American Petroleum Institute

API PUBL*4637 96 ■ 0732290 0551695 130 ■

Analysis of Causes of Failure in High Emitting Cars

Health and Environmental Sciences Department
Publication Number 4637
February 1996

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ANALYSIS OF CAUSES OF FAILURE IN HIGH EMITTING CARS

Health and Environmental Sciences Department

API PUBLICATION NUMBER 4637

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OCTOBER 1995

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ACKNOWLEDGMENTS

THE FOLLOWING PEOPLE ARE RECOGNIZED FOR THEIR CONTRIBUTIONS OF TIME AND EXPERTISE DURING THIS STUDY AND IN THE PREPARATION OF THIS REPORT:

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PREFACE

by The American Petroleum Institute

Although new vehicles are designed to control exhaust emissions to specific levels for a significant portion of their useful lives, it is well known that these standards are substantially exceeded on average by vehicles in actual use. Inadequate maintenance, component failures, and tampering with emissions control systems are known to contribute to this problem.

In 1994 the American Petroleum Institute (API) sponsored a study to evaluate the primary causes of high emissions in the light-duty vehicle fleet. The effort focused on an analysis of emissions data from tests conducted both before and after the performance of repairs on 1981 and newer model vehicles. The data were compiled from five independently conducted programs which assessed the maintenance condition of vehicles representative of the in-use fleet. The compiled database was analyzed to: (1) assess the prevalence of different types of emission control system defects in the fleet; (2) classify the causes of those defects (e.g., malmaintenance, component failure, tampering, etc.) and (3) determine the contribution of those defects to fleet-average emissions.

Summary of fleet characteristics

The compiled database contained emissions and repair information on about 800 carbureted and fuel-injected automobiles representing a broad spectrum of geographic areas, maintenance histories and operating conditions. The carbureted cars were generally older models with higher odometer mileage (and thus higher emissions) than the fuel injected vehicles utilized in this study.

Results

This study produced the following results:

> *There are a substantial number of tampered or failed components, as well as normal maintenance items, on in-use light duty motor vehicles which are repairable. Large reductions in in-use emissions would accompany the repair of these components.*

One EPA survey of vehicles that had not been exposed to any inspection/maintenance programs found that, on a fleet-wide basis, carbureted cars contained an average of 2.8 failed components in contrast to an average of 1.2 failed components for fuel injected automobiles. It was estimated that the repair of all failed components on this fleet of

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vehicles would reduce composite (HC+NOx+CO/10) exhaust emissions by 69% for carbureted automobiles and by 39% for fuel injected cars.

There are several classifications or categories of faults that cause excess emissions.

These faults are related to either 1) component failures (both mechanical and electrical); 2) need for replacement or adjustment of maintenance items (spark plugs, ignition timing, etc.); and 3) tampering of emissions control components. The percentage of overall failures seen in each of these categories was as follows:

Percent of Failures by Category

Fuel System	Mechanical Failures	Electrical Failures	Malmaint-enance	Tampering
Carburetor	37	28	25	10
Fuel Injection	24	57	18	1

Failures of mechanical and electrical components are substantially more prevalent than tampering and maintenance related items - particularly in newer, fuel injected vehicles.

There are a few specific types of faults which have a significant effect on overall fleet emissions.

About 35% of the composite fleet emissions of carbureted vehicles is due to defective fuel metering systems. Defective oxygen sensors contribute an additional 10% of emissions. Ignition tune-up faults cause about 9% of the emissions.

Defective oxygen sensors cause from 22% to 15% of the emissions from light-duty fuel-injected vehicles. The variation in effect may be related to whether or not the fleet evaluated was subject to inspection and maintenance. Ignition tune-up was the only other fault that had a pronounced effect on the composite emissions from fuel-injected vehicles, ranging from 8% to 3%, depending on the test fleet.

Replacement of defective catalysts provides only small benefits for both carbureted and fuel injected vehicles.

Vehicle emissions warranty recalls provide only small reductions in fleet composite emissions.

Vehicle emissions warranty recalls are conducted regardless of the magnitude of the impact of the fault on emissions. In addition, the small emissions reductions from recall

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repairs may be related to the fact that these benefits have been based on tests of well-maintained vehicles with under 50,000 odometer miles. Therefore, many recall repairs probably have negligible benefits. It also should be noted that the purpose of warranty recalls may not necessarily be to provide significant reductions of in-use emissions.

Conclusions

The results of this study can be helpful in focusing on productive, cost-effective strategies for reducing excessive in-use vehicle emissions. For instance, the following strategies are worth evaluating:

- The periodic replacement of oxygen sensors as a routine engine maintenance requirement, similar to current requirements for spark plug replacement.

- A greater emphasis on improvements in component durability. Recently instituted 10 year/100,000 mile emissions warranty requirements by the EPA and the California Air Resources Board should result in increased durability.

- Identification of high-effectiveness repair strategies for inspection and maintenance programs. Comprehensive evaluations to determine which repair items are most effective in reducing emissions will provide benefits to consumers, repair technicians and air quality.

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TABLE OF CONTENTS

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TABLE OF CONTENTS (continued)

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LIST OF FIGURES

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LIST OF TABLES

Table | Page

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LIST OF TABLES (continued)

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EXECUTIVE SUMMARY

Under contract to the American Petroleum Institute (API), Sierra Research, Inc. (Sierra) analyzed emissions and diagnostic data collected from vehicles recruited from customer service to determine the primary causes of excessive exhaust emissions in the motor vehicle fleet.* The primary data sources used for this study were two programs conducted by the U.S. Environmental Protection Agency (EPA), two programs conducted by the California Air Resources Board (CARB), and one joint EPA-Industry program. The focus of the effort was on 1981 and later model year passenger cars and light-duty trucks. In addition to analyzing emissions test data from those five programs, data presented in CARB's Technical Support Document prepared for on-board diagnostic system regulations were reviewed. That report contained emissions data for catalyst, oxygen sensor, and exhaust gas recirculation (EGR) system repairs. Finally, a limited review of EPA and CARB recall data was performed to determine the fraction of fleet-average emissions that is reduced through recall actions.

ANALYSIS OF IN-USE DATA

Data from five sources were evaluated for this project:

- EPA-Industry Cooperative Test Program (CTP);
- EPA Hammond, IN Test Program;
- EPA Phoenix, AZ Test Program;
- CARB Fuel-Injected Vehicles Study; and
- CARB Enhanced I/M Pilot Project.

The databases contained baseline (i.e., as-received) emission results conducted using the Federal Test Procedure (FTP) for over 1000 vehicles. Nearly 800 of those vehicles

* Note that this study did not evaluate evaporative control system defects, which could be a significant source of excessive hydrocarbon emissions.

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also received repair to the emission control system (in some cases multiple repairs were performed) and were tested again over the FTP before being released to the owner. The repair information was used to identify the types of defects corrected and to determine the emission reductions from repair. Because of the large number of individual emission control components that can be repaired on a vehicle (i.e., well over 200), the repairs were classified according to the following categories:

- Carburetor replacement/rebuild (for carbureted vehicles);
- Carburetor/fuel metering system adjustment/repair (carbureted vehicles);
- Fuel injector replacement (for fuel-injected vehicles);
- Fuel injection/fuel metering system adjustment/repair (fuel-injected vehicles);
- Ignition system tune-up repair (i.e., spark plugs, ignition wires, distributor);
- Other ignition system component repair (e.g., coil, knock sensor, etc.);
- EGR system repair;
- Air injection system repair;
- Catalyst replacement;
- Electronic control unit replacement (i.e., the vehicle computer);
- Oxygen sensor replacement; and
- Other sensor replacement/repair.

The emissions impact associated with repairing defects in the above categories was estimated on a per-repair basis, and estimates were extrapolated to the fleet based on the fraction of defects observed in the in-use fleet. Those estimates were prepared

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independently for carbureted and fuel-injected vehicles. A summary of the results of the analysis follows.

Emission Reductions from Repair of Defective Components

Estimating the effects of emission reductions from repair of individual components was complicated by the fact that most of the databases analyzed in this effort contained before- and after-repair data on vehicles receiving more than one repair between tests. For that reason, a regression technique was developed to estimate the FTP emissions reductions from individual system/component repairs. A summary of that analysis for fuel-injected vehicles is contained in Table ES-1. As shown in the table, the electronic control unit (ECU) and the oxygen sensor are the two most important categories of emission control component repairs in terms of the magnitude of FTP emissions reductions. Note that Table ES-1 includes only the repairs that resulted in a decrease in the weighted FTP "score" (defined in this analysis as HC + NOx + CO/10) of more than 0.2 g/mi,* and only results that were significant at the 90% confidence level are included.

Comparing the results presented in Table ES-1 to a similar analysis prepared for carbureted vehicles indicated that the emissions effect associated with the repair of ECU and oxygen sensor failures is less severe for carbureted vehicles, and that repairs of fuel system metering failures have a greater impact.

