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**VALVE TIMING—ITS EFFECT ON
EMISSIONS AND FUEL ECONOMY**

By

R. L. Bechtold and W. F. Marshall

MASTER

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VALVE TIMING—ITS EFFECT ON EMISSIONS AND FUEL ECONOMY

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R. L. Bechtold¹ and W. F. Marshall²

ABSTRACT

The effects of valve timing on exhaust emissions and fuel consumption were investigated experimentally. Emission control through the use of varied valve timing compared to conventional emissions control hardware was documented along with the effects of valve timing on emissions. Fuel consumption trends with changed valve timing were determined. The engine design of the test vehicle allowed independent adjustment of intake and exhaust valve timing.

Emissions and fuel consumption were determined for steady-state speeds of 20 through 60 mph in 10 mph increments. A wide variety of intake and exhaust valve timing combinations were tested and the results compared to those of the production vehicle before modification.

These results showed that valve timing has a significant effect on oxides of nitrogen emissions, but additional emissions control hardware is necessary to meet current and proposed emission regulations. Compared to emission control, varied valve timing holds more promise for reduced fuel consumption through a gain in cycle efficiency at various speeds.

INTRODUCTION

Much previous work has been completed documenting the effects of valve timing on exhaust emissions (1-2)³. A major attraction to valve timing as a pollution control device is emission control without external emissions control hardware such as exhaust manifold air injection and EGR. It was the intent of this study to show the effect of valve timing changes on exhaust emissions and fuel economy of a 1976 production automobile relative to a baseline of full external emission controls and also to a baseline of no external emission controls with standard valve timing. The data presented in this report represent results from vehicle tests covering a wide range of speeds. Valve timing changes referred to in this report represent static adjustments of either the intake or exhaust valve timing. It is recognized that present vehicles have camshafts with valve timing which is the result of many compromises of emissions/vehicle performance. For valve timing to be a practical emission control and economy device, it must be a dynamic system which would optimize valve timing depending on engine conditions.

¹Mechanical engineer.

²Project leader.

³Underlined numbers in parentheses refer to items in the list of references at the end of this report.

THEORY AND PREVIOUS WORK

The main benefit of variable valve timing is reduced exhaust emissions through the mechanism of charge dilution with residual combustion products--often referred to as internal EGR. This is accomplished in a variety of ways; one which appears to be quite effective is early intake valve opening. As the opening point of the intake valve is advanced in the engine cycle, higher pressures are encountered in the combustion chamber, and increasing amounts of exhaust gases are admitted into the intake manifold (figure 1). The momentum of the incoming fuel/air mixture in the intake tract and the lowering pressure in the combustion chamber after the exhaust valve has opened cause the exhaust gases which were admitted into the intake manifold to flow into the combustion chamber during the next cycle. Early intake valve opening has been shown to be effective in lowering both hydrocarbon (HC) and oxides of nitrogen (NO_x) (1,2).

Early intake valve closing has been shown to have little effect on emissions, but it does have a bearing on the effective compression ratio in the cylinder (2). The compression ratio generally increases slightly when intake valve closing is advanced which results in slightly higher NO_x and slightly lower HC (2) at a typical road load and speed.

Early exhaust valve closing has been shown to be effective in lowering HC and NO_x emissions (1,2). This is due to the trapping of quench layer gases in the cylinder to be mixed with a new fuel/air charge since these gases are generally the last ones to leave the cylinder on the exhaust stroke of the cycle. Quench layer gases contain high concentrations of hydrocarbons; if retained, an overall lowering of HC emissions is possible. Oxides of nitrogen emissions are reduced because internal EGR is increased by trapping a larger percentage of quench layer gases.

The amount of valve overlap in an engine has been related to reduced NO_x and HC emissions (3-4). Valve overlap is defined as the length of time in crankshaft degrees that both the intake and exhaust valves are open when the piston nears top dead center (TDC) between the exhaust and intake strokes of the cycle. Increased valve overlap increases the amount of internal EGR by allowing exhaust flow into the intake manifold when the intake valve opens on the exhaust stroke. It also draws exhaust gases from the exhaust manifold during the intake stroke due to delayed exhaust valve closing (1, 3-4).

Figure 1. - Combustion chamber configuration and valve placement during valve overlap.

Increased valve overlap can be assumed to be a combination of early intake valve opening and late exhaust valve closing.

Although the effects of varied valve timings have already been studied, most of the tests have been done on engines set up on dynamometers. Small amounts of in-car, road-load data have been available to substantiate the test stand results.

