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

Volume II

Modeling of Inspection/Maintenance Systems

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
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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.

1. INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

The objectives of this project were to determine the effect of mandatory vehicle inspection and maintenance on vehicle exhaust emissions and to identify the more cost effective procedures for diagnosing and restoring to specification those maladjusted or malfunctioning engine components which most significantly affect emissions. This volume describes the development of the inspection/maintenance (I/M) economic effectiveness model and the study results. The model provides a consistent and systematic framework for evaluating the economic effectiveness of inspection and maintenance procedures using data developed in the experimental portion of the study (see Volume III).

The model is sensitive to the following variables:

- The total and discounted investment costs, annual inspection costs, system operational costs, vehicle maintenance costs, and user inconvenience costs.
- The technological complexity introduced into the inspection/maintenance program with emphasis on the degree of inspection automation.
- Private, public or mixed ownership/management of inspection and maintenance stations.
- Inspection interval, the number, size and locations of inspection stations; and manpower including skills and training requirements.
- The existing voluntary maintenance program effectiveness.

The study involved the following work sequence:

- A literature survey was made and direct discussions were held with automobile manufacturers and automobile associations to acquire applicable cost and operational data and to identify candidate inspection/maintenance procedures.
- Statistical evaluations of acquired data were performed to develop models of inspection procedures, maintenance effectiveness and deterioration and capital costs.
- An internally consistent system model was constructed using both contract developed and acquired data to evaluate the economic effectiveness of four candidate inspection/maintenance strategies.

1.2 SUMMARY

The following conclusions were drawn from the economic-effectiveness study:

- The six most effective engine parameters to maintain in a mandatory inspection/maintenance program are the three idle adjustments (air-to-fuel ratio, rpm and timing), elements of the ignition system when causing misfire and the induction system components including positive crankcase ventilation valve and air cleaner. The air injection (reactor) system should also be inspected and maintained on vehicles equipped with this type of 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 reductions over a four year period are between 10 to 15 percent for carbon monoxide and 2 to 3 percent for hydrocarbons. Oxides of nitrogen emissions 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 to 22 percent for hydrocarbons and 20 to 33 percent for carbon monoxide. Oxides of nitrogen emissions are increased from 3 to 5 percent by this treatment.

- Maximum emissions reductions are achieved with the direct inspection and maintenance of the ignition and induction system components in addition to the idle parameters. The cost of this inspection is relatively high compared with the resulting emissions reductions, making this procedure less cost effective than the inspection and maintenance of idle parameters.

- State inspection lanes are almost always more cost effective than franchised garages.

- The most cost effective inspection frequency is once yearly.

- Nondispersive, infrared emission measurement instruments are preferred for state-lane emission inspections.

- Cost effectiveness considerations must include the effect of decreasing one emission species while increasing another. For example, a substantial decrease in carbon monoxide by leaning fuel-to-air ratio will result in a moderate increase in oxides of nitrogen.

- Air reactor and engine modification controlled vehicles responded similarly to the inspection/maintenance procedures evaluated.

2. SYSTEM DEFINITION AND ASSUMPTIONS

The general framework for the development of the system effectiveness model is discussed in this section. The model focuses upon those system elements which affect the ordinal ranking of alternate inspection/maintenance procedures when their economic effectiveness is compared. These elements are described in Figure 2-1 and are summarized below:

- Engineering design
- Economic factors
- Design constraints
- System effectiveness

The shaded areas indicated on the figure denote those variables which were not studied either because their impact on selection of procedures was considered minimal or due to lack of data.

2.1 ENGINEERING DESIGN

As shown in Figure 2-1, engineering design involves the definition of inspection/maintenance procedures and inspection facilities configurations. These will be discussed below.

2.1.1 Inspection/Maintenance Procedures

Optimum inspection procedures are to be defined based upon two approaches:

- Direct diagnosis of engine parameter maladjustment or malfunction using conventional or more sophisticated garage type equipment.
- Inferences of engine maladjustments or malfunctions from the measurement of exhaust emissions under various engine load conditions.

Two limited maintenance strategies--"predetermined" (specified) and "adaptive" were considered for use with these two inspection approaches. The inspection approaches and maintenance strategies will be discussed in further detail below.

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

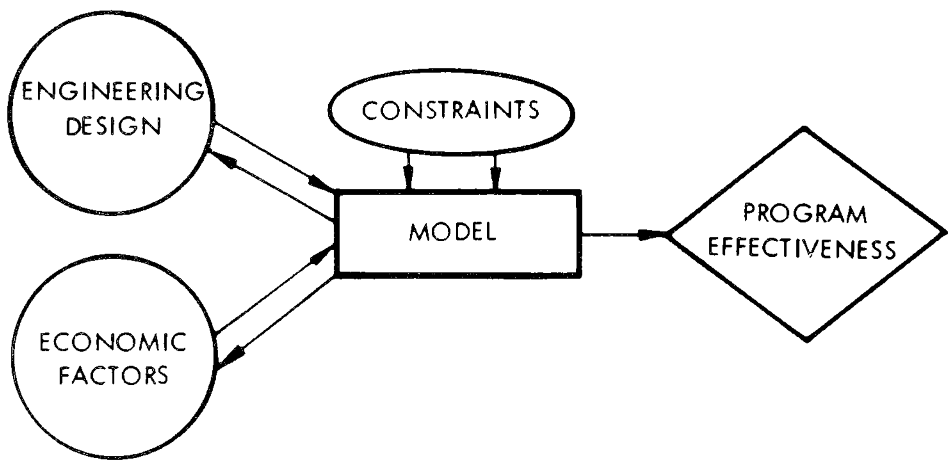


Figure 2-1. Basic System Framework

Inspection Procedures

The inspection procedures to be evaluated must satisfy the following criteria:

- Implementation must be cost effective
- Procedures must identify with high probability the malfunctions which affect vehicles emissions
- Economic impact on a single vehicle owner must be small.

The criteria imply that inspection must be used to limit the maintenance options open to the repairing agency. This will protect the vehicle owner by limiting maintenance to those repairs and adjustments shown to be cost effective. It is also essential that the engine parameters which are more costly to restore to specification are correctly diagnosed with a high degree of certainty. For example, idle maladjustments may be diagnosed with a lower level of reliability than, for example, the malfunctioning of the pump in an air injection system because the cost impact of an idle adjustment is significantly less than pump replacement.

Car owner cost and inconvenience must be minimized to encourage the cooperation of the motoring public. Only those malfunctions shown to occur in five percent or more of the vehicles in the field are addressed. Frequently the malfunctions which occur at lower frequencies do not contribute significantly to overall emissions and in some cases may be costly to diagnose and repair. For example, carburetor main and power metering circuit malfunctions are not evaluated since both a dynamometer and a carbon monoxide emission instrument are required at the repairing agency to effect a reliable diagnosis. Even with this equipment, a lengthy inspection is required to isolate a specific carburetor problem since the diagnosis may be confounded by plugged air cleaners, PCV systems or leaking exhaust valves.

In addition to cost, the vehicle owner can be significantly inconvenienced if his vehicle must be reinspected after mandatory maintenance has been performed. Rather than impose this requirement, it will be assumed that a vehicle emission surveillance program, such as described in Ref. 1, is concurrently being conducted. Vehicles would be randomly selected from the general population and inspected to monitor the emission and engine maintenance states resulting from an enforced inspection/maintenance program. This will provide data on the effectiveness and durability of the maintenance being performed.

Inspection procedures are to be developed for use in both franchised garages and state inspection lanes. With franchised garages, specified inspection procedures are applied prior to maintenance. Those vehicles which do not comply with quantitative specifications (i.e., fail a specified performance level) are then maintained, usually directly following the inspection process, by the same service organization. The advantages of this approach are:

- No large, new capital expenditures are required to initiate the inspection/maintenance program
- The vehicle owner is only inconvenienced once since inspection and maintenance are performed by the same organization.

Some control over the inspection/maintenance procedure is lost in this case because an unbiased inspection as might be performed by a state agency without profit motivation may not have been made.

A state-lane inspection provides the benefit of high vehicle throughput but at the expense of less comprehensive diagnosis. Labor costs associated with direct parameter inspection dominates inspection costs and therefore suggest automating the state lane inspection procedure as much as possible. The start-up and capital equipment costs of the state lane system therefore are high.

The following ground rules were established for selecting inspection procedures:

- Engine parameter inspection procedures of both short duration (approximately 3 minutes) and long duration (approximately 30 minutes) are to be defined.
- Engine emission signature inspections are to include both loaded (dynamometer) and unloaded (static) operating conditions.

Engine parameter inspection procedures to satisfy the short duration requirement will have to be highly automated and, therefore, are likely to be performed in a state-lane inspection system. It does not appear realistic to use currently available commercial equipment to perform three-minute engine parameter inspections because of the time required to attach instruments directly to the power train. However, direct engine parameter inspection within a state-lane system may be feasible if remote sensing equipment is hypothesized. A sensor which is inserted into the tail pipe and measures idle fuel-to-air ratio, idle rpm and misfire would appear to be technologically feasible and is evaluated for use in a state-lane inspection system. RPM, for example, might be sensed by accoustical pressure; idle fuel-to-air, by an emissions measurement; and misfire, by a radio frequency sensor.

Idle emission signature measurements are also evaluated as a means for performing a short duration inspection. Both timing and rpm maladjustments can be inferred from an idle HC emission measurement.

More complex engine parameter inspection procedures are required to diagnose electrical and induction (fuel-to-air related) subsystem malfunctions. A commercially available engine electronic analyzer is required to inspect the primary and secondary ignition subsystems. Simple tests which are available to diagnose some of the components affecting fuel-to-air ratio (i.e., PCV system, air cleaners, and air injection pumps) were evaluated in this study. No simple, reliable procedures are available for inspecting off-idle carburetor metering malfunctions and the cost of repairing these malfunctions is usually high. Therefore, these malfunctions are not considered in this study even though the engine parameter survey, Volume III, indicated that a moderate number of these malfunctions exist in the vehicle population.

An alternate inspection procedure using emissions measured at various engine loadings was also studied. Statistically designed experiments (see Volume III) showed that high HC emissions (greater than 350 ppm) under moderate engine loading are generally indicative of a misfiring cylinder(s) although several other malfunctions such as severely advanced timing, failed-air injection system and rich carburetor metering can sometimes confuse the diagnosis. High CO emissions under engine load are almost always indicative of a fuel-to-air mixture ratio anomaly. This condition may result from restricted flows in components such as PCV, air cleaner and air injection pump, or from excessively rich idle adjustments. Therefore, emission measurements can at best point only to groups of failures. For this study, failures and maladjustments have been grouped into three subsystems: ignition subsystem, induction subsystem and idle adjustments. Table 2-1 shows the emission signature most likely to yield a correct diagnosis of failures in each subsystem.

Maintenance Procedures

As a result of different inspection procedures, the maintenance state of the vehicle will be known with different levels of precision. Malfunctioned/maladjusted components are most precisely defined by the direct parameter inspection. Maintenance therefore can be limited to specific adjustments and repair. The emission signature inspection diagnosis only groups malfunctions or maladjustments and specific components within a suspected subsystem must be reinspected to determine the nature of the failure and the required maintenance. The former maintenance procedure has been defined as "predetermined" or "specified" and the latter as "adaptive." By adaptive, it is meant that maintenance action is only taken as a consequence of a reinspection at the component level to assess those subsystem components which are out of specification or failed. For example, high CO emission in a loaded mode may be the result of a component malfunction which can be either directly or indirectly diagnosed. If failed components are not found during reinspection the most probable explanation for the observed high CO emissions is a failure in the carburetor fuel metering circuits. Even though most garages cannot directly inspect for this malfunction because a chassis dynamometer is required, the carburetor may be repaired based on the fact that other malfunctions have not been found which would explain the high emissions level. Where the probability of correctly identifying a subsystem failure must be high due to high maintenance cost, the adaptive approach to maintenance has been selected. This approach is similar to the key mode inspection approach proposed by Cline in which "truth charts" are used to guide further inspection and maintenance (Reference 2). However, the extent of maintenance required in a mandatory inspection maintenance program will be limited on the basis of either cost or a low probability of correct diagnosis.

Table 2-1. Summary of Emission Mode Diagnostic Sensitivity to Parameter Malfunction or Maladjustment

Subsystem/Parameter	Emission Signature			
	Sensitive CO Mode	Confounding Parameter	Sensitive HC Mode	Confounding Parameter
Idle, Timing			I*	Advanced timing and misfire
Rpm			I*	Slow idle rpm and misfire
ICO (idle F/A)	I*	Induction related parameters; air reactor, PCV, air cleaner		
Ignition, Misfire			M,H	Failed vacuum advance
Vacuum Advance			M,H	
Induction, Air Cleaner	H*	Failed PCV, rich float	H	Misfire
PCV	M	Severely maladjusted ICO, rich float, air cleaner		
Leakage	M	(Severely maladjusted ICO, rich float, air cleaner)		
Float Level	M,H	All induction related parameters		
Air Reactor	I,M,H	All induction related parameters	I	Advanced timing, slow idle rpm

* Failed air reactor will also confound this diagnosis on vehicles so equipped.

I Idle.

M Moderate speed cruise load.

H Acceleration or high-speed cruise load.

Predetermined maintenance is best applied where there is a high probability of correctly identifying specific malfunctions/maladjustments from a subsystem inspection. The present study (see Volume III) has shown that idle maladjustments or malfunctions occur frequently and are inexpensive to repair even if the diagnosis is incorrect. However, an evaluation has been made of both adaptive and predetermined maintenance procedures in conjunction with an idle HC or CO emissions inspection and the adaptive maintenance procedure was found to be more cost effective.

2.1.2 Inspection/Maintenance Facilities

Design of a state-lane inspection system must include consideration of the following factors:

- Complexity of the inspection procedure
- Number of vehicles to be inspected and their density distribution
- Air quality criteria of the region
- The means used to enforce the program.

The complexity of the procedure affects the inspection time and the degree of required automation. In the case of a state-operated system, the degree of automation and, hence, the personnel requirements are quite significant to costs.

Inspection station sites should be located to minimize user inconvenience. An urbanized region, the Los Angeles Basin, was selected for this study, thus allowing the simplifying assumption in the model that state inspection sites are uniformly distributed. The number and configuration of inspection sites will be governed by the total number of vehicles to be inspected, the inspection time and the vehicle density. Using multiple inspection lanes rather than single lanes tends to reduce facility cost since land and automated equipment may be shared, but will increase travel time for the vehicle owner since the sites will be more disperse. The greater the vehicle density the more cost effective it is to use multiple inspection lanes because inspection sites will of necessity be near to each other and travel time will be a less significant economic factor than the reduced cost of the facilities.

Demographic and inspection station data assumed for the Los Angeles Basin are:

- Controlled vehicle population - 4 million
- Urban area - 1250 square miles
- State-lane positions - 15
- Average speed to and from inspection station - 22 mph.

A franchised garage system is less flexible with regard to locating inspection sites than is the state-lane system, however, the direct capital costs are minimal. In this study, it is assumed that additional costs required to modify our upgrade franchised garage facilities for the purposes of this program will be reflected as an adjusted overhead on direct labor costs rather than as a direct capital expenditure.

For the state-operated system, some of the more significant inspection station configuration variables such as the number of inspection lanes per site were optimized during the study. For the franchised garage system, the number and distribution of facilities was taken as a known input to the study.

The ranking of inspection/maintenance procedures by cost effectiveness is not anticipated to be sensitive to regional demographic data but is likely to be sensitive to the weighing factors applied to the individual emission reductions in the system figure of merit. These weighing factors can be selected to reflect either national or regional air quality criteria.

The administration of the program requires three functional activities:

- Inspection scheduling
- Failure reporting
- Data recording and storage.

The functional flow of these activities is shown in Figure 2-2 and is described below. The data acquisition system requires a two-part, prepunched card identifying the vehicle, its owner and the month in which the vehicle is to be inspected. This card normally would be part of the vehicle registration package. The owner presents the card at a state-lane station where

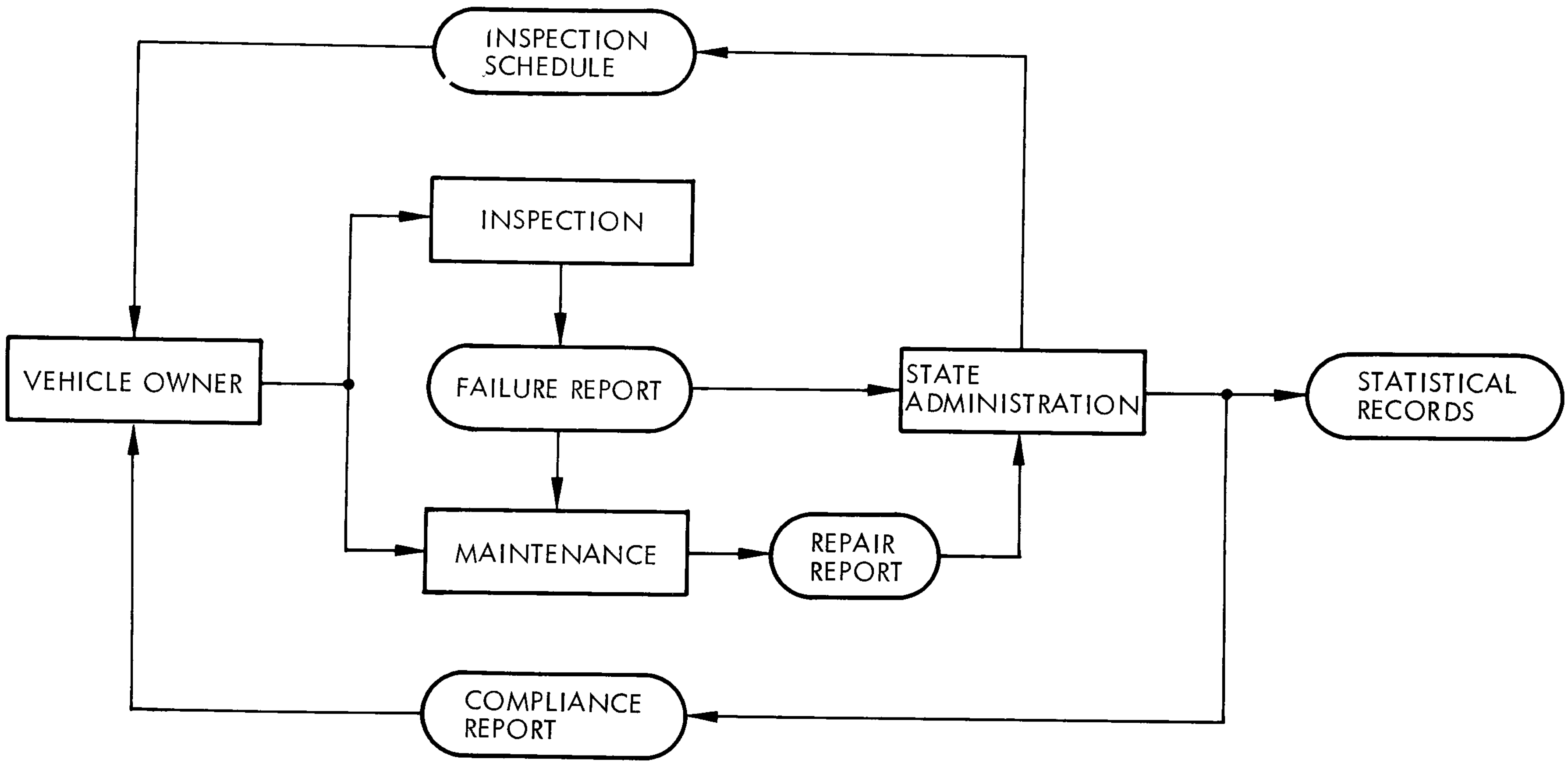


Figure 2-2. Enforced Maintenance Program Administration

the information officer inserts it into a key punch. This officer also operates a display console which verifies the data acquisition procedure. Concurrently, an aide inserts the sensing probe in the exhaust pipe. Due to variations in tail pipe locations and size, this task probably cannot be readily automated.

The analog output signal from the instrument which senses either emissions or acoustic pressure is converted to digital output, and the results are punched on the card. The punched card is verified against the display console and one copy of the card is returned to the owner. For those vehicles rejected, a failure report is provided which lists the engine parameters to be diagnosed and/or maintained. The prescribed maintenance is performed and verified by a franchised garage on the owner's hard copy, which is returned to the enforcement agency.

Both the failure and compliance reports are filed within a storage and retrieval system. Periodic comparisons are made to determine if enforcement action is required.

2.2 ECONOMIC FACTORS

The benefits in reduced emissions obtained from an inspection/maintenance (I/M) program must be compared with its cost to determine the program's overall economic effectiveness. The relevant costs here are the explicit and implicit costs to implement the program. Explicit costs include expenditures to construct facilities and to perform inspection/maintenance operations. Implicit costs are less tangible and generally are not expressed in monetary units. They include, for example, the time the vehicle owner spends in inspection and maintenance related activities. Station location and configuration design were determined by considering both types of costs. Only explicit costs are included in the costs quoted for the different inspection/maintenance programs.

Other benefits that may be important include the influence of mandatory engine maintenance on vehicle safety, operating economy and major engine repair. The cost impact of these benefits were not evaluated because data are not available which relate these effects to the maintenance actions required by the objective of this study (i.e., type and extent of maintenance). One further simplifying assumption is that the cost of providing training for both the inspection and maintenance activities will not be included. Both of the above simplifications are not anticipated to impact significantly the ordinal ranking of the cost effectiveness of inspection/maintenance procedures because the resulting costs are nearly constant for the system and relatively insensitive to specific procedures.

Capital costs to be considered are those for equipment, land and facilities. Operating costs include utilities, labor, materials, spares, fringe benefits and general administration. In addition, the implicit costs associated with user inconvenience will be considered.

2.3 CONSTRAINTS

Constraints were placed on system design by the contract work statement. The emission inspection procedure is to be designed to obtain diagnostic information rather than to yield emissions measurements which correlate well with the Federal emission test procedure. Equally important is that procedures are to be developed to reduce HC and CO emissions. That is, only those maintenance procedures and policies which primarily influence HC and CO emissions will be selected for evaluation. This is because only HC and CO emissions were considered when the emissions control equipment was developed for the 1966-1970 vehicles studied. The effect of selected procedures on NO emissions were to be estimated after the fact. Additional constraints relate to the social impact of an enforced inspection program. A primary criterion for system design is to impose no extraordinary burden on any one vehicle owner.

2.4 PROGRAM EFFECTIVENESS

Measures of system performance include the actual emission decrements effected, the user time lost in traveling to and from the station and waiting for the inspection and maintenance to be accomplished as well as the effectiveness of the inspection (probability of correct diagnosis).

These measures of inspection/maintenance system performance were either used to evaluate emissions abatement performance or to establish systems cost A figure of merit then was formulated from these elements and was optimized by selecting values for the system design variables.

3. INSPECTION/MAINTENANCE SYSTEM MODEL DEVELOPMENT

The purpose of this section is to describe the development of mathematical models with which to evaluate the effectiveness of mandatory inspection/maintenance procedures. Specifically, the following major models are described:

- Inspection and maintenance procedure effectiveness and maintenance deterioration
- Operating procedures and their impact on direct labor and user-inconvenience times
- Labor and user-inconvenience operating costs; and equipment, buildings and land to capital costs
- Measures of program effectiveness including total costs, resultant emission reductions and an overall system figure of merit.

These models were developed through the data acquisition and synthesis phases described below.

3.1 SYSTEMS DATA ACQUISITION

Data required for the development of inspection/maintenance models and for defining system constants were derived from the following sources:

- Historical data from outside sources
- Contract-developed data.

The available data bank is summarized in Table 3-1 and consists of data from the Environmental Protection Agency surveillance programs, California Air Resources Board (CARB) surveillance programs, American Automobile Association (AAA) two-year fleet test, Scott Research Laboratories (SRL) New Jersey cycle development data and the TRW-developed data from the parameter survey and statistical experiments described in Volume III. A large portion of these data was analyzed statistically to develop inspection/maintenance models (see Table 3-1). 1966 and 1967 vehicles with both engine modification and air reactor exhaust emission control systems were evaluated. Primary attention was focused on data sets containing both control types.

Table 3-1. Summary of TRW Data Related to Study Program

APPLICABLE TRW DATA BANK	Vehicle Acquisition		Development Goal		Degree of Maintenance, %		Sample Characteristics		Modeling Application		APPLICABLE REFERENCE
	Captive	Random	Cycle	Parameter	Idle Adjust.	Gen. Tune-up*	Size	Model Year	Type	Models Developed	
EPA (HEW) Surveillance	Rental		ACID* Clay-ton		20		500	68-69	Effectiveness of Idle adjustments & Emission Signature	No	Ref. 10
California ARB		Private	Surveil-lance				1000*	66-69	Deterioration	Yes	Ref. 11
GM Idle		Private		Idle ad-justment	100		228	66-68	Effectiveness of idle adjustments & Emission signature	Yes	Ref. 5
AAA Fleet	Company Fleet			Manufact-urers tune up effect-iveness	100	100	100	66-67	Deterioration, Effectiveness of General Tuneup	Yes	Ref. 7
EPA (HEW) Certification	Industry					100	150	68-69		No	--
Clayton ** Diagnostic			Key Mode	Selected Malfunctions					Emission signa-tures	No	--
SRL-New Jersey		Private	Quick			25	200		Effectiveness, Diagnostics	No	--
TRW-CRC-APRAC CAPE-13	Private		33 Emis sion modes	11 typical failures	100	100	22	66-70	Emission response to failures, main-tenance effective-ness	Yes	Volume III
TRW-CRC APRAC Cape-13		Private		Parameter frequency & distributions	0	0	226	66-69	Frequency and ex-tent of malfunction	Yes	Volume III

* General tuneup includes both ignition and carburetor repair and adjustment as required to restore engine to manufacturer's specifications.