Excess Emissions Versus Nature of Defect

In addition to identifying which components were repaired, this analysis classified defects according to the type of failure, i.e., mechanical failure, electrical failure, malmaintenance, and tampering. The assignment of failure type was based on the

* An exception to this criterion was made when EGR system repairs were performed. In those cases, the repair was included in the analysis if NOx emissions decreased by at least 0.2 g/mi, regardless of the effect on HC and CO emissions.

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Table ES-1. Emission Reductions Associated with the Repair of Fuel-Injected Vehicles.

Category	Reduction in FTP Emissions (g/mi)			
	HC	CO	NOx	Score[a]
Injector Replacement	0.68	10.08	-0.24	1.41
Fuel Metering System Repair	0.56	7.93	0.22	1.36
Ignition System Tune-up Repair	ns[b]	ns	ns	1.00
Other Ignition System Repair	0.94	ns	ns	ns
EGR Repair	ns	ns	0.85	ns
Air Injection Repair	ns	ns	ns	1.96
Catalyst Replacement	ns	ns	1.27	1.59
ECU Replacement	3.48	34.83	ns	6.91
Oxygen Sensor Replacement	1.46	29.87	ns	4.11
Other Sensor Replacement/Repair	ns	ns	ns	ns

[a] Score = HC + NOx + CO/10. Score values and individual HC, CO, and Nox values were computed in independent regression analyses, and therefore may not be equal.
[b] Not significant at the 90% level. Regression statistics are included in Appendix A.

available mechanic comments, and therefore was somewhat subjective. In general, the following approach was used to determine defect type: replacement of spark plugs and ignition wires, timing adjustments, etc., were considered maintenance repairs; carburetor rebuilds/replacements, EGR system failures, air injection system failures, etc., were considered mechanical failures; and defective sensors and other electronic or wiring defects were labeled electrical failures. Repairs were labeled as tampering if there was a clear indication in the mechanic comments that the component had been tampered, or if a critical emission control component was missing (e.g., the air pump).

Based on the above assignments, it was possible to estimate the fraction of excess emissions that are the result of each of these failure modes. Although there is a moderate amount of uncertainty associated with these estimates, the analysis indicates

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that 48-63% of the excessive emissions* from fuel-injected vehicles are related to electrical component failure, while only 25-32% of the excessive emissions from carbureted vehicles are related to electrical component failures. Malmaintenance contributed 11-22% and 22-32% to excessive exhaust emissions for fuel-injected and carbureted vehicles, respectively. Finally, the contribution of mechanical failures ranges from 18-28% for fuel-injected vehicles and 31-46% for carbureted vehicles. It is also interesting to note that the contribution of tampering to excess emissions from fuel-injected vehicles is $\leq$ 2%, while it ranges from 7-16% for carbureted vehicles, depending upon which database was analyzed.

<u>Incidence of Defects in the Motor Vehicle Fleet</u>

In addition to the increase in FTP emissions associated with individual component defects, the frequency with which those defects occur in the vehicle fleet is important in determining the total excess emissions produced by motor vehicles. A specific defect may cause a ten-fold increase in emissions on a single vehicle, but if there are few of those defects in the fleet, the overall impact could be relatively insignificant. Thus, there was interest in identifying the frequency of component/system defects in the fleets being analyzed for this study. This was complicated by the fact that vehicles recruited for laboratory testing were not randomly selected in most cases. In general, the laboratory databases contained a larger proportion of high emitting vehicles than was characteristic of the in-use fleet. Thus, the incidence of component failures observed in the laboratory databases had to be re-weighted to reflect the fleet of vehicles from which they were selected. This weighting procedure was based on results of IM240 tests, which were performed on a large sample of randomly selected vehicles in the Hammond and Phoenix fleets (i.e., component failure rates for the laboratory fleets

* In the context of this discussion, excessive emissions refer to the difference in the average emission rate of a fleet of vehicles in their baseline (i.e., before-repair) configuration and after identification and repair of defects.

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were calculated for both IM240 passing and failing vehicles, and those results were weighted by the fraction of IM240 passing and failing vehicles in the in-use fleet).

The results for the Hammond fleet are contained in Table ES-2. (Refer to the body of the report for similar results for the Phoenix and CARB Enhanced I/M Pilot Project fleets. Only the Hammond results are presented in this summary because that is the largest of the databases analyzed in this effort, and readers are likely to be most familiar with that test program.) As seen in the table, there is a higher fraction of failures in carbureted vehicles, particularly for the fuel management system. This is not unexpected, since the carbureted vehicles are, on average, older than the fuel-injected vehicles (i.e., 6.7 versus 3.8 years), and the fuel control system is not as durable. Thus, the results presented in Table ES-2 do not reflect carbureted and fuel-injected vehicles at equal mileage intervals, but rather in their then-current state (i.e., in the 1990 to 1992 time period).

The effects of vehicle age on component failure rates were assessed by analyzing data from only 1983 to 1985 model year vehicles. That evaluation revealed similar failure rates for carbureted and fuel-injected vehicles for most components. For example, there was a 17% catalyst failure rate for both carbureted and fuel-injected vehicles, oxygen sensor failures occurred on 25% of the carbureted vehicles and 31% of the fuel-injected vehicles, and EGR failures occurred on 38% of the carbureted vehicles and 31% of the fuel-injected vehicles. However, the fuel metering system failure rate (e.g., idle speed, idle CO, choke adjustments, MAP sensor, etc.) for 1983 to 1985 model year carbureted vehicles was more than double that of the same model year fuel-injected vehicles (69% versus 30%).

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Table ES-2. Baseline Component Failure Rates for the Hammond Fleet, Including Vehicles Passing and Failing the IM240 Test.

Fuel System	System/Component	Failure Rate[a]
Carbureted[b]	Carburetor	23.1%
	Fuel Metering System	67.0%
	Ignition Tune-up	65.0%
	Other Ignition	13.3%
	EGR System	40.4%
	Air Injection System	27.6%
	Catalyst	11.3%
	Electronic Control Unit	6.1%
	Oxygen Sensor	23.0%
	Other Sensors	3.6%
Fuel-Injected	Fuel Injector(s)	9.5%
	Fuel Metering System	14.2%
	Ignition Tune-up	41.3%
	Other Ignition	6.2%
	EGR System	15.0%
	Air Injection System	2.3%
	Catalyst	7.0%
	Electronic Control Unit	1.4%
	Oxygen Sensor	26.0%
	Other Sensors	1.8%

[a] Failure rates shown have been adjusted to account for over-sampling of IM240 failures in the subset of vehicles receiving repairs and retests.

[b] Note that the carbureted fleet is older; therefore, the higher component failure rates were not unexpected.

As Table ES-2 shows, ignition-related defects occur frequently in both the carbureted (78%) and fuel-injected (47%) vehicles. Although not as great, the incidence of oxygen sensor failures (approximately 25%) is more important, considering the significant emissions impact of defective oxygen sensors shown in Table ES-1.

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Impacts of Defects on Fleet-Average Emissions

The overall impact of defective components on the fleet-average emission rate was calculated by combining the FTP increase as a result of those defects and the fraction of those defects observed in the fleet. The analysis treated fuel injected and carbureted vehicles independently. The results of that analysis are presented in Table ES-3 for the Hammond fleet. Note that the contribution of component defects to fleet average emissions does not sum to 100% in Table ES-3 because emissions remain after repair. The estimates in this table again indicate that the defects of significance differ between fuel-injected and carbureted vehicles. Failures leading to high emissions in carbureted vehicles are generally related to mechanical failure and malmaintenance (as observed by the large influence that carburetor/fuel system defects have on the fleet average emission rate), while failures leading to high emissions in fuel-injected vehicles are often related to sensors or electrical problems.

Another point to be made in reference to Table ES-3 is the relatively small impact that catalyst malfunctions have on the fleet-average emission rate. Two factors contribute to this: the incidence of catalyst failures is low, and the effect of repair of defective catalysts is not as large as one might imagine. This can be explained by noting that engine-out emissions for a properly functioning late-model vehicle are on the order of 2 g/mi HC, 20 g/mi CO, and 2 g/mi NOx. A catalyst with a 90% efficiency for HC and CO and a 70% efficiency for NOx would result in an emission reduction of 1.8 g/mi HC, 18 g/mi CO, and 1.4 g/mi NOx. On the other hand, a vehicle with a malfunctioning closed-loop fuel control system (e.g., having a bad ECU or oxygen sensor) can have before-repair emissions as high as 10 g/mi HC and 150 g/mi CO, and the repair of those defects can bring emission rates down to certification levels (i.e., 0.41 g/mi HC and 3.4 g/mi CO). Thus, repairing those defects has a much larger effect on the reduction in FTP emissions than does repairing what might be considered the "heart" of the emission control system - the catalyst.

