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AN INVESTIGATIVE STUDY OF ENGINE LIMITING

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By

R. L. Bechtold

Date Published—February 1978

Bartlesville Energy Research Center
U.S. Department of Energy
Bartlesville, Oklahoma

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By

R. L. Bechtold
BARTLESVILLE ENERGY RESEARCH CENTER
U.S. DEPARTMENT OF ENERGY
BARTLESVILLE, OKLAHOMA 74003

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CONTENTS

	<u>Page</u>
Abstract.....	1
Introduction.....	1
Description of experimental apparatus and procedure.....	2
Test engine and dynamometer set-up.....	2
Experimental procedure.....	3
Fuel used.....	4
Exhaust gas sampling and analysis.....	5
Experimental results and discussion.....	5
Summary.....	13
References.....	14
Appendix A - air/fuel ratio calculation.....	15

ILLUSTRATIONS

Fig.

1. Ford 351W engine on go-power test stand.....	2
2. Dynamometer control panel.....	3
3. "Dummy" lifters (center) as installed in the engine.....	4
4. Specific fuel consumption at constant and at variable speed (taken from reference 6.).....	5
5. BSFC vs brake horsepower.....	7
6. Brake specific HC emissions vs brake horsepower.....	7
7. Exhaust temperature vs brake horsepower.....	8
8. Air-fuel ratio vs brake horsepower.....	8
9. Brake specific CO emissions vs brake horsepower.....	10
10. Brake specific NO _x emissions vs brake horsepower.....	10
11. Percent increase in efficiency vs brake horsepower output.....	11

TABLES

1. General engine specifications.....	2
2. Experimental test modes.....	3
3. Fuel inspection data.....	5
4. Calculated efficiency.....	11
5. Fuel consumption and exhaust emissions at idle (650 rpm, 0 ft-lb torque).....	11
6. Driving cycle weighting factors.....	12
7. Fuel economy calculated from simulated cycles.....	12
8. Exhaust emissions calculated from the simulated urban cycle (hot start).....	12

The Bartlesville (Okla.) Energy Research Center of the Department of Energy has conducted research to determine the operating characteristics of a variable displacement engine. The effect of operation with half the normal number of cylinders of a multicylinder engine at given power outputs was investigated. The changes in fuel consumption and exhaust emissions with varying displacement at a constant power output was documented. The potential energy conversion efficiency gains are discussed for a range of power outputs and engine speeds.

DESCRIPTION OF EXPERIMENTAL APPARATUS AND PROCEDURE

Test Engine and Dynamometer Setup

The engine used in the experimental program was an 8-cylinder 1975 Ford engine rated at 150 net horsepower as installed in a vehicle (figure 1). Table 1 lists the general specifications of this engine. Emission controls consisted of specified spark timing, exhaust-gas-recirculation (EGR), exhaust port air injection, and an oxidation catalyst of monolith construction. The catalyst installation was unique in that it was used on only one bank of cylinders--control of one bank being sufficient to satisfy the 1975 model year vehicle emissions regulations.

The dynamometer used in the test setup was of the waterbrake type (Model D-752) manufactured by Go-Power Systems of Palo Alto, California. (Figure 2 shows the control console for this unit.) Water was supplied to the unit at a regulated pressure of 50 psi by an auxiliary pump. Torque measurement was accomplished by measuring the reaction force transmitted through four fluid-filled cylinders connected to the cradled absorber unit. Torque readings were corrected to a calibration curve generated by applying known torques to the unit.

FIGURE 1. - Ford 351W Engine on Go-Power Test Stand

TABLE 1. - General engine specifications

Engine make.....	Ford Motor Company
Engine configuration.....	V-type, 8-cylinder
Displacement, cu. in.....	351
Net rated power @ 3,800 rpm.....	150 bhp
Net rated torque @ 2,800 rpm.....	244 ft/lb
Bore and stroke.....	4.00 in. x 3.50 in.
Compression ratio.....	8.0:1
Emission controls.....	spark timing, EGR, air pump and oxidation catalyst

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ABSTRACT

An experimental study was conducted to determine the effect of cylinder cut-out or "engine limiting" on fuel consumption and exhaust emissions for a current technology V-type 8-cylinder engine. Increases in energy conversion efficiency while operating with only 4 cylinders ranged from 10 to 40 pct compared to operation with 8 cylinders at the same power outputs. The speeds and loads chosen were representative of those required to operate a 4,500-lb vehicle at speeds up to 60 mph. Hydrocarbon emissions increased at low speed/load points under 4 cylinder operation. An insignificant change in carbon monoxide emissions was observed while an increase in oxides of nitrogen emissions resulted at the higher speed/load points.