**Clayton's analysis of HEW surveillance data also available.

In addition, cost data for capital equipment were obtained from emission measurement system component manufacturers, labor and materials costs from Chilton's Manual (Reference 3) and land and facility costs from a previous TRW report on safety compliance (Reference 4). The development of models from these data sets is discussed in the following subsections.

3.2 INSPECTION AND MAINTENANCE MODELS

Inspection and maintenance models to be developed are of three types:

- Models relating emissions reductions to maintenance treatments
- Models relating vehicle population attributes, such as extent of engine parameter maladjustment, frequency of malfunction, and emission signatures to the diagnostic (inspection) procedures
- Rates of deterioration of engine subsystems and their effect on emissions.

3.2.1 Emission/Maintenance Model

The emission/maintenance model predicts the change in composite emissions which occur when a specified engine parameter is returned to its nominal or manufacturer's recommended state. This model is schematically shown in Figure 3-1 and mathematically in Equation (3.1) below.

$$\Delta e_j = \sum_{i-1}^{n} \int_{c.p.}^{3\sigma} P(P_i) \frac{\partial e_j}{\partial P_i} dP_i \qquad (3.1)$$

where:

c.p. = policy statement rejection criterion (cut-point)

$P(P_i)$ = probability of finding a parameter at $P_i + dP_i$ with a specified inspection procedure (from engine parameter survey Section 2.0, Volume III)

$\frac{\partial e_j}{\partial P_i}$ = response coefficient defining the change in "j" emission per change in parameter "i" (from orthogonal experiments, Section 3.0, Volume III).

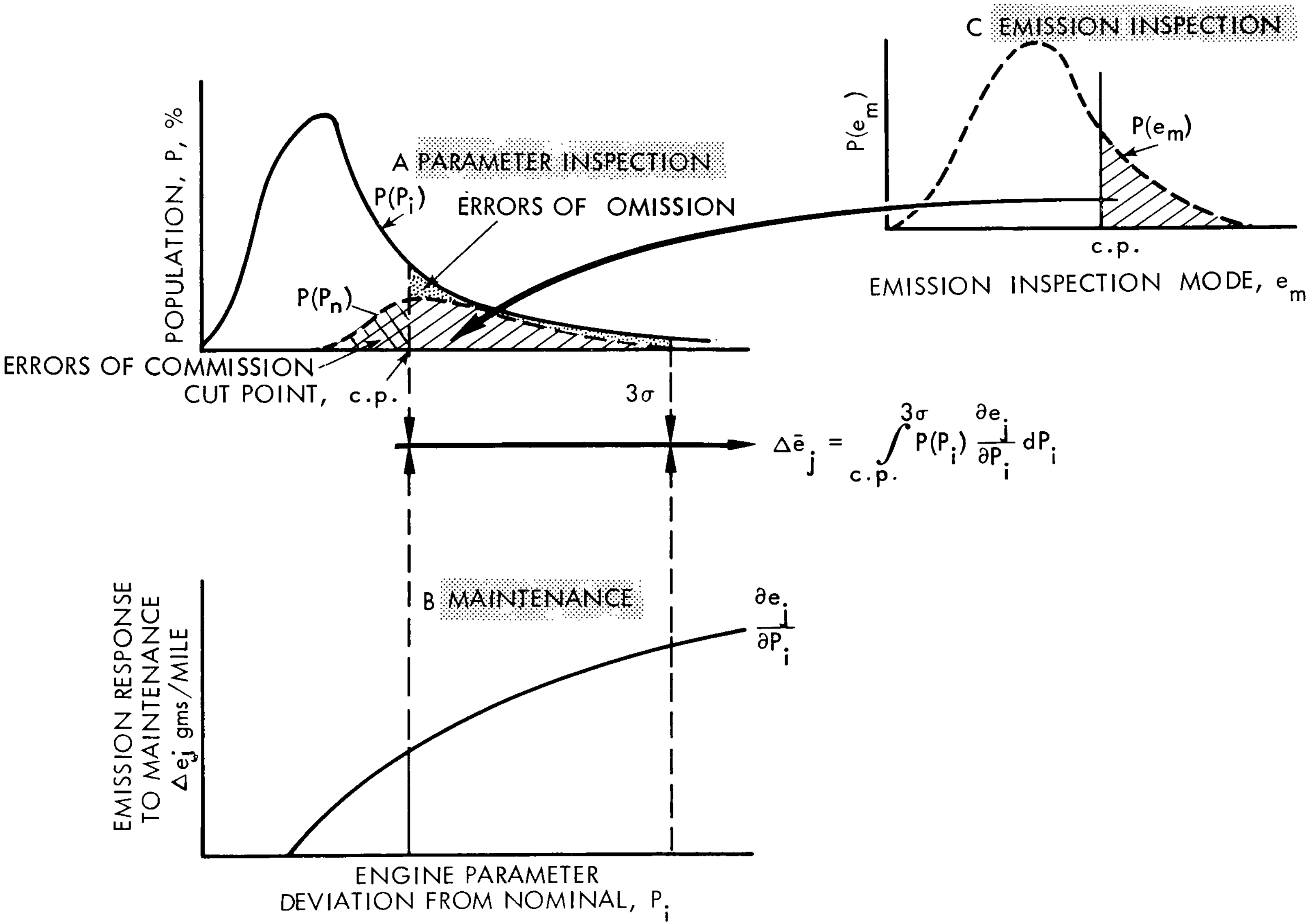


Figure 3-1. Relationship Between Inspection and Maintenance Models

Inspection procedures involve the quantitative measurement of either engine and control device adjustments or exhaust emissions. The vehicle is rejected or accepted based upon whether the adjustments or emissions fall outside specified bounds. Inspection of engine and control device adjustments involves the steps shown in Figure 3-1 (steps A and B). The distribution function for the deviations of engine parameters P_i from manufacturers specifications expected in a general population is shown at A. An inspection rejection level or cut point for the parameter P_i is also indicated. Those vehicles in which the maladjustment of parameter P_i exceeds the cut point level would be rejected to maintenance. The effect of adjusting parameter P_i to specification upon exhaust emissions is shown in B. Attributes of the population rejected in A are combined with the emission influence coefficient of B to predict the emission reduction achieved by this inspection/maintenance process.

Evaluating the effectiveness of inspection based upon measuring exhaust emission involves a further step shown in Figure 3-1C. The distribution of emission levels measured using diagnostic modes or cycles for a population of cars in shown. Again those vehicles with exhaust emissions above the cut point level would be rejected to maintenance. The distribution of maladjustments of parameter P_i for this rejected population is shown in A. Similar distribution curves would result for other parameters which have a significant impact on emissions. Again the effect of the inspection/maintenance process upon emissions is obtained using the new distribution shown in A with the influence coefficient of B.

An objective of the study will be to determine the placement of inspection cut points which optimizes the cost-effectiveness of the process. The upper limit used in the integration to determine emission reductions is the 3σ value of the parameter. This accounts for the 99.9 percent of the population and probably is a reasonable limit for failures or malfunctions in operable vehicles.

Distribution functions of the type just described have been developed from sample vehicle populations which reflect in-use, exhaust emission controlled vehicles. Some typical distributions are shown in Figure 3-2. Data from the Parameter Survey (see Volume III) and the General Motors Idle Adjustment Program (Reference 5) were used.

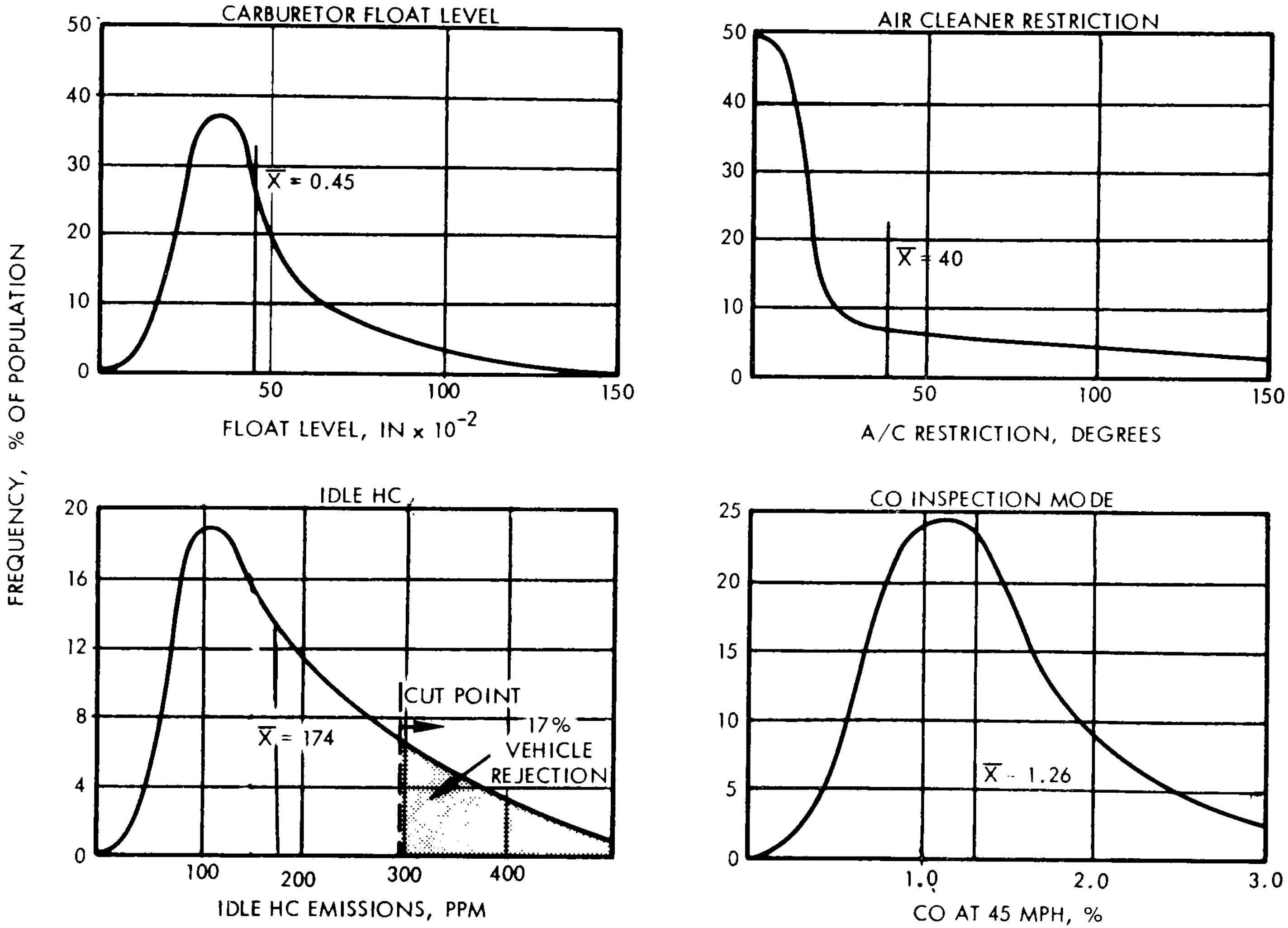


Figure 3-2. Typical Distributions of Emissions-Related Vehicle Attributes

3.2.2 Emission Inspection Model

Figure 3-1C illustrates the distribution of specific mode or cycle exhaust emissions for a population of vehicles. The vehicle fraction rejected by the inspection will usually contain multiple parameter malfunctions:

$$P(e_m)_{c.p.} = f\left[P(P_i, P_2 \ldots P_n)\right]_{c.p.} \qquad (3.2)$$

where:

$P(e_m)_{c.p.}$ = vehicles with emissions $>e_m$ rejected by cut point, c.p.

$P(P_n)$ = set of parameters within $P(e_m)$ to be maintained

The cutpoint on the distribution represents the levels of emission at which vehicles will be rejected. The distribution of the set of parameters to be maintained, $P(P_n)$, for the emission inspection rejected population is shown schematically in the dashed curve on Figure 3-1A. Some of the vehicles which were rejected by the emission inspection procedure are in the distribution which falls to the left of the optimum parameter cutpoint signifying that repair of these vehicles will not be cost-effective. These errors are termed "commission" errors. The region outside of the parameter distribution $P(P_n)$ but within $P(P_i)$ to the right of the cutpoint represent those vehicles which have been permitted to pass the emission inspection but have excessive parameter deviations from nominal. These errors are called "omission" errors.

The implication here is that an emission inspection does not uniquely identify individual maladjustments but points to failures within families of related engine parameters. These families may be classified as a subsystem. This is consistent with the fact that the diagnostic modes were shown to point to more than one out-of-specification parameter in the statistically designed experiments (see Volume III). The development of the relationship between emission inspection signatures and the subsystem maladjustments diagnosed is presented below. Carbon monoxide emission data were obtained from the TRW parking lot survey and hydrocarbon emission from the General Motors data. These data were used to develop the relationships expressed by Equation (3.2).

Idle Adjustments

GM data were used to develop a functional relationship of the type shown in Equation 3.2 for the idle adjustments. The procedure used was as follows:

- The idle adjustment deviations from manufacturer's specification were developed from the as-received and as-adjusted data.
- Inspection emission mode(s) cut points were systematically selected and the rejected vehicles were sorted from the population.
- Statistical attributes of the idle parameters (mean, standard deviation and failed fraction) were developed for the rejected fractions.

The effects of applying idle mode CO and HC emission cut points are shown respectively in Figures 3-3 and 3-4. They identify the mean deviations in the rejected population of idle fuel-to-air ratio measured as idle CO, timing and idle rpm. For example, applying a cut point of 4% in an idle CO emission inspection (Figure 3-3) rejects vehicles with an average idle CO deviation from the specification of about 4.2%. Similarly, an idle HC cut point of 350 ppm (Figure 3-4) is required to reject vehicles with approximately the same average deviation of idle CO adjustment, but this procedure rejects only 55% as many vehicles as would have been rejected at the ICO cut point. An idle HC emission measurement however is more effective than the idle CO in diagnosing rpm and timing deviations. Average deviations are 0.9 degree and 12 rpm greater by using an idle HC rather than an idle CO emission cut point. For engine modification vehicles, there is a sharp break in mean value of the idle adjustment parameters at about 300 ppm where further increases in cut point do not significantly influence those values.

Since a 300 ppm idle HC cut point appeared optimum, a dual idle emission inspection was evaluated using this value and a range of idle CO cut points as shown in Figure 3-5. The effect of a dual mode inspection is to reject more vehicles at lower mean values of the parameters than idle CO or HC emission inspections taken singularly at identical cut points. The vehicle rejected fraction for dual emission inspections is not the sum of the rejections calculated from the individual emission inspections since a

GM DATA
ENGINE MODIFICATIONS

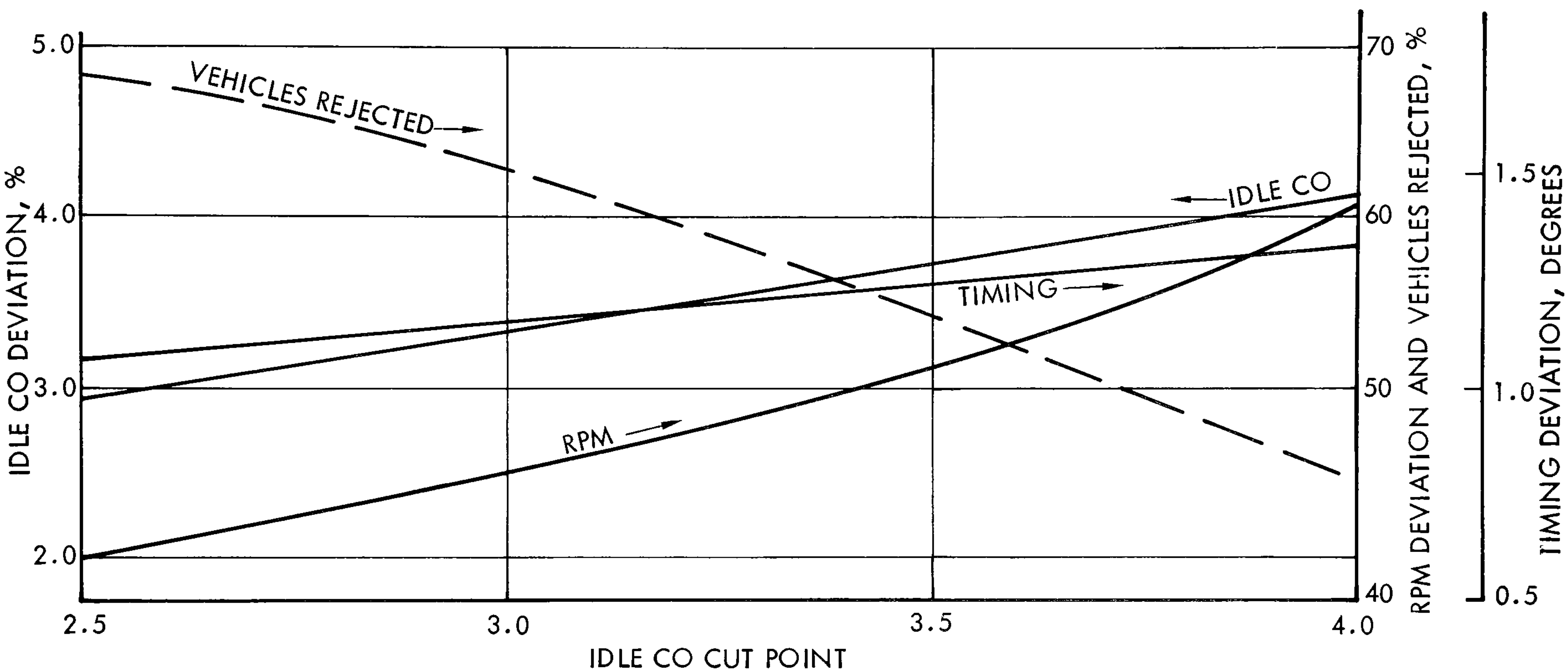


Figure 3-3. Idle Parameter Sensitivity to Idle CO Inspection Criteria

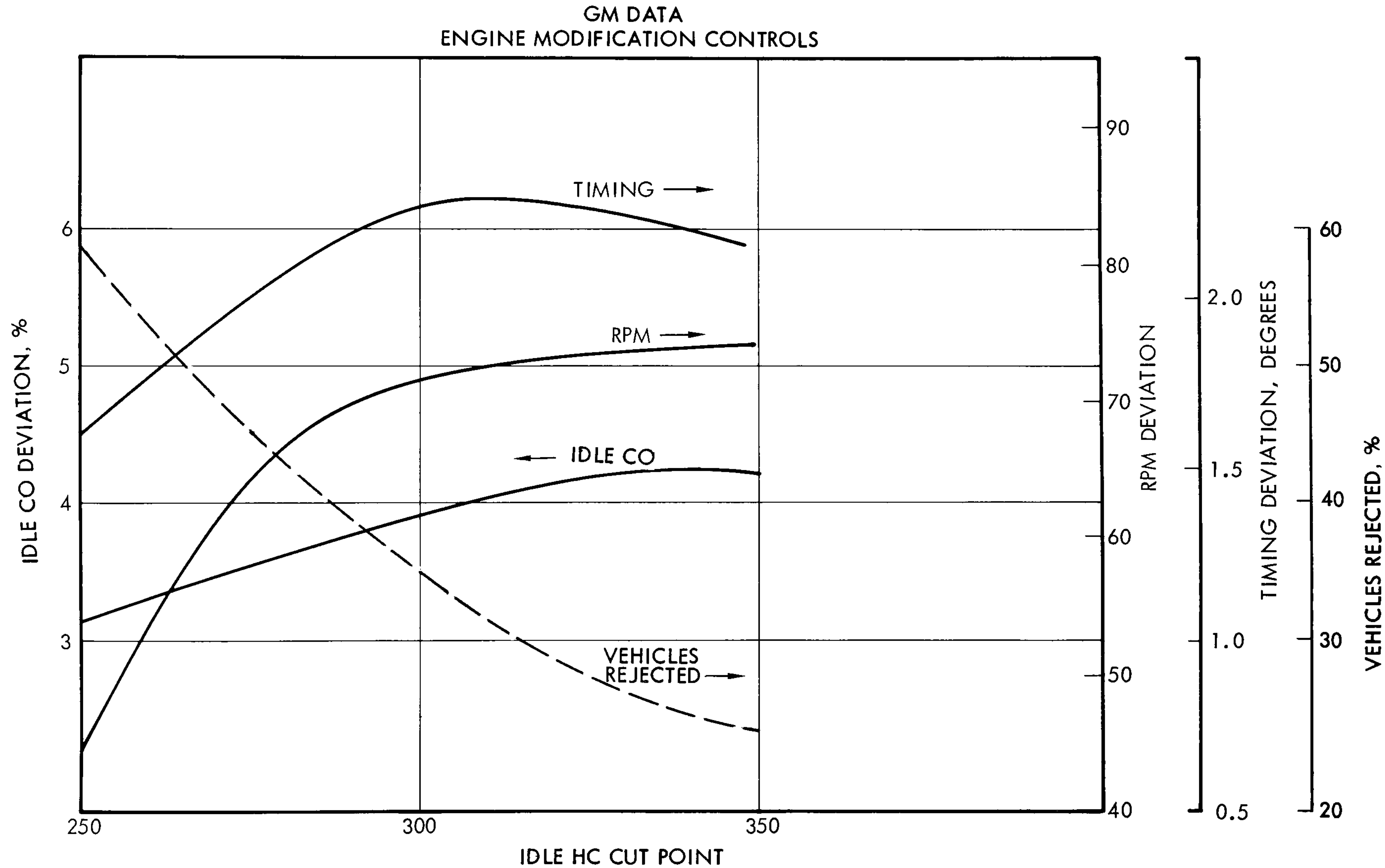


Figure 3-4. Idle Parameter Sensitivity to Idle HC Inspection Criteria

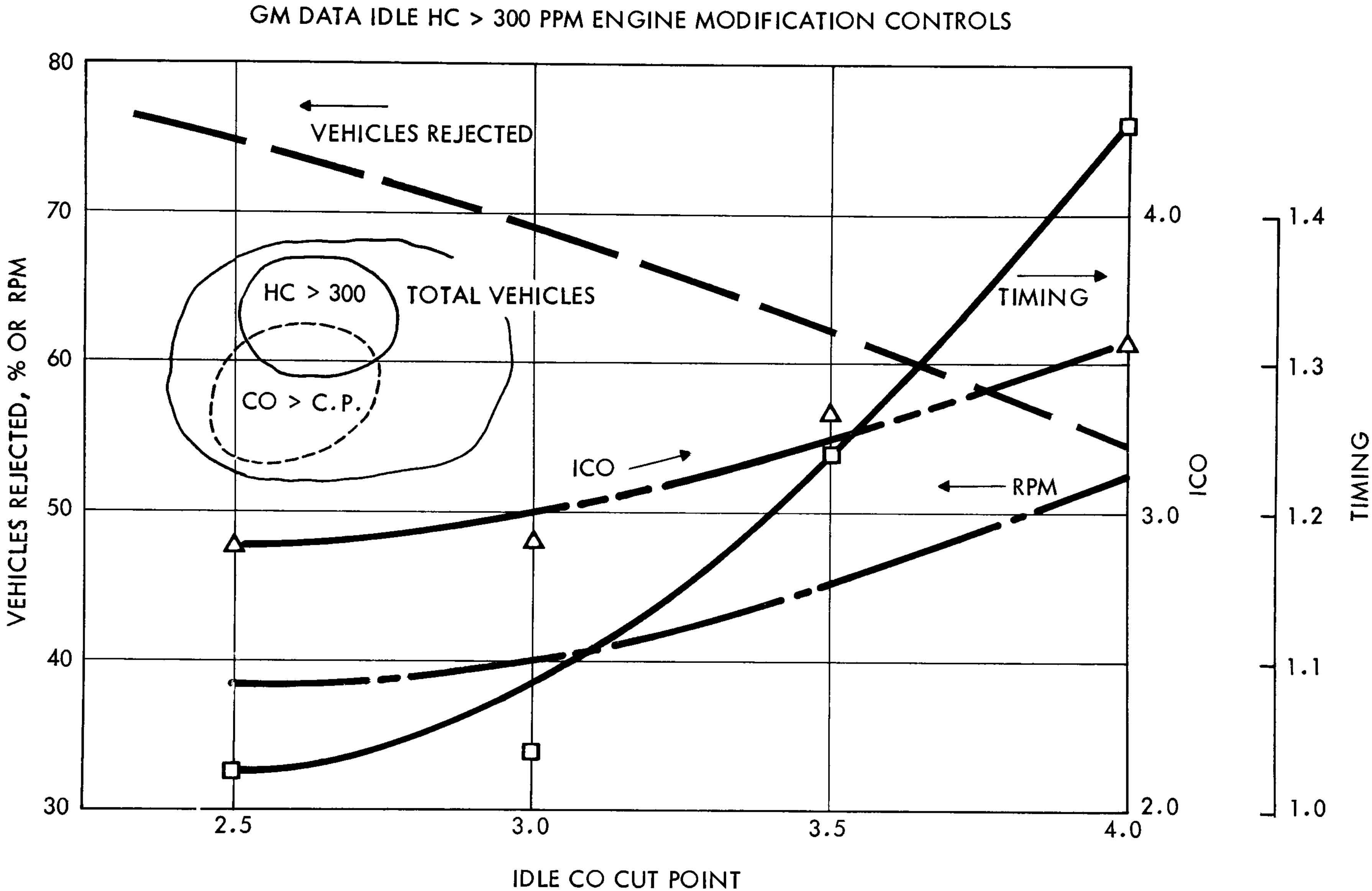


Figure 3-5. Idle Parameter Sensitivity to Multiple Inspection Criteria

number of vehicles will fail both tests. The total of the vehicles rejected is the sum of vehicles failing each inspection less the fraction which have failed both criteria as shown schematically in Figure 3-5.

