8. TELEDYNE CONTINENTAL MOTORS EMISSIONS DATA AND ANALYSIS AND FLIGHT TEST RESULTS

Bernard Rezy

Teledyne Continental Motors
Mobile, Alabama

This presentation covers the results of a National Aviation Facilities Experimental Center (NAFEC) emissions contract. The emissions data are currently being reviewed by NAFEC and therefore this presentation cannot be approved by NAFEC at this time. The conclusions presented are those of Teledyne Continental Motors (TCM).

EMISSIONS DATA AND ANALYSIS

Under NAFEC contract DOT FA74NA-1091, Teledyne Continental Motors has tested five different engine models covering combinations of all engine categories in current production in the range from 100 to 435 brake horsepower. Engines are divided into five major types: carbureted, fuel injected, direct drive, geared, and turbocharged. Table 8-1 illustrates the combinations of engine categories tested. Engine displacements of 200, 360, 406, and 520 cubic inches were selected to cover the current production range. The five engine models tested were O-200A, IO-520D, TSIO-360C, Tiara 6-285B, and GTSIO-520K. Each engine was tested at seven steady-state modes of operation defined to simulate airport activity. The engine conditions in each mode are given in table 8-2.

Emissions data were categorized by three separate fuel system schedules: baseline, case 1, and case 2. Baseline is defined as the average fuel flow rate established by the fuel system's production tolerance band when operated with the mixture control at the full-rich position. Case 1 is defined as the minimum allowable fuel flow rate established by the engine certification. Case 1 for most modal conditions is approximately the best power. Case 2 is defined as the fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety limit occurred with the engine operating on a propeller test stand. Safety limits that developed during testing were cylinder-head overheating or inadequate acceleration from a given mode of operation.

Figures 8-1 to 8-5 represent the mixture-strength fuel schedules for the five engine models tested. Each figure shows the fuel-air equivalence ratio for the three fuel system schedules (baseline, case 1, and case 2) as a function of power. Also shown for reference are the modal power points on the auxiliary abscissa scale. All the fuel-injected engines tested (figs. 8-2 to 8-5) exhibited the same general trend in mixture strength, that is, richer at low power, leaner at the midpower range, and richer at maximum power. This trend may be rationalized by considering the present fuel-injection system design. Rich mixtures are required at the low-power idle/taxi regime to provide adequate fuel distribution to all cylinders and to ensure adequate engine transient response (acceleration). Since the present fuel system is not temperature compensating, the fuel flow required for the idle/taxi modes depends on the fuel-air ratio required for cold-day operation. As the induction air temperature increases, the resultant fuel-air mixture is enriched. Leaner mixtures are acceptable and desirable in the midpower range where fuel distribution is good and cylinder-head temperatures are well within the limits. Richer mixtures are required at high-power points for cylinder-head cooling and detonation suppression. The Federal Aviation Administration (FAA) requires that the minimum fuel flow rate certified be at least 10 percent above the fuel flow rate at which detonation occurs.

The mixture-strength schedules of the engines tested also exhibit the same trend with respect to baseline, case 1, and case 2 fuel schedules. A wider equivalence ratio band exists between each fuel schedule at low power, and this band decreases to a minimum at maximum power. This is due to the larger tolerance band associated with controlling low fuel flow rates. In figure 8-1, the carbureted O-200A engine's fuel schedule for baseline and case 1 follows the delivery characteristics of a typical commercial single-venturi carburetor. Case 2 illustrates the narrowing margin available between an uninstalled safety limit and the minimum allowable fuel flow (case 1) as power increases. Cylinder-head overheating was the safety limit encountered for the climb and takeoff modes, while inadequate acceleration was the safety limit encountered for the idle, taxi, and approach modes. Figure 8-2 illustrates the mixture-strength schedules for the IO-520D, a fuel-injected, 520-cubic-inch-displacement engine. Again the margin available between an uninstalled safety limit and the minimum allowable fuel flow decreases as power increases. The fuel-injected engines exhibited the same safety limits as the carbureted engine, that is, cylinder-head overheating during climb and takeoff modes and inadequate acceleration for the idle, taxi, and approach modes. Figure 8-3 shows the mixture-strength schedules for the Tiara 6-285B, a geared, fuel-injected, 406-cubic-inch-displacement engine. These curves indicate a much narrower band between baseline, case 1, and case 2. This is attributed to the high-speed engine design, allowing a higher percentage of the maximum fuel flow at low-speed conditions. Figure 8-4 illustrates the mixture-strength schedules for a turbocharged, fuel-injected, 360-cubic-inch-displacement TSIO-360C engine. Figure 8-5 shows the mixture-strength schedules for a geared, turbocharged, fuel-injected, 520-cubic-inch-displacement GTSIO-520K engine.

It is important to note that the five different engine mixture-strength schedules thus far discussed are for the specific engines tested.

The combined production tolerance effect of both fuel flow and induction airflow has not been determined to date. Also, the effects of engine cumulative operational time on mixture-strength schedules, and therefore on emissions, has not been determined.

Figures 8-6 to 8-10 are plots of the emission levels for the five engine models tested. The figures present the emission levels in percent of the EPA standard as a function of time-weighted, fuel-air equivalence ratio. Emission levels above 100 percent are over the standard; levels below 100 percent are within the standard. The time-weighted, fuel-air equivalence ratio ϕ_{tw} is defined as the summation of the product of the modal time and the modal equivalence ratio divided by the total cycle time. In equation form

$$\phi_{tw} = \frac{\sum_{i=1}^{7} T_i \phi_i}{27.3}$$

where

T_i time in mode i

ϕ_i equivalence ratio in mode i

The time-weighted equivalence ratio provides a means of establishing baseline, case 1, and case 2 emissions levels as a function of a common reference for each pollutant. The results of "leaning" can therefore be quickly recognized. As expected, leaning the engines decreased carbon monoxide (CO) and hydrocarbons (HC) but increased oxides of nitrogen (NO_x).

In figure 8-6, the O-200A engine baseline mixture-strength schedule results in a ϕ_{tw} of 1.43 with CO above the standard, HC slightly over the standard, and NO_x below the standard. Leaning to case 1 results in a ϕ_{tw} of 1.19 with corresponding reductions from baseline of 27 percent for CO and 43 percent for HC. However, NO_x increased by 221 percent, resulting in a level well over the standard. Additional leaning to case 2 resulted in a ϕ_{tw} slightly less than stoichiometric, 0.99, with decreases from case 1 of 39 percent for CO and 37 percent for HC. The NO_x emissions continued to increase, resulting in a 69-percent increase over case 1. Leaning the O-200A engine did not reduce all three pollutants (CO, HC, and NO_x) below the EPA limits.

Figure 8-7 shows the emissions levels for the IO-520D engine. The baseline mixture-strength schedule resulted in a ϕ_{tw} of 1.43, with CO and HC above the standard and NO_x well below the limit. Decreases of 34 percent for CO and 19 percent for HC were observed when the engine was leaned to a ϕ_{tw} of 1.23 (case 1); NO_x increased 118 percent but remained considerably below the limit. Case 2, ϕ_{tw} of 1.12, resulted in levels for all three pollutants below the EPA standards, with decreases from case 1 of 34 percent for CO and 37 percent for HC; NO_x increased by 83 percent. From figure 8-7 an estimated band of time-weighted, fuel-air equivalence ratios that meet all EPA standards can be determined. This total band ranges from a ϕ_{tw} of 1.02 to 1.16. However, when case 2 is considered (uninstalled safety limits), this band is reduced to a ϕ_{tw} range of 1.12 to 1.16, which results in a ±1.75 percent tolerance band on fuel-air ratio for the complete seven-mode cycle.

Tiara 6-285B emission levels are presented in figure 8-8. Tiara differs considerably from the previous engines discussed (O-200A and IO-520D) in that the HC limit never exceeded the EPA standards. The primary reason for this is the higher engine speeds associated with a geared engine. Increasing the idle and taxi engine speeds provides better engine breathing with less short circuiting of the incoming charge and thus lower hydrocarbon emissions. The baseline mixture schedule resulted in a ϕ_{tw} of 1.24, with CO the only pollutant over the standard. Leaning to case 1 resulted in a ϕ_{tw} of 1.13, with corresponding reductions from baseline of 33 percent for CO and 26 percent for HC; NO_x increased by 105 percent. Additional leaning to case 2 resulted in a ϕ_{tw} of 1.10, with decreases from case 1 of 20 percent for CO and 7 percent for HC; NO_x increased by 45 percent. A narrow band of ϕ_{tw} (1.04 to 1.10) existed where all pollutants were below the EPA standard. However, this band was leaner than the uninstalled safety limits.

Figure 8-9 represents the emission levels for the TSIO-360C engine. This engine was the only engine tested that exhibited HC levels higher than the CO levels, as defined by the EPA standard. Fuel-air, cylinder-to-cylinder distribution is the predominant factor in the high hydrocarbon levels. A "runner" type of induction system coupled with short connecting tubes to the respective cylinder ports promotes variations in air distribution. Fuel distribution can also be affected by the oscillating flow within the short connecting tubes. Cylinder-head temperature variations tend to support this theory. Low-power, cylinder-head temperature variations are significantly larger for this engine than for the "spider" type of manifolds of the Tiara or GTSIO-520K engines. The baseline mixture schedule resulted in a ϕ_{tw} of 1.34, with both CO and HC well over the standards. The NO_x values were the lowest recorded of the five engines tested. Decreases of 51 percent for CO and 27 percent for HC were observed when the engine was leaned to a ϕ_{tw} of 1.19 (case 1); NO_x increased 630 percent but was still below the standard. Leaning to case 2, ϕ_{tw} of 1.10, resulted in a decrease from case 1 of 27 percent for CO and 31 percent for HC. But the NO_x emissions increased by 72 percent, resulting in a level exceeding the EPA standard. Leaning the TSIO-360C engine could not reduce all three pollutants below the EPA limits.

Figure 8-10 illustrates the emission levels associated with the GTSIO-520K engine. As in the case of the other geared engine (Tiara) the HC and NO_x levels were below the EPA standard for the three mixture schedules tested. Carbon monoxide, however, could not be reduced below the limit while the engine was operating within the uninstalled safety limit. The baseline mixture schedule resulted in a ϕ_{tw} of 1.38, with CO the only pollutant over the EPA standard. Leaning to case 1 resulted in a ϕ_{tw} of 1.24, with corresponding reductions from baseline of 24 percent for CO and 14 percent for HC; NO_x increased by 219 percent. Additional leaning to case 2 resulted in a ϕ_{tw} of 1.08, with decreases from case 1 of 28 percent for CO and 24 percent for HC; NO_x increased by 57 percent. A narrow band of ϕ_{tw} (0.98 to 1.03) can be estimated where all pollutants are below the EPA standard; however, this band is leaner than the uninstalled safety limits.

With the stipulation that neither production tolerances nor the effect of engine cumulative operation time have as yet been established, the exhaust emissions levels presented thus far represent the pollutant levels associated with the three mixture-strength fuel schedules (baseline, case 1, and case 2).