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The results presented in Table ES-3 were combined for the two fuel systems and for all components to calculate the overall effect on FTP emissions of repairing identifiable defects in the Hammond fleet. Repair of all identified defects is projected to reduce emissions of 1981 and later model year vehicles by 63% HC, 72% CO, and 16% NOx, which reflects an upper limit of achievable emission reductions from this fleet of vehicles. For fuel-injected vehicles (which are, on average, newer than the carbureted vehicles in this fleet), the overall benefits of repair are considerably less for HC and CO (41% HC, 47% CO), while NOx is similar (20%). The fuel-injected vehicle reductions are generally consistent with the benefits that EPA has estimated for "enhanced" vehicle inspection and maintenance (I/M) programs. There are two reasons why the actual emission reductions achieved in an I/M program would be somewhat less than the reductions achieved in these test programs. First, the cost of the diagnoses and repairs to correct all defects would sometimes exceed the repair cost limits applicable to an I/M program. Second, the quality of the repairs performed under these test programs is higher than what could be expected for the typical commercial repair.

Although not part of the scope of work for this project (because it is not an exhaust emission control component), a rough estimate of the effect that defective positive crankcase ventilation (PCV) valves have on fleet-average HC emissions was also made. Assuming that a defective PCV valve results in an increase of 1.2 g/mi HC (from MOBILE5a), defective PCV valves would contribute an additional 8% of the fuel-injected exhaust HC emission rate and 6% of the carbureted HC emission rate.

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Table ES-3. Contribution of Defective Components to the Fleet-Average Emission Rate for the Hammond Database.

Fuel System	System/Component	Contribution to FTP Emissions			
		HC	CO	NOx	Score
Carbureted	Carb Rebuild/Replacement	ns[a]	11%	2%	7%
	Fuel Metering System Repair	34%	42%	-13%	29%
	Ignition Tune-up	24%	ns	ns	13%
	Other Ignition Repair	ns	ns	ns	ns
	EGR System	ns	ns	21%	ns
	Air Injection System	< 1%	8%	ns	< 1%
	Catalyst	5%	< 1%	8%	4%
	ECU	5%	8%	-3%	5%
	Oxygen Sensor	8%	17%	-5%	10%
	Other Sensors	ns	ns	1%	ns
Fuel-Injected	Injector Replacement	5%	5%	-2%	3%
	Fuel Metering System Repair	< 1%	< 1%	2%	< 1%
	Ignition Tune-up	2%	2%	ns	8%
	Other Ignition Repair	3%	-1%	ns	ns
	EGR System	ns	ns	11%	< 1%
	Air Injection System	< 1%	< 1%	ns	< 1%
	Catalyst	< 1%	< 1%	9%	3%
	ECU	4%	3%	ns	2%
	Oxygen Sensor	25%	37%	-1%	22%
	Other Sensors	ns	ns	< 1%	< 1%

[a] Repair effects were not significant for these systems/components.

REVIEW OF CARB'S OBDII ANALYSIS

Data contained in CARB's Technical Support Document prepared for the September 1989 Board hearing regarding revised on-board diagnostic regulations (i.e., "OBDII") were analyzed as part of this project. The purpose of this effort was to provide

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alternative estimates of the effect of component failure on fleet-average emissions. Three components were considered in the CARB report: catalyst, EGR, and oxygen sensor. For fuel-injected vehicles, defective catalysts were estimated to contribute 3% to the fleet-average FTP-weighted emission rate (i.e., "score," as defined above), which is consistent with the results of our analysis of repair data described above. In contrast, defective oxygen sensors were estimated to contribute 7% to the fleet-average FTP score, while our analysis indicates a 22% effect. Finally, EGR failures were projected to contribute 5% to the fuel-injected vehicle NOx fleet-average emission rate using the CARB OBDII database and 11% using the Hammond database. The difference between the results was expected, as the data used in CARB's analysis were collected seven to eight years ago. Because all of our analyses are focused on 1981 and later model year vehicles, lower defect rates would be expected for datasets with a lower average vehicle age. In fact, the average age of the vehicles in the OBDII database was 4.4 years, while the average age of the Hammond vehicles was 4.8 years. More importantly, the fraction of high-mileage vehicles (i.e., over 100,000 miles) was much higher in the Hammond database (12.4%) compared to the OBDII database (3.9%).

REVIEW OF RECALL DATA

Recall data from EPA and CARB were reviewed and a rough estimate of the impacts of recall actions on fleet-average emissions was prepared. That analysis revealed that actual vehicle recalls have a very small impact on in-use emissions, amounting to reductions of 1.3%, 2.1%, and 1.5% for HC, CO, and NOx, respectively. Since vehicles selected for recall testing are well-maintained vehicles with less than 50,000 miles, this suggests that the majority of excess emissions in the fleet result from maintenance problems or defects that occur beyond the "useful life" of the vehicle. As an example, data from the Hammond program indicated that fuel-injected vehicles had an 11% oxygen sensor failure rate for vehicles with less than 50,000 miles. For vehicles with more than 50,000 miles, the oxygen sensor failure rate increased to 40%.

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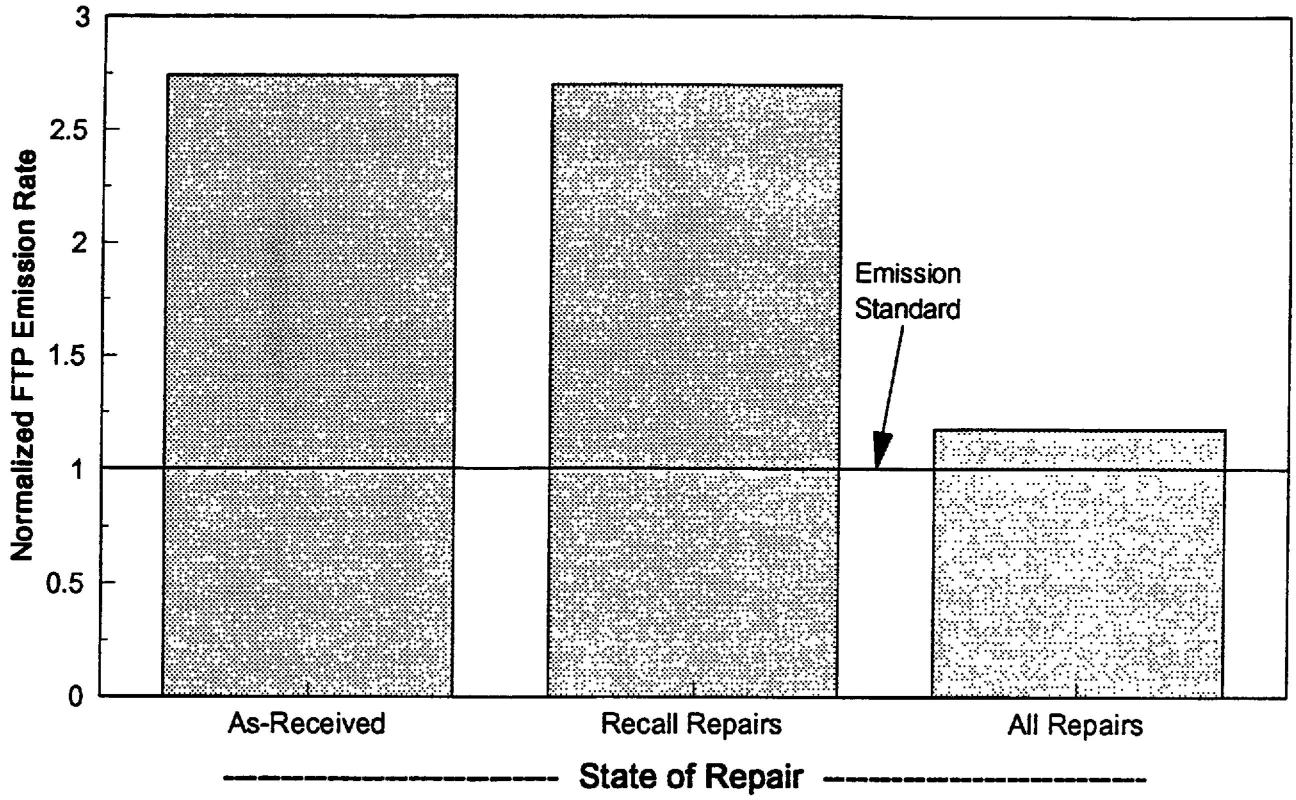

Figure ES-1. Contribution of Repairable Defects Relative to the Fleet-Average Emission Standard (HC + NOx + CO/10) for the Hammond Database.

