THE ECONOMIC EFFECTIVENESS OF MANDATORY ENGINE MAINTENANCE FOR REDUCING VEHICLE EXHAUST EMISSIONS

VOLUME I
EXECUTIVE SUMMARY

AUGUST 9, 1971

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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PREFACE

This report consists of three volumes entitled: "The Economic Effectiveness of Mandatory Engine Maintenance for Reducing Vehicle Exhaust Emissions". The following are the titles given for each volume:

- Executive Summary, Volume I
- Modeling of Inspection/Maintenance Systems, Volume II
- Inspection and Maintenance Procedures Development, Volume III

The first volume summarizes the general objectives, approach and results of the study. The second volume presents the analytical modeling of a mandatory inspection/maintenance system and simulation results obtained using that system model. The experimental programs conducted to develop input data for the model are described in Volume III.

The work presented herein is the product of a joint effort by TRW Systems Group and its subcontractor, Scott Research Laboratories. TRW, as the prime contractor, was responsible for overall program management, experimental design, data management and analysis, and the economic-effectiveness study. Scott conducted the emission instrument evaluation and acquired and tested all of the study vehicles. Scott also provided technical assistance in selecting emission test procedures and in evaluating the test results.

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VOLUME I

1. INTRODUCTORY SUMMARY

The effects of mandatory vehicle inspection and maintenance were investigated to assess the most cost-effective procedures for periodically diagnosing and restoring to specification those engine components having significant effects on vehicle exhaust emissions. Two classes of inspection procedures were evaluated:

- Direct measurement of engine parameter adjustments (malfunctions) using conventional or more sophisticated garage-type equipment
- Inference of engine parameter maladjustments or malfunctions from the measurement of engine exhaust emission levels (signatures) under varying loading conditions.

The former inspection procedure would most likely be performed in a franchised or certified, privately owned garage. The effectiveness of combinations of direct parameter measurements which resulted in short (approximately 3 minutes) and long (approximately 30 minutes) inspections were evaluated. Because direct parameter measurements using existing diagnostic equipment are time consuming, remote sensing instruments felt to be technically feasible were hypothesized and evaluated for use in direct diagnosis in state inspection lanes.

The emission signature inspection procedure requires more sophisticated equipment and instrumentation. Emission signatures for hydrocarbons, carbon monoxide and carbon dioxide would be measured under several engine loads. The use of emission signature inspection results in a higher vehicle inspection throughput but at the expense of a greater investment in capital equipment.

The general framework of the study focuses on those system elements which affect the ranking of the alternative inspection and maintenance procedures in an economic effectiveness sense. The tasks include:

- Systems definition
- Statistical characterization of vehicle maintenance states in an urban region

- Development of procedures for inspecting and maintaining those malfunctioning engine parameters which significantly influence emissions
- Development of a computerized system model for evaluating the candidate procedures within a systematic application framework.

A summary of these tasks is presented in the following sections of this volume.

Conclusions derived from this study are:

- The six most effective engine parameters to maintain are the three idle adjustments (air-to-fuel ratio, rpm and basic timing), elements of the ignition system when causing misfire, as well as the positive crankcase ventilation valve and air cleaner of the induction system. The air injection system should be inspected and maintained on cars equipped with this type of air pollution control equipment.
- Inspection and maintenance of the idle adjustments was found to be a very cost effective procedure for controlling carbon monoxide emissions. Typical average emission reductions over a four year period are between 2 to 3 percent for hydrocarbons and 10 to 15 percent for carbon monoxide. Oxides of nitrogen emissions are increased by 4 to 7 percent.
- Control of both hydrocarbon and carbon monoxide emissions requires inspection and maintenance of the ignition and induction systems in addition to the idle parameters. Optimum inspection/maintenance procedures yield a typical average emission reduction over a four year period of 15-22 percent for hydrocarbons and 20-33 percent for carbon monoxide. Oxides of nitrogen emissions are increased from 3 to 5 percent by this treatment.
- The most cost effective inspection frequency is once yearly.
- State inspection lanes are usually more cost effective than franchised garages.
- Nondispersive, infrared emission measurement instruments are preferred for state-lane applications.

The above conclusions were based on currently available data, some of which were either of limited reliability or based upon small test populations. In addition, the effectiveness of maintenance was inferred from a limited set of representative power trains (i.e., 1966-1970 vehicles). Considerable emission reductions may be possible when the precontrolled vehicle population is included in the inspection/maintenance program.

Additional experiments are recommended to determine the effect on inspection/maintenance procedures of:

- Precontrolled and NO_x controlled vehicles in an urban population
- The reliability with which commercial repair agencies can diagnose and repair vehicle exhaust control and related systems
- Differing urban regional air quality requirements, vehicle population composition, and general vehicle maintenance states.

2. SYSTEM CONSIDERATIONS

The relationship between system design and economic factors must be clearly understood so that inspection/maintenance procedures are selected in combinations to yield optimal cost and performance. Three fundamental elements were considered in the development of the vehicle emission inspection/maintenance system model (Figure 2-1):

- Engineering design
- Economic factors
- Constraints

System design and the associated economic factors are dependent upon regional demography, socioeconomic considerations and available or foreseeable technology.

2.1 ENGINEERING DESIGN

Engineering design factors fall into two categories: inspection and maintenance procedures and facilities configuration. Significant factors to be determined when selecting optimum procedures are: the extent and complexity of inspection and maintenance procedures, the rejection criteria, and the frequency of inspection. Configuration factors to be considered are:

- Number and type of inspection stations for typical demographic regions
- Degree of automation of procedures
- Type and complexity of sensing instruments
- The information system to support administrative and enforcement decisions.

Of particular interest is the definition of optimally combined inspection/maintenance procedures for a state vehicle inspection system.

ENGINEERING DESIGN	ECONOMIC FACTORS	CONSTRAINTS	PROGRAM EFFECTIVENESS
• PROCEDURES	• COSTS	• ENVIRONMENT	• TOTAL SYSTEM COST
INSPECTION TYPE PASS/FAIL CRITERIA MAINTENANCE TYPE INSPECTION INTERVAL RELIABILITY	CAPITAL EQUIPMENT LAND USER INCONVENIENCE OPERATIONS MATERIAL TRAINING	DEMOGRAPHIC CLIMATIC AIR QUALITY	
• CONFIGURATION	• TIME	• TECHNOLOGY	• RESULTANT EMISSION LEVEL
INSPECTION FACILITY - NUMBER, LOCATION, SIZE, DESIGN MAINTENANCE FACILITY - NUMBER, LOCATION INFORMATION STORAGE/RETRIEVAL REGIONAL PARTITIONING	USER TIME INSPECTION TIME MAINTENANCE TIME	STATE-OF-THE-ART FORECASTS	
	• BENEFITS	• SOCIAL	
	SAFETY PREVENTIVE MAINTENANCE OPERATING ECONOMY	METHOD OF FINANCING USER INCONVENIENCE COST BURDEN	

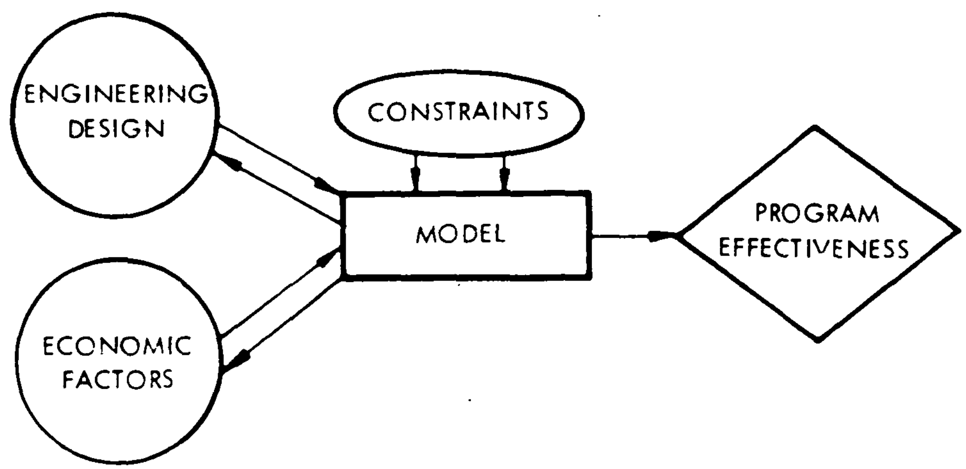


Figure 2-1. Basic System Framework

Inspection/Maintenance Procedures

This study considers the program impact on the vehicle owner as well as the extent to which exhaust emissions can be controlled. To reduce the impact of a mandatory inspection/maintenance program on the vehicle owner, minimum cost and minimum time maintenance procedures were considered. From a control and enforcement point of view, this is also desirable, since it:

- Protects the vehicle owner by minimizing his financial obligations
- Specifies easily implemented procedures compatible with existing commercial practice
- Provides greater assurance that a vehicle's emissions will be reduced, since only those maintenance treatments shown to be effective in reducing emissions are considered.

The approaches studied for the inspection procedures were:

- Direct diagnosis of engine parameters using conventional or more sophisticated garage-type equipment. This approach is well suited to inspection by franchised-garages.
- Inferences of malfunction from measurement of engine exhaust emission signatures. This approach is best suited for use in state inspection lanes.

Maintenance strategies of two types were defined. These strategies involve either "predetermined" maintenance or "adaptive" maintenance.

