Emissions and Fuel Economy of a Vehicle Equipped with the Eaton Valve Selector

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Background

The Environmental Protection Agency receives information about many systems which appear to offer potential for emission reduction or fuel economy improvement compared to conventional engines and vehicles. EPA's Emission Control Technology Division is interested in evaluating all such systems, because of the obvious benefits to the Nation from the identification of systems that can reduce emissions, improve fuel economy, or both. EPA invites developers of such systems to provide complete technical data on the system's principle of operation, together with available test data on the system. In those cases for which review by EPA technical staff suggests that the data available shows promise, confirmatory tests are run at the EPA Motor Vehicle Emission Laboratory at Ann Arbor, Michigan. The results of all such test projects are set forth in a series of Technology Assessment and Evaluation Reports, of which this report is one.

The deactivation of one or more engine cylinders is a method that has been proposed as offering potential for vehicle fuel economy improvements. At low power outputs the throttle is nearly closed. This introduces a "throttling loss", which is the energy that the engine must expend to draw the fuel-air mixture through the carburetor throttle opening. By operating an engine on a reduced number of cylinders, and operating these cylinders at higher power levels, the throttling losses are appreciably reduced.

A cylinder deactivation system is being considered for use in several 1981 Cadillac models. Other cylinder deactivation systems are currently under development in the United States. Since EPA had not tested a cylinder deactivation system designed for current vehicles, EPA contacted the Eaton Corporation and requested the loan of a vehicle with the Eaton Valve Selector System installed. Eaton made available a system installed in a development vehicle.

EPA is also testing other cylinder deactivation systems. A similar Eaton system was tested in a prototype vehicle provided by Cadillac Motor Division of General Motors and the results of those tests are reported in TEB report #80-14, "Emissions and Fuel Economy of the Cadillac Modulated Displacement System." An aftermarket retrofit system was tested in several 1979 V-8 vehicles and the results of those tests are reported in TEB report #80-18, "Emissions and Fuel Economy of the Automotive Cylinder Deactivation System (ACDS)." Six years ago, EPA tested a vehicle with 4 cylinders deactivated. The results of that test are given in TAEB report #75-11, "Evaluation of the MSU 4-Cylinder Conversion Technique for V-8 Engines."

The conclusions drawn from the EPA evaluation tests are necessarily of limited applicability. A complete evaluation of the effectiveness of an emission control system in achieving performance improvements on the many different types of vehicles that are in actual use requires a much larger sample of test vehicles than is economically feasible in the evaluation test projects conducted by EPA. The conclusions from the EPA evaluation test can be considered to be quantitatively valid only for the specific test cars used; however, it is reasonable to extrapolate the results from the EPA test to other types of vehicles in a directional manner, i.e. to suggest that similar results are likely to be achieved on other types of vehicles.

Summary of Findings

The vehicle provided by Eaton was a development vehicle. This vehicle was put together to demonstrate mechanical features of the Eaton Valve Selector System. Eaton informed EPA before testing that very little effort had been devoted to optimizing this vehicle for either emissions or fuel economy. The generally negative test results should be viewed with this caveat.

In the 8 cylinder mode, the vehicle's FTP emissions were: HC 0.58 gm/mi, CO 4.23 gm/mi; and NOx 1.99 gm/mi. FTP fuel economy was 14.6 mpg. These emission levels exceed the 1981 emission standards of HC 0.41 gm/mi, CO 3.4 gm/mi, and NOx 1.0 gm/mi.

In the 8 cylinder mode, the vehicle's HFET emissions were: HC 0.09 gm/mi, CO 0.11 gm/mi, and NOx 2.86 gm/mi. Fuel economy was 21.0 mpg.

In the automatic mode, when compared to the 8 cylinder mode, the vehicle's FTP emissions were: HC unchanged, CO increased 22%, and NOx decreased 4%. Fuel economy increased 5%. For the HFET: HC increased 107%, CO was 16 times higher, and NOx decreased 20%. HFET fuel economy increased 6%.

In the 6 cylinder mode, when compared to the 8 cylinder mode, the vehicle's FTP emissions were: HC up 130%, CO up 200%, NOx down 10%. Fuel economy increased 3%. The vehicle's HFET emissions were: HC up 190%, CO 30 times higher, and NOx decreased 19%. HFET fuel economy increased 5%.

