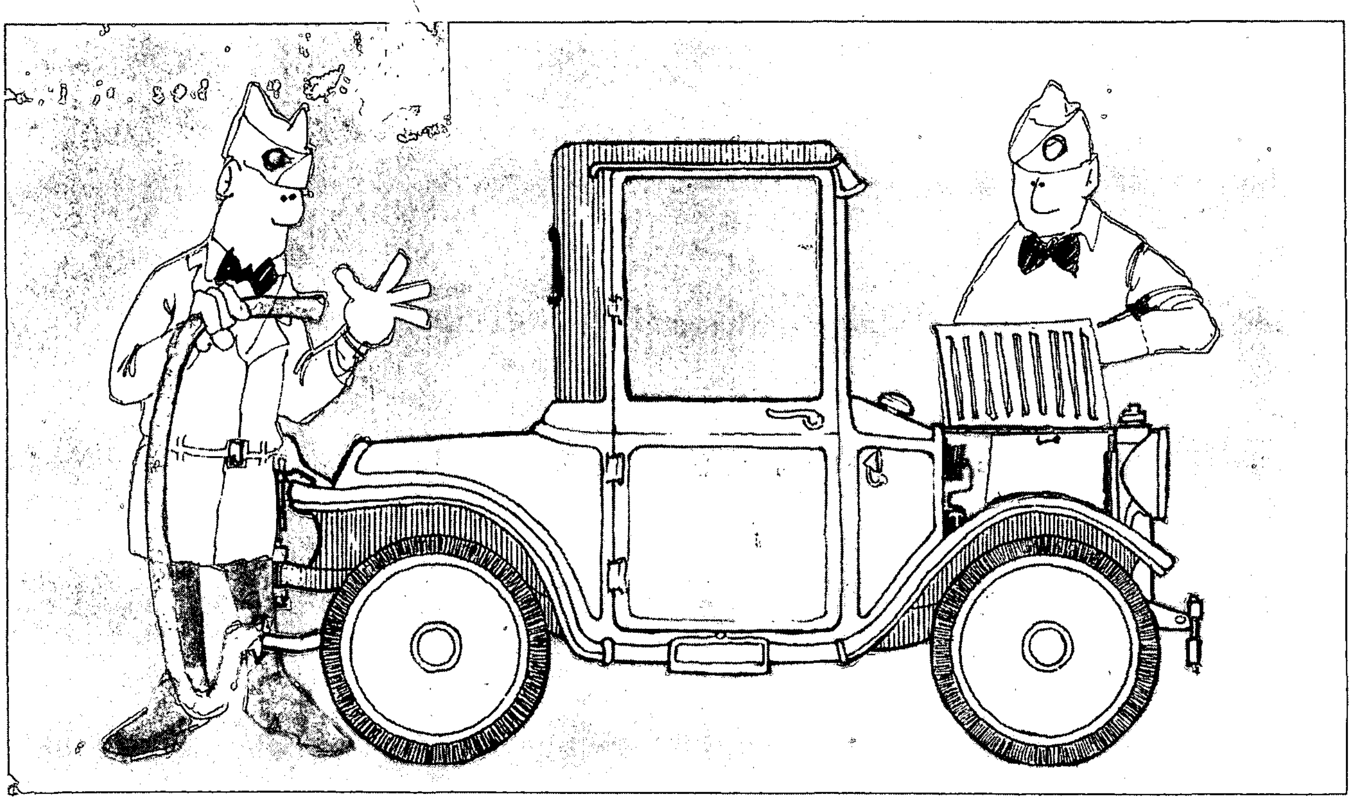
The Economic Effectiveness of Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions

CRC Extended Phase I Study

Interim Report



January 1972

In Support of:
APRAC Project Number CAPE-13-68
for
Coordinating Research Council, Inc.
Thirty Rockefeller Plaza
New York, New York 10020

and
Environmental Protection Agency
Air Pollution Control Office
5600 Fishers Lane
Rockville, Maryland 20852

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1.0 INTRODUCTION AND SUMMARY

An investigation was made of the feasibility of controlling exhaust emissions through a program of mandatory vehicle inspection and maintenance. This study differed from the one previously reported in that exhaust emission quantities, i.e., levels and reductions, were estimated based on a constant volume sampling (CVS) procedure. The developed economic-effectiveness model provided the vehicle for conducting this analysis. The model has been designed to consider the following factors in evaluating the attractiveness of inspection/maintenance:

- extent and frequency of the inspection and maintenance procedures applied
- quantitative inspection criteria to be applied in identifying and rejecting malfunctioned vehicles
- design and cost of state inspection lanes including their number, size and location
- user time spent in travelling to and waiting at inspection and maintenance stations
- time and cost of selective maintenance operations as performed in a certified garage
- the existing and required air quality of the region under study.

To support this model, empirical data have been developed based upon statistically designed experiments which defined both the general maintenance states of large vehicle populations and the sensitivity of exhaust emissions to engine malfunctions. Two basic types of inspection approaches were evaluated:

- Direct diagnosis of engine parameters (maladjustments and malfunctions) using conventional or more sophisticated garage-type equipment.
- Inference of engine parameter deviations from manufacturer's specification using measurements of exhaust emission levels (signatures) under differing engine loads.

Both of these procedures were previously evaluated using a figure of merit based on weighted emission reductions as measured by the 1968 Federal test procedure (composite, seven-mode). The results of that study for the Los Angeles region showed that either the direct diagnosis and maintenance of the idle adjustments (rpm, timing and F/A) or an emissions signature inspection at idle and load followed by maintenance of the idle adjustments and ignition system were cost effective.

The results of the study reported herein using emission reductions based upon constant volume sampling and the seven-mode driving cycle support the general conclusions of the previous study with regard to Los Angeles. Conclusions of a more specific nature are:

- The most cost-effective inspection interval is approximately yearly regardless of the inspection/maintenance procedures applied.
- Inspection procedures performed in a state lane using the measurement of emission levels under load are generally more cost-effective than those performed in franchised garages using conventional diagnostic instruments, but produce smaller emission reductions.
- A statistical analysis of the emission reductions for the baseline and test fleets has revealed that the predicted differences in mean emission levels is significant at greater than the 90 percent level of confidence. Furthermore, the statistically significant emission reductions at a 95 percent level of confidence are nearly 2/3 of the predicted values.
- The cost-effectiveness of vehicle inspection/maintenance is highly dependent on the demographic characteristics and air quality needs of a given region.
- The figure of merit (annularized discounted total program cost divided by the weighted five-year reductions of emissions) is very sensitive to the relative weighting assigned to HC, CO and NO_x emission reductions and to the extent of imposed maintenance.
- The figure of merit and emission reductions are highly sensitive to the rate of maintenance deterioration, the effectiveness of voluntary maintenance of ignition misfire and idle fuel-to-air ratio adjustment and the reliability of the repair.
- On a percentage basis, emission reductions based upon mass measurements are smaller than those based upon volumetric measurements.
- On an absolute basis (tons/year), emission reductions based upon mass measurements are slightly greater than those based upon volumetric measurements.
- When using similar inspection/maintenance procedures, larger percentage reductions for HC and NO and smaller reductions for CO are estimated based upon mass emissions as compared to volumetric emissions.

- Emission reductions are most sensitive to the inspection approach used to reject vehicles and to the extent of the imposed maintenance.

The above conclusions are based upon interim data. The study results will be upgraded and revised with a consistent set of emissions data based upon larger populations of vehicles in a final report at the conclusion of the program. The primary purpose of this interim study is to provide general guidance for those states contemplating inspection/maintenance programs as part of their implementing strategy for meeting the new Federal air quality standards. Those states actually implementing programs such as described in this report should consider performing pilot studies on a small scale to verify that the estimated results presented herein can be achieved within the framework of their specific requirements and within the capability of their existing maintenance organizations.

2.0 SYSTEM STUDY RESULTS

This section presents a discussion of the results obtained by applying the revised data bank and economic-effectiveness computer model described in Appendices A and B. This study consisted of the following three major parts:

(1) A comparative analysis of economic-effectiveness results obtained from Phase One using the Federal 1968 open cycle emission test procedure with results based upon a seven-mode, closed CVS mass emissions test procedure.

(2) An evaluation of the basic study ground rules and assumptions to determine their impact on procedure effectiveness.

(3) An assessment of the feasibility of vehicle inspection/maintenance in several typical urban centers.

The new economic-effectiveness model provided the means for conducting this study. Using this model and the developed mass emissions data base, the performance of each of the previously studied inspection/maintenance procedures was simulated over a chosen time period. As in the Phase One study, two general inspection alternatives were examined within the framework of the economic-effectiveness model: (1) an engine parameter inspection, followed as necessary, by specific parameter maintenance; and (2) a mode emission inspection leading to further diagnosis and corrective maintenance.

Since each of these two basic approaches contains a large number of possible variations, candidate strategies were selected in advance of the actual analysis. The results of the previous study using concentration based emissions and the input data described in Appendix A were used to guide this selection. Table 2-1 is a summary of the inspection/maintenance alternatives examined.

In addition to these main strategies, a program of inspecting and maintaining only the idle air-to-fuel adjustment was examined for regions characterized by high CO loadings. The estimated performance characteristics of each of the enumerated strategies was used as a basis for conducting the comparative analysis required in Parts 1 and 3 above and for the system sensitivity studies of Part 2.

TABLE 2-1

Inspection/Maintenance Procedures Studied

Strategy Engine Parameter Diagnostic	Inspection/Maintenance Procedure
1) Idle (State Lane)	I/M of: ICO, rpm
2) Idle (Franchised Garage)	I/M of: ICO, rpm, timing
3) Extensive A (Franchised Garage without Dynamometer)	I/M of: ICO, rpm, timing, misfire
4) Extensive A (Franchised Garage Dynamometer)	I/M of: ICO, rpm, timing, misfire
5) Extensive B (Franchised Garage Dynamometer)	I/M of: ICO, rpm, timing, misfire, A/P, PCV, A/C
Emission Signature Analysis	
1) Idle (State Lane)	Measure ICO, IHC Adjust ICO, rpm, timing
2) Extensive A (State Lane Emission Under Load)	Measure ICO, IHC, AHC Adjust ICO, rpm, timing Repair misfire
3) Extensive B (State Lane Emission Under Load)	Measure ICO, IHC, AHC, CCO Adjust ICO, rpm, timing Repair misfire, PCV, A/C

ICO, idle CO emission measurement
IHC, idle HC emission measurement
AHC, loaded mode HC emission measurement
CCO, loaded mode CO emission measurement

2.1 Analysis of Inspection/Maintenance Procedures Using Mass Emissions Data

To develop results utilizing the mass emission measurements, the following data sets were converted to a mass emission basis:

- Influence coefficients relating changes in mass emissions to changes in engine parameter settings obtained from Phase One Orthogonal Test Program
- Vehicle emission levels based on 1972 Federal Test Procedures from the Extended Phase One fleet deterioration program
- Emission decay rates based on converted ARB Surveillance Program Data.

To measure the impact of the mass emissions data on various strategies, a comparison was first made between the mass emissions data and the concentration emissions data obtained from the Phase One orthogonal experiments conducted to develop emission response coefficients. These data are fundamental to predicting the effectiveness of engine parameter maintenance in reducing emissions. In conducting this analysis, an attempt was made to keep as many of the system factors (e.g., pass/fail criteria) constant within the economic-effectiveness model as possible. In general, the mass emissions influence coefficients are consistent and similar to their corresponding concentration values. For a given change in an engine adjustment the resultant change in exhaust emissions when measured in mass units was found to be somewhat smaller than when measured in concentration units. There are, however, several significant deviations from these general statements. Two of the most significant influence coefficients, i.e., $\partial HC/\partial ICO$ and $\partial CO/\partial RPM$, have undergone a change in sign when recomputed in terms of mass units and there has been a substantial increase in absolute magnitude for two of the other influence coefficients, i.e., $\partial CO/\partial ICO$, $\partial CO/\partial timing$. Table 2-2 shows expected emission reductions in terms of both mass and concentration units for typical engine adjustments. These values were computed using the fundamental relationship:

$$\Delta e_i = \sum_i \Delta P_j \frac{\partial e_i}{\partial P_j} R_j \ldots \qquad (2\text{-}1)$$

where

Δe_i = expected emission reduction for i^{th} specie

ΔP_j = average adjustment for j^{th} parameter

$\frac{\partial e_i}{\partial P_j}$ = influence coefficient (Table A-1)

R_j = vehicle rejection fraction for i^{th} parameter (i.e., percent of automobiles that failed the pass/fail criteria for the j^{th} parameter)

TABLE 2-2
Expected Emission Reduction for Typical Parameter Adjustments

(GRAMS/MILE)

$$\Delta E = \Sigma \Delta P_i \frac{\partial e}{\partial P_i} R_i$$

PARAMETER	HC		CO		NO	
	MASS	CONC	MASS	CONC	MASS	CONC
ICO	+ 0.037	-0.252*	8.09	4.74*	0	-0.036*
RPM	0.131	0.187	-0.374	+0.274*	-0.005	-0.006
TIMING	0.082	0.126	-0.482	-0.095*	0.165	0.192
MISFIRE	0.333	0.365		-		-
A/P	0.026	0.071	0.282	0.401	0	0.002
PCV	0.039	0.047	1.04	1.56	-0.369	-0.367
A/C	0.021	0.027	1.49	2.12	-0.060	-0.069

*SIGNIFICANT CHANGES IN SIGN OR ABSOLUTE VALUES

To illustrate this computation procedure, consider estimating HC emission reductions caused by adjusting ICO. This example uses a vehicle rejection rate of 30%, an ICO average reduction of 4% and an average emission response of .0314.

$$\Delta e_i = \Delta P_j \times \frac{\partial e_i}{\partial P_j} \times R_j = (4) \times (0.0314) \times (.30)$$

$$\Delta e_i = 0.037 \text{ grams/mi}$$

A similar and consistent approach was used for computing the remaining emission reductions shown in Table 2-2. It should be noted that emission values with a minus sign signify an increase in emissions. These sign changes will result in smaller percentage emissions reductions for a given procedure than were obtained in Phase One.

The results of this analysis utilizing mass units show that the effectiveness of idle adjustments is different from that found in the previous concentration units study. For example, the results presented in Table 2-2 show that a timing adjustment reduces the overall effectiveness of an idle CO adjustment (i.e., a timing adjustment produces an increase in CO emissions whereas an idle CO adjustment produces a decrease in CO emissions). The greatest difference in predicted reductions between mass and concentration emissions is attributable to the effect of an idle CO adjustment. The idle CO adjustment on a mass basis has negligible effect on HC and NO while on a concentration basis it produced appreciable emission increases. The net effects are larger mass emission reductions for HC and NO and somewhat smaller CO emission reductions.

2.1.1 Comparison of Results for Mass/Concentration Data

Table 2-3 presents inspection/maintenance program results based on comparative mass and concentration data. Shown are the program figures of merit, average cost per vehicle and resultant emission specie reductions for the various inspection/maintenance strategies. The figure of merit is defined as the total annual program cost (discounted capital, direct and indirect operational and user inconvenience costs) divided by the weighted four-year average emissions reductions in tons per year ($0.6\ \Delta HC + 0.1\ \Delta CO + 0.3\ \Delta NO$). Average vehicle costs include direct inspection costs for all vehicles (amortized capital and labor) and direct maintenance costs on rejected vehicles (parts and labor) per year. Emission reductions are the average values over a four-year program. This information was derived from computer simulations employing identical pass/fail criteria for both the mass and concentration emission based models. This table shows that the figure of merit as computed directly from mass units is substantially better than the corresponding concentration result, although the percent emission reductions are generally lower. This is due primarily to the larger absolute emission reductions achieved. Table 2-4 shows a comparison of the expected emission reductions for several candidate strategies. With the exception of the CO reduction for an Extensive B program, all of the mass based emission reductions on an absolute basis are larger than their concentration emission counterparts.

TABLE 2-3

Comparative Inspection/Maintenance Program Results

(4 YEAR PROGRAM)

Strategy	FIGURE-OF-MERIT $/TON +++		COST PER VEHICLE $		AVERAGE EMISSION REDUCTIONS PERCENT HC		CO		NO	
	MASS	CONC	MASS	CONC	MASS	CONC	MASS	CONC	MASS	CONC
ENGINE PARAMETER DIAGNOSTICS										
1. IDLE (STATE LANE)	190	320	1.50	1.50	3	0	6	15	0	-7
2. IDLE (FRANCHISED)	260	370	2.50	2.50	3	3	5	13	3	-3
3. EXTENSIVE A+ (FRANCHISED)	410/310	460	5.70/6.50	6.00	9/17	18	5/5	14	3/3	0
4. EXTENSIVE B++ (FRANCHISED)	490	540	13.50	12.00	19	22	9	33	0	-5
EMISSION SIGNATURE ANALYSIS										
6. IDLE (STATE LANE)	290	430	1.90	2.50	0	2	5	12	2	-4
7. EXTENSIVE A+ (STATE LANE)	-/240	360	2.50	4.00	7	'11	5	16	2	-4
8. EXTENSIVE B++ (STATE LANE)	400	410	6.00	6.00	9	15	7	20	0	-3

+ IDLE PLUS IGNITION TUNEUP, WITHOUT/WITH DYNAMOMETER

++ IDLE PLUS IGNITION PLUS INDUCTION TUNEUP

+++ L.A. BASIN WEIGHTING FUNCTION

TABLE 2-4

Comparison of Absolute Emission Reductions Between Mass/Concentration Data

Strategy	Mass HC	Mass CO (tons/day)	Mass NO	Concentration HC	Concentration CO (tons/day)	Concentration NO
1) Idle (Franchised)	15	282	11	7	277	-6
2) Extensive B (Franchised)	99	545	0	56	696	-8

These improvements in emission reductions using the mass data are largely attributable to the differences in influence coefficients previously discussed.

As anticipated, smaller percentage reductions of hydrocarbons and CO result for almost all strategies using the mass data. This is caused in large part by the substantially higher emission levels which are measured using the 1972 procedure which results in lower percent emissions reductions. The results for the emission inspection approach, although more difficult to explain in terms of a change in the model, appear consistent with engine parameter inspection results. The costs for both basic approaches are similar to those developed from the concentration data. The double entry for the Extensive A program represents an ignition tune-up without and with a dynamometer. The use of a dynamometer permits the diagnosis of ignition system misfire at load and identifies approximately twice as many ignition failures.

In summary, the following conclusions can be drawn from this comparative analysis:

- No change in the ordinal ranking of inspection/maintenance procedures occurs upon converting from concentration to closed seven-mode cycle mass emissions test data.
- Higher absolute HC and NO emission reductions result when using mass data.
- Slightly lower absolute CO emission reductions result when mass emissions data are used.
- Similar program costs are obtained for both data sets.

2.1.2 Reoptimization of Procedures

An extension of the previous analysis was to reoptimize the inspection/maintenance procedures based upon mass emissions data. A five-year time period was studied to determine if predicted emission levels stabilized at the end of that period. Projections of the performance of mandatory vehicle inspection/maintenance programs were limited to no more than five years because of:

- Uncertainty in estimating the effects of major engine malfunctions which may occur beyond that period.

- Lack of experimental emission time history data beyond 50,000 miles (i.e., approximately five years).

Table 2-5 presents the results of the reoptimization for several strategies. The main information to be obtained from this table is that the performance criteria (i.e., figure of merit) for the reoptimized procedures is consistent with the results reported in Section 2.1.1. The generally lower figure of merit is caused by the larger emission reductions which result from both the proper evaluation time period and higher vehicle rejection rates. The higher vehicle rejection rates have resulted in slightly higher program costs (as shown by the increase in average cost per vehicle). The ordinal ranking of the procedures has remained unchanged through the reoptimization. It appears, as discussed later, that higher rejection rates do not substantially alter the figure of merit. Thus, for a comparable figure of merit one can achieve higher emission reductions by specifying a more severe pass/fail criteria. One should also note that a five-year program does not always result in establishing an emission equilibrium level. Emissions for the more extensive maintenance procedures

TABLE 2-5
Optimized Inspection/Maintenance Program
Performance Based Upon Mass Emissions Data

(FIVE YEAR PROGRAM)

INSPECTION/MAINTENANCE PROCEDURES	FIGURE-OF-MERIT \$/TON +++	COST PER VEHICLE \$	EMISSION REDUCTIONS, PERCENT		
			HC	CO	NO
ENGINE PARAMETER DIAGNOSTICS					
1. IDLE (STATE LANE)	155	1.60	3	7	0
2. IDLE (FRANCHISED)	200	3.00	4	6	6
3. EXTENSIVE A+ (FRANCHISED)	300/230	6.00/7.00	10/21	6/6	6/6
4. EXTENSIVE B++ (FRANCHISED)	350	13.50	23	12	3
EMISSION SIGNATURE ANALYSIS					
5. IDLE (STATE LANE)	225	1.90	0	6	2
6. EXTENSIVE A+ (STATE LANE)	-/190	2.50	9	6	2
7. EXTENSIVE B++ (STATE LANE)	320	5.75	9	8	0

+IDLE PLUS IGNITION TUNEUP, WITHOUT/WITH DYNAMOMETER
++IDLE PLUS IGNITION PLUS INDUCTION TUNEUP WITH DYNAMOMETER
+++ L.A. BASIN WEIGHTING FUNCTION

occasionally continue to decrease slowly. It should be noted that the models' predictive power may be severely taxed as extrapolations further into the future are attempted. Some of the fundamental assumptions such as constant owner behavior patterns with respect to maintenance may be altered by the existence of a program.

