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Emissions and Fuel Economy of a Cadillac Prototype with Modulated Displacement Engine.

by

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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 Test 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 output, the throttle is nearly closed. This introduces a throttling loss which is the energy 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. The operating cylinders are therefore run at a high brake-mean-effective pressure (BMEP) and therefore potentially more efficiently.

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. Because EPA had not recently tested a cylinder deactivation system designed for current vehicles, EPA contacted the Cadillac Motor Division of GM and requested the loan of a vehicle with a cylinder deactivation system installed. Cadillac made available a system installed in a prototype vehicle.

EPA is also testing other cylinder deactivation systems. A similar system was tested in a demonstration vehicle provided by Eaton. The results of these tests are reported in TEB report #80-16 "Emissions and Fuel Economy of the Eaton Valve Selector." An aftermarket retrofit system was tested in several 1979 V-8 vehicles. The results of these tests are reported in a TEB report #80-18, "Emissions and Fuel Economy of the Automotive Cylinder Deactivation System (ACDS)." Six years ago, EPA also 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.

Description

The test vehicle had an Eaton Valve Selector system installed. This is a valve deactivation system being developed by the Eaton Corporation for installation by the vehicle manufacturer. The concept is to improve vehicle fuel economy by selectively shutting off engine cylinders during periods of light engine loads. The cylinders are deactivated by a mechanical system that unloads the intake and exhaust valve rocker arm fulcrum points. A more detailed description of the Eaton Valve Selector is given in the appendix.

In this application, the valve selector is integrated into the total vehicle/engine package. 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 selector.

Test Vehicle Description

The test vehicle was a 1979 Cadillac Coupe De Ville that had a 6.0 liter Cadillac engine installed to replace the stock 7.0 liter engine. Cadillac had installed the Eaton Valve Selector system on this engine. This installation included the electromechanical valve selector, electronic control unit, engine sensors and a modified camshaft. The engine sensors interfacing with the electronic control unit included rpm, water temperature, throttle angle, manifold vacuum and transmission gear. The vehicle had a single point, throttle body, digital, electronic fuel injection system. A closed loop emission control system was used. Additional vehicle details are given in the appendix.

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.

The selection of cylinder deactivation modes was accomplished by the vehicle operator sequencing the control logic after starting the vehicle. It required 15 to 20 seconds to perform this task. Since the control logic always resets to the 8 cylinder mode when turned off, it was necessary to reset the control logic for bag 1 (cold start) and bag 3 (hot start) of FTP for the 4 cylinder and automatic modes. Therefore, 30 seconds of idle time was added to bag 1 and bag 3 of the FTP. For comparability 30 seconds of idle was added to all FTP's including the eight cylinder mode.

Additional tests were conducted as an evaluation tool. These consisted of steady state emission tests and acceleration tests.

Discussion of Results

The objective of this test program was to further evaluate the potential fuel economy benefits of cylinder deactivation and to determine the effects on vehicle emissions. These 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
   The results are given in Table 1 below. The operation of this vehicle on 4 cylinders instead of 8 cylinders caused HC and CO emissions to increase, NOx to decrease, and fuel economy to increase. Operation of this vehicle in the automatic mode caused little change in either HC emissions or fuel economy and caused reductions in CO and NOx emissions.

Table 1
Cadillac Modulated Displacement Prototype Vehicle
FTP Mass Emissions
(grams per mile)

Test Number	HC	CO	CO_2	NOx	MPG
8 cylinder (baseline)					
80-1997	.33	2.86	744	1.36	11.8
80-2001	.34	3.46	745	1.55	11.8
4 Cylinder					
80-2003	.85	38.71	602	1.55	13.3
80-2007	1.31	72.27	605	1.16	12.3
80-2334	.92	38.60	586	1.20	13.7
Automatic Selection					
80-2009	.32	2.05	718	1.31	12.3
80-2271	.29	2.75	763	1.32	11.5

In the 8 cylinder mode the vehicle's NOx emissions did exceed the 1981 emission standards of 0.41 gm/mi HC, 3.4 gm/mi CO and 1.0 gm/mi NOx. Fuel economy was 11.8 mpg. Vehicle driveability was good.