INTRODUCTION

The power required to propel a typical passenger vehicle through an ordinary urban environment varies greatly. High power is needed for acceleration while at other times such as deceleration or idle, little or no shaft power output is required. Between these two extremes is steady-speed vehicle operation which requires a constant but relatively low power output compared to that needed for acceleration or climbing.

Most passenger vehicles use 4-stroke cycle, spark-ignition, homogenous charge, throttled engines for propulsive power. It is an inherent characteristic of this type of engine that the best energy conversion efficiency (at a given engine speed) occurs during full-load, wide-open-throttle (WOT) operation. At conditions other than full-load operation, the engine is using more fuel for a given power output than might be needed if the part-load penalty were not encountered. An ideally suited 4-stroke cycle engine in order to handle a varying power requirement, would be one which could change its size so that it operated at full-load at all times. This would assure the highest energy conversion efficiency and the lowest fuel consumption for a given driving cycle.

A high percentage of the engines used in passenger vehicles are of multicylinder design (4, 6, and 8 cylinders). The power output, or "size" of these engines can be effectively changed by varying the number of operating cylinders. Thus, if a multicylinder engine is operating at full load and the power requirement is reduced, the new power output might be met through changing the number of operating cylinders rather than restricting the fuel/air mixture to the engine. This would allow the remaining cylinders to operate nearer full-load in a more efficient mode. In this manner a close approximation to the ideal powerplant previously mentioned could be achieved.

¹Mechanical engineer.

A cooling tower was used in place of a radiator and was set to maintain an engine temperature of 180° F. Fuel flow was measured using a Fluidyne Model 1250 positive displacement flowmeter. All tests were conducted in a controlled environment of 80° F.

Experimental Procedure

Baseline fuel consumption and emissions data were generated with the engine operating on all 8 cylinders. Ten speed/load points were chosen for testing (table 2). The speeds chosen represent typical engine speeds in current vehicles between 30 and 60 mph in high gear. The upper limit of the power levels that were chosen represent half of the maximum output at each speed with 8-cylinder operation. This was done so that full throttle or near full throttle operation would occur when operating with 4-cylinders. The lower limit of power level represents slightly less than the power

TABLE 2. - Experimental Test Modes

Engine speed, rpm	Engine load, brake horsepower		
	Low	Mid-range	High
1,200	10	17.5	25
1,600	15	25	35
2,000	30	40	50
650	0, idle condition

FIGURE 2. - Dynamometer Control Panel

required for road/load operation of a 4,500-lb full-size vehicle. The intermediate power is the arithmetic average of the maximum and minimum power.

After baseline testing was completed, cylinders 3, 2, 5, and 8 were disabled out of a normal firing order of 1-3-7-2-6-5-4-8. The cylinders were disabled by substituting "dummy" lifters for the normal ones. The "dummy" lifters were shorter in height than normal lifters and did not contact the camshaft. Sufficient clearance was allowed between the rocker arm and the valve to prevent inadvertent opening of either valve due to expansion or contraction of engine parts caused by temperature changes. A depression in the top of the "dummy" lifters kept the pushrods from coming out of place (figure 3). The remainder of the valve train was set to factory specifications and operated as normal. No other modifications were made to the engine except that the power valve in the carburetor was deactivated. The spark plugs in the "dead" cylinders were allowed to operate and no change in spark timing was made for 4-cylinder operation. A number of tests were then conducted at the same speed/load points as those of the 8-cylinder baseline tests.

Fuel Used

The fuel used for the experimental work was an unleaded regular grade specified for use by the manufacturer of the engine. Inspection data of the fuel are shown in table 3. All testing was done with this gasoline which came from a single batch of fuel.