In the 4 cylinder mode for both the FTP and HFET, HC and CO emission increases were even greater than those that occurred for the 6 cylinder or automatic modes of operation. Compared to the 8 cylinder mode, NOx decreased 10% for the FTP and 37% for the HFET. Fuel economy decreased 10% for the FTP and 3% for the HFET.

Vehicle driveability was good when operating on 8 cylinders. Driveability ranged from poor to marginal in the 4 cylinder, 6 cylinder, and automatic modes.

Description

The Eaton Valve Selector is being developed by the Eaton Corporation's Engine Components Division and the Engineering and Research Center. The concept is to improve vehicle fuel economy by selectively shutting off engine cylinders during periods of light engine load.

The principle is explained by Eaton as follows:

"The conventional spark-ignition engine has its power output controlled by a throttle. At low power output, the throttle is nearly closed in order to limit the amount of fuel-air mixture drawn into the cylinder. However, this small throttle opening introduces a "throttling loss", which is the energy the engine must expend to draw fuel-air through the throttle opening. Because of this, an engine runs most efficiently when unthrottled.

"The unthrottled state can be approached by operating only the number of cylinders needed to give the required power, and operating them at high power-per-cylinder levels. In doing so, the throttle is at a wider opening and there are fewer cylinders drawing air through that opening. This reduces the vacuum in the intake manifold, thereby reducing the throttling loss per cylinder.

"Also, there are fewer cylinders experiencing throttling loss. This strategy is accomplished through use of the Eaton Valve Selector. At low power levels, valve selectors deactivate the valves on one or more of the cylinders; for full power output, they restore valve operation.

"In each of the deactivated cylinders, the piston continues to reciprocate, but the intake and exhaust valves are closed. Since the gases in the cylinders are merely compressed and expanded by the piston, no energy is consumed as pumping losses, although normal frictional losses are still present. Furthermore, by closing both valves the cylinders are not cooled by the flow of air and, consequently, there is no hesitation in firing once the valves are reactivated."*

To deactivate the cylinders, Eaton has developed a mechanical system to unload the intake and exhaust valve rocker arm fulcrum points. The system is shown in Figures 1 and 2 below:

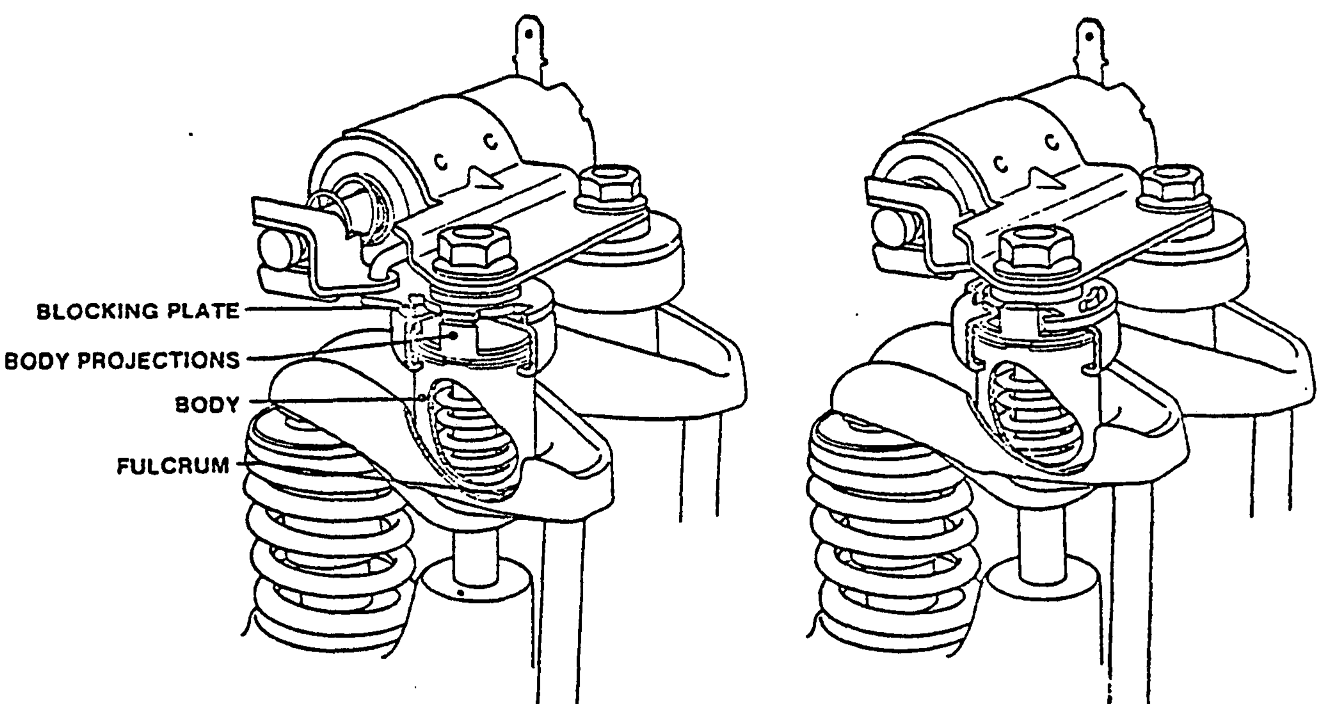

Figure 1 Valve Enabled **Figure 2** Valve Deactivated

EATON VALVE SELECTOR MECHANICAL DETAILS

* Eaton Corporation product literature "Eaton Valve Selector- A Unique System for Conserving Energy in Automotive Engines."

"On the conventional overhead valve, pushrod engine configuration, the selector is mounted on the intake and exhaust valve rocker arm studs, above the rocker arm fulcrums. In the enabled mode, as shown in Figure 1, the selector body is restrained from moving upward by contact between projections on body and the blocking plate above it. The fulcrum is held down by the body and the valves operate normally.

"When the selector is energized (to deactivate the valves) as shown in Figure 2, the blocking plate is rotated by the solenoid to align windows in the blocking plate with the projections on the body. As the rocker arm is lifted by the pushrod, the fulcrum rides up the stud and lifts the body, since the body is no longer restrained by the blocking plate. The rocker arm pivots about the tip of the valve and the valve remains closed.

"The body is spring loaded downward, but is internally constrained to a maximum downward position. This internal spring provides correct valve gear action and ensures normal hydraulic lifter function when the valve gear is in the deactivated mode.

"The solenoid force is less than that required to overcome blocking plate/body friction when the valve is lifted. This prevents deactivation of the valve while it is lifted, which would cause the valve to seat abruptly.

"The valve selector has also been adapted to rocker shaft engines and overhead cam/finger-follower engines.*

The four standard cylinders without the valve selector have zero valve lash due to the action of the hydraulic lifters. The four cylinders with the deactivators must have a few thousandths of an inch (tenth of a millimeter) hydraulic lifter clearance to permit the mechanism to function. To compensate for these differences, the camshaft lift profile is modified for the four cylinders with deactivators. This gives the valve selector cylinders a camshaft lift profile that is equivalent to the standard camshaft lift.

"In practice the valve selector must be integrated into the total vehicle/engine package. Typically engine rpm, water temperature, throttle angle, manifold vacuum, and transmission gearing are monitored by a set of sensors. This information is fed into an electronic control unit. Based on this information and programmed instructions, the number of operating cylinders is determined and appropriate signals are sent to the valve selectors.

"Eaton claims that the following are typical fuel economy improvements that should be attainable in various operating modes:

Idle	40%
Deceleration	40%
Low-Speed Cruise	25%
Highway Cruise	15%
Light Acceleration	10% *

* Eaton Corporation product literature "Eaton Valve Selector- A Unique System for Conserving Energy in Automotive Engines."

Test Vehicle Description

The test vehicle was a 1979 Cadillac DeVille that had a 6.0 liter Cadillac engine installed to replace the stock 7.0 liter engine. The Eaton Valve Selector was installed on the vehicle. This included the electro-mechanical valve selector, electronic control unit, engine sensors, and the modified camshaft. The engine sensors which interface with the electronic control unit included rpm, water temperature, throttle valve angle, manifold vacuum, and transmission gear. The carburetor and control units were modified 1980 prototype units. Additional vehicle details are given in the appendix.

Since this was a development vehicle, Eaton had installed a set of valve selector operating mode control switches. By selecting the appropriate switch, the engine could be made to continuously operate on either 4, 6, or 8 cylinders. A fourth operating mode, automatic, allowed the valve selector control unit logic to automatically select 4, 6, or 8 cylinder operation.

In the automatic mode, the vehicle was programmed to operate on 8 cylinders at idle, speeds below 20 mph, and at heavy load. The vehicle was programmed to operate on 4 cylinders while cruising at steady speeds under 50 mph, while decelerating, and during light accelerations. The vehicle was programmed to operate on 6 cylinders while cruising at higher steady speeds and during light to moderate accelerations.