The emission time-history profiles shown in Figures 2-1 and 2-2 are for several levels of imposed maintenance. The so-called baseline fleet time histories were developed based upon estimating the extent and frequency of voluntary maintenance as well as the rate of maintenance deterioration. Figure 2-1 shows the results of an idle adjustment program which involved direct engine parameter inspection in a franchised garage and optimal inspection pass/fail criteria. Panels A, B and C show time history plots generated by the computer model of hydrocarbons, carbon monoxide and oxides of nitrogen emissions, respectively. This idle adjustment program has its largest impact on the percentage reduction of CO and NO_x emissions and its smallest impact on HC. The emission levels for the baseline test have stabilized after the fifth year. The resultant emission reductions relative to the baseline fleet at the end of the fifth year are substantially larger than for the first several years of the program.

A similar trend in the time effects on emission reductions can be seen by examining Figure 2-2. The more extensive inspection/maintenance program shown in this figure (i.e., inspection and maintenance of idle plus ignition plus induction variables) yields greater HC and CO emission reductions than were achieved by the idle parameter inspection/maintenance program. The CO emission levels appear stable after five years. The larger HC emission reductions are attributable to correcting misfire because of maintenance to the ignition system. The model clearly overestimates HC emission reductions for the more extensive maintenance procedures since the predicted absolute emission levels at the end of five years for vehicles treated in this mandatory inspection/maintenance program are lower than for these vehicles when they are new (6.5 gm/mi). This is a combined data and model deficiency which results from assuming a linear deterioration rate and selecting what is probably a high value for this rate. Clearly, the on-going fleet deterioration experimental data will be required to correct this deficiency. Percentage reduction of hydrocarbon

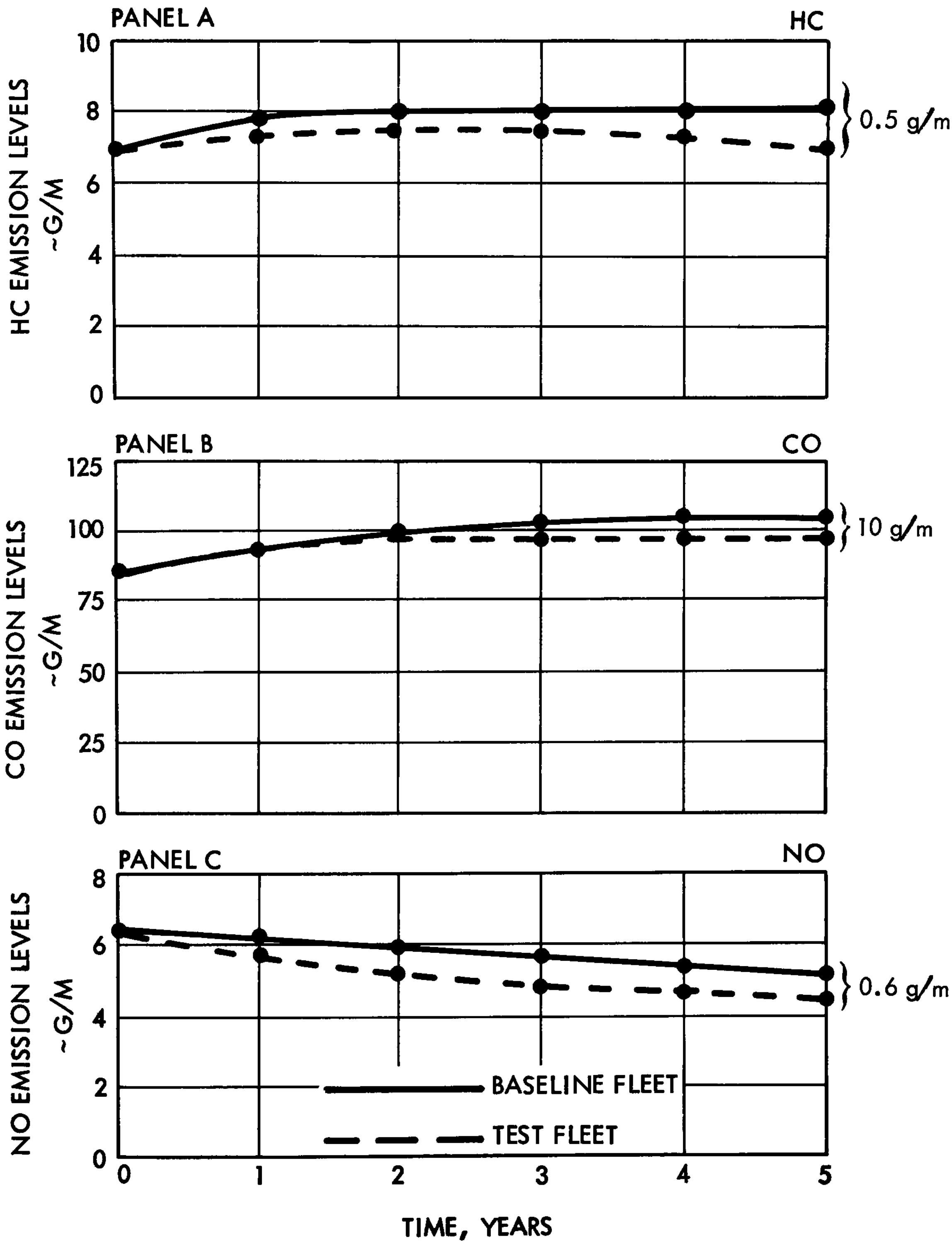


FIGURE 2-1. Mass Emission Time Histories for an Optimum Idle Inspection and Repair Program

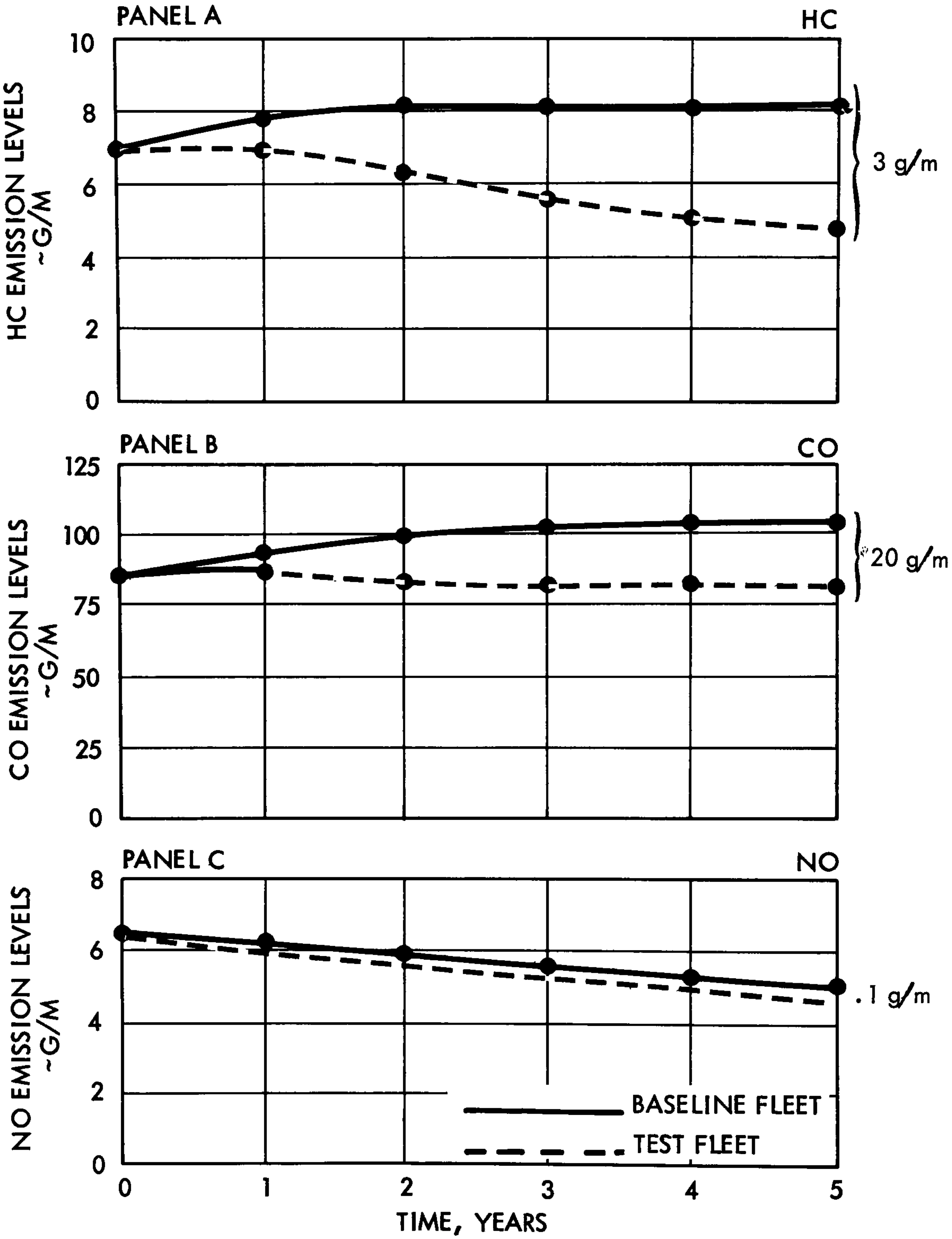


FIGURE 2-2. Mass Emission Time Histories for an Optimum, Extensive B Engine Parameter Inspection and Repair Program

actually exceeds that of carbon monoxide. For these extensive inspection/maintenance procedures, the differences between baseline and test fleet NO emissions is insignificant. This results because the positive benefit of retarding timing is largely off-set by the effect of leaner air-to-fuel mixtures which result from repair of the induction system.

The percentage emission reductions presented thus far were based on an average reduction over the five-year time period of the program. One would obtain larger emission reduction percentages if computations were made at the end of the program period. Table 2-6 shows a comparison between the emission reductions expected at the end of the fifth year with those averaged over the life of the program. In general, the emission reductions computed at the end of five years are nearly twice as large as those averaged over the program.

A last step in this reoptimization of the inspection/maintenance procedures is to compare the optimal pass/fail criteria. Table 2-7 presents this comparison for both engine parameter and mode emission pass/fail criteria. Reoptimization of the system has resulted in choosing more restrictive rejection criteria for both parameters and emissions. For example, in the case of ICO, a pass/fail criteria of 4% was optimal using the concentration data, whereas a value of 3% is now estimated. This lower value will result in larger vehicle rejection fractions which, in turn, will yield higher emission reductions.

2.1.3 Relaxation of Optimal Procedures

A figure of merit based on the ratio of total program costs to weighted emission reductions is utilized in the current economic-effectiveness model for screening procedures. This ratio provides a simple and convenient method for ordinally ranking the various inspection/maintenance strategies. The inspection/maintenance procedure ranked highest based upon the figure of merit however generally involved a simple inspection procedure and limited maintenance and does not produce the largest reduction of exhaust

TABLE 2-6 Expected Emission Reductions at End of Five Years Optimal Inspection Criteria

Strategy	Emission Reductions: End of 5 Years, % HC	CO	NO	Average Over 5 Years, % HC	CO	NO
Engine Parameter Diagnostics						
1. Idle (state lane)	4	12	0	3	7	0
2. Idle (franchised)	6	11	11	4	6	6
3. Extensive A+ (franchised)	40*	11	11	21*	6	6
4. Extensive B++ (franchised)	43*	21	3	23*	12	3
Emission Signature Analysis						
5. Idle (state lane)	0	11	4	0	6	2
6. Extensive A+ (state lane)	12	12	2	9	6	2
7. Extensive B++ (state lane)	13	15	0	9	8	0

+ Idle plus ignition, with dynamometer

++ Idle plus ignition plus induction tuneup (with dynamometer)

* Over predicted due to uncertainties in misfire deterioration rate data and rejection rate fraction.

TABLE 2-7 Optimal Engine Parameter and Mode Emission Pass/Fail Criteria for Precontrolled Vehicles

L.A. BASIN EMISSION WEIGHTING FUNCTION

ENGINE SUBSYSTEM/PARAMETERS	OPTIMAL PARAMETER VALUE: MASS	CONC	OPTIMAL MODE VALUE: MASS	CONC
• IDLE				
• IDLE CO	3.0%	4.0%	ICO=3%	ICO = 4%
• RPM	520 RPM	525 RPM	IHC=300 PPM	IHC = 300 PPM
• TIMING	4.4 DEG	10 DEG		
• IGNITION				
• MISFIRE	2.5 %	2.5%	AHC=300 PPM	AHC = 400 PPM
• NO_x	--	--	--	--
• INDUCTION				
• AIR PUMP	PLUGGED	PLUGGED	++ CCO=1%	+ ACO = 1%
• PCV	0 PSI	PLUGGED		
• AIR CLEANER	105 DEG	105 DEG		
• CHOKE HEAT RISER	--	--	--	--
• CHOKE BLADE SETTING	--	--	--	--

+ MODE 6 (15-30 MPH ACCELERATION)

++ CLAYTON CRUISE

emissions. The question then is asked whether equivalent exhaust emission reductions can be achieved with the simpler inspection/maintenance program by using less optimum rejection criteria while achieving the same cost effectiveness as the more comprehensive inspection/maintenance procedure. To make this comparison, the highest ranking inspection/maintenance strategy is varied from optimum until its figure of merit is equal to the figure of merit of the next most attractive strategy. This operation was accomplished by changing the optimized pass/fail criteria developed for the highest ranking procedure to produce larger emission reductions and increased cost. In turn, the next most attractive strategy can be relaxed to the third and so on until all strategies have been intercompared.

To illustrate this technique, consider the information presented in Table 2-8. Performance measures (e.g., figures of merit) are given for

TABLE 2-8
Relaxation of Optimal Procedures

(FIVE YEAR PROGRAM)

	FIGURE-OF-MERIT $/TON	COST PER VEHICLE $	EMISSION REDUCTIONS PERCENT HC	CO	NO
ENGINE PARAMETER DIAGNOSTICS					
1. IDLE (FRANCHISED)	200 (230)	3.00 (3.75)	4 (5)	6 (6)	6 (7)
2. EXTENSIVE A^{+} (FRANCHISED)	230	7.00	21	6	6
EMISSION SIGNATURE ANALYSIS					
3. EXTENSIVE A$^{\pm}$ (STATE LANE)	190 (225)	2.50 (3.00)	9 (10)	6 (8)	2 (3)
4. IDLE (STATE LANE)	225	1.90	0	6	2

$^{+}$IDLE PLUS IGNITION TUNEUP WITH DYNAMOMETER the two most attractive procedures for each basic inspection strategy. In the case of the parameter inspection strategy, the idle program is varied until its figure of merit is equal that of the Extensive A maintenance program. The optimal figure of merit for the idle program is $200/ton while the optimal figure of merit for the Extensive A program is $230/ton. By adjusting the pass/fail criteria, a new figure of merit of $230/ton was obtained for the idle program. The associated costs and emission reductions for both programs can now be directly compared with the figure of merit held constant. The numbers in parentheses represent system performance data for the modified program. The result of relaxing the idle program has been to increase both program costs and emission reductions. The idle program however still does not compare favorably with the Extensive A program in terms of hydrocarbon emission reductions. Selection of either program for implementation in a given region would depend primarily on the type of air pollution problem encountered in that region.

A similar comparison was made for the emission inspection strategy. In this case, the Extensive A program is more cost effective than the idle program. Here again, the most attractive program was relaxed until its figure of merit equalled the next strategy. For the Extensive A program, its figure of merit was increased from $190/ton to $225/ton. This increase resulted in a slightly higher emission reductions and program costs. In this case the Extensive A program is always most attractive.

2.1.4 Statistical Analysis of Results

Predictions of system performance for a program of vehicle inspection/maintenance are uncertain because of the variability in the data sets used in the estimate. The ordinal ranking of the procedures using computed figures of merit may change when the projected emission reductions are reduced to reflect the fraction of this reduction which can be achieved at a stated statistical confidence level. As a consequence, a preliminary statistical analysis was performed of the results presented in Section 2.1.2.

The approach taken in this statistical study required the use of the emission distributions data developed from the on-going fleet deterioration experiment. Figure 2-3 shows a comparison of the pre and post tune emission distributions derived from the deterioration experiment for HC, CO and NO, respectively. The mean values of these distributions have been superimposed on the mean emission levels predicted from the computer model using the pre and post maintenance data for the baseline and test fleets, respectively. Thus, both the mean emission levels and their variances are based on approximately equivalent states of vehicle maintenance.

A student's statistical test, as described in Appendix A was conducted using pre and post maintenance emission distributions for each specie in order to estimate the emissions reductions at a specified confidence level. Table 2- 9 presents a comparison of test and baseline fleet statistical data, including the expected value of the pre and post tuned emission means, along with scores and confidence limits on predicted emission reductions at the time of maintenance. As can be seen, the null hypothesis that there is no difference in mean emission levels between the test and baseline fleets can be rejected with greater than 90% confidence for both HC and CO (viz, t (computed) > t (critical at 90% confidence level)). The null hypothesis cannot be rejected for the case of NO. It should be pointed out, however, that the candidate inspection/maintenance procedures were not designed to reduce NO.

It therefore is concluded that the test and baseline emission levels came from different populations, and consequently that the predicted emission reductions are not due entirely to chance.

Table 2-9 shows the 90% confidence bands about the estimated mean emission reductions which were achieved with the Extensive B maintenance. A comparison of these results with those in column three shows that approximately 65% of the computer model predicted emission reductions for HC and CO can be claimed at the lower 90% confidence limit. One therefore would have a 95% level of confidence that emission reductions will exceed the value predicted at this lower limit.

FIGURE 2-3

PRE AND POST MAINTENANCE EMISSIONS DESTINATIONS
Based on the 1972 Federal Test Procedure
Fleet Deterioration Program

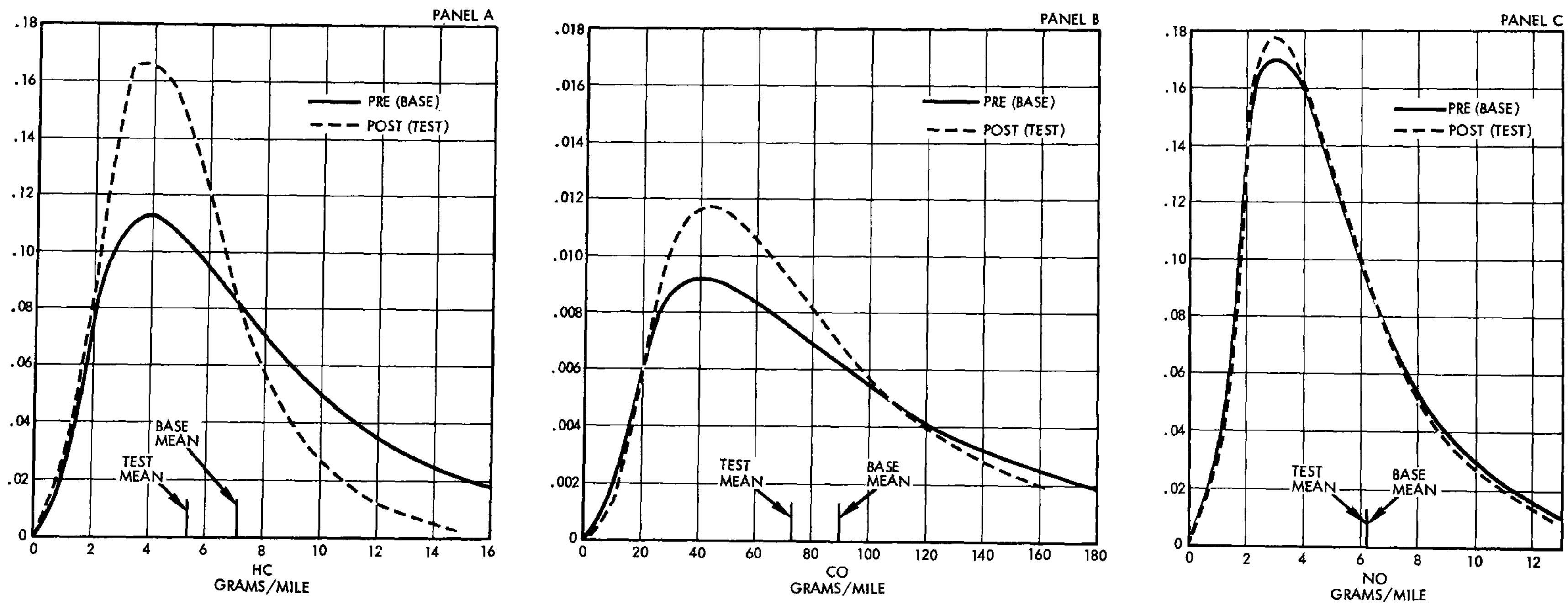


TABLE 2-9

Influence of Several Confidence Statements on Estimated Maintenance Effectiveness-Diagnostic, Extensive B Inspection

Emissions, gms/mi

Specie	Maintenance Pre	Maintenance Post	Expected Reduction*	90% Confidence Band on Reduction^{+}	"t" Statistic** Computed	"t" Statistic** Critical @ 90%$^{+}$
HC	7.1	5.4	1.7	± 0.65	3.3	1.28
CO	87.7	73.5	14.2	± 5.1	2.9	1.28
NO	6.2	6.2	0	± 0.37	0	1.28

*Expected reduction estimated from economic-effectiveness model

$^{+}$Based on pooled pre and post maintenance variances from the 150 vehicle, fleet deterioration experiment emissions data and a 90% confidence level

**When t (computed) > t (critical at 90%) there is greater than a 90% confidence that the expected emission reductions is greater than zero.