FIGURE 3. - "Dummy" Lifters (Center) as Installed in the Engine

Exhaust Gas Sampling and Analysis

Exhaust gases were sampled continuously from an undiluted stream for unburned hydrocarbons (HC), carbon monoxide (CO), oxides of nitrogen (NO_x), oxygen (O_2), and carbon dioxide (CO_2). The analytical methods were: CO and CO_2 by nondispersive infrared, HC by flame ionization detection, O_2 by polarographic technique, and NO_x by chemiluminescence analyzer.

EXPERIMENTAL RESULTS AND DISCUSSION

The main advantage of operating an engine on a varying number of cylinders is reduced specific fuel consumption. The change in specific fuel consumption for a typical passenger car spark-ignited engine (figure 4) is dependent on both speed and load (7)². (Specific fuel consumption in this case will always be the fuel consumed per hour per brake horsepower output, referred to as brake specific fuel consumption or BSFC.) As the load is increased at a constant speed, the BSFC decreases to a minimum value near full load. The hump in the BSFC curve near full load is due to carburetor enrichment of the air-fuel mixture. It then decreases again to a value near the minimum. Depending on the fuel system, it could be said that the BSFC at a constant speed generally decreases as load increases. For a given power requirement and speed, it is usually more efficient to have an engine of capacity only large enough to supply the needed power. At full-load operation a minimum BSFC point is reached at a mid-speed point as shown in the lower curve in figure 4.

The results from this study showed that at an equal power output and speed, the 4-cylinder mode of operation was more fuel efficient than operation on all 8 cylinders (figure 5). The widest difference was observed at the lowest speed and power outputs tested. At constant speed operation the

TABLE 3. - Fuel inspection data

Gravity, °API.....	61.3
Reid vapor pressure, psi.....	10.0
Octane No.:	
ASTM research.....	92.0
ASTM motor.....	84.3
Hydrogen/carbon atom ratio.....	1.88
Sulfur content, wt-pct.....	0.054
Distillation, ASTM D-86, °F:	
IBP.....	89
Percent evaporated:	
5.....	116
10.....	129
20.....	155
30.....	182
40.....	206
50.....	225
60.....	243
70.....	265
80.....	294
90.....	338
95.....	376
End point.....	411
Composition, vol-pct:	
Aromatic.....	22
Olefin.....	11
Saturate.....	67

FIGURE 4. - Specific Fuel Consumption at Constant and at Variable Speed (taken from reference 6.)

²Underlined numbers in parentheses refer to items in the list of references at the end of this report.

decrease in BSFC is mainly due to decreased pumping losses from less throttling of the intake air (7). The power levels for which data are reported are those specified in table 2 and represent low, mid-range, and high outputs at each speed. The spark timing was set to the manufacturer's specifications under 8-cylinder operation and was unchanged for 4-cylinder operation. This prevented knock under the more highly loaded 4-cylinder operation condition.

In general, the specific fuel consumption difference between 8- and 4-cylinder operation at a constant speed decreased as the power output increased. A limiting case for comparison occurs when the 4-cylinder mode reaches full power output. As the 8-cylinder mode of operation reaches full power, its specific fuel consumption settles near the 4-cylinder full power value. The difference between the two cases is the absolute power output--at full load the 8-cylinder mode has twice the power output of the 4-cylinder mode.

Specific HC emissions show that at the speed/load points tested, 8-cylinder operation resulted in lower HC output than 4-cylinder operation (figure 6). The greatest difference occurred at the low power 1,200 rpm test point. At this speed/load condition, the HC output was approximately half that of the engine using only 4 cylinders. As the speed and load were increased to the 2,000 rpm test points, the difference in HC output was relatively insignificant. The absolute value of specific HC emissions also decreases as the speed and load are increased. This is probably due to the higher exhaust temperatures which accompany higher speeds and loads (2,4,6).

At the low speed/load points, the exhaust temperature during 4-cylinder operation was lower than during 8-cylinder operation (figure 7). This is likely due to air delivered by the air pump causing the exhaust gases to be more diluted. Since the air/fuel ratio varied only slightly between 4- and 8-cylinder operation at the 1,200 rpm test points (figure 8), and since the BSFC was less for 4-cylinder operation, the amount of raw exhaust must have decreased under 4-cylinder operation (see appendix A for air/fuel ratio calculation). The air-injection pump, however, delivers air at a volume independent of the amount of cylinders operating. The raw exhaust during 4-cylinder operation is then diluted more than the raw exhaust during 8-cylinder operation with a resulting decrease in exhaust temperature. This effect could explain the increased HC emissions at the low speed/load points under 4-cylinder operation.