Figures 8-11 to 8-15 represent the effect of modal equivalence ratio on CO, HC, and NO_x levels for each of the engines tested. Each figure illustrates the pollutant as a percent of the EPA standard as a function of modal equivalence ratio decrease from case 1. The curves clearly show the effects of each mode on the total cycle emission level as the modes are leaned beyond the lean limit of the engine model specifications. Case 1 was chosen as the starting point from which the leaning was referenced since leaning beyond case 1 has already been demonstrated as mandatory in order to reduce CO and HC to values below the EPA standard. Each modal curve has been identified with symbols that also locate two important points of reference, case 2 (flagged symbols) and the stoichiometric fuel-air ratio (closed symbols). The closed symbols represent the reduction in modal equivalence ratio required to provide a stoichiometric mixture and the corresponding emission level for the cycle. The flagged symbols represent the reduction in modal equivalence ratio required to lean to the uninstalled modal safety limit. Dashed lines are extrapolations of available data.

A significant amount of intelligent and useful information can be derived from these curves. From figure 8-11(a) the effect of modal leaning on CO for the O-200A engine can be determined. For example, if only the climb mode was leaned to case 2 ($\Delta\phi = 0.03$ decrease from case 1), the CO percent of the EPA standard would drop from 154 to 140 percent, or a change in reduction of 14 percent. Any combination of modal leaning can be predicted as illustrated in table 8-3, in which the taxi, climb, and approach modes are leaned to case 2. Note that the resultant CO emission level for this example is approximately equal to the case 2 value for the overall cycle (fig. 8-6). This can be rationalized by the relative effect that each mode has on the overall cycle results. Climb, approach, and taxi are the significant modes for CO reduction, while idle and takeoff have virtually no effect. Although climb and approach have the greatest effect on CO, taxi becomes the most promising mode for leaning when consideration is given to the case 2 uninstalled safety limits. This conclusion is further supported when modal leaning effects on HC are analyzed (fig. 8-11(b)). However, figure 8-11(c) shows that a penalty must be accepted when consideration is given to the resulting NO_x levels.

Figure 8-12 represents the modal leanout effects for the IO-520D engine. The predominant modes for CO reduction were again climb and then approach. The taxi mode had little effect, as opposed to the O-200 results. Leaning the climb mode alone will bring the IO-520D engine within the CO limits if the modal installed safety limit can be leaned below the present uninstalled safety limit. This fact will be pursued later during the analysis of our flight test results.

Figure 8-13 illustrates the effect of modal leaning for the Tiara 6-285B engine. Since the hydrocarbons were below the standard for all fuel schedules tested, the modal leanout trade-off affects only CO and NO_x. In case 2, the only practical mode for leanout adjustments is climb, which comes very close to meeting the standard. Some additional reduction can be attained by leaning the approach mode.

The TSIO-360C modal leanout curves are presented in figure 8-14. Again, the climb mode is the most promising mode for CO reduction; however, taxi is the only mode for consideration for HC reduction. Leaning both climb and taxi to case 2 will significantly reduce CO and HC; however, HC and NO_x will still be over the EPA standard.

From figure 8-15 the GTSIO-520K engine resembles the results of the other geared engine, Tiara, in that HC and NO_x are within the limits and climb is the predominant mode affecting CO reduction.

FLIGHT TEST RESULTS

The modal leanout curves present a detailed picture of what is possible in modal leaning below the present engine fuel flow specifications (case 1). To determine what reductions are possible, the difference between uninstalled and installed safety limits must be understood. To accomplish this, TCM modified fuel systems to simulate the mixture strength schedules of case 1 and case 2. Leaned systems were delivered to Cessna for the O-200A to be flight tested in the Cessna 150 and for the TSIO-360C to be flight tested in the Cessna T337. Rockwell International received leaned systems for the GTSIO-520K to be flight tested in the Aero Commander 685. Under the NAFEC contract, TCM conducted flight testing on the IO-520 engine installed in a Cessna 210.

Separate reports by Cessna will cover the results of the O-200A and TSIO-360C flight tests. For completeness of this report, however, a brief summary of the results is given in table 8-4. To date, flight tests have not been conducted on the GTSIO-520K engine.

Teledyne Continental flight tested the IO-520D engine on the baseline and case 2 mixture-strength schedules as defined in figure 8-2. The case 1 mixture schedule would be tested only if flight test results indicated problems with case 2. Determining the effect of climatic constraints, 0° to 100° F ambient temperature, was considered mandatory during the flight tests. Cold weather testing was conducted at Fargo, North Dakota; hot weather testing was conducted at Del Rio and Laredo, Texas. Instrumentation consisted of an oscillograph that recorded manifold pressure, fuel flow, engine speed, and throttle position. A temperature strip-chart recorder monitored the six cylinder heads as well as the exhaust gas, inlet and exit cooling air, induction air, ambient air, fuel, and oil temperatures. Additional data logged manually consisted of cooling-air differential pressure, pressure altitude, indicated and vertical airspeed, oil pressure, fuel pump pressure, fuel metered pressure, cowl flap position, wing flap position, and mixture control position.

As discussed previously, cylinder-head overheating was the uninstalled safety limit encountered for the climb and takeoff modes; inadequate acceleration defined the uninstalled safety limit for the idle, taxi, and approach modes. Figure 8-16 depicts a cold weather (30° F) acceleration test for the baseline fuel schedule. The curves represent manifold absolute pressure, engine rpm, and fuel flow as a function of time. The acceleration test was an instantaneous throttle burst from idle. Note that engine speed immediately responded from zero time; and after 3.4 seconds had elapsed, the engine had attained full speed and fuel flow. Figure 8-17 illustrates a cold weather (30° F) throttle burst from idle for the case 2 fuel schedule. As in the preceding example, manifold pressure peaked in less than a second; however, engine speed and fuel flow began to rise but then decreased. The engine would continue to run at this low speed until the throttle was brought back to idle and then slowly moved to the full-throttle position.

At 30° F ambient temperatures, no acceleration problems occurred for the taxi or approach modes. Further testing at 0° F was therefore mandatory as colder inlet conditions will produce leaner fuel-air ratios since the present fuel-injection system is not temperature compensating. Suitable environmental conditions could not be found, and as a result TCM funded rental time at the Eglin Air Force Base climatic hangar. The Eglin climatic hangar has the capability of maintaining 0° F and a wind velocity simulating the approach mode. Results at 0° F for the baseline fuel schedule were acceptable; however, case 2 acceleration from taxi and idle was impossible as the engine would not operate at those fuel flows. Acceleration from the simulated approach mode was acceptable for the case 2 fuel system. As expected, no cylinder-head overheating occurred during any of the cold ambient testing. Hot weather testing was conducted near Del Rio and Laredo, Texas, in order to provide the required 100° F ambient conditions. With the less-dense induction air (richer mixture), no acceleration problems occurred for baseline or case 2 fuel schedules at idle, taxi, or approach.

Figure 8-18 depicts the case 2 fuel schedule results for the cooling climb tests at both cold- and hot-day conditions. The maximum and minimum cylinder-head temperatures, as well as the outside air temperatures, are plotted as a function of pressure altitude. A maximum cylinder-head temperature of 395° F occurred during the hot-day testing, well within the model specification limit. The case 2 fuel schedule at takeoff and climb was therefore acceptable.

The uninstalled safety limits are compared with the actual flight tests in table 8-5. Case 2, as defined earlier, is the fuel flow rate corresponding to the leanest fuel-air ratio obtainable before a safety limit occurred with the engine operating on a propeller test stand. Fuel flow rate was the parameter defining case 2 since the present fuel systems do not meter as a function of fuel-air mass ratio. The carbureted system meters fuel by sensing induction-air pressure drop across the venturi and ambient pressure (float bowl). The present, continuous-flow, fuel-injection system controls fuel flow in response to changes in throttle plate angle and engine speed. Compressor discharge pressure is also referenced on turbocharged engines. Temperature, and therefore air density, is not a controlling factor. It is not surprising therefore that the flight test results differ from the uninstalled-safety-limit (case 2) results.

Using the IO-520 data in table 8-5 as an example, all modes exhibiting an acceleration safety limit, except approach, became more of a hazard as temperature decreased, indicating leaner fuel-air ratios than case 2. The simulated approach made at 0° F temperature did not exhibit an acceleration problem. This was probably due to the windmilling effect of the high-velocity air across the propeller blades, which aids the engine in accelerating during a closed-throttle approach. As predicted, cylinder-head overheating did not occur in the takeoff and climb modes for the IO-520 installation. However, this was not true for the TSIO-360C installation. Reliable projections of uninstalled cooling data to actual installations will require a detailed understanding of the cooling air distribution for each installation. However, since climb operation may be conducted at speeds higher than the best-rate-of-climb speed, it is feasible to predict a mixture strength at climb leaned to case 2. The takeoff mode, as discussed previously, has little or no effect on the emission levels and therefore should be set at baseline. Case 2 can therefore be defined as the installed safety limits for the IO-520/Cessna 210 and TSIO-360C/Cessna T337 installations, provided the present fuel-injection system is modified to schedule fuel-air ratio and provided the airframe manufacturer can accept (if necessary) a performance penalty during climb.

Analysis of the flight tests and emission data led to the following conclusions:

(1) Baseline fuel schedules for the engines tested do not meet the EPA exhaust emission standards.

(2) Case 1 fuel schedules for the engines tested do not meet the EPA exhaust emission standards.

(3) Case 2 fuel schedules for the IO-520D and Tiara 6-285B engines met the EPA exhaust emission standards.

(4) Case 2 fuel schedules for the O-200A, TSIO-360C, and GTSIO-520K engines do not meet the EPA exhaust emission standards.

(5) Individual modal leaning should be restricted to the climb, approach, and taxi modes.

(6) Carbon monoxide contribution occurs principally during the climb mode.

(7) Hydrocarbon contribution occurs principally during the taxi mode.

(8) Approach mode is the second largest contributor to carbon monoxide and hydrocarbon emissions.

(9) Uninstalled engine safety limits (case 2) differ from installed engine safety limits.

POSSIBLE EMISSION REDUCTIONS

The flight test results presented the problems associated with leaning the present fuel systems to the case 2 fuel schedule. Some modes could be leaned to the case 2 fuel schedule; others could be leaned between case 1 and case 2. Using the IO-520 engine as an example, each mode can be analyzed for possible emissions reductions. In the idle and taxi modes the mixture-strength ratio is limited to that which permits safe transient response. The leanest fuel-air ratio will occur on a cold day. Leaning below case 1 was impossible for the idle mode. However, leaning below case 1 was possible in the taxi mode, resulting in a $\Delta\phi$ of 0.07, approximately halfway between case 1 and case 2. Takeoff has an insignificant effect on emissions and therefore will not be leaned out. Climb and approach could be leaned to the case 2 fuel schedule.

A total reduction from case 1 of 31 percent for CO and 19 percent for HC can be predicted (fig. 8-12). Oxides of nitrogen will increase by 81 percent but remain well below the limit. In terms of the EPA limits, CO, HC, and NO_x will be 86, 78, and 54 percent of the standard. Applying the production tolerance band, resulting from the baseline - case 1 fuel schedules (fig. 8-2), to the minimum installed fuel schedule reveals the nominal emission levels that can be expected:

Fuel schedule	Emission level, percent of EPA standard		
	CO	HC	NO_x
Minimum	86	78	54
Nominal	150	115	24
Baseline	189	119	14

These projections do not consider any engine-to-engine production tolerances or the effect of engine cumulative time. The differences between the nominal and baseline levels represent the reductions possible by modal leaning within the installed safety limits for the IO-520D/Cessna 210 installation. A similar analysis can be made for the TSIO-360C engine. Approach could be leaned to case 2. Climb, although not verified as yet, will be leaned to case 2 for the purpose of this analysis by increasing the aircraft's rate-of-climb speed.