The values of inspection/maintenance procedure performance predicted by the economic effectiveness model and presented in Table 2-5 can now be adjusted to reflect their minimum anticipated performance. Table 2-10 shows inspection/maintenance procedure performance values which have been discounted to reflect the smaller emission reductions which can be achieved with a 95% level of confidence. Ninety-five out of one hundred times program results would be expected to be at least as good as indicated in this figure. It is significant to note that the ordinal ranking of procedures as reflected by the figures of merit has generally changed to favor those procedures employing the direct diagnosis of engine parameter malfunctions. The sole exception to this statement is a key mode emission inspection coupled with adjustment of idle parameters and ignition subsystem repair. The primary reason for these changes in ranking is the larger emission reductions achieved with these procedures relative to the pooled estimate of variances in the emissions data. This is dramatically illustrated by comparing the five-year average emission reductions presented in the last three columns of Table 2-10 with those of Table 2-5.

Several known and significant deficiencies exist in the economic-effectiveness model at this point in its development. Specifically, maintenance is assumed to be reliably performed and the engine parameter deterioration rates are inferred from incomplete data sets. Therefore, those states or cities contemplating the implementation of mandatory vehicle inspection/maintenance programs are urged to use the results reported herein as a guide in selecting the procedures which best fit their needs. A carefully designed pilot program employing large vehicle (300 to 600) and service organization (30 to 60) samples should be conducted to verify that the results estimated in this report are achievable within their existing framework of service organization capability and vehicle owner maintenance habits. The model may then be validated against these data and used in its predictive mode to determine expected future emission reductions.

TABLE 2-10
Optimized Inspection/Maintenance Performance Based on Mass Emission Reductions Stated at the Lower 95% Confidence Level

Inspection/Maintenance Procedures	Figure of Merit $/ton[+++]	Cost per Vehicle	Emission Reductions, % HC	CO	NO
Engine Parameter Diagnostics					
1. Idle (state lane)	393	1.60	0.2	4.9	-2.0
2. Idle (franchised)	501	3.00	0.2	2.8	4.0
3. Extensive A[+] (franchised)	325	7.00	17	3.3	3.2
4. Extensive B[++] (franchised)	485	3.50	18	8.4	0.8
Emission Signature Analysis					
5. Idle (state lane)	1062	1.90	-3.0	3.5	0.7
6. Extensive A[+] (state lane)	293	2.50	6.1	4.0	0.9
7. Extensive B[++] (state lane)	517	5.75	5.5	5.4	-2.4

[+] Idle plus ignition tuneup, without/with dynamometer

[++] Idle plus ignition plus induction tuneup

[+++] L.A. basin weighting function

2.2 System Sensitivity Studies

The purpose of the system sensitivity studies was to establish the effects of the following variables on procedure effectiveness and selection:

- Engine adjustment deterioration rates
- Engine parameter and mode emission pass/fail criteria
- Frequency of vehicle inspection
- Levels of voluntary maintenance
- Figure of merit emissions weighting factors
- User inconvenience costs
- Labor rates for franchised garage and state lane inspection
- State lane facility configuration

An important aspect of a sensitivity analysis involves defining a so-called nominal or standard case. The impact of various changes in system input on program performance is then measured relative to this reference. The nominal case selected as a reference for this analysis is an idle parameter inspection/maintenance program for the Los Angeles basin. In some cases assessment was also made of the influence of system variables on the performance of a program which involved more extensive inspection and maintenance.

The following sections present a discussion of the results of the sensitivity analysis. Section 2.2.1 evaluates the impact of inspection criteria, the nature of voluntary maintenance and parameter deterioration rates on procedure effectiveness. Section 2.2.2 presents a discussion of the proposed state lane inspection system and an assessment of the system configuration tradeoffs. Section 2.2.3 discusses the impact of several key system operational variables such as the frequency of vehicle inspection. Finally in Section 2.2.4, an analysis is made of the impact of variations in the weighting factors assigned to the reduction of emission species in the system figure of merit upon the selection of optimum inspection/maintenance procedures.

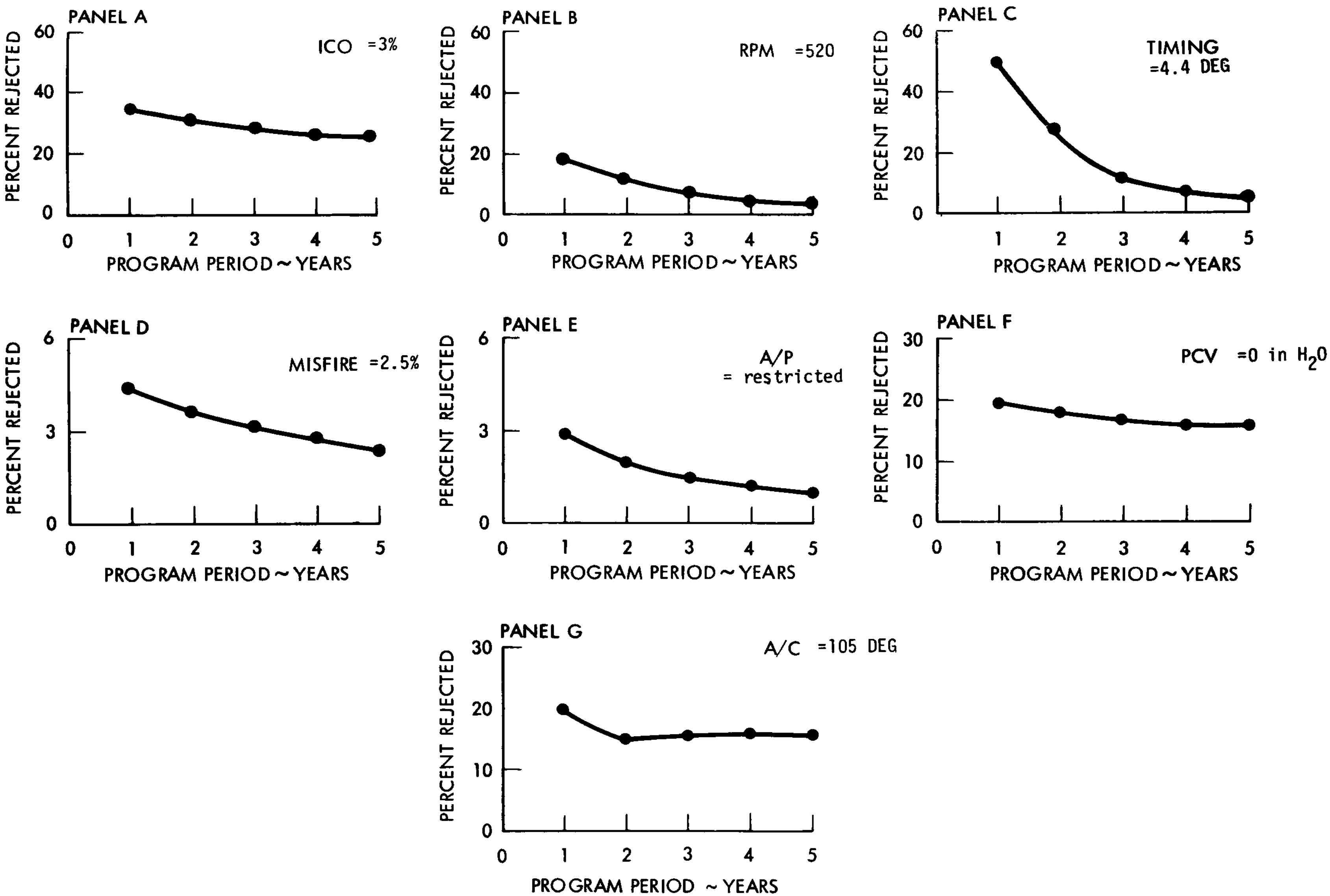
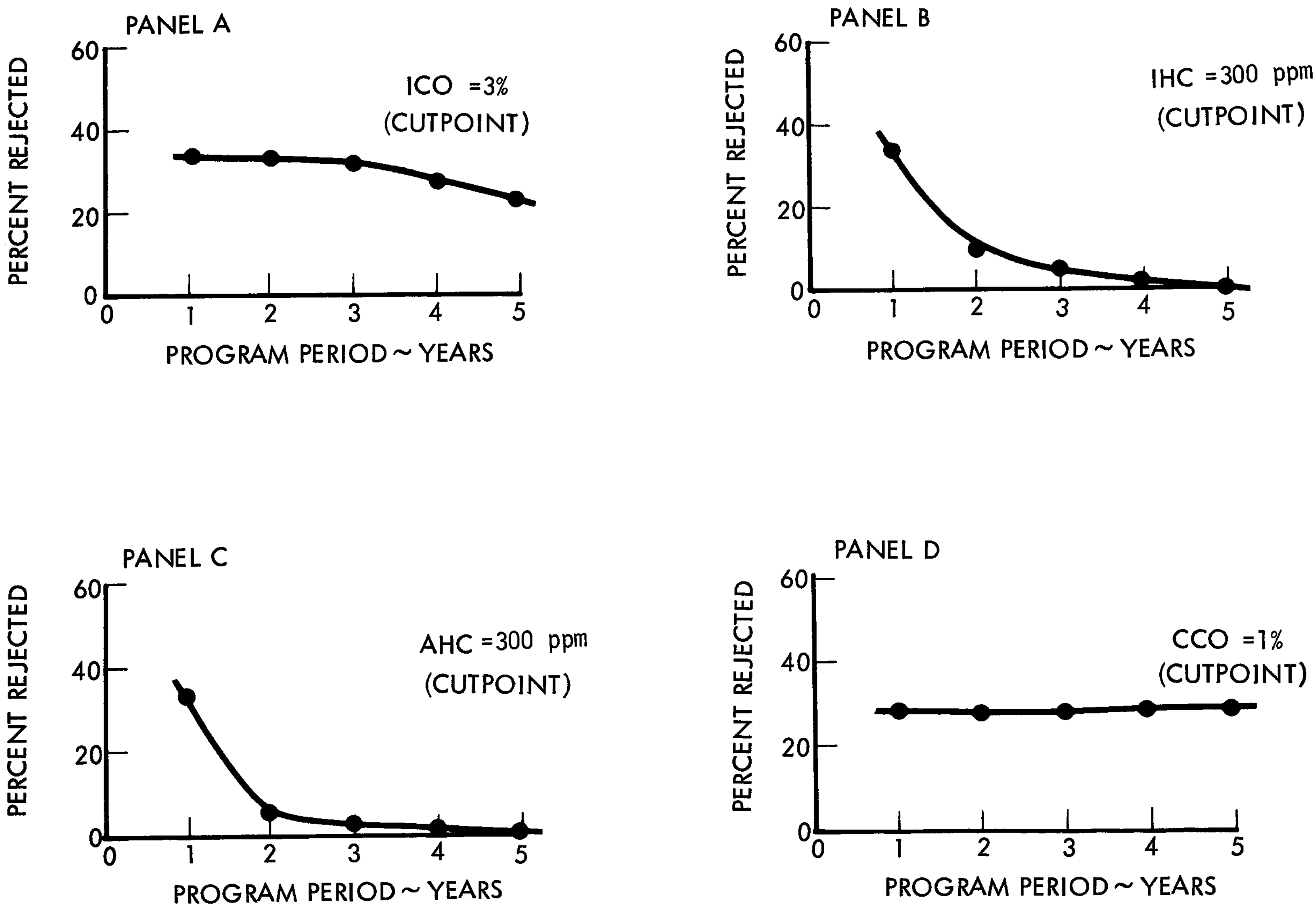


FIGURE 2-4 Changes in Parameter Rejection Fractions With Time

FIGURE 2-5 Rejection Fractions Resulting from an Emission Signature Inspection Followed by an Extensive B Maintenance



2.2.1 Inspection/Maintenance Procedure Sensitivity

The sensitivity of system performance to the basic input data and assumptions which characterize the inspection/maintenance procedures is presented herein. The extent of voluntary maintenance and criteria for inspection appear to be the most significant variables in terms of their impact on procedure effectiveness.

Fraction of Vehicles Rejected

Figure 2-4 shows the percentage of vehicles rejected based upon various engine parameter maladjustments and malfunctions for an Extensive B maintenance program over a five year interval. This figure is for an optimal pass/fail criteria using a direct engine parameter inspection procedure. At the first inspection interval, the state of maintenance of vehicles varies widely resulting in high initial vehicle rejection fractions with values ranging between 20-50% of the vehicle population. At subsequent inspection intervals engine adjustments in the population are under better control and the vehicle rejection fraction decreases. Very little decrease in rejection fraction with time is found for idle fuel-to-air ratio while a substantial decrease is found for timing. This sensitivity of the rejection fraction to individual engine adjustments relates directly to their deterioration rates and to the degree to which they are out-of-specification at program initiation. For example, a large percentage of vehicles have timing maladjustments most of which are corrected during the first inspection/maintenance cycle. Since timing adjustments deteriorate slowly, subsequent inspections with a fixed pass/fail level find fewer and fewer malfunctions of this type. Over five years, the rejection fraction for timing was found to drop from 50 to 10%. For the more highly leveraged, but infrequent malfunctions such as misfire, air pump failure and air cleaner or PCV component restrictions, a more nearly constant rejection fraction occurs over the five-year program period.

Figure 2-5 presents the fraction of vehicles rejected by an emission inspection using both idle and loaded mode measurements of CO and HC. As can be seen, the rejected fractions based upon CO measurements are relatively insensitive to the program duration. This is because the emission inspection approach is not a reliable procedure for diagnosing the induction system malfunctions under study and a large number of errors of omission occur. Usually, CO emissions measured under load identify only 30 to 40% of the actual malfunctions of interest in the induction system. Since a relatively small percent of these component malfunctions are identified and corrected with these inspection procedures, the rejection fraction remains high. As anticipated, rejection fractions for an inspection of CO emissions at idle are similar to those for a direct engine parameter inspection.

Inspections using both idle and loaded HC emission levels result in a vehicle rejection level which decreases sharply with inspection program duration. This is because the first inspection finds most of the misfires within the general population with few errors of omission being committed. The mean level of HC emissions measured during vehicle inspections decreases substantially because of the large HC response to misfire, thus low levels of rejection result during subsequent inspection intervals.

Pass/Fail Criteria

The influence of pass/fail criteria for the three idle adjustments of timing, rpm and idle CO upon the average emission reductions achieved over five years by an idle engine parameter inspection is shown in Figure 2-6. The effect of varying the pass/fail criteria is determined by varying one of the three idle inspection pass/fail criteria while holding the other two at optimal levels. Optimum HC reductions apparently do not occur until the rpm and idle CO pass/fail criteria are set close to manufacturer's specification. The effect of the timing pass/fail criteria upon HC and CO emissions is very small. The sensitivity of NO emissions to timing however tends to drive the optimal timing rejection point toward lower values. The optimal pass/fail criteria for the three idle parameters, therefore, are close to the specification value for each.

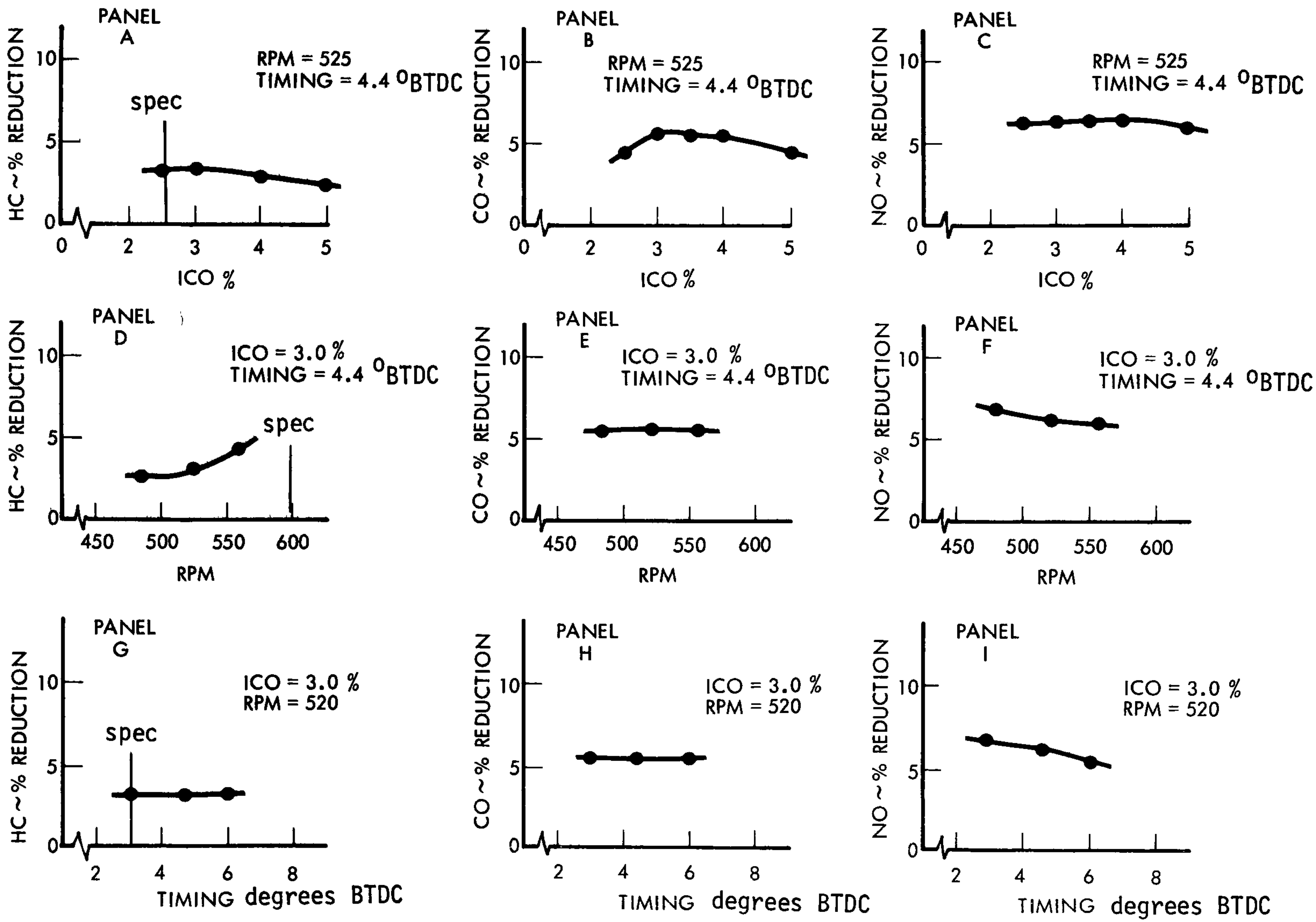


FIGURE 2-6 Effects of Pass/Fail Criteria on Five-Year Average Emission Reductions

The sensitivity of emission reductions to variation in the pass/fail criteria near their optimal values is not substantial because a failure criteria placed close to specification leads to rejecting a large vehicle population in which the average maladjustment is small. The product of the average malfunction deviation from specification and failure frequency therefore remains relatively constant with small variations of pass/fail criteria.

As shown in Figure 2-7, the figure of merit for idle adjustments is less sensitive to variations of the pass/fail criteria than were the emissions reductions. The pass/failure criteria which yield optimum values for the figure of merit however also tend to produce maximum emissions reductions. Similarly the value of the figure of merit is not sensitive to pass/fail criteria placed on PCV and air cleaner flow restriction.

Parameter Deterioration Rates and the Extent of Voluntary Maintenance

The influence of uncertainties in the basic input data was also studied. Figure 2-8 shows the sensitivity of the figure of merit (Panel A) and emissions reductions (Panel B, C and D) to the deterioration rates of idle fuel-to-air ratio (ICO) and misfire when these rates are varied by ±30% of the nominal rates shown in Table A-2. The figure of merit is based on Region I weighting factors and an idle adjustment program. The rate of deterioration of idle fuel-to-air ratio tends to effect procedure performance most significantly. It should be noted that the ±30% variation of deterioration rates from nominal was selected arbitrarily for this study. A similar analysis for the program involving an engine parameter inspection and the maintenance of idle adjustments, ignition system components causing misfire and the induction system components showed that the figure of merit and HC emission reductions were extremely sensitive to the ignition system deterioration rate. Generally, those engine parameters most strongly influencing emissions are those which were found to be most sensitive to uncertainties in deterioration rates.