As the speed and load were increased, the exhaust temperature under 4-cylinder operation rose to equal that of 8-cylinder operation (high load, 1,600 rpm; and low load, 2,000 rpm). At the higher speed/load points (2,000 rpm mid-range and high load) the exhaust temperature under 4-cylinder operation is higher than that of the 8-cylinder mode. This could be due to more HC oxidation occurring outside the cylinders under 4-cylinder high load operation because of a richer air/fuel ratio (high load, 2,000 rpm) or poor distribution causing some cylinders to run excessively rich.

FIGURE 5. - BSFC vs Brake Horsepower

FIGURE 6. - Brake Specific HC Emissions vs Brake Horsepower

FIGURE 7. - Exhaust Temperature vs Brake Horsepower

FIGURE 8. - Air-fuel Ratio vs Brake Horsepower

The specific CO emissions are virtually the same during both modes of operation except at the high load 2,000 rpm test point (figure 9). At this speed/load point, the CO emissions are much higher under 4-cylinder operation because of the rich air/fuel ratio needed (figure 8) to develop the required power output. During all the other operation modes, the overall air/fuel ratio is lean enough (due to the air pump) so that CO emissions vary little between 4- and 8-cylinder operation.

The specific NO_x emissions indicate higher peak combustion temperatures for 4-cylinder operation (figure 10). At all but the low load, 1,200 rpm test point, the 4-cylinder NO_x emissions were higher than the 8-cylinder emissions. This is a direct result of the higher power output required of each cylinder during 4-cylinder operation (3,5-6). At 1,200 rpm, as the load was increased, a nearly linear increase in NO_x production occurred during 4-cylinder operation. With 8 cylinders, NO_x emissions reached a peak at mid-load, decreasing slightly at the high-load point. For operation at 1,600 rpm, both the 4- and 8-cylinder mode showed increasing NO_x production with increase in load. The main difference at 1,600 rpm is that the absolute NO_x emissions are much higher during 4-cylinder operation. At 2,000 rpm during 8-cylinder operation the same trend of increasing NO_x production with increasing load was present as was recorded at the 1,600 rpm test points. During 4-cylinder operation, the trend is reversed at the high-load test point. This is in accordance with the richer air/fuel ratio needed at the high-load 2,000 rpm test point in order to develop the required power (3,5).

It has already been shown that operation of an engine on half its normal number of cylinders (if possible, for a given power output) results in lower specific fuel consumption. In order to quantify this difference, the energy conversion efficiency for each test point for both 4- and 8-cylinder operation was calculated using averaged power output and fuel consumption values from replicate tests. Efficiency was calculated using the following formula:

$$\text{Eff.} = \frac{\text{Power output (HP)} \cdot 33,000 \left(\frac{\text{ft lbf}}{\text{HP min}} \right) \cdot 60 \left(\frac{\text{min}}{\text{hr}} \right) \cdot 100(\%)}{\text{Fuel rate} \left(\frac{\text{lb fuel}}{\text{hr}} \right) \cdot 18,827 \left(\frac{\text{Btu}}{\text{lb fuel}} \right) \cdot 778 \left(\frac{\text{ft lbf}}{\text{Btu}} \right)} \quad (1)$$

which reduces to:

$$\text{Eff.} = 13.52 \frac{\text{Power output}}{\text{Fuel rate}} \quad (2)$$

The energy content of the fuel given as 18,827 Btu/lb was arrived at by assuming a lower heating value of 116,000 Btu/gas and using the known specific gravity of the fuel. Calculated efficiency of the engine during both modes of operation and the difference between the modes is shown in table 4. For all the test points considered, the efficiency during 4-cylinder operation was greater than during 8-cylinder operation. The greatest increase in efficiency occurred at those test points having the smallest power output. The change in efficiency is nearly independent of speed between the two modes of operation (figure 11, second order data fit).