Test Procedures

Exhaust emission tests were conducted according to the 1977 Federal Test Procedure (FTP) described in the Federal Register of June 28, 1977, and the EPA Highway Fuel Economy Test (HFET) described in the Federal Register of September 10, 1976. The vehicle was not tested for evaporative emissions.

Additional tests were conducted as an evaluation tool. The tests consisted of hot start LA-4 cycles, steady state, and acceleration. The LA-4 driving cycle is the basic FTP driving cycle. The results of these hot start LA-4 tests are somewhat similar to bags 2 and 3 of the FTP.

Discussion of Results

The objective of this test program was to evaluate the potential fuel economy benefits of cylinder deactivation and to determine the effects on vehicle emissions. The test results are summarized in the tables and figures in the following paragraphs. Additional tabulations of the data are given in the appendix.

1. Federal Test Procedure

Overall, the operation of the vehicle on a reduced number of cylinders caused HC and CO emissions to increase. NOx emissions tended to decrease slightly. Fuel economy changes ranged from a 10% decrease to a 5% increase. These results are tabulated in Table 1.

TABLE 1
Eaton Valve Selector Equipped Demonstration Vehicle
FTP Mass Emissions
grams per mile

Test No.	HC	CO	CO_2	NOx	MPG
8 Cylinder (Baseline)					
80-1683	.66	4.71	604	2.01	14.5
80-1673	.49	3.74	596	1.97	14.7
4 Cylinder					
80-1661	3.07	78.62	539	1.80	13.2
6 Cylinder					
80-1672	1.34	12.49	563	1.75	15.1
Automatic Selection					
80-1666	.60	5.20	566	1.89	15.4
80-1675	.58	5.13	573	1.92	15.2

In the 8 cylinder mode, the vehicle's HC, CO, and NOx emissions exceeded the 1981 emission standards of HC 0.41 gm/mi, CO 3.4 gm/mi, and NOx 1.0 gm/mi. However, the vehicle did meet the CO and NOx standards for 1980 of CO 7.0 gm/mi, and NOx 2.0 gm/mi. Vehicle driveability was good.

Due to a rich misfire condition, the 4 cylinder mode caused the largest increases in HC and CO emission levels over the 8 cylinder levels. HC increased to a level 5 times higher and CO increased to a level 19 times higher. NOx decreased 10%. The vehicle badly failed to meet the 1980 HC and CO standards. Fuel economy decreased 10%. Vehicle driveability was poor. The vehicle lacked sufficient power to follow the driving schedule when accelerating at speeds above 10 mph.

The 6 cylinder mode caused HC emissions to double and CO emissions to triple when compared to the 8 cylinder mode. NOx decreased 10%. The vehicle was unable to meet the 1980 HC or CO standards. Fuel economy increased a negligible amount. Vehicle driveability was acceptable.

When operated in the automatic mode instead of 8 cylinder mode, the vehicle's CO emissions increased 22%, and NOx increased 4%. HC was unchanged. Fuel economy increased 5% and was the best of any mode. The vehicle did not meet the 1981 emission standards but did meet the 1980 CO and NOx standard while exceeding the HC standard.

Vehicle driveability was inconsistent in the automatic mode. Although the driver had adequate power for acceleration, it was difficult to follow the driving schedules during cruise and light acceleration; the valve selector frequently shifted between 4, 6, and 8 cylinder modes of operation. This caused frequent power surges and power losses making it very difficult to follow the driving schedule.

2. Highway Fuel Economy Test

Overall, the operation of the vehicle on a reduced number of cylinders caused HC and CO emissions to increase substantially. Fuel economy changes ranged from a 3% decrease to a 5% increase. These results are tabulated in Table II below.

Table II
Eaton Valve Selector on Prototype 1980 Cadillac
HFET Mass Emissions
grams per mile

Test No.	HC	CO	CO_2	NOx	MPG
8 Cylinder (Baseline)					
80-1684	.09	.12	426	2.93	20.8
80-1694	.08	.09	420	2.86	21.1
80-1674	.09	.11	418	2.78	21.2
4 Cylinder					
80-1664	.61	49.57	381	1.90	19.2
80-1697	.97	29.75	383	1.60	20.5
80-1662	.59	24.14	379	1.89	21.2
6 Cylinder					
80-1699	.37	3.40	403	2.28	21.7
80-1701	.21	1.52	396	2.36	22.2
80-1671	.21	1.99	392	2.31	22.4
Automatic Selection					
80-1703	.14	1.70	415	2.41	21.2
80-1705	.12	1.25	390	2.32	22.6
80-1667	.15	1.88	389	2.14	22.6
80-1676	.13	1.85	388	2.28	22.7

In the eight cylinder mode, the vehicle's average emissions were HC .09 gm/mi, CO .11 gm/mi, and NOx 2.86 gm/mi. Fuel economy was 21.0 mpg. Vehicle driveability was good.