The effects of various levels of voluntary maintenance on the effectiveness of a mandatory inspection/maintenance program were also studied. Figure 2-9 shows the results of changing the effectiveness of voluntary maintenance. Varying the effectiveness of voluntary maintenance by

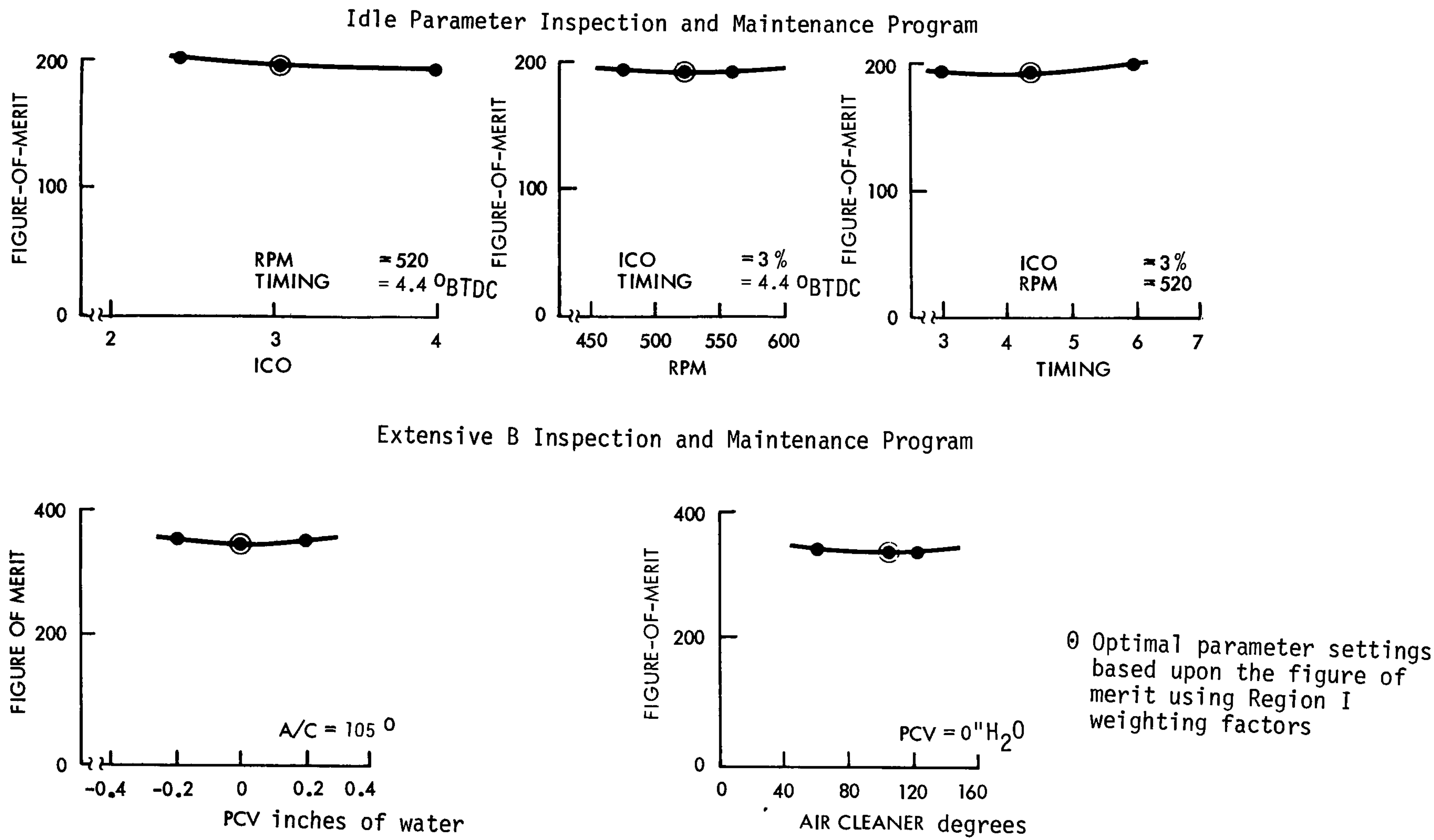


FIGURE 2-7 Sensitivity of Figure of Merit to Engine Parameter Pass/Fail Criteria

Idle Parameter Inspection and Maintenance Program

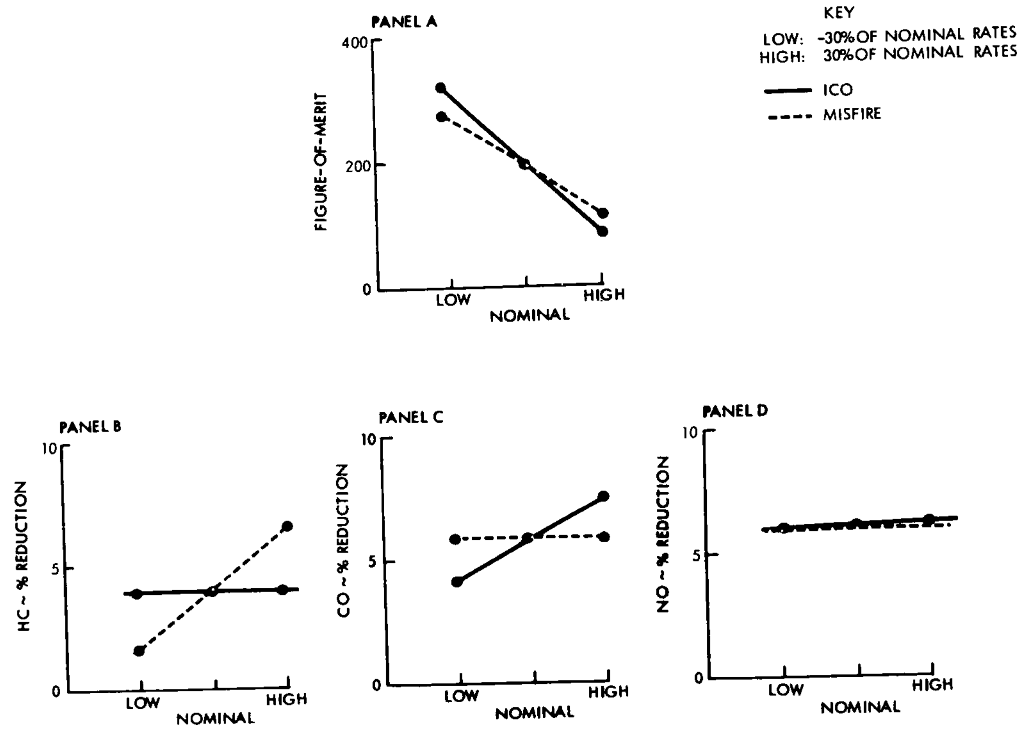


FIGURE 2-8 Influence of Parameter Deterioration Rates on Procedure Effectiveness

Idle Parameter Inspection and Maintenance Program

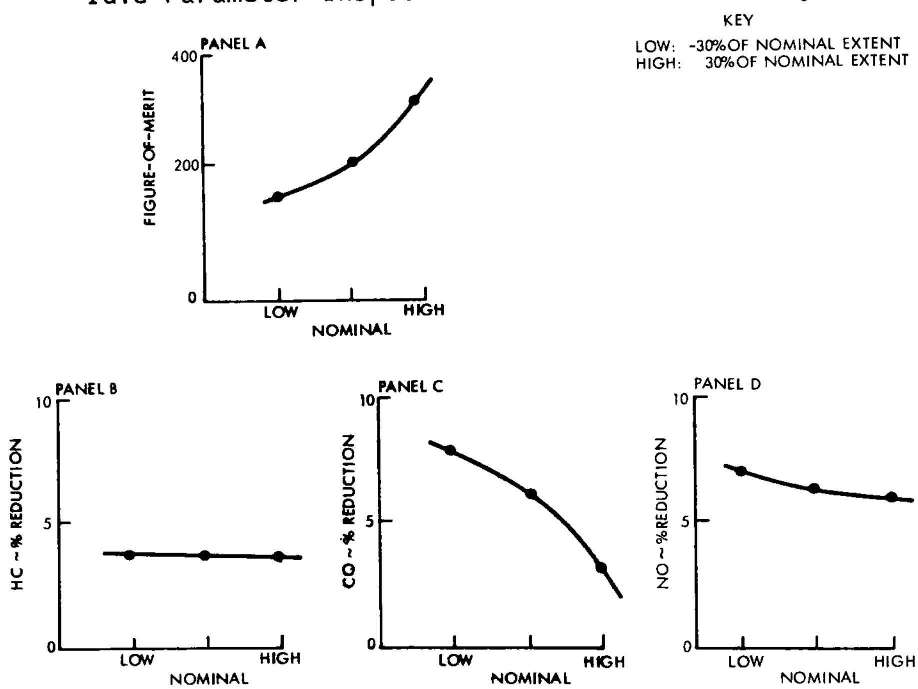


FIGURE 2-9 Influence of Voluntary Maintenance on Procedure Effectiveness

±30% of the baseline values resulted in a 150% change in the figure of merit for the idle adjustment program. Most of this change can be attributed to the large impact of voluntary maintenance on CO emissions. Further data to characterize the frequency and extent of voluntary maintenance are required in view of the sensitivity of the effectiveness of a program of mandatory vehicle inspection and maintenance to these factors.

Maintenance Effectiveness

Once specific malfunctions have been identified by vehicle inspection the next issues are the reliability with which a repair or adjustment can be effected by a service organization and the effect of imperfect maintenance performance on a mandatory program. Program effectiveness is detrimentally affected when repairing agencies either fail to make a required repair or inadequately make it because of poor mechanic skill or diagnostic equipment limitations. One of the more poorly maintained adjustments identified in the engine parameter survey is idle fuel-to-air ratio (idle CO). This parameter is likely to be set rich by service organizations to minimize subsequent customer complaints. The effect of failure to set idle CO to the average specification value of 2.5% is shown in Figure 2-10. As can be seen, setting idle CO one percent richer than average specification can almost completely negate the effectiveness of an idle adjust program for controlling CO emissions. It therefore appears important that franchised service organizations undergo a certification procedure to assure adequate standards of performance.

2.2.2 System Configuration

The purpose of this section is to demonstrate the capacity of the Economic-Effectiveness model to determine the optimal design of a state lane inspection system.

Figure 2-11 is an artist's conception of a state lane inspection station. This particular one-lane inspection station configuration is equipped with a dynamometer for making loaded mode emission measurements. It has been designed to process approximately 50,000 vehicles annually. The total capital cost for this one-lane station with the attendant

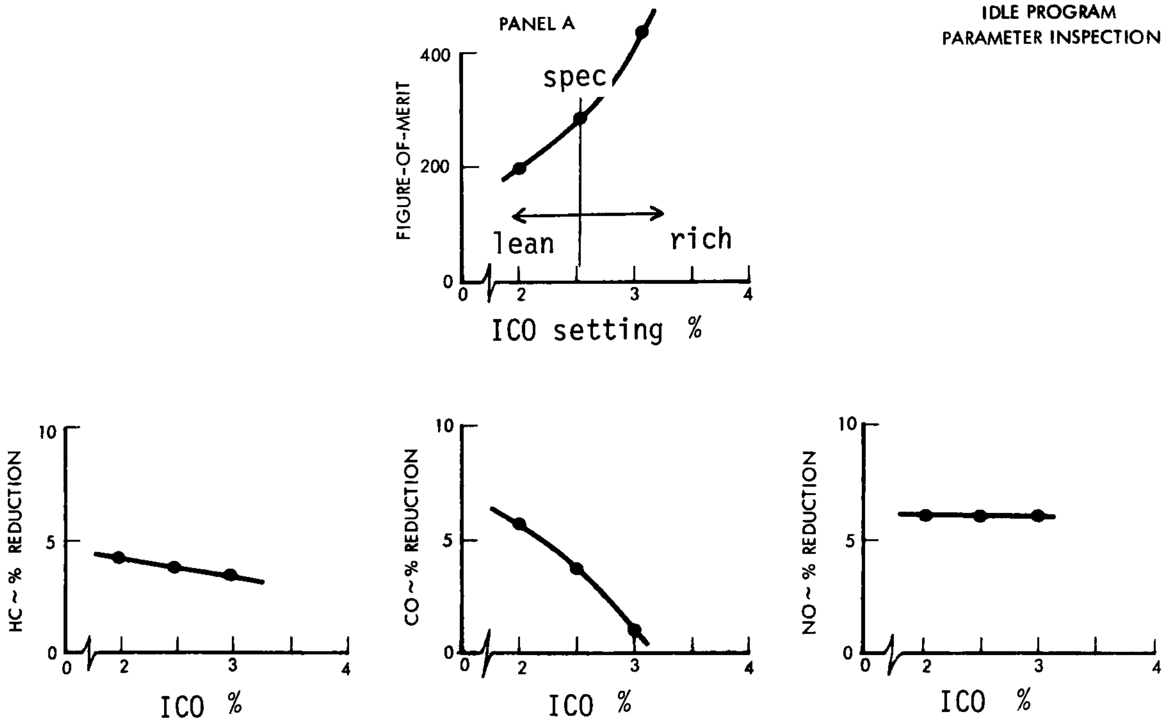


FIGURE 2-10
Influence of ICO Adjustment on Procedure Effectiveness

computer and measuring equipment is $45,000. A computer readout showing inspection times, costs and other salient information for the state lane system is given in Table 2-11. The inspection times used in the analysis were 1.5 minutes for an idle emission inspection and 2.2 minutes for a loaded-mode emission inspection.

A key tradeoff in designing a state lane inspection system is the number of lanes at each inspection station and the number of stations required to provide the total number of inspection lanes for a given region. Obviously the more lanes each station has, the fewer the required number of stations. This decision involves trading off user inconvenience costs with inspection station capital and labor costs. Labor and capital

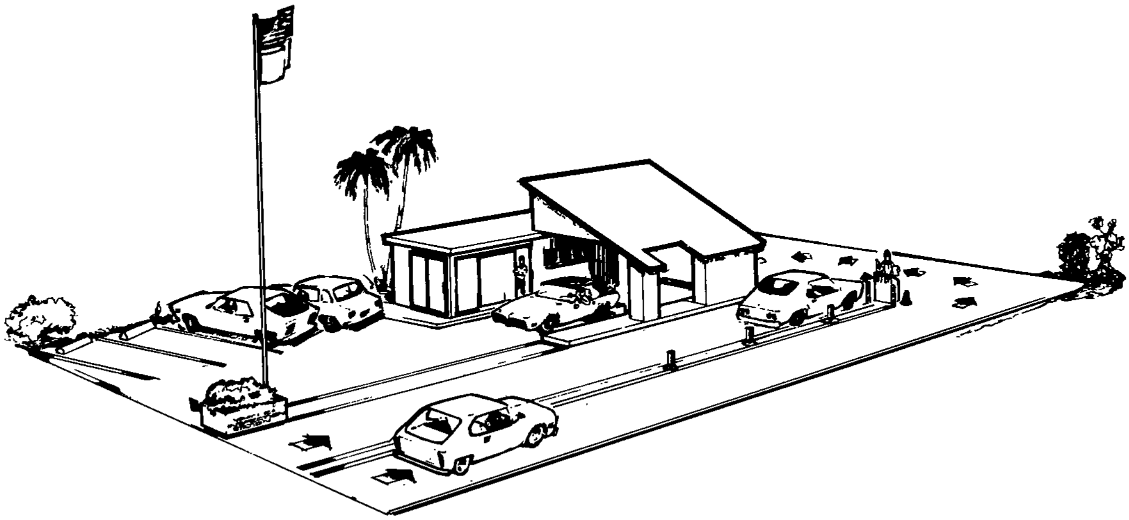


FIGURE 2-11
Artist Conception of State Lane Inspection Station

TOTAL NUMBER OF STATE OPERATED INSPECTION LANES	40
NUMBER OF LANES PER SITE	1
TOTAL NUMBER OF SITES	40
VEHICLE INSPECTION TIMES	
IDLE	1.50 MIN
LOADED	2.20 MIN
EQUIPMENT REQUIREMENTS AND COSTS	
NDIR	2000.00 DOLLARS/LANE
COMPUTER	15000.00 DOLLARS/LANE
MISC.	3000.00 DOLLARS/LANE
DYNO	7000.00 DOLLARS/LANE
INFORMATION PROCESSING COSTS	.50 DOLLARS/CAR
USER TIME COSTS	2.00 DOLLARS/HR.
TOTAL USER TIME	13.18 MIN
NUMBER OF STATE EMPLOYEES	2
STATION SIZE	600.00 SQ. FT.

TABLE 2-11 Typical Input Data Describing a Single Lane State Inspection Station

costs are directly proportional to the number of inspection lanes while user inconvenience costs vary inversely with the number of lanes.

Figure 2-12 shows the results of trading off the total number of lanes and the number of lanes per station for a prescribed state lane system. Panel A shows the influence of the number of lanes per station

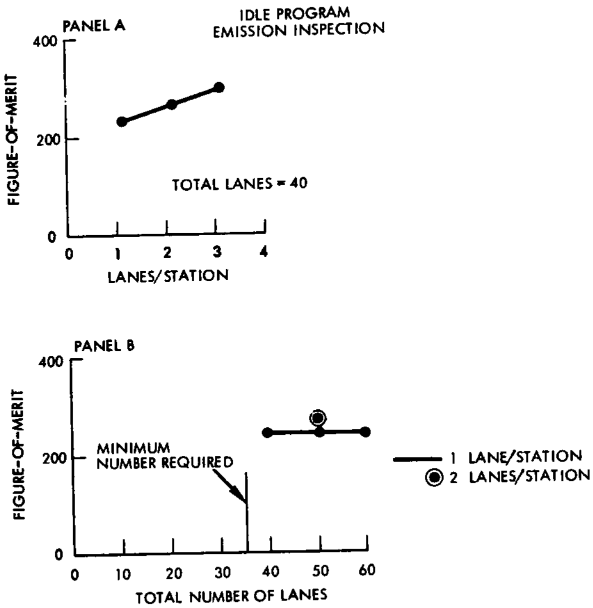


FIGURE 2-12
Influence of System Configuration on Procedure Effectiveness

on the figure of merit for a system with 40 total lanes. As can be seen, the lowest figure of merit for the stated procedure occurs at one lane per station. This is because user inconvenience costs, when valued at $2/hr., tend to dominate system capital costs. Labor costs, moreover, do not directly impact this tradeoff since they are primarily related to the total number of vehicles inspected. Panel B shows the results of a similar tradeoff exercise, except that the total number of lanes has been varied, while holding the number of lanes per station constant. Here the total inspection costs nearly balance user inconvenience costs and result in an invariant figure of merit. A minimum of 35 complete lanes are required to process the control vehicles (1966-1970) for Region I. When the number of lanes per station is increased to two, for a 50-lane system, the associated figure of merit is comparable with the results shown in Panel A.

2.2.3 Operational Variables

Frequency of vehicle inspection is one of the most significant operational variables in a program of vehicle inspection/maintenance. Figure 2-13 shows the results of a parametric analysis of various inspection periods. Panel A reveals that a yearly inspection is most cost effective

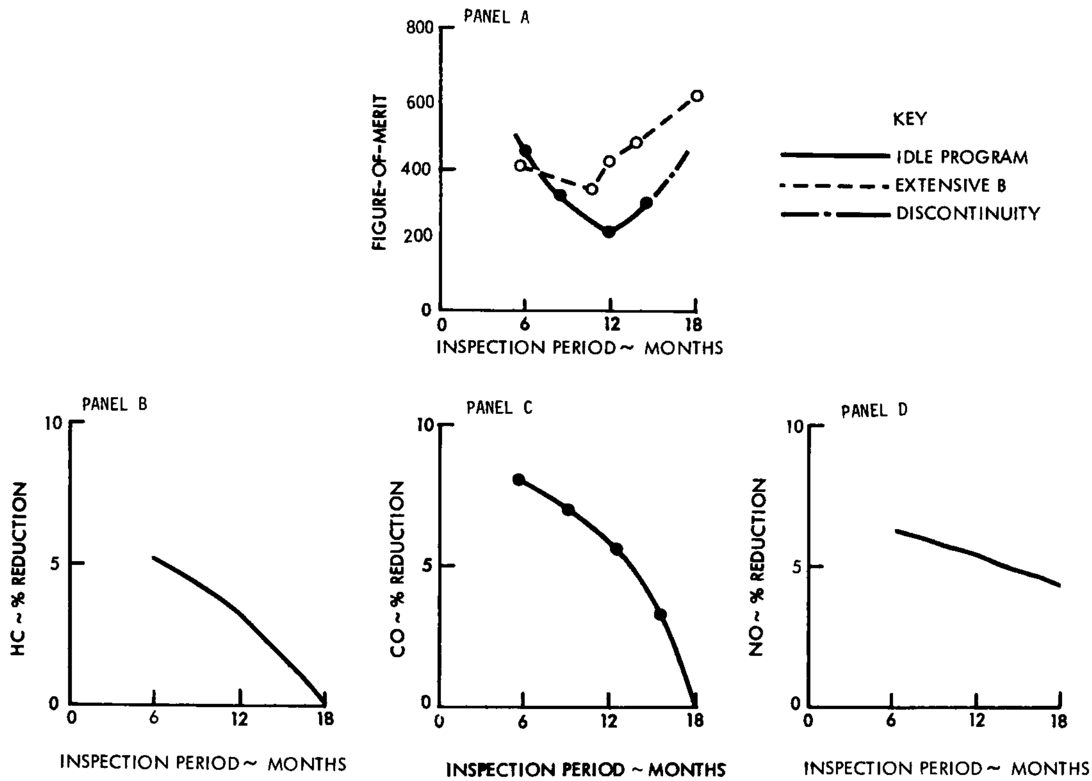


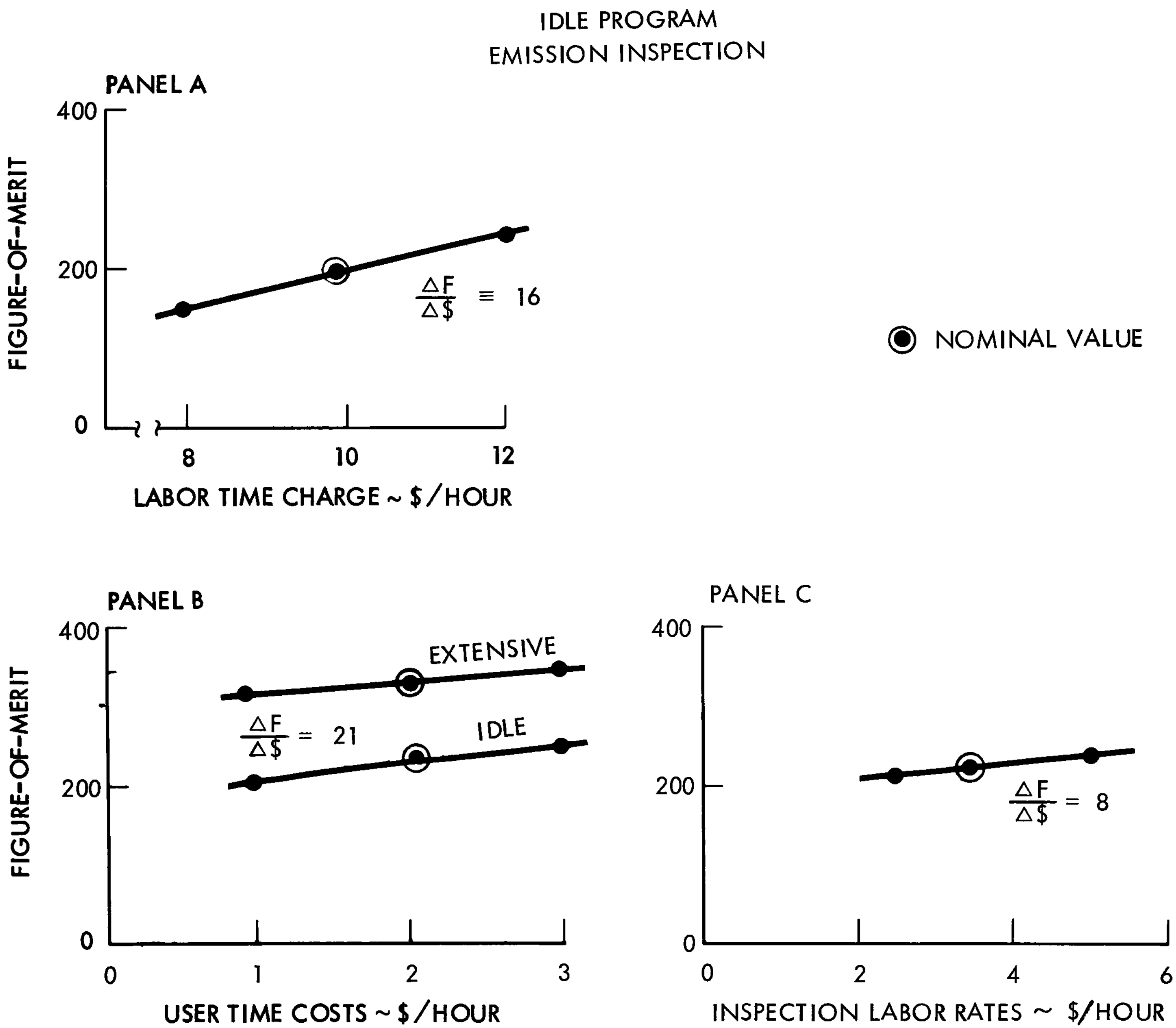
FIGURE 2-13
Influence of Inspection Period on Procedure Effectiveness

for an idle parameter maintenance program. For a more extensive maintenance program, the optimal inspection period appears to be ten months.