Air Injection System

Diagnostic modes sensitive to malfunctions of the air reactor emission control system are the closed throttle HC and CO modes and loaded CO modes (see Volume III, Section 4). Of the closed throttle modes, the HC emissions during deceleration should be most selective of air reactor failures as indicated by its response relative to the other parameters evaluated. Alternatively, Cline (Reference 6) has suggested that the dilution factor has strong diagnostic content since this parameter reflects excess air added to the exhaust. A dilution factor near unity as opposed to a typical value of 1.3 would indicate a malfunctioning or failed system. There were seven (6%) indicated cases of substantial air reactor system malfunction within the GM data set, a cut point of 1500 ppm on the 50-20 deceleration mode would have found only 4%. The most effective emission signature is an idle mode inspection for dilution correction factor which rejects vehicles at values less than or equal to 1.0 (Figure 3-6).

Because severe idle maladjustments can reduce dilution factors to near unity on otherwise nominally performing systems, a mode substantially out of the idle carburetor circuit might offer some improvement. The 30 mph dilution factor mode was found to make no errors of commission using a cut point of 1.2, although two vehicles with poor idle performance were omitted (Figure 3-6). For the economic-effectiveness study, an idle diagnosis for air reactor malfunction using a dilution correction factor cutpoint of 1.0 will be used for the emission inspection since it is shown to yield the highest probability of a correct diagnosis.

Air Cleaner, PCV and Air Pump

The emission signature response coefficients (Vol. III) showed that the more highly loaded CO modes are most sensitive to PCV and air cleaner restrictions. An analysis of the parameter survey data in Table 3-2 indicated that 18% of the 136 vehicles were rejected with a cut point criteria of 2.5% using the 30 mph CO mode. This mode appears to have fair diagnostic sensitivity to PCV and air pump, identifying 39% and 60%, respectively, of those

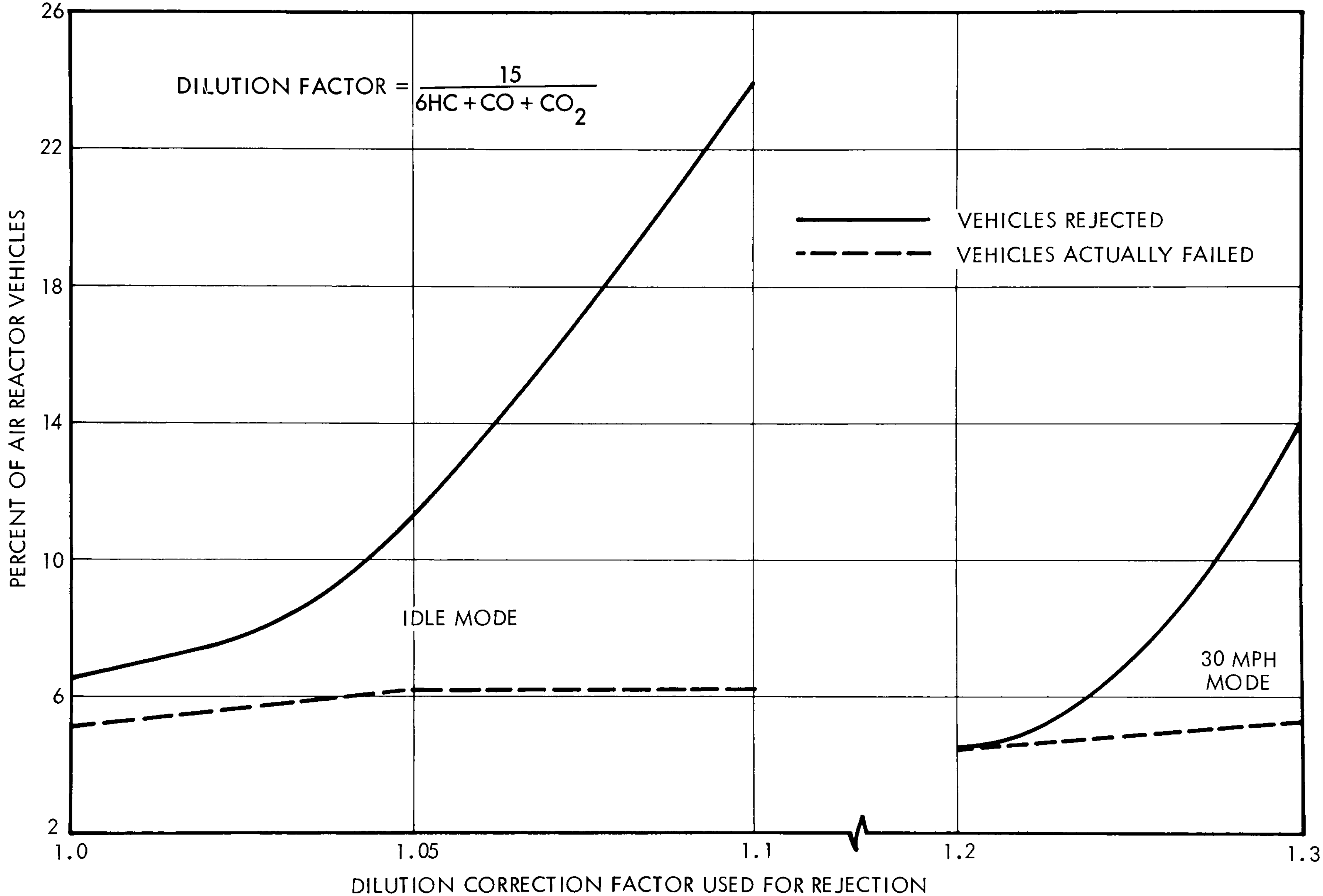


Figure 3-6. Air Reactor Malfunction Sensitivity to Dilution Correction Factor Inspection Criteria

Table 3-2. Summary of Parameter Survey Vehicles with CO at 30 mph ≥ 2.5 Percent (Vehicle Data Set = 136)

Vehicle Number	CO at 30 mph (%)	Air Cleaner (% Blockage)	PCV (In. H_2O)	Float Deviation* (in.)	Air Pump**
107	5.0	13	-0.2	0	
110	5.0	0	(0.1)	NR†	
124	3.2	↓	-0.2	0.03	
133	5.0	↓	(0.2)	NR	
134	↓	↓	-0.5	NR	
136	↓	↓	-0.2	0	
140	3.0	↓	-0.4	NR	
146	5.0	↓	-0.2	(0.06)	
147	3.0	3	-0.1	(0.06)	
151	2.5	0	(0)	0.03	(FAILED)
187	4.5	↓	-0.2	-0.1	
192	5.0	↓	(0)	(0.07)	
197	5.0	75	-0.2	0	
202	3.9	0	-0.1	0	
206	2.5	0	-0.2	0	
208	2.8	17	-0.8	0	
210	3.0	0	-0.3	(-0.13)	
212	3.0	10	-0.1	NR	(FAILED)
215	3.5	90	-0.1	0.03	(FAILED)
223	3.1	55	(0)	0	
238	5.0	50	-0.2	0	
241	3.1	40	(0)	(0.07)	
248	2.9	45	-0.1	0.03	
501	3.7	0	(0.1)	0	
505	4.2	0	NR		
Failure Criteria	≥ 2.5	--	≥ 0	≥ 0.06	≤ 0.2%

* Positive values indicate rich float setting

**Change in CO in going from the disconnected to connected state

† NR, not recorded.

Note: Circled figures show items which failed cut point criteria.

vehicles with failures. For example, a total of 18 PCV failures were found of which seven were identified by the CO emission inspection (about 39%). Increasing the cut point to 3.0% decreased the number of PCV and air pump failures identified by one unit each with only a 3.5% reduction in total rejected vehicles. It would, therefore, appear that a cut point of 2.5% is near optimum and it is the one evaluated within the economic-effectiveness study.

Misfire

It is assumed that significant levels of misfire (i.e., greater than 2.5%) will be diagnosed with either an idle or highly loaded mode HC emission measurement. A 2.5% misfire rate will result in a 250 ppm increase in an otherwise nominal HC emission signature. Assuming the malfunction is randomly distributed throughout the vehicle population, this increase in HC emission would result in identifying at least 50% of the vehicles which misfire at idle using an idle HC cut point of 400 ppm.

A more sophisticated inspection would involve an HC emission inspection at load where incipient misfire at idle is exposed. Approximately twice as many vehicle misfires would be diagnosed with this procedure. A loaded mode HC cut point of 300 ppm would be expected to identify approximately 50% of those vehicles which would misfire at idle. The GM data indicate that all misfire malfunctions may be identified with cut points as high as 400 ppm. Therefore, both values will be investigated in the economic-effectiveness study.

3.2.3 Deterioration Model

In an attempt to obtain deterioration of maintenance data, several data sources were evaluated:

- The AAA fleet program conducted on 1966 air injection and 1967 engine modification vehicles (Reference 7)
- The CARB vehicle emissions surveillance data for model years 1966-69 (Reference 11).

In the former program, two fleets of company vehicles underwent manufacturers' recommended maintenance every 12,000 miles or when the driver complained. Approximately fifty vehicles were tested in each model year every 4000 miles. The AAA allowed TRW direct access to its basic data in order to obtain mode emissions and idle parameter adjustments to supplement the reported data of Reference 7.

The CARB surveillance data by model year were also utilized to develop deterioration models. This program is used by California to determine vehicle compliance with emission standards over the first 50,000 miles of the vehicle's life. Over 1000 randomly acquired vehicles have been tested for hot cycle emissions in this program. However, statistical data are not available on the vehicles' general engine maintenance states.

Subsystem deterioration models were developed from the AAA data set through statistical analyses. The sum of the effects of subsystem deterioration rates was then constrained to fit the ARB surveillance data.

<u>AAA Fleet Data Evaluation</u>

To assess the stability and effect of idle adjustments on emission levels, the AAA data were plotted against cumulative mileage for a random selection of vehicles (make/model/years). Figures 3-7 and 3-8 depict these results. Exhaust emissions as determined using the full Federal procedure (post-tune emissions measurements were made in the hot state). Idle rpm, A/F and timing are shown plotted against cumulated mileage. Ordinates have been selected for the idle parameters such that their slopes are inversely related to emission level. To aid interpretation, the idle adjustments are coded to the emission they most significantly effect (i.e., in the figures both timing and HC are solid lines). In a large number of instances (approximately 60%) both the trends and variations in the emission profiles are explained in part by the idle adjustments. It is also of interest to note that typically both HC and CO follow similar trends. This is based on observation of the total data set, not only Figures 3-7 and 3-8. In a few instances, unexpected emission changes occurred which opposed the trend of the idle adjustments and which were not corrected by maintenance (see the post-tune HC in Figure 3-8).

The following conclusions are indicated:

- Idle rpm trends to be relatively unstable while timing appears to be relatively stable.
- Each parameter tends to degrade with a characteristic slope over long periods of time (8000-12,000 miles) after an adjustment.

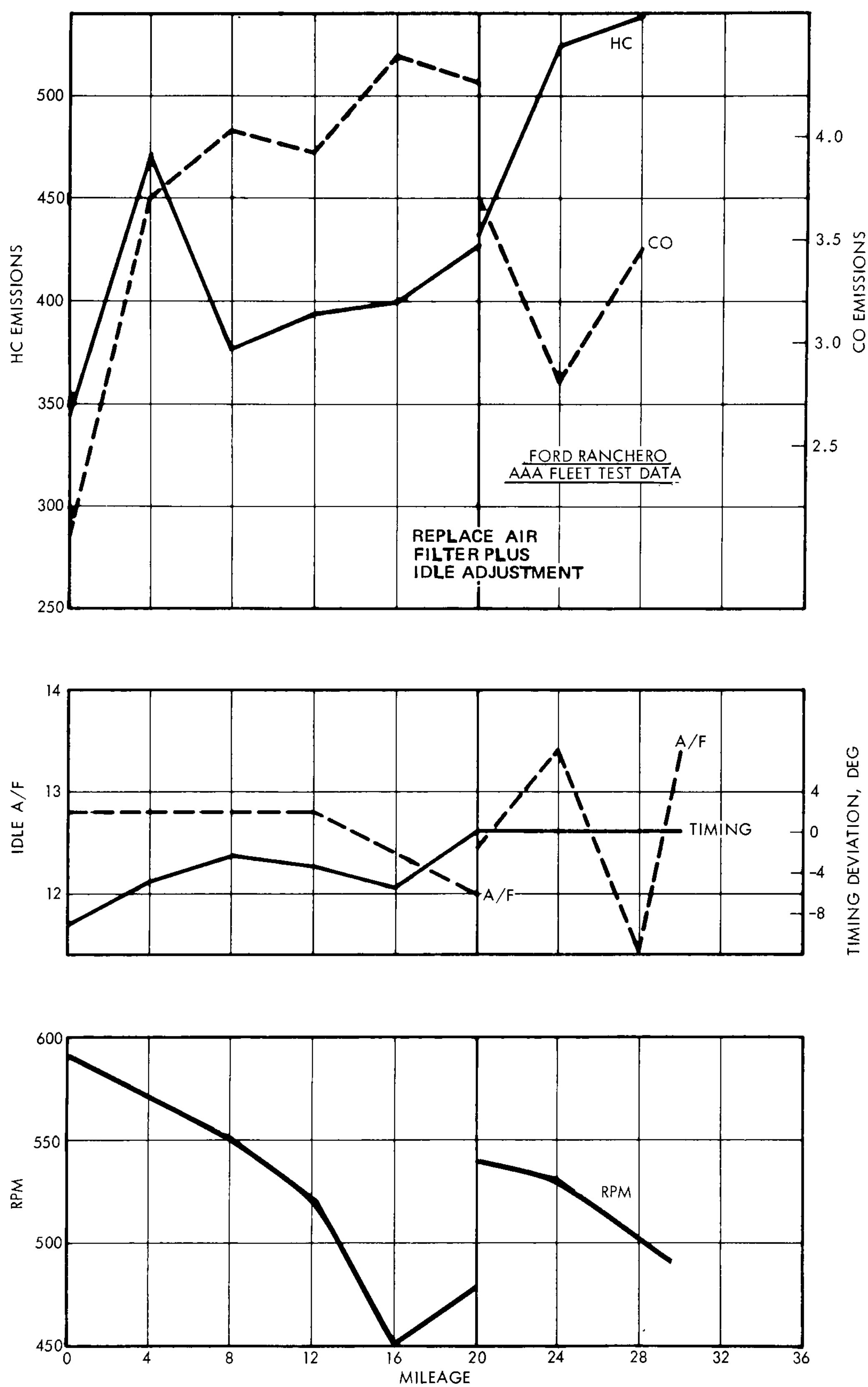


Figure 3-7. Emission and Idle Engine Parameter Deterioration Histories

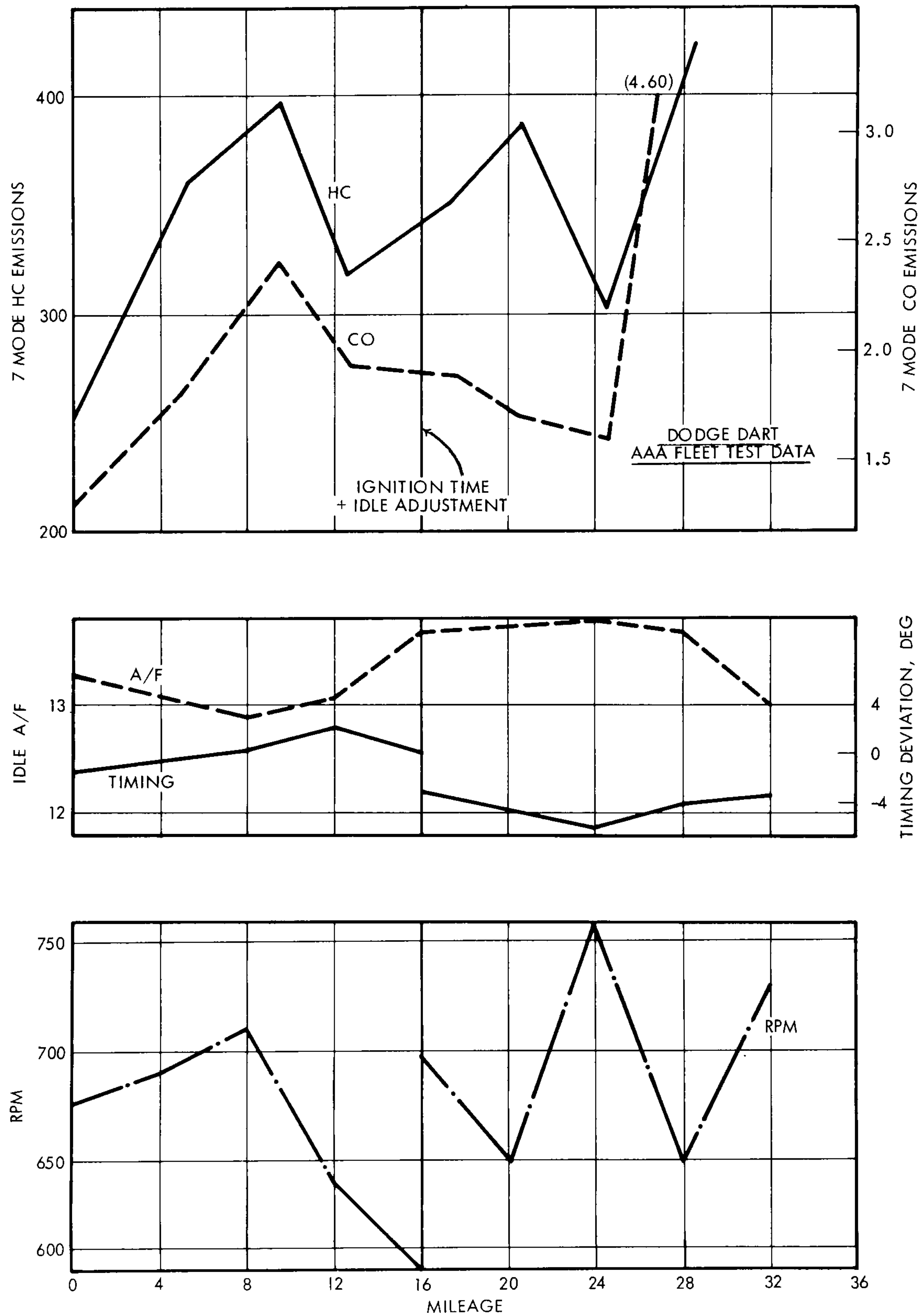


Figure 3-8. Emission and Idle Engine Parameter Deterioration Histories

The AAA fleet data were then placed on punched cards and the data were segregated by the subsystem maintained (i.e., idle and idle plus ignition). The following analyses were performed to characterize the statistical properties of both emissions and engine parameters:

- All vehicles undergoing periodic idle adjustment plus ignition system maintenance were pooled and classified by mileage range. Statistics on mean engine parameter premaintenance values were developed.

- The premaintenance emissions (HC and CO) for idle plus ignition maintenance were regressed against mileage and the idle parameters.

Engine Parameter Stability

Two statistical characteristics which are of interest in characterizing idle adjustment deterioration are the changes in mean values and distribution (variance) as a function of accumulated mileage over a maintenance interval. These results (Table 3-3) suggest fairly rapid trends in the deterioration of the idle adjustments from specified manufacturers' settings. The data sets are admittedly small but they substantiate the trends previously indicated in the parameter survey (Volume III). These trends are:

- Mean timing tends to become more advanced with mileage, increasing between 0.6 to 1.4 degrees in 12,000 miles.

- Idle rpm is very unstable as indicated by its large standard deviation (±100 rpm).

- Idle CO increases with mileage, mean increases of 0.6 to 0.7% being typical in 12,000 miles.

These observations are consistent with the trend of the parameter survey data and the estimated frequency of voluntary maintenance (12,000 to 14,000 miles). The largest descrepancy is for the idle CO settings where mean values for this parameter in the survey were found to be larger by some 200%. This suggests that of all of the field adjustments, idle F/A is the least accurately set. Since most garages are not equipped nor motivated to accurately set idle F/A, this result is not surprising.

AAA data suggests that to a first approximation emission degradation models can be approximated by a long-term, moderately shallow trend line component due to deterioration and deposit build-up and an unstable trend line component due to the less stable idle adjustments.

Table 3-3. Idle Adjustment Deterioration Rates

AAA Fleet Test

Parameter	Mean Value and Distribution	
	0-3000 miles	9000-16500 miles
Idle, CO, $\overline{P}$	0	0.61%
σ_P	0.94	2.04%
Timing, $\overline{\Delta P}$	0	1.45 deg
$\sigma_{\Delta P}$	0	3.51 deg
Idle rpm, $\overline{\Delta P}$	0	-1 rpm
$\sigma_{\Delta P}$	0	97 rpm

$\overline{P}$ = mean level of idle parameter or its deviation from specification

σ = estimate of the standard error of P or ΔP

Therefore, a deterioration model, composed of long-term degradation which is functionally related to accumulated mileage and a more random factor related to idle adjustment stability was developed.

$$FHC = \underbrace{Ko + Km \text{ Mileage} + \sum_{j=1}^{n}}_{\text{rings, valves, ignition, carburetion}} \underbrace{K_j \Delta P_j}_{\text{idle adjustment}}$$

where:

FHC = Federal hot cycle emission

Km = Regression coefficient on mileage

K_j = Regression coefficient on the "j" idle adjustment

P_j = Deviation from specification of "j" idle adjustment

For a vehicle which has undergone periodic, tuneup maintenance, the superimposed elements resemble those of Figure 3-9. The long-term deterioration elements are represented by the monotonically increasing dashed line. The emissions, due to the more random idle adjustment parameters, are schematically represented as periodic noise whose rms value tends to increase over a maintenance interval. At the end of the interval, the idle adjustments are restored to manufacturers' specification and, again, they degrade from their null points. To test this hypothetical model, a series of regression analyses were performed with the AAA data partitioned into air reactor (AIR) and Engine Modification (EM) populations. Régressions performed were:

- Mileage only
- Mileage plus idle adjustments exclusive of idle CO
- Mileage plus all the idle adjustments.

If the hypothesized model is correct, the following trends can be expected to develop:

- The regression (slope) coefficient on mileage should decrease as the idle adjustment variables are added to the regression analysis since changes in some of these variables result in skewed emissions changes.