FIGURE 9.-Brake Specific CO Emissions vs Brake Horsepower

FIGURE 10.-Brake Specific NO_x Emissions vs Brake Horsepower

Fuel consumption at the idle mode (table 5) showed a decrease during 4-cylinder operation to approximately half that during 8-cylinder operation. This suggests that the fuel required at idle is mainly the minimum amount needed for initiation of combustion. The amount of fuel consumed during idle is a very important factor in fuel economy during urban-type driving situations. A vehicle while idling consumes fuel but does not travel any distance to the detriment of the overall fuel economy. Steady-state operating mode simulations (1,8) of the hot-start Environmental Protection Agency (EPA) urban driving cycle have shown heavy dependence on the idle mode ($\approx 30\%$ of the total time spent in the urban driving cycle).

Exhaust emissions at idle showed decreases in HC, CO, and NO_x (table 5) during 4-cylinder operation when measured on a mass emission basis. Hydrocarbons decreased on the order of 23 pct, CO decreased 30 pct, while NO_x decreased approximately 58 pct. This change can be attributed to the difference in air fuel ratio between 4- and 8-cylinder operation. The overall air/fuel ratio was leaner during 8-cylinder operation ($\approx 25:1$) than during 4-cylinder operation ($\approx 22:1$) even though the amount of air delivered by the air pump was the same in both cases. Thus, during 4-cylinder operation the air/fuel ratio in the cylinder itself must have been richer than the overall air/fuel indicated and explains why the NO_x emission was greatly reduced. The increase in HC and CO emissions was probably due to inability of the catalyst to handle the larger amount of raw exhaust during 8-cylinder operation.

In an effort to relate the steady-state results that were obtained to the EPA urban and highway driving cycles, weighting factors were developed for the steady-state speed/load conditions and are presented in table 6. These weighting factors were chosen to best

TABLE 4. - Calculated Efficiency

Speed, rpm	Nominal power output, bhp	Efficiency		Pct 1/ difference
		8-cylinder operation	4-cylinder operation	
1,200	10	14.69	19.45	32.40
1,200	17.5	20.87	26.33	26.16
1,200	25	25.09	30.44	21.32
1,600	15	15.73	22.17	40.94
1,600	25	21.81	26.60	21.96
1,600	35	26.44	30.91	16.91
2,000	30	22.39	26.48	18.27
2,000	40	27.21	29.70	9.15
2,000	50	28.59	31.34	9.62

1/ Pct difference = $\frac{\text{Efficiency 4-cyl. op.} - \text{Efficiency 8-cyl. op.}}{\text{Efficiency 8-cyl. op.}} (100\%)$

TABLE 5.-Fuel Consumption and Exhaust Emissions at Idle (650 rpm, 0 ft-lb torque)

Mode of operation	Fuel rate, lb/hr	HC, gm/hr	CO, gm/hr	NO_x , gm/hr
8-Cylinder.....	4.52	128.1	29.4	2.4
4-Cylinder.....	2.15	98.1	20.6	1.0

FIGURE 11.-Percent Increase in Efficiency vs Brake Horsepower Output

simulate the EPA driving cycles from the available test points (1,8). For both the urban and highway driving cycles the lowest power output at each speed was weighted more heavily than the other test points at that speed because the power output was estimated to be the equivalent road load power needed at that engine speed. (It was the initial intent of the program to evaluate "cylinder limiting" or "dual displacement" engine concepts over the entire road load envelope expected, and thus, the relatively high power modes at each speed.)

Using these weighting factors and the steady-state values of fuel consumption and mass emission rates, it was possible to calculate the contribution of each speed/load point to each individual driving cycle. The results from the fuel economy calculations show that with engine limiting there is a dramatic increase in fuel economy over both the urban and highway driving cycles (table 7). These figures represent a potential gain in fuel economy between 8- and 4-cylinder operation, i.e., the difference in fuel economy between the same vehicle driven over the specified driving cycles with an 8-cylinder engine and a 4-cylinder engine of half the displacement of the 8-cylinder engine. A practical control system utilizing the "cylinder limiting" or "dual displacement" concepts would call for a mixture of 4- and 8-cylinder operation (or integral values between) over the driving cycles. This would provide satisfactory performance but would also limit the gain in fuel economy to something less than what is shown in table 7.