Panels B through D of Figure 2-13 show predicted emission reductions for the idle parameter maintenance program. These emission reductions represent the average values achieved over a five-year period of program operation. As expected, the more frequent inspection periods, e.g., six months, yield larger reductions for all three emission species. In the cases of HC and CO, Panel B and C, the emission reductions tend towards zero as the frequency of inspection approaches 18 months. This is because the voluntary maintenance program undergone by the baseline fleet becomes equivalent in terms of achieving emission reductions to the 18-month idle parameter inspection/maintenance procedure. The relatively high rate of idle CO and rpm deterioration with time result in a substantial HC and CO sensitivity to inspection frequency. The trend towards zero emission reductions at 18 months is not observed for NO. The voluntary maintenance program does not strongly affect NO emissions (Table A-2) and consequently reductions produced by the inspection/maintenance procedures will appear as an improvement. The low rate of change in NO emission reductions with respect to frequency of inspection can be attributable to the relative low timing deterioration rate.

Because labor costs dominate capital costs for a state lane or franchised garage inspection system, it becomes important to assess the impact of various labor rate structures on the program figure of merit. Panels A, B and C of Figure 2-14 show the influences of franchised garage labor rates, user time costs and state lane wage rates on program effectiveness. The nominal values used in this analysis are denoted by a circled dot. For the idle parameter maintenance program, the figure of merit appears most sensitive to user time costs and least sensitive to state lane wage rates. As a measure of this sensitivity, the derivatives for the figure of merit, with respect to each of these variables, (i.e., $\Delta F/\Delta\$$), has been computed for the range studied. Results of these calculations show that the franchised garage labor rates (Panel A) have twice as much impact per unit change as state lane labor costs (Panel C). Costs associated with user inconvenience have even a larger impact. This is because user costs are computed based upon the total vehicle population while, for example

FIGURE 2-14 Influence of Labor Costs and User Inconvenience Costs on Procedure Effectiveness



garage repair costs are incurred on rejected vehicles only. To evaluate the influence of user inconvenience costs more fully, a sensitivity study was also performed for an extensive maintenance program and is shown along with the results of an idle parameter maintenance program on Panel B. Although the figure of merit has increased, its rate of change with user inconvenience cost is about the same as that of the idle program. Again this is attributed to the dominance of operating costs in a vehicle inspection/maintenance program.

2.2.4 Weighting Factors for Emission Reduction

One of the more uncertain assumptions used in the analysis is involved in specifying values for the emission weighting factors which are used for combining the computed reductions of each emission specie into a program figure of merit. Weighting factors which have often been used for the Los Angeles basin involve weighting HC by six-tenths, CO by one-tenth, and NO by three-tenths. This weighting of the relative importance of emission species reflects the particular air pollution problem in this region. Regions with a different type of air pollution problem would be expected to assign a different weighting to specie emission reductions.

To improve the understanding of the influence of these weighting factors on procedure effectiveness, a parametric study was performed. Presented in Table 2-12 are the results of the study for three different weighting functions. Case 1 employs the values for the Los Angeles basin

TABLE 2-12
Influence of Emission Weighting Function on Procedure Effectiveness (W_{HC}, W_{CO}, W_{NO})

Engine Parameter Inspection	Figure of Merit		
	Case 1 (0.6,0.1,0.3)	Case 2 (0.9,0,0.1)	Case 3 (0.1,0.9,0)
1. Idle (franchised)	200	570	35
2. Extensive A+ (franchised)	230	250	75
3. Extensive B++ (franchised)	350	470	80

\+ Idle plus ignition with dynamometer

++ Idle plus ignition plus induction tune-up (with dynamometer) which have been studied. The emission factors for Case 2 place a heavy emphasis on reducing HC, while Case 3 stresses CO reduction. Results for Case 3 show a substantial reduction in the figure of merit but no change in the ordinal ranking of the procedures. This lower figure of merit is the result of the large weighting factor and emission reduction, in tons, for CO. For Case 2 a change in the ordinal ranking of the procedures has resulted. The Extensive A program is now substantially more attractive than the idle program. This can be attributed to the high HC weighting factor and the fact that the Extensive A program was designed primarily for reducing hydrocarbons. The figures of merit for Case 2 are poorer than for the Case 1. This again is caused by the much lower emission reductions, in tons, obtained for HC for an equivalent dollar expenditure. It is concluded that placing primary emphasis on HC reductions results in selecting a procedure which diagnoses and corrects engine misfire while placing emphasis on CO reductions primarily leads to the selection of an idle CO adjustment program. It should be noted that the most cost-effective procedure may not be selected if regional authorities require emission reductions in excess of those estimated for optimal strategies in order to achieve their air quality goals.

2.3 Regional Evaluation

While the air quality problem is national in scope, its specific characteristics vary considerably between basic geographic regions. The effectiveness of mandatory vehicle inspection/maintenance for controlling emissions therefore must be analyzed on a regional basis. It is conceivable that a general program design could be used regardless of the air quality problem of a particular region. However, it is much more likely that particular regional characteristics will necessitate a specifically designed program to achieve maximum cost-effectiveness. From the other viewpoint, it is essential to investigate the sensitivity of an optimal inspection/maintenance program design to regional variables in order to determine the advantage of programs tailored to the needs of specific regions.

Regional analyses were therefore performed using the cost-effectiveness computer model. Their purpose was to obtain preliminary data on the regional sensitivity of optimal inspection/maintenance program design. In addition to the Los Angeles basin (Region I), three other urban areas were selected for analysis. This sample was specially chosen to provide a wide range of regional air quality and demographic conditions. Los Angeles has a photochemical smog problem that is related to high HC and NO_X concentrations. Region II was selected because CO is the major pollutant with HC being of secondary concern. Region III involves a rather balanced situation. While there is an incipient HC problem, air quality degradation is due rather equally to HC, CO and NO. Region IV's altitude of approximately 5000 feet above sea level makes its air quality problem different still. Because of the reduced air pressure at such altitudes, the fuel metering of the IC engine carburetor is considerably altered. The resultant high fuel-to-air ratio leads to considerable unburned HC, which is by far the dominant pollutant. It is evident then, that this small sample of four regions provides a wide range of air quality problems.

2.3.1 Regional Characterizations

Presented below is a list of important data required to characterizing the various regions:

- Emission Surveillance Data
- Demographic Data
  - Regional Area (effective)
  - Average Travel Time
  - Vehicle Population Density
  - Vehicle Powertrain Distributions
  - Economic Factors
- Vehicle General Maintenance State
- Vehicular Emission Reduction Goals
- Emission Specie Weighting Function

Regional differences were characterized in the model in several basic ways. First, the different abatement goals for the three pollutant species were reflected in different regional weighting functions for total emission calculations. These emission weighting factors are shown in Table A-5. For example, in Region I where high HC concentrations occur, HC was assigned a relative weight of 0.6, CO of 0.1 and NO of 0.3. On the other hand, in the case of Region II where CO is of prime concern, CO was assigned a relative weight of 0.6, HC of 0.1 and NO of 0.3. Weighting factors were assigned in a similar manner to Regions III and IV to reflect specific air quality objectives. The effect of these weighting factor variations is to force the optimal program design towards one which minimizes emissions of the most heavily weighted emission specie.

A second source of regional differences was the set of motor vehicle population characteristics. Surveillance data taken in Region I were used to estimate present emission levels for each region (Reference 5). Resultant vehicle emission rates in grams/mile for the emission controlled portion of the automobile fleet appear in Table A-5. These data vividly show the unique problem of Region IV caused by the altered air-to-fuel metering at high altitudes. Emissions of CO and HC are dramatically higher with commensurate low values of NO when compared with the other regions. The HC and CO emission levels for Regions II and III are slightly lower than that of Region I because the emission controlled vehicles in these regions have accumulated fewer miles than the vehicles in Region I. These lower mileage levels are attributable to the relatively newer population of emission controlled cars (i.e., 1968-1970) in regions outside the state of California.

Regional variations in the population of uncontrolled, controlled and post-1970 vehicles were accounted for in the model. Roughly, two-thirds of the vehicle population in Regions II, III and IV were uncontrolled in 1971, as compared with less than one-half of the Region I population. The high proportion of controlled vehicles in the Region I population is a direct reflection of the more restrictive California emission control statutes adopted during the 1960's.

The geographical size of the region and average driving speed were also included in regional characterization. These data were particularly crucial in assessing the user inconvenience time and therefore in developing inspection system configurations associated with the inspection/maintenance program. Another important regional factor was the absolute size of the vehicle population. In the regions considered, the emission controlled vehicle population varied from four million cars for Region I to 600,000 cars for Region IV.

Finally, regional differences in costs should be incorporated in the model. While the preliminary regional analysis results presented below does not reflect these differences, provision has been made in the model to include regional variations of construction and labor costs. Variations in labor and construction costs between regions would lead to different labor intensities (or capital intensities) in the optimal regional program designs.

These regional data, particularly regional vehicle and air quality characteristics, provided the basis for the regional evaluation of optional inspection/maintenance programs which is presented in the following section.

2.3.2 Comparison of Regional Programs

The approach taken in assessing the impact of regional differences on optimum vehicle inspection/maintenance programs consisted of:

- Designing an optimal program for each region using the given data set
- Comparing the performance characteristics of optimal programs between regions.

To identify accurately the most cost-effective program within a region requires an evaluation of both those inspection/maintenance alternatives previously used (i.e., idle and extensive) as well as several "customized" strategies. These "customized" strategies generally take the form of an idle CO inspection/maintenance program for regions characterized by high CO weighting factors. An alternative for areas having a critical hydrocarbon problem is to incorporate an idle misfire analysis into the basic idle program. It will be seen that both of these procedures yield results which are somewhat more cost-effective for Regions II and IV than using the procedures previously identified.

The main problem in designing cost-effective program(s) for each region involved determining optimum specific pass/fail inspection criteria. Numerical values for these criteria were obtained using the developed linear programming algorithm. Table 2-13 shows the derived inspection pass/fail criteria for several inspection/maintenance alternatives. As could be expected, those regions with a high CO problem tend to reject a larger percentage of CO related engine parameters (e.g., idle CO), whereas regions experiencing an HC problem tend to fail more vehicles based on rpm, timing and misfire.

Parameter	I (Idle)	II (Idle CO)	III (Idle CO)	IV (Idle + Ignition
ICO (%)	3	3	3	3
rpm (rpm)	525	N.I.	N.I.	560
Timing (Deg-BTDC)	4.4	N.I.	N.I.	3
Misfire (%)	N.I.	N.I.	N.I.	2.5

N.I. - Not Inspected

TABLE 2-13
Optimal Parameter Pass/Fail Inspection Criteria for Selected Regional Programs

Utilizing these pass/fail criteria together with the regional data, a series of computer simulation runs were made for the four regions. Tables 2-14 and 2-15 present the results of the computer evaluation for both idle and extensive programs of inspection/maintenance. The basic case consisted of a direct engine parameter inspection undertaken in a franchised garage. A similar set of results would have been achieved if an emission signature inspection program had been analyzed.

TABLE 2-14
Comparison of Regional Programs Employing a Parameter Inspection Strategy

IDLE MAINTENANCE

PARAMETER INSPECTION

REGION	FIGURE-OF-MERIT $/TON	COST PER VEHICLE $	EMISSION REDUCTIONS PERCENT		
			HC	CO	NO
I					
IDLE	200	3.00	4	6	6
IDLE (MISFIRE)	300	6.00	10	6	6
II					
IDLE CO ONLY	35	2.50	1	7	0
IDLE	50	3.00	3	6	0
III					
IDLE CO ONLY	55	2.50	1	7	0
IDLE	70	3.00	3	6	0
IV					
IDLE	940	3.00	1	1	13
IDLE (MISFIRE)	550	6.00	6	1	13

TABLE 2-15
Comparison of Regional Programs Employing a Parameter Inspection Strategy

EXTENSIVE A AND B MAINTENANCE

PARAMETER INSPECTION

REGION	FIGURE-OF-MERIT $/TON	COST PER VEHICLE $	EMISSION REDUCTIONS PERCENT		
			HC	CO	NO
I					
A	230	7.00	21	6	6
B	350	13.50	23	12	3
II					
A	110	6.80	21	6	0
B	120	13.50	23	11	-4
III					
A	140	6.80	21	6	0
B	165	13.50	23	11	-4
IV					
A	275	7.00	16	1	13
B	380	13.25	17	4	6

A IDLE PLUS IGNITION WITH DYNAMOMETER
B IDLE PLUS IGNITION PLUS INDUCTION

Tables 2-14 and 2-15 list three system performance variables used for regional contrasts. They are:

- Figure of merit in terms of total cost per weighted ton reduction
- Average cost per vehicle per inspection
- Emission specie average five-year reductions in percent.

An analysis of Table 2-14 indicates that an idle CO only inspection/maintenance policy yields the most cost-effective strategy for both Regions II and III. The corresponding figure of merit for Region II is nearly an order of magnitude less than for the Region I idle maintenance programs. This is caused by the high weighting factor given CO for Region II. In terms of CO emission reductions, a program in which only idle CO is maintained is preferred over a total idle maintenance program because adjustments in both timing and rpm tend to increase CO. Examination of the predicted emission reductions shows a seven percent decrease for a program of idle CO maintenance only whereas a total idle maintenance program yields a six percent reduction over the five years. Because of driveability problems resulting from adjusting idle CO only, that fraction of vehicles with low idle speed may also require adjustment. This requirement should not significantly influence the previously stated conclusions.

A comparison of the performance characteristics of an idle plus unloaded misfire inspection program with the "standard" idle program yields somewhat ambivalent results. For Region I, the addition of an unloaded misfire diagnosis cannot be justified in terms of its cost effectiveness (a figure of merit of $200/ton for idle maintenance versus $300/ton for idle maintenance with misfire). In the case of Region IV, however, a substantially improved figure of merit has been achieved with the addition of an idle misfire inspection. The improved figure of merit can be directly attributed to the larger hydrocarbon emission reductions achieved and to the corresponding large hydrocarbon emission weighting factor assigned to Region IV. The generally lower percent reduction of HC and CO emissions for Region IV is primarily caused by the much higher vehicle emission levels. The converse is the case for NO_X.

The results for the more extensive maintenance programs tend to show less performance variation across regions. The resultant figures of merit for each region are more nearly the same than for the idle programs. In the case of Regions II and III the figure of merit has increased almost twofold whereas Region IV's figure of merit has decreased by at least two-thirds. Again for Region IV, this can be explained by the heavy emphasis placed on hydrocarbons in the figure of merit. The corresponding hydrocarbon reductions produced by the extensive maintenance programs appear to be about the same across all regions. The substantial differences in regional CO and NO emission reductions can be attributed to different pass/fail criteria and vehicle emission levels.

Figures 2-15 through 2-17 show Region IV emission time histories for HC, CO and NO, respectively for an Extensive B program. These graphs were generated directly by the Economic Effectiveness Computer Program. Whereas the test fleet emission profiles appear similar to those developed for other regions, the baseline fleet emission history is somewhat different in shape (Figure 2-2). This difference can be attributed directly to the use of Region I's (Los Angeles) voluntary maintenance schedule in Region IV. A logical future development would be the construction of unique maintenance models for each region. It should also be noted that the significantly richer carburetion at altitude will probably effect the value of the emission response coefficients which were measured at a near sea level elevation. The CO and NO emission reductions projected for timing, rpm, air cleaner and PCV maintenance therefore are probably overestimated.

In summary, the viability of mandatory vehicle inspection/maintenance programs depends upon the demographic characteristics of a given region. For regions characterized by a high CO problem (e.g., Region II) either a program in which an idle air-to-fuel adjustment is made or the standard idle maintenance program appears very cost effective. Use of these same programs for a region having a high HC problem (e.g., Region IV) produces results which have poor cost-effectiveness. Controlling HC emissions requires a more extensive maintenance program. For Region IV the extensive maintenance treatment generates the most cost-effective results both in terms of hydrocarbon reduction and in terms of the figure of merit. A primary conclusion from these results is that absolute CO emission