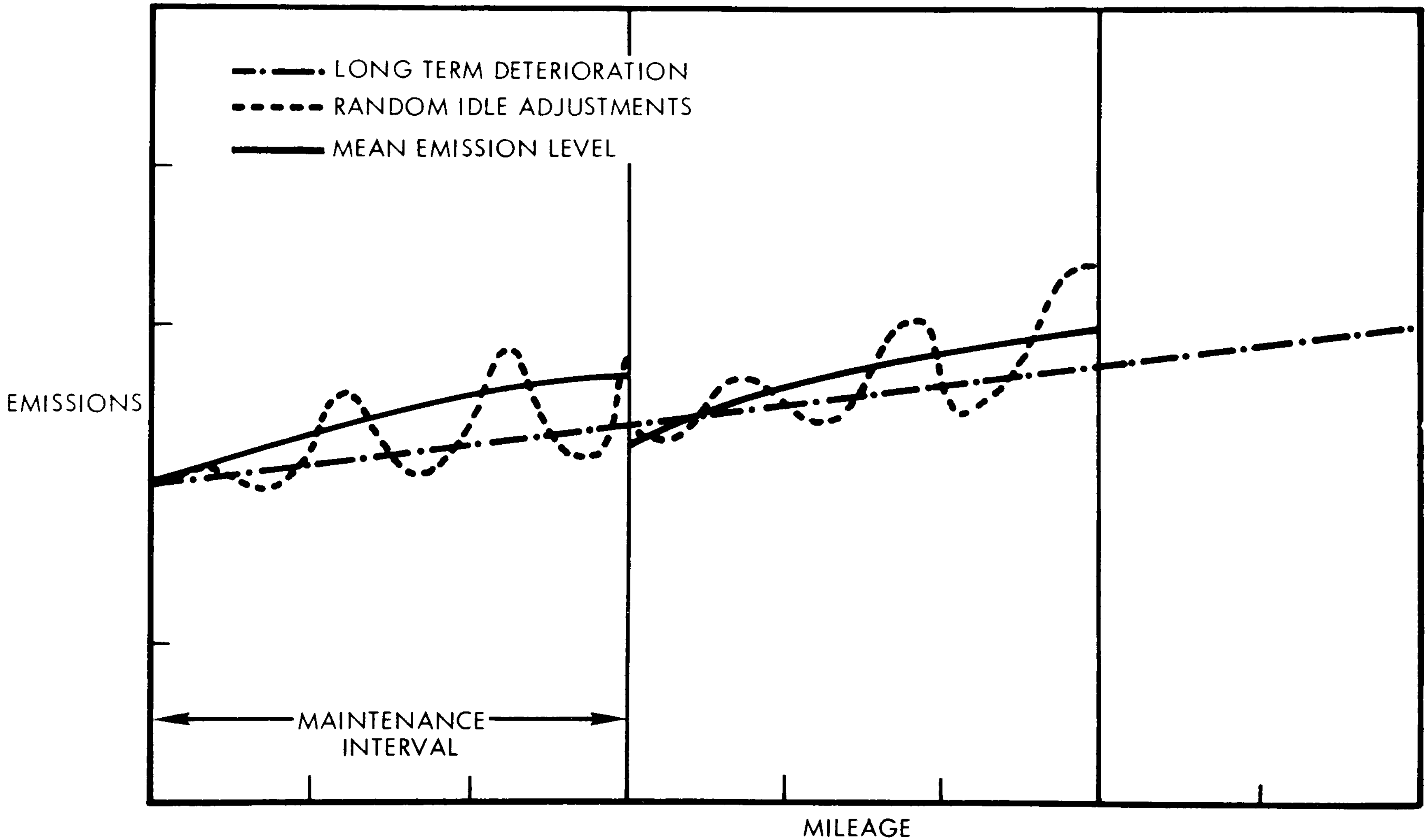


Figure 3-9. Illustrative Emission Decay Profiles

- Those parameters which are strongly correlated to emissions should have a statistically significant "t" statistic which is a measure of the regression curve fit (greater than 2.0).

The following significant trends were noted:

- Idle CO is always a highly significant variable and mileage is also significant in most cases for HC emissions.
- The remaining idle adjustments, timing and idle speed (not shown here), are only infrequently found to be significant variables. Significant idle adjustment effects occur in a more or less random manner within the total set of regressions.
- The multiple correlation coefficients and "t" statistic values always increased when idle adjustment variables were considered in addition to mileage when explaining emission degradation. The regression slope coefficient on mileage decreased in this case.

The following conclusions are based on these observations and the data summarized in Tables 3-4 and 3-5.

- There is a basic deterioration rate, K_m, (1.44-2.2 ppm HC and 0-0.03% CO per 1000 miles) which is independent of the idle adjustments (i.e., determined after setting ΔP_j to specification values).
- HC and NO emissions from air reactor controlled vehicles were more sensitive to variations in the parameters studied than were CO emissions. The reverse was the case for engine modification controlled vehicles.
- The high value of the "t" statistic for the idle CO effect upon emission degradation and the corresponding significant decrease in the mileage regression coefficient indicate that this maladjustment is significant and explains part of (20-30%) the emission degradation originally attributed to mileage.

The coefficients determined from the larger data set with the larger accumulated mileage range were selected to guide the determination of deterioration profiles at the subsystem level (see shaded coefficients in Tables 3-4 and 3-5).

Table 3-4. Regression Analysis Study of HC Emission Deterioration Factors

(AAA AS-RECEIVED DATA SET)

EMISSION	CONTROL TYPE	$HC/10^3$ MILES		HC/°TIM		HC/%CO		N	$\overline{M}$ MILES	R^2
		K_M	t_M	K_{TIMING}	t_{TIMING}	K_{ICO}	t_{ICO}			
HC	AIR	2.2	3.4	-0.62	2.0	22	5.6	122	21,800	.57
HC	AIR	2.4	2.1	0	0	41.8	5.2	63	13,700	.66
HC	EM	1.44	3.3	2.22	1.3	16.0	6.8	146	17,900	.60
HC	EM	0.40	0.47	1.55	0.85	14.4	4.6	82	11,300	.52

AIR - AIR INJECTION SYSTEM

EM - ENGINE MODIFICATION

t_J - THE "t" STATISTIC ON THE REGRESSION COEFFICIENT, K_J (SIGNIFICANT FOR $t \geq 2.0$)

$HC = K_O + K_M\ M + K_{TIMING}\ \Delta P_{TIMING} + K_{ICO}\ P_{ICO} + K_{RPM}\ \Delta\ RPM$

WHERE

HC - FEDERAL HOT COMPOSITE EMISSIONS

K_J - REGRESSION COEFFICIENT ON VARIABLE J"

M - THOUSANDS OF MILES

P_J = VALUE OF THE VARIABLE

R^2 - MULTIPLE CORRELATION COEFFICIENT

N - SAMPLE SIZE

Table 3-5. Regression Analysis Study of CO Emission Deterioration Factors

(AAA AS-RECEIVED DATA SET)

EMISSION	CONTROL TYPE	$CO/10^3$ MILES		CO/°TIM		CO/%CO		$\overline{ICO}$ %	N SAMPLE	$\overline{M}$ MILES	R^2
		K_M	t_M	K_{TIMING}	t_{TIMING}	K_{ICO}	t_{ICO}				
CO	AIR	0	0	0	0	0.41	16.0	2.6	122	21,800	.84
CO	AIR	-.004	0.6	0	0	0.43	10.0	2.4	63	13,700	.82
CO	EM	-.006	1.2	.008	.95	0.27	7.0	3.2	82	11,300	.91
CO	EM	.030	5.3	.011	.5	0.27	9.0	2.5	146	17,900	.72

AIR - AIR INJECTION SYSTEM

EM - ENGINE MODIFICATION

t_J - THE "t" STATISTIC ON THE REGRESSION COEFFICIENT, K_J (SIGNIFICANT FOR $t \geq 2.0$)

$CO = K_O + K_M\ M + K_{TIMING}\ \Delta P_{TIMING} + K_{ICO}\ P_{ICO}$

WHERE

CO - FEDERAL HOT COMPOSITE EMISSIONS

K_J - REGRESSION COEFFICIENT ON VARIABLE J"

M - THOUSANDS OF MILES

P_J = VALUE OF THE VARIABLE

R^2 - MULTIPLE CORRELATION FACTOR

N - SAMPLE SIZE

CARB Surveillance Data Evaluation

The California ARB vehicle emissions surveillance data describe composite, hot cycle HC and CO emission degradation with accumulated mileage for the vehicle model years 1966 through 1970. This is the only large definitive data set which indicates long-term deterioration rates and, therefore, it was selected to represent the performance of a baseline fleet subjected to voluntary maintenance. These data were used to:

- Estimate the effectiveness of voluntary maintenance as it is currently occurring.
- Verify idle adjustment deterioration rates derived from the AAA data.
- Characterize the performance of the baseline fleet in the economic-effectiveness study.

The deterioration rate data from the AAA fleet program and the estimated frequency and effectiveness of voluntary maintenance were combined and used to reconstruct the ARB surveillance data analytically. The results of the evaluation are shown in Figure 3-10 which compares the predicted emission profile against the ARB profile. It should be noted that the initial 12,000 miles of the ARB profile, to the extent that it is free of major induction, engine seasoning and ignition system deterioration effects, are indicative of emission changes produced by deterioration of the idle adjustments. The problem was to select the frequency and effectiveness of voluntary maintenance which would yield the best prediction of the ARB degradation data. The reliability level of the frequency data led to the selection of the effectiveness of voluntary maintenance as the unknown to be determined. A fit with the ARB emission profiles was achieved by varying the reduction in emissions obtained with voluntary maintenance.

Data Synthesis

A reasonable range of maintenance effectiveness and its apportionment along the three subsystems was first estimated using data available from the literature (GM idle program, Reference 5) and the results of pre- and post-tuneup data from the statistically designed experiments of this study (see Volume III). Maintenance effectiveness in percent

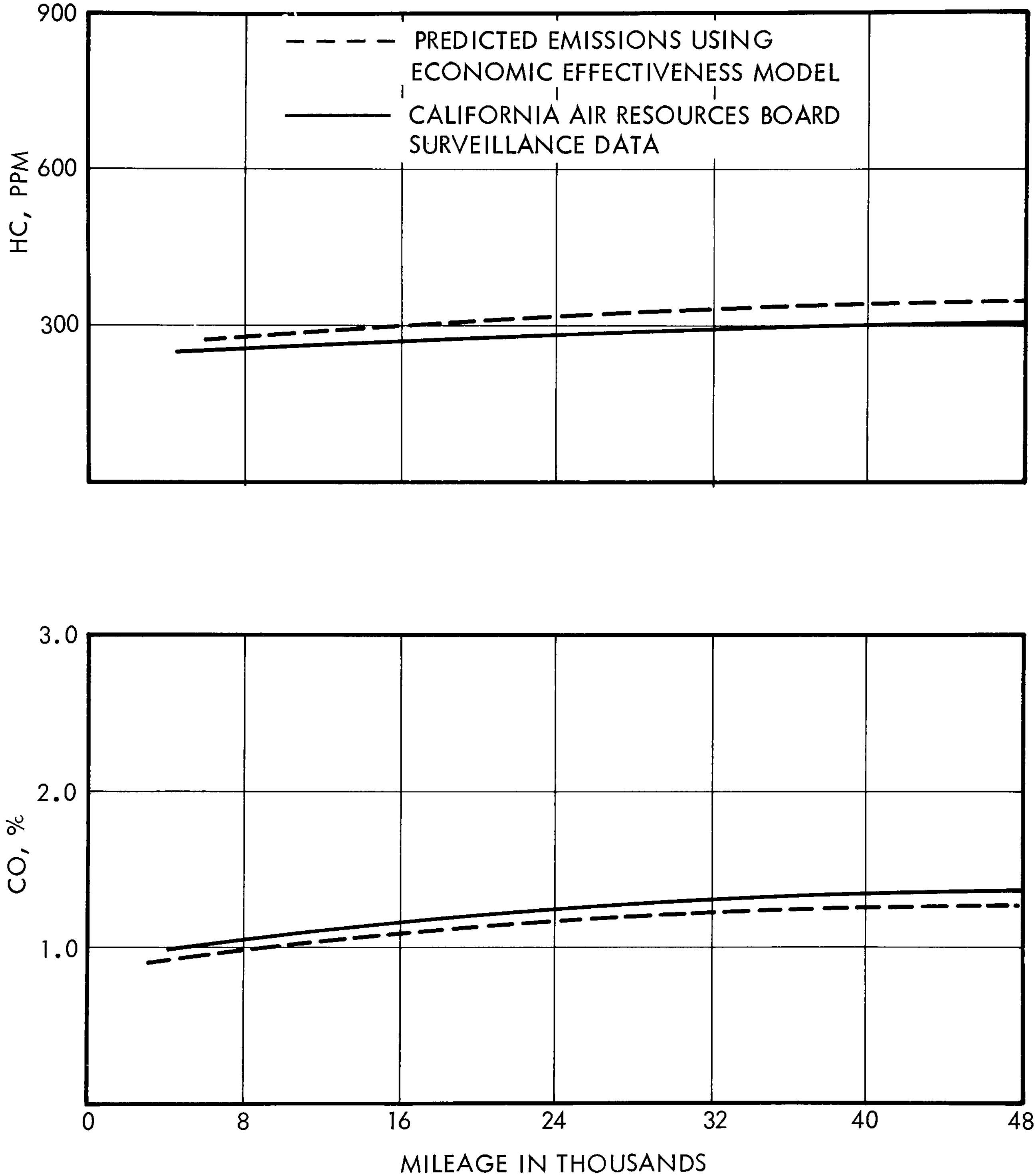


Figure 3-10. Comparison of Base Line Actual and Predicted Emission Profiles

reduction is given for emissions and ordered in Table 3-6 by an increase in the extent of the maintenance.

A proration of maintenance effectiveness over the major subsystems (idle, induction and ignition) can be made by subtracting the GM idle adjustment effect from the effect of the Scott Research Laboratories' major tuneup on 22 vehicles (Table 3-6). Making the assumption that the residual difference is primarily attributable to maintaining the secondary ignition system and the induction system for HC and CO, respectively, and subjectively reflecting the engine parameter survey, the following proration was derived.

Table 3-6. Subsystem Proration of Maintenance Effectiveness

Emission Reduction	Subsystem Emission Reductions, %			SRL Tuneup* Emissions Reduction,%
	Idle Adjustment**	Ignition	Induction	
HC	6	12†	7	25
CO	15	-	7	22
NO	0†	-	-5	-5

*Based on pre- and post-maintenance of 22 orthogonal test vehicles (Volume III).
**From GM Idle Adjustment Program.
†Based on engine parameter emission response surfaces from the orthogonal tests.

The data show that significant HC emission reductions will have to come from maintaining the secondary ignition system, whereas significant CO reduction can be achieved by the simpler idle fuel-to-air ratio adjustment.

To a first approximation, the subsystem deterioration rates should be proportional to the subsystem maintenance effectiveness (i.e., a subsystem requires maintenance in direct proportion to the degree it deteriorates). The emission deterioration rate data from the AAA fleet evaluation and ARB emission deterioration profile adjusted for proportionality with subsystem maintenance effectiveness are shown in Table 3-7.

Table 3-7. Comparison of Estimated Subsystem Deterioration Rates Using Several Data Sets

EMISSION DETERIORATION	SUBSYSTEM	DETERIORATION RATE, de/dM					
		AAA		ADJUSTED ARB		TRW STUDY	
		AIR	EM	AIR	EM	AIR	EM
HC, $\frac{PPM}{10^3 \text{ MILES}}$	IDLE ADJUST	.50	.80	0.6	0.6	0.8	1.0
	INDUCTION	.50	.50	0.6	0.6	0.6	0.7
	IGNITION	1.70	.90	1.5	1.0	2.0	2.0
CO, $\frac{\%}{10^3 \text{ MILES}}$	IDLE ADJUST	.008	.013	.009	.009	.016	.020
	INDUCTION	0	.030	.004	.004	.004	.006
NO, $\frac{PPM}{10^3 \text{ MILES}}$	IDLE TIMING					2.8	2.8
	INDUCTION					-1.6	-2.4

The comparison between these two data sets is surprisingly good considering the quality of the data and the nature of the required approximations. The values selected for this study are shown in the final column. They reflect a compromise between the AAA, ARB and TRW parameter survey data.

The NO deterioration rates in Table 3-7 were estimated from the combined engine parameter survey, orthogonal experiment and air cleaner experiment data, presented in Volume III. It is assumed NO is predominately influenced by basic timing and loaded mode fuel-to-air ratio. This assumption is strongly supported by the emission mode response to these parameters derived from statistical experiments described in Volume III.

Therefore, the air cleaner restriction experiments, which are free from deviate timing influences, were used to derive a linear relationship between the increased composite CO emissions resulting from induction subsystem malfunction and the associated change in NO emissions. The resultant relationship derived from the 11 basic power trains tested in the air cleaner experiment is:

$$\frac{dNO}{dM} = - \frac{dNO}{dCO} \frac{dCO}{dM} = - 1.6 \frac{PPM}{10^3 \text{ miles}}$$

where: dCO/dM = change in CO emissions per thousand miles (.004) (Table 3-7)
dNO/dCO = 400 ppm/% (weighted average of 11 power trains from regression analyses)

The influence of timing is estimated using the rate of deterioration of timing as indicated by the AAA data and the composite emission response derived from the definitive orthogonal experiment (Volume III)

$$\frac{dNO}{dM} = \frac{dNO}{dt} \frac{dt}{dM} = 2.8 \frac{PPM}{10^3 \text{ miles}}$$

where: dNO/dt = average composite NO emission response to timing deviation, 34 ppm/deg (from orthogonal data, Vol. I)
dt/dM = deterioration of basic timing, 8.2×10^{-2} deg/10^3 miles (from Table 3-3).

The projected deterioration rates were then evaluated within the model framework to determine the compatibility of the total input data set. This data set consists of the following for both engine modification and air reaction emission control systems.

- Subsystem deterioration rates
- Effectiveness of subsystem voluntary maintenance
- Response coefficients from the definitive, orthogonal experiment
- Frequency and extent of engine parameter maladjustment and malfunction
- Frequency of voluntary and enforced maintenance.

The results of the preliminary studies with these data indicated that the estimated deterioration rates for the idle adjustments and percent misfire were too low. These deterioration rates were therefore adjusted upward to those values shown in the last column of Table 3-7. These values were used in all of the procedure evaluation studies reported in Section 5.

3.2.4 Estimate of Vehicle Fraction Rejected to Maintenance

When multiple failures exist in a vehicle and are to be detected using several inspection procedures, the combined rejection criteria (i.e., idle CO and HC) will not fail the additive sum of the rejected population of the two independent cutpoints since some vehicles will have failed both tests.

A statistical analysis of the parameter survey data (Volume III) indicated that to a good approximation most failures are statistically independent (exceptions being the failure pairs timing-dwell and idle rpm-idle fuel-to-air ratio both of which are weakly correlated). Applying the assumption of mutual independence allows the construction of a relatively simple statistical model for calculating the number of vehicles rejected to maintenance (i.e., the probability of finding "X" failures in a specific vehicle), Reference 8.

3.3 OPERATING PROCEDURES AND LABOR REQUIREMENTS

Operating costs associated with inspection/maintenance procedures were developed from existing data or from work structure breakdowns. These procedures serve as the specification against which labor grade rates are selected. These data were developed from industry standards such as flat rate labor and parts manuals for those inspection/maintenance procedures applied in garages. When work element times were not available, they were estimated; in some cases, these estimates were verified from observations of diagnostic center operations. Specifically, the following work breakdown structures were developed:

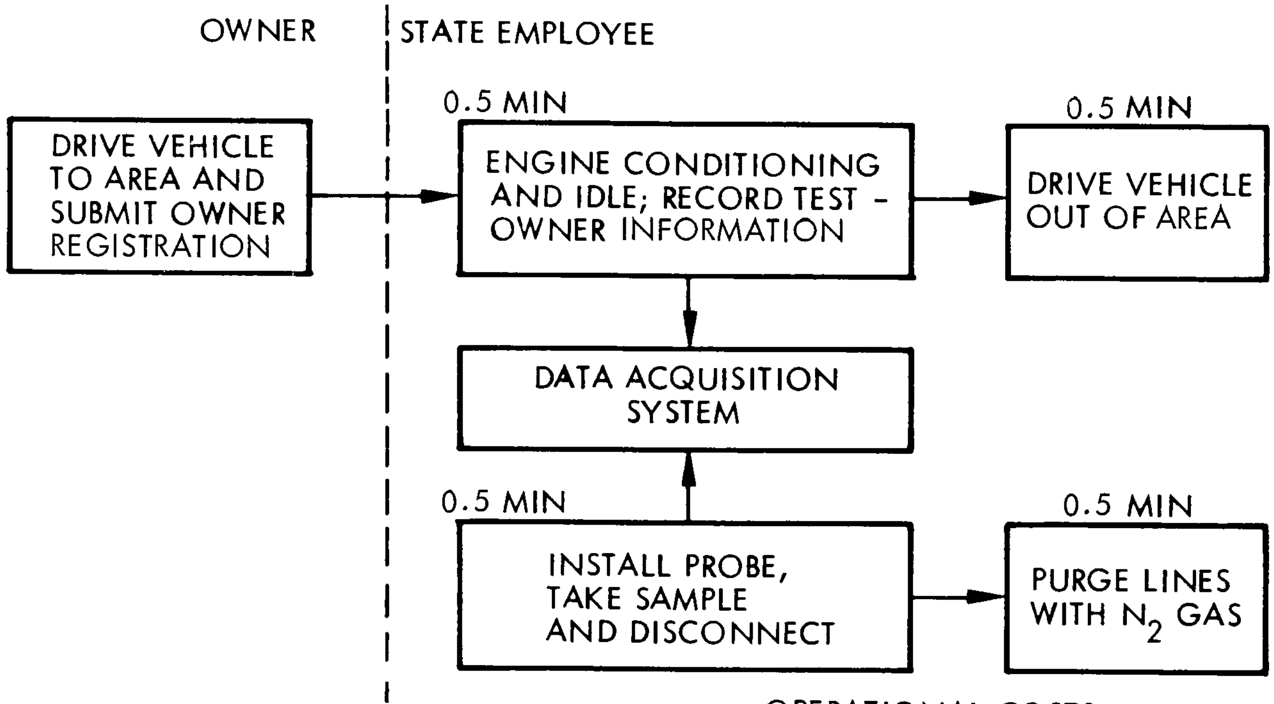
- State-lane inspection procedures using remote sensing instruments
- Garage diagnostic and maintenance operations.

State-Lane Inspection

A typical operating sequence for a state-lane inspection using an idle emission signature approach is shown in Figure 3-11. The vehicle owner is assumed to stay with and operate his own vehicle throughout the inspection. Two parallel functions are required: 1) data acquisition and recording, and 2) exhaust sampling probe or acoustic sensor positioning. The data acquisition is part of the more general function of program enforcement which would probably be integrated into an existing, analogous function, such as the state licensing of automobiles. Costs may therefore be shared between this program and the inspection enforcement program. With a highly automated, digital information system, administration costs would be minimal and functionally similar to those of existing, large scale billing operations.

Therefore, a fixed direct operating charge of $.50/vehicle is assessed for the enforcement function. The inspection procedure is estimated to require one minute and two employees. A half-minute of slack time is available for preparing the probe for the next vehicle. Sample line purging could be automatically or manually performed at this time.

IDLE INSPECTION TIMELINES AND COST



FIXED EQUIPMENT COSTS

NDIR	$ 2,000
DATA ACQUISITION	15,000
MISCELLANEOUS	
TOOLS, WORK BENCHES, OFFICE EQUIPMENT	1,000
TOTAL	$ 18,000

OPERATIONAL COSTS

ADMINISTRATION	1 MIN X $5/HR	$ 0.08
MECH. NO. 1	1 MIN X $3/HR	0.05
MECH. NO. 2	1 MIN X $4/HR	0.07
DATA MANAGEMENT		0.50
		$ 0.70

Figure 3-11. Operational Flow Diagram for State Inspection Lanes

The use of a dynamometer for acquiring data under engine load would require an additional minute for setting up the dynamometer and making a loaded mode measurement. As long as remote sensing equipment is used (i.e., that doesn't require direct attachment to the vehicle) the above described procedure should be insensitive to the use of either an emission measurement or an engine parameter measurement. Typical operational and equipment costs are $.70 per vehicle and $18,000, respectively.

The labor grade of the information officer assigned to these tasks is estimated to be slightly higher than that of an average mechanic (approximately $4/hr.) and slightly lower for the aide (approximately $3/hr.). Therefore, the average wage used to cost direct labor is $3.50/hr. A burden factor of 50% is applied to cover the cost of fringe benefits and indirect operating costs. This burden rate does not include the amortization of capital equipment which is carried as a separate account.

Costs per inspection lane range from approximately $18,000 for a simple idle emission inspection (Figure 3-11) to $25,000 for inspections requiring simple dynamometer loading. The $7,000 costs include the dynamometer plus additional data handling equipment required for the installation.

Facilities costs are based on both land acquisition and structure. Typically, basic site layout is priced for the following design elements:

- Land occupied by structure and employee parking (6,600 ft^2)
- Land required for egress and exit from the inspection lane (600 to 1,000 ft^2) plus land required to contain the to-be-inspected vehicles (estimated from vehicle lane throughput)

All required land is priced at $2/$ft^2$, which is equivalent to the cost of commercial property located in areas of high traffic flow.