In the 4 cylinder mode there were significant changes in emissions and fuel economy compared with operation on 8 cylinders. HC emissions increased by a factor of 3 tc 1.03 gm/mi, CO increased by a factor of 15.8 to 49.86 gm/mi (There was considerable variability in CO emissions results.), and NOx decreased 10%. Fuel economy increased 11%. HC, CO and NOx emissions all exceeded the 1981 emission standards. Vehicle driveability was poor. There was stretchiness (a lack of response to accelerator pedal movement), insufficient power to follow most acceleration rates, engine lag (delay in response to pedal movement), and many more transmission shifts than normal.

In the automatic mode HC emissions were not significantly changed from operation with 8 cylinders. CO decreased 24% and NOx decreased 10%. Fuel economy was not significantly changed. NOx emissions again exceeded the 1981 emission standards. Vehicle driveability was good.

2. Highway Fuel Economy Test
Overall, the vehicle had the least emissions in the automatic cylinder deactivation mode. Fuel Economy was best in the 4 cylinder mode. These results are given in Table II below.

Table II
Cadillac Modulated Displacement Prototype Vehicle
HFET Emissions

Test Number	HC	CO	CO_2	NOx	MPG
8 Cylinder (baseline)					
80-1998	.06	.33	466	1.89	19.0
80-2002	.06	.29	463	2.30	19.1
4 Cylinder					
80-2004	.19	15.41	371	2.01	22.4
80-2008	.21	17.83	380	1.94	21.7
80-2335	.23	21.56	383	1.35	21.2
Automatic					
80-2010	.04	.18	451	.98	19.6
80-2014	.04	.07	448	1.05	19.8
80-2264	.04	.09	449	.95	19.7
80-2272	.04	.08	458	1.01	19.4

In the eight cylinder mode, the vehicle's average emissions were 0.06 gm/mi HC, 0.32 gm/mi CO, and 2.10 gm/mi NOx. Fuel economy was 19.0 gm/mi. Driveability was good.

In the 4 cylinder mode there were again significant changes in emissions and fuel economy from operation on 8 cylinders. HC emissions tripled to 0.21 gm/mi, CO emissions increased by a factor of 57 to 18.27 gm/mi, and NOx emissions decreased 15%. Fuel economy increased 14%. The same driveability problems encountered in the 4 cylinder, FTP tests were observed. Namely, there was stretchiness, lack of power for acceleration, engine lag and more transmission shifts than normal.

In the automatic mode, HC emissions were reduced 33%, CO emissions were reduced 67%, and NOx emissions decreased 52% when compared to 8 cylinder operation. Fuel economy increased by approximately 3%.

3. Steady State Tests

Overall, the operation of the vehicle on a reduced number of cylinders caused mixed effects on emissions. HC and CO emissions were quite low in all modes for most speeds and relatively unaffected by the number of cylinders in operation. NOx emissions tended to remain unchanged as the number of operating cylinders increased. However, when operating on 8 cylinders, NOx emissions increased markedly at 45 mph and, when operating on 4 cylinders, NOx emissions increased markedly at 55 mph.

Compared to the 8 cylinder mode, fuel economy showed a 6 to 33% improvement when the vehicle was operated with 4 cylinders. Similarly when compared to the 8 cylinder mode, fuel economy showed a 0 to 18% improvement when the vehicle was operated in the automatic mode. The 4 cylinder and automatic modes showed similar emission and fuel economy results at 35 and 45 mph but differed at 55 mph. This was expected because in the automatic mode, the vehicle would probably select 4 cylinders for the light engine loads imposed at 35 and 45 mph, but switch to either 6 or 8 cylinders for the moderate engine loads imposed at 55 mph.

The results are tabulated in Table IV in the Appendix. The fuel economy results are plotted in Figure 1 on the following page.