FIGURE 2-15 HC Emission Time History for Region IV

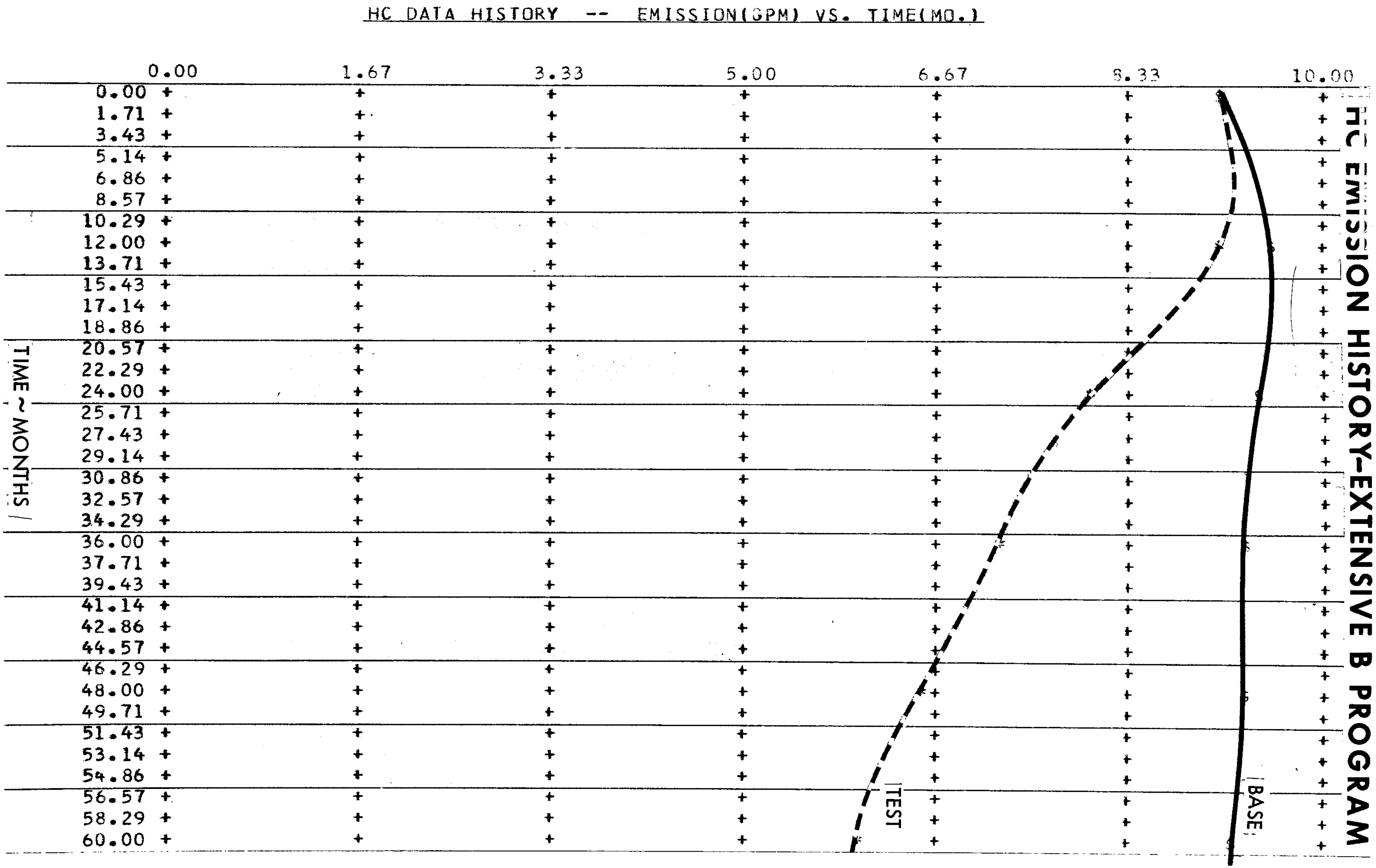


FIGURE 2-16 CO Emission Time History for Region IV

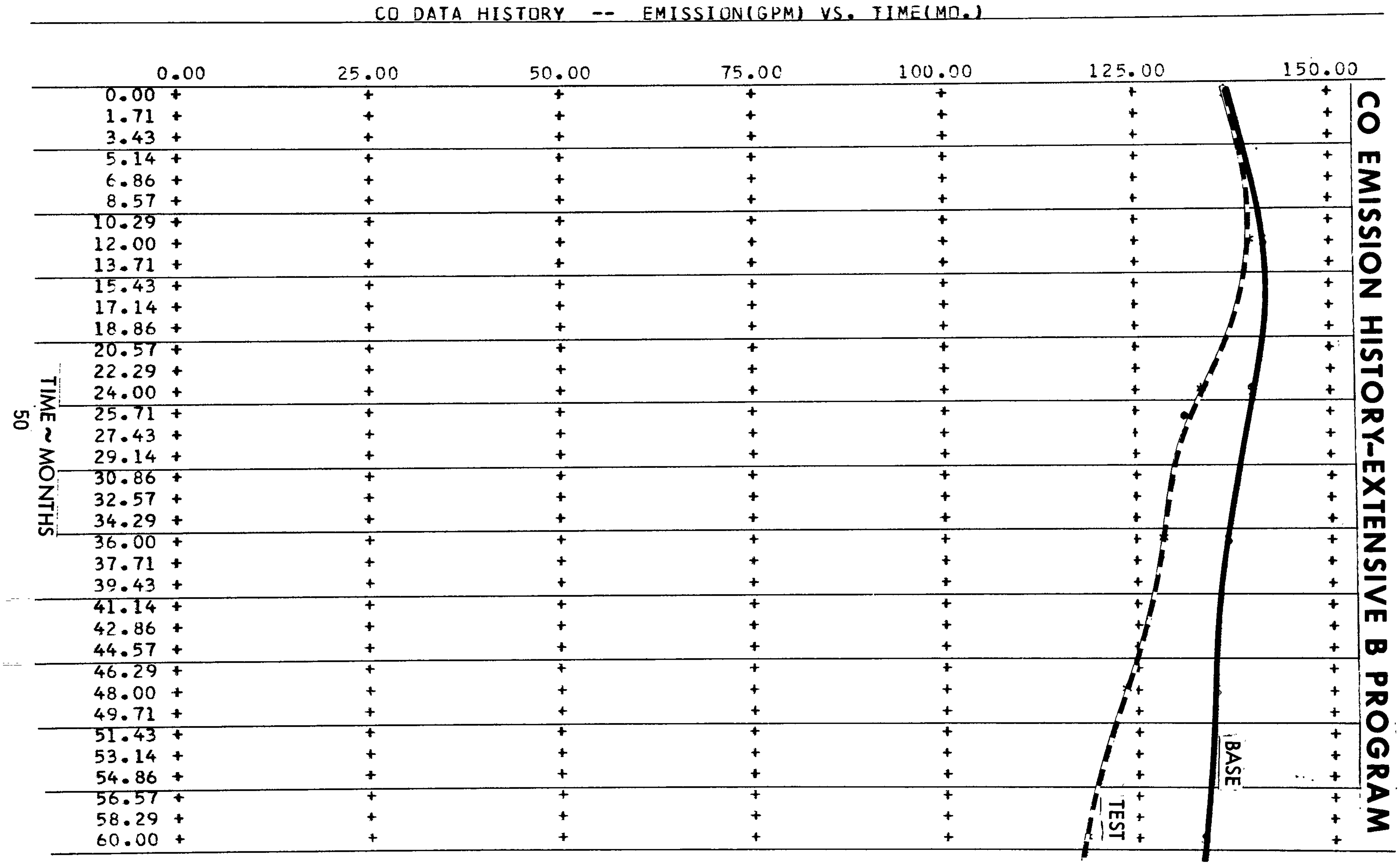
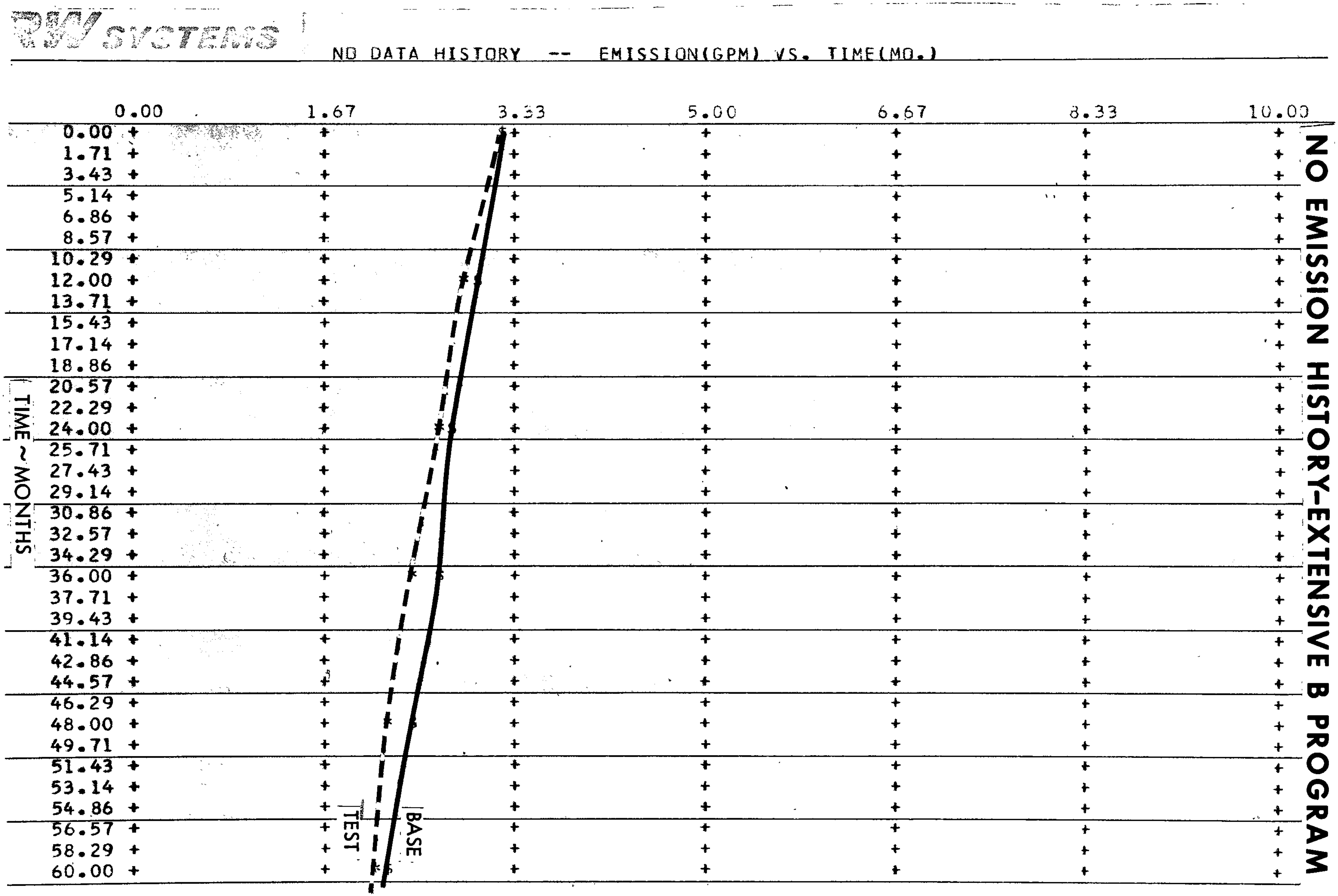


FIGURE 2-17 NO Emission Time History for Region IV



reductions (tons) from automobiles can be achieved for considerably less cost than comparable hydrocarbon reductions. Although no specific procedures were examined for reducing NO, it appears that the cost of a comparable NO reduction falls somewhere in between the cost of reducing CO and HC. The most attractive inspection/maintenance strategies from Tables 2-14 and 2-15 for the four regions are summarized below in Table 2-16.

TABLE 2-16
Selected Inspection/Maintenance Programs for the Regions Studied

Region	Strategy	Principal Specie Reduced
I	Idle parameter inspection/maintenance or load mode emission inspection and Extensive A maintenance	HC, CO, NO
II	Idle CO only inspection/maintenance	CO
III	Idle CO only inspection/maintenance	CO
IV	Direct inspection of idle parameters and ignition misfire and Extensive A maintenance	HC

3.0 CONCLUSIONS

Data from previous sections generally support the conclusions of the original study with respect to the cost and effectiveness of inspection/maintenance procedures. The detailed conclusions of this three-part study are summarized in this section.

3.1 Mass Emission Analysis

The primary objective of the mass emission analysis was to compare the effectiveness of inspection procedures as determined using the newer constant volume sampling (CVS) mass emissions measurements with those determined using concentration emission measurements. Although differences in figures of merit and emission reductions result from using the different emissions test methods, the economic-effectiveness ranking of the several inspection/maintenance procedures investigated was not changed.

- Absolute emissions reductions (tons) calculated on a mass basis are usually slightly larger than when calculated on a concentration basis, thus resulting in a better figure of merit.
- Percentage reduction of emissions from a test fleet when referenced to their respective baseline fleet emission levels are larger for NO and smaller for HC and CO when measured on a mass basis.

Reoptimization of the inspection/maintenance procedures utilizing mass emissions data resulted in slightly greater emissions reductions than were achieved in the earlier analyses. For the idle adjustment inspection/maintenance programs, the increased emission reductions ranged from one to several percent of the baseline fleet level. The most significant impact of reoptimization occurred for the case of a direct engine parameter inspection followed by extensive maintenance. For this case, increased emissions reductions of three and four percent were achieved for NO and HC, respectively. CO emission reductions remained about the same. Higher vehicle rejection fractions and therefore costs resulted, but the net effect was to improve the figure of merit. Additional conclusions derived from the model using Los Angeles basin emission weighting factors are as follows:

- Inspection of emissions in selected operating modes finds less than half of the timing, PCV and air cleaner malfunctions within the vehicle population.
- The most cost effective inspection/maintenance procedure (figure of merit of 155) is a direct inspection of idle rpm and idle CO in a state inspection lane followed by adjustment of these parameters. Five-year average HC, CO and NO emission reductions are 3, 7 and 8%, respectively.
- The second most cost effective inspection/maintenance procedure (figure of merit of 190) employs idle mode HC and CO and loaded mode HC emission inspection in a state inspection lane followed by the adjustment of the idle parameters and the repair of ignition system components causing misfire. Five-year average HC, CO and NO emission reductions of 9, 6 and 2% are achieved, respectively.
- The largest emission reductions are obtained with a direct engine parameter inspection followed by an Extensive B maintenance program, all performed by franchised garages. This program is 5 to 8 times more costly than the most cost effective inspection/maintenance procedure, however, the HC and CO emission reductions achieved are nearly double those obtained using the Extensive A state lane emission inspection procedure.
- Emission reductions at the end of five years are approximately twice those obtained on the average over a five-year period.
- The emission means observed in the pre and post tune population as measured by the fleet deterioration experiment are statistically different at the 90% confidence level.
- The Extensive A procedure becomes most cost effective when the statistically significant emission reductions are used in place of the predicted mean value emission reductions in the figure of merit.

3.2 Sensitivity Studies

Sensitivity studies were performed to determine the influence of the input data and assumptions on the results of this study. In general, the figure of merit was found to be sensitive to:

- The weighting factors assigned to emission species, particularly when CO reductions are weighted heavily, i.e., 0.9.
- Direct program costs such as maintenance, labor and user inconvenience.

Both the emission reductions and the figures of merit achieved were found to be sensitive to:

- The effectiveness with which repair is made by a service organization. For example, failure to set average fuel-to-air ratio 1% richer than average specification resulted in nearly complete ineffectiveness of an idle maintenance program to control CO.
- The effectiveness of voluntary maintenance as it is currently occurring. Obviously, as vehicles are better maintained voluntarily, a mandatory program becomes less necessary.
- The estimated rate of deterioration of the engine parameters, particularly idle fuel-to-air ratio and misfire.
- The frequency of imposed inspection and maintenance. Once yearly is nearly optimum.

3.3 Regional Impact of Inspection/Maintenance Effectiveness

The economic-effectiveness of mandatory programs of inspection/maintenance is most influenced by the emission reduction weighting factors assigned for various regions. Weighting factors which stress CO reduction generally result in a program that does little to control HC and NO emissions. Large absolute reductions of CO occur, thereby resulting in extremely good figures of merit (35 to 55 $/ton). Those procedures which adjust idle fuel-to-air ratio to specification are most effective. CO emission reductions can be approximately doubled by maintaining components of the induction and air reactor systems, but at four times the cost and with figures of merit which are twice as large as that of the simpler idle adjustment program.

In regions where photochemical smog is a problem and HC and NO emission reductions are heavily weighted, timing adjustments and ignition system repair become important. Little reduction of CO emissions is desired since NO emissions would be adversely affected. For Region IV where HC is most heavily weighted, maintenance of idle timing and ignition system misfire is over three times more cost effective than performing idle adjustments (idle CO and rpm).

APPENDIX A

STUDY GROUND RULES AND DATA BASE

A.1 Introduction

Presented and discussed herein are the study ground rules and assumptions used in conducting the current Economic Effectiveness study. Also presented are the emissions weighting factors and regional demographic characteristics utilized in the analysis.

A.2 Basic System Ground Rules

The general study ground rules are:

- The economic-effectiveness of the procedures investigated is determined by calculating a figure of merit, which is defined as follows:

$$\text{Figure of merit} = \frac{\text{annularized, discounted total program cost}}{\sum_{i=1}^{3} W_i[\text{baseline emissions}(e_{b_i})\text{-test emissions}(e_{t_i})]} \qquad \text{(A-1)}$$

- Only vehicles with emission control equipment (air reactor and engine modification) are considered (i.e., 1966-1970).
- The effects of vehicles entering and leaving the population because of attrition and new production is not considered.
- Mean values of emissions predicted for vehicle populations treated by both the engine parameter and emission inspection procedures are allowed to vary with time and with the extent of maintenance, however, the variances about these means are assumed to be time invariant.
- Basic maintenance of those engine adjustments not covered in the enforced maintenance procedure is assumed to be performed voluntarily by the vehicle owner.
- All maintenance is performed in franchised garages. Mandatory maintenance is limited to restoring the following parameters to manufacturer's specification: idle adjustments of fuel-to-air ratio, timing and rpm; components of the ignition system when causing misfire; the induction system components of air cleaner and positive crankcase ventilation (PCV) system when severely restricted; and components of the air injection system when failed.

- Inspection procedures requiring large capital expenditures (i.e., the purchase of equipment for either remote sensing or exhaust emission measurements) are always performed within a state operated system.
- All vehicles failing a state inspection are reinspected by the maintenance organization.
- All maintenance by service organizations is assumed to be reliably performed and only those idle adjustments adversely affecting emissions are restored to specification.
- Pass/fail inspection criteria are optimized for the first inspection interval and remain invariant with time.
- The cost of maintenance labor and parts are based upon Chiltons flat rate manual.
- State inspections require 1.5 minutes for the idle mode test and 2.2 minutes for the idle plus loaded mode tests. State labor rates average $4/hour.
- Emissions reductions are based on measurements made with the constant volume sampling (CVS) closed seven-mode test procedure.
- The initial maintenance state of the vehicle population, the rate of engine parameter deterioration and the effectiveness of voluntary maintenance were assumed to be identical for the four regions studied.

A.3 Basic Input Data

The basic cost and emissions data described in the previous study, References 1 and 2, were used in this study. These data are summarized in Tables A-1, A-2, A-3 and A-4.

A.3.1 Emission and Cost Data

The seven-mode CVS mass emissions response coefficients from the 11 power trains tested in the definitive orthogonal experiment were weighted by their approximate fraction in a California population to obtain the population average reported in Table A-1. Although these coefficients are similar to those based on concentration measurements, they are sufficiently different to effect predictions of emissions reductions for inspection/ maintenance procedures.

TABLE A-1 Emissions Responses to Engine Parameter Changes (Definitive Orthogonal Experiment)

Emission, Δe	Emission Response to Engine Parameter Changes, $\partial e^{+}/\partial P$					
	Timing Δe/deg	Idle RPM Δe /rpm	PCV Δe/in H_2O*	Air Cleaner Δe/deg**	Idle CO Δe/%	Misfire e/%
HC, g/m	0.055	-0.006	0.48	0.0010	0.031	1.11
CO, g/m	-0.32	0.020	12.6	0.072	6.75	-
NO, g/m	0.11	0.00029	-0.52	-0.0024	0.034	-
49 mph CO, %	-0.0030	0	0.12	0.0028	0.017	-
33 mph CO, %	0.00137	0	0.74	0.0039	0.031	-
Idle						
HC, ppm	7.97	-0.55	-15.1	0.18	8.27	80.4
CO, %	0.0012	0.00034	0	0.00018	0.87	-
0-15 mph HC, ppm	6.41	-0.067	29.8	0.094	1.25	115.0

+ units of numerator given in first column
* PCV restriction measured by crank case pressure at idle
**air cleaner restriction measured by AC tester in degrees

TABLE A-2 Equipment and Procedures Required for Diagnosing Engine Parameter Malfunctions

Subsystem Inspection	Engine Parameter		Emission Signature	
	Equipment	Procedure	Equipment	Procedure
Idle				
- rpm	Tachometer	Idle rpm	NDIR HC analyzer	Idle HC
- Timing	Timing light	Basic Timing	NDIR HC analyzer	Idle HC
- Fuel-to-Air	Fuel-to-air or NDIR CO analyzer	Idle CO	NDIR CO analyzer	Idle CO
Ignition-Misfire	Engine electronic analyzer/dynamometer (optional)	Misfire at idle and 50-mph road-load	NDIR HC analyzer/ dynamometer	45-mph HC
Induction				
- PCV	Pressure gage	Idle crankcase pressure	NDIR CO analyzer/ dynamometer	45-mph CO
- Air Cleaner	AC air cleaner tester	Pressure drop across element	NDIR CO analyzer/ dynamometer	45-mph CO
- Air Reactor	Fuel-to-air or NDIR CO analyzer	Direct visual inspection & change in CO upon disconnecting the. air pump	NDIR CO analyzer/ dynamometer	45-mph CO

TABLE A-3 State Inspection Lane Configurations and Costs

No. Inspection Lanes	No. Information Officers	No. Support Personnel	Data Acquisition Item Costs, $/Site*	
			(1)	(2)
1	1	1	20 K	22 K
2	2	2	33 K	37 K
3	2	3	45 K	51 K

* Add $7,000/lane for dynamometer for loaded mode inspection.

(1) One emission specie
(2) Two emission species

TABLE A-4 Franchised Garage Inspection/Maintenance Labor Times

Subsystem	Engine Parameter	Time (hours)*	
		Inspection	Maintenance
Idle Adjustments	ICO and rpm	0.10	0.20
	Timing	0.05	0.10
Secondary Ignition	Plug, distributor and wire harness	0.25	1.30
Induction	Air cleaner	0.05	0.2
	PCV	0.05	0.3
	Air injection	0.15	0.6

*All labor charged at $10.00/hour

Franchised garages are assumed to use commercially available instrumentation and equipment to perform vehicle inspections, although a new procedure for diagnosing air reactor system malfunction is required. The equipment, instrumentation and procedures required for diagnosing engine parameter malfunctions are presented in Table A-2. The influence of the number of inspection lanes in a state inspection facility upon manpower requirements and equipment costs is shown in Table A-3. The productivity of data acquisition equipment and personnel increases with the number of test lanes because of time sharing. For example, two information officers with automated data acquisition equipment can handle three inspection lanes. Inspection and maintenance labor times are shown in Table A-4. These times were developed using flat rate manuals and rough time studies.

A.3.2 Demographic Data

The effectiveness of mandatory inspection/maintenance programs was studied in four urban centers with contrasting air quality problems. A summary of the demographic data for the four urban centers is presented in Table A-5. Data fundamental to characterizing a region include air quality goals, motor vehicle exhaust emission levels as measured by a vehicle surveillance program and the number and number density of the vehicle population to be inspected and maintained.

The estimated vehicle mass emission levels for Region I for a 1966-1970 exhaust-controlled population with an average odometer reading of 32,000 miles (Reference 3) were used as the basic data for all regions because of a lack of information on automobile emission levels for Regions II, III and IV. Further, it was assumed that the engine parameter deterioration rates for these three regions were identical to Region I. Since exhaust controls were not utilized in Regions II, III and IV until 1968, their mass emission levels at the start of a mandatory inspection/maintenance program were assumed to be equivalent to Region I at an average odometer reading of 22,000 miles. To include the effect of altitude on the estimated mass emission levels of Region IV, the emission levels for an odometer reading of 22,000 miles were adjusted (Reference 4) by the following amounts:

HC = 1.3 x Region I mass emission level

CO = 1.6 x Region I mass emission level

NO = 0.5 x Region I mass emission level

The emission weighting factors of Table A-5 were selected based on a literature survey as well as upon discussions with regional air pollution control personnel. They are considered as only rough measures of the desired air quality. In Region II, for example, traffic is extremely congested and approximately one-third of the total driving time is spent idling. This causes relatively high CO concentrations at ground level. Thus, a high weighting was placed upon CO emissions reductions for this region.