A typical layout of an inspection facility is schematically shown in Figure 3-12. Provision is made for securing the instrument and information system when they are not in service. An environmentally controlled, enclosed module is also provided for stores, records, on-site instrument servicing, and general administration. The vehicle inspection site is covered and elevated to keep it free of water or snow and to minimize the discomforture of the test personnel. Estimated cost for this

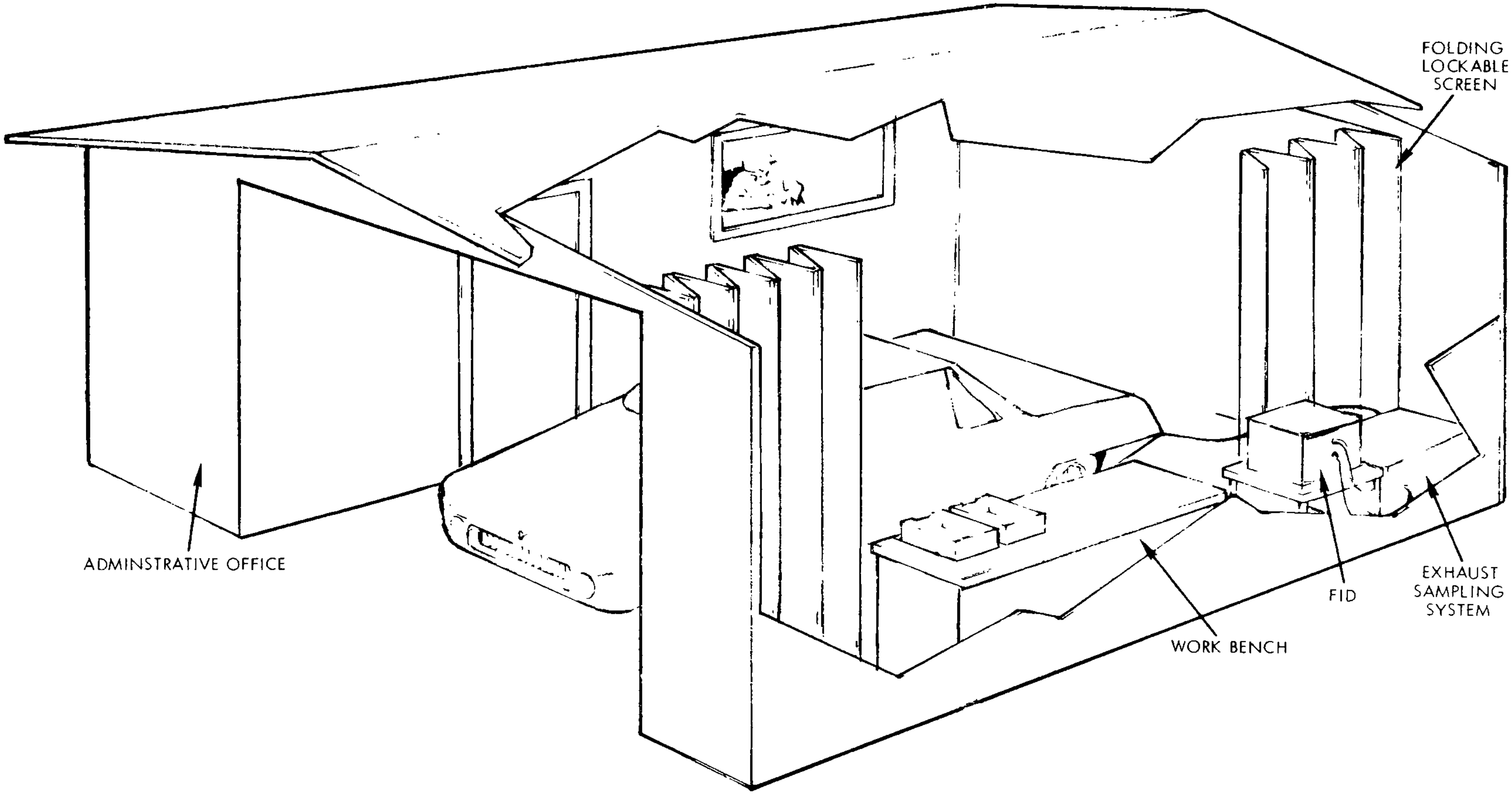


Figure 3-12. Typical State Inspection Station

structure and its services is $\$10/ft^2$. Approximately 1200 square feet of covered area are required. Total facility costs, equipment, land and structure, will nominally range between $44,000 to $52,000 per lane. These investment costs, when amortized, constitute a very small fraction of the cost per vehicle inspected.

Franchised Garage Inspection

The cost and direct labor of inspection and the associated maintenance in a franchised garage were established from three sources depending on whether conventional or advanced equipment is to be used. These were:

- Chilton's Labor Guide and Parts Manual (Reference 3)
- Inspection labor times as measured on the as-received vehicles in the orthogonal tests (Volume III)
- Coarse operations analyses for hypothesized advanced equipment such as remote sensing devices.

Inspection labor times for the individual parameters were measured during the initial inspection of the orthogonal test vehicles. These inspection times were subtracted from the total estimated job times abstracted from the flat rate manual to differentiate between the costs associated with inspection (instrument hookup) and actual maintenance (adjustment or replacement). This differentiation is important in allocating costs between 100% inspection and fractional maintenance when studying procedures using franchised garages. All labor costs for garage inspection/maintenance are charged at a rate of $10/hr. This is a burdened rate which includes overhead factors and profit. An additional $.50/ vehicle is charged for program enforcement (i.e., the information system required for recording, processing, storing and disseminating inspection/ maintenance data). Labor times and equipment requirements used in this study are summarized in Table 3-8.

Table 3-8. Franchised Garage Inspection/Maintenance Labor Times and Equipment

Subsystem	Component	Equipment	Time (hours)	
			Inspection	Maintenance
Idle Adjustments	ICO/rpm	NDIR CO and Tachometer	0.10	0.20
	Timing	Timing Light	0.05	0.10
Secondary Ignition	Plugs, distributor and wire harness	Scope and Dynamometer	0.25	1.30
Induction	Air Cleaner	Pressure drop across element	0.05	0.2
	PCV	Crankcase pressure at idle	0.05	0.3
	Air Injection	Air flow at idle or NDIR CO and CO_2	0.15	0.6

4. SYSTEMS MODEL

Automotive emission control through a program of inspection and maintenance can be accomplished by employing any one of a number of basic strategy alternatives. The application of a system analysis approach, the keystone of which is a mathematical simulation model, provides the mechanism for thoroughly evaluating the various alternatives available. It will be seen that such a model can be an effective management tool for examining the impact of various policy statements on emission levels. By describing and relating the various physical and economic components of the system, the model serves as a device for translating specific emission policy statements into estimated emission levels and costs. The impacts of alternative policies are thus converted into comparable quantitative measures. By defining an objective function, the net effects of each strategy alternative can be immediately compared with others to assess their relative attractiveness.

For all practical purposes, the model can be viewed as an abstract extension of a real world vehicle inspection maintenance system. The engineering elements define the relationships between program policy decisions and resulting emission levels. This is done through a series of transformations linking specific pass/fail criteria on the inspected attribute to appropriate maintenance and subsequently to resultant emission levels. The emission data are then interfaced with the corresponding economic information in order to evaluate system cost effectiveness. The other salient engineering aspect of the program design is the system configuration. The number, size and location of both inspection and maintenance facilities required to operate the program are determined using vehicle population, inspection interval and operational times. The economic factors considered in the model include both capital and direct operating costs. In addition to these explicit costs, consideration is given to the costs assigned to user inconvenience. These implicit costs must be accounted for in terms of overall system performance. Lastly, the model assesses the impact of regional air quality requirements and present state-of-the-art instrumentation on program goals and system configuration.

To obtain more insight into the relationships between the various program components, consider the system diagram in Figure 4-1; here, the engineering and economic factors discussed above have been described using two mathematical submodels. The emissions predictor model, shown on the left, incorporates all of those elements involved in transforming policy decisions to emission predictions.

The cost estimator model determines the various costs associated with operating the program. The communication between the emissions predictor and cost estimator models is provided by the operational analysis model. This model determines the user times involved in interfacing with the program. Once both emission levels and costs have been obtained for any given policy set, the data are summarized using a single performance value, a systems figure of merit. The other important factor needed in measuring system performance are the baseline emission profiles which reflect the current "state of nature" (i.e., voluntary maintenance). These then are the basic models required in translating specific control strategies into actual emission levels which can be tested in terms of their overall cost effectiveness. Presented in the next two sections are detailed technical discussions of the emissions predictor model, cost estimator model and operational analysis model.

4.1 EMISSIONS PREDICTOR MODEL

The effectiveness of engine parameter inspection procedures depends upon their ability to identify specific engine parameter malfunctions. This is particularly true for the case of the emission signature inspection where several engine malfunction interactions can interfere in identifying specific ones. In order to provide a consistent basis for comparison, emission reductions were calculated using basic transformations relating mode emission levels, engine parameter settings and mean emission levels. Mathematically, this relationship can be expressed by:

$$\Delta e_m \xrightarrow{T_1} \Delta P_i \xrightarrow{T_2} \Delta e_j \qquad (4.1)$$

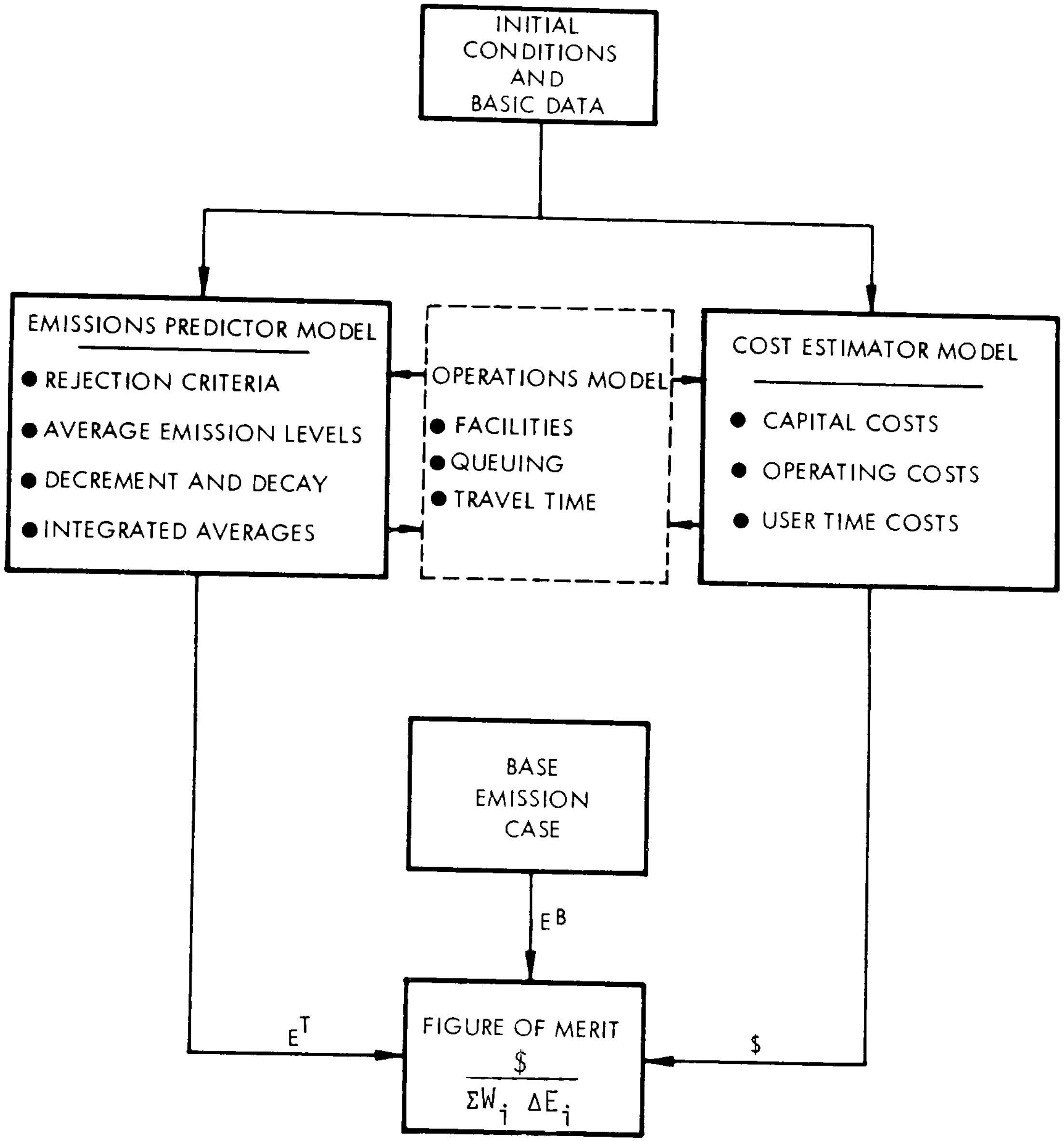


Figure 4-1. Systems Model Flow Diagram

where: e_m = m^{th} mode emission (e.g., idle CO)

ΔP_i = i^{th} engine parameter (e.g., idle adjustment)

Δe_j = mean composite emission level (e.g., carbon monoxide)

T = transformation, mathematical relationship between parameters (see Figures 3-1 through 3-4)

For the engine parameter diagnostic inspection, only the last transformation, T_2, is required in translating engine parameter inspections to mean emission levels. The emission signature inspection requires both transformations in translating a specific mode emission measurement to a mean emission value. To arrive at suitable relationships between the various mode emission, parameter settings and mean emission levels necessitated the partitioning of the engine system into several classifications. For analytical purposes, this partitioning can be expressed in matrix notation where the columns represent power train types and the rows, engine subsystems. Depicted below is a symbolic representation of such a matrix for one emission specie.

		Power Train	
		Air Reactor	Engine Modification
	Idle	a_{11}	a_{12}
Δe_j =	Ignition	a_{21}	a_{22}
	Induction	a_{31}	a_{32}

The a_{ij}'s are the response coefficients derived from the orthogonal test for each ordered pair of subsystem and power train types. Mathematically, this can be expressed by the following relationship:

$$\Delta e_j = \Sigma a_{ij} \, \Delta P_i \tag{4.2}$$

A similar relationship exists between the several inspection signature mode emissions and the corresponding engine parameters:

$$\Delta e_m = \Sigma b_{ij} \, \Delta P_i \tag{4.3}$$

The partitioning of the engine system into specific subsystems allows for a more detailed characterization of the contributions made by maladjustment of the various parameters to emission levels. A schematic of the emissions predictor model is shown in Figure 4-2. With specific policy criteria as input, the model first ascertains the number of vehicles failing the given inspection procedure. This is accomplished by projecting the various pass/fail criteria into the appropriate mode emission or engine parameter distribution. Except for the air cleaner parameter, all of the engine parameters evaluated were assumed to be normally distributed. This assumption leads to a straightforward method for relating pass/fail criteria to the percentage of vehicles whose parameter settings were outside the criterion range. In the case of the air cleaner parameter, an exponential distribution was found to be a good fit of the experimental test data. Emission distributions are positively skewed and, therefore, cannot be described in terms of a normal function. Thus, logarithmic transformations of the emission data were required resulting in a log-normal distribution characterization.

Using the inspection procedure policy criteria, the model divides the population into two fleets--an accepted and a rejected subfleet. The rejected vehicles will undergo maintenance resulting in a reduction or increase in overall emission levels. The mean emission levels represented by both subsets are then deteriorated over the subsequent inspection interval. It should be pointed out that all emission levels and parameter values utilized in this analysis are in terms of a mean value which is the composite of accepted and rejected subfleets. This characterization permits a number of simplifying assumptions, in particular in the case of adjusting emissions levels and parameter values for the effects of maintenance treatments. Although the variability of engine parameter adjustments is assumed constant with time, the mean values are adjusted after each maintenance interval.

Due to lack of sufficient experimental data on both emission and parameter deterioration rates, the model assumes that all engine parameters within a subsystem decay identically and according to the linear rule:

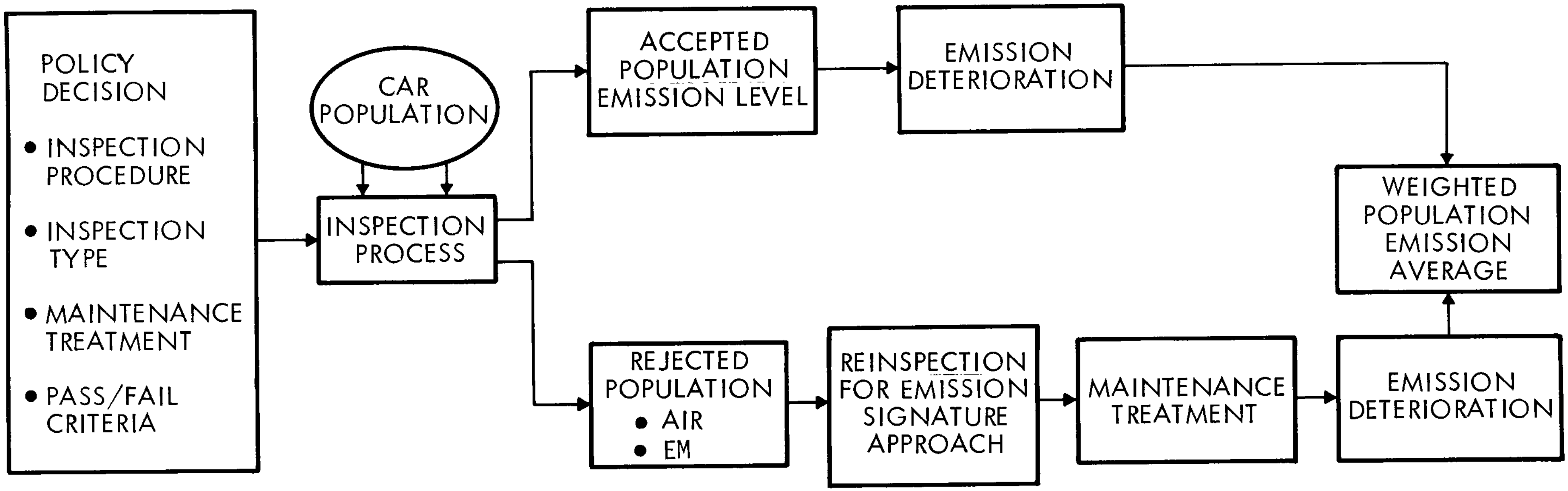


Figure 4-2. Emission Predictor Model Flow Diagram

$$\frac{dPi}{dM} = K \frac{de_j/dM}{de_j/dP_i} \qquad (4.4)$$

where: M = mileage

K = scaling constant proportional to number of parameters within a subsystem

P_i = i^{th} engine parameter mean value change with mileage

$\dot{e}_j$ = j^{th} composite emission

The subsystem emission deterioration rates in Table 3-7 (de_j/dM) are used directly in computing the changes in composite emission levels as a function of time. The response coefficient, de_j/dP_i, is derived from the statistically designed experiments (see Volume III, Section 4). After the deterioration process has taken place, the two subfleets are recombined to obtain an updated mean emission level. This recombination is based on emission levels from both subfleets as well as the inspection rejection fraction. Equation (4.5) presents the relationship between these components.

$$e_j = re_{Rj} + (1-r)\, e_{Aj} \qquad (4.5)$$

where: e_j = j^{th} emission for combined fleet

e_{Rj} = j^{th} emission for rejected fleet

e_{Aj} = j^{th} emission for accepted fleet

r = rejection fraction

In the idealization of the model, all of the above events occur instantaneously at the end of an inspection interval. The adjustment deterioration transient over the next inspection interval for the accepted and rejected vehicles is taken as the extension of the previous decay transient. The deterioration profile is shifted by an appropriate degree to account for differences in absolute emission levels attributable to maintenance. At the end of an inspection interval, the model combines the partitioned test population and computes a weighted average mean emission level. The test population then undergoes another instantaneous inspection and maintenance process, followed by subsequent inspection intervals in a manner completely analogous to that described above.

To obtain a measure of the effectiveness of the various procedures, it was necessary to compare their performance with some "benchmark." For this study the fleet undergoing enforced maintenance was contrasted with a fleet subjected to voluntary maintenance reflecting the ARB surveillance data. A model was developed for predicting the emission levels of this baseline fleet over the four-year program. The maintenance treatment program for the baseline consisted of a yearly minor adjustment and ignition repair with a major tuneup every third year. To allow for the situation where the enforced maintenance treatment is less than the baseline, a "conservation of maintenance" principle was applied. The principle states that the sum of all subsystem maintenance is invariant with time, although that maintenance which occurs as a consequence of inspection is more effective. The vehicles which pass the inspection procedure are assumed to get the same voluntary maintenance as the baseline fleet.

All of the above is directed at predicting emission histories which must then be transformed into a single valued figure of merit. This implies performing an integration of emissions for both the test and base populations using the predicted emission histories. For the base population, this involves integrating each segment and summing over all segments. In the case of the test population, however, the emission profiles for both the accepted and rejected vehicles must be integrated separately and then weighted to obtain a mean integrated value for that inspection interval. These weighted average values are then summed over all inspection intervals and subtracted from the equivalent base population total to obtain the gross value of reduced emissions effected by the imposed program. All of the emission computations performed within the model are done in terms of composite measurements. However, the emission time histories and total daily emission levels are converted to grams per mile and tons per day, respectively. These conversions are done using procedures set forth in the Federal Register, Reference 9.

The major assumptions and ground rules utilized in formulating the emissions predictor model are summarized below:

- All emissions and engine parameter transformations are based on mean values.
- All inspection/maintenance activities are performed instantaneously.

- Engine parameter adjustments and emission levels are deteriorated at the subsystem level.
- Conservation of subsystem maintenance is imposed.
- Vehicles are maintained to manufacturer's specification when they fail an inspection.
- A 100% reliability is achieved in detecting engine parameter malfunctions.
- Inspection of parameter adjustments at the garage prior to maintenance is required of all vehicles failing an emission inspection.
- The program is evaluated over a four-year period utilizing 1966-69 control technology.
- Subsystem parameter adjustments and emission levels decay linearly with time.
- Average driving speed to and from inspection stations is 22 mph.
- The transformation between mean emissions and log-normal mean emissions is linear.

4.2 COST ESTIMATOR MODEL

The economic elements of the system are highly sensitive to both the inspection frequency and specific engine parameter and/or emission mode pass/fail criteria. In addition, economic considerations are closely related to the number and type of inspection and maintenance facilities available in the demographic area being simulated. In general, the economics of an imposed inspection and maintenance program involve both direct and indirect resource costs. The former are the common costs related to the real exchanges of funds for material, goods and services, while the latter include resource expenditures that are not necessarily accompanied by real flow of funds.

The costs associated with capital investment requirements are a function of the basic inspection/maintenance strategies. For the case of a franchised-garage system, no direct capital investment will be accounted for in the program. This assumption presupposes that franchised licenses will be awarded only on condition of a satisfactorily equipped garage. The state inspection/franchised-garage maintenance strategy does require a capital investment for the inspection facilities.

These costs will depend on the size of the car population, the length of the inspection interval, and specific instrumentation and equipment requirements. In the model, it is assumed that all investments come on-stream at time zero and that no existing state facilities are employed. Separate investment calculations are performed for the building, land and equipment requirements for each state-lane station. The contribution of these investment costs to annual costs is calculated using the concept of a sinking fund. This can be interpreted either as financing through bonds which are payable in full upon maturity or through internal funds which must be replaced in full at the end of a fixed period.

For each inspection interval, direct operating costs must be added to the above indirect operating costs to obtain the total system operating costs. Under the direct category are separate calculations for wage costs, administrative costs and miscellaneous operating costs for both inspection and maintenance. In addition, a charge for parts is incurred under the maintenance activity.

The system costs so far discussed are explicit costs which involve real exchanges of funds for material goods and services. From a social standpoint, however, the costs that result from such an inspection and maintenance program are better measured by the appropriate costs of all resources employed in the program; i.e., the value of all resources if employed in their best alternative use. If it is assumed that the data employed in the above calculations are rough measures of the marginal values of those resources employed in their best alternative uses, it is necessary to add an estimate of the implicit cost represented by driver inconvenience to the computed explicit costs to arrive at a better approximation to the system social cost. The total time spent by users in inspection and maintenance is considerable, and it is reasonable to expect that, without an imposed program, this resource would be employed in other pursuits from which the individual would derive a benefit. The model, therefore, computes a monetary estimate of these lost benefits which compose the value of private time expended on the program.

The model also includes procedures to account for time effects on system costs. It is desired to base the cost calculations on inflated rather than constant dollar costs, all costs can be inflated at a constant annual rate. Because of available mechanisms for employing funds productively and, thus, earning an interest or profit, it is not realistic to weight a dollar cost incurred today on an equal basis with a similar cost incurred at some future date. Future costs must be discounted by a rate related to the productivity of capital. All costs are thus discounted at an assumed constant annual rate.

In summary, once system investment costs have been computed, the model evaluates the inspection interval, indirect and direct operating costs, and the private user-costs for both inspection and maintenance. These costs are summed for a single interval, discounted by factors appropriate to the end of that interval and then summed over all intervals to provide a measure of total program cost. Figure 4-3 depicts the relationship between the various cost components comprising the system. The flow diagram was constructed for the case of a state-lane inspection/ franchised-garage maintenance strategy. For a franchised-garage system, no capital costs would appear.