Figure ES-1 illustrates the contribution to the fleet-average weighted FTP "score" of recall repairs versus the non-recall repairs described above for vehicles in the Hammond database. The emission levels have been normalized by the emission standard to which these vehicles were certified (i.e., 0.41 HC + 1.0 NOx + 3.4 CO/10), which is also shown in the figure. Figure ES-1 indicates that recall actions have a small impact on fleet-average emissions, but that if all identifiable defects are repaired, emissions are within 25% of the certification standard. The level of emissions remaining above the standards can be attributed to general aging and deterioration of emission control components that would not necessarily be positively identified as a defect.

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Section 1
INTRODUCTION

Under contract to the American Petroleum Institute (API), Sierra Research, Inc. (Sierra) conducted a study of on-road motor vehicle emissions data to determine the primary causes of excessive exhaust emissions in the in-use motor vehicle fleet.* That topic is important from the perspective of how to craft motor vehicle control programs to effectively reduce in-use emissions. The analyses performed in this effort attempted to quantify the emissions impacts of individual emission control system component defects, the prevalence of those defects in the in-use motor vehicle fleet, and the overall contribution of those defects to fleet-average emissions. In addition, the primary causes of defective emission control system components were categorized according to whether the defect was the result of a mechanical component failure, electrical component failure, poor maintenance, or tampering. Estimates of the magnitude of each of these failure modes on excessive emissions were then made.

The primary data sources used for this study were two programs conducted by the U.S. Environmental Protection Agency (EPA), two programs conducted by the California Air Resources Board (CARB), and one joint EPA-Industry program. The focus of the effort was on 1981 and later model year light-duty cars and trucks. In addition to analyzing emissions test data from those five programs, data presented in CARB's Technical Support Document prepared for on-board diagnostic system regulations were reviewed. That report contained emissions data for catalyst, oxygen sensor, and exhaust gas recirculation (EGR) system repairs. Finally, a limited review of EPA and CARB recall data was performed to determine the fraction of fleet-average emissions that are reduced through recall actions.

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* Note that this study did not evaluate evaporative control systems defects, which could be a significant source of excessive hydrocarbon emissions.

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ORGANIZATION OF THE REPORT

Immediately following this introduction, Section 2 presents the results of the analysis of the five databases referenced above and contains the majority of the results from this study. The analysis of data from CARB's OBDII Technical Support Document is contained in Section 3, while the overview of EPA and CARB recall data is provided in Section 4. Finally, a list of references cited in the report is provided.

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Section 2
ANALYSIS OF DIAGNOSTIC DATA

Determination of the causes and magnitude of excessive exhaust emissions in the vehicle fleet was a multi-step process involving the analysis of many different data sources. The first step in that process was the acquisition of data not already in-house and reformatting all databases to a common structure for subsequent analysis. Once reformatted, the data were evaluated (both collectively and for each individual database) for the following:

- the types of emission control system defects in each fleet (e.g., catalyst system, fuel delivery system, etc.);
- the prevalence of emission control system defects in each fleet (i.e., what fraction of vehicles contain specific types of defects);
- the primary causes of those defects (e.g., tampering, malmaintenance, mechanical component failure, electrical component failure);* and
- the contribution that those defects have on excessive exhaust emissions in the vehicle fleet.

The last item above is complicated by the fact that each database analyzed in this study used different vehicle selection criteria, which generally resulted in a larger proportion of high emitting vehicles in the sample than in the corresponding fleet from which that sample was drawn. Thus, analysis of inspection and maintenance short

* The primary cause of individual defects was determined by evaluating mechanic comments in conjunction with the type of repair. For example, replacement of spark plugs and/or ignition wires was considered a maintenance repair, carburetor rebuilds or replacements were considered mechanical failures, and oxygen sensor replacements were considered electrical failures. Repairs were categorized as tampering if there was a clear indication in the mechanic comment field that the component had been tampered.

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test data (i.e., IM240) was also performed so that results from the databases could be extrapolated to the fleet.

This section of the report presents a description of the databases used in the analysis (with summary statistics from those databases), the types and prevalence of defects observed in the fleets analyzed, the primary causes of those defects, and the effect that those defects have on the fleet-average emission rate.

DATABASE DESCRIPTION

Emissions data collected on 1981 and later model year light-duty cars and trucks from five separate databases were analyzed in this study to determine the primary causes of excessive exhaust emissions in the in-use vehicle fleet. Two databases were compiled by the U.S. Environmental Protection Agency (EPA), two were compiled by the California Air Resources Board (CARB), and one was compiled as part of a cooperative test program conducted by EPA and automobile manufacturers. A brief description of each database is contained below.

Cooperative Test Program (CTP) Data

Under the CTP, data were collected on a sample of 265 vehicles by EPA and participating vehicle manufacturers. Vehicles included in the program were 1981 and later passenger cars and light trucks that had failed the Michigan I/M short test. These vehicles were procured for detailed diagnosis, emission testing and repair. Specific elements of the program included those listed below.

- Characterizing the as-received emission rates of each vehicle (on commercial fuel) according to a variety of I/M procedures, including extensive loaded pretest operation, extended idle pretest operation and a cold start;
- Measuring the as-received emissions using the Federal Test Procedure (FTP) (commercial and certification fuel);

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- Conducting a complete and detailed engine and emissions system diagnosis on each vehicle for causes of the observed FTP and/or I/M failures;
- Ordering the repairs indicated by the diagnosis by their anticipated FTP emissions benefit (from highest to lowest);
- Conducting incremental remedial maintenance (based on the ranked repair items) to reduce FTP HC and CO emissions within the following mileage-dependent levels:

  150% of cert standards for vehicles < 50,000 miles
  200% of cert standards for vehicles > 50,000 miles

  and verifying the emission reductions by additional FTP and I/M tests performed after each significant repair; and
- Conducting additional remedial maintenance on vehicles already repaired to acceptable FTP levels to achieve acceptable short test response (i.e., I/M pass), again verifying emission reductions with I/M testing performed after each significant repair.

A copy of the CTP data was obtained from EPA on magnetic tape. Hardcopy descriptions of the record format and field descriptions were also provided by EPA.

Although the CTP data can be used to estimate the emission reduction from repair, it is not possible to use this database to determine a fleet-average component failure rate. That is because the vehicle selection criteria (i.e., I/M short test failures) resulted in a larger proportion of high emitting vehicles in the database than would be expected in the fleet from which they were selected. In some of the other databases analyzed for this project (i.e., Hammond and Phoenix), IM240 scores were used to translate the sample results to the fleet. However, the CTP database does not contain sufficient information (e.g., I/M scores) on the Michigan fleet to be able to extrapolate the results to the fleet. In addition, this database does not contain diagnostic information on vehicles passing an I/M test, which could contain defects resulting in excessive FTP emissions.

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EPA Indiana Data

The base emission rate equations and I/M benefits developed for MOBILE5a were based on data collected in a program sponsored by EPA in Hammond, IN. Although most of the vehicles included in the Hammond program were tested at an I/M lane over the IM240 cycle, a subset of vehicles was recruited for more extensive FTP testing at a local laboratory. Vehicles tested at the lane using IM240 were chosen at random (within specific model-year groups), while those recruited for FTP testing were intentionally selected to result in an approximate 50/50 mix of passing and failing vehicles. The FTP results from those vehicles were used to develop IM240-to-FTP correlations, I/M identification rates, and after-repair emission rates for MOBILE5a. Because the lab FTP data did not reflect the in-use fleet (i.e., they were more heavily weighted with high emitters), the ratio of IM240 pass and fail rates observed at the lane was used to re-weight the lab sample when EPA developed the I/M identification rate matrices for MOBILE5a.

The lab FTP data from the Hammond program were used in this effort by analyzing the FTP results in conjunction with the "narrative" (NARR) and "component" (ECOMP) files acquired from EPA's "MICRO" database.* The narrative file contains a comment field describing the vehicle's condition and any repairs that may have been performed for each test conducted. The component file contains a coded listing of defective emission control components for the as-received case. The as-received information was used to identify the malfunctioning components leading to high emissions, and the after-repair FTP information was used to quantify those malfunctions. These results were translated to the fleet by re-weighting the lab sample by the ratio of IM240 pass

* The MICRO database is maintained at Wayne State University and contains data from a variety of EPA emissions test programs.

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and fail rates observed at the lane. The lane IM240 data had been received from EPA in a previous study conducted by Sierra for API (Sierra, 1994).

EPA Arizona Data

An EPA contractor (Automotive Testing Laboratories) has been performing IM240 tests in conjunction with the existing I/M program in Mesa, AZ (a suburb of Phoenix) since 1992. Some of the data collected in that program were used by EPA in a comparison of IM240 and "Acceleration Simulation Mode" (ASM) testing (EPA, 1993), and additional data have been collected since the publication of that report. As with the Hammond program, a subset of the IM240 tested vehicles were recruited for FTP testing at a local laboratory. The focus of testing has been on 1983 and later fuel-injected vehicles (only a small number of carbureted vehicles were tested in that program), and an approximate 50/50 mix of IM240 passing and failing vehicles was selected for FTP testing.