TABLE A-5
Regional Attributes

ATTRIBUTES	REGION I	REGION II	REGION III	REGION IV
o VEHICLE POPULATION	4.0×10^6	2.8×10^6	0.87×10^6	0.6×10^6
o REGIONAL AREA (SQ. MI.)	1250	1212	62	700
o POPULATION DISTRIBUTION (1971) (%)				
o PRE CONTROL	44	64	71	63
o CONTROL	51	32	27	33
o POST 1970	5	4	2	4
o EMISSION WEIGHTING FACTORS				
o HC	0.6	0.1	0.3	0.9
o CO	0.1	0.6	0.4	0.1
o NO_x	0.3	0.3	0.3	0.
o VEHICLE EMISSION LEVELS (G/M)				
o HC	7.1	7.0	7.0	9.1
o CO	87.7	86.0	86.0	137.4
o NO_x	6.2	6.4	6.4	3.2

The total automobile population and metropolitan regional area were taken from Reference 5 for Region I and Reference 6 for Region II. The percentage breakdown of the automobile population for the four regions by the categories of uncontrolled, controlled and 1971 automobiles were derived from Reference 7. The number of maintenance garages in Region I was provided by the local Highway Patrol.

APPENDIX B

ECONOMIC EFFECTIVENESS COMPUTER MODEL

B.1 Introduction

This appendix presents a discussion of the major economic effectiveness model revisions and program developments undertaken during this study. These revisions and developments include:

- The emissions prediction model has been revised to calculate emission reductions based on closed seven-mode cycle (CVS) mass emission data.
- A statistical analysis model was developed to estimate confidence limits on predicted emission reductions.
- A linear program optimizer was developed for determining optimum parameter and mode emission pass/fail criteria.
- Regional demographic models were formulated for characterizing various urban areas.

B.2 Estimated Emission Time Histories

The estimation of emission time histories is central to the calculation of emission reductions. As a consequence of converting the model to a mass basis, both maintenance and deterioration models required revision.

B.2.1 Emission Reduction Model

Emission reductions achieved by parameter inspection/maintenance is calculated with a procedure essentially identical to the method used previously to estimate composite emission reductions (Reference 1). Calculations were performed to assess whether the interaction of two engine adjustments upon emissions should be considered in the model. The frequency of interactions found to be statistically significant at or above the 90% level of confidence is summarized in Table B-1. As can be seen, the most frequently occurring interactions (i.e., four out of eleven vehicles) are idle rpm with idle CO (BE) for HC; and a confounded interaction of timing with restricted air cleaner or idle rpm with PCV for CO and NO (AD=BC). The above interactions were not found to have a significant impact on predicted mass emission reductions. The effect of the

TABLE B-1

The Number of Cars Out of those Tested for which Statistically Significant* Effects were Determined

Definitive Orthogonal Experiment

Main Effects

Composite	A Timing	B Idle RPM	C PCV (8)**	D Air Cleaner	E Idle CO	F Air Pump (3)**
HC	10	11	4	3	3	3
CO	6	6	5	8	9	3
NO	11	3	6	6	3	1
Mass						
HC	8	9	2	3	2	3
CO	7	8	3	7	8	3
NO	11	1	3	3	2	1

Interactions

Composite	AB=CD +	AC=BD +	AD=BC +	AE	BE	CE	DE
HC	5	0	1	0	2	0	1
CO	3	3	4	1	5	2	1
NO	2	4	5	2	1	1	2
Mass							
HC	3	1	3	0	4	2	1
CO	2	2	4	2	2	3	2
NO	2	2	4	3	0	1	1

*Statistically significant at or above the 90% confidence level

**Maximum of 11 data points per parameter with exception of PCV (8 data points) and air pump (3 data points)

+Confounded interaction effect--there is an equal probability of either interaction timing-air cleaner interaction on estimates of NO mass emission reductions was found to be the most significant of the frequently occurring interactions. Even here, neglecting the interaction effect resulted in only a 9% error in the prediction of the emission change caused by maintaining the air cleaner and timing, simultaneously. Therefore, as was done on the previous study, interaction effects were not considered when calculating emissions changes resulting from maintenance.

B.2.2 Deterioration of Maintenance

After maintenance, engine adjustments will deteriorate resulting in both mass and inspection mode emission changes. The previous model reflected this effect as a direct change in composite emissions, the change being prorated to each of the three major subsystems (idle, ignition and induction). Although this approach is consistent with the existing ARB (Reference 3) and AAA (Reference 8) composite emissions (seven-mode) data banks, it is inconsistent with the mass emissions data (CVS, seven-mode) used in this study. Since parameter deterioration data will be available at the conclusion of the Extended Phase One study, a modeling approach which is consistent with this data, while bridging deficiencies in the current data base, was selected.

The approach taken was to use the mass emission influence coefficients, $\partial e/\partial p$, derived from the definitive orthogonal experiment in conjunction with the best estimate of the rate of deterioration of the individual parameters to calculate the emission deterioration rate. A residual term is retained to reflect the emission deterioration caused by engine parameters not considered in this study such as compression loss as well as carburetor and cylinder deposit effects. An emission deterioration equation of the following form was developed:

$$\frac{\Delta \bar{e}_i}{\Delta M} = \left.\frac{\Delta \bar{e}_i}{\Delta M}\right|_o + \sum_{i=1}^{3} \sum_{j=1}^{10} \left[\frac{\partial e_i}{\partial p_j} \times \frac{\Delta \bar{p}_j}{\Delta M} \right] \qquad \text{(B-1)}$$

where:

$\frac{\Delta \bar{e}_i}{\Delta M}$ = population average mass emission deterioration as a function of mileage, emission level/mileage, (grams/mile)/mile

$\left.\frac{\Delta \bar{e}_i}{\Delta M}\right|_o$ = component of emissions change because of engine deterioration effects not considered in this study, emission level/mileage, (grams/mile)/mile

$\frac{\partial e_i}{\partial p_j}$ = mass emission change caused by a change in parameter level, Δp_j (grams/mile)/parameter level change

$\frac{\Delta \bar{p}_j}{\Delta M}$ = parameter level average deterioration as a function of mileage, parameter level change/mile

The above formulation necessitated converting the deterioration rates of the previous study which were based on subsystem values to direct parameter deterioration rates. This was performed by solving for the engine parameter deterioration term in Equation B-1:

$$\frac{\Delta \bar{p}_j}{\Delta M} = K_{ij} \left[\frac{\Delta e_i}{\Delta M} - \left.\frac{\Delta \bar{e}_i}{\Delta M}\right|_o \right] \Big/ \frac{\partial e_i}{\partial p_j} \qquad \text{(B-2)}$$

K_{ij} = factor for apportioning emission changes at the subsystem level to the several engine parameters significantly influencing a specific emission species, e_i.

This approach generally results in a set of linear equations which are insufficient in number to solve explicity for $\Delta \bar{p}_j/\Delta M$ and K_{ij}. Therefore, it was necessary to begin by selecting values of K_{ij} in order to compute parameter deterioration rates. These values were then used with the voluntary maintenance model to predict emission time histories on a CVS mass basis. The predicted emission time histories were next compared against the ARB emission surveillance data (Reference 3). The selected values of

K_{ij} were then adjusted to bring these two sets of data into correlation. Table B-2 shows the engine parameter deterioration rates calculated using the described procedure.

Figures B-1 through B-3 show the ARB surveillance data transformed to a 1972 Federal mass emissions basis for HC, CO and NO, respectively. These data were developed by first transforming to CVS mass units using the following equations:

$$HC_{mass} = -.036 + 0.0381\ HC_{7M} - 0.64 \times 10^{-4}\ HC^2_{7M} + 0.339 \times 10^{-7}\ HC^3_{7M} \qquad (R^2 = 0.71) \qquad \text{(B-3)}$$

$$CO_{mass} = 28.6 + 38.1\ CO_{7M} - 13.4\ CO^2_{7M} + 1.89\ CO^3_{7M} \qquad (R^2 = 0.75) \qquad \text{(B-4)}$$

$$NO_{mass} = 4.68 - 0.0072\ NO_{7M} + 0.743 \times 10^{-5}\ NO^2_{7M} - 0.148 \times 10^{-8}\ NO^3_{7M} \qquad (R^2 = 0.68) \qquad \text{(B-5)}$$

These equations were developed from a least squares curve fit of the seven-mode cold start CVS mass data to the hot seven-mode composite data acquired during the previous program (Reference 2).

Finally, the mass emission data base was adjusted to reflect the higher emissions levels measured with the 1972 Federal Test Procedure. The ARB data were curve fitted and transformed to CVS using equations B-3 through B-5. The transformed data were then transposed by adjusting the vertical scale to match the emission levels actually measured with the 1972 Federal Test Procedure at an average actual accumulated mileage of 32,000 miles. These premaintenance 1972 mass emissions measurements were obtained from the ongoing fleet deterioration experiment, Table B-3.

As a consequence of both voluntary and enforced maintenance and the subsequent deterioration of this maintenance, the population means for the engine parameter settings and the mass and mode emission levels must be adjusted. These adjustments are made immediately prior to the next inspection interval using the following equations:

TABLE B-2 Engine Parameter Deterioration Rates and Voluntary Maintenance Effectiveness

Parameter	Deterioration Rate $\frac{\partial P_j}{\partial M}$	Emission Decrease for Voluntary Maintenance, %[+] HC	CO	NO
ICO	1×10^{-4} %/mile	0	9	0
rpm	-7.5×10^{-4} rpm/mile	2	0	0
Timing	6.7×10^{-4} deg/mile	2	-1	0
Misfire	5.8×10^{-5} %/mile	8	0	0
Air pump	2.5×10^{-6} psig/mile	0	0	0
PCV	5.4×10^{-6} in H_2O/mile	0	1	0
Air cleaner	2.7×10^{-3} deg/mile	0	1	0

[+] % reduction relative to premaintenance level

TABLE B-3

Mass Emissions for in-use Vehicles as Measured by the 1972 Federal Test Procedure (gm/mi)
(CRC APRAC CAPE-13 Fleet Deterioration Experiment)

	Uncontrolled	Pre 1971 Controlled	1971
HC	11.3	7.1	4.3
CO	122.0	88.0	51.0
NO	4.4	6.2	6.3

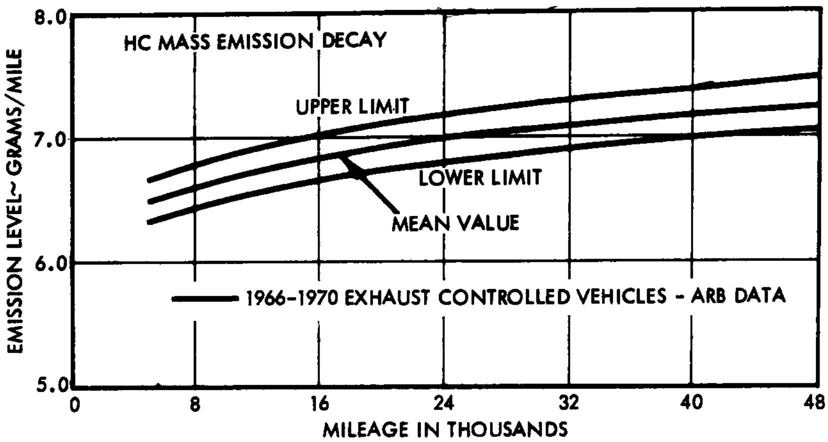


FIGURE B-1 HC Mass Emission Decay

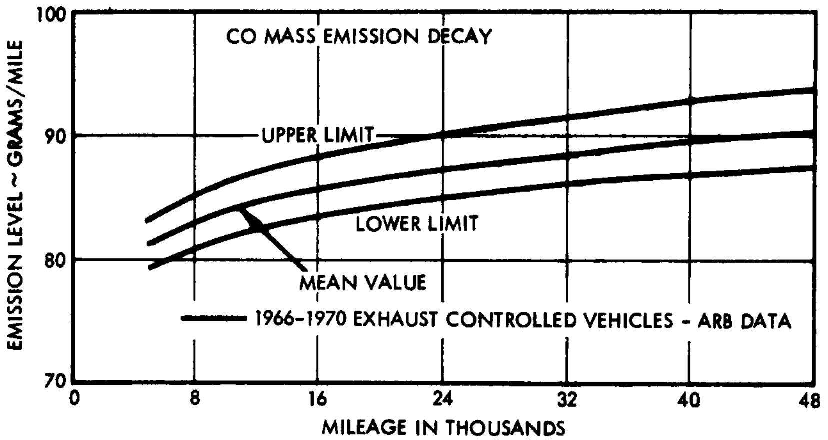


FIGURE B-2 CO Mass Emission Decay

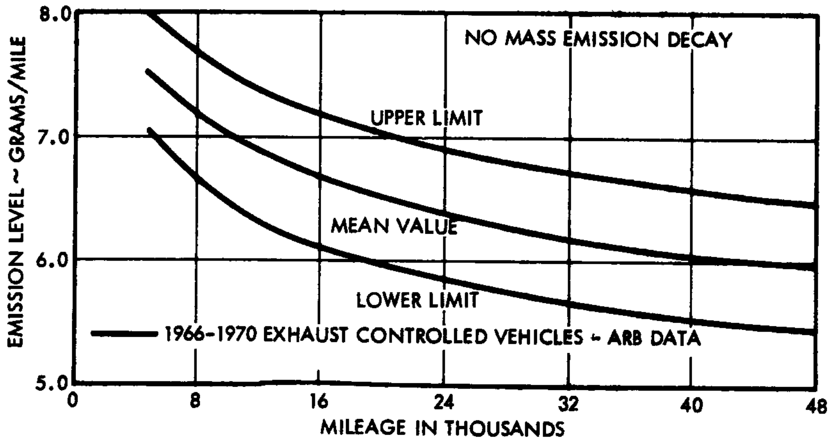


FIGURE B-3 NO Mass Emission Decay

$$\text{Mean Parameter Setting}\Big|_{\text{Final}} = \text{Mean Parameter Setting}\Big|_{\text{Initial}} \qquad \text{(B-6)}$$

$$P_{j,M+\Delta M} \qquad\qquad P_{j,M}$$

$$+ \text{ (Mean Parameter Setting Decay - Parameter Maintenance)}$$

$$- R_j \Delta \overline{P}_{m+t,j} + \frac{\partial P_j}{\partial M} \Delta M$$

where:

Mean parameter setting decay = $\frac{\partial P_j}{\Delta M}$ (from equation B-2)

Parameter maintenance = change in mean parameter level resulting from voluntary and enforced maintenance.

$$\text{Mean Emission Level}\Big|_{\text{Final}} = \text{Mean Emission Level}\Big|_{\text{Initial}} \qquad \text{(B-7)}$$

$$e_{n,M+\Delta M} \qquad\qquad e_{n,M}$$

$$+ \text{ (Mean Emission Level Decay - Emission Reduction)}$$

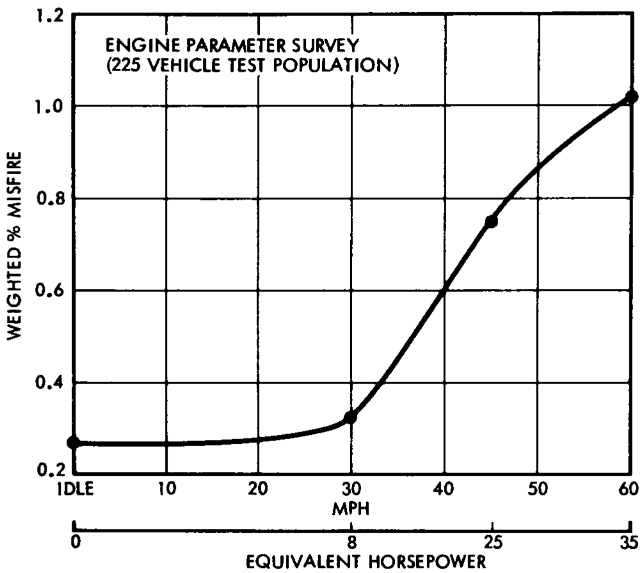
$$+ \sum_{j=1}^{10} \frac{\partial e_n}{\partial p_j} \underbrace{\left(\frac{\partial P_j}{\partial M} \Delta M - \Delta P_j \right)}_{\Delta e_i}$$

B.3 Parameter Inspection Models

The misfire and positive crankcase ventilation valve inspection models were modified to improve the precision of the results and to reflect more accurately the engine parameter field survey (Reference 1).

B.3.1 Misfire Model

The previously used misfire model did not allow both the frequency and extent of misfire to vary non-linearly with engine load and speed, Figure B-4. When misfire effects were calculated for the seven-mode cycle, misfire was assumed to be constant and equivalent to misfire at the average 50 mph road load for the test cycle. The misfire influence coefficient, $\Delta HC/(\%\ \text{misfire})$, was developed from the statistically designed experiment using an electronic firing line interrupter which simulated a constant level of misfire independent of load. To reflect the sensitivity of misfire to engine load, the Federal seven-mode cycle



(estimated)

FIGURE B-4 Percent Misfire at Test Condition Loading weighting factors were used to develop an approximate population weighted average misfire rate. All closed throttle modes (idle and deceleration) were assumed to have a misfire rate equivalent to that at no load. The resulting calculation is shown in Table B-4. A mode weighted value for misfire of 0.68% misfire is estimated. This value, when multiplied by the influence coefficient, predicts the emission reductions achieved when all of the misfiring vehicles within the population are maintained. This weighting procedure is appropriate for concentration based emission measurements, but is only an approximation for mass based HC emissions.

Inspection at heavier loads will tend to find incipient misfires at low load, thus decreasing the probability of a substantial frequency of high load misfires on the following inspection. To reflect this situation, the population weighted percent misfire was assumed to decrease exponentially to half its original value according to the following equation:

$$M = M_o e^{-kN}$$

k = time constant yielding 50% of M in five years

M_o = initial population weighted misfire rate, 0.68%

N = number of inspection intervals

B.3.2 Positive Crankcase Ventilation Valve (PCV) Model

The earlier PCV model assumed for simplification that this device either failed or operated nominally. This assumption is consistent with the method of malfunction simulation used in the orthogonal test, but does not reflect actual PCV valve degradation. Data from Reference 10 (Figure B-5) indicates that HC and CO emissions vary approximately linearly with PCV volumetric flow rate and that flow rate reductions occur gradually because of deposit buildup. To reflect this condition using the data in-hand (i.e., crankcase pressure measurements from the parameter field survey) the PCV inspection model was revised to describe the time, varying frequency and extent of malfunction of this device.

TABLE B-4 Calculation of % Misfire for Seven Mode Cycle
(1966-1970 Exhaust Controlled Vehicles)

Seven Mode Federal Cycle	Horsepower/Mode	(A) % Misfire/Mode (Figure 3-4)	(B) Federal Register Mode Weighting Factor	% Misfire/Mode (A x B)
Idle	0	0.27	0.042	0.01134
0-30 mph Acceleration	25	0.75	0.244	0.18300
30 mph Cruise	8	0.32	0.118	0.03776
30-15 mph Deceleration	0	0.27	0.062	0.01674
15 mph Cruise	3	0.27	0.050	0.01350
15-50 mph Acceleration	30	0.90	0.455	0.40950
50-0 mph Deceleration	0	0.27	0.029	0.00783
TOTAL			1.000	0.67967

Crankcase pressure was the only indicator of PCV maintenance state obtained in the engine parameter survey. The distribution function for crankcase pressure (inches of water) is shown in Figure B-6 and was used to establish pass/fail criteria for the PCV system. PCV system flow rate and, therefore, emissions were assumed to vary linearly with crankcase pressure since data relating PCV flow to crankcase pressure under load were not available.

B.4 Statistical Inference Model

The results derived from the economic effectiveness model are basically deterministic. That is, the predicted emission reductions are computed utilizing fixed relationships for each operational step. Obviously, a real program of vehicle inspection/maintenance involves activities which cannot be characterized deterministically. For example, consider the impact of maintenance effectiveness on overall program performance. Presently the model assumes that all maintenance undertaken by the service organization is performed with complete reliability. In actuality, garages will not be able to set all engine adjustments exactly to manufacturers' specification. The resulting uncertainty in maintenance effectiveness is directly translated into uncertainties in predicted emission reductions.

To evaluate the implications of the program uncertainties, a statistical inference model was developed. The function of this model was to:

- Test whether model predicted emission reductions are statistically significant (i.e., greater than zero)
- Estimate confidence limits on statistically significant emission reductions
- Estimate confidence limits on the emission time history profiles.

The model utilizes the emission predictions for both the baseline and test fleets to perform these various statistical tests.