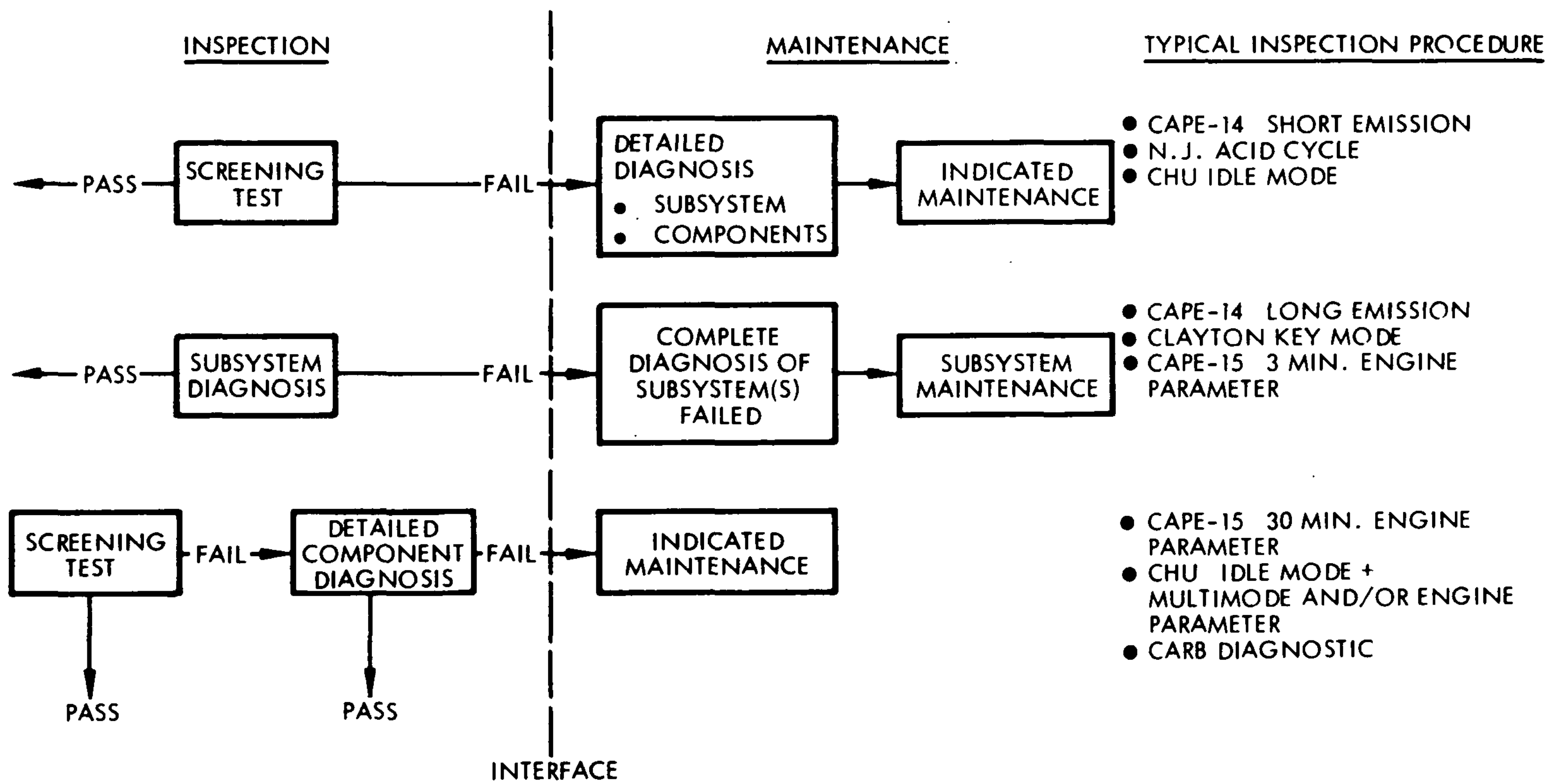
With predetermined maintenance, those components and subsystems which influence emissions substantially were first identified. The best inspection procedures for identifying failures or maladjustments of these components and subsystems were then selected. Vehicles failing an inspection based upon a rejection criteria for each maladjustment are then sent to maintenance where only the specified components are corrected regardless of the state of the remainder of the engine and emission control systems. This approach is most effective where there is a high probability that the inspection procedure correctly identifies the malfunction and where the cost of inspection is approximately equal to that of the specified maintenance activity. As an example, an idle-emission measurement screening test might be coupled with specified maintenance procedures for restoring failed vehicles to manufacturers' specifications with respect to idle rpm, idle air-to-fuel ratio and idle timing. Some of the rejected vehicles will receive an idle parameter adjustment even though an engine parameter outside of those considered in the maintenance program will have caused the vehicle to be rejected.

An adaptive maintenance program is based on diagnostic data acquired during the initial inspection supplemented by those obtained during re-inspection at the maintenance station. All of these data are then used to identify components which require maintenance. Thus, the probability of making a correct diagnosis is high, but at the expense of higher inspection costs. The diagnosis of maladjustments then controls the extent of maintenance performed although a limit is placed upon the engine subsystems which are treated.

The study objective is to determine the extent to which it is economically feasible to transfer detailed diagnostic activities previously associated with maintenance to the inspection process. In Table 2-1, generalized procedures are shown in which various levels of diagnosis are transferred from the maintenance to the inspection activity. Vehicle power train screening tests require obtaining a minimum amount of diagnostic information and implies either further and complete diagnosis at the garage or a predetermined maintenance policy. Vehicle subsystem diagnosis and detailed component diagnosis (possibly preceded by a screening test) place increased emphasis upon obtaining diagnostic information during the inspection process.

Vehicle power train exhaust emission screening tests are typified by the idle and New Jersey ACID cycle (Reference 1) tests. In these tests only minimal diagnostic data on actual failures of the emission control system are obtained with the vehicle being rejected for maintenance based solely upon abnormally high emissions. Diagnosis of actual maladjustments and failures must be done at the maintenance station where the mechanic's skill is important to the effectiveness of the inspection/maintenance program in reducing emissions.

Table 2-1. Generalized Inspection/Maintenance Procedures



With subsystem inspections an attempt is made to group components or adjustments into logical functional combinations such that a malfunction of any of the components of a subsystem can be determined by measurement at a single sensing point. The Clayton key mode procedure (Reference 2), as well as the short and long emission inspection procedures which are to be defined under this study fall into this classification. Only those subsystems which have failed undergo detailed diagnosis during the maintenance procedure.

A detailed diagnosis during the inspection process completely eliminates diagnostic decisions during maintenance by providing a specific repair list. Because complex and possibly automated instrument systems are required to perform the detailed diagnosis in a cost effective manner, it may be advantageous to perform a screening test to limit the number of cases sent to detailed diagnosis as is shown in Table 2-1.

As the inspection process is changed from screening to detailed component diagnosis, inspection equipment and labor skill become increasingly important. The probability of a correct diagnosis and repair is increased at the expense of significantly higher inspection costs and user inconvenience. Inspection/maintenance processes which fall into the three generalized procedures categories just described were evaluated in this study.

Inspection Station Siting

To estimate the capital equipment and facilities requirements, a number of demographic characteristics are needed for the area in which an inspection/maintenance system is to be implemented. It is expected that the preponderance of program cost will be incurred in the metropolitan areas of regions under consideration, and that the design of equipment and facilities will be dictated by the requirements of these urban centers. Because the study's primary objective is to select the best procedures from those available, the relative effectiveness of procedures is of primary concern. Therefore, it is felt to be important to evaluate procedures within a consistent demographic framework rather than to explore all ramifications of regional demography. For these reasons we selected the demographic features of the Los Angeles Basic for the study.

2.2 ECONOMIC FACTORS

Benefits in reduced emissions obtained from an inspection/maintenance program must be compared with cost to arrive at the program's overall economic effectiveness. The relevant costs are the explicit and implicit costs of such a program. Explicit costs involve resources expenditures to construct facilities as well as the cost of inspection/maintenance operations. Implicit costs, for example, reflect a cost assignable to the time a user spends in inspection and maintenance-related activities. While the design of an economically effective program must consider both implicit and explicit costs, the costs which are quoted for various program alternatives are based on explicit costs, since only these result in a direct monetary outlay. Station location and configuration design however were determined by including both costs.

2.3 CONSTRAINTS

Several restrictions were placed on systems to be considered in the study. For example, this study considers exhaust emission inspection procedures which are oriented toward malfunction diagnosis rather than to emission measurements which correlate well with those obtained using the Federal emission test procedure. Procedures were to be defined to diagnose maladjustments and component failures which would result in both high HC & CO composite emissions. The effect of these policies on NO_x emissions was estimated after the fact rather than considered in selecting procedures because the 1966-1970 vehicles studied were not equipped with NO_x control devices. A further consideration imposed during the selection of inspection/maintenance procedures was that a substantial reduction be effected on at least one of the major pollutants (i.e., 15% or greater) regardless of the cost effectiveness of a particular procedure or strategy.

2.4 PROGRAM EFFECTIVENESS

Measures of system performance included actual emission reductions achieved, user time lost in traveling and waiting during inspection and maintenance, and the effectiveness of the inspection process (probability of a correct diagnosis). These performance factors were combined to yield an estimate of the emission reduction over a four year period as well as system cost. A figure of system merit was formulated from these elements and optimized by selection of the system design variables.

3. PROCEDURES EVALUATION

The following approach was used to evaluate the effectiveness of mandatory maintenance of vehicle emission control systems:

- A data base was acquired from which basic emission and cost models were developed
- Systems tradeoff studies were performed using an analytical computer model.

3.1 DATA ACQUISITION

Data pertinent to the evaluation of inspection/maintenance procedures were sought to describe the following characteristics quantiatively:

- Frequency and extent of malfunctions and maladjustments as they occur in vehicles in a general user population
- Vehicle exhaust emission sensitivity to selected engine malfunctions and maladjustments
- Emission diagnostic mode sensitivity to malfunctions and maladjustments
- Inspection and maintenance costs
- Deterioration rates of emission sensitive engine and control device variables.

Experimental data were developed as indicated in the flow diagram of Figure 3-1.

3.1.1 Frequency and Extent of Malfunction

Malfunction and maladjustment data from commercial diagnostic centers were obtained and evaluated. These data were found to be unsatisfactory for study purposes for two reasons:

- Quantitative measurements were generally not provided (i.e., a component or adjustment was either characterized as acceptable or as unacceptable)
- Failure criteria were not provided.

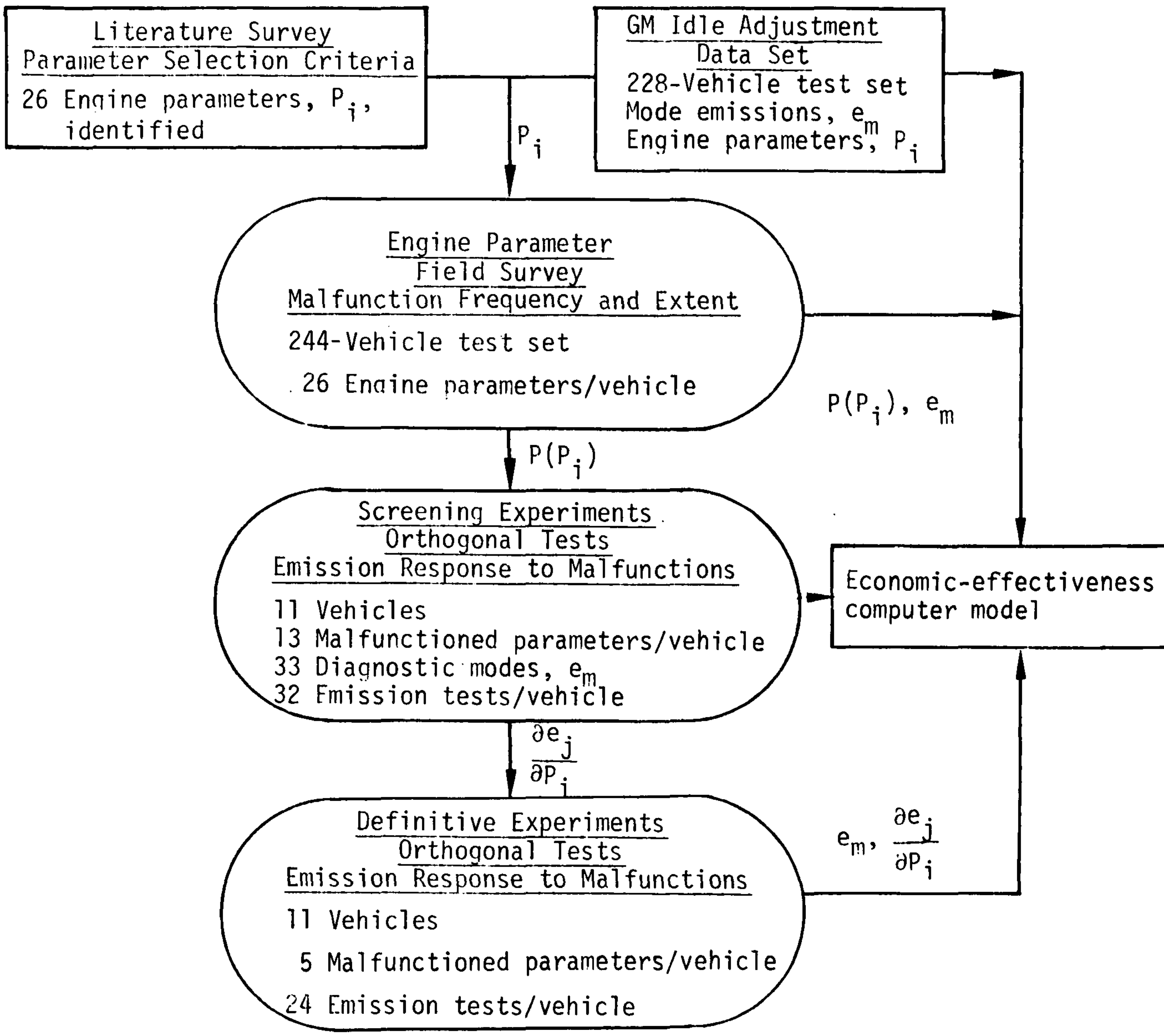


Figure 3-1. Experimental Program Flow Diagram

Although these data provided quantitative insight into the frequency of failures in a user vehicle population, they were inadequate for quantitative analyses. Therefore, an experimental study was undertaken on a randomly selected group of 227 vehicles to measure the frequency and extent of malfunctions and maladjustments of components known or suspected to have a significant effect on emissions. Table 3-1 summarizes data obtained in this study. A more detailed description of the test program is contained in Volume III.