4.3 OPERATIONS MODEL

The operations model provides the linkage between the emission predictor model and the cost estimator model. It calculates the size, location and number of inspection and maintenance stations required to implement the program optimally. In making these determinations, the model trades off user-inconvenience costs with the capital costs for facilities. It does this by computing the driving time to and from the station and waiting time at the station. Waiting times at inspection station locations are derived from a queuing model. This model assumes a Poisson distribution of vehicle arrival times at the inspection station. Adding the traveling time and waiting time to the actual vehicle inspection time yields the total inconvenience time. For the case of the emission signature inspection, an added travel time for some vehicles is incurred for reinspection. This additional time is charged against the program if the failed vehicle passes its second inspection. No user time charges are

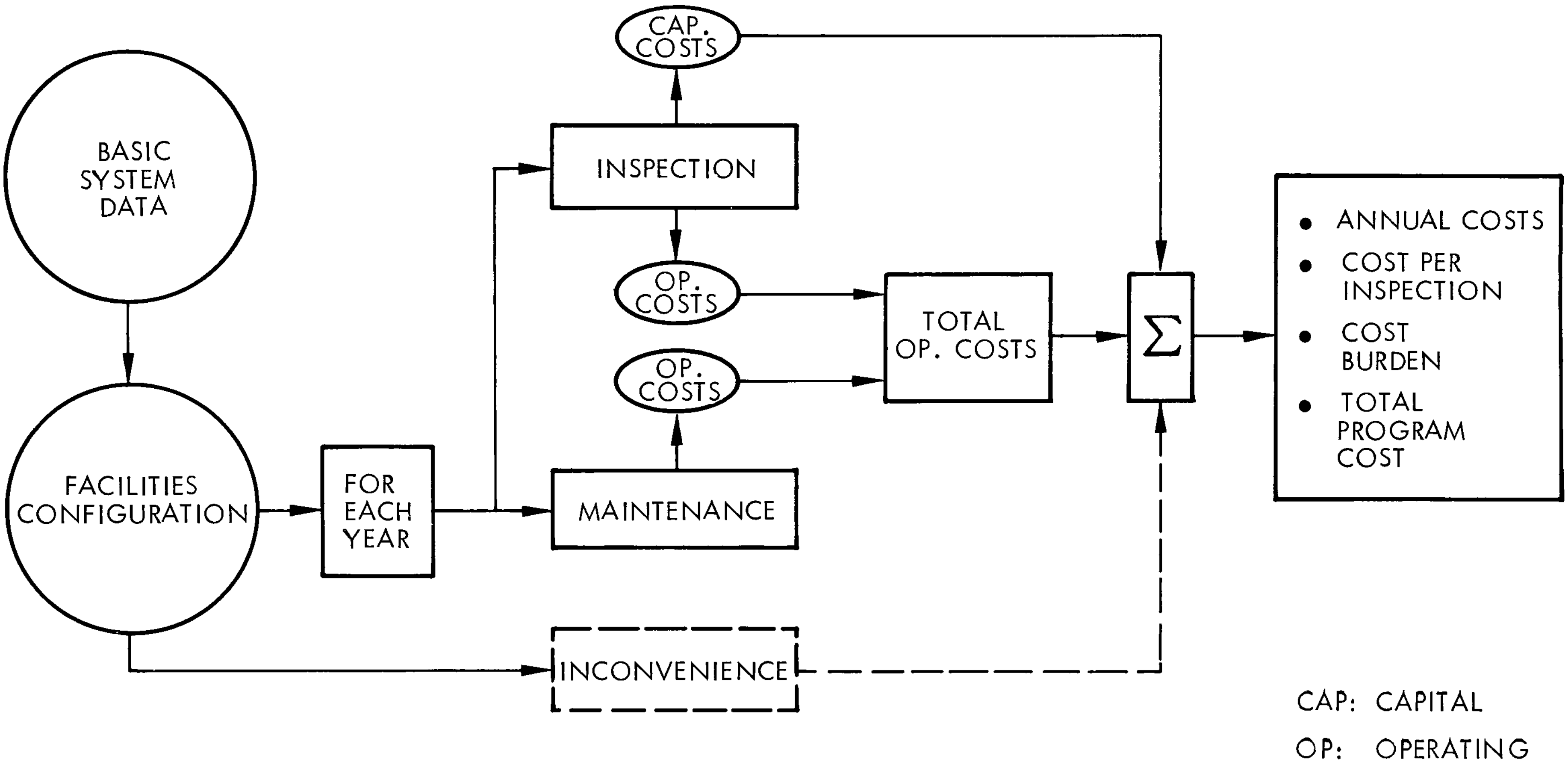


Figure 4-3. Cost Estimator Model Flow Diagram

allocated for the corresponding maintenance activities since these would probably have to be performed even in the absence of an enforced program.

The conversion of these times to a direct dollar amount is done using a social cost of $1/hr. Thus, a direct comparison can be made between these costs and the designed facilities costs. The more stations deployed in the system, the lower the social cost to the public. However, capital investment costs required to set up the system may more than offset the savings achieved by the shorter driving times.

Another operational aspect analyzed by this model is the tradeoff between a labor-intensive versus an equipment-intensive system. Here, the implications of a fully automated monitoring and recording system are traded against the inherent advantages of a manual, low capital equipment system. Generally speaking, the equipment costs associated with the measuring and recording equipment are small in comparison with the overall operational costs and, thus, the issue revolves around the reliability of each system.

4.4 CRITERIA FOR POLICY EVALUATION

Up to this point, we have described the manner in which the simulation model computes measures of emission levels and relevant costs for a given policy statement regarding vehicle inspection and maintenance. We need now to identify an acceptable figure of merit which embodies within a single value a measure of the goals of the program. Comparison of different values of the figure of merit permits rapid assessment of relative economic-effectiveness of various policies. Ideally, then, we would select that policy set (i.e., inspection interval, emission level, pass/fail criteria, etc.) with the "best" figure of merit. Here, the term "best" refers to the lowest value of the figure of merit.

Unfortunately, no one figure of merit appeared to embody all of the desired characteristics. The simulation model instead has the capability of examining several different figures of merit, thus permitting a determination of the sensitivity of the optimal decision to the chosen objective function. The most relevant figure of merit and the one utilized throughout this study can be expressed by:

$$\text{Figure of Merit} = \frac{\text{Program Cost}}{\Sigma W_i \ \Delta E_{ci}}$$

where: W_i = weighting function for each emission specie

ΔE_{ci} = emission difference between baseline and test program

This relationship provides a basis for comparing base and test population emission levels with the cost of the test program. The figure of merit units are in discounted dollars per weighted tons of emission reductions. Thus, program effectiveness can be read in terms of so many dollars to achieve a reduction of one composite ton.

As can be seen, the weighting function establishes the degree to which emission specie reductions impacts the program design. Having fixed the weighting of emission reductions the model can determine the optimal pass/fail criteria and system design for the several proposed inspection/maintenance strategies. In actuality, the weighting of emission reductions must reflect the air pollution problem of the various urban centers. Since some regions are more concerned with high ambient CO levels than with HC levels, they would weight CO reductions higher than those of HC or NO. As discussed in Section 2, the Los Angeles Basin was selected for testing the feasibility of a program of vehicle inspection/ maintenance. For this case, the weighting function given in Table 4-1 was utilized in the overall economic-effectiveness evaluation.

Table 4-1. Regional Weighting Function

Emission	Weight
HC	60%
CO	10%
NO	30%

This weighting function, developed from EPA data (Reference 10) places equal weight on both HC and CO in terms of actual tons reduced. That is, since CO emission levels in terms of tons/day are six times those of HC, the net contribution of both after weighting is about the same.

The mechanism for actually determining the most attractive policy set from among the several proposed inspection/maintenance approaches should include not only the figure of merit, but also the inspection costs per car and attendant emission reductions. These latter two parameters are important in that they relate to the practical aspects of emission control. For example, it could be assumed that a program producing emission reductions less than 15%, no matter how economically attractive, would not be very effective as a control scheme. The guidelines selected for this study are in the form of the following cost constraints and emission reductions goals:

- Average cost of six dollars per car was the maximum allowable
- A program which provides emission reductions (HC and/or CO) of less than 15% was unacceptable.

These guidelines when used in conjunction with the figure of merit provide the criteria for analytically identifying the "best" inspection procedure and system design.

Each combination of inspection procedure and system design can be looked upon as a strategy. By examining the various strategies with the economic-effectiveness model, an ordinal ranking of these strategies based on their figures of merit can be developed. It becomes fairly straightforward to then identify the optimal strategy by merely selecting the one which ranks first and conforms to the cost and actual emission reductions guidelines described above.

5. MODEL SIMULATION RESULTS

The preceding sections described the system framework, assumptions, and input data required to evaluate the economic-effectiveness of an inspection/maintenance approach to vehicle emission control. Two basic questions to be resolved are: 1) the viability of the approach, and 2) the most attractive procedures in terms of a stated criteria.

The answer to the first question lies with the establishment of specified emission reductions goals and associated economic constraints. For this study emission reductions of approximately 15% for a specified emission specie(s) were required of each maintenance treatment in order to consider the procedure set viable. For example, the idle adjustment program is designed to primarily reduce CO emissions. Therefore, any idle maintenance procedure should provide at least a 15% reduction in CO emissions. Furthermore, any selected procedure should not increase the hydrocarbon concentrations above the stated baseline. As for the cost implications, it was held that for a program to be feasible the average cost should not exceed $6/car/inspection interval. These two criteria (i.e., 15% reduction and $6 maximum cost) when used in conjunction with the figure of merit formed the criteria for selecting the most cost-effective system.

Two basic inspection/maintenance approaches were examined within this context.

Engine Parameter Inspection: This approach provides for the direct inspection of the various parameter adjustments specified in the procedure. If the inspection procedure reveals parameter settings outside a predetermined range they are reset through appropriate maintenance to manufacturer's specification.

Emission Signature Inspection: Under this alternative, measurements are made of the vehicle's exhaust emissions using several engine loadings (i.e., driving modes). If the resultant mode emissions are higher than some preset criterion, the vehicle will be rejected and will undergo direct diagnosis at the repair facility and, if required, corrective maintenance.

Several mode emission signatures have been identified that allow detection of component malfunctions at the subsystem level.

Embodied in each of these two approaches are a number of substrategies. Simulations were performed to evaluate the degree to which the figure of merit, and, therefore, the policy decision is sensitive to changes in the values of the design variables. For the case of multidecision inspection procedure (i.e., several parameter settings or mode emissions) a matrix of candidate values was evaluated by holding all but one variable constant.

The analysis was conducted in two phases. The objective of the first phase was to evaluate the various alternatives within each of the major strategies. Here, tradeoffs between maintaining engine subsystems (i.e., idle, ignition and induction) and combinations thereof were performed. In order to obtain a consistent base for comparing the effectiveness of the subsystem strategies, an optimization of procedures was undertaken. In the case of the engine parameter inspection procedure, this involved determining optimal pass/fail values for timing, rpm, idle CO and air cleaner blockage. For the emission inspection procedure, emission signatures using both idle and loaded CO and HC modes were evaluated. Based on a consistent evaluation of this information for both basic strategies, an assessment of the general feasibility of a vehicle inspection/maintenance program was made.

Presented in Table 5-1 are representative summary results which fit our performance criteria for the several strategies examined with the model. Depicted for each engine parameter inspection and emission inspection procedure are the figure of merit, cost per inspection/maintenance per car, and expected emission reductions. Each strategy presented has been optimized with respect to the figure of merit by varying the pass/fail criteria for the engine parameters or mode emissions and the interval of inspection. Inspection of Table 5-1 reveals that the most cost-effective procedure for reducing CO is an engine parameter inspection followed, if necessary, by an idle maintenance treatment. Within this option two inspection alternatives are evaluated, a state-lane inspection and a franchised garage inspection. Applying our emission reductions goals criteria it would appear that either procedure will be satisfactory.

Table 5-1. Summary of Most Cost Effective Inspection/Maintenance Procedures
4-Year Average Emission Reductions

Inspection/Maintenance Procedure	Figure of Merit $/Ton	Cost per Vehicle $	Emission Reduction % HC	CO	NO
Engine Parameter Diagnostics					
A. Short Inspection (State Lane)					
• Idle (ICO and rpm)	315	1.50	0	15	-7
B. Long Inspection (Franchised)					
• Idle (ICO, rpm, timing)	366	2.50	3	13	-3
• Idle + Ignition	455	6.00	18	14	0
• Idle + Ignition + Induction	537	12.50	22	33	-5
Emission Signature Analysis					
A. Idle Mode (State Lane)					
• Idle (CO emission)	422	2.50	2	12	-4
• Idle (CO and HC emission)	458	2.50	3	11	-4
B. Loaded Mode (State Lane)					
• Idle + Ignition	356	4.00	11	16	-4
• Idle + Ignition + Induction	411	6.00	15	20	-3

Note: Shaded rows show those procedures which passed performance and cost criteria.

Actually, if more emphasis were placed on reducing CO levels, i.e., through a reweighting of the payoff function, the state-lane procedure would emerge as the most cost effective. Examining the more elaborate engine parameter inspection/maintenance procedures (i.e., idle + ignition and idle + ignition + induction) indicates that substantial reductions in emissions can be achieved. However, these reductions are more than offset by increased program costs, primarily attributable to repair parts and increased inspection/maintenance labor times. The cost of the latter procedure, actually exceeds the upper economic constraint established for the study. NO emissions increase because of the higher combustion temperatures associated with leaner carburetion. This increase is partially offset by retarding the basic timing.

In order to determine the long-term effects, it is important to examine the emission time histories for the various procedures. Shown in Panels A, B and C of Figure 5-1 are HC, CO and NO emission profiles, respectively, for the idle engine parameter inspection/maintenance procedure. For this analysis, the identification of acceptable procedures was limited to those that substantially reduced HC and CO emission levels. The main conclusion to be drawn from Figure 5-1 is that an idle adjustment program has its largest effect on CO levels. While an average reduction figure of some 13-15% was obtained from this procedure, it is obvious that a much larger CO reduction, i.e., 20-25% can be achieved once an equilibrium point has been reached. The equilibrium point is defined as that emission level where the fraction of vehicles being rejected is a constant and the emission level has stabilized at a new level. For CO an equilibrium point at year four has not been reached and, therefore, the anticipated emission reductions for year five should be greater. The small differences in baseline and test fleet HC emission levels can be attributed to the slight effect of the idle parameter adjustments (e.g., idle CO, rpm, timing) on composite HC. A small effect also is shown in increased NO emission levels. For all the alternatives examined, the NO emission level did not increase beyond 7% and usually remained invariant around 4%. The NO emission profile is most affected by a timing adjustment.

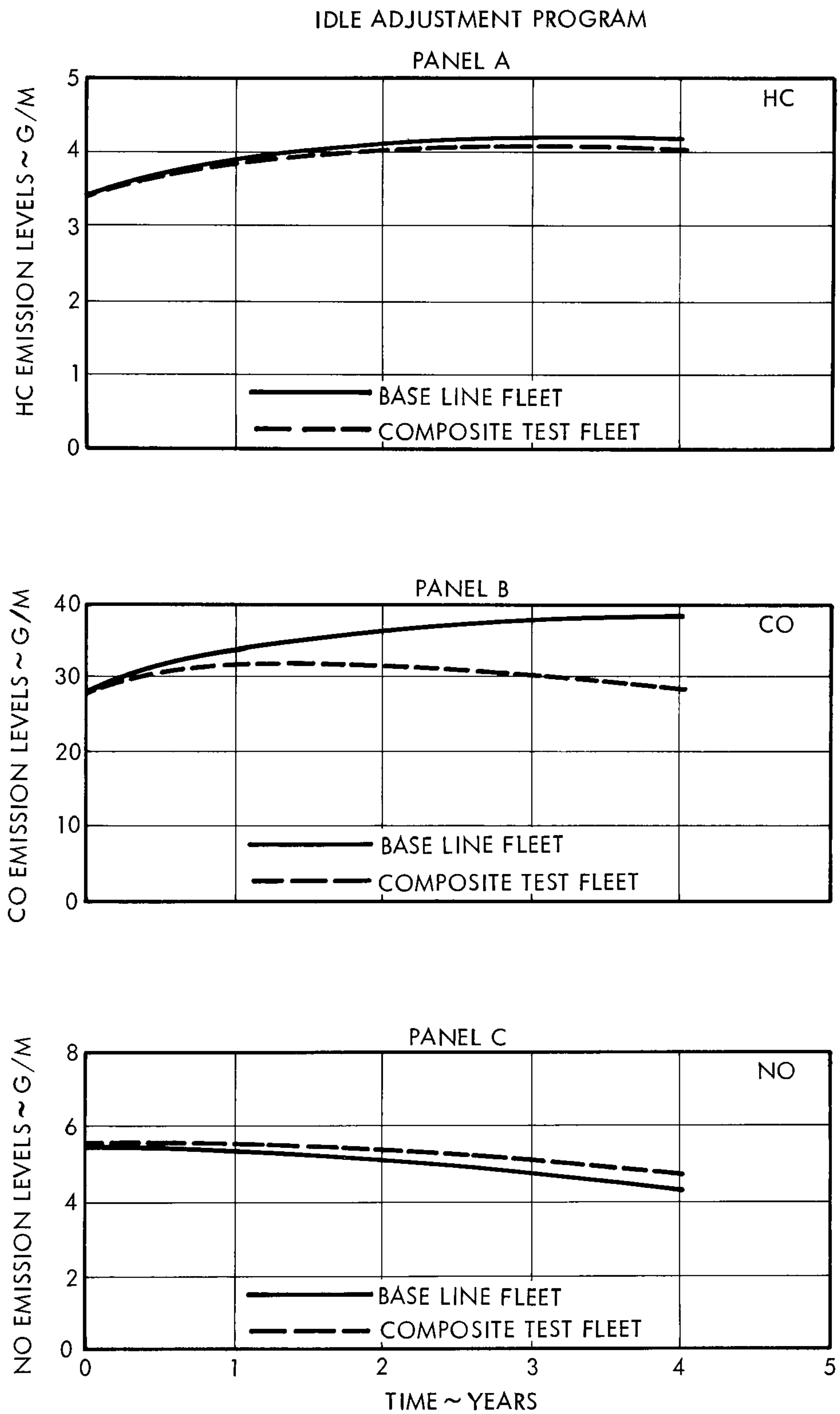


Figure 5-1. Emission Time Histories — Engine Parameter Inspection

The model also predicted a similar set of emission time histories for the emission signature inspection procedure. Presented in Figure 5-2 are representative emission histories for maintenance treatments involving either an idle + ignition maintenance or an idle + ignition + induction tuneup. As could be expected, these inspection/maintenance procedures are more effective in reducing emission levels than for the case of a simple idle adjustment program. As exhibited in Table 5-1, these two procedures are the most cost-effective of any of the major maintenance procedures examined. Their biggest contribution over the idle maintenance strategy is in reducing hydrocarbon emission levels, the primary reason being the replacement of ignition subsystem components. Although the emission reductions experienced with an emission inspection procedure are not as great as with the engine parameter inspection, the overall cost-effectiveness is appreciably higher.

The third strategic variable analyzed by the model is the frequency of inspection. Here the interest is in examining the impact of varying inspection frequencies on program effectiveness, i.e., the tradeoff of benefits obtained from shorter inspection intervals with the added cost. A typical tradeoff of inspection frequency for one policy alternative is presented in Figure 5-3. As can be seen, the lowest figure of merit value occurs for inspection intervals in the range of 12-14 months. For administration reasons a 12-month frequency of inspection should prove most cost-effective. The dotted segment of the curve describes the situation where the emission reductions approach zero and the figure of merit infinity.

This discussion has centered on some of the summary level results obtained from the study. A more detailed discussion of the two basic inspection policies follows.

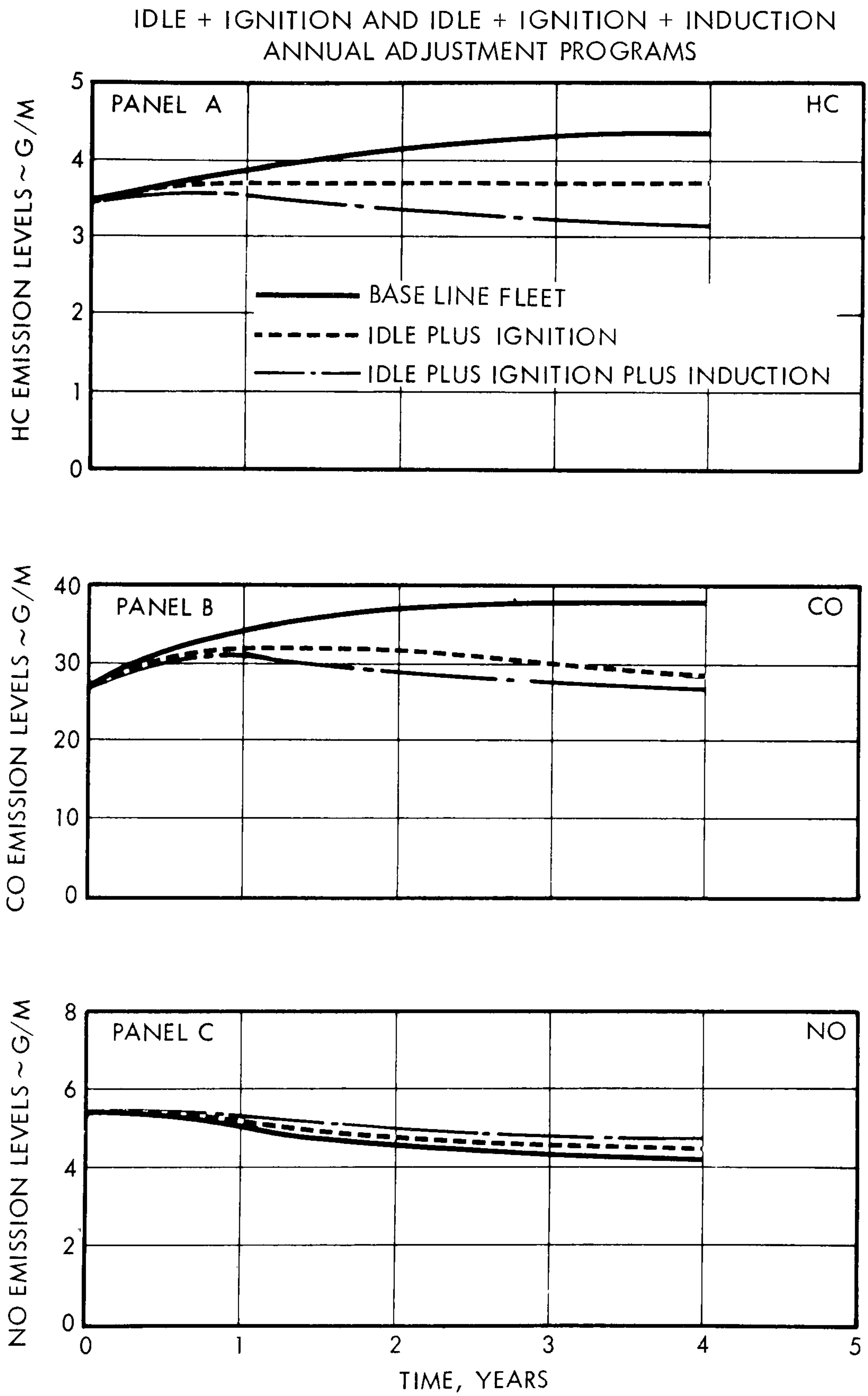


Figure 5-2. Emission Time Histories — Emission Inspection Procedure

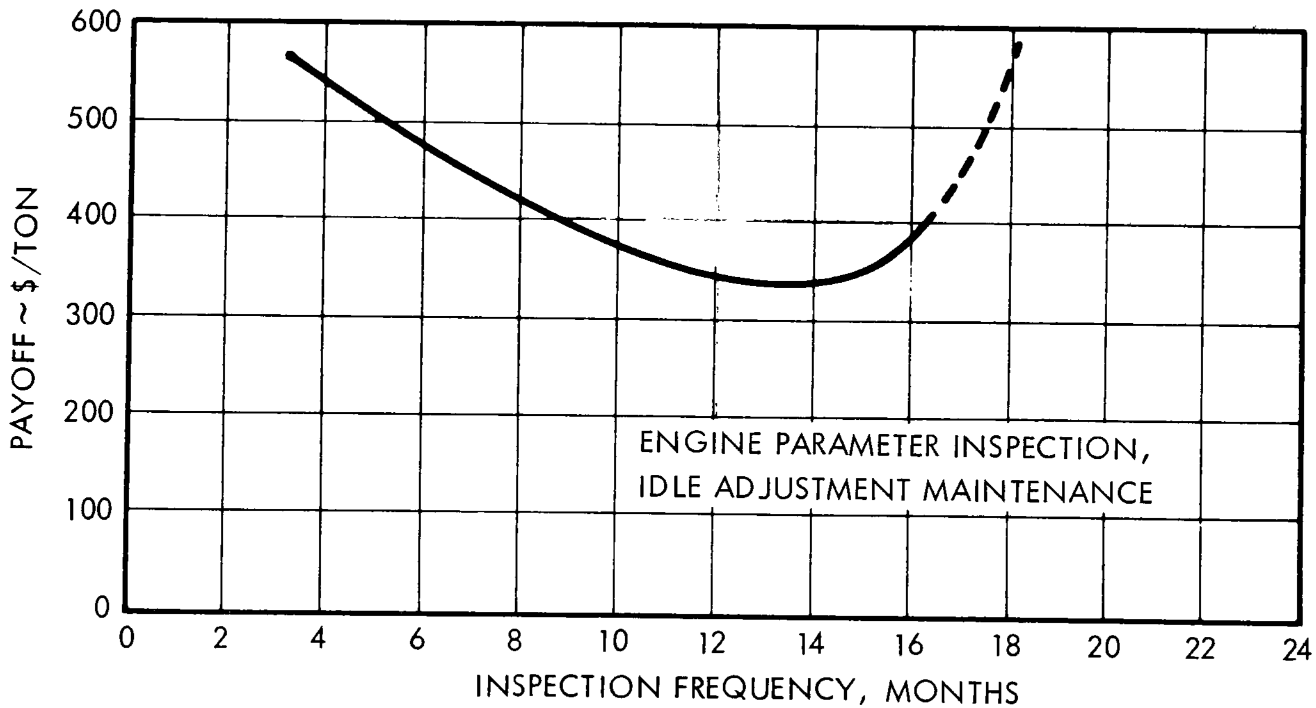


Figure 5-3. Impact of Inspection Period on Program Effectiveness

5.1 ENGINE PARAMETER INSPECTION/MAINTENANCE PROCEDURES

The engine parameter inspection procedure offers the advantage of minimizing the number of diagnostic errors (i.e., errors of omission and commission) during the inspection activity. This characteristic makes this approach extremely attractive in terms of effectiveness and reliability. Shown in Figure 5-4 are resulting figures of merit obtained in simulating various pass/fail criteria and combinations of engine idle parameters. Panels A and B depict figure of merit contours for various idle CO, timing and rpm pass/fail cutpoints. Two rpm cutpoints, -75 rpm and -50 rpm, were sufficient to detect substantial changes in the shape of these cost-effectiveness contours. The more compact the contours are, the more optimal the system has become. The most cost-effective contour plotted (i.e., $350-400/ton) suggests that the optimal pass/fail criteria for the idle subsystem are idle CO = 3.7%, timing = 7 degrees, rpm = 75. Changes in idle CO are indicated to have the largest overall effect on program cost-effectiveness even though this emission species has the smallest weighting factor.