The main sources of uncertainty in predicting the performance of candidate inspection/maintenance programs can be divided into two sets. The first set consists of those uncertainties associated with the inspection/maintenance process, namely:

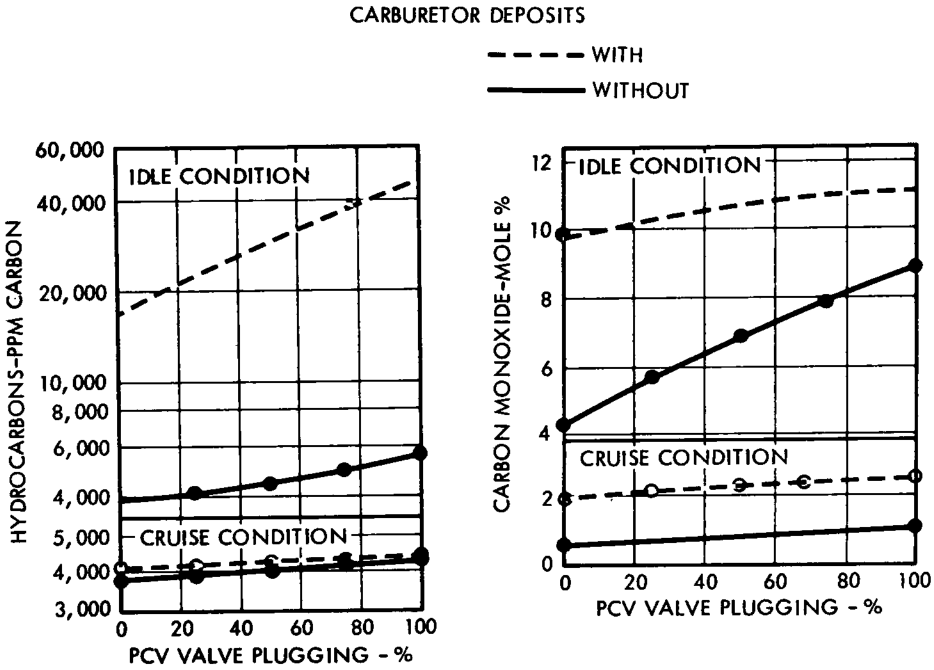


FIGURE B-5 Effect of PCV Valve Plugging, Carburetor, Venturi and Throttle Body Deposits on Exhaust CO and HC Emissions (Reference 10)

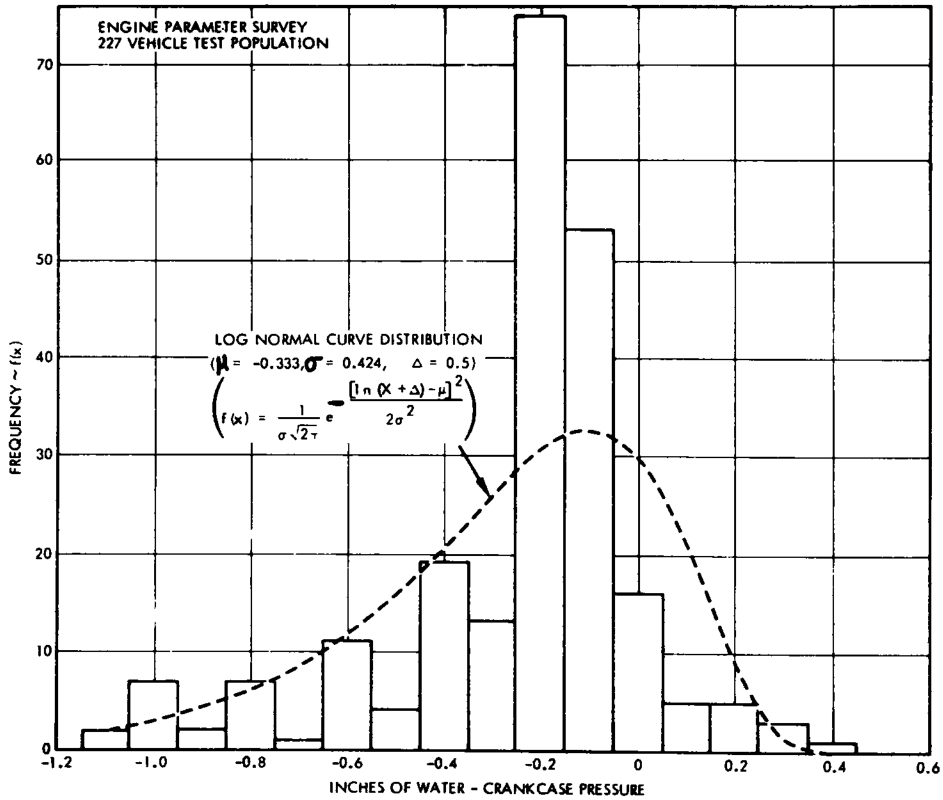


FIGURE B-6 PCV Crank Case Pressure Distribution Pre -1971 Exhaust Controlled Vehicles

- Inspection measurement variance (i.e., instrumentation)
- Maintenance reliability

The other set entails those uncertainties in the actual emissions data base. These uncertainties are due to the fact that attributes of the total population have been estimated from relatively small samples. In the case of influence coefficients derived from the orthogonal experiments, the selected 11 cars were assumed to be characteristic of the total population. The chief sources of uncertainty in the emissions data base are:

- correlation of emissions-to-engine parameter variation (i.e., residual error from orthogonal experiments)
- vehicle manufacturer-to-manufacturer emissions variability
- emissions variability caused by out of specification engine parameters (a function of maintenance state).

The emission distributions for each specie are estimated during each inspection/maintenance period using the distributions for the previous period convoluted with the maintenance effects and associated error terms. These distributions are then statistically compared with those for the baseline fleet.

The standard "t" score statistical test is used in comparing these distributions. The null hypothesis used to test whether the two samples came from different populations, i.e., that the means are significantly different, is:

$$H_0: u_T = u_B$$

where: u_T = test mean
u_B = base mean

The alternative hypothesis is:

$$H_1: u_T < u_B$$

If the analysis produces a positive test, the null hypothesis can be rejected and that a difference in means does exist (accept H_1). Utilizing the computed statistic, we can also establish confidence limits around the predicted emission reduction at each time point.

$$a \leq \overline{x} \leq b$$

where a = lower confidence limit

b = upper confidence limit

$\overline{x} = X_B - X_T$

If two-sided 90% confidence limits are placed on the distribution then it can be stated that there is a 90% chance that the predicted emission reductions will fall within these limits. If the upper and lower tails of the distribution curves are similar it can also be stated that there is a 95% change that the emission reductions will exceed the value a.

The figure of merit can now be recomputed using the statistically significant emission reductions. Once this has been accomplished, the various inspection/maintenance procedures can be reordered based on the revised figure of merit. The reordered set can then be compared to the initial set to determine whether the relative attractiveness of the candidate procedures has been altered.

Presently, the statistical inference model (Figure B-7) has been incorporated into the economic effectiveness processor. Because of the lack of necessary input data, e.g., deterioration and maintenance uncertainties, the model will not reproduce the actual emission specie distributions. In the interim, the experimental data developed from the fleet deterioration test has been used to estimate confidence limits on the predicted emission reductions (see Section 2.1.4).

B.5 Linear Programming Algorithm

The determination of an optimum set of engine parameter or mode emission pass/fail criteria for use in analyzing various inspection/maintenance procedures represents a complex problem. Presently, the updated economic effectiveness processor contains a total of 30 unique engine parameter settings (i.e., 10 parameters x 3 control types) and 12 unique mode emission distributions (i.e., 4 modes x 3 control types).

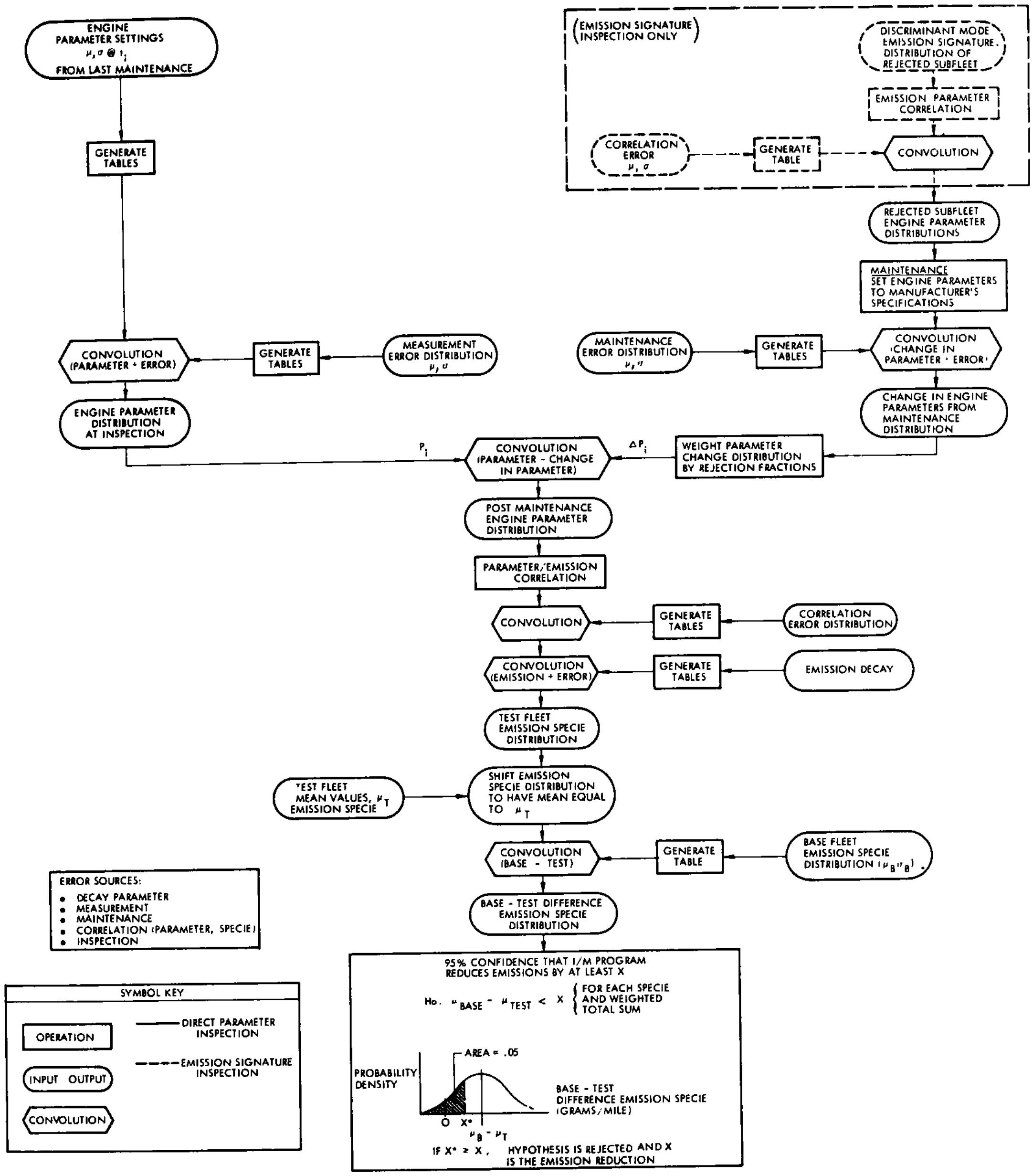


FIGURE B-7 Statistical Analysis Model Flow Chart

It is the pass/fail criterion which ultimately determines the rate of vehicle rejection and thus, to a considerable degree, the cost and improvement in emissions achieved by each candidate inspection/maintenance strategy. Determination of the optimum parameter or emission mode pass/fail criteria is therefore critical to both the basic system design and the relative merit of a given procedure. Presented in the following paragraphs is a brief overview of the approach used in determining optimal criteria.

Linear programming offers a useful, although approximate solution to selecting optimum pass/fail criteria. A computational subroutine, therefore, was devised to estimate locally optimal cutpoints by means of a linear programming algorithm. The relationship between the objective function of the linear program and its independent variables, X_j, used in this application, i.e., engine parameter adjustments, is given below.

$$Z = \sum_i \sum_j \frac{\partial e_i}{\partial P_j} \hat{W_i} (R_j \Delta P_j)$$

$\frac{\partial e_i}{\partial P_j}$ (influence coefficient), change in emission of i^{th} specis per unit change in j^{th} parameter setting

W_i = relative weight assigned to i^{th} emission specie

$R_j \Delta P_j$ = optimum average value of parameter "j" relative to the total vehicle population.

The objective function, Z, is the weighted reduction in emissions to be achieved by mandatory maintenance and the problem is to identify specific values of $R_j \Delta P_j$ which maximize Z.

The maximization may be subject, however, to two basic classes of inequality constraints:

- The emission reduction for each specie may be constrained to exceed a minimum level, otherwise, the procedure is of no interest. This requirement may be stated by the inequality constraint

$$\sum_j \frac{\partial e}{\partial P_j} (R_j \Delta P_j) \geq b_i$$

where b_i = threshold reduction for i^{th} emission specie

- The average cost per vehicle per inspection may be constrained to not exceed a given value

$$\sum_j d_j R_j \leq g$$

where g = maximum allowable cost per vehicle

d_j = a prorated cost per unit adjustment of the j^{th} parameter

The "b_i's" are normally expressed in terms of some minimum percentage emission reduction desired for each exhaust pollutant, e.g., 20 percent CO reduction for an extensive maintenance procedure. These values are exactly analogous to the emission reductions program goals employed in earlier studies. The cost constraint equation is used to relate the cost of adjusting engine parameters with total system costs. The "g" coefficient represents an assigned program cost for a given inspection/maintenance procedure that cannot be exceeded.

The above analytical approach yields estimates of the optimal average adjustment, X_j, for each parameter. These initial values can then be employed in an interactive process to estimate values of the optimal cutpoints of each parameter for each inspection/maintenance process. This scheme is shown in Figure B-8.

The first step computes a set of mean values for the engine parameter settings for the rejected vehicle population. This is accomplished by adding the ΔP_j values obtained from the linear programming algorithm to the original engine parameter reference specifications. Using the basic engine parameter distributions, a systematic search is made to find the pass/fail criteria which will yield the calculated mean values. In this manner the linear programming algorithm provides a mechanism for determining pass/fail criteria for multiparameter inspections. The same basic technique is also used in deriving mode emission cutpoints for the emission inspection strategy.

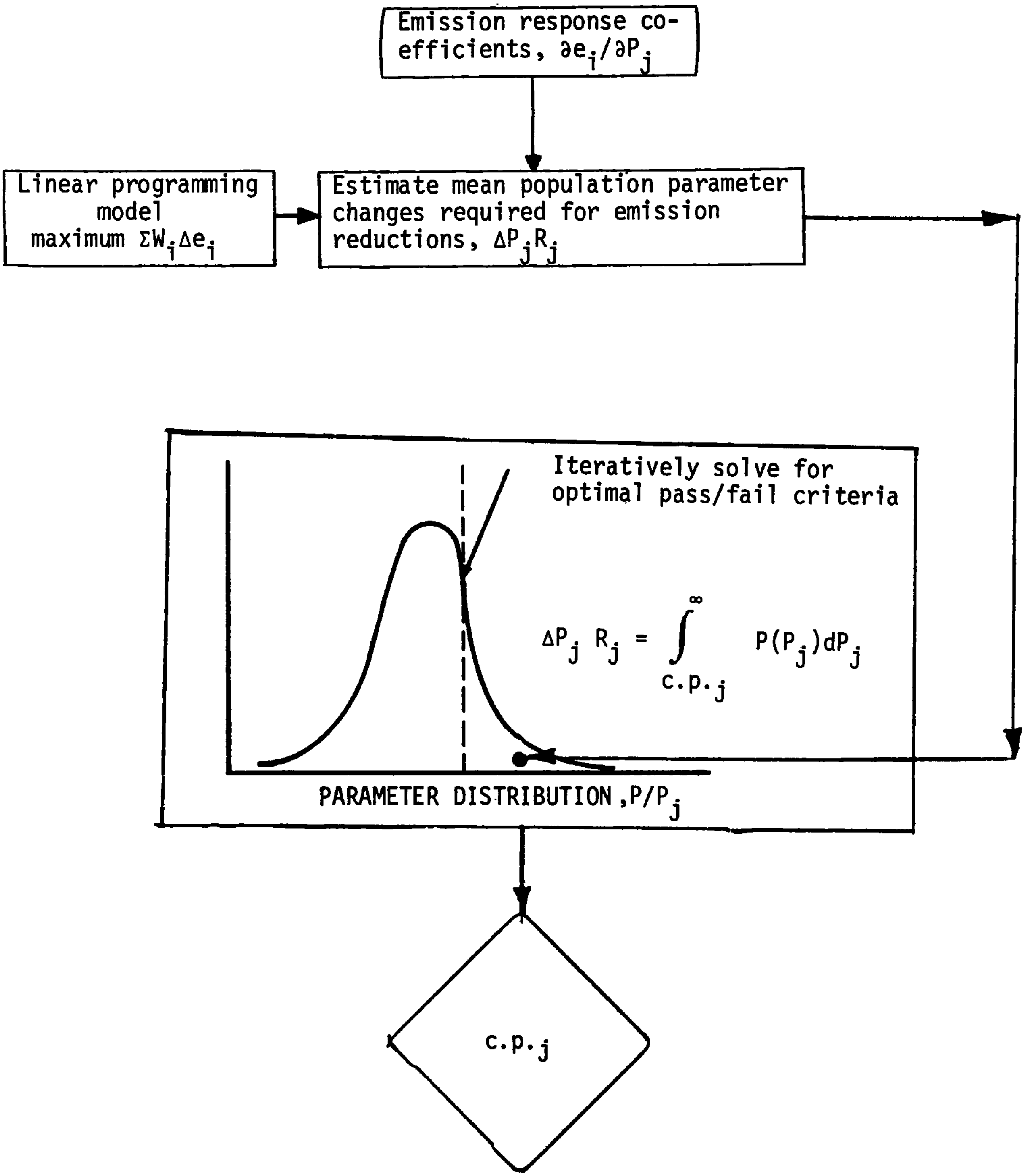


FIGURE B-8

Linear Programming Interactive Scheme

B.6 Economic-Effectiveness Computer Processor

To accommodate the program developments discussed herein, a substantial modification of the Phase One Economic-Effectiveness Computer Processor was required. A schematic diagram of the revised processor is shown in Figure B-9. The processor is used to simulate the performance of various vehicle inspection/maintenance procedures over a given time interval. The key input data required by the processor include:

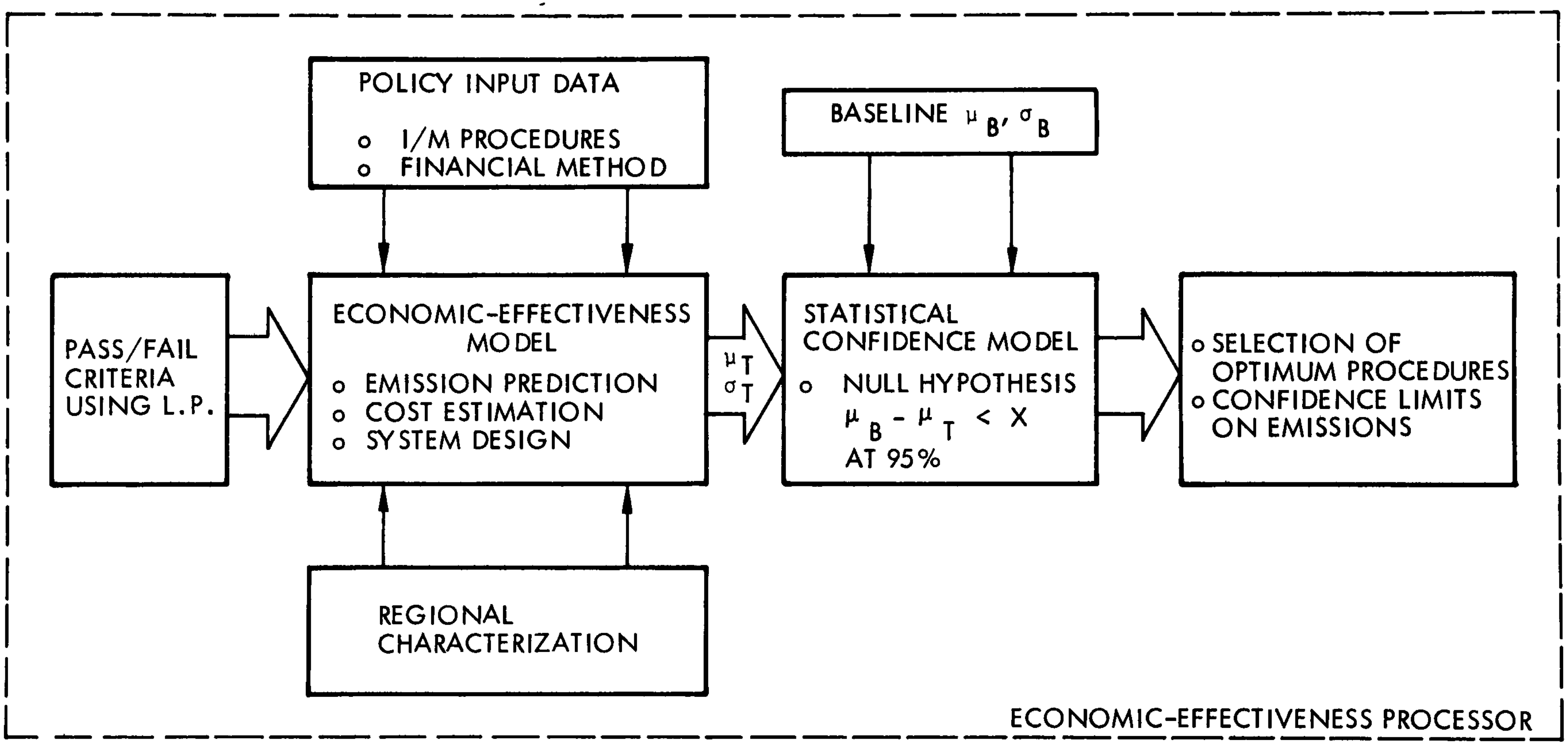
- strategy selection
- regional identification
- system pass/fail criteria

The first two inputs are specified based on the inspection/maintenance procedure selected for study and the urban area of interest. The system pass/fail criteria are then estimated utilizing the linear programming algorithm discussed in the previous section. Having identified the type of strategy to be examined, e.g., idle parameter inspection, the economic-effectiveness (E/E) model is used in a simulation mode to predict resultant vehicle emission levels at the end of each year and to estimate the cost of the program. In the case of a state lane inspection, it is also used to design and size the basic inspection system. In addition to vehicle emission levels and program costs, the E/E model computes a figure of merit for each inspection/maintenance strategy. This figure of merit is used to rank the overall attractiveness of those inspection/maintenance strategies under study.

Another mechanism used for screening inspection/maintenance strategies is to perform a statistical analysis on the projected emission levels. This operation employs the new statistical confidence model. The emission levels predicted for the test fleet are contrasted statistically with those of the baseline fleet. Figure B-9 depicts this statistical comparison. A final product of the statistical analysis is the development of confidence limits on all predicted emission time histories.

FIGURE B-9

Economic-Effectiveness Program Design



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