Table 3-1. Summary of Extent and Frequency of Typical Engine Parameters Measured in the Field

227 Vehicles From Parameter Survey Experiment

Parameter	Estimate of mean $\overline{X}$	Estimate of Standard Deviation S	% Unsatisfactory
Δ Timing, deg relative to specification	0.9	5.8	76
Vacuum Advance, deg.	19.4	6.0	33
% Available Voltage $\frac{\text{coil avail.}}{\text{plug reqd.}}$,	303	133	12
Misfire Rate at 30 mph, %	12.0	0.0	2.7
45 mph, %	15.3	5.4	4.4
60 mph, %	17.6	8.4	9.7
ICO, %	3.72	1.90	60
Δ IRPM (rpm), relative to specification	-9	94	70
Δ Float Level (in.) relative to specification	0.02	0.22	34
A/C Restriction, deg.	40	50	23
PCV Pressure, in. H_2O	-0.3	0.5	12
Air Pump Pressure, psi	4.1	2.2	11
Odometer Reading, mi.	33528	18643	

Diagnostic equipment and procedures typical of a well equipped diagnostic center were used to characterize the maintenance states of these in-use vehicles. Of primary interest to an emission inspection/maintenance program are those parameters which deteriorate or malfunction frequently and which result in emissions increases. The mean deviations from the manufacturer's specification or a zero reference point as well as the standard error about this mean are shown in Table 3-1 for the ten most emission-sensitive and most frequently maladjusted engine parameters. Idle fuel-to-air ratio, timing, idle rpm, secondary ignition misfire, air pump failure, air cleaner restriction, positive crankcase ventilation valve restriction, float level, and percent available voltage were selected as the most important parameters for further study.

3.1.2 Emission Sensitivity to Malfunction

The influence of the parameters identified in Table 3-1 upon exhaust emissions was first estimated from published data. Again it was found that quantitative data describing the effects of different levels of malfunction and maladjustment on vehicle emissions were inadequately described in the literature.Where available, the data generally described the effect upon emissions of combinations of maintenance such as replacement of plugs, points and condensor (References 4, 5 and 6). Single malfunction effects were difficult to extract. Where single malfunctions were studied, data were available for a limited number of power trains and for only a few variables (References 7, 8 and 9). Therefore a test program involving two statistically designed subexperiments was conceived and conducted to obtain data describing exhaust emission responses to malfunctions. These subexperiments, described in Figure 3-1, were:

- Screening experiment of parameters found frequently to be out of adjustment to determine those which significantly affect emissions

- Definitive experiment to determine quantitatively with a high confidence level the relationships between emissions and malfunctions for those malfunctions indicated by the screening experiment to be most important.

Screening Experiment

The ten parameters listed in Table 3-1 plus manifold vacuum leakage (typified by disconnected or punctured vacuum hoses and associated accessories) were evaluated in a screening experiment. The objectives of this experiment were to:

- Identify the most important of these malfunctions

- Validate the effectiveness of statistically designed experiments in defining emissions response to engine parameters

- Identify the most discriminating diagnostic emission modes.

A statistically designed, orthogonal experiment was performed to develop linear mathematical relationships (response surfaces) between exhaust emissions and engine parameters. The statistical design selected was a 1/64 fractional factorial experiment performed at two settings for each variable. This design allowed for the clear derivations of all main effects as well as an indication of interactions effects.

Both mass and composite emissions were measured simultaneously using a modified, variable dilution mass sampling technique. In addition, emissions were measured for 33 trial diagnostic modes encompassing known and proposed exhaust emission inspection procedures. HC, CO, CO_2, NO and NO_2 measurements were made for all modes/cycles.

The test sequence was as follows:

- An emissions test was performed on the as-received vehicle

- A major engine tuneup was done and the emission tests performed.

- The 11 malfunctions/maladjustments were set following the experiment design and emission tests were performed after each set of adjustments.

An emission test as used in the above test description is defined as combined mass, composite and diagnostic mode emission measurements. Only hot composite and mass measurements were made during the statistically designed experiment.

Eleven basic power trains were tested which were representative of 1966-1969 California vehicles having engine modification and air injection emission control systems. The power trains were selected to reflect the U.S. population with regard to engine type and manufacture.

Exhaust emissions sensitivity to malfunction was found to be similar between power trains and the coefficients determined in this study were highly correlated with those found in the literature for those adjustment effects which were statistically significant. When combined with the parameter survey data, these results were used to develop an index of overall effectiveness. This index represents the emission reductions which would be expected when a specific parameter (P_i) is restored to nominal or specification value in all of the vehicles in a general population.

$$EI_{ij} = (\overline{P_i - P_{spec}}) \frac{\partial e_j}{\partial P_i}$$

where

EI_{ij} = average emissions reduction of emission j due to maintenance of parameter i.

$\overline{P_i - P_{spec}}$ = average deviation of parameter i measured in the parameter survey.

$\partial e_j / \partial P_i$ = response of emission j to parameter i as measured in the screening experiment.

Composite effectiveness indices (EI) developed by weighting the 11 power trains for the 11 parameters evaluated in the screening experiment are shown in Table 3-2 with the significant parameters shaded. Those parameters shown to have potentially significant influences when kept in adjustment through a mandatory vehicle inspection and maintenance program

Table 3-2. Most Probable Emission Reduction (Combined Data from Engine Parameter and Screening Experiments)

$$EI^{*} = (P_i - P_{spec})\ \partial e/\partial P_i$$

Emission	Timing	Misfire	Vacuum Advance	ICO	Air Cleaner	PCV**	Air Pump	Float	Leak	IRPM
HC, ppm	10.8	72.0	2.26	-170					10.5	9.4
CO, %				0.61	0.18	0.06	0.05	-0.03†	-0.02	
NO, ppm	24.6		-6.3†			-20.9†		7.7		

*Composite value obtained by a population weighting of 11 basic power trains.

**PCV, positive crankcase vent system.

†Negative values indicate an emissions increase upon maintenance.

are the idle adjustments (rpm, timing, fuel-to-air ratio), misfire and induction system components (positive crankcase ventilation system, air injection system and air cleaner restrictions). These malfunctions and adjustments, with the exception of misfire, were selected for definitive study within a more statistically powerful experiment. Misfire was omitted as it had no indicated interaction with the other parameters and was adequately characterized. Although float level and vacuum advance have strong effects on CO and NO emissions, their malfunction frequencies were such that they would not be expected to have significant impact on total emissions to the atmosphere.

Thirty-three diagnostic modes were evaluated in the screening orthogonal experiment. Exhaust emission responses to changes in the selected engine parameters were obtained for each of the diagnostic modes. Modes were sought which were highly diagnostic of either one class of malfunction (engine subsystem) or of specific components or adjustments.

Typical emissions responses to the range of engine malfunctions simulated in the experiment are shown in Tables 3-3 and 3-4. Modes are grouped by the level of engine loading (closed throttle, low, medium and high load). Certain malfunctions such as the restriction of the reactor air pump, PCV valve and air cleaner were set at their extremes (plugged). In the field they will be in varying states of deterioration. Therefore, emission responses to these parameters generally would be expected to be less than those shown. The following conclusions were drawn from these results:

- Exhaust emissions measured in modes which load the engine at similar levels tend to have similar response to malfunctions.

- CO emissions measured using modes involving low to moderate engine load levels are sensitive to induction system type malfunctions, such as float setting, air leak, air cleaner and PCV. Basic timing however can sometimes confuse the diagnosis.

- For air reactor controlled vehicles, a malfunction of this device can confuse a CO emission diagnosis of either the idle parameter maladjustments in the closed throttle modes or induction system malfunctions at load.

Table 3-3. Typical Vehicle Malfunction Sensitivity to Operating Mode—HC Emissions

Screening Experiment, 90% Confidence Level

Mode	Δe, Change in Emissions in Going From the Low to High Level of a Parameter, ppm						
	Misfire$^{2.5\%}_{0}$	Timing$^{+7°}_{-10°}$	RPM$^{+50}_{-100}$	ICO$^{2.0\%}_{-0.5}$	Float$^{+1/4''}_{-1/8''}$	A/C$^{Restricted}_{Spec}$	PCV$^{Plug}_{Spec}$
Idle F*	298	154					
Idle (11)**	392	237	-145	168			
Idle (27)	324	128	-56	79			
30-15 F		386		389	-409		
50-20 F	311	363	-780			228	294
30F	313	71			-70	40	
24C (28)	308	64			-72	35	36
30A (14)	335	100	-53	46	-75	86	
+2 mph/sec (12-14)	379	148	-88	52		67	
40C (29)	321	46			-47	51	
0-25 F	309	110			-36		
15-30 F	301	94			-48		27
0-30A (18)	369	138	-91	81	-66	92	
60S (30)	359	119			-30	37	
60P (25)	328	77		33	-44	70	
+3mph/sec (6-8)	332	95			-27	33	28

*1968 Federal 7 mode cycle.

**See Vol. III, p 3-29 for corresponding mode number location.

Table 3-4. Typical Vehicle Malfunction Sensitivity to Operating Mode — CO Emissions

Screening Experiment, 90% Confidence Level

Δe, Change in Emissions in Going From the Low to High Level of a Parameter, %							
Mode*	Misfire$^{2.5\%}_{0}$	Timing$^{+7^\circ}_{-10^\circ}$	RPM$^{+50}_{-100}$	ICO$^{2.0\%}_{-0.5}$	Float$^{+1/4''}_{-1/8''}$	A/C$^{Restricted}_{Spec}$	PCV$^{Plug}_{Spec}$
Idle F				2.2958		0.5525	
Idle 11				2.8879			
Idle 27			0.3837	2.7545		0.5717	
30-15				1.5941		0.5348	-0.4275
50-20				1.7744		0.7517	
30F		-0.6160					
24C		-0.9366			-0.9947		0.6846
30A					-0.6352		
+2 mph/sec		-1.3778			-0.5147	0.6572	
40C		-2.7870				1.4717	
0-25		-0.8153			-0.9442	0.5869	
15-30		-0.8910			-0.9873		0.5547
0-30A		-0.7985					
60S						0.7380	
60P				0.7287		1.1620	0.9888
+3 mph/sec		-0.9795			-0.7812	0.8499	

*See comment on Table 3-3.