The 4 cylinder mode caused the greatest increases in HC and CO emissions over 8 cylinder emission levels. NOx was the lowest of the four configurations. However, fuel economy decreased approximately 3%. HC emissions increased to .72 gm/mi, CO emissions increased to 34.43 gm/mi, and NOx emissions decreased 38%. These increases in HC and CO emissions and the extreme variability in test results were due to an engine rich misfire condition when operating on 4 cylinders.

Vehicle driveability was marginal in the 4 cylinder mode. The vehicle lacked sufficient power to follow the driving schedule when accelerating at speeds above 10 mph. The transmission upshifts and downshifts were very erratic.

In the 6 cylinder mode, HC emissions tripled to .26 gm/mi, CO emissions increased by a factor of 30 to 2.3 gm/mi, and NOx decreased 19% when compared to the 8 cylinder emission levels. Fuel economy increased 5%.

In the 6 cylinder mode, vehicle driveability was again poor. The engine transmitted a roughness to the driver. Also there were numerous transmission upshifts and downshifts which caused difficulty in following the driving schedule.

In the automatic mode, the HC emissions doubled, CO emissions went up by a factor of 16, and NOx decreased 20% when compared to 8 cylinder operation. Fuel economy increased 6%. Again vehicle driveability was marginal in the automatic mode for the same reasons as for the FTP. At times the mode shifting was very erratic.

3. LA-4 Cycles

In order to acquire emissions and fuel economy information on the vehicle as soon as possible, the vehicle was given a series of hot start LA-4 tests shortly after arriving. These hot start LA-4 are somewhat similar to bags 2 and 3 of the FTP. These tests consisted of a prep LA-4 in the desired mode, followed by a 10 minute soak, and then an LA-4 test for emissions and fuel economy.

The results are tabulated in Table III below. For comparison purposes, the FTP bags 2 and 3 combined results are also given.

Table III
Eaton Valve Selector on Prototype 1980 Cadillac
Hot Start LA-4 Mass Emissions
grams per mile

Test No.	HC	CO	CO_2	NOx	MPG
8 Cylinder					
80-1683*	.34	.93	582	1.99	15.2
80-1693	.19	.38	569	2.16	15.6
80-1673*	.23	.43	573	1.95	15.5
4 Cylinder					
80-1695	2.16	118.92	498	1.83	12.8
80-1696	3.70	79.65	514	1.22	13.6
80-1661*	2.61	71.67	519	1.65	13.8
6 Cylinder					
80-1698	1.27	8.71	546	1.54	15.7
80-1700	1.26	9.78	539	1.64	15.9
80-1672*	.94	7.85	543	1.60	15.9
Automatic Selection					
80-1702	.26	1.22	536	2.17	16.5
80-1704	.22	.94	533	2.15	16.6
80-1666	.31	1.02	542	1.90	16.3
80-1675	.27	1.88	546	1.91	16.1

*Bag 2 and Bag 3 FTP mass emissions used to calculate equivalent hot start LA-4 mass emissions.

The effect of the various operating modes (cylinder selection) on emissions, fuel economy, and driveability were similar to the FTP effects.

4. Steady State

Overall, the operation of the vehicle at steady state on a reduced number of cylinders caused only a relatively small change in emissions. HC and CO emissions were quite low and nearly unaffected by the number of cylinders in operation. Except at 55 mph, NOx emissions and fuel economy increased as the number of operating cylinders was reduced.

These results are tabulated in Tables V and VI in the appendix. The NOx and fuel economy results are plotted in Figures 3 and 4 below.