From figure 8-14 a total reduction from case 1 of 21 percent for CO and 2 percent for HC can be expected. Oxides of nitrogen will increase by 71 percent, resulting in absolute percent of EPA standards of 91 for CO, 177 for HC, and 109 for NO_x. Applying the baseline - case 1 fuel schedule tolerance band (fig. 8-4) results in the following emission levels:

Fuel schedule	Emission level, percent of EPA standard		
	CO	HC	NO_x
Minimum	91	177	109
Nominal	207	240	12
Baseline	234	246	9

Again, engine-to-engine production tolerances and the effect of engine cumulative time were not considered. Nominal and baseline differences represent the reduction possible by modal leaning within the projected installed safety limits for the TSIO-360C/Cessna T337 installation.

Based on these examples, it does not appear practical to pursue individual modal leaning for each engine presently in production. The time involved to flight test, modify, and recertify all production engines will delay development of more significant emissions reduction concepts.

DISCUSSION

Q - G. Kittredge: The main thing that struck me with your presentation, compared to the preceding two by AVCO and NAFEC, is that the engines you are talking about include several which would be drastically affected if EPA were to go ahead with the tentative plans to eliminate the NO_x and HC standards. You did have several engines where they were the limiting pollutants?

A - B. Rezy: Yes, that is right.

Q - W. Westfield: George, I have to direct this to you and also to Bernie. Are you referring to Bernie's statement about 630 percent increase in NO_x for one case?

A - G. Kittredge: Yes.

Q - W. Westfield: Is a percentage term the right term to use in this case or should we be talking absolute numbers?

A - B. Rezy: I think he's talking absolute numbers. We've indicated that we went over the limits as we leaned out.

Q - W. Westfield: I realize that, but you're 630 percent over baseline which was well under. So you're talking 630 percent of a very small number.

A - L. Helms: The initial curves that you presented showed baseline, case 1 and case 2, where case 2 was identified as the uninstalled safety limit. There were several cases there where it appeared the uninstalled safety limit was equivalent to the lean production. Is that right?

A - B. Rezy: It was very close to the lean production limit.

Q - L. Helms: On your cold weather tests, could you tell me how you did those? Specifically, did you start the engine, warm it up, then make the adjustments and make the test runs?

A - B. Rezy: Yes, that is correct.

Q - L. Helms: At any time did you try to start the engine with the modified fuel metering system?

A - B. Rezy: Yes, we did try and it would not start. We had to heat the engine to get it to start. Once we could get it started, we then conducted our tests. That's at 0°.

Q - G. Kittredge: In your cold weather testing, you identified several conditions where you had acceleration problems. How fundamental do you feel these problems are? Are they solvable with a reasonable amount of developmental effort or are they basic to the fixed design of the engine?

A - B. Rezy: We feel that if you can hold fuel-air ratio, which these present fuel injection systems cannot in the idle/taxi modes, you then could run at those conditions. That does not include any production tolerances. We don't know what the true emission level would be if we had a fuel injection system that could control the fuel-air ratio in the idle/taxi modes.

Q - G. Kittredge: With the experience that you now have, do you feel you are getting good data using the emission test procedures that have gradually evolved over the 3 years of experience that you have?
A - B. Rezy: Yes.

COMMENT - W. Westfield: On the first chart of your conclusions you said that none of the engines could meet the limit at case 1, but then the next thing you said was two engines could meet the limit at case 2.

A - B. Rezy: That's true, case 2 is leaner than case 1.

TABLE 8-1

ENGINE MODEL	0-200 A	TSIO-360 C	TIARA 6-285 B	IO-520 D	GTSIO-520 K
RATED BHP	100	225	285	300	435
DISPLACEMENT CU. IN.	201	360	406	520	520
PROPELLER RPM	2700	2800	2000	2850	2267
CARBURETED	●				
FUEL INJECTED		●	●	●	●
DIRECT DRIVE	●	●		●	
GEARED			●		●
TURBOCHARGED		●			●

TABLE 8-2

MODE NO.	MODE NAME	WEIGHTED TIME IN EACH MODE (Minutes)	ENGINE CONDITIONS Percent Power	ENGINE CONDITIONS Propeller Speed
1	Idle Out	1.0	-	600 RPM
2	Taxi Out	11.0	-	1200 RPM
3	Take-Off	0.3	100%	100% of Max. RPM
4	Climb	5.0	80%	90% of Max. RPM
5	Approach	6.0	40%	87% of Max. RPM
6	Taxi In	3.0	-	1200 RPM
7	Idle In	1.0	-	600 RPM
TOTAL		27.3		

TABLE 8-3

MODE	EMISSION LEVEL AT CASE 2 (Percent of EPA Standard)	DELTA REDUCTION IN EMISSION LEVEL FROM CASE 1 (Percent of EPA Standard)
Taxi	118.	36.
Climb	140.	14.
Approach	145.	9.
	$\sum$DELTAS =	59.

$$\begin{bmatrix}\text{Resultant Percent}\\ \text{of EPA Standard}\end{bmatrix} = \begin{bmatrix}\text{Percent of}\\ \text{EPA Standard}\\ \text{at Case 1}\end{bmatrix} - \sum\text{DELTAS}$$

$$= 154\% - 59\% = 95\%$$

TABLE 8-4

ENGINE	FUEL SCHEDULE	COMMENTS	
0-200A	Case 1	Acceptable for all conditions. Minor backfiring during throttle closure	
	Case 2	Unacceptable, engine would not operate below 1700 rpm and cylinder overheating occurred. Unsafe for flight tests	
TSIO-360C	Case 1 The fuel schedule for Case 1 was slightly leaner than the desired schedule	Idle-Taxi	- exhibited some roughness, acceleration marginally acceptable
		Take-Off	- cylinder overheating
		80% Climb	- cylinder head temperature would be over limit if corrected to a 100°F day
		40% Approach	- acceleration acceptable
		Closed Throttle Approach	marginally acceptable, minor engine - stumble on simulated go-arounds
	Case 2	Idle-Taxi	- engine rough, acceleration was poor
		Take-Off	- not evaluated since Case 1 already exhibited cylinder overheating
TSIO-360C	Case 2	80% Climb	- exceeded cylinder head temperature limit without 100°F ambient day correction.
		40% Approach	- acceleration acceptable
		Closed Throttle Approach	- unacceptable acceleration, engine died on occasion

TABLE 8-5

Engine/Aircraft Mode	Case 2 Mixture Schedule Uninstalled Safety Hazard	Case 2 Mixture Schedule Installed Safety Results
O-200A/Cessna 150		
Idle	Acceleration Limit	Unacceptable engine operation, unsafe for flight tests
Taxi	Acceleration Limit	
Take-Off	Cylinder Head Limit	
Climb	Cylinder Head Limit	
Approach	Acceleration Limit	
TSIO-360C/Cessna T337		
Idle	Acceleration Limit	Engine rough, poor acceleration
Taxi	Acceleration Limit	Engine rough, poor acceleration
Take-Off	Cylinder Head Limit	Not evaluated since Case 1 at cylinder head limit
Climb	Cylinder Head Limit	Exceeded cylinder head temperature
40% Approach	Acceleration Limit	Acceleration acceptable
Closed Throttle Approach	Acceleration Limit	Unacceptable acceleration, engine died on occasion
IO-520/Cessna 210		Engine would not accelerate at 30° F
Idle	Acceleration Limit	Engine would not operate to Case 2 idle fuel flows at 0° F
Taxi	Acceleration Limit	Engine would not operate to Case 2 taxi fuel flows at 0° F
Take-Off	Cylinder Head Limit	Cylinder head temperature within limits
Climb	Cylinder Head Limit	Cylinder head temperature within limits
40% Approach	Acceleration Limit	Simulated approach at 0° F was acceptable
Closed Throttle Approach	Acceleration Limit	Simulated approach at 0° F was acceptable