- The fast idle modes (1500 and 2500 rpm) are not substantially different from the closed throttle modes in providing diagnostic information.
- Closed throttle HC emissions will generally diagnose maladjusted idle rpm and timing, although an air reactor system malfunction on vehicles so equipped will confuse the diagnosis.
- Basic timing dramatically affects NO emissions under any engine load condition.
- The effect of misfire rates greater than 2.5% upon HC emissions in all modes predominates over the effect of most other malfunctions simulated.

Definitive Emissions Response Study

The six engine parameters having the largest effectiveness indices were evaluated in a more powerful statistical experiment (see Figure 3-1) having the objectives to:

- Develop a generalized data bank from which engine parameters and emission signature inspection/maintenance models can be synthesized for the economic-effectiveness study.
- Determine the important interactions between engine parameters and their effect on engine exhaust emissions.
- Characterize those parameters known to have non-linear emissions response surfaces.

In addition to the main-line experiment, the following subexperiments were performed:

- An air cleaner deterioration test was performed wherein the effect of three levels of restriction was evaluated for vehicles otherwise adjusted to manufacturer's specifications.
- Vehicle stability tests were performed to assess base line emission changes over the test period for a vehicle set to manufacturer's specification.

A statistically designed, orthogonal experiment was performed to characterize the emissions response of the six engine parameters, Table 3-2, for 11 basic power trains. The experiment was a one-half fractional factorial design run at two levels for four parameters and at three levels for idle CO. Three levels of idle CO were selected because both HC and CO composite emissions had been previously shown to have nonlinear responses to this maladjustment (References 5 and 6).

Population weighted response surfaces, $\partial e_j/\partial P_i$, for the 11 power trains evaluated are shown in Table 3-5 for HC, CO and NO emissions. These composite values reflect the average population emission sensitivity of engine modification and air injection system controlled vehicles. The following conclusions are indicated:

- Both engine modification and air reactor controlled vehicles generally respond to the same degree to engine parameter changes.
- Air reactor controlled vehicles are slightly less sensitive than engine modification vehicles to induction system malfunctions.
- Air reactor controlled vehicles, on balance, are as sensitive as engine modification vehicles to idle adjustments.
- All six of the engine parameters investigated significantly affect emissions and were selected for evaluation in the economic-effectiveness study.

The experimental design also permitted the determination of parameter interaction effects on emissions. For example, the simultaneous adjustment of any two engine parameters may not result in an emission change which is the sum of the effects (taken separately). An interaction may be hypothesized to have occurred under this situation which may increase or decrease the emission change. Timing and idle rpm, for example, are shown to have interactions which affect CO emissions for air reactor controlled vehicles.

Air Cleaner Experiment

Air cleaner experiments were performed for those power trains shown in the preceding experiment to have an emission response to air cleaner restriction. The objective of these tests was to determine the nonlinear response of emissions to air cleaner restrictions. Clogged cleaners were simulated by taping closed the air cleaner element and then cutting vertical slits at five equal spaces around the circumference. The remaining engine

Table 3-5. Summary of Composite, 7-Mode Emissions Responses to Engine Parameters — Definitive Statistical Experiment

Vehicle Control	Composite Emission j	Parameter Response, $\partial e_j/\partial p_i$ Timing degree	Idle RPM	Idle CO %	Misfire+ %	Air* Cleaner	PVC*	Air* Pump
Air Injection System	HC ppm	9.94	-0.525	-4	116	1.1	28	154
	CO %	0.009	-7×10^{-4}	0.196		0.82	0.35	1.54
	NO ppm	30.5	0.164	-1.07		292	0	-53
Engine Modification	HC ppm	7.25	-0.892	-18	100	29	58	
	CO %	-0.008	-6.6×10^{-4}	0.176		0.85	0.51	
	NO ppm	38.3	0.063	-8.2		-114	208	

*Emission change is based on going from the nominal to a restricted state.

+Misfire results are obtained from the screening experiment.

parameters were set to the manufacturer's specification. The extent of air cleaner restriction, Figure 3-2, was measured both as an increase in CO at 50 mph road load and with an AC air cleaner tester.

The exhaust emission response to air cleaner restriction as determined from the orthogonal test is also plotted on Figure 3-2. Except for Vehicle No. 602, the orthogonal test data points compare favorably with those obtained during the air cleaner experiment.

Several vehicles (602, 604 and 610) exhibited nonlinear emissions response to an air cleaner restriction. Several vehicles had responses to air cleaner restriction which were highly unstable as indicated by data scatter as well as by the difficulties in setting up the simulated malfunction. Because vehicles with nonlinear air cleaner response curves also exhibited substantial ranges of linearity, only the linear responses derived from the definitive test were used in the economic-effectiveness study.

3.1.3 Exhaust Emission Signatures

Diagnostic modes were again evaluated using data from the definitive orthogonal tests to determine which were most selective in identifying malfunctions at either the subsystem or component/adjustment level. The results of this evaluation are shown in Volume III (Sections 3 and 4) for selected modes.

The general conclusions based upon data from the screening experiment were still found to apply. Conclusions of a more specific nature were:

- The 33 mph Clayton key-mode cycle is equivalent to the more heavily loaded modes of the Federal cycle in diagnostic content.
- The 50 mph Clayton key mode contains no additional diagnostic information than was already present in the lower loaded modes for the engine parameters evaluated.
- The 1500 rpm fast idle mode contains no diagnostic information not already present in the idle modes.

There may be some utility in the 50 mph Clayton mode in revealing induction system power circuit malfunctions and verifying the results of the 33 mph mode. It is evident that all special emission signature modes (eg, Clayton key-mode) can be approximated using modes of the seven-mode cycle.

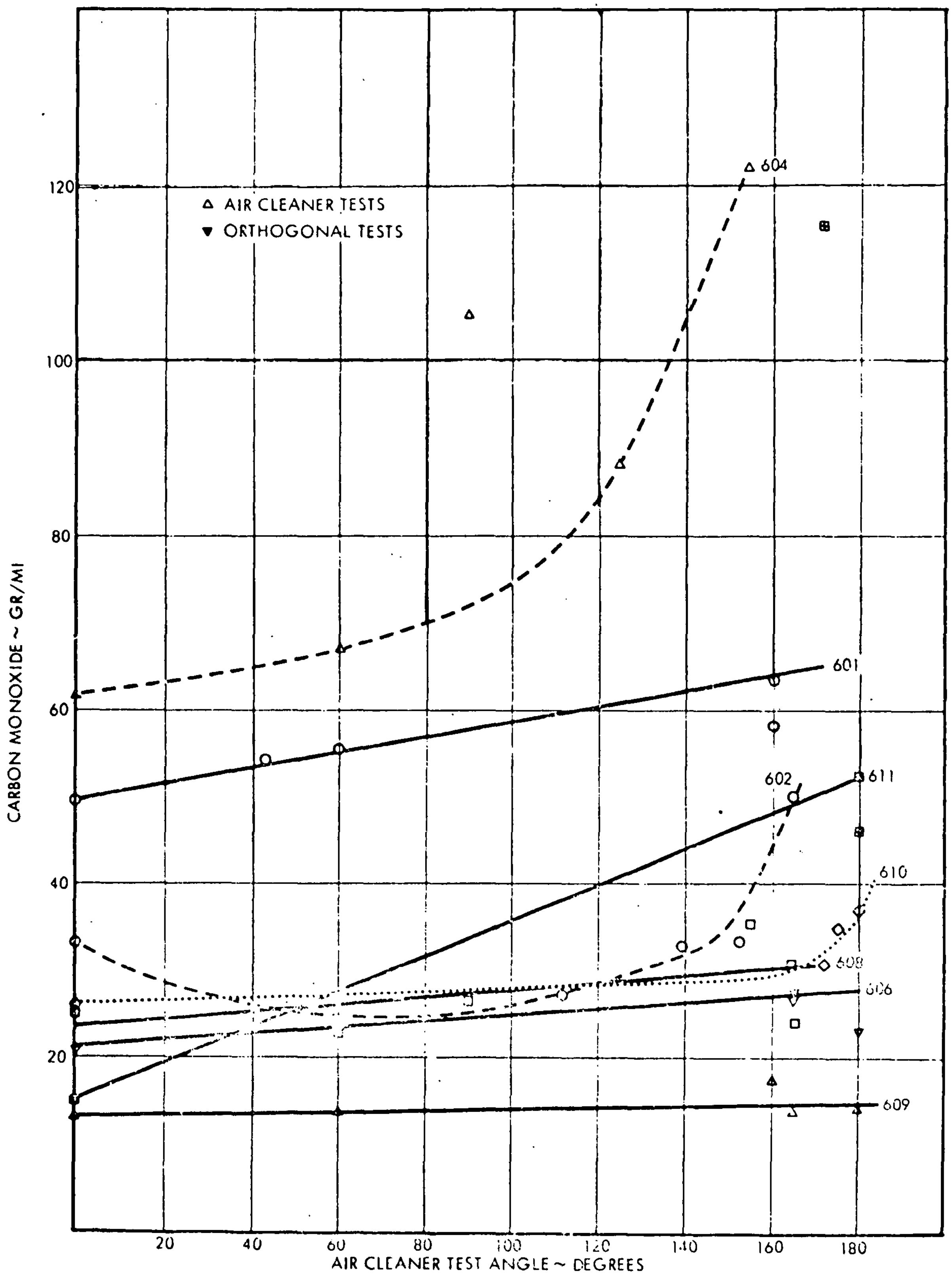


Figure 3-2. Effect on Air Cleaner Restriction on CO Mass Emissions

Exclusive use of the modes of the seven-mode Federal cycle for the emission signature study permitted the use of data from the General Motors (GM) idle adjustment study. These data are compared with the parameter survey data in Table 3-6. The two sets of data agree fairly well considering the acquisition source and relatively small sample. Vehicles in the parameter survey would be expected to be further out of specification because of their higher average mileage.

The GM data were used to develop relationships between exhaust emission rejection cut points and the mean values of the engine idle parameter settings found for vehicles in the rejected population. The parameter survey data were used to develop equivalent relationships for inspections based upon direct inspections of engine adjustments. It would have been more desirable to have used a single data set for analysis of both emission signature and engine parameter inspections. However, the high correlation between the GM data and that obtained during our parameter survey eliminates the possibility of large errors.

Mean values for the idle adjustments referenced to manufacturers' specifications for the rejected fraction of vehicles were plotted against varying rejection levels or cut point values for single as well as multiple emission signature measurements (see Volume II). The following results were obtained:

- Idle CO emissions are the most powerful single inspection signature (i.e., identifies the most idle maladjustments).
- The addition of an idle HC emission inspection identifies, on the average, larger idle rpm, and timing adjustment deviations.
- Mean values of the idle parameters for those vehicles rejected vary approximately linearly with the idle CO emission rejection level.

3.1.4 Inspection and Maintenance Costs

The cost and direct labor of inspection and the associated maintenance were established from three sources. These sources, depending on whether conventional or advanced equipment was used, were:

Table 3-6. Comparison of Parameter Survey and General Motors Idle Adjustment Program

Air Injection and Engine Modification Controls

Statistic		GM Idle Program*	Parameter Survey
Sample:	Size	228	227
	Model, Year	1966-68	1966-69
	Mileage	20,000	33,500
Idle Adjustments:	ΔRpm	-21	-9
	ΔTiming, deg	0.3	0.9
	Idle CO, %	3.37	3.72
Malfunctions:	Air Pump	6%	10%
	Idle Misfire	2.2%	2.2%

*See Reference 4.