This database was evaluated in a similar fashion to that described above for the Hammond data. The FTP data were obtained from EPA's MICRO database, along with narrative and component files for this test program, and the sample results were extrapolated to the fleet by comparing IM240 failure rates for vehicles tested at the lab to the larger sample of vehicles receiving IM240 tests at the I/M lane. The Arizona lane IM240 results had also been received from EPA in a previous study conducted by Sierra for API (Sierra, 1994).

CARB Fuel-Injected (CARBFI) Vehicle Study

Under this program, Radian Corporation, under contract to CARB, obtained a sample of 58 high-mileage, fuel-injected vehicles that were tested at CARB's El Monte laboratory. The CARBFI database contains diagnostic, emission testing and repair

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information for these vehicles, which cover model years 1980 through 1985. All the vehicles appear to be either "moderate" FTP emitters or higher.

Similar to the CTP database, CARBFI follows a procedure of baseline diagnosis (with a diagnostic coding scheme that is an expanded version of that used in-house by CARB), followed by incremental repair and retesting. The emission tests performed consist of a baseline (i.e., before repair) FTP followed by Hot-505s after each incremental repair. A final FTP was also conducted after all repairs had been performed. As with the CTP database, extrapolation of these data to the fleet is not possible. This database represents a subset of the 1980 to 1985 model year fleet, and the baseline emission characteristics are not reflective of the entire fleet. Nonetheless, the baseline and after-repair emissions data were used in this analysis to estimate the emission reductions from repairing specific emission control components.

<u>CARB I/M Pilot Project Data</u>

During the latter half of 1994, the California Bureau of Automotive Repair (BAR) and CARB conducted an "Enhanced Inspection and Maintenance Pilot Project" to investigate the feasibility of meeting EPA's enhanced I/M performance standard using a "hybrid" program design. Under the proposed program, vehicles suspected of having the highest emissions would be required to be tested at centralized (i.e., "test-only") I/M facilities, while other vehicles could be tested at decentralized (i.e., "test and repair") facilities.

As part of the Pilot Project, CARB recruited over 600 vehicles selected at random from Department of Motor Vehicle registration records for vehicles soon to be due for an I/M test. The owners of the vehicles were required to participate; failure to cooperate resulted in denial of registration renewal. As a result, the "capture rate" for the selected vehicles was very high. Each of the vehicles was tested in an "as received"

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condition at CARB's laboratory using both the IM240 and ASM tests. Most of the failing vehicles received a full FTP and then were repaired by BAR mechanics at Clayton Industries' facilities near the CARB laboratory. The IM240 standards were used as the after-repair target for about half of the vehicles and the ASM standards were used as the target for the rest of the vehicles. Diagnosis and repair work continued until the vehicles either passed the target test or additional repairs would cause total expenditures to exceed about $500-$600.* At the completion of the repair work, another FTP was conducted. Some of the passing vehicles also received an FTP. FTP emissions for other passing vehicles can be estimated from the IM240 test results (using a regression equation), which is the approach used in some of the analyses presented in this report. Because the vehicles in the Pilot Project were selected at random, regardless of emission level, there was no need to re-weight results to reflect the fleet of vehicles from which they were selected.

SUMMARY STATISTICS

As discussed above, the databases used for this project varied considerably in terms of how the vehicles were selected for each program. This can be seen from the baseline HC, CO, and NOx FTP scores summarized in Table 2-1. As observed in that table, the mean emission rates for the CTP, Hammond, and CARBFI databases are very similar, particularly when fuel technologies (i.e., carbureted and fuel-injected) are combined. When the data are compared by fuel delivery technology, similarities are observed for all of the databases that had carbureted vehicles included in them; there is more variability when the fuel-injected results are compared. Reasons for this distribution of emission levels among the databases include those listed below.

* Based on discussions with CARB staff, the repair cost criteria used were somewhat vague and not precisely consistent with the $450 repair cost minimum for waivers specified in the federal Clean Air Act.

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- The CTP and CARBFI databases contain only vehicles that were likely to fail an I/M short test. Thus, average emission rates from those databases are expected to be higher than the other databases.

Table 2-1. Baseline FTP Emission Levels of the CTP, Hammond, Arizona, CARBFI, and California I/M Pilot Project Databases.

Fuel System	Database	(n)	Mean Mileage	Mean Emission Rate (g/mi)		
				HC	CO	NOx
All	CTP	237	54,800	1.86	26.32	1.14
	Hammond	678	69,600	1.72	24.75	1.16
	Phoenix	243	76,100	1.19	14.17	1.18
	CARBFI	43	60,200	2.03	28.76	2.18
	CA I/M Pilot[a]	504	78,200	1.00	15.06	1.10
Carbureted	CTP	114	65,500	2.06	28.79	1.39
	Hammond	154	85,500	2.67	36.23	1.41
	Phoenix	-	-	-	-	-
	CARBFI	-	-	-	-	-
	CA I/M Pilot	146	99,600	1.92	28.60	1.50
Fuel-Injected	CTP	123	44,900	1.68	24.03	0.91
	Hammond	524	64,900	1.44	21.37	1.09
	Phoenix	243	76,100	1.19	14.17	1.18
	CARBFI	43	60,200	2.03	28.76	2.18
	CA I/M Pilot	358	69,500	0.62	9.54	0.94

[a] FTP scores for the California I/M Pilot Project database were estimated for some vehicles based on IM240-to-FTP correlation equations.

- Although the Hammond and Pilot Project databases include I/M passing vehicles, the average emission level of carbureted vehicles in those databases is similar to the CTP database. That can be explained by noting the mean mileage level for each database and considering when the programs were conducted. The CTP data were collected primarily in the latter half of 1987, which resulted in a lower mean mileage than the Hammond database (in which vehicles were tested primarily from 1990 to 1992) and the California I/M Pilot Project database (where vehicles were tested in the latter half of 1994). It would be expected that because of the higher mean mileage level of the Hammond and Pilot Project databases, there would be a higher proportion of higher emitting vehicles in those data sets which may be causing the mean emission levels to be elevated. (In fact, nearly 75% of the carbureted vehicles in the Hammond database failed 0.8 g/mi HC, 15 g/mi CO, and 2.0 g/mi NOx IM240 cutpoints, and nearly

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65% of the carbureted vehicles in the Pilot Project database failed those cutpoints.)

- Comparing the fuel-injected results, there appears to be a more easily explainable pattern of emission rates. Both the CTP database and the CARBFI database have the highest emissions (for HC and CO), but those programs targeted high emitting vehicles only. The Hammond and Phoenix databases, which consist of a nominal 50/50 mix of IM240 passing and failing vehicles, have mean emission levels between the CTP and CARBFI databases and the Pilot Project database. The California I/M Pilot Project database has the lowest emission levels because it was randomly selected and represents the California fleet. (Only 25% of the Pilot Project fuel-injected vehicles fail 0.8/15/2.0 HC/CO/NOx IM240 cutpoints.)

Because of the differing proportion of high emitting vehicles in each database, and because each program applied different criteria to determine whether a vehicle was to receive repair, there is a different proportion of vehicles that received repair and re-testing in each program. For example, all vehicles received repairs in the CARBFI database, while 22% of the vehicles in the California I/M Pilot Project database received repairs. In addition, the level of repair differed in each program. As noted above, vehicles in the CTP study were repaired to meet 1.5 to 2.0 times their certification levels (depending on vehicle mileage), whereas vehicles in the California I/M Pilot Project were repaired to meet IM240 or ASM cutpoints. As might be expected, these differences in repair criteria resulted in different mean after-repair levels for each database. This is observed in Figures 2-1a and 2-1b, which show the mean baseline and after-repair FTP emission rates (for vehicles that received repairs) for carbureted and fuel-injected vehicles, respectively. Finally, each of the databases considered in this study contained vehicles subject to different I/M histories, which could have had an impact on the average before-repair emission rates observed in Figures 2-1a and 2-1b (e.g., most of the vehicles tested in the Hammond program had never been subject to an I/M program prior to testing (or had only been through a

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single "cycle"), while vehicles in the Phoenix database had been subject to a fairly stringent I/M program for most of their lives).

DATABASE REFORMATTING

Because the databases analyzed in this study were compiled at different times by two different organizations, the format of the data varies considerably, particularly with respect to how repairs are coded. The CTP, CARBFI, and Pilot Project databases contain coded repair information, but the coding scheme is not consistent. At the other extreme, the Hammond and Phoenix databases contain a coded description of the vehicles' baseline condition (i.e., the ECOMP files described above), but do not have coded information for each repair cycle. The only information describing repairs in the Hammond and Phoenix databases is contained in the narrative files.