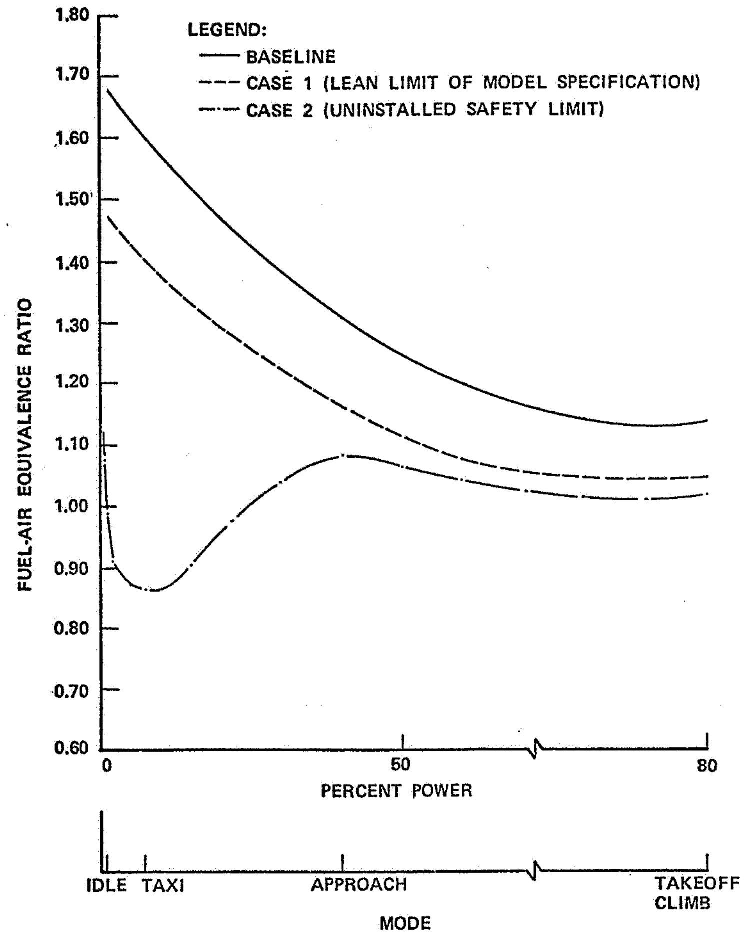

Figure 8-1

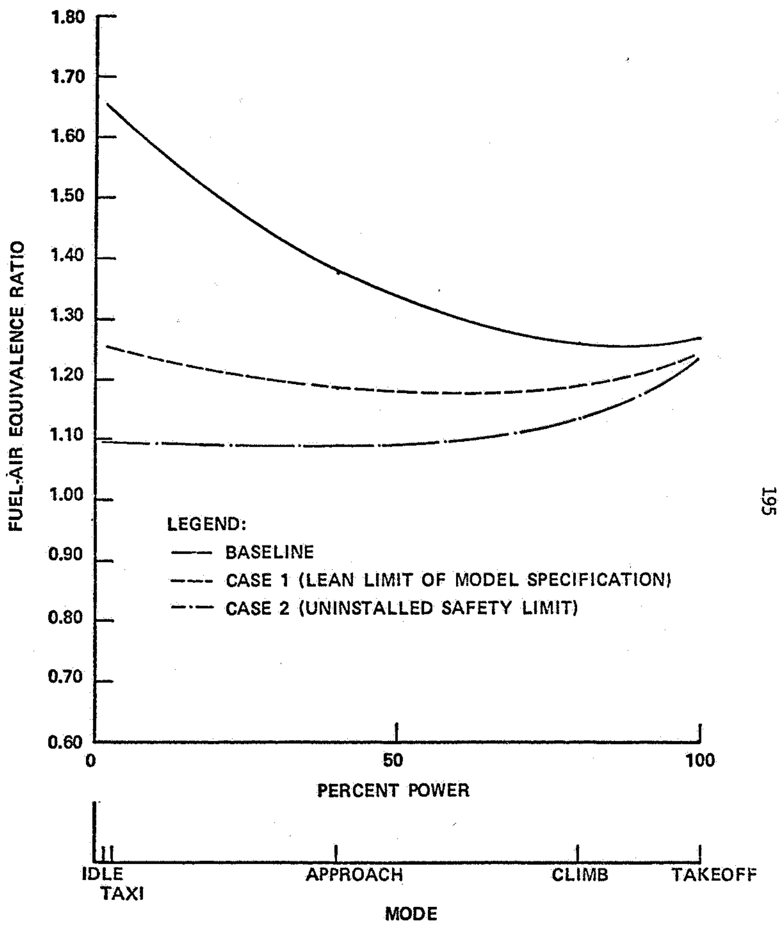

Figure 8-2

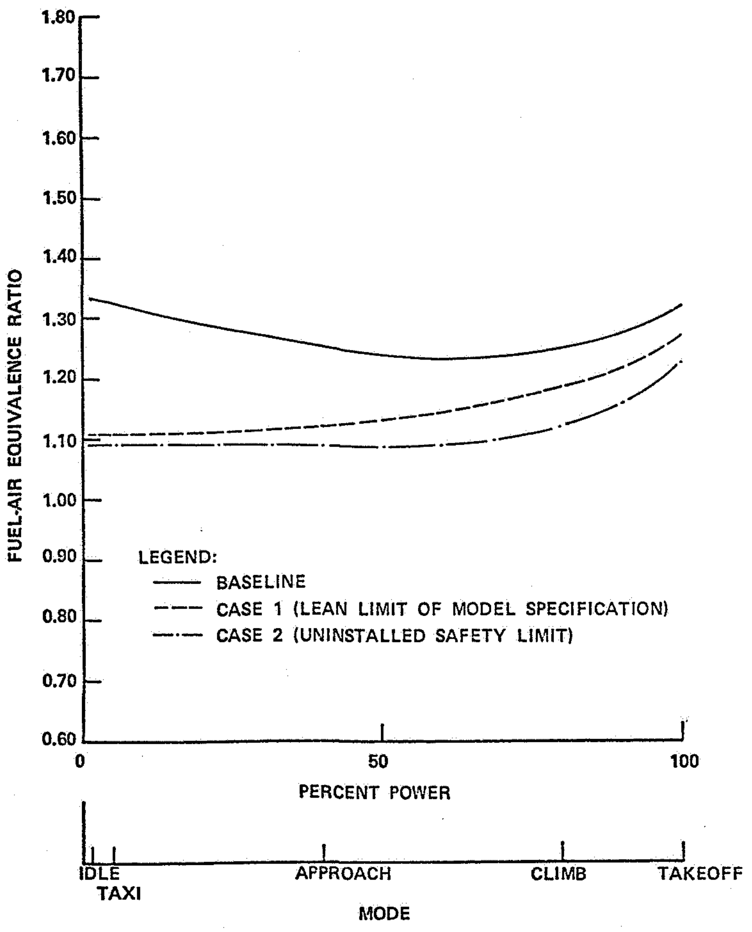

Figure 8-3

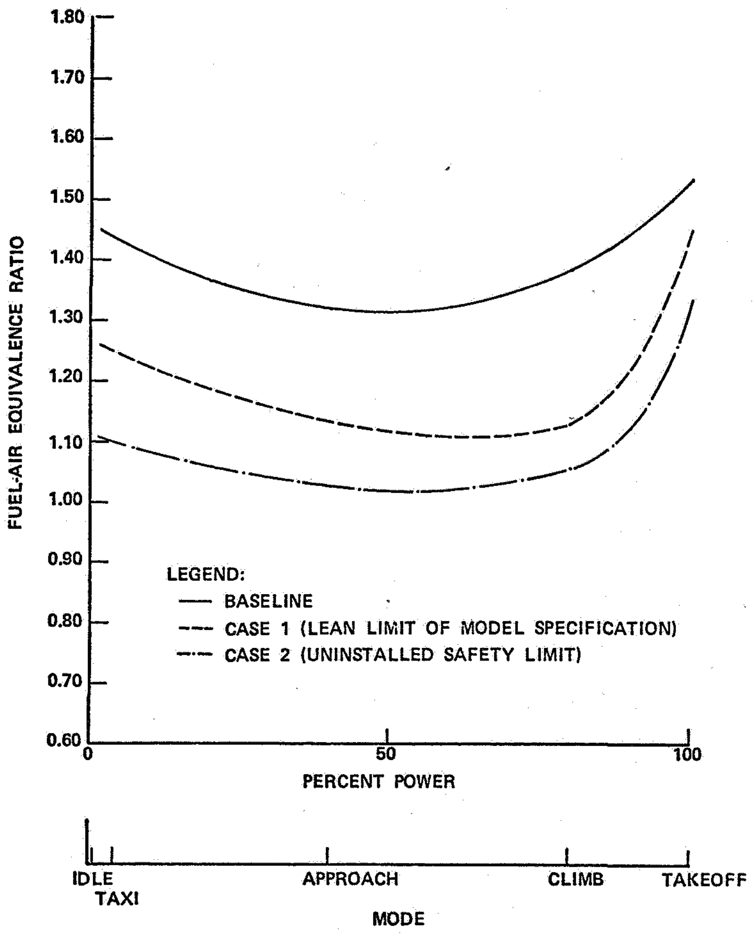

Figure 8-4

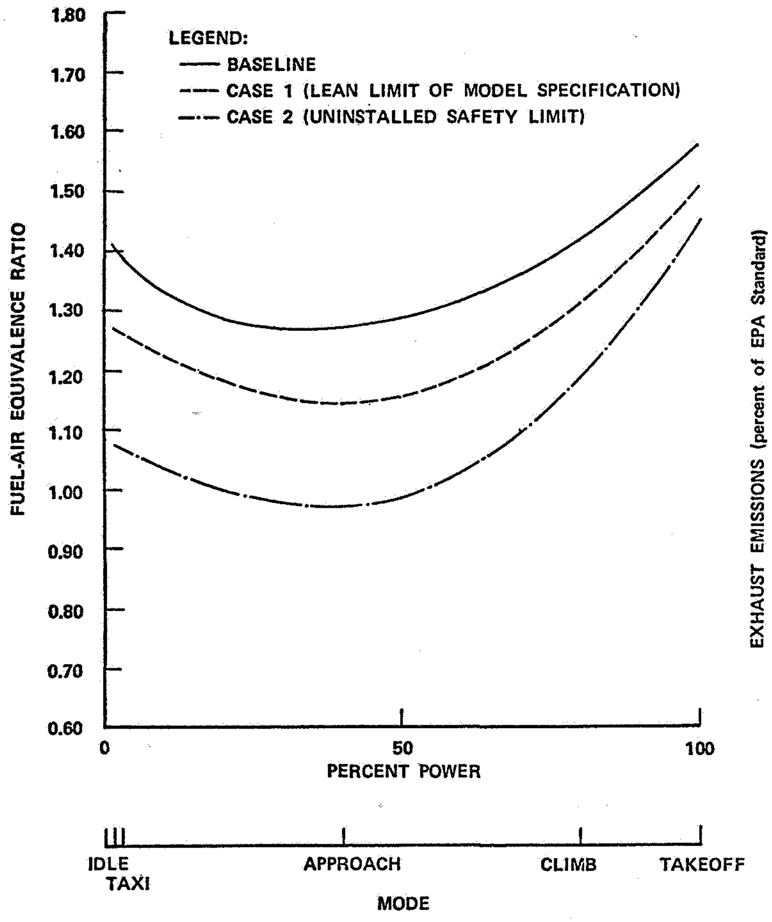

Figure 8-5

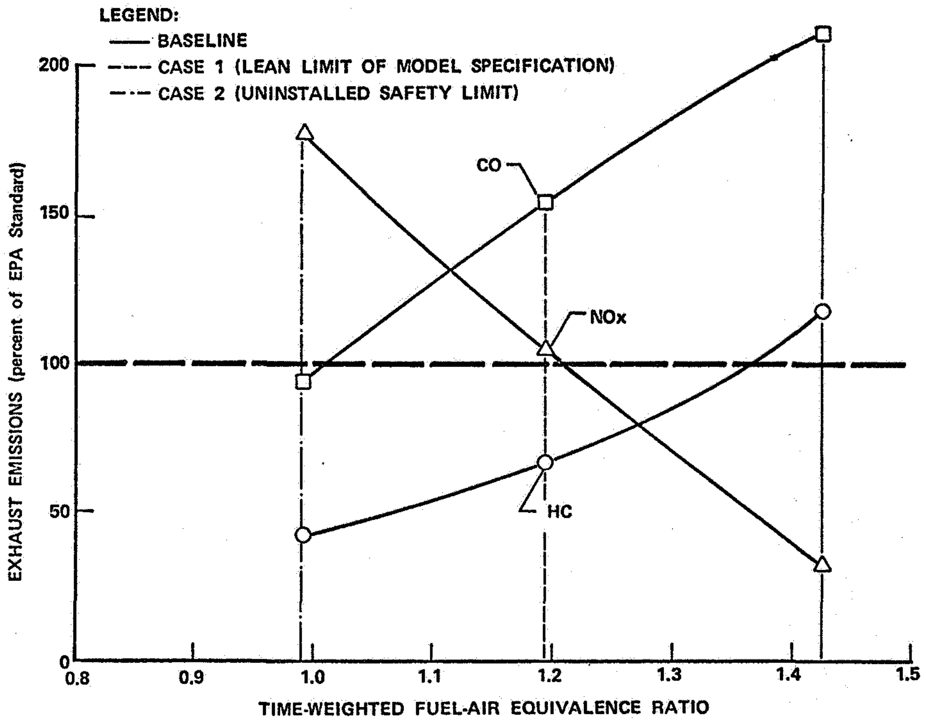

Figure 8-6

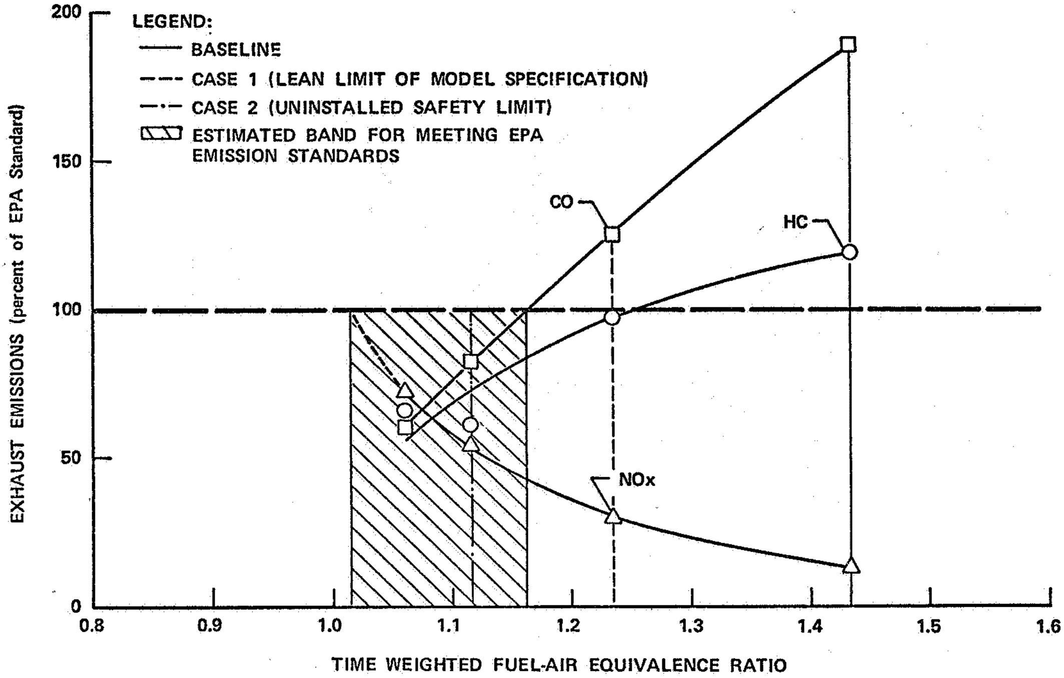

Figure 8-7

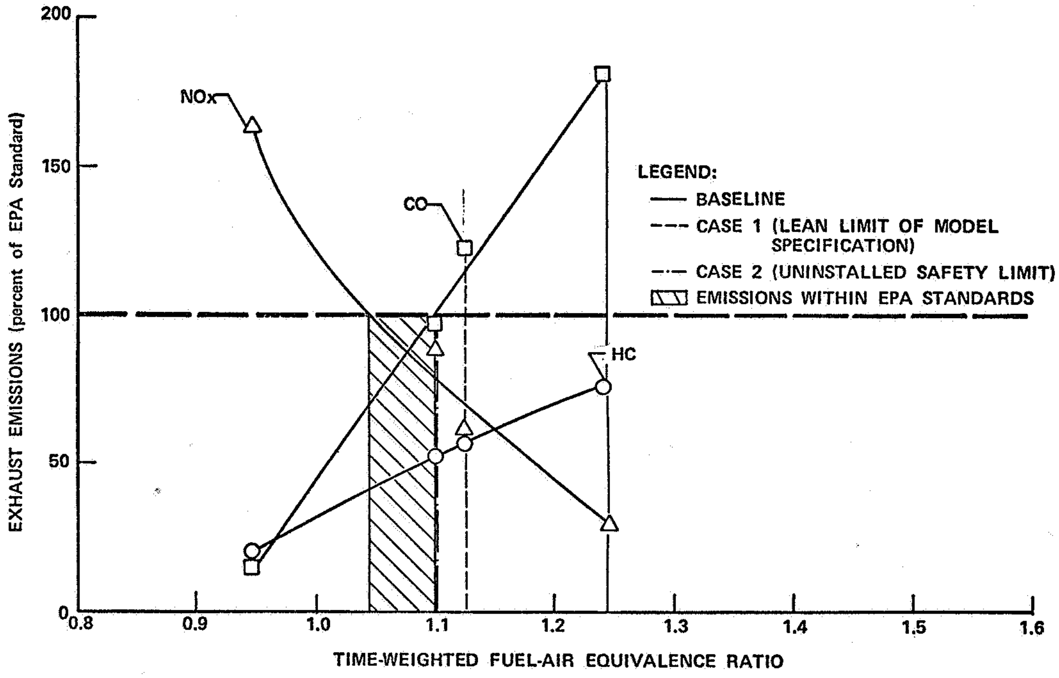

Figure 8-8

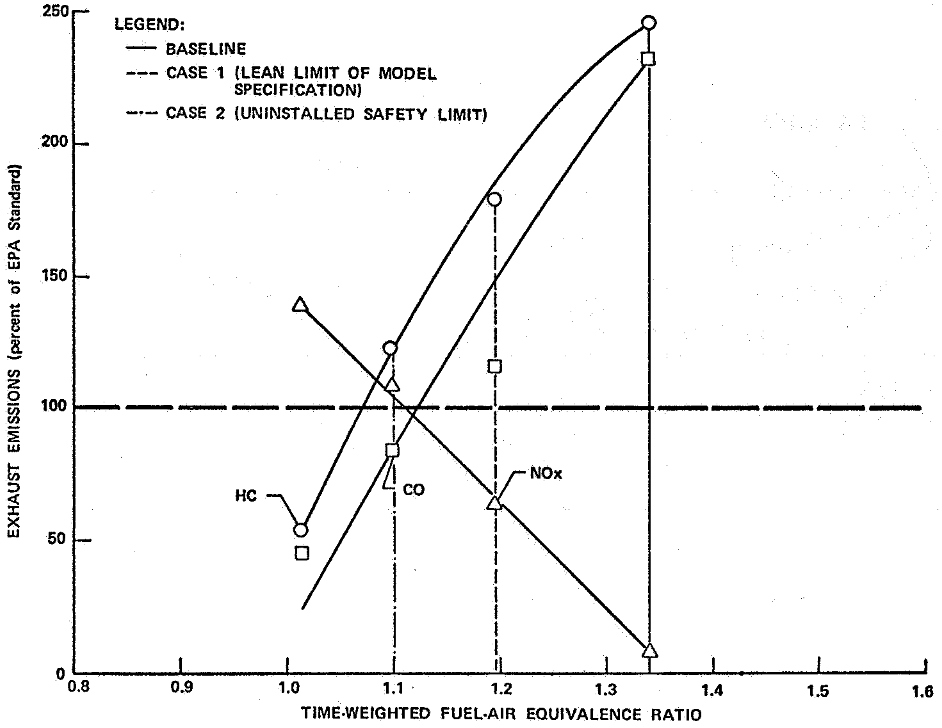

Figure 8-9

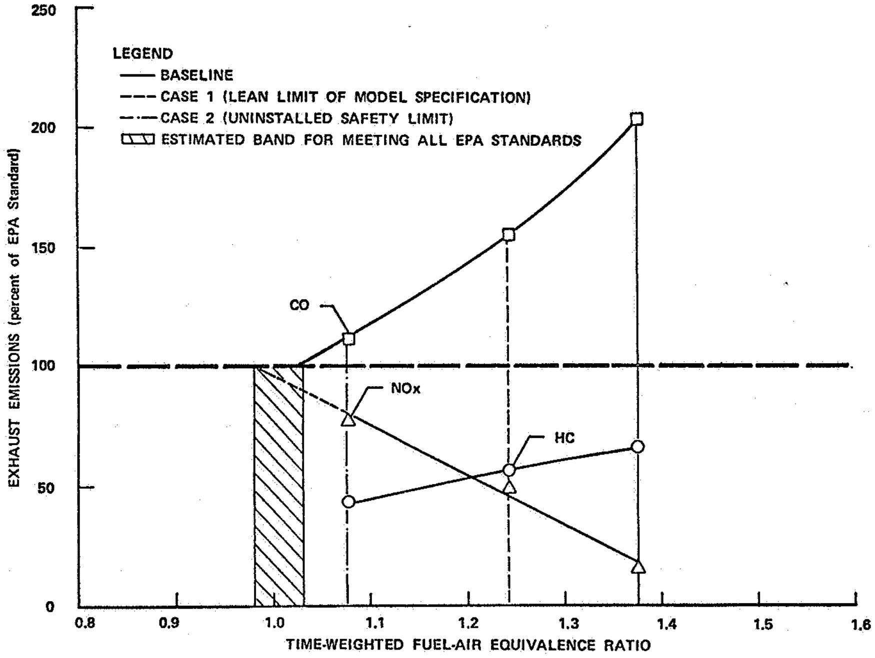

Figure 8-10