- Chilton's Labor Guide and Parts Manual
- Engine parameter inspection labor times derived from the orthogonal test experiments
- Coarse operations analyses for hypothetical advanced equipment such as remote sensing devices.

The Chilton data was used to estimate labor costs for diagnoses using conventional garage equipment. Judgment was required in separating the diagnosis times from actual maintenance times, since the procedures investigated in this study are usually not specifically evaluated in the flat rate manuals.

All labor costs for garage inspection/maintenance are charged at a rate of $10 per hour. This is a burdened rate which includes overhead factors and profit. Labor rates for state inspection stations consist of direct labor at $3.50 per hour and overhead factor of 50% to account for fringe benefits and general administration. An additional 50 cents per vehicle is charged for program enforcement (i.e., the information system required for recording, processing, storing and disseminating inspection/maintenance data).

Additional ancillary data, such as demographic constants, user inconvenience costs and average trip speed are based upon the Los Angeles region which was the reference point for the economic-effectiveness study. All of the above data are described in greater detail in Volumes II and III.

Investment Costs

Regional land costs were considered in the estimation of investment costs associated with station siting. National land cost data acquired by TRW on a program of vehicle safety compliance performed for the Bureau of Highways was used to evaluate land costs for rural, urban and metropolitan regions (Reference 10). Equipment costs for diagnostic and emissions testing were acquired from a number of vendor sources. In addition, cost and performance data for prospective, prototype emissions instruments and automated data acquisition systems were developed.

A coarse operations analysis of procedures and work station configurations was conducted to support the costing of inspection lanes. A typical layout of an inspection station is shown in Figure 3-3.

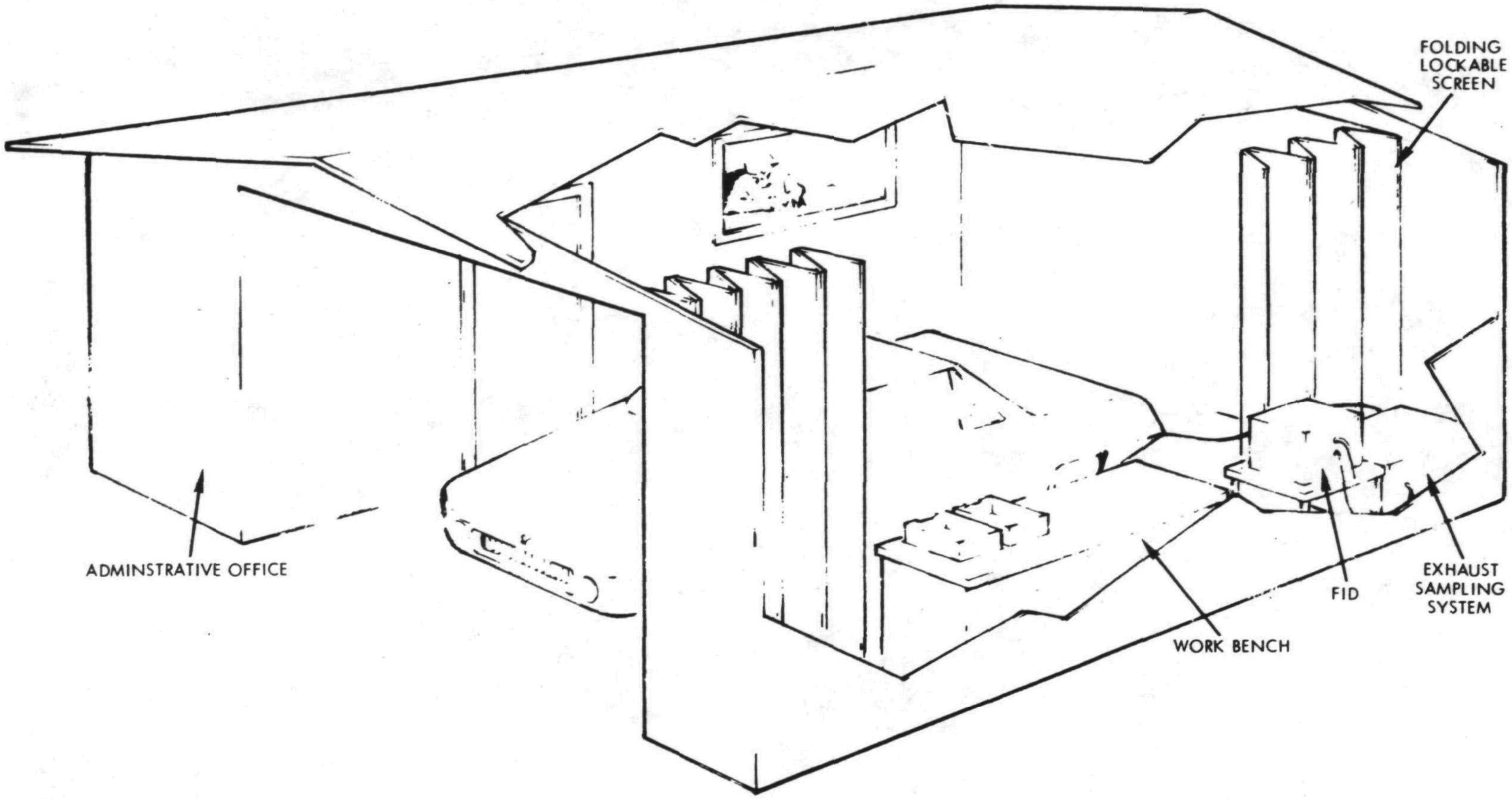


Figure 3-3. Typical Station Configuration for State Inspection

An evaluation of prototype models of advanced emissions instruments was undertaken to select those generic types most suitable to state inspection lanes. Precision, accuracy and cost data pointed toward nondispersive infrared devices as those best suited to our requirements.

Scope of Voluntary Maintenance

It is important to establish the extent and frequency of voluntary tuneup maintenance to assess its current cost and effectiveness. An equally important consideration is that enforced maintenance will probably only require performing a portion (idle adjustments) of the total required vehicle maintenance. Under these circumstances, it seems reasonable to assume that the remainder of the required maintenance will be performed voluntarily at a frequency equal to that of current voluntary maintenance. Data on voluntary maintenance are scant, usually conflicting, and vague. For example, the often-quoted 1965 Look magazine survey indicated only 34% of the vehicle owners had tuneup work performed within a 12-month interval. A 1966 poll of the service industry indicated perhaps 88% of the nation's vehicles were tuned during a 12-month interval (Reference 11). Recent TRW data based on an employee poll suggest that 79% of 1966-1969 vehicles undergo an annual tuneup.

Data from a recent surveillance program on 1966-1969 vehicles conducted for Standard Oil involving a random selection of California vehicles (Reference 12) indicate a tuneup maintenance frequency of 12 to 13 months. A 12-month frequency was selected for the study to simplify calculational procedures and because it represented a reasonable estimate of maintenance frequency for a newer vehicle population in which many cars are still under warranty.

3.1.5 Deterioration of Maintenance

Estimates of the rate at which tuneup adjustments deteriorate are also essential to evaluate alternate maintenance treatments. Analysis of the American Automobile Associaton (AAA) data (Reference 13) suggests that to a first approximation, degradation models must be developed for the following three subsystems:

- Idle adjustments of fuel-to-air ratio, idle rpm, and timing which affect all emissions (HC, CO, and NO).

- Induction subsystem (PCV, air cleaner, and air pump) which predominantly influences CO and NO emissions.
- Secondary ignition subsystem (misfire) which affects only HC emissions.

The deterioration of most components and adjustments except timing generally results in reducing NO_x emissions. For example, rich carburetion and retarded timing result in lower peak combustion temperatures and, therefore, lower NO_x emissions.

NO_x emission deterioration rates were derived based on the high correlation which was found between CO and NO_x composite emissions using the previously discussed air cleaner experiment data and the estimated rate of deterioration of basic timing.

Deterioration data for CO and HC were developed for each of the major engine subsystems-induction (PCV, air pump, carburation, manifold leak), ignition (misfire), and idle adjustment (rpm, timing, and CO) using a combination of AAA and California Air Resources Board (ARB) data.

The rate of deterioration of engine parameters was combined with current, voluntary maintenance program data (frequency and effectiveness), to reconstruct the emissions degradation shown by the California ARB surveillance data. This was done assuming that average voluntary maintenance occurs every 12,000 miles on 1966 - 1969 vehicles. The effectiveness of voluntary maintenance was obtained from Reference 4. This set of data was adjusted through iteration until the ARB surveillance data for composite HC and CO were matched. The following deterioration rates expressed as a function of mileage were derived.

Table 3-7. Subsystem Deterioration Rates

Power Train	Subsystem	Deterioration Rate, $\partial e_j/\partial M$, gms/mi^2		
		HC	CO	NO
Air Injection	Induction	7×10^{-6}	8.7×10^{-5}	-5.7×10^{-6}
	Ignition	2.3×10^{-6}	0	0
	Idle	9.3×10^{-6}	3.5×10^{-4}	10^{-5}
Engine Modification	Induction	8×10^{-6}	1.3×10^{-4}	-8.6×10^{-6}
	Ignition	2.3×10^{-5}	0	0
	Idle	1.2×10^{-5}	5.6×10^{-4}	10^{-5}

3.2 ECONOMIC-EFFECTIVENESS MODEL

An economic-effectiveness model was then developed to provide a method for systematically examining the impact of various strategic (inspection-lane or franchised-garage) and tactical (inspection/maintenance procedures) program policies on system costs and resultant emission levels. The model developed is capable of analyzing the effectiveness of various emission inspection test techniques including the four alternatives to be studied on the project (i.e., engine parameter, idle emissions and key mode). The model calculates the relative effectiveness and cost of state-lane or franchised-garage inspection operations. In addition, it can treat cases where the required maintenance treatment is either adaptive or predetermined, that is, cases where either the maintenance treatments are selected on the basis of a reinspection or specified in advance for all rejected vehicles. Volume II presents a detailed discussion of the economic-effectiveness model.

The general ground rules for the economic effectiveness analyses were as follows:

- The economic-effectiveness of a particular inspection/maintenance approach to vehicle emission control is related to specified emission reduction goals and economic constraints. For this study a reduction of at least 15% for any of the emission species was required of each maintenance strategy with an attendant program cost not to exceed $6 per car per inspection/maintenance interval.
- The two basic emission control approaches (air reactor and engine modification) were treated in the model as separate populations.
- The specific vehicle population evaluated was that of Los Angeles with an estimated population of 4 million emission controlled vehicles.
- The effects of new vehicles entering and leaving the population due to attrition and new production was ignored.
- A 4-year performance period was assumed.
- Mean values of the emissions for both the engine parameter and emission signature populations were allowed to vary with time and with the degree of maintenance, however, the variances about these means were assumed to be time invariant.
- Emissions changes due to engine parameter deterioration were considered at the subsystem level (i.e., induction, ignition and idle adjustment subsystems).
- Basic maintenance was assumed to be performed voluntarily by the vehicle owner for those subsystems not treated by the enforced maintenance procedure.