Before analysis of the repair data could proceed, it was necessary to reformat all databases into a common structure. This was accomplished by merging the mechanic comments with emission results for each vehicle. The comments regarding repairs were then manually translated into a coding scheme that (1) identified the system and component subject to repair; (2) identified the type of repair; and (3) identified the likely reason for component failure. This was a time-consuming process involving nearly 800 vehicles among the five databases, but consistent coding was necessary before analysis of the repair actions could proceed.

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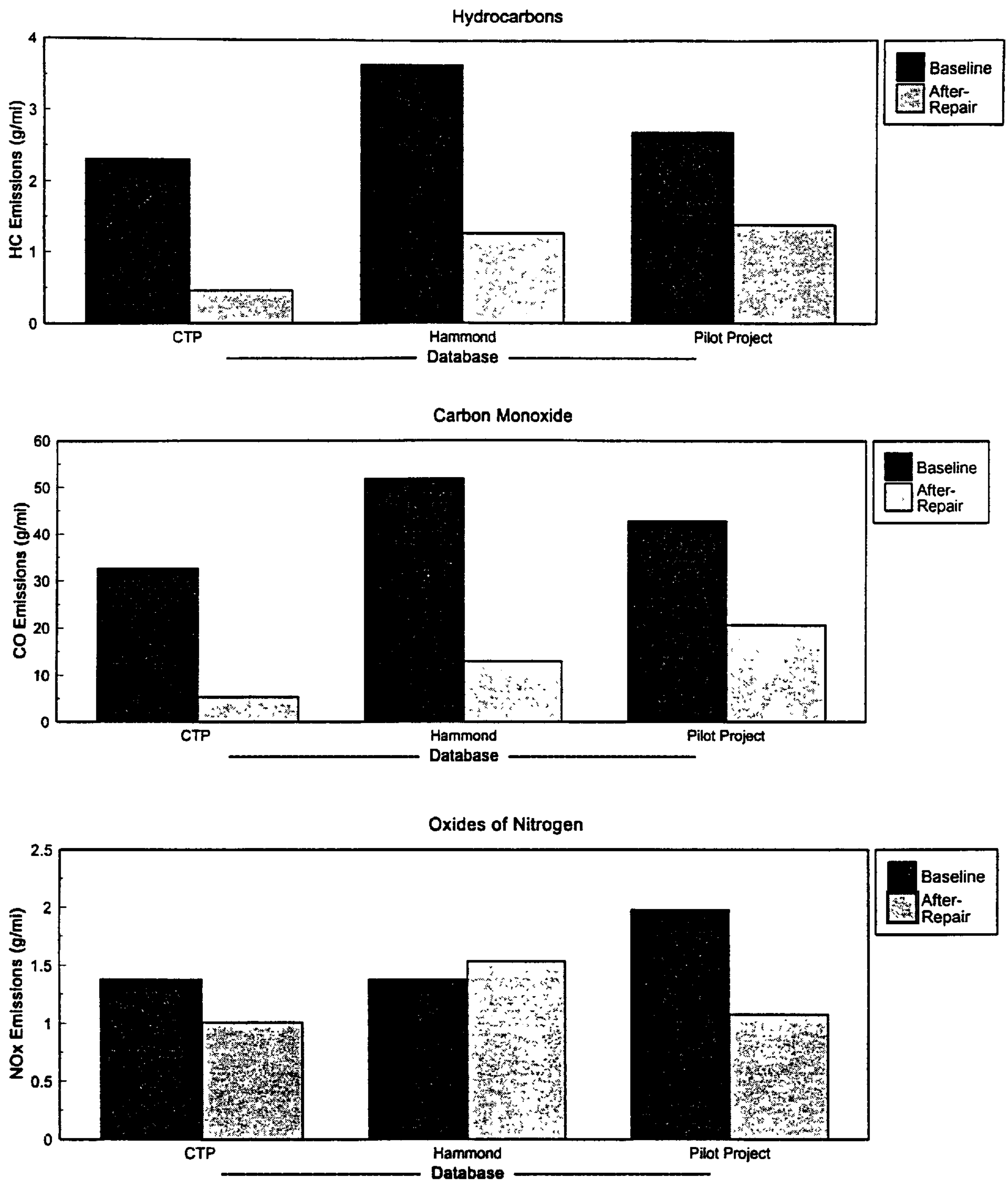

Figure 2-1a. Comparison of Mean Baseline and After-Repair FTP Emission Rates from 1981 and Later Model Year Carbureted Vehicles Receiving Repair in the CTP, Hammond, and California I/M Pilot Project Databases.

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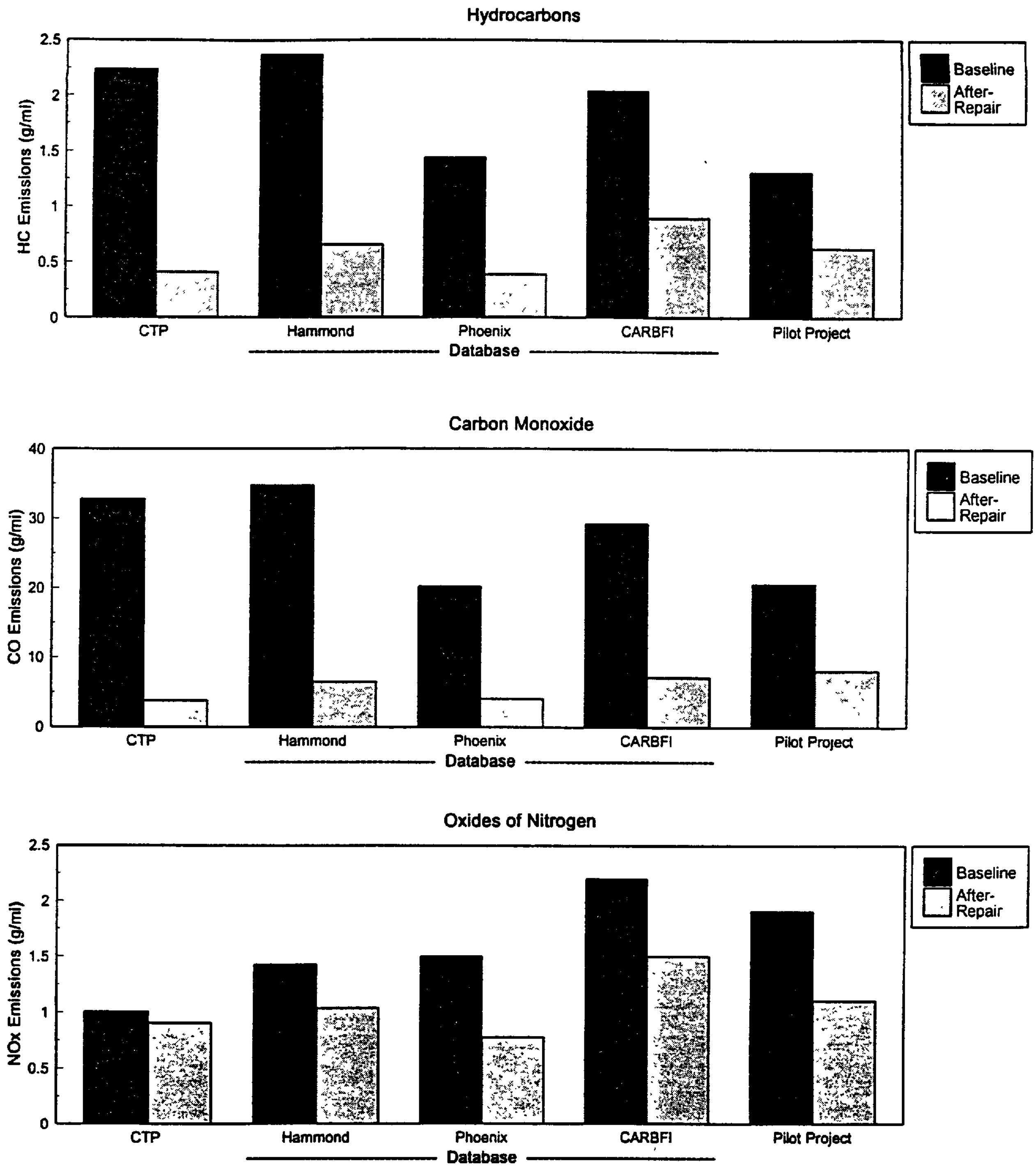

Figure 2-1b. Comparison of Mean Baseline and After-Repair FTP Emission Rates from 1981 and Later Model Year Fuel-Injected Vehicles Receiving Repair in the CTP, Hammond, Phoenix, CARBFI, and California I/M Pilot Project Databases.

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The system and component codes used in this analysis followed a structure proposed by Sierra in a study performed for EPA in 1989 (Sierra, 1989), and a summary of those codes is shown in Table 2-2. Because of the large number of individual codes, repairs were classified by major components and systems according to the following definitions, based on the codes contained in Table 2-2:

- Carburetor replacement/rebuild (system 2, component 2);
- Carburetor adjustment/fuel metering system repair (system 2, components 2-25; system 11, component 9);
- Fuel injector replacement (system 3, component 3);
- Fuel injection/fuel metering system adjustment/repair (system 3, components 2, 6-43; system 11, component 9);
- Ignition system "tune-up" repair (system 4, components 2-3, 5-6);
- Other ignition system repairs (system 4, components 4, 7-23);
- EGR system repair (system 5, components 2-14);
- Air injection system repair (system 8, components 2-15);
- Catalyst replacement (system 9, components 3-7);
- Electronic control unit replacement or repair (system 10, component 2);
- Oxygen sensor replacement (system 11, component 2); and
- Other sensor replacement or repair (system 11, components 10-21).

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Table 2-2. System and Component Codes Used to Standardize Repair Data from the CTP, Hammond, Phoenix, CARBFI, and California I/M Pilot Project Databases.

1 **Air Induction**
- 2 air door
- 3 air filter
- 4 air cleaner housing - ach
- 5 cold air duct
- 6 hot air duct
- 7 intake manifold
- 8 turbocharger - tc
- 9 charge air cooler - cac
- 10 supercharger - sc
- 11 sensor / switch / solenoid
- 12 hoses / vacuum lines
- 13 gasket / seal
- 14 wire / harness / fuse
- 15 other

2 **Carburetion**
- 2 carburetor assembly
- 3 idle mixture adj. limiting device
- 4 idle mixture
- 5 idle speed
- 6 idle speed control isc
- 7 throttle/throttle controls
- 8 throttle position sensor - tps
- 9 mixture control solenoid - mcs
- 10 mixture control solenoid - mcs, cmds
- 11 choke adjustment (notches)
- 12 choke adjustment (vacuum break)
- 13 choke adjustment limiting device
- 14 choke heater
- 15 choke (misc.)
- 16 early fuel evaporation - efe (electric)
- 17 engine coolant temp. sensor - ects
- 18 intake air temperature sensor - iats
- 19 vacuum diaphragms
- 20 fuel pump
- 21 fuel filter
- 22 hoses
- 23 gasket / seal
- 24 wire / harness / fuse
- 25 other

3 **Fuel-Injection**
- 2 air flow sensor
- 3 injector(s)
- 4 diesel injector(s)
- 5 diesel fuel supply pump
- 6 throttle body - tb
- 7 throttle controls
- 8 throttle position sensor - tps
- 9 fuel pump
- 10 fuel filter
- 11 fuel distributor
- 12 fuel pressure regulator
- 13 fuel delivery/return line

3 **Fuel-Injection (Continued)**
- 14 fuel pump relay - fpr
- 15 diesel fuel injection pump
- 16 diesel fuel heater
- 17 diesel speed governor
- 18 diesel smoke puff limiter - spl
- 19 diesel glow plugs
- 20 diesel water separator
- 21 inertia fuel shutoff switch - ifss
- 22 idle speed control - isc
- 23 idle air control valve - iacv
- 24 iacv hoses
- 25 cold start valve
- 26 early fuel evaporation - efe (electrical)
- 27 engine coolant temp. sensor - ects
- 28 cam position sensor (smpi)
- 29 crankshaft position sensor - cps
- 30 manifold surface temp. sensor - msts
- 31 intake air temperature sensor - iats
- 32 diesel fast idle solenoid
- 33 diesel cold start solenoid
- 34 diesel altitude control solenoid
- 35 hoses
- 36 hoses (air flow sensor & throttle body)
- 37 hoses (vac hoses, pressure regulator, ect
- 38 gasket / seal
- 39 wire / harness / fuse
- 40 other
- 41 idle CO
- 42 idle speed
- 43 aux. air regulator

4 **Ignition**
- 2 distributor assembly (cap & rotor)
- 3 ignition timing
- 4 ignition timing limiting device
- 5 spark plugs and / or wires
- 6 spark plugs and / or wires
- 7 breakerless pickup (all types)
- 8 ignition module
- 9 spark timing control module
- 10 coil/coil pack
- 11 dwell / points
- 12 vacuum advance assembly
- 13 spark delay devices
- 14 knock sensors - ks
- 15 engine speed sensor
- 16 camshaft position sensor
- 17 crankshaft position sensor - cps
- 18 engine coolant temperature sensor - ects
- 19 thermal vacuum switch - tvs
- 20 hoses
- 21 gasket / seal
- 22 wire / harness / fuse
- 23 other

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Table 2-2. System and Component Codes Used to Standardize Repair Data from the CTP, Hammond, Phoenix, CARBFI, and California I/M Pilot Project Databases (Continued).

5 EGR
- 2 egr valve assembly
- 3 egr filter
- 4 egr spacer plate
- 5 egr function sensor - egrs
- 6 egr function control - egrc
- 7 delay solenoid/valve
- 8 vacuum amplifier
- 9 vacuum reservoir
- 10 engine coolant temperature sensor - ects
- 11 thermal vacuum switch - tvs
- 12 hoses / vacuum lines
- 13 wire/harness/fuse
- 14 other

6 PCV
- 2 pcv valve or orifice
- 3 pcv filter
- 4 oil filler cap
- 5 hoses
- 6 wire / harness / fuse
- 7 other

7 Evaporative Control
- 2 canister
- 3 canister filter
- 4 canister purge solenoid / valve
- 5 fuel filler cap
- 6 fuel restrictor
- 7 fuel tank
- 8 fuel line (supply/return)
- 9 vapor separator
- 10 pressure relief valve
- 11 rollover valve
- 12 anti siphon valve
- 13 hoses / vacuum lines
- 14 gasket / seal
- 15 wire / harness / fuse
- 16 other

8 Secondary Air Injection
- 2 secondary air injection filter
- 3 secondary air injection pump
- 4 secondary air bypass valve - sabv
- 5 secondary air anti-backfire valve - sabfv
- 6 secondary air anti-backfire valve - sabfv
- 7 secondary air switching valve - sasv
- 8 secondary air pulse valve - sapv
- 9 drive belt
- 10 upstream injection tube(s)
- 11 downstream injection tube(s)
- 12 hoses / vacuum lines
- 13 gasket / seal
- 14 wire / harness / fuse
- 15 other

9 Exhaust After-Treatment
- 2 thermal reactor
- 3 warm-up oxidation catalyst - wuoc

9 Exhaust After-Treatment (Continued)
- 4 warm-up three way catalyst - wutwc
- 5 oxidation catalyst - oc
- 6 three way catalyst
- 7 three way catalyst
- 8 trap oxidizer, continuous - toc
- 9 trap oxidixer, periodic - top

10 Engine Control
- 2 powertrain control module - pcme
- 3 powertrain control module (trans.) - pcmt
- 4 body control module - bcm

11 Sensor/Solenoid/Valve
- 2 oxygen sensor - o2s
- 3 oxygen sensor - heated - o2sh
- 4 air conditioner sensor - acs
- 5 barometric absolute pressure sensor
- 6 coolant level sensor - cols
- 7 engine coolant temperature sensor - ects
- 8 fuel temperature sensor
- 9 manifold air pressure sensor - map
- 10 manifold vacuum sensor - mvs
- 11 manifold vacuum zone switch - mvzs
- 12 wide open throttle switch - wots
- 13 engine speed sensor
- 14 torque sensor
- 15 cylinder chamber temperature sensor
- 16 catalyst temperature sensor
- 17 thermal vacuum switch - tvs
- 18 vehicle speed sensor - vss
- 19 wire / harness / fuse / vacuum line
- 20 gasket / seal
- 21 other

12 On-Board Diagnostics
- 2 malfunction indicator light - mil
- 3 mil bulb check
- 4 obd system
- 5 diagnostic trouble codes - dtc
- 6 service reminder
- 7 data link connector - dlc
- 8 wire / harness / fuse

13 Engine/Exhaust
- 2 engine block
- 3 cooling system
- 4 coolant fan control
- 5 intake/exhaust valves
- 6 auxiliary vacuum pump
- 7 belt tension
- 8 exhaust manifold
- 9 early fuel evaporation - efe (heat riser)
- 10 mufflers
- 11 exhaust port liner/double walled pipe
- 12 tailpipe
- 13 other
- 14 cylinder compression pressure (psi - xxx.)
- 15 cylinder leak down (percent - xx.x)
- 16 vacuum lines (general)

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Not all of the components listed in Table 2-2 are included in the repair categories defined above. For the air induction system, the effects of repair were generally found to be insignificant (when analyzed according to the methodology described below), and those repairs were not considered in this analysis. Evaporative control system defects were not analyzed since the focus of this effort was on exhaust emission reductions. Although repair effects of PCV system defects were not analyzed (due to lack of data), that system is discussed later in this section. Finally, several specific components from system 13 were analyzed independently (i.e., repairs to the cooling system, intake/exhaust valves, and exhaust manifold), and the effects of repair were found to be insignificant. When components 2 to 12 in system 13 were combined, there was a calculated effect from repair for carbureted vehicles only. However, because those repairs encompassed so many different subsystems, it was unclear how those results could be extrapolated to the fleet with any confidence, and they were neglected.