EXPERIMENTAL PROGRAM

The vehicle chosen for the study was a 1976 Fiat 131, two-door sedan. The specifications of this vehicle are given in table 1. This automobile was chosen because of its wide availability and low cost and because its engine has separate camshafts controlling the intake and exhaust valves (figure 1). (No currently produced domestic engines have this type of valve control design.) This feature allows control of the intake valves independent of the exhaust valves. The system used to drive the camshafts also permitted easy access for changing valve timing. The emission control devices (air pump, EGR, spark retard) used on the standard vehicle are similar to those used on many present cars for compliance with 1976 Federal emissions standards.

For both the intake and exhaust cams, three positions of the camshaft relative to the engine crankshaft were tried. These positions were: (1) the standard or stock position of the camshaft as it came from the factory; (2) advance of the camshaft 17 crankshaft degrees; and (3) retard of the camshaft 17 crankshaft degrees. It was decided that all three positions of each camshaft should be tried plus all of the possible combinations between the two. This resulted in nine combinations or test cases of valve timing. Table 2 shows the valve timing specifications for all nine combinations of valve timing.

The spark timing for each test case was chosen to be minimum advance for best specific fuel consumption (mbsfc). The mbsfc point at each speed was determined by measuring fuel consumption and the torque output of the driveshaft at each spark timing setting. By knowing the driveshaft speed, it is possible to calculate a brake specific fuel consumption (bsfc) which relates to the power being delivered to the rear axle of the car. All the mbsfc spark timing setting points were determined with the use of a chassis dynamometer which allowed the load to be adjusted to the corresponding road load.

The bsfc was calculated in the following manner. The fuel rate was determined by the following equation:

$$\text{Fuel rate} = \frac{\text{Fuel consumed, lbm}}{\text{Time, seconds}} \quad (1)$$

TABLE 1. - 1976 Fiat 131 specifications

A. Engine:	
Cycle.....	Four-stroke, gasoline
Number of cylinders.....	4
Carburetion (No. of barrels).....	2
Bore and stroke.....	3.31 in. x 3.12 in.
Displacement.....	107.13 cu. in.
Compression ratio.....	8:1
Horsepower, SAE net.....	86 hp @ 6,200 rpm
Torque, SAE net.....	90 ft-lb @ 2,800 rpm
B. Transmission:	
Type.....	Manual 5-speed synchromesh plus reverse
N/V (5th gear).....	57.7
C. Emission Controls:	
Spark Retard.....	
EGR (Exhaust Gas Recirculation).....	
Air Pump.....	

TABLE 2... Cam timing specifications

	<u>(0,17)</u>	<u>(-17,0)</u>	<u>(-17,17)</u>	<u>(17,17)</u>	<u>(0,0)¹</u>	<u>(-17,-17)</u>	<u>(17,0)</u>	<u>(0,-17)</u>	<u>(17,-17)</u>
Valve overlap (crankshaft degrees).....	0	0	0	10	10	10	27	27	44
Intake valve opening point....	5° BTC	12° ATC	12° ATC	22° BTC	5° BTC	12° ATC	22° BTC	5° BTC	22° BTC
Intake valve closing point....	53° ABC	70° ABC	70° ABC	36° ABC	53° ABC	70° ABC	36° ABC	53° ABC	36° ABC
Exhaust valve opening point....	110° ATC	127° ATC	110° ATC	110° ATC	127° ATC	154° ATC	127° ATC	154° ATC	154° ATC
Exhaust valve closing point....	12° BTC	5° ATC	12° BTC	12° BTC	5° ATC	22° ATC	5° ATC	22° ATC	22° ATC

NOTE. - Valve lift, intake, and exhaust, all cases - 0.382 in.

(0,0) Represents the valve timing events of the engine in its stock configuration. The first number inside the parentheses denotes the change in crankshaft degrees the intake cam was moved, while the second specifies the same for the exhaust cam. A positive number implies advance with respect to the initial setting while a negative number means retard.

The power in the driveshaft was calculated by equation 2 with torque measured in inches-lbf and driveshaft speed in rpm.

$$\text{Driveshaft hp} = \frac{(\text{Driveshaft torque})(\text{Driveshaft speed})}{63025.4} \quad (2)$$

Brake specific fuel consumption can consequently be determined by dividing equation 1 by equation 2 to yield:

$$\text{bsfc} = \frac{\text{Fuel rate}}{\text{Driveshaft hp}} \quad (3)$$

Each value of bsfc for different spark timings at a single speed and valve timing combination was plotted with the minimum value corresponding to the mbsfc setting. Figure 2 shows a typical plot of bsfc versus spark timing at a constant speed.