The economic effectiveness model (Figure 3-4) consists of three major elements

- Emissions predictor model
- Cost estimator model
- Operations model

The emissions prediction model describes in detail the process involved in predicting emission time histories and total integrated average emissions based on the fraction of vehicles rejected to maintenance, emission

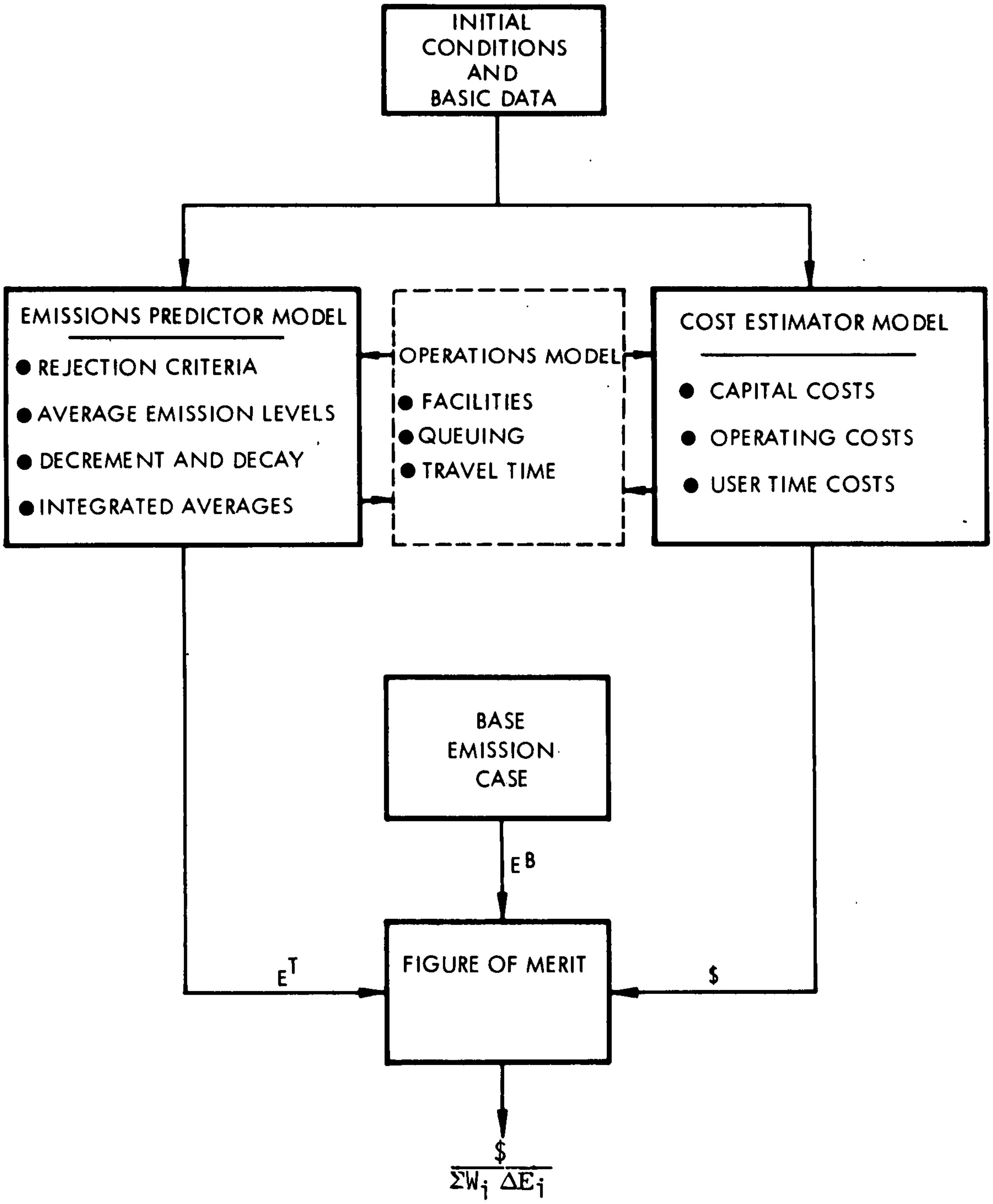


Figure 3-4. Systems Model Flow Diagram

reduction effected by maintenance and the maintenance deterioration with vehicle use. The effectiveness of candidate inspection/maintenance procedures was measured by comparing the resultant emission levels to some reference or base line case. For the present model, the base line case was the situation where vehicles are maintained voluntarily by the owner. Cost to implement a specific inspection/maintenance program includes: (1) capital costs, (2) operating costs and (3) user inconvenience cost. A figure of merit for each alternative inspection/maintenance program was determined using the emission reduction between the test and base line case as well as the total program cost.

3.2.1 Emission Predictor Model (Figure 3-5)

The model is configured to predict average hydrocarbon, carbon monoxide and oxides of nitrogen emission levels for time-invariant base line and test fleet populations. Figure 3-5 shows the procedures utilized by the model for determining test population emissions over the life of the program. The model first determines the average emission levels for each emission (HC, CO and NO) using experimental data. Next, an inspection procedure divides the test population into two parts: (1) a subpopulation of accepted vehicles with low emission levels; and (2) a subpopulation of rejected vehicles with high emission levels. The model then computes emission levels for the two populations at the time of the next inspection. For the accepted subpopulation, the emission levels are assumed to decay at their preinspection rates. For the rejected subpopulation, maintenance is performed which results in a measurable, average change in emissions. Using these new emission levels as a base, the model then decays the exhaust emission levels for this rejected subpopulation using a predetermined rate. Once the decayed emission levels have been obtained for the two subpopulations, the model combines them to compute the total average emission level for each emission component.

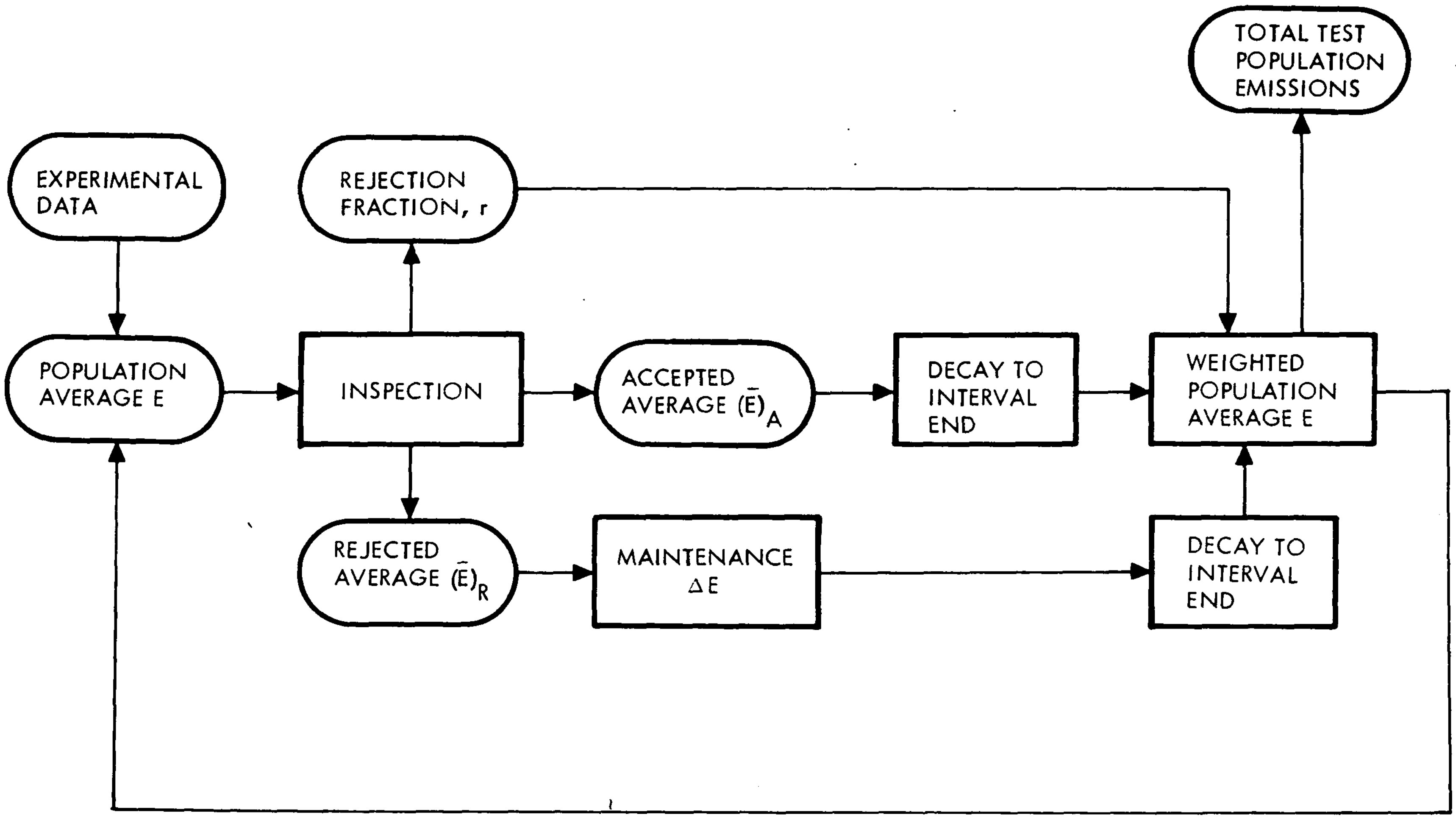


Figure 3-5. Emission Predictor Model Flow Diagram

3.2.2 Cost Estimator Model (Figure 3-6)

Inspection, maintenance and user-time costs comprise the main elements of the cost estimator model. The model estimates capital and direct operating costs for both the inspection and maintenance processes. All capital costs are discounted over a specified period and are added to the projected direct operating costs to obtain total annual operating costs. Total program costs over the time period considered are computed as the sum of these annual operating costs, discounted to present value. These costs are quoted exclusive of the user inconvenience costs which are included in the evaluation of alternative inspection/maintenance processes.

3.2.3 Operations Model

The operations model provides the linkage between the emission predictor model and the cost estimator model. It determines size, location, and number of facilities required to maintain the program. In making these determinations it trades off user-inconvenience costs with the capital costs for facilities. Thus, given any system configuration, the model computes the average waiting time using a queueing algorithm. Driving times to and from the station locations are calculated from demographic considerations (i.e., number of vehicles per square mile). This information is used to determine the inconvenience cost the public must bear. The operations model analyzes the implications of a labor-dominated versus an equipment-dominated operation. Through these considerations, it then selects the optimal degree of automation.

