

It would appear from this test program, even with systems that were not optimized, that TWC closed-loop systems could provide efficient emission control of heavy-duty gasoline engines as well as the same overall advantages as currently achieved with similar systems on light-duty passenger car gasoline engines. Design improvements to the heavy-duty truck engine would appear justified as a result of the feasibility study.[2]

References

1. "Gaseous Emission Regulations for 1984 and Later Model Year Heavy-Duty Engines," Federal Register, Vol. 45, No. 14, Monday, January 21, 1980.

2. Hansel, Dr. James G.; Cox, Timothy; Nugent, Thomas, "The Application of a Three-Way Conversion Catalyst System to a Heavy-Duty Gasoline Engine," SAE Paper 810086 (1981).

3. Cox, Timothy; Diatchun, Zachary; Nugent, Thomas; Passavant, Glenn; Ragsdale, Larry, "1972-73 Heavy-Duty Engine Baseline Program and NOx Emission Standard Development," EPA Technical Report EPA-AA-SDSB-80-01, March 1981.

4. Cox, Timothy P., "Heavy-Duty Gasoline Engine Emission Sensitivity to Variations in the 1984 Federal Test Cycle," SAE Paper 801370 (1980).

Appendix A

IHC 404 Confirmatory Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
11	1978 production engine, no EGR, one air pump, air to air mixers between the two dummy TWC and two dummy oxidation catalysts, feedback carburetor, open-loop at wide open throttle and under 120°F, medium carburetor response, 530 millivolt control point, fabribated exhaust.	3.28 3.18 3.32	47.70 46.37 48.81	8.18 7.66 8.53	0.707 0.689 0.698
12	Version 11, except the system is completely closed-loop.	3.38 3.43 3.53	46.10 44.11 43.94	8.41 7.98 8.47	0.698 0.690 0.704
13	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburator response, 530 millivolt control point, fabricated exhaust.	0.21 0.23 0.33 0.41 0.51 0.47	0.96 0.84 1.14 2.23 2.32 0.85	0.93 0.90 1.67 1.45 1.55 1.74	0.679 0.692 0.709 0.717 0.724 0.664
15	1978 production engine, no EGR, no air pump, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricated exhaust.	0.51 6.45 0.55	19.59 16.86 23.64	0.76 0.75 0.67	0.700 0.765 0.707
16	Version 15 except the system is completely closed-loop.	0.63 0.49 0.58	16.33 16.20 16.52	0.80 0.80 0.82	0.706 0.686 0.712

Appendix A (cont'd)

IHC 404 Confirmatory Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
17	Version 15 with the carburetor response in the slow position.	0.88	17.36	1.77	0.686
		0.84	18.66	1.76	0.699
		0.85	18.93	1.65	0.683
19	1978 production engine, no EGR, no air pump, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.86	16.27	1.51	0.693
		0.90	20.65	1.17	0.686
		0.84	16.50	1.44	0.676
		0.78	20.80	1.41	0.696
		0.85	25.52	1.12	0.740
		0.75	19.25	1.59	0.700
20	Version 19 except the system is completely closed-loop.	1.04	15.09	1.51	0.691
		0.76	14.70	1.36	0.695
		0.86	15.16	1.37	0.697
21	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricated exhaust.	0.45	2.22	2.11	0.698
		0.37	1.92	2.02	0.695
23	Version 21 with the carburetor response time in the slow position.	0.34	0.85	2.17	0.710
		0.40	0.96	2.14	0.712
24	Version 21 except the system is completely closed-loop with the carburetor response in the slow position.	0.71	0.57	1.91	0.735
		0.39	0.72	1.95	0.729
		0.40	0.73	1.97	0.726

Appendix A (cont'd)

IHC 404 Confirmatory Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
26	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, completely closed-loop, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.45 0.42 0.42	0.75 0.79 0.87	1.71 1.83 1.76	0.727 0.727 0.722
27	1978 production engine, no EGR, two air pumps, air to air mixers between the two TWC catalysts and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, fast carburetor response, 530 millivolt control point, fabricated exhaust.	0.64 0.58	2.10 2.10	2.04 2.12	0.726 0.725
35	1978 production engine, EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 350 millivolt control point, fabricated exhaust.	0.28 0.33	0.98 1.40	3.08 3.14	0.726 0.717
37	1978 production engine, EGR, no air pumps, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 350 millivolt control point, fabricated exhaust.	0.42 0.43	5.48 7.75	3.07 3.14	0.682 0.688

Appendix A (cont'd)

IHC 404 Confirmatory Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
41	1978 production engine, no EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 350 millivolt control point, fabricated exhaust.	0.47 0.50	1.23 1.17	3.93 3.89	0.689 0.688
43	1978 production engine, no EGR, no air pump, two TWC catalysts, no oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.92 1.02	19.46 23.82	3.03 2.63	0.649** 0.636**
45a.	1978 production engine, EGR, one air pump, air to air mixers between the two TWC and two oxidation catalysts, feedback carburetor, open-loop at WOT and under 120°F, medium carburetor response, 530 millivolt control point, fabricated exhaust.	0.38 0.41	1.39 0.85	0.99 1.13	0.697 0.705
49	1978 production engine, EGR, one air pump, air to air mixers between the two dummy TWC and two dummy oxidation	3.70 3.51	48.65 48.31	5.51 5.45	0.722 0.642

** Test conducted after installation of new piston.

Appendix A (cont'd)

IHC 404 Confirmatory Hot Start Tests

Version Number	Engine Configuration	Emissions HC (g/BHP-hr)	CO (g/BHP-hr)	NOx (g/BHP-hr)	BSFC (lb. fuel/BHP-hr)
49	catalysts, feedback carburetor, open-loop at WOT and under 120°F medium carburetor response, 530 millivolt control point, fabricated exhaust, (version 11 with EGR).				
53	Version 49 at the 350 millivolt control point.	3.54 3.42	33.16 33.89	5.85 5.95	0.672 0.662
55	Version 49 without EGR at the 350 millivolt control point.	3.72 3.71	38.78 39.34	8.68 8.74	0.645 0.649