Exhaust emissions were measured using a constant volume sampling (CVS) system (5). The dynamometer inertia weight was set at 3,000 lb and the road load was adjusted at 50 mph to the value specified by the Environmental Protection Agency (EPA) for that inertia weight. All emission tests were conducted in a chassis dynamometer room with controlled environment.

Figure 2. - Typical plot of BSFC vs spark timing.

RESULTS

The effect of valve timing on exhaust emissions can be expressed in two different ways. First, emission rates can be examined as a function of valve overlap. The relative advance of the camshaft (or camshafts, as in this case) can also be shown to have an effect on emissions. In this study an equal amount of overlap was achieved by differing amounts of either intake or exhaust cam advance.

In figure 3, NO_x emissions are shown as a function of the amount of overlap at a vehicle speed of 50 mph. Physical limitations (contact between valves and piston) of the engine reduced the number of valve timing combinations that could be examined in the high valve overlap region. However, it can still be seen that an increase in valve overlap caused a marked decrease in NO_x emissions. Further reduction in NO_x could probably be accomplished by retarding the spark setting from mbsfc, but with a fuel consumption penalty.

The relatively close spacing of the data points at a single valve overlap point shows that valve overlap generally has more effect on NO_x emissions than does camshaft advance. The three points comprising the data at 0 overlap were obtained by (1) retarding the intake cam 17 crankshaft degrees while simultaneously advancing the exhaust cam 17 degrees; (2) advancing the exhaust cam 17 degrees with the intake cam in its initial position; and (3) retarding the intake cam 17 degrees. The engine produced comparable NO_x emissions at three very different valve timings, but with the same amount of overlap.

An overlap of 10° was obtained at three different valve timing settings. This is the amount of overlap present with the cams in their stock settings. The other points at this valve overlap setting correspond to simultaneously advancing or retarding both the intake and exhaust cams. This situation is analogous to advancing or retarding the camshaft in a typical single-camshaft-engine. The results,

Figure 3. - NO_x emissions vs intake and exhaust valve overlap.

Figure 4. - NO_x emissions vs cam advance with constant valve overlap (10 degrees).

shown in figure 4, indicate that for a given overlap, advancing the cams results in an increase of NO_x , whereas retarding the cams results in a slight decrease.

Twenty-seven degrees of overlap was attained by either advancing the intake cam 17 degrees or retarding the exhaust cam 17 degrees. The second condition yielded the lower NO_x value of the two shown which suggests that late exhaust valve opening is a more effective method of EGR than early intake valve opening. In both cases, EGR is accomplished by having exhaust gases backflow into the intake manifold.

An overlap of 44 degrees was obtained by advancing the intake cam and retarding the exhaust cam. This condition resulted in the lowest NO_x emissions.

The influence of valve timing on carbon monoxide (CO) emissions was much less than the effects on NO_x . Figure 5 shows the effects of valve overlap on CO emissions at 50 mph. Emissions of CO decreased with increased overlap with little difference between cam advance positions except in the 10 degree overlap case. Figure 6 shows the A/F (air/fuel) ratios in the data in figure 5. These data show that while the A/F ratio remained relatively constant, CO emissions did decrease as valve overlap increased.

As for CO, valve timing had only a minor influence on HC emissions. In figure 7, HC emissions are shown as a function of intake and exhaust valve overlap. Decreasing the overlap from the stock value of 10 degrees results in an increase in HC emissions, whereas an increase in overlap to 27 degrees showed virtually no change. Further increase in overlap to 44 degrees again showed an increase in HC emissions. The effect of camshaft advance on HC emissions at a constant overlap (10 degrees) is shown in figure 8. An increase of approximately the same magnitude resulted when the cams were either

Figure 5. - CO emissions vs intake and exhaust valve overlap.

Figure 6. - Air-fuel ratio at various valve overlaps at 50 mph.

Figure 7. - HC emissions vs intake and exhaust valve overlap.