3.2.4 Figure of Merit

A description has been given in the manner in which the model predicts vehicle population emission levels and relevant system costs based on a specified inspection/maintenance program. To measure the cost/effectiveness of the various candidate programs, a weighted figure of merit is applied.

$$\text{Payoff, \$/ton} = \frac{\text{Program Cost}}{\Sigma W_i \ \Delta E_{ci}}$$

where W_i = weighting factor for the "i" emission

ΔE_{ci} = emission difference between base and inspection/maintenance test population over four-year period

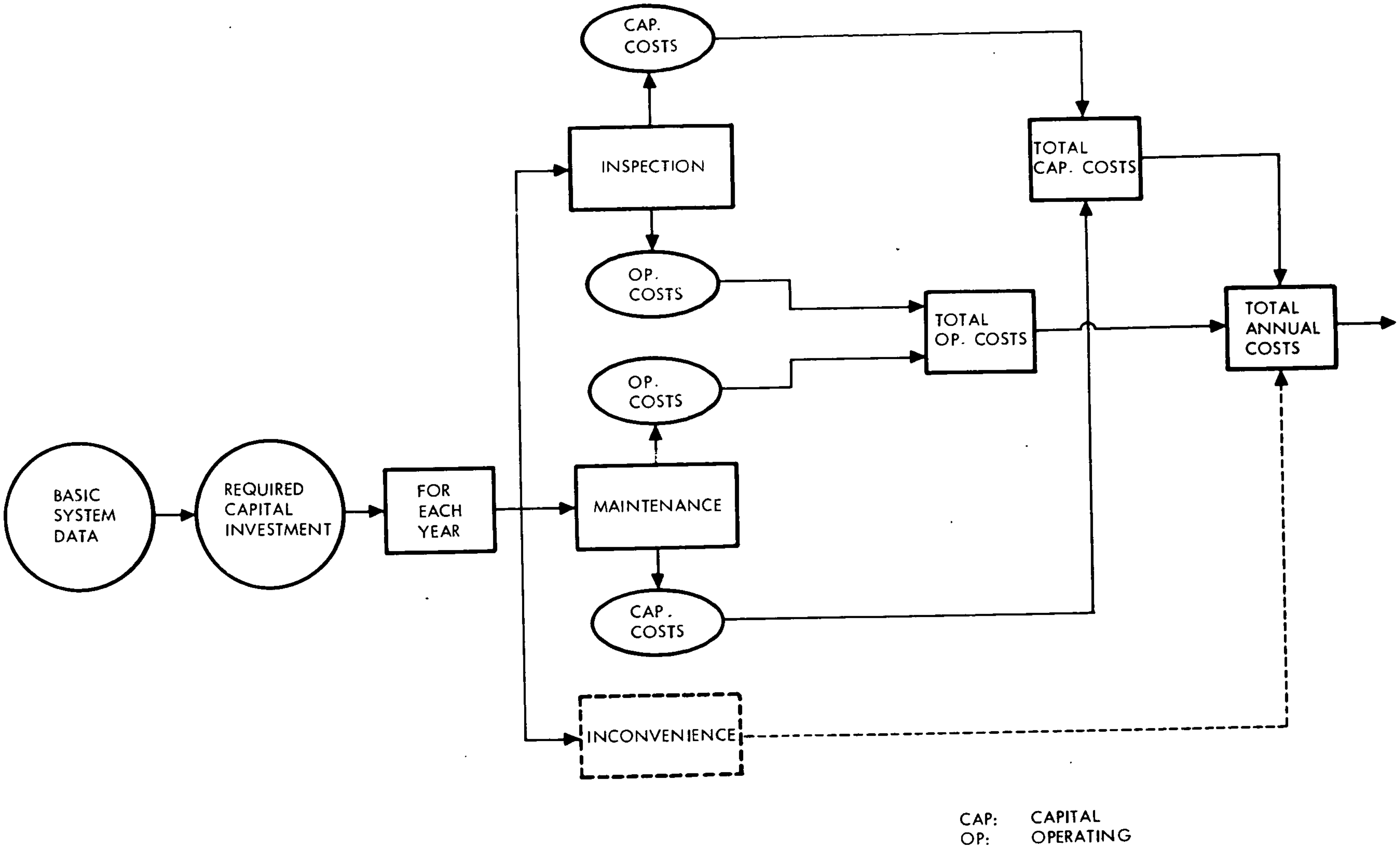


Figure 3-6. Cost Estimator Model Flow Diagram

$$\Delta E_{ci} = \int_{0}^{48,000} e_i \, dM$$

where e_i = "i" emission, grams/mile

M = accumulated vehicle mileage, miles

The weighting factors, W_i, were selected to reflect the fractional emission reductions which will be achieved upon meeting the 1975 Federal vehicle emissions standards (Reference 14). These weighting factors are 0.1, 0.6 and 0.3 for CO, HC and NO, respectively. Integration limits are from program initiation to 48,000 average accumulated vehicle miles, thus reflecting a four-year program time frame.

4. ECONOMIC EFFECTIVENESS STUDY RESULTS

Using the systems model and the developed emissions data, an assessment was made of the relative economic effectiveness of the several proposed inspection/maintenance strategies. Two general strategies were evaluated within the framework of the systems model: (1) an engine parameter inspection, followed, as necessary, by specified parameter maintenance; and (2) a mode emission signature analysis leading to further diagnosis and corrective maintenance. Each of these two approaches contains a number of substrategies and tactics. To evaluate effectively the impact of the more significant substrategies on program effectiveness, a computer matrix simulation approach was used. The technique permits evaluation of the degree to which the figure of merit (F/M) is sensitive to the design variables.

Shown in Table 4-1 for both the engine parameter diagnostics and emission signature analysis strategies are the figure of merit, cost per inspection/maintenance per car and optimized emission reduction for each of the substrategies evaluated. The figure of merit used throughout this study is defined as the present net worth cost of the program divided by the four-year emission reduction effected. An assessment of the "best" alternative within a given strategy can easily be made by comparing the corresponding figures of merit and selecting the one with the smallest numerical value. Annual program cost per vehicle and the attained emission reduction percentages have also been listed so that a convenient comparison can be made with results from other studies.

Referring to Table 4-1, the average cost of $1 to $3 per vehicle for the idle adjustment program is not inconsistent with the $3 per car estimated during the GM adjustment program and the $6 per car for the New Jersey inspection program (Reference 4). The corresponding idle adjustment emission reduction for hydrocarbons and carbon monoxide approximates the results from the GM experiment (Reference 4) when their results are adjusted for maintenance deterioration effects.

The simulation indicated that a short duration parameter inspection performed in a state inspection lane provides the most cost-effective system with a figure of merit of 320. The state-lane inspection procedure modeled

Table 4-1. Summary of the More Cost Effective Inspection/Maintenance Procedure

Procedure	Figure of Merit ($/Ton)	Cost Per Vehicle ($)	Emission Reduction***		
			HC (%)	CO (%)	NO (%)
Engine Parameter Diagnosis					
1. Idle (State Lane)	320	1.50	0	15	-7
2. Idle (Franchised)	370	2.50	3	13	-3
3. Extensive A* (Franchised)	460	6.00	18	14	0
4. Extensive B** (Franchised)	540	12.00	22	33	-5
Emission Signature Analysis					
5. Idle (State Lane)	430	2.50	2	12	-4
6. Extensive A* (State Lane)	360	4.00	11	16	-4
7. Extensive B** (State Lane)	410	6.00	15	20	-3

*Idle Plus Ignition Subsystem Inspection.

**Idle Plus Ignition Plus Induction Subsystem.

***Average emission reduction over a four-year period.

consisted of remotely sensing idle carbon monoxide concentration and idle rpm. This inspection/maintenance procedure resulted in an average 15% reduction of carbon monoxide emissions over a four-year period following initiation of a mandatory program. Hydrocarbon emissions were unchanged while oxides of nitrogen emissions increased 7%. The prorated cost of this inspection/maintenance procedure was estimated to be $1.50 per vehicle with the cost of program administration being about one third of the total.

A short duration idle parameter inspection procedure also was evaluated for use in franchised garages with conventional diagnostic equipment. This procedure produced emissions changes which were similar to those resulting from the short duration state inspection lane procedure just described. The cost of short duration inspection in franchised garages however was higher than that of the similar state-lane inspection and therefore the franchised garage inspection procedure was found to be less economically effective with a figure of merit of 370.

The simulation demonstrated that idle adjustment inspection/maintenance was more cost effective than either the mixed idle plus ignition procedure or the complete idle, ignition and induction maintenance which had figures of merit of 460 and 540, respectively. The study indicated that the more comprehensive inspection/maintenance procedures will result in emission reductions of as much as 33%, however, at significantly higher program costs (average owner annual cost of $12.00). Sections 4.1 and 4.2 present more detailed results on the two major strategies studies.

Conclusions regarding the cost effectiveness of various inspection/maintenance strategies are affected by the weighting factors assigned to individual emissions. In the figures of merit just presented a reduction of hydrocarbon emissions was weighted six times more heavily than an equivalent reduction of carbon monoxide emission. Nevertheless the selected optimum strategy is really only effective in reducing carbon monoxide emissions. In areas having photochemical "smog" problems the figure of merit should probably be reweighted to further increase the importance of HC and NO_x reductions. Clearly maintenance of the ignition subsystem and even the induction subsystem will become important if hydrocarbon emissions are to be controlled effectively.

The equipment required for state-lane inspections always includes HC and CO emission instruments and a simple dynamometer when loaded mode emission signatures are required. Inspection in franchised garages requires conventional diagnostic equipment and optionally, a simple dynamometer. A more detailed list of equipment required for the procedures evaluated can be found in Table 4-2.

4.1 Engine Parameter Inspection

Of the two strategies evaluated, the engine parameter inspection approach minimizes the number of diagnostic errors because maladjustments and malfunctions are directly identified and maintenance is performed only on the engine parameters shown to effect emissions significantly. Therefore for the identical vehicle rejection fractions, this procedure would be expected to effect larger emission reductions than an emission signature inspection.

Emission time histories for the most cost-effective program, an idle adjustment program, using 1966-1970 vehicles are presented in Figure 4-1. The base line fleet case reflects voluntary maintenance. Only the idle adjustment engine parameters are inspected annually and maintained in the inspected fleet. Depicted in panels A, B and C of Figure 4-1 are model-generated, time history plots of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emissions. This idle adjustment program has its largest impact on carbon monoxide emission levels and its least, on oxides of nitrogen emission levels. The data are based on a one-year inspection/maintenance cycle over a four-year program life.

In addition to an idle adjustment program, other parameter inspection/maintenance strategies were assessed (see Table 4-1). In these cases, the overall figures of merit were found to be considerably poorer than that of the idle adjustment program. Although these more elaborate procedures substantially reduce HC emission levels below those produced by the idle adjustment program, these reductions are more than offset by the increased program operational costs. This higher cost is primarily associated with the more difficult and lengthy inspections which must be made to find ignition and induction system malfunctions. For example, 15 minutes of inspection time on 100% of the vehicles are required to find those 3 to 4% which have engines that misfire under load. This increased cost may be worth the improved air quality in regions of chronic air pollution and large vehicle populations.