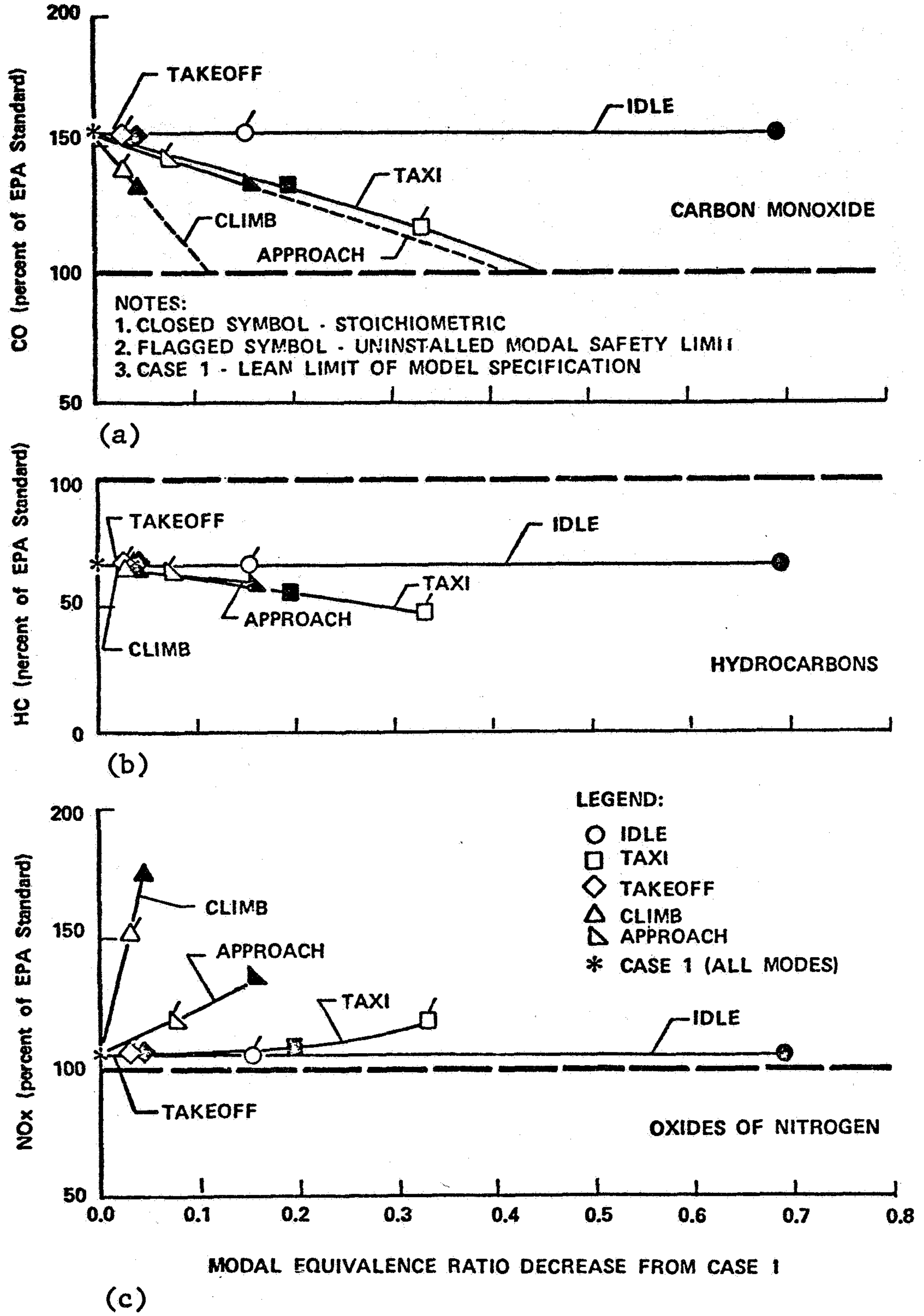
200
150
100
50
CO (percent of EPA Standard)
TAKEOFF
IDLE
TAXI
CLIMB
APPROACH
CARBON MONOXIDE
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION
(a)
100
50
0
HC (percent of EPA Standard)
TAKEOFF
IDLE
TAXI
APPROACH
CLIMB
HYDROCARBONS
(b)
200
150
100
50
NOx (percent of EPA Standard)
LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◺ APPROACH
* CASE 1 (ALL MODES)
CLIMB
APPROACH
TAXI
IDLE
TAKEOFF
OXIDES OF NITROGEN
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
MODAL EQUIVALENCE RATIO DECREASE FROM CASE 1
(c)