Figure 8. - HC emissions vs cam advance with constant overlap (10 degrees).

advanced or retarded 17 degrees. The HC emissions rates are shown in figure 9 for all the valve timing combinations, including the baseline case of full emission controls and the case of standard camshaft timing and ignition timing with no emission controls. [Note that the various tests (other than the baseline cases) are identified by the amount of intake and exhaust cam advance, labeled in sequence. For example, (0,17) means the intake cam is in its stock timing position while the exhaust cam has been advanced 17 crankshaft degrees from its stock position.] The marked increase over baseline cases is attributed to spark timing differences. Figure 10 shows the HC emissions for the two baseline cases (no emission controls and full emission controls at equal spark timing) versus vehicle speed in mph. This shows the detrimental effect EGR (for control of NO_x) can have on HC emissions.

Figure 9. - HC emissions for the various cam timing combinations tested.

In figure 11, CO emissions for the various test cases are shown. These data show that CO emissions are virtually independent of cam timing. Although CO emissions for the baseline vehicle appear to be high, 1976 EPA emissions standards were met.

Figure 10. - HC emissions vs speed at equal spark timing.

Oxides of nitrogen emissions for the various test conditions are shown in figure 12. The lowest emissions were obtained with the full emission control baseline engine case. By comparing the baseline case with no controls and the (0,0) cam timing case at mbsfc spark timing, it can be deduced that spark timing has a significant effect on NO_x production. Oxides of nitrogen production with the high overlap (17,-17) cam settings could be reduced by retarding the spark timing. Table 3 shows the spark timing used for the two baseline cases and the standard cam timing (0,0) mbsfc spark timing case. Minimum advance for best specific fuel consumption spark timing varied little from these values for the other cam timing cases tried.

Table 4 shows the fuel economy for the two baseline cases and the best fuel economy obtained from the various cam timing settings at each speed. The cam setting giving the best economy at each speed is shown. In all cases, retarding the exhaust cam produced the best results.

Table 5 shows the mean fuel economy obtained from all nine valve timing combinations at each speed

Figure 11. - CO emissions for the various cam timing combinations tested.

Figure 12. - NO_x emissions for the various cam timing combinations tested.

TABLE 3. - Baseline spark timing in °BTDC

Speed, mph	Baseline, full and no controls	mbsfc Timing
20	5	30
30	15	40
40	20	50
50	27	55
60	30	55

plus the percent deviation of each valve from the mean. The (0,-17) valve timing combination produced the greatest increase over the entire speed range. The other two cases which included retarded exhaust valve timing produced different results. The (-17,-17) case produced a general increase over the average across the speed range. However, the increase is small and is due to the late closing of the intake valve which limits the compression ratio (2). The (17,-17) valve timing case produced significant fuel consumption increase across the entire speed range and especially at the lower speeds. This is due to the high valve overlap (44 crankshaft degrees) at this condition which makes the engine more suited to high-speed operation (1). As can be seen from table 5, the fuel economy at this valve timing combination increases with speed but never reaches the average for any of the higher speeds tested.

TABLE 4. - Fuel economy results in mpg

Speed, mph	Baseline, full controls	Baseline, no controls	Best economy		
			Miles/ gallon	Cam Advance	Degrees of overlap
20	29.38	25.67	38.88	(0,-17)	27
30	28.66	27.85	39.75	(0,-17)	27
40	27.38	27.90	35.39	(-17,-17)	10
50	27.08	27.48	31.45	(0,-17)	27
60	25.15	25.35	29.84	(-17,-17)	10

TABLE 5. - Percent change in mpg¹ from the mean of all the combinations at each speed

	Speed, mph				
	20	30	40	50	60
Mean, mpg.....	37.52	37.45	34.38	30.77	27.48
Pct. change from the sample mean:					
(0,17).....	-3.48	.15	.23	-1.90	-2.35
(-17,0).....	.39	3.94	-.32	-1.07	-2.35
(-17,17).....	1.51	.19	.29	.29	.84
(17,17).....	1.28	-1.66	-1.76	-.03	1.62
(0,0).....	3.29	3.43	.92	1.61	-.05
(-17,-17).....	2.48	1.11	2.92	.97	2.95
(17,0).....	0.00	-2.54	.06	-1.43	-.36
(0,-17).....	3.62	6.14	2.02	2.21	1.82
(17,-17).....	-9.09	-10.84	-4.29	-.63	-2.04

¹Miles per gallon calculated from mass balance using CVS results.