The exhaust emissions calculated for the simulated urban cycle show a large increase in NO_x output, but relatively unchanged CO and HC emissions (table 8). The increase in NO_x

TABLE 6. - Driving Cycle Weighting Factors

Engine speed, rpm	Engine load, bhp	Total time weighting factors	
		Urban cycle	Highway cycle
650	0	0.32	0.05
1,200	10	.22	.06
1,200	17.5	.14	.03
1,200	25	.06	.03
1,600	15	.10	.20
1,600	25	.05	.10
1,600	35	.05	.10
2,000	30	.04	.30
2,000	40	.01	.08
2,000	50	.01	.05

TABLE 7.-Fuel Economy Calculated from Simulated Cycles

Mode of operation	Driving cycle		
	Urban (Hot start)	Highway	Combined urban/highway
8-Cylinder.....	11.52	17.81	13.70
4-Cylinder.....	15.28	21.66	17.62
Pct difference...	+32.6	+21.6	+28.6

TABLE 8.-Exhaust Emissions Calculated from the Simulated Urban Cycle (Hot Start)

Mode of operation	HC, gm/mile	CO, gm/mile	NO_x , gm/mile
8-Cylinder.....	2.67	2.14	2.30
4-Cylinder.....	2.67	2.31	4.53
Pct difference...	+0.0	+7.8	+97.1

emissions is indicative of the higher specific power output of the engine while operating with 4 cylinders. As was the case for the fuel economy calculations, the emissions result represent the extremes of operation over the simulated driving cycle. The actual results, should "engine limiting" or "dual displacement" concepts be applied in an engine control system, should lie somewhere between these two extremes assuming no transient effects from switching the number of operating cylinders.

SUMMARY

For the power outputs tested, 4-cylinder operation used less fuel than 8-cylinder operation because throttled four-stroke cycle engines operate more efficiently as full-load operation is approached. The largest improvements were recorded at the low speed/load points. As speed or load was increased, the difference in fuel consumption between 4- and 8-cylinder operation decreased for an equal power output.

Hydrocarbon emissions were somewhat higher during 4-cylinder operation than during 8-cylinder operation at low speed/load points. Alternate emission controls (retarded spark and/or a larger catalyst) should be able to cope effectively with the increase. An insignificant difference in CO emissions existed between 4- and 8-cylinder operation. Oxides of nitrogen emissions were generally higher during 4-cylinder operation. For a given speed, the increase in NO_x emissions increased as the load was increased. The increased NO_x emissions of the high-load condition at each speed could pose an NO_x control problem. Alternate control strategies (increased EGR, spark retard, etc.) might effectively control the increase.

Fuel economy calculated from simulated EPA urban and highway driving cycles showed a large increase under 4-cylinder operation compared to 8-cylinder operation. A practical control system utilizing 4- and 8-cylinder operation over the driving cycles would not show as great an increase. The results show a potential gain in fuel economy.

The exhaust emissions from the simulated urban driving cycles (hot start) showed practically no change in CO and HC emissions. A large increase (97.1 pct) was estimated for NO_x emissions which is indicative of the higher specific power output of the engine during 4-cylinder operation.

The concept of "engine limiting" or "dual displacement" appears to be a viable energy conservation technique. It allows a throttled 4-stroke cycle engine to operate more efficiently over a wide range of speeds and loads. Changed or alternate emission controls might be necessary to cope with the increase in NO_x emissions during 4-cylinder operation.

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APPENDIX A. - Air/Fuel Ratio Calculation

The air/fuel ratio was calculated using a carbon balance method. The air pump assured that there was excess oxygen available for reaction. It was assumed that the concentrations of HC and NO_x were small compared to CO₂ and O₂ concentrations. Given that the hydrogen to carbon atom ratio was 1.88 from inspection data, the following reaction could be written:

Calculation of air/fuel ratio is by definition,

$$A/F = \frac{\text{mass of air}}{\text{mass of fuel}} \quad (2)$$

Using the elemental balances and combining (1) and (2) yields;

$$A/F = 9.87 \left(\frac{1.47a + 0.97b + c}{a + b} \right) \quad (3)$$

The variables a, b, and c represent respectively the number of moles of CO₂, CO, and O₂ in the dry exhaust. Dividing through equation 3 by the total number of moles in the dry exhaust (6.53a + 4.65b + 4.76c) yields the following equation in terms of percentage concentrations:

$$A/F = 9.87 \left(\frac{1.47 \%CO_2 + 0.97 \%CO + \%O_2}{\%CO_2 + \%CO} \right) \quad (4)$$

Equation 4 is the final result and is used for all A/F calculations.