Figure 8-11

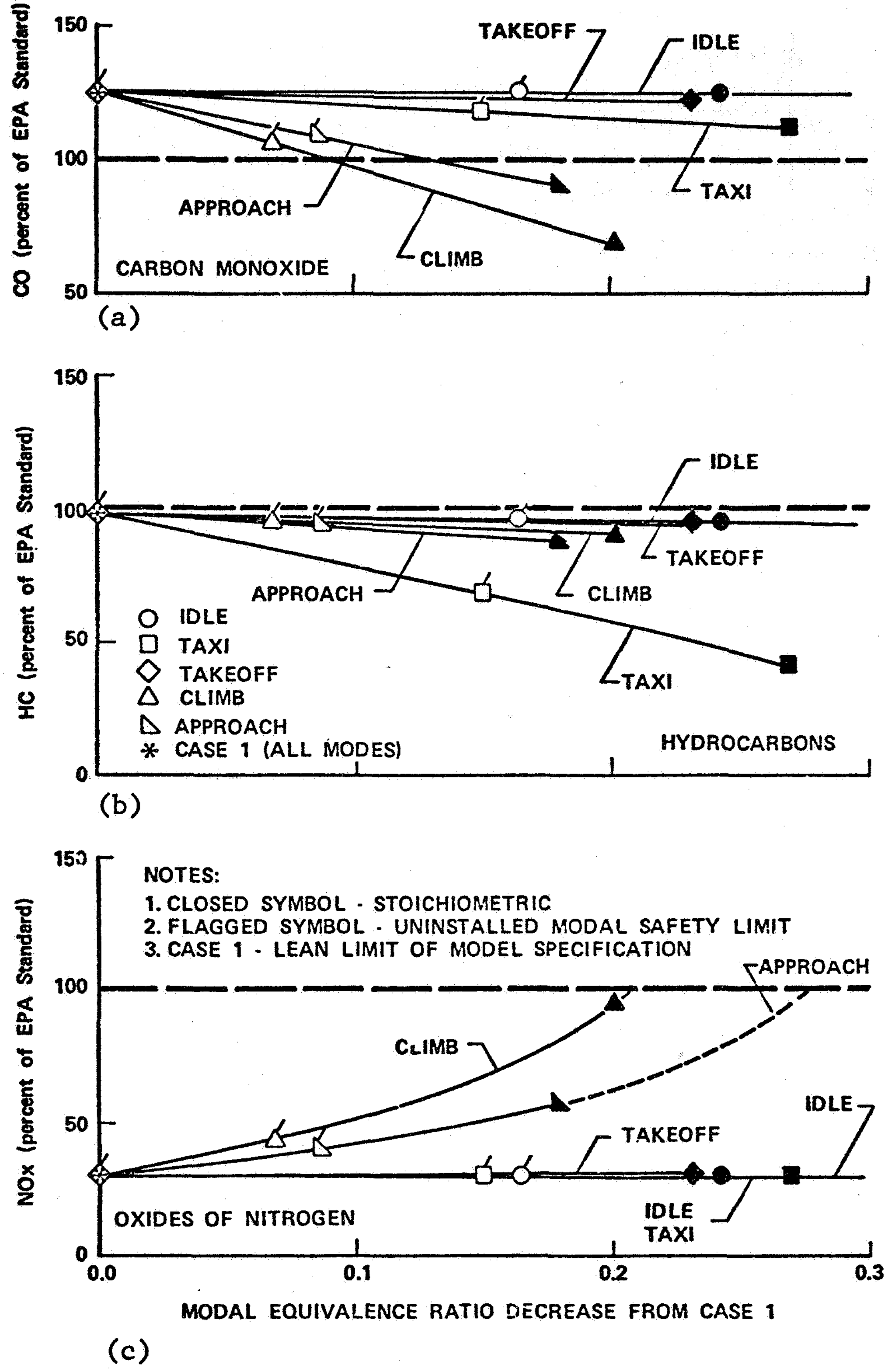
CO (percent of EPA Standard)
150
100
50
TAKEOFF
IDLE
TAXI
APPROACH
CLIMB
CARBON MONOXIDE
(a)
HC (percent of EPA Standard)
150
100
50
0
IDLE
TAKEOFF
CLIMB
APPROACH
TAXI
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◺ APPROACH
* CASE 1 (ALL MODES)
HYDROCARBONS
(b)
NOx (percent of EPA Standard)
150
100
50
0
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION
APPROACH
CLIMB
IDLE
TAKEOFF
IDLE
TAXI
OXIDES OF NITROGEN
0.0
0.1
0.2
0.3
MODAL EQUIVALENCE RATIO DECREASE FROM CASE 1
(c)

Figure 8-12

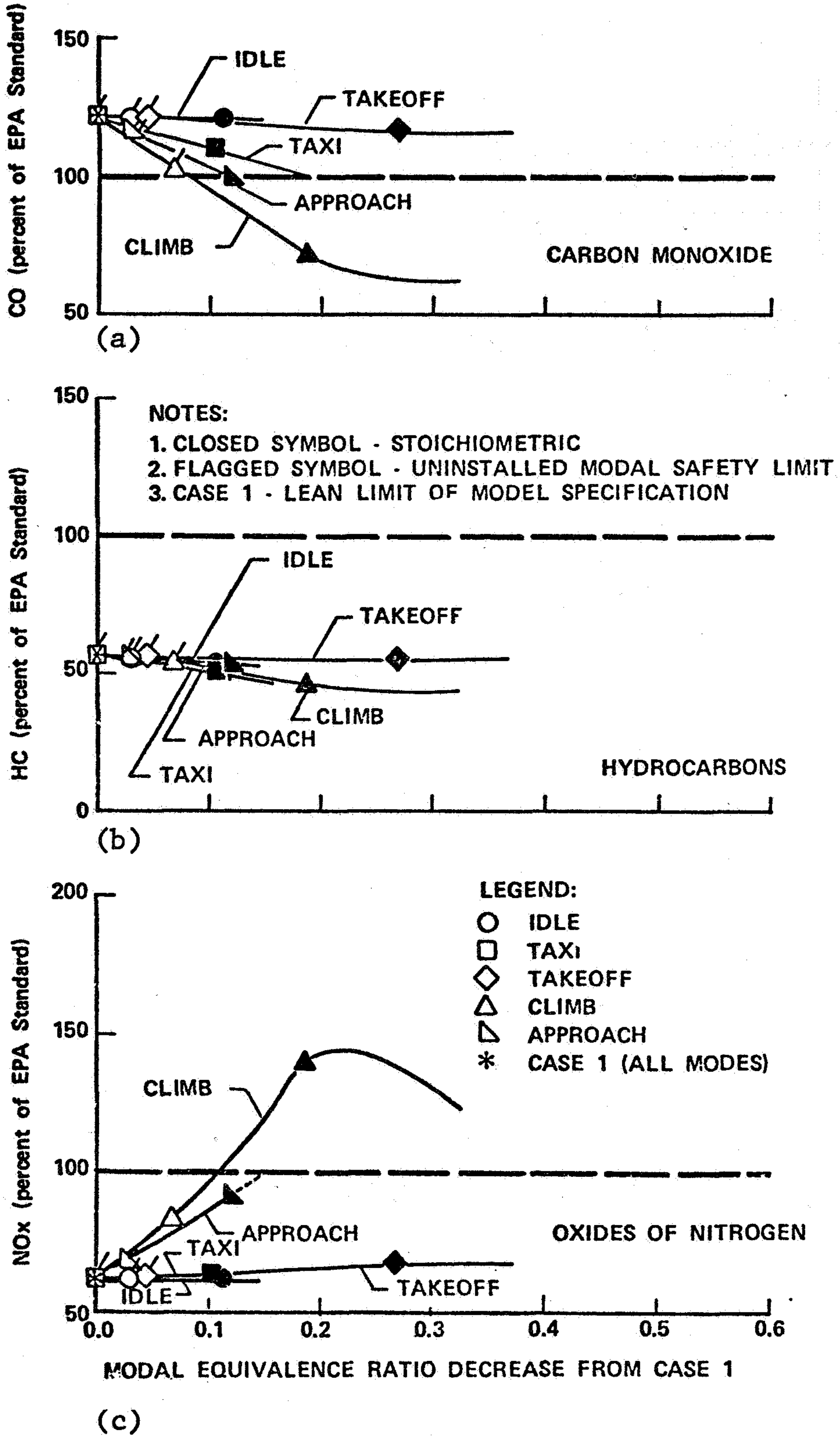
CO (percent of EPA Standard)
150
100
50
IDLE
TAKEOFF
TAXI
APPROACH
CLIMB
CARBON MONOXIDE
(a)
HC (percent of EPA Standard)
150
100
50
0
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION
IDLE
TAKEOFF
CLIMB
APPROACH
TAXI
HYDROCARBONS
(b)
NOx (percent of EPA Standard)
200
150
100
50
LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◺ APPROACH
✱ CASE 1 (ALL MODES)
CLIMB
APPROACH
TAXI
IDLE
TAKEOFF
OXIDES OF NITROGEN
0.0
0.1
0.2
0.3
0.4
0.5
0.6
MODAL EQUIVALENCE RATIO DECREASE FROM CASE 1
(c)