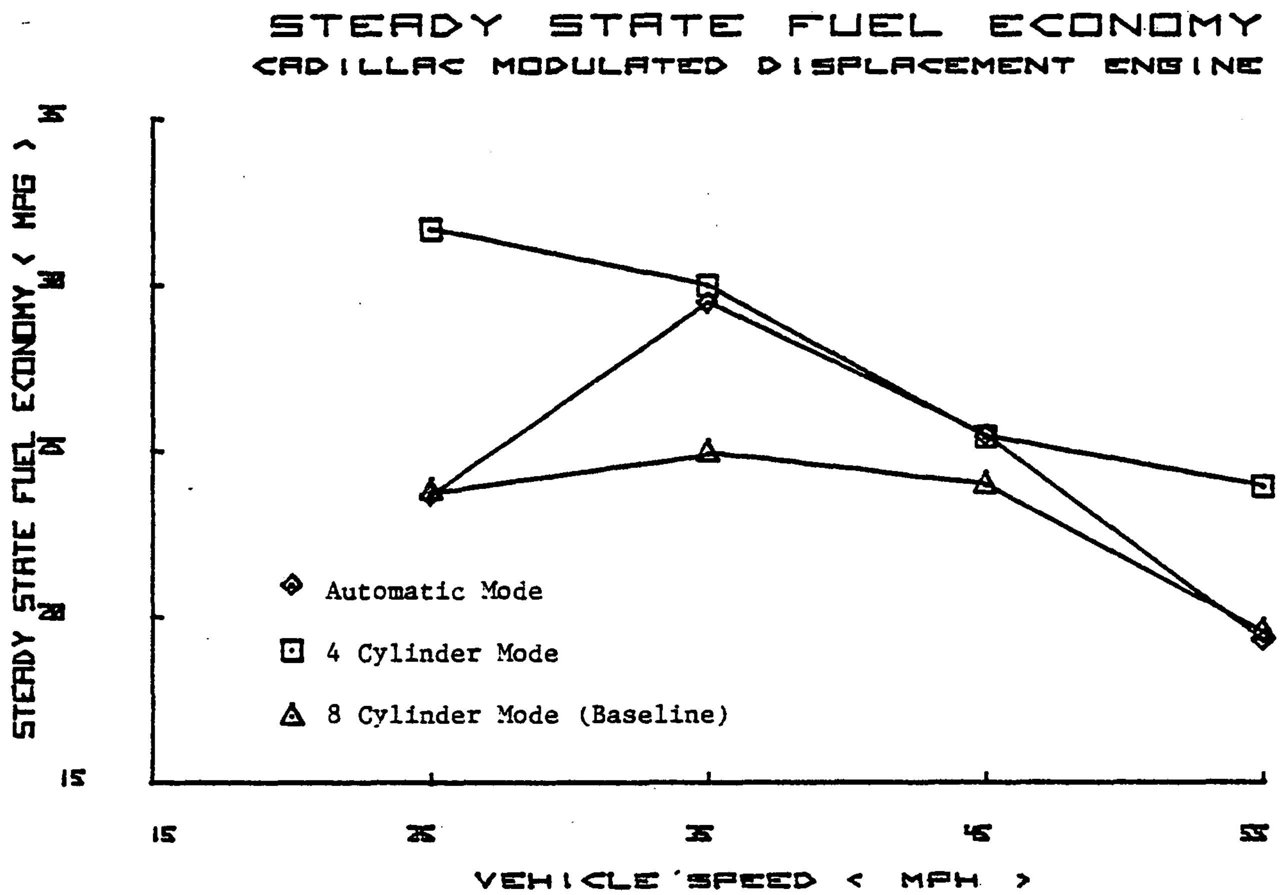

Figure 1

4. <u>Discussion of results</u>
When this test vehicle was operated with a reduced number of cylinders, FTP fuel economy increased up to 11%. HFET fuel economy increased between 3 and 14%. However, the benefits in the automatic mode, the most probable mode the vehicles would have when marketed, was minimal. This trend is in agreement with information supplied by Cadillac personnel. They had said the fuel economy benefits for the FTP and HFET cycles would be no more than 5%.

The greatest fuel economy benefits for the modulated displacement test vehicle occurred during steady state tests. Fuel economy increases ranged from 0 to 33% during these steady state tests. To achieve these benefits in actual vehicle driving would require a very steady vehicle speed. Therefore, the larger fuel economy benefits of the system would probably only occur when the vehicle was operated on level roads with a cruise control.

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 summarized below in Table V. Complete results are given in the appendix.