Each repair was also classified according to the type of repair action taken by the mechanic, i.e., adjust, replace, reconnect, clean, rebuild, or restore continuity. Finally, the repairs were designated as electrical component failures, mechanical component failures, malmaintenance, or tampering. The data were compiled in a series of Excel spreadsheets, which were then converted to ASCII files for subsequent analysis. A sample of the spreadsheet for the CTP database is illustrated in Table 2-3.

EMISSION REDUCTIONS FROM REPAIR

During the initial phases of this project, it was hoped that sufficient emissions data on individual component repair would be available so that the change in emissions as a result of repair could be calculated on a component-specific basis. Unfortunately, a large fraction of the vehicles included in the repair database received multiple repairs between FTP tests, even though the test protocol in some cases (e.g., CTP) called for

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Table 2-3. Sample Spreadsheet Identifying Repair Actions in a Common Format - CTP Database.

Vehicle Number	Repair Number	Model Year	Fuel System	FTP Test	FTP Results (g/mi)				System Code	Component Code	Repair Action	Reason
					HC	CO	NOx	Score				
1	0	81	Carb	B	1.94	71.61	0.12	9.216				
	1			A	0.39	6.64	0.50	1.550	10	2	6	E
				R	1.55	64.97	-0.38	7.666				
2	0	83	Carb	B	4.84	49.00	0.54	10.280				
	1			A	5.14	89.10	0.30	14.350	4	2	2	M
	1								4	3	1	M
				R	-0.30	-40.10	0.24	-4.070				
2	1	83	Carb	B	5.14	89.10	0.30	14.350				
	2			A	2.19	21.60	0.94	5.290	1	16	2	T
	2								1	13	2	T
				R	2.95	67.50	-0.64	9.060				
2	2	83	Carb	B	2.19	21.60	0.94	5.290				
	3			A	0.72	9.70	1.05	2.740	2	4	1	M
	3								2	5	1	M
				R	1.47	11.90	-0.11	2.550				
3	0	85	TBI	B	1.08	21.87	0.17	3.433				
	1			A	0.32	6.36	0.16	1.120	10	2	2	E
				R	0.75	15.51	0.01	2.313				
3	1	85	TBI	B	0.32	6.36	0.16	1.120				
	2			A	0.31	6.22	0.15	1.084	3	40	2	F
				R	0.01	0.14	0.01	0.036				
3	2	85	TBI	B	0.31	6.22	0.15	1.084				
	3			A	0.19	2.71	0.35	0.806	11	2	2	E
				R	0.13	3.51	-0.20	0.278				
4	0	82	Carb	B	8.32	81.26	1.88	18.322				
	1			A	1.65	12.16	2.87	5.736	2	2	2	M
				R	6.67	69.10	-0.99	12.586				
4	1	82	Carb	B	1.65	12.16	2.87	5.736				
	2			A	1.47	10.84	2.79	5.340	8	8	2	F
				R	0.18	1.32	0.08	0.396				
4	2	82	Carb	B	1.47	10.84	2.79	5.340				
	3			A	1.53	10.08	3.24	5.778	1	3	4	M
	3								2	5	2	M
	3								4	12	2	F
	3								4	3	2	M
	3								6	3	2	M
	3								13	5	1	M
	3								13	13	1	M
				R	-0.06	0.76	-0.45	-0.438				

NOTES

FTP Test Codes:
- B = Baseline
- A = After-repair
- R = Reduction from repair

FTP Results:
- Score = HC + NOx + CO/10

Repair Action Codes:
- 1 = Adjusted
- 2 = Replaced
- 3 = Reconnected
- 4 = Cleaned
- 5 = Rebuilt
- 6 = Continuity Restored

Reason Codes:
- E = Electrical component failure
- F = Mechanical component failure
- M = Maintenance
- T = Tampering

FTPs after each repair. Because of the large number of multiple repairs and because of a desire to use FTP values to assign emission reductions, a methodology had to be

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developed to estimate FTP improvements for individual repairs. This was accomplished with the regression technique described below.

Methodology to Estimate the Effects of Individual Component Repair

From the databases analyzed in this project, it is possible to determine the improvement in FTP emissions due to component repairs. In some cases, FTP improvement data exist for individual repairs; however, a large fraction of the FTP tests were conducted after multiple component repairs. It was desired to identify the emission benefit from an individual component repair based on the average of the entire data set. This was accomplished by casting the problem according to the following linear equation:

$$\sum_{i=1}^{N_c} \delta_{ij} \; B_i = (\Delta FTP)_j \qquad j = 1, N_r$$

where:

i is an index specifying individual components;

N_c is the total number of components that could be repaired;

j is an index specifying a particular repair action (i.e. a particular set of repairs) for which FTP improvement data are available (one or more components may be repaired in a single repair action);

N_r is the total number of repair actions for which FTP data are available;

B_i is the average benefit of repairing component i stated as an improvement in FTP emissions (this is the unknown that is being determined); and

$(\Delta FTP)_j$ is the observed improvement in FTP emissions from repair action j.

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The above terms define the existing data. To analyze these data, the term δ_{ij} is defined as having the value 1 if component i is repaired in repair action j and having the value 0 otherwise; i.e.,

$$\delta_{ij} \begin{cases} 1 & \text{if component } i \text{ is repaired in action } j \\ 0 & \text{if component } i \text{ is NOT repaired in action } j \end{cases}$$

The values of B_i can be found by using a linear regression analysis (with zero intercept) where the input data are the values of δ_{ij} and ($\Delta FTP)_j$ for each data point.

This approach assumes that the emission benefit of each component repair is independent of the benefits of other component repairs that take place in the same repair action. It also assumes that each component repair has the samimprovement in FTP emissions (i.e., B_i), regardless of the original state of the vehicle prior to repair. Although the first assumption can be argued, it was felt that the regression approach described above was more valid in this analysis than simply taking the mean FTP improvement of individual repairs because data points did not have to be discarded using the regression methodology. The second assumption is less of an issue in the final analysis of repair data, which segregated vehicles into normal and high emitter groups on the basis of before-repair emission levels.

Results of the Regression Analysis

To perform the regression analysis, it was necessary to create a repair array (i.e., δ_{ij}) for each FTP before- and after-repair couple. This was accomplished by analyzing the ASCII versions of the repair data files created from the FTP data and the mechanic comments (i.e., Table 2-3) in a FORTRAN post-processor and creating three sets of arrays based on:

- system codes (i.e., a series of 14 1s and 0s for each FTP before- and after-repair couple);
- component codes (i.e., a series of 224 1s and 0s for each FTP before- and after-repair couple); and

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- repair type as defined above (i.e., a series of 10 1s and 0s for each FTP before- and after-repair couple).

The resulting data files were then processed in a SAS routine using a "backward elimination" regression procedure (with zero intercept) in which the user specifies which variables (i.e., components) to include in the regression and the program removes variables until those left are significant at the 90% level. A number of different runs were performed, both on individual components and on systems. That evaluation helped to define the 10 fuel-injected and 10 carbureted repair types ultimately chosen for analysis.

The repair data were segregated according to fuel system type (i.e., carbureted and fuel-injected) prior to analysis. Although it was desirable to also analyze the data according to model-year group (e.g., 1981-1985 and 1986+), there were concerns that doing so would compromise the sample size too severely. The results of the regression analysis are summarized in Tables 2-4a and 2-4b for carbureted and fuel-injected vehicles, respectively. (Appendix A contains the SAS output for those regressions. That appendix includes more detail of the regression statistics, and it contains the regression results for intermediate steps in the analysis, i.e., the regression results with the non-significant components included.) Note that those results are from all repair actions in the five databases where the diagnosis was considered accurate ("OK"). The decision as to whether a diagnosis was OK or faulty was based on the difference between the before-repair and after-repair FTP "score." (In this analysis, the FTP score was defined as HC + NOx + CO/10.) The cutoff used to distinguish between an OK and a faulty diagnosis was 0.2 g/mi for the FTP score, except in cases where there was an EGR repair aimed at NOx reductions. Those repairs were considered OK if the NOx emission rate decreased by more than

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0.2 g/mi, regardless of the effect that the repair may have had on HC and CO emissions.

Regressions were performed for each pollutant independently and for the composite FTP "score." It should be noted that the correlation coefficients (i.e., r^2 values) resulting from the regressions were poor, generally ranging from 0.2 to 0.5. However, it is not uncommon for vehicle emissions data to demonstrate significant scatter, resulting in poor correlations when regressions are