TABLE 6. - Emission results for the various cam timings at 50 mph

	Emissions, g/mile		
	Oxides of nitrogen	Carbon monoxide	Hydrocarbons
Baseline:			
Full controls.....	0.99	4.86	0.15
No controls.....	1.98	1.45	.11
Cam timing combinations, (intake cam advance, exhaust cam advance):			
(0,17).....	6.54	1.97	.83
(-17,0).....	6.19	1.95	.79
(-17,17).....	6.22	1.94	.74
(17,17).....	5.48	1.98	.69
(0,0).....	4.40	1.91	.60
(-17,-17).....	4.05	1.75	.71
(17,0).....	4.69	1.76	.70
(0,-17).....	3.55	1.82	.56
(17,-17).....	3.04	1.58	.74

DISCUSSION

Valve timing was shown to have a noticeable effect on all exhaust emissions but more so concerning NO_x than HC or CO. A summary of results is given in table 6. The mechanism by which the change in NO_x takes place is internal EGR caused by changes in valve timing. The amount of valve overlap was shown to have a stronger effect than cam timing alone. The amount of valve overlap must therefore determine how much exhaust gas is retained in the cylinder between the exhaust and intake strokes of the cycle. Spark timing also has a

strong effect on NO_x production. Advancing the spark timing to mbsfc generally causes increased peak cylinder pressure and temperature which in turn causes increased NO_x emissions.

Carbon monoxide emissions were affected in a favorable way by increase in valve overlap. This reduction in CO is most probably due to retention of more quench layer exhaust gases. Quench layer exhaust gases are usually the last gases expelled from the cylinder during the exhaust stroke (6). Thus, some of the exhaust gas normally expelled is retained and mixed with a new charge, allowing oxidation in the subsequent combustion process.

Unburned hydrocarbons tend not to follow the same trend as CO emissions. Mechanisms other than quench gas retention must come into operation since HC emissions first decrease with increase in valve overlap, but then increase again at high levels of overlap. The increase is most likely caused by short-circuiting of unburned intake fuel/air mixture through the exhaust valve. Short-circuiting of the intake mixture is a common trait of high overlap camshafts (1).

Spark timing has an appreciable effect on HC emissions. At lower values of spark timing, burning occurs later in the combustion cycle and causes higher gas temperatures. A high exhaust gas temperature allows oxidation of HC in the exhaust manifold outside the cylinder. Spark timing was shown to have much less effect on CO emissions.

Table 4 shows the valve timing combinations for best fuel economy. At all speeds best fuel economy resulted with the exhaust cam retarded 17 degrees. This change allows a longer time span during the expansion stroke before the exhaust valve is opened. This effectively increases the mean effective pressure acting on the piston during the expansion stroke and thus increases the cycle efficiency. Road loads at steady-state (as were used in this study) use only a fraction of the power available at any speed. Thus, even small gains in mean effective pressure can be significant.

Valve timing can have a significant effect on exhaust emissions due to its effect on the quantity of internal EGR. Emissions of NO_x decreased as the amount of valve overlap increased. Camshaft retard caused a slight decrease in NO_x . Carbon monoxide emissions decreased with increase in valve overlap and both advance or retard of the camshafts at constant valve overlap. Hydrocarbon emissions decreased with a small increase in overlap but then increased again at large amounts of overlap. Both advance and retard of the camshafts at a constant overlap increased HC emissions. The magnitude of change of both the HC and CO emissions was much smaller than the change in NO_x emissions.

Spark timing had a significant effect on NO_x and HC levels. Increasing the spark timing from the baseline setting to mbsfc caused a large increase in HC and NO_x emissions. Carbon monoxide emissions increased but only by a small amount.

Fuel consumption decreased with increase in spark timing to mbsfc. The greatest gain in fuel economy in the valve timing changes was found at the lower speeds (20, 30, and 40 mph). Late exhaust valve opening showed an increase in fuel economy relative to the other valve timing combinations tested.

Valve overlap, in general, tends to show more promise for decrease in fuel consumption than for exhaust emission control.

SUMMARY

The results of this report can be summarized as follows:

1. Valve timing can significantly change exhaust emissions, but additional control hardware is necessary to meet current and proposed emissions regulations.
2. Oxides of nitrogen emissions were affected to a much greater extent than were unburned hydrocarbons or carbon monoxide.
3. Valve timing holds more promise for increased fuel economy than for decreased exhaust emissions.
4. To gain the most benefit from varied valve timing, a control system must be developed to allow automatic changes in valve timing during engine operation. Hardware costs and reliability have been major drawbacks to the systems (7) which have already been developed.

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