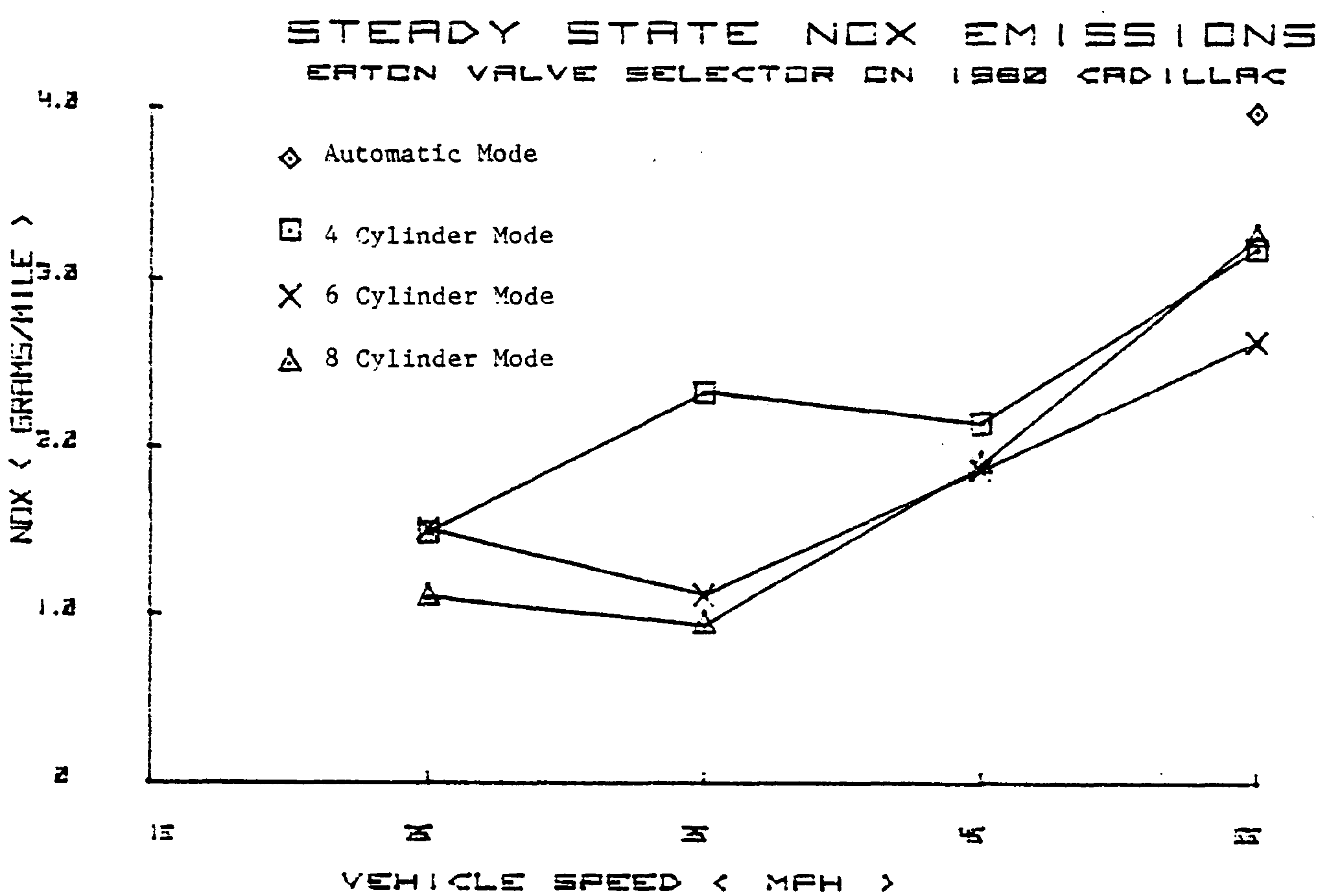

FIGURE 3

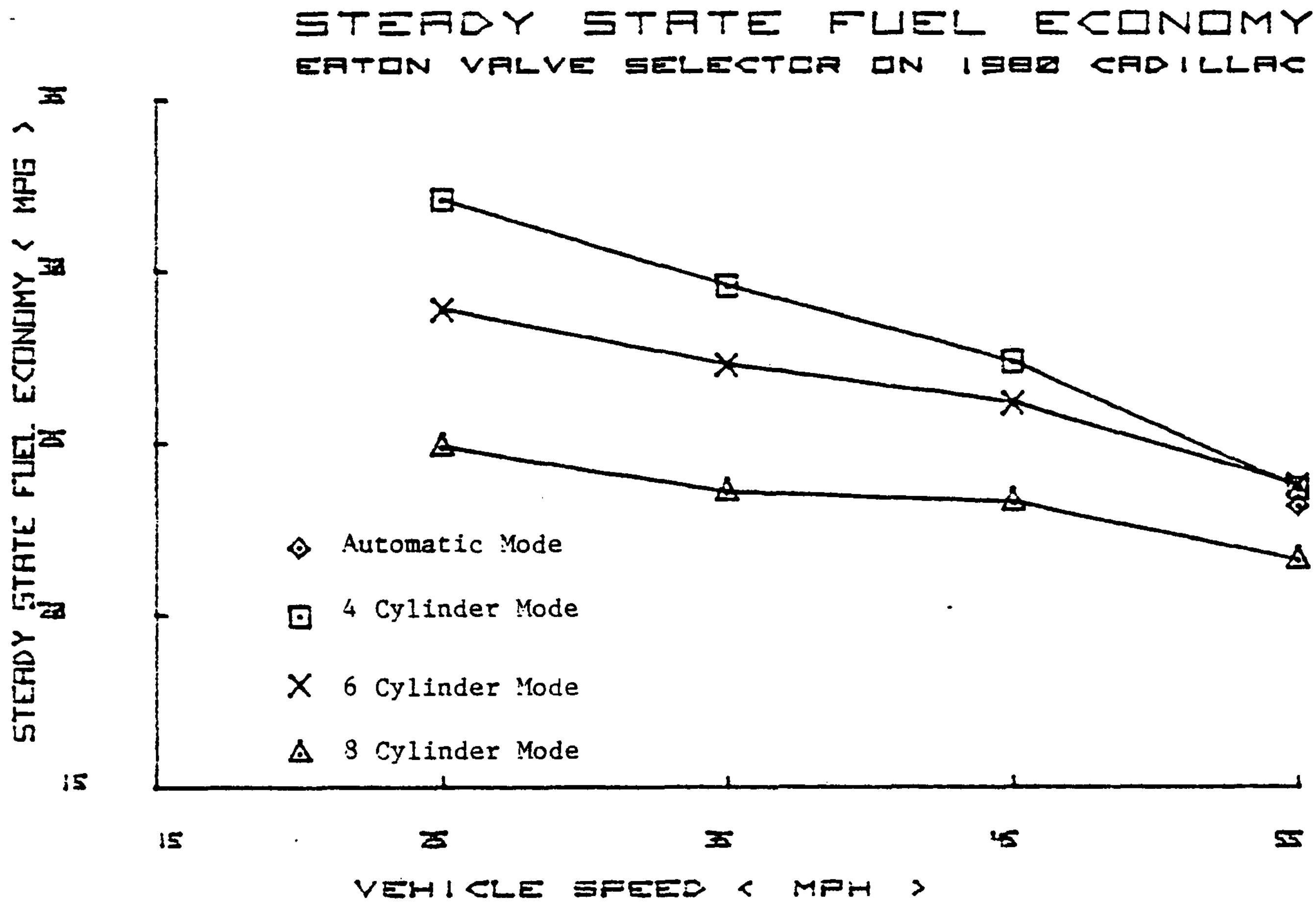

FIGURE 4

Figure 4 shows that this vehicle's fuel economy is rather insensitive to vehicle speeds between 25 and 45 mph. Fuel economy drops only moderately when the speed is increased to 55 mph. This is unusual since most vehicles show a greater relative change in fuel economy.

5. Acceleration Tests

At the conclusion of the emission tests, acceleration tests were performed on the vehicle using a chassis dynamometer. To minimize tire slippage, the chassis dynamometer's front and rear rolls were coupled together for this test. The results are tabulated below in Table IV.

TABLE IV
Eaton Valve Selector on Prototype Cadillac
Acceleration Times
Seconds

	8 Cylinder		Automatic		6 Cylinder		4 Cylinder	
	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2	Run 1	Run 2
0-25	4.0	4.0	4.2	5.2	6.5	6.6	14.3	10.4
0-35	6.1	6.1	6.3	6.3	9.6	9.7	19.7	15.8
0-50	10.2	10.3	10.5	10.6	15.2	15.4	30.4	26.9

Note: These acceleration tests were not necessarily conducted at wide open throttle. During the course of testing the vehicle it became evident that under some operating conditions, the vehicle would accelerate best at part throttle. These acceleration tests were conducted for best acceleration.

The vehicle probably remained in 8 cylinder mode during automatic mode tests.

Conclusions

Overall, when operated on less than 8 cylinders, this vehicle's FTP emissions increased greatly due to extreme mixture enrichment. The vehicle's fuel economy decreased appreciably in 4 cylinder mode. There was a small tendency for improved fuel economy when operating on 6 cylinders. However, best fuel economy was achieved in the automatic mode.