Table III
Cadillac Modulated Displacement Prototype Vehicle
Average Acceleration Times
seconds

Speeds	8 Cylinder	6 Cylinder	4 Cylinder
0-25	4.3	6.3	11.4
0-35	6.6	9.4	17.0
0-45	9.4	13.3	23.6
0-55	13.2	18.4	34.0

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

Conclusions

The vehicle did not meet the 1981 NOx standards of 1.0 gram/mile when tested in the 8 cylinder mode. FTP emissions were .34 gm/mi HC, 3.16 gm/mi CO and 1.46 gm/mi NOx. Fuel economy for the FTP was 11.8 mpg and for the HFET it was 19.0 mpg.

In the 4 cylinder mode, the Modulated Displacement vehicle showed a sharp increase in emissions over 8 cylinder emission levels. HC increased by a factor of 3, CO increased by a factor of 15.8, and NOx decreased 10%. Fuel economy increased 11% for the FTP and 14% for the HFET. The vehicle did not meet the 1981 emission standards for HC, CO or NOx.

In the automatic mode, the Modulated Displacement vehicle, except for a CO reduction, showed little change in emissions from 8 cylinder emission levels. HC was unchanged, CO decreased 24%, and NOx decreased 10%. FTP fuel economy was essentially unchanged. HFET fuel economy increased by approximately 3%.

The vehicle was unable to follow the FTP and HFET driving schedules in the 4 cylinder mode. Vehicle driveability was acceptable in the 8 cylinder and automatic modes for both the FTP and HFET.

The largest fuel economy benefits for the modulated displacement vehicle will probably only be achieved when the vehicle is operated at constant speeds by the vehicle's cruise control unit.

Test Vehicle Description

Chassis model year/make - 1979 Cadillac Coupe DeVille
Vehicle I.D. 6D47T99140709
Emission Control System - Prototype Cadillac with modulated displacement engine

Engine

type . . . . Otto Spark, OHV, V-8
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/108kW
fuel metering . . . . . Rochester, single point, throttle body, digital, electronic fuel injection
fuel requirement . . . . Unleaded, tested with Indolene HO

Drive Train

transmission type . . . 3 speed automatic
final drive ratio. . . . 2.41

Chassis

type . . . . 2 door sedan
tire size P215-75R15
curb weight 4350
inertia weight 4500
passenger capacity . . . 6

Emission Control System

basic type . . . . air injection
dual bed catalyst
closed loop
EGR

Eaton Valve Selector Description

Principle of Operation

"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."*

Eaton Valve Selector Hardware

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 2 and 3 and described below.

"On the conventional overhead valve pushrod 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 2, the selector body is restrained from moving upward by contact between projections on the 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 3, 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.