Figure 8-13

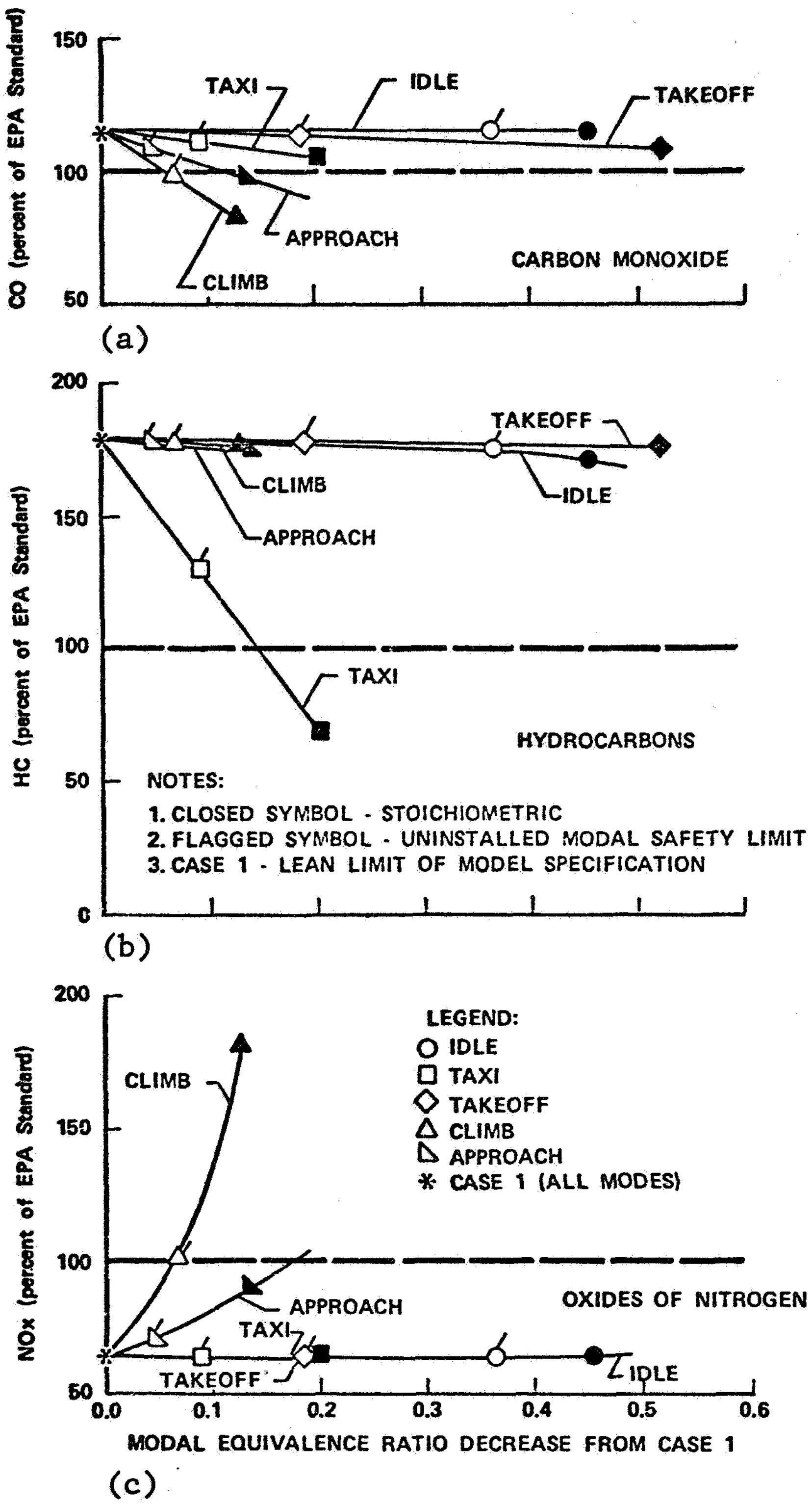
CO (percent of EPA Standard)
150
100
50
TAXI
IDLE
TAKEOFF
APPROACH
CLIMB
CARBON MONOXIDE
(a)
HC (percent of EPA Standard)
200
150
100
50
0
TAKEOFF
CLIMB
IDLE
APPROACH
TAXI
HYDROCARBONS
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION
(b)
NOx (percent of EPA Standard)
200
150
100
50
LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
APPROACH
* CASE 1 (ALL MODES)
CLIMB
APPROACH
TAXI
TAKEOFF
IDLE
OXIDES OF NITROGEN
0.0
0.1
0.2
0.3
0.4
0.5
0.6
MODAL EQUIVALENCE RATIO DECREASE FROM CASE 1
(c)

Figure 8-14

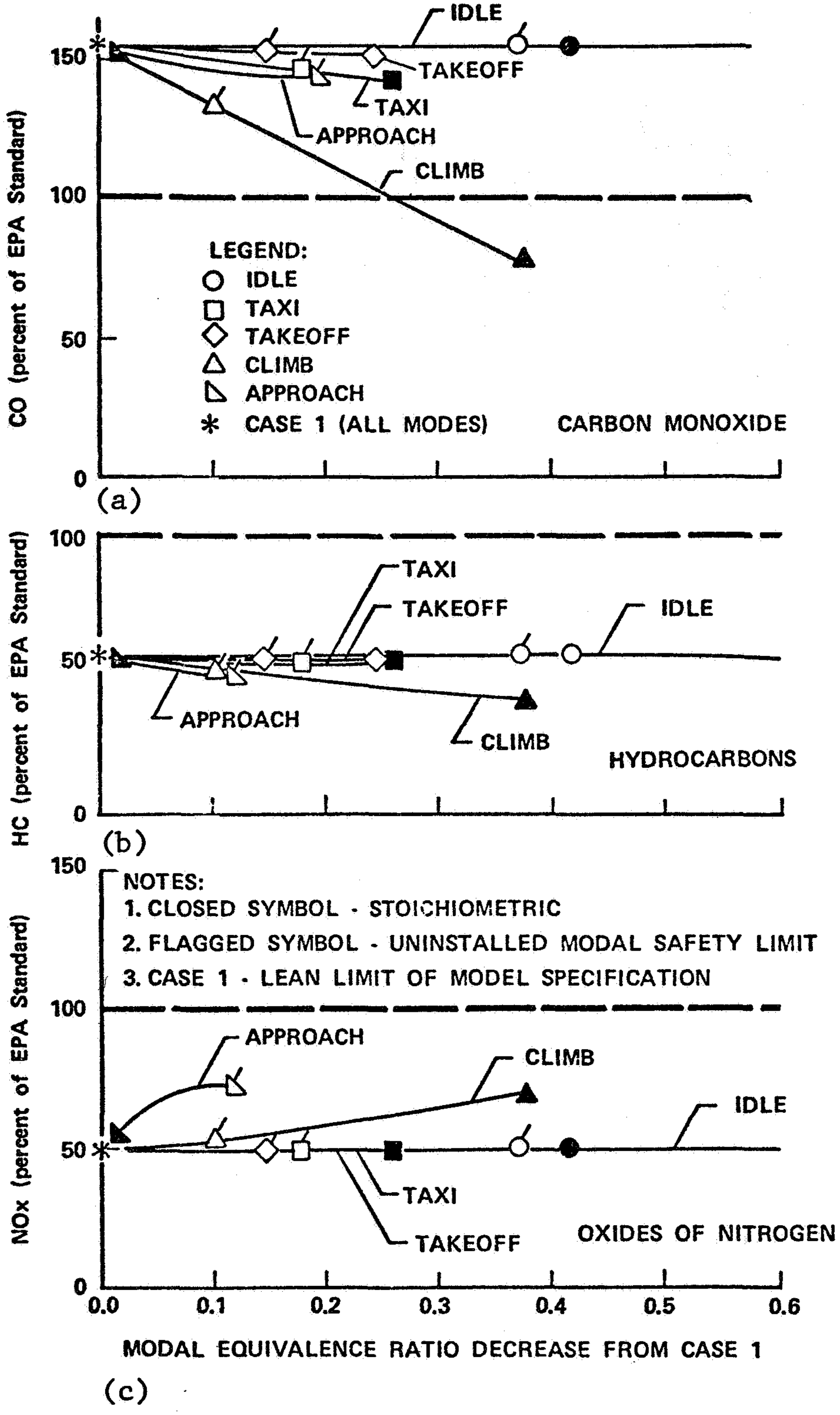
CO (percent of EPA Standard)
150
100
50
0
IDLE
TAKEOFF
TAXI
APPROACH
CLIMB
LEGEND:
○ IDLE
□ TAXI
◇ TAKEOFF
△ CLIMB
◺ APPROACH
* CASE 1 (ALL MODES)
CARBON MONOXIDE
(a)
HC (percent of EPA Standard)
100
50
0
TAXI
TAKEOFF
IDLE
APPROACH
CLIMB
HYDROCARBONS
(b)
NOx (percent of EPA Standard)
150
100
50
0
NOTES:
1. CLOSED SYMBOL - STOICHIOMETRIC
2. FLAGGED SYMBOL - UNINSTALLED MODAL SAFETY LIMIT
3. CASE 1 - LEAN LIMIT OF MODEL SPECIFICATION
APPROACH
CLIMB
IDLE
TAXI
TAKEOFF
OXIDES OF NITROGEN
0.0
0.1
0.2
0.3
0.4
0.5
0.6
MODAL EQUIVALENCE RATIO DECREASE FROM CASE 1
(c)