Vehicle driveability was good when operating on 8 cylinders. Driveability ranged from poor to marginal in the 4 cylinder, 6 cylinder, and automatic modes.

This vehicle did not demonstrate the claimed benefits for a cylinder deactivator system. However, Eaton had informed EPA prior to testing that this was a developmental vehicle on which little work had been done to improve emissions or fuel economy.

TEST VEHICLE DESCRIPTION

Chassis model year/make - 1979 Cadillac DeVille
Vehicle I.D. - 6D69599195507
Emission control system - Prototype Cadillac demonstration vehicle modified for Eaton Valve Selector

Engine

type	Otto Spark, OHV, V-8 (1980 prototype)
special features	Eaton Valve Selectors installed on 4 cylinders
bore x stroke	96.0 x 103.0 mm/3.78 x 4.06 in.
displacement	6.0 liter/368 CID
compression ratio	8.2:1
maximum power @ rpm	145 horsepower/108 kW
fuel metering	4 venturi carburetor
fuel requirement	unleaded, tested with indolene HO unleaded and commercial unleaded

Drive Train

transmission type	3 speed automatic
final drive ratio	2.41

Chassis

type	4 door sedan
tire size	GR78 X 14
curb weight	4355
inertia weight	4500
passenger capacity	6

Emission Control System

basic type	air injection EGR oxidation catalyst

TABLE V
Eaton Valve Selector on Prototype 1980 Cadillac
Steady State Mass Emissions
grams per mile*

Test No.	Speed	HC	CO	CO_2	NOx	MPG
8 Cylinder (Baseline)						
80-1686	0 (Idle)*	2.21	.61	4378	1.45	.50
80-1686	25 mph	.11	.08	355	1.10	24.9
80-1685	35 mph	.11	.00	375	.94	23.6
80-1685	45 mph	.09	.00	381	1.90	23.3
80-1685	55 mph	.07	.00	410	3.26	21.6
4 Cylinder						
80-1665	0 (Idle)*	1.25	3.72	4336	2.72	.50
80-1605	25 mph	.11	.12	276	1.49	32.1
80-1663	35 mph	.15	.11	299	2.33	29.6
80-1663	45 mph	.08	.00	323	2.15	27.4
80-1663	55 mph	.06	.00	374	3.19	23.7
6 Cylinder						
80-1670	0 (Idle)*	1.23	.00	4109	2.13	.45
80-1670	25 mph	.09	.07	307	1.51	28.9
80-1669	35 mph	.11	.00	325	1.12	27.3
80-1669	45 mph	.08	.00	338	1.87	26.2
80-1669	55 mph	.07	.00	373	2.64	23.8
Automatic Selection						
80-1668	55 mph	.07	.00	382	3.98	23.2

*0 MPH (Idle) mass emissions are given in grams per hour and gallons per hour.

TABLE VI
Eaton Valve Selector on Prototype 1980 Cadillac
Steady State Mass Emissions
grams per mile*

Test No.	No. Cylinders	HC	CO	CO_2	Nox	MPG
Idle*						
80-1665	4 Cylinder	1.25	3.72	4336	2.73	.50
80-1670	6 Cylinder	1.23	.00	4109	2.13	.45
80-1686	8 Cylinder	2.21	.61	4378	1.45	.50
25 MPH						
80-1665	4 Cylinder	.11	.12	276	1.49	23.1
80-1670	6 Cylinder	.09	.07	307	1.51	28.9
80-1686	8 Cylinder	.11	.08	355	1.10	24.9
35 MPH						
80-1663	4 Cylinder	.15	.11	299	2.33	29.6
80-1669	6 Cylinder	.11	.00	325	1.12	27.3
80-1685	8 Cylinder	.11	.00	375	.94	23.6
45 MPH						
80-1663	4 Cylinder	.08	.00	323	2.15	27.4
80-1669	6 Cylinder	.08	.00	338	1.87	26.2
80-1685	8 Cylinder	.09	.00	381	1.90	23.3
55 MPH						
80-1663	4 Cylinder	.06	.00	374	3.19	23.7
80-1669	6 Cylinder	.07	.00	338	1.87	26.7
80-1668	Automatic	.07	.00	382	3.98	23.2
80-1685	8 Cylinder	.07	.00	410	3.26	21.6

* 0 MPH (Idle) mass emissions are expressed in grams per hour and gallons per hour.