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

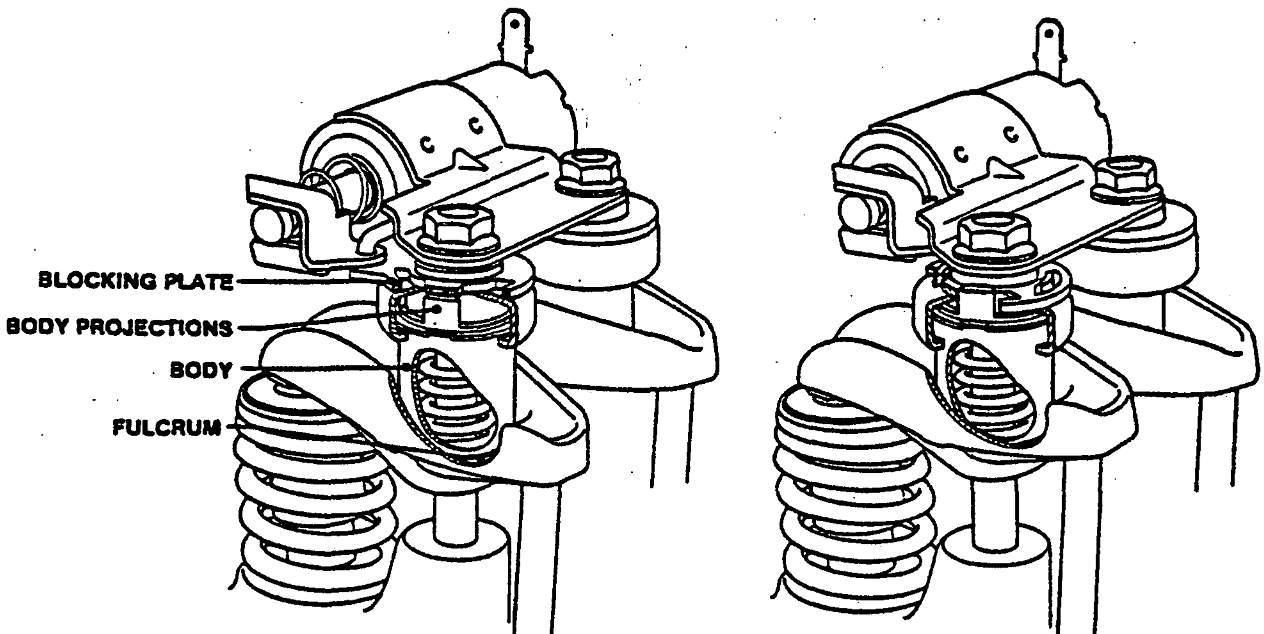

Figure 2 Valve Enabled Figure 3 Valve Deactivated

Eaton Valve Selector Mechanical Details

"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 adopted 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 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."

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

Table IV
Cadillac Modulated Displacement Prototype 1981 Vehicle
Steady State Emissions
(grams per mile)*

Test Number	Vehicle Speed	HC	CO	CO_2	NOx	MPG
8 Cylinder (Baseline)						
80-1999	0 mph*	2.23	6.70	5834	1.40	.67
80-1999	25 mph	.79	.01	373	.41	23.8
80-2247	25 mph	.06	.04	372	.30	23.8
80-2000	35 mph	.09	.00	356	.78	24.9
80-2270	35 mph	.06	.00	354	.61	25.0
80-2000	45 mph	.05	.00	371	1.56	23.9
80-2270	45 mph	.05	.00	368	1.41	24.1
80-2000	55 mph	.05	.00	451	.45	19.6
80-2270	55 mph	.06	.00	455	.44	19.5
4 Cylinder						
80-2005	0 mph*	.79	2.87	4218	3.82	.48
80-2249	25 mph	.05	.03	280	.78	31.7
80-2006	35 mph	.07	.00	300	.59	29.5
80-2249	35 mph	.05	.00	290	.55	30.5
80-2006	45 mph	.04	.00	352	.64	25.2
80-2248	45 mph	.04	.00	345	.29	25.7
80-2006	55 mph	.03	.02	367	2.07	24.1
80-2248	55 mph	.03	.00	372	1.30	23.8
Automatic						
80-2011	0 mph*	.93	.00	6972	2.85	.77
80-2011	25 mph	.07	.00	374	.33	23.7
80-2012	35 mph	.08	.02	301	.57	29.5
80-2012	45 mph	.04	.00	348	.60	25.5
80-2012	55 mph	.02	.00	459	.61	19.3

* 0 mph (idle) mass emissions are given in grams per hour and fuel economy is given in gallons per hour.

Table V
Acceleration Tests on Prototype Modulated Displacement Cadillac
seconds

Speeds	8 Cylinder run 1	8 Cylinder run 2	6 Cylinder run 1	6 Cylinder run 2	4 Cylinder run 1	4 Cylinder run 2
0-5 mph	.8	.8	1.3	1.1	1.9	2.0
0-10 mph	1.5	1.5	2.2	2.1	3.6	3.8
0-15 mph	2.3	2.3	3.4	3.2	5.9	6.1
0-20 mph	3.2	3.2	4.8	4.5	8.4	8.7
0-25 mph	4.3	4.3	6.3	6.2	11.1	11.6
0-30 mph	5.4	5.4	7.9	7.7	14.0	14.5
0-35 mph	6.6	6.6	9.5	9.3	16.7	17.3
0-40 mph	7.9	7.9	11.4	11.1	19.7	20.3
0-45 mph	9.4	9.3	13.3	13.0	23.3	23.9
0-50 mph	11.4	11.3	15.6	15.2	27.7	28.3
0-55 mph	13.2	13.3	18.6	18.2	33.6	34.4