Figure 8-15

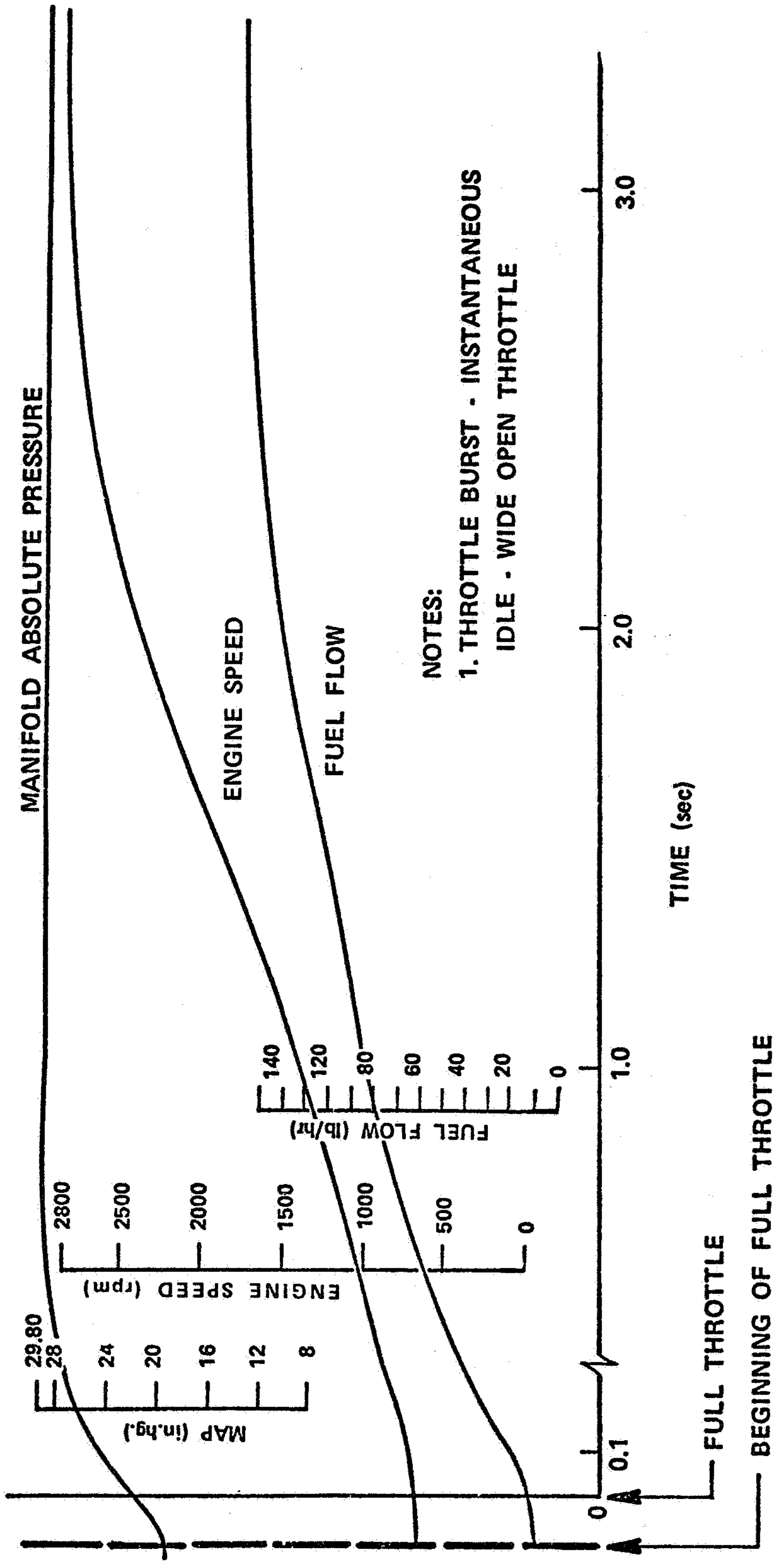
MANIFOLD ABSOLUTE PRESSURE
ENGINE SPEED
FUEL FLOW
NOTES:
1. THROTTLE BURST - INSTANTANEOUS
IDLE - WIDE OPEN THROTTLE
MAP (in.hg.)
29.80
28
24
20
16
12
8
ENGINE SPEED (rpm)
2800
2500
2000
1500
1000
500
0
FUEL FLOW (lb/hr)
140
120
80
60
40
20
0
0
0.1
1.0
2.0
3.0
TIME (sec)
FULL THROTTLE
BEGINNING OF FULL THROTTLE

Figure 8-16

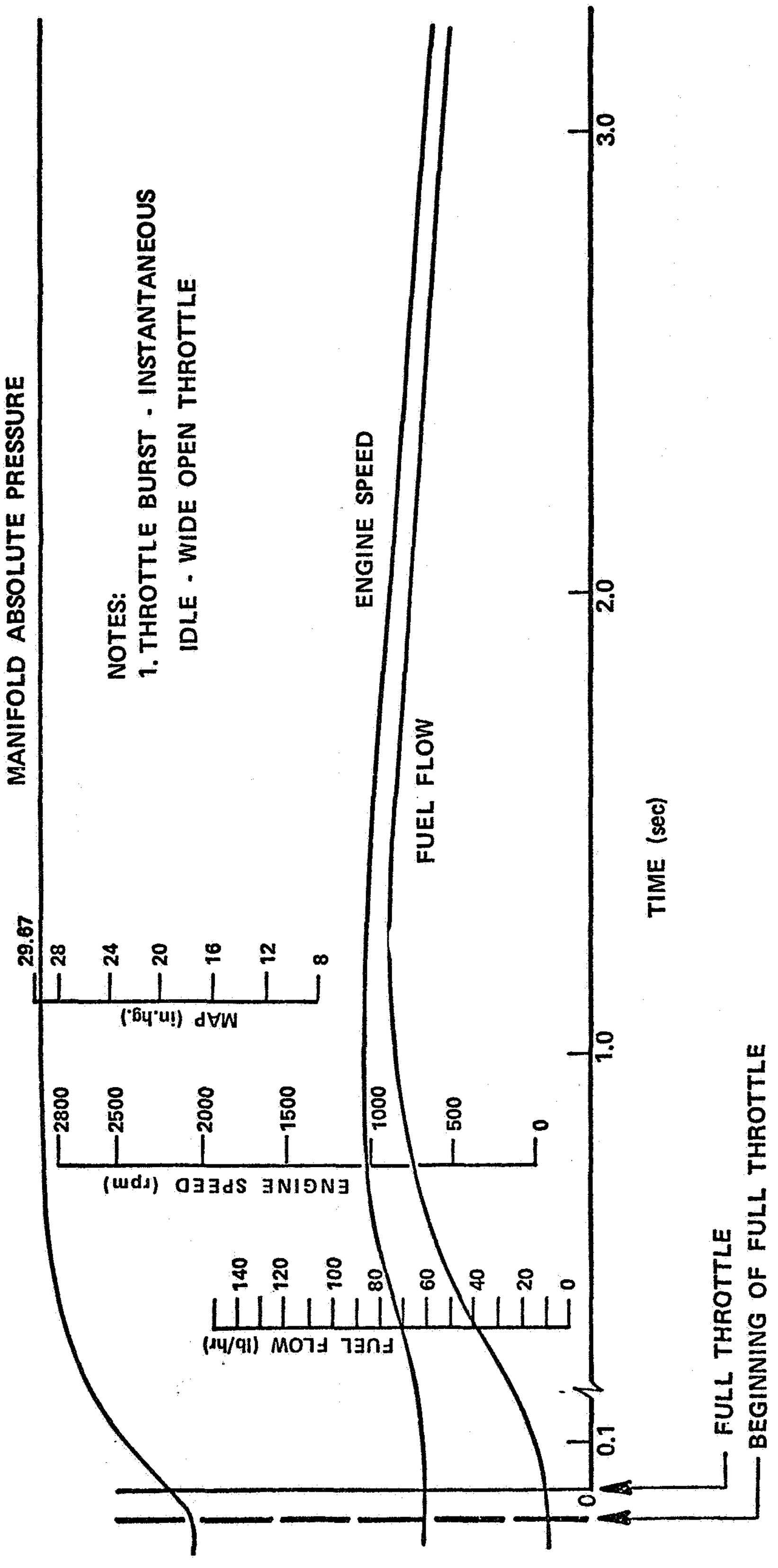
MANIFOLD ABSOLUTE PRESSURE
NOTES:
1. THROTTLE BURST - INSTANTANEOUS
IDLE - WIDE OPEN THROTTLE
ENGINE SPEED
FUEL FLOW
MAP (in.hg.)
29.67
28
24
20
16
12
8
ENGINE SPEED (rpm)
2800
2500
2000
1500
1000
500
0
FUEL FLOW (lb/hr)
140
120
100
80
60
40
20
0
TIME (sec)
0
0.1
1.0
2.0
3.0
FULL THROTTLE
BEGINNING OF FULL THROTTLE

Figure 8-17

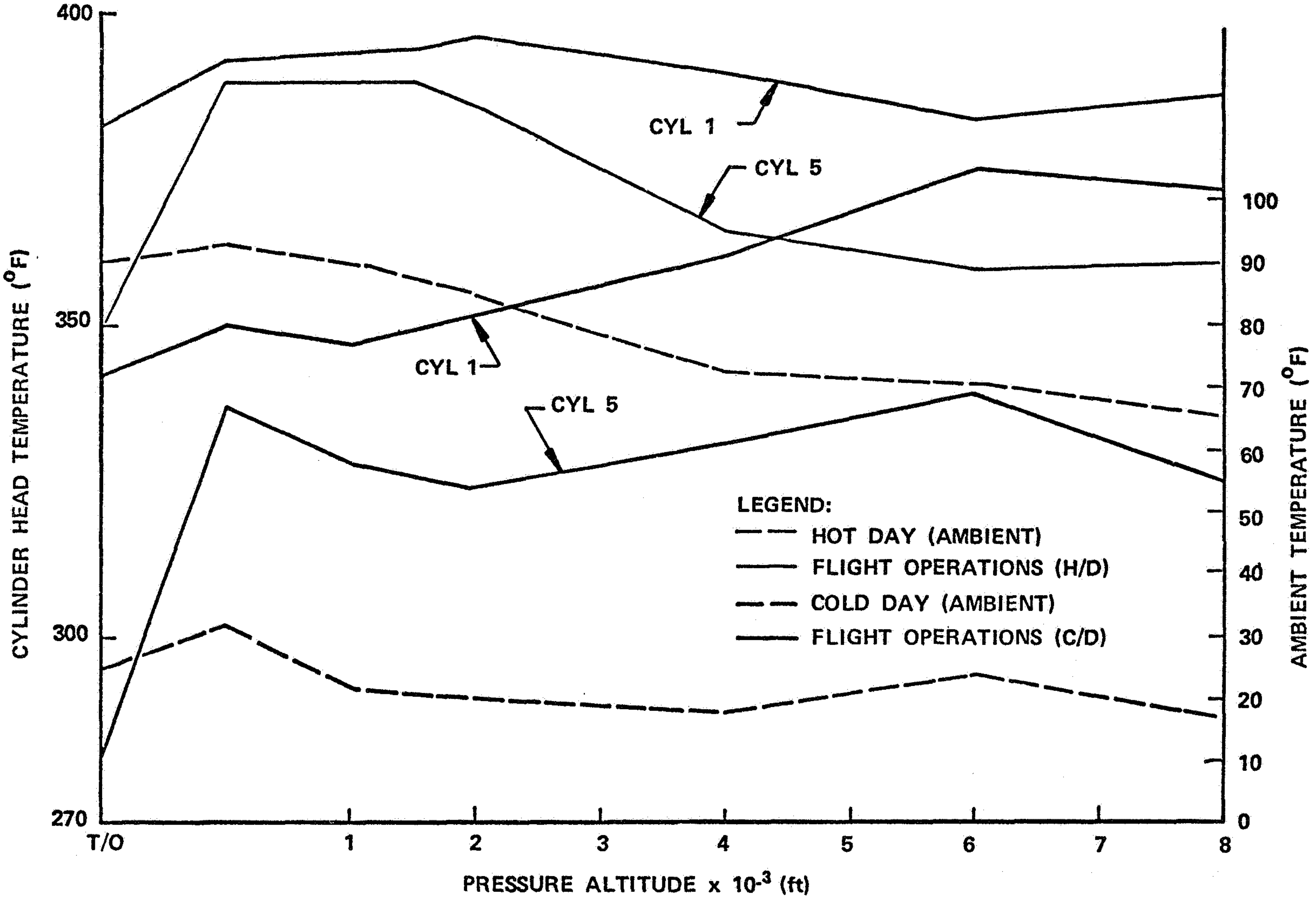
CYLINDER HEAD TEMPERATURE (°F)
400
350
300
270
AMBIENT TEMPERATURE (°F)
100
90
80
70
60
50
40
30
20
10
0
T/O
1
2
3
4
5
6
7
8
PRESSURE ALTITUDE x 10^-3 (ft)
CYL 1
CYL 5
CYL 1
CYL 5
LEGEND:
HOT DAY (AMBIENT)
FLIGHT OPERATIONS (H/D)
COLD DAY (AMBIENT)
FLIGHT OPERATIONS (C/D)

Figure 8-18