Panel C shows the simulation results for the air cleaner component of the induction subsystem. The abscissa value represents the degree to which the air cleaner passages were blocked. An optimal pass/fail value of roughly 105^o of blockage was determined from the analysis.

These four engine parameters were the only ones optimized with respect to a range of cutpoint values. The other three engine parameters--ignition, air pump and PCV--were maintained on the basis that they failed a single cutpoint as discussed in Section 3. For the PCV system, all vehicles (approximately 12%) which had positive crankcase pressures were assumed to be sufficiently plugged to require repair. Any vehicle misfiring in the range of engine load of the seven-mode cycle were also failed. These assumptions are consistent with the data acquired. However, for the case of the malfunctions involving air-fuel flows such as PCV and air reactor system restrictions, a parameter optimization would be possible if vehicle population distributions of flow rate through these devices were available. Since this was not the case, it was assumed that only those devices which were completely failed were maintained.

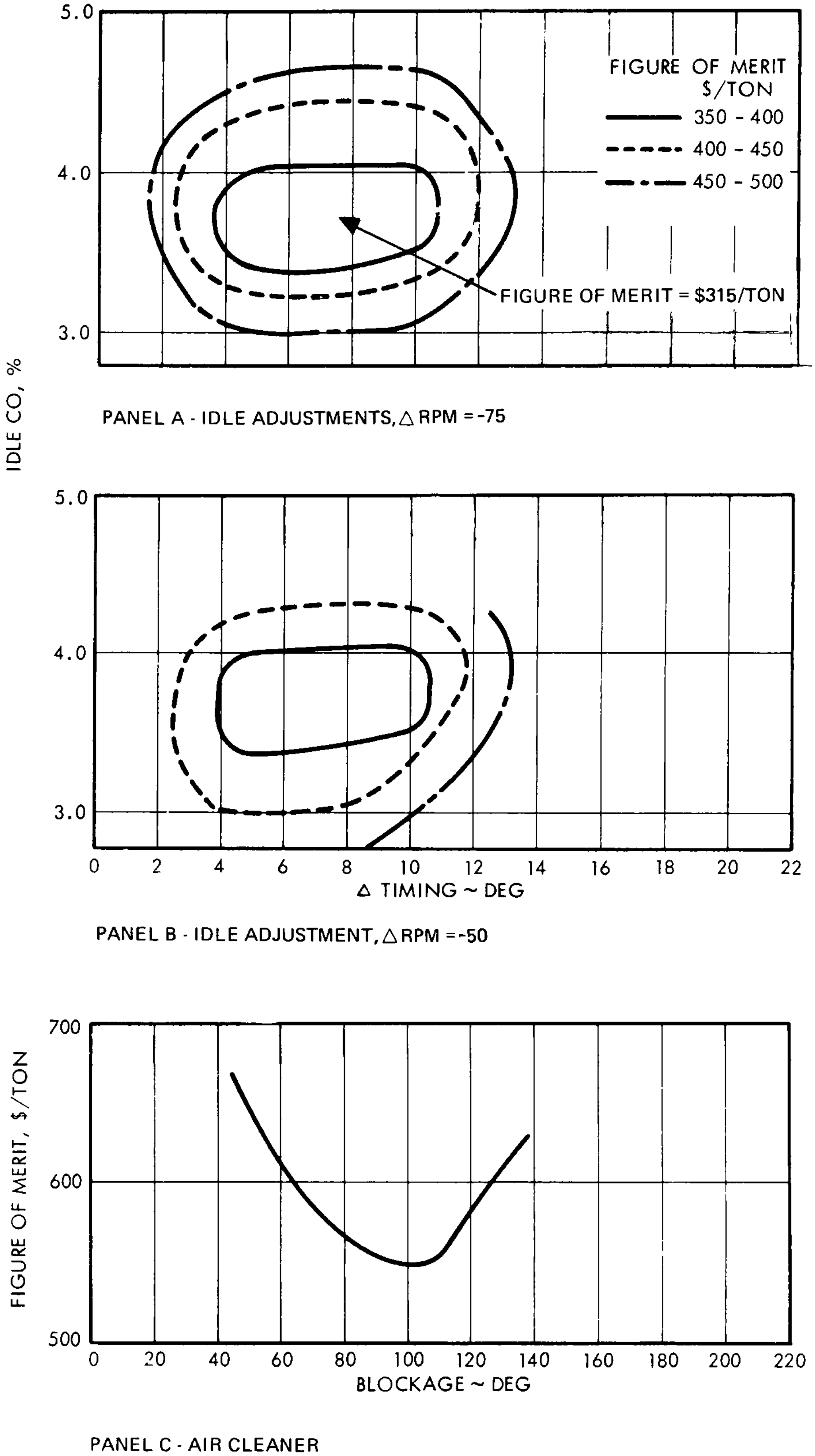


Figure 5-4. Engine Parameter Subsystem Optimization

Table 5-2 presents an optimal set of engine parameter settings for the several subsystem combinations. These criteria produce a series of emission time history plots similar to those presented in Figure 5-1. Whereas, Figure 5-1 related emission histories for an idle inspection/maintenance program, Figure 5-5 relates emission histories for an idle + ignition and idle + ignition + induction tuneup. As anticipated, these more complete maintenance programs reduce emission levels substantially below those produced by an idle adjustment program. This is especially true in the case of hydrocarbon emissions. In all cases these programs tend to improve with time. This condition is attributed to the fact that the vehicle population has not reached a state of equilibrium.

The simulation model examined the operational characteristics of the various inspection/maintenance alternatives over a four-year time horizon. Selection of a four-year period was based on the desire to minimize the impact of the following factors on determining the most cost-effective program design.

- Uncertainty in predicting the implications of proposed 1975 Federal standards.
- Uncertainty in estimating the effects on emissions of major engine repair beyond four years.
- Lack of experimental emissions deterioration data beyond 50,000 miles (i.e., approximately four years).

As stated earlier, the vehicle population fleet was divided into two emission control classes--air injection reactor (AIR) and engine modification (EM). Figures 5-6a, b and c presents the emissions profiles for these power trains for an idle adjustment program. Hydrocarbon emissions show that the AIR emission controlled vehicles are slightly more sensitive and responsive to an idle adjustment program. The higher sensitivity of AIR cars to the various maintenance programs can be traced to both the larger emission decrements achieved as well as to their lower rates of emission decay. Data utilized for this study showed that AIR cars as a general class have higher emission levels initially than do engine modification vehicles. Since most AIR cars are of an older vintage, (i.e., 1966-67) their emission levels would tend to be higher due to the additional mileage accrued. The main reason that the weighted average emission curve

Table 5-2. Optimum Inspection Strategies 4-Year Average Emission Reductions

Weight Factors: HC = .6, CO = .1, NO = .3

OPTIMUM EMISSION INSPECTION	
ENGINE SUBSYSTEM	MODE EMISSION CUT POINTS
• IDLE, FUEL TO AIR ADJUSTMENT ONLY	ICO = 4.0%
• IDLE, IDLE PARAMETERS	ICO = 4.0% IHC = 300 PPM
• IDLE + IGNITION	ICO = 2.5% IHC = 300 PPM LHC = 400 PPM
• IDLE + IGNITION + INDUCTION	ICO = 2.5% IHC = 300 PPM LHC = 300 PPM LCO = 1.0 %
OPTIMUM ENGINE PARAMETER INSPECTION	
ENGINE PARAMETER	PARAMETER CUT POINT
• AIR CLEANER	105 DEG. BLOCKAGE
• PCV	PLUGGED
• AIR PUMP	FAILED
• MISFIRE (IGNITION)	2.5%
• TIMING	7 Δ DEG.
• RPM	-75 Δ RPM
• IDLE CO	4%

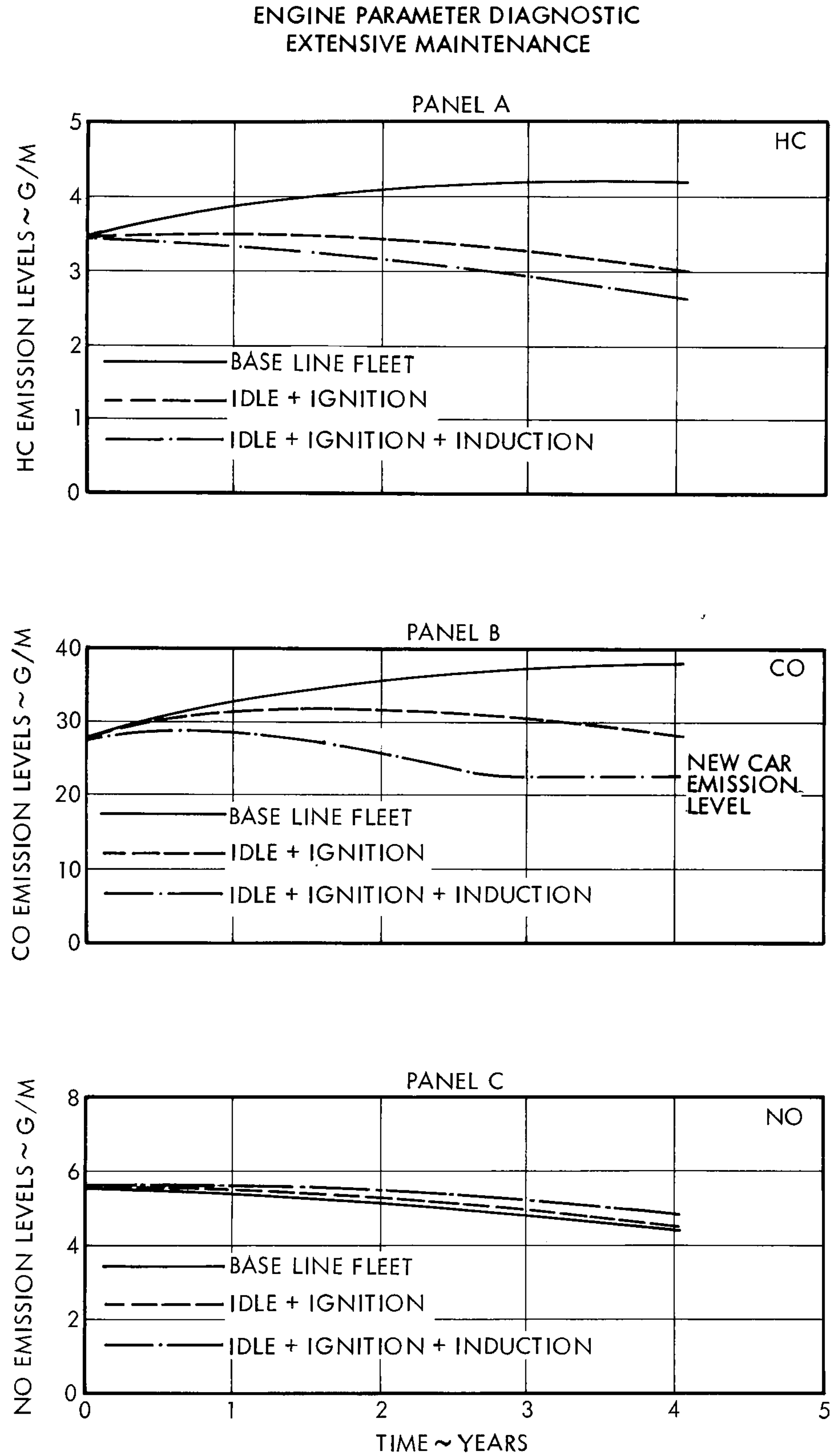


Figure 5-5. Emission Time History for Several Parameter Inspection Procedures

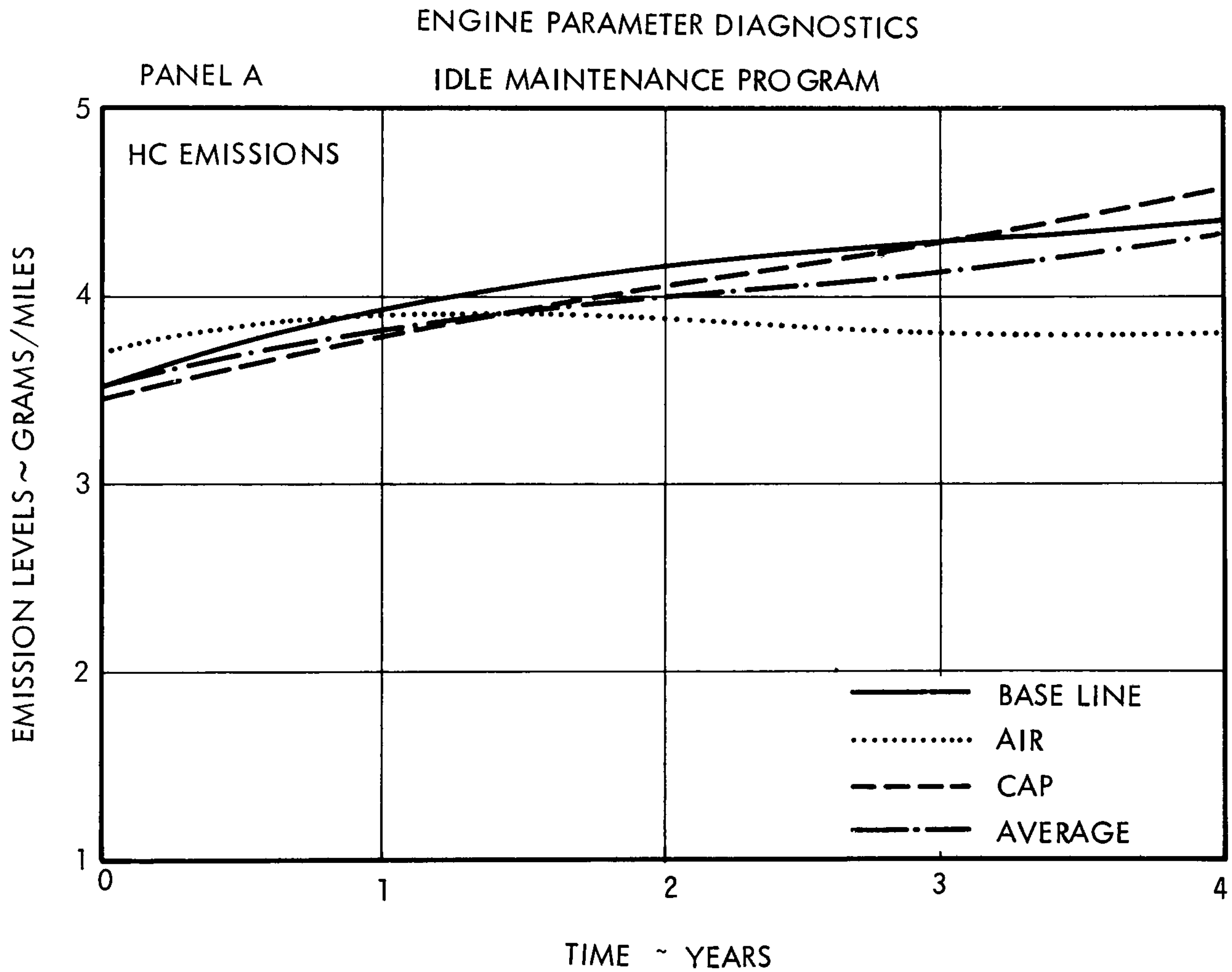


Figure 5-6a. Power Train Emission Histories — Panel A

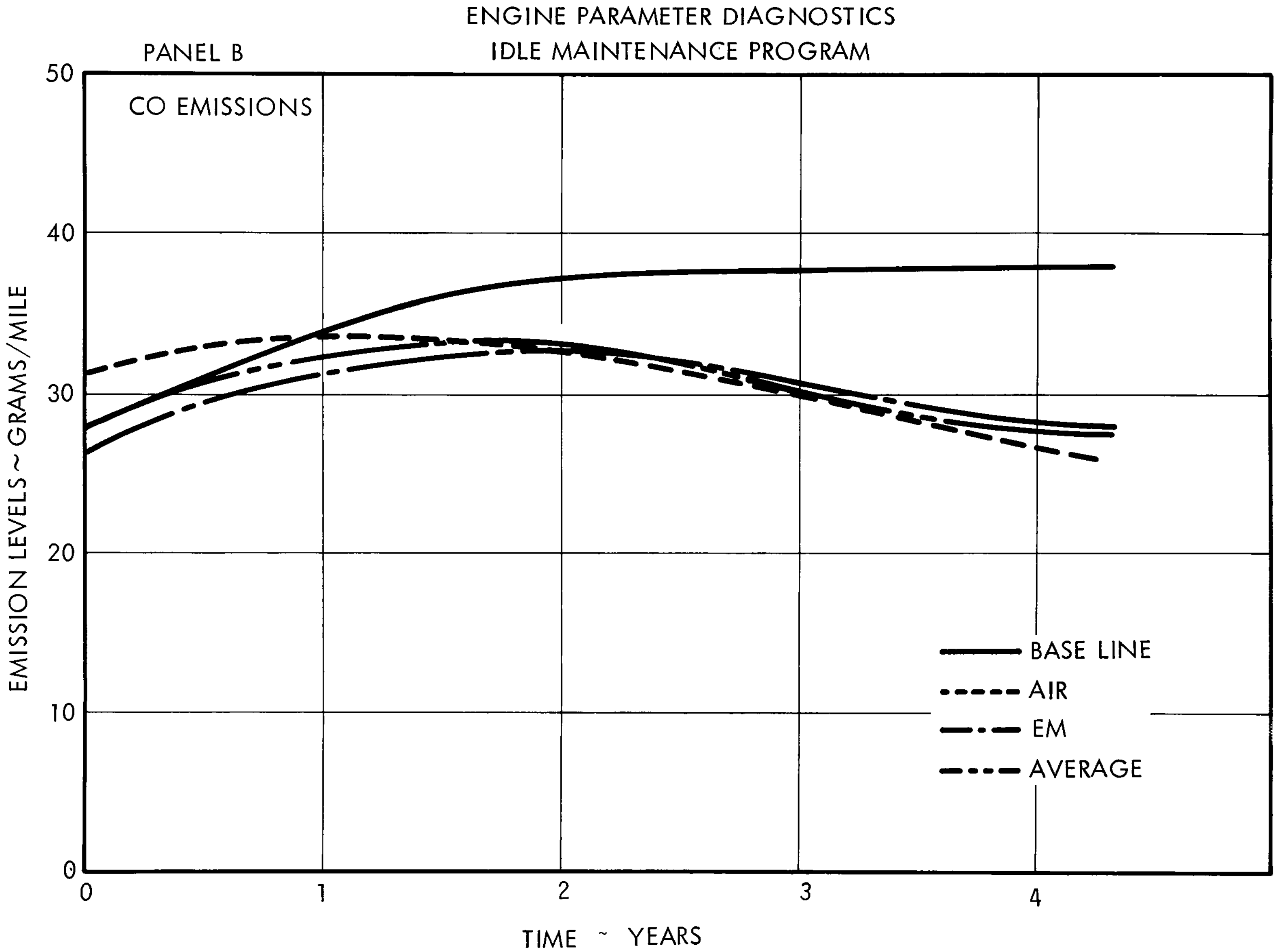


Figure 5-6b. Power Train Emission Histories — Panel B

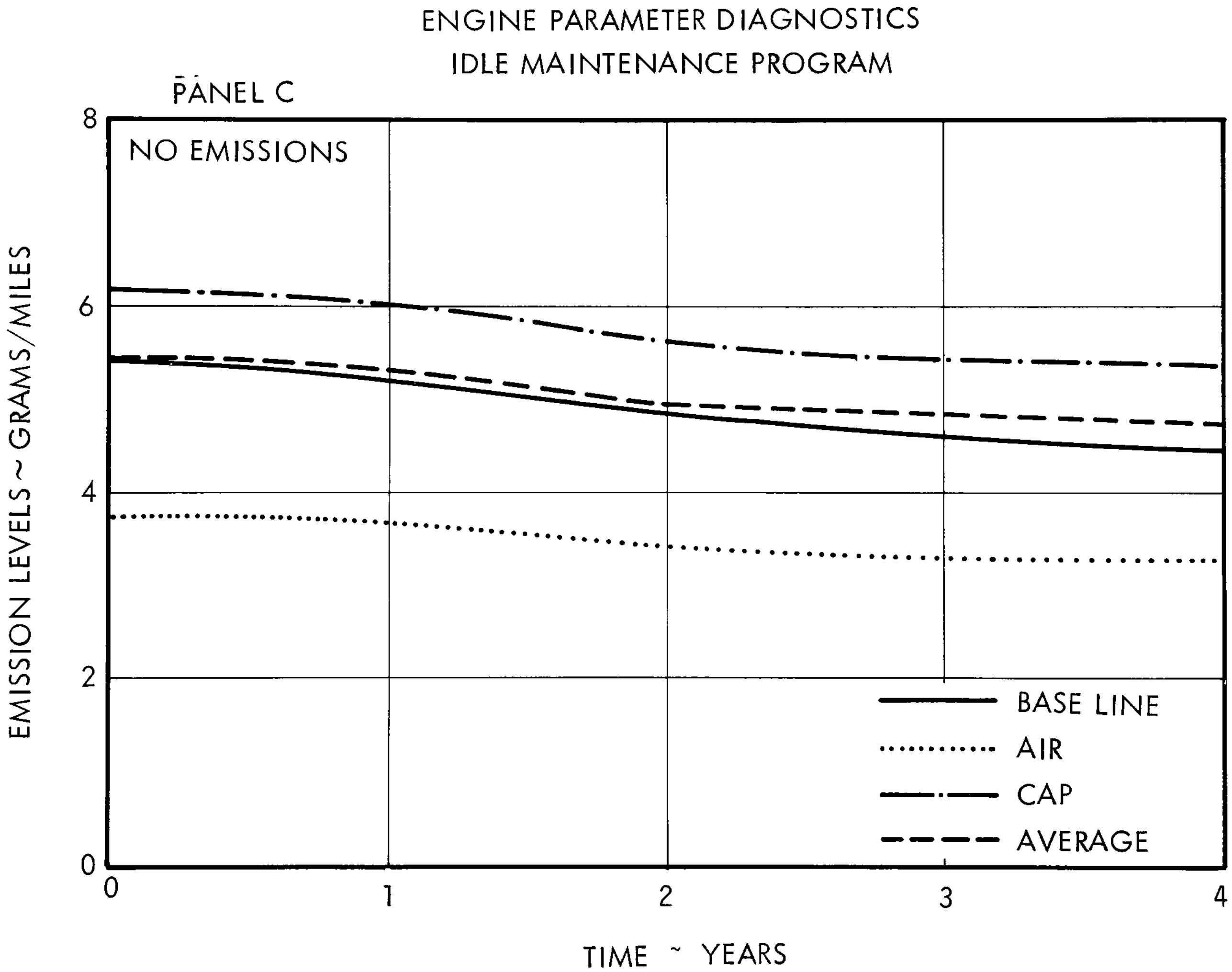


Figure 5-6c. Power Train Emission Histories — Panel C

does not more strongly reflect this fact is that AIR vehicles comprise only 30% of the Los Angeles population. CO emissions are nearly equally responsive to idle adjustment for both power train types, Panel B. NO emissions show (Panel C) a trend of a gradual reduction over time. This is largely attributable to richer carburetion (i.e., increasing CO emissions level) with time when enforced carburetor maintenance is not imposed. AIR equipped vehicles are less sensitive to F/A ratio since CO emissions are oxidized to CO_2 in the air reactor, hence, AIR vehicles are operated at richer carburetion with lower NO emissions.

A summary level matrix of engine parameter diagnostic procedures is presented in Table 5-3. Examination of this table reveals that the short inspection-idle maintenance procedure is most cost-effective. However, the resultant HC emission reductions are not appreciable, ranging from 0 to 3%. The basic difference between these two candidates is that the first one employs a state-lane inspection system whereas in the second both the inspection and maintenance activities are conducted in a franchised garage. In terms of the actual inspection process, only idle CO and rpm are examined in the state-lane system. This situation accounts for the fact that changes in both hydrocarbons and oxides of nitrogen are negligible, these species being strongly affected by timing. The average cost-per-vehicle of the two alternatives falls between $1-3 and is not in conflict with the $3/car reported for the GM adjustment program and the $6/car reported for the present New Jersey inspection program. The other alternatives listed, although producing larger emission reductions either have significantly larger figures of merit or fail to meet the stated performance criteria.