Table 4-2. Equipment and Procedures Required for Diagnosing Engine Parameter Malfunctions

Subsystem	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	NDIR CO Analyzer	Idle CO	NDIR CO Analyzer	Idle CO
Ignition-Misfire	Engine electronic Analyzer/Dynamometer	Misfire at 45-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	NDIR CO/CO_2 Analyzer	Idle dilution correction	NDIR CO Analyzer/ dynamometer	CO Connected - CO Disconnected

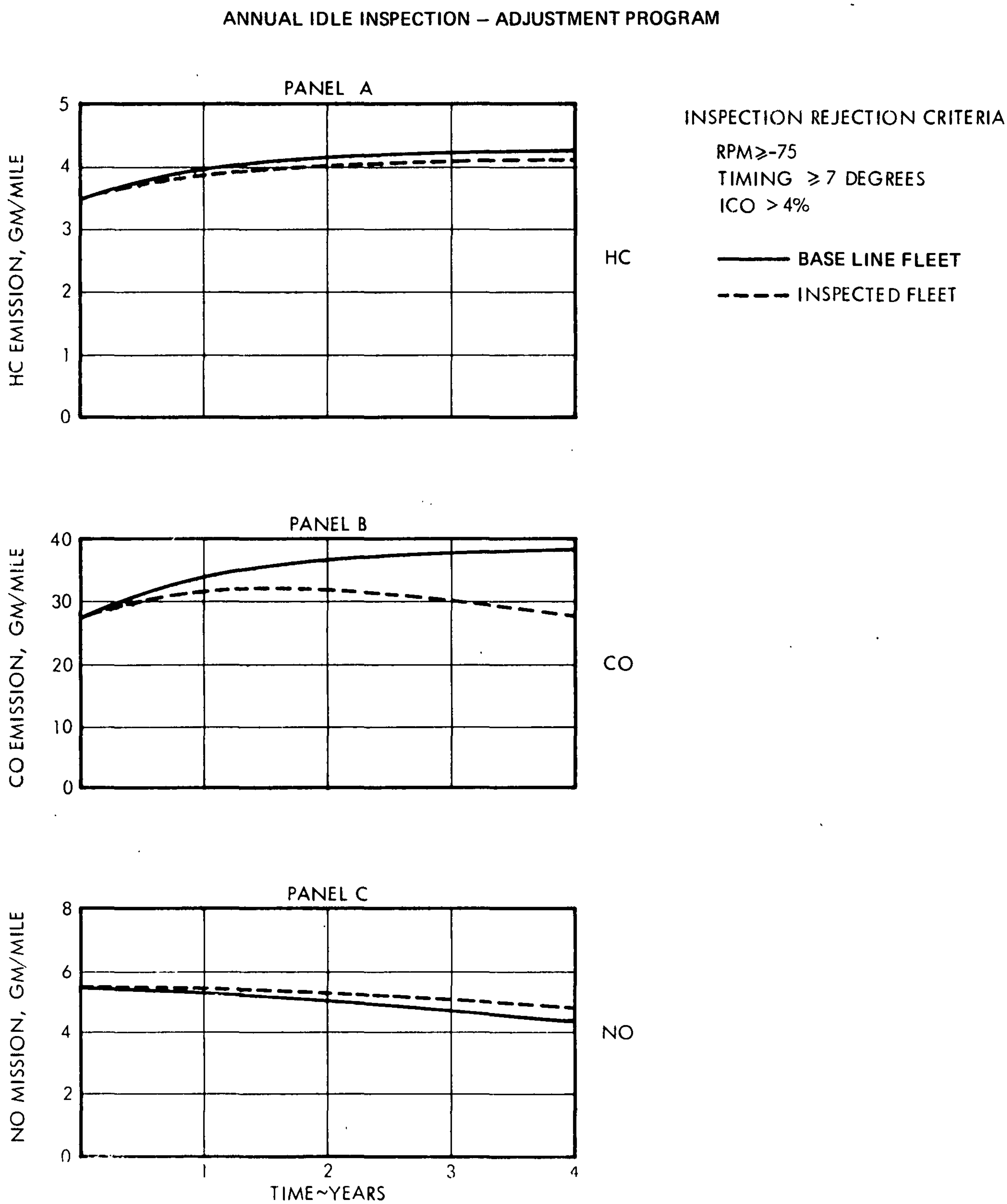


Figure 4-1. Emission Time History for Engine Parameter Inspection - Idle Adjustment Maintenance

4.2 Mode Emission Signature Analysis

The mode emission signature strategy generally results in low operating costs and relative ease of program implementation. On the other hand, the re-occuring problem of vehicle inspection errors (omission and commission) reduces the effectiveness of this procedure. That is, some vehicles will be rejected with failures which are not part of the mandatory maintenance program (errors of commission). In other instances, vehicles will not be identified although they had repairable malfunctions (errors of omission). To minimize the effect of this deficiency and yet provide low program costs, emission inspection modes must be selected judiciously for their ability to identify specific engine parameter maladjustments. For this study, four emission modes--idle CO and idle HC as well as HC and CO emissions under engine load--were selected for use in an emission screening inspection.

The idle CO emission inspection/maintenance strategy is not as cost effective as the idle parameter inspection/maintenance approach (figure of merit of 430 as compared to 320 for the idle parameter inspection). The negligible HC emissions reduction along with the larger increase in NO emissions for the idle CO emission inspection results from the fact that the emission inspection does not diagnose deviate timing as accurately as does the engine parameter inspection. For the same reason, NO emissions are not changed even when an idle HC emissions inspection mode is added. The addition of this mode, however, does result in rejecting vehicles with larger average deviations in idle rpm, and thus, produces a substantial reduction in HC emissions. Smaller CO emission reductions result because vehicles are being rejected with lower average values of idle CO.

The combined idle modes and the loaded HC mode emission inspection is extremely cost effective and offers substantial emission reductions (see Figure 4-2); 11% and 16% for HC and CO, respectively. The low figure of merit results from the high weighting factor (0.6) on HC reduction and significantly shorter time for inspection (one additional minute) than the conventional scope diagnosis. The lower emissions reductions relative to engine parameter inspections are due to the large number of errors of omission. For example, approximately 50% of the air reactor and air

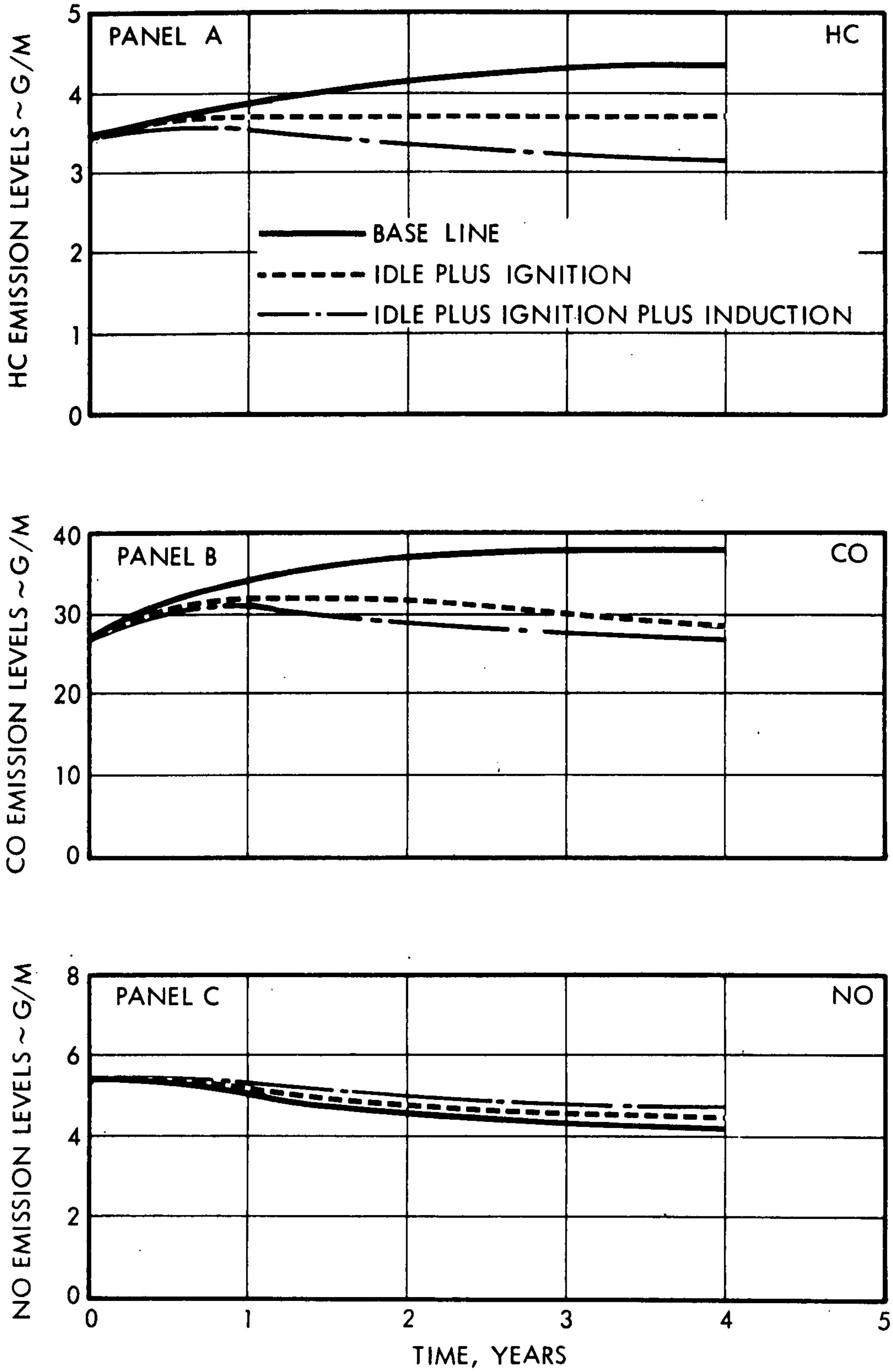


Figure 4-2. Emission Time Histories — Annual Emission Signature Inspection Using Loaded Modes

cleaner malfunctions go undetected. Also, idle HC emission is a poor discriminator of timing deviation. Approximately 50% of the advanced timing deviations remaining undiscovered.

The emission time history profiles for the two most cost effective emission inspection/maintenance procedures are presented in panels A, B and C of Figure 4-2. The general trend of these plots is much the same as those exhibited in Figure 4-1. The lower hydrocarbon levels achieved using the emission signature inspection approach is attributed to the fact that substantial reductions are possible when misfiring ignition subsystems are repaired. This failure was not cost-effective to repair in the state-lane idle parameter inspection strategy.

4.3 Conclusions and Recommendations

The previous discussion indicates that the cost effectiveness of the evaluated procedures tends to be strongly influenced by the inspection process, whereas the magnitude of the possible emissions reductions are most sensitive to the extent of imposed maintenance. Lowest figures of merit are estimated for the engine parameter inspection with idle adjustment maintenance and for the emission signature approach with idle adjustment maintenance plus ignition subsystem repair. Based on the stated assumptions and data of this study, the following inspection/maintenance procedures are most attractive:

- Engine idle parameter inspection and maintenance performed by franchised garages.
- Emission signature inspection in a state inspection lane followed by maintenance of the idle and ignition subsystems within a franchised garage.

These two cases provide sufficient latitude to satisfy the needs of varying state air quality programs. A state with a chronic photochemical "smog" problem may choose to maximize the reduction of all emissions; a state which is primarily concerned with CO emissions might be satisfied with only an idle adjustment program. Also, less populated states may not wish to impose a state-lane inspection with its attendant startup and user inconvenience costs.

These conclusions are based upon using the 1968 Federal test procedure as the best means of predicting vehicle exhaust emissions to the atmosphere. The weighting factors used for each of the emission species were selected on the basis of a region with a photochemical "smog" air pollution problem and having a large population of controlled vehicles such as the Los Angeles Basin.

Due to the limitations imposed by the above assumptions, by the rapidly changing control system technology, and by the change in Federal emissions measurement procedure from a volume to mass emissions basis, it is recommended that the basic emissions related data in the economic-effectiveness model be improved and expanded.

The objectives of future work would be to strengthen deficiencies in the economic-effectiveness model by acquiring and introducing more definitive experimental data to:

- Describe more accurately the frequency and extent of engine and control device malfunctions and their associated emission signatures for vehicles in several regional populations.
- Predict the effects of maintenance on emission reductions for precontrolled and California 1971 NO_x controlled vehicles.
- Describe the degradation of engine parameters with time and the associated change in mass emissions as measured with the 1972 Federal procedure.
- Characterize the effectiveness with which specified maintenance can be performed by a commercial service organization.

The upgraded model would then be available to determine the effectiveness of inspection/maintenance as a strategy which can be used to meet regional ambient air quality.

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