Although the most complex inspection/maintenance procedures are highly effective in reducing emissions, costs of both inspection and maintenance escalate rapidly. For example, every vehicle must undergo an ignition system diagnosis with an electronic analyzer even though only 3-5% of the vehicles will be found to be misfiring. This incrementally increases the cost per vehicle by $2.50 without, as yet, effecting an emission reduction by subsequent repair. A similar problem is found with the induction system where costly inspections are required to find

Table 5-3. Optimal Engine Parameter Subsystem Inspection Strategies
4-Year Average Emission Reductions

WEIGHT FACTORS: HC = .6, CO = .1, NO = .3

SUBSYSTEM INSPECTED	FIGURE OF MERIT $/TON	COST PER INSPECTION $	% EMISSION REDUCTION HC	CO	NO
• IDLE PARAMETERS					
• STATELANE	315	1.50	-0	15	-7
• FRANCHISED	366	2.50	3	13	-3
• IGNITION	472	4.00	16		1
• INDUCTION	573	6.00	5	19	-2
• IGNITION + IDLE PARAMETERS	455	6.00	18	14	0
• INDUCTION + IGNITION + IDLE	537	12.50	22	33	-5

Note: Shaded rows show those procedures which passed performance and cost criteria.

repairable malfunctions which affect air-to-fuel ratio. In addition, the costs of repair in terms of parts and direct labor charges are substantially higher than for the simple idle adjustments.

The result is significantly higher costs to effect emission reductions, even though maintenance is quite effective on those vehicles with diagnosed failures. This fact suggests that if the inspection costs common to all vehicles can be substantially reduced, a more cost-effective procedure will evolve. As we will show in the following section, an emission signature inspection procedure will partially satisfy this requirement.

5.2 EMISSION SIGNATURE INSPECTION/MAINTENANCE PROCEDURES

Conceptually, a mode emission inspection offers several distinct advantages over an engine parameter inspection. The advantages lie with lower cost and relative ease of implementing the inspection procedure. The basic disadvantage of this strategy is the recurring problem of vehicle inspection errors. These inspection errors are the direct result of the inability to ascertain precisely which vehicles have malfunctions using an emissions measurement. This imprecision is caused by the confounding effects of engine malfunctions on mode emissions. In some instances a mode emission inspection will allow vehicles to pass even though they have engine malfunctions. This type of error is known as an omission error. Conversely, the testing procedures may fail a vehicle even though it does not have a malfunction which can be repaired with adequate cost-effectiveness. This type is called commission error.

The economic-effectiveness model was used to examine a wide range of emission inspection alternatives. Shown in Figure 5-7 are a series of simulations for various emission inspection procedures and their associated cutpoint criteria. An inspection/maintenance program using idle CO as an inspection criteria is shown in Panel A. The coupled idle maintenance treatment consists of adjusting the rpm, timing and idle CO. An optimal value of around 4% gives the lowest figure of merit. Panel B shows the sensitivity of program effectiveness to variations in hydrocarbon cutpoint. In this idle emission screening procedure both CO and HC were used as malfunction indicators. An idle hydrocarbon cutpoint of 400 ppm in conjunction

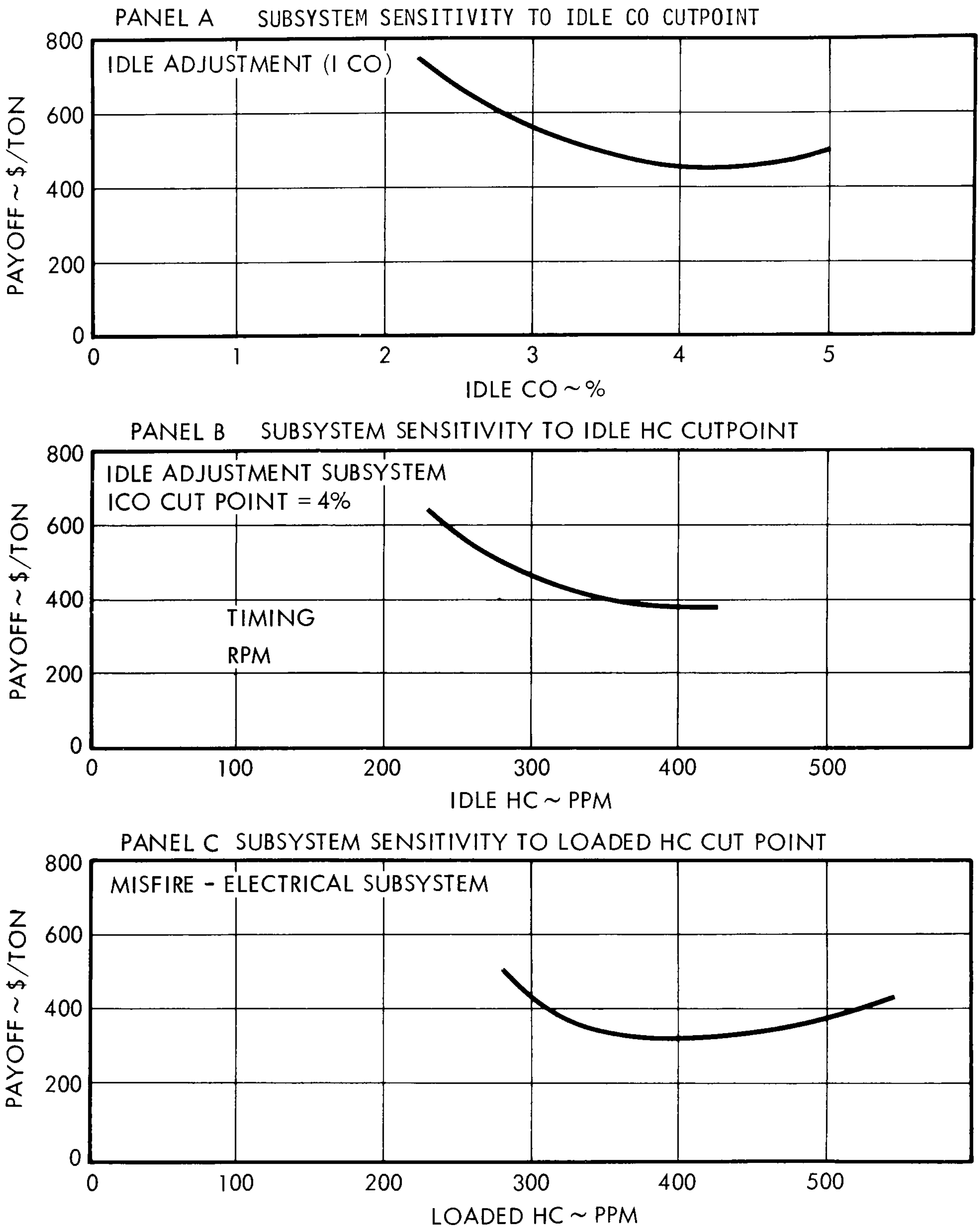


Figure 5-7. Sensitivity of the Figure of Merit to Mode Emission Inspection Criteria

with an idle CO cutpoint of 4% yields the optimal figure of merit. Panel C depicts the results for an idle plus ignition inspection/maintenance policy. Here, HC emissions measured with the engine loaded in acceleration is used to diagnose the state of the vehicle's ignition system. This loaded mode which was used in screening both ignition and carburetor subsystems malfunctions provided the least confounding of any of the modes analyzed. Again a value of 400 ppm appears to be optimal. Summarized in Table 5-2 are actual optimal cutpoint criteria obtained from evaluating the alternatives within the mode emission inspection approach. These combinations of cutpoints provide, in general, the best figure of merit. However, we will see that in some cases these procedures are not compatible with system performance requirements.

The effectiveness of the various inspection/maintenance alternatives are indicated by the emission time histories presented in Panels A, B and C of Figure 5-8. Shown for each specie are emission histories for an idle emission inspection and adjustment program. The screening procedure used in this case was a combination of idle CO and idle HC emissions. This combination of emission inspection modes provided a less effective procedure than when idle CO was used alone. Idle HC was added to detect timing and rpm malfunctions. As with the engine idle parameter inspection approach, this program has its largest effect on carbon monoxide reduction. The general trends of these plots are much the same as those exhibited in Figure 5-1. The lower hydrocarbon levels for the idle emission inspection approach can be attributed to the fact that a timing adjustment was included in these procedures; this was not the case for the corresponding state-lane engine parameter inspection procedure.

Emission profiles for different types of emission control devices are shown in Figures 5-9a, b and c for the idle inspection and adjustment procedure. The resulting trends in the emission profiles are similar to those for the engine parameter inspection procedure.

Table 5-4 presents a summary of the emission inspection procedures. The combined idle modes and loaded HC mode inspection is extremely cost-effective and offers substantial emission reductions, 11% and 15% for HC and CO, respectively. The good figure of merit results from the high

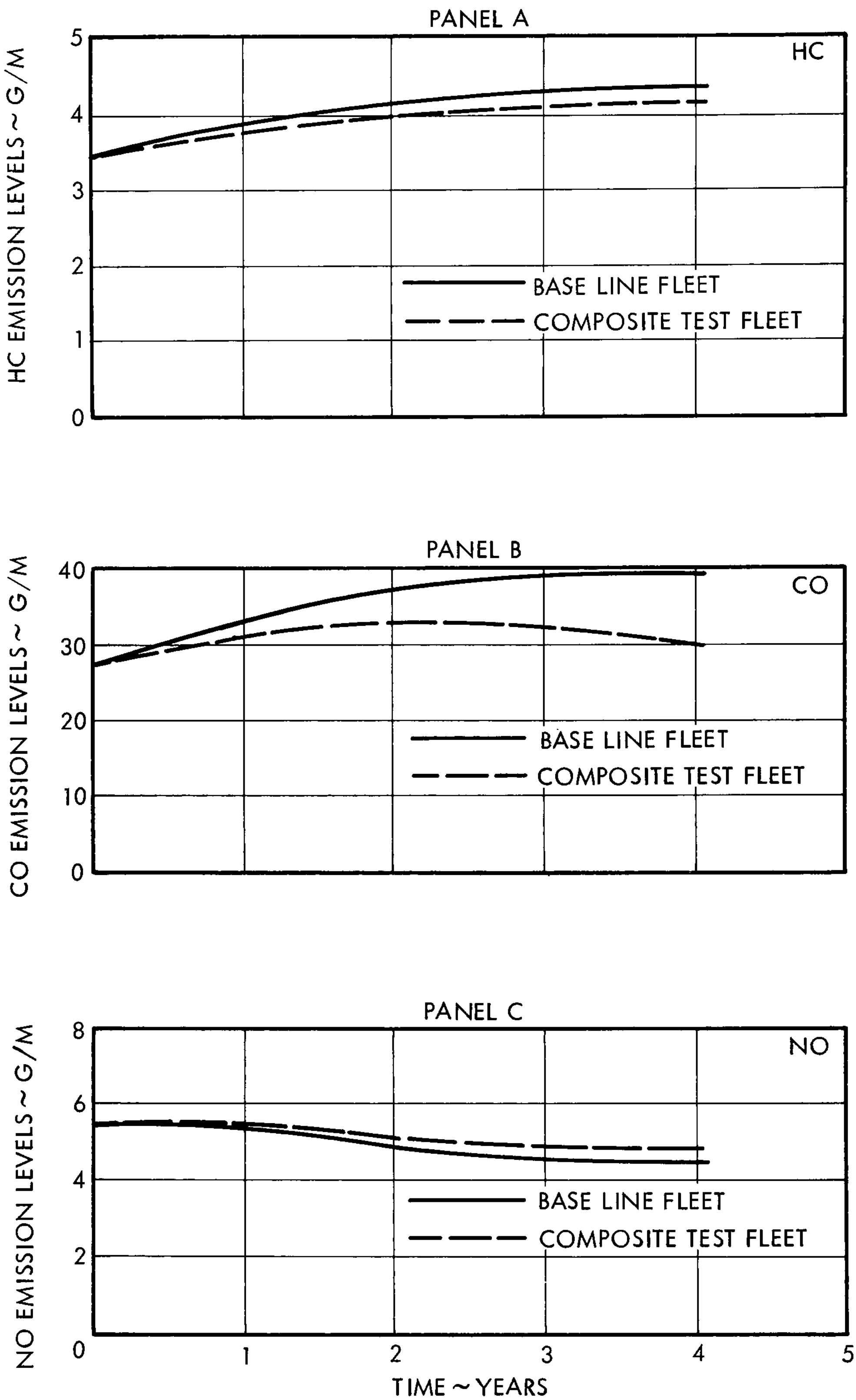


Figure 5-8. Emission Time Histories for an Idle Emission and Adjustment Program

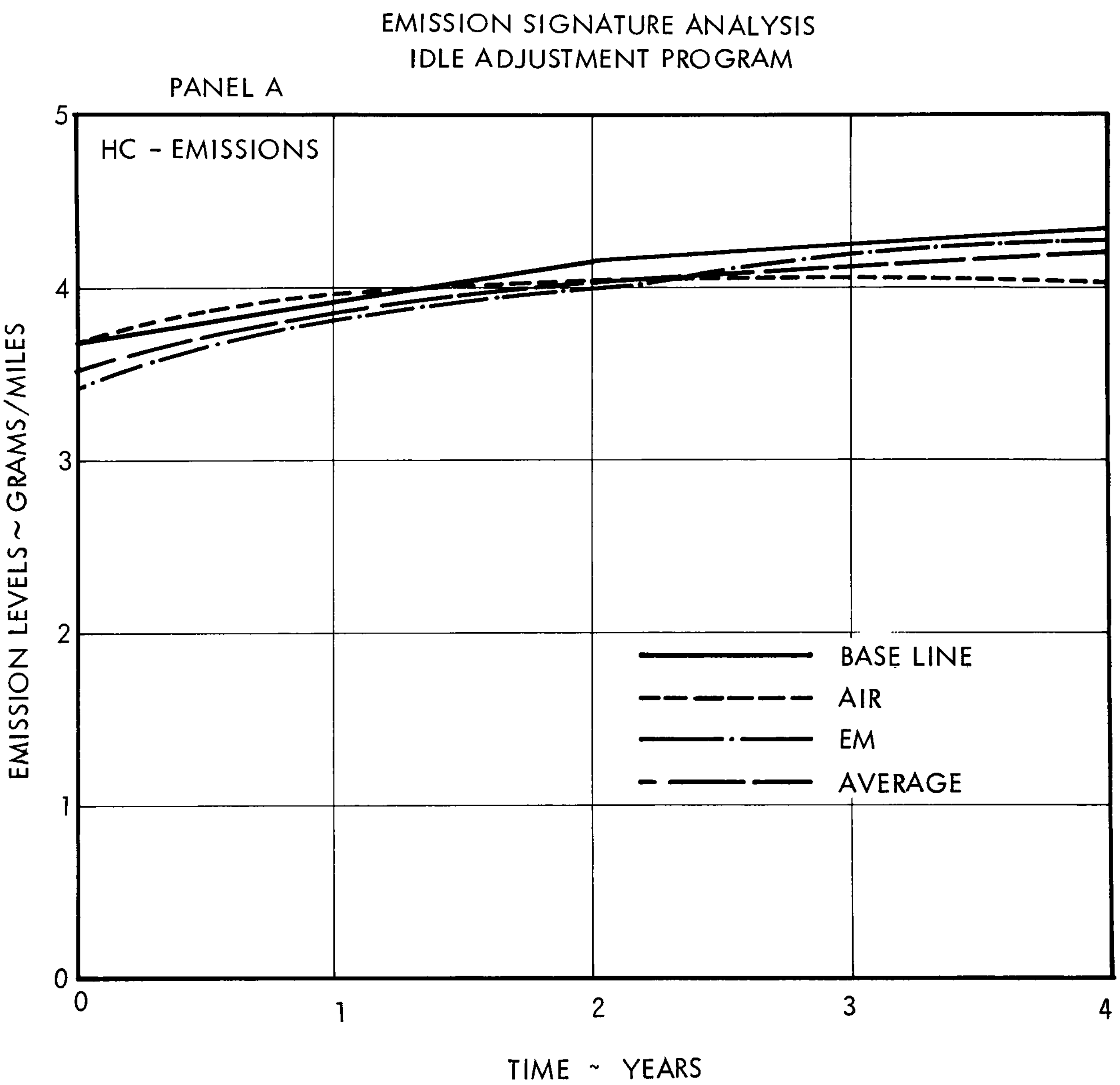


Figure 5-9a. Power Train Emission Histories — Panel A

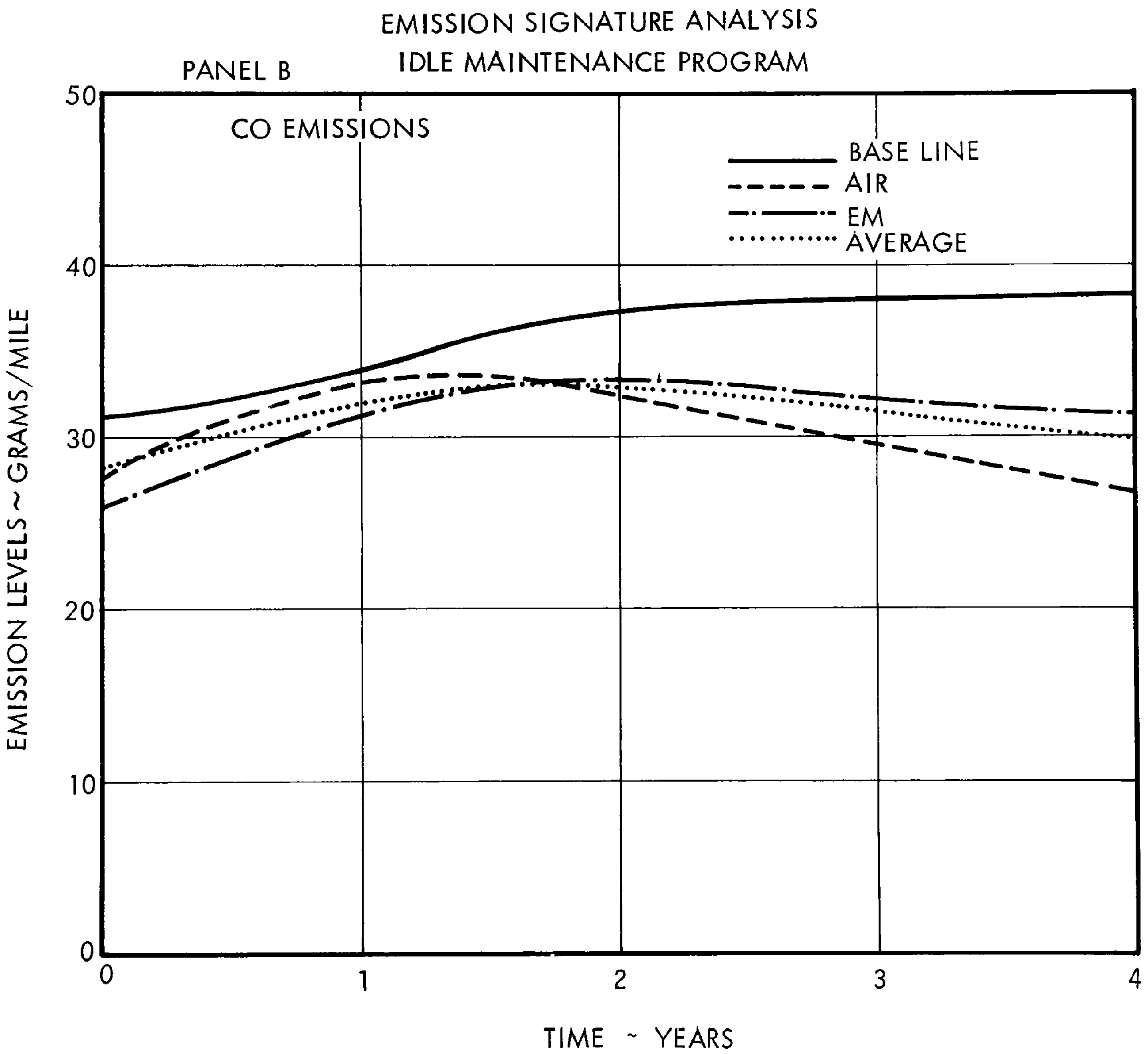


Figure 5-9b. Power Train Emission Histories — Panel B

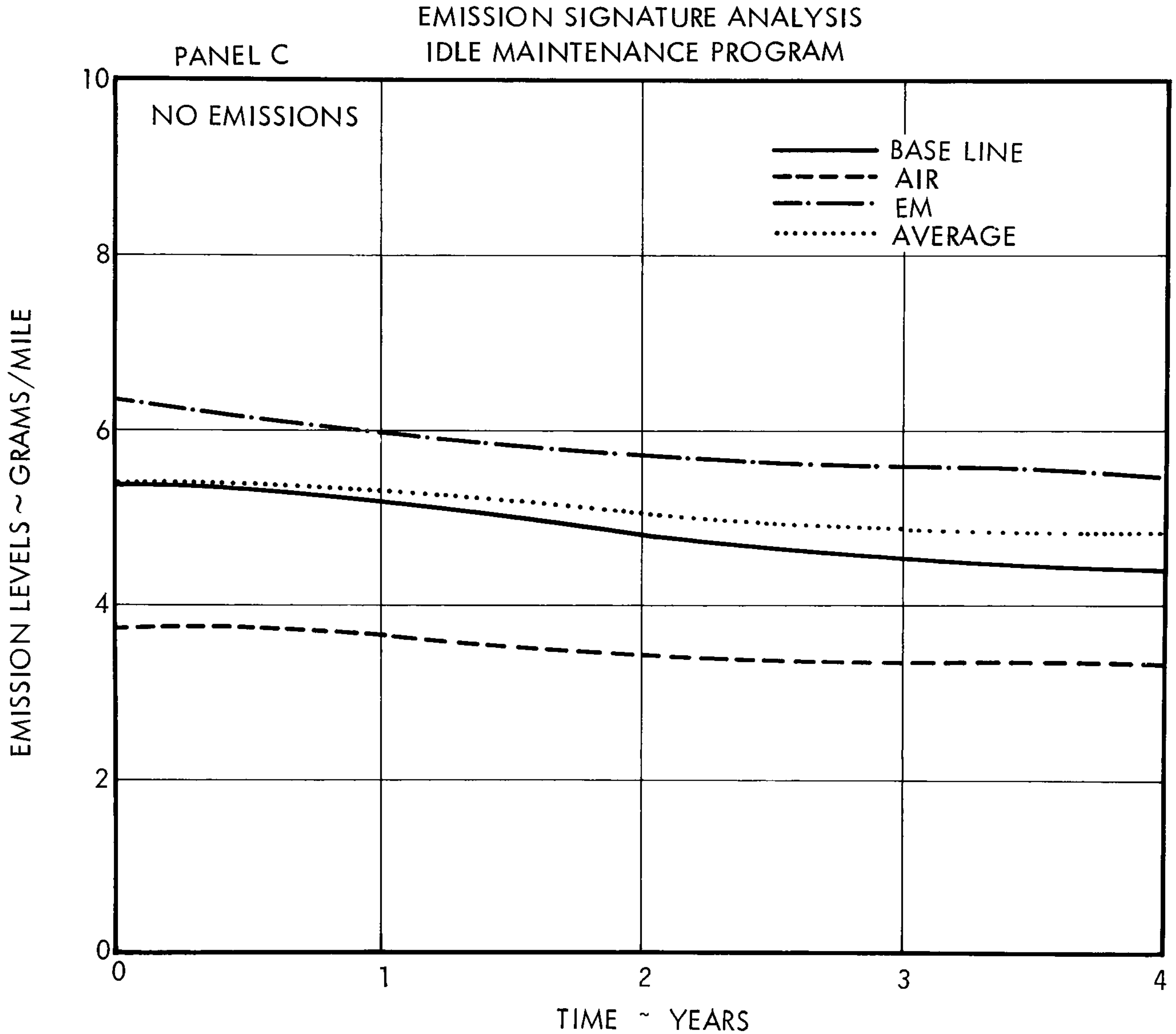


Figure 5-9c. Power Train Emission Histories — Panel C

weighting factor (0.6) on HC and significantly lower time regime for inspection (one additional minute) when compared to the conventional scope diagnosis which takes 15 minutes. The lower emission reductions when induction system repairs are included in the procedures are due to the large number of errors of omission. These omission errors, in general, tend to reduce the effectiveness of the several inspection procedures. Errors of commission directly impact on the costs associated with operating the program. These higher program costs result from the added time required to reinspect each vehicle that failed the initial screening inspection.

Table 5-4. Optimal Emission Signature Inspection Strategies

4-Year Average Emission Reductions
Weight Factors: HC = 0.6, CO = 0.1, NO = 0.3

INSPECTION MODE	SUBSYSTEM	FIGURE OF MERIT $/TON	COST PER INSPECTION $	% EMISSION REDUCTION HC	CO	NO
● IDLE CO	IDLE PARAMETERS	422	2.50	2	12	-4
● IDLE (CO + HC)	IDLE PARAMETERS	458	2.50	3	11	-4
		394	2.00	-2	12	-4
● IDLE (CO + HC) + LOADED (HC)	IDLE PARAMETERS IGNITION	356 †	4.00	11	16	-4
		280 *	3.00	10	13	-3
● IDLE (CO + HC) + LOADED (HC+CO)	IDLE PARAMETERS IGNITION + INDUCTION	411 †	6.00	15	20	-3
		315 *	4.00	12	19	-4

† Constrained optimum to obtain a 15% reduction in HC or CO

* Unconstrained optimum

Note: Shaded rows show those procedures which passed performance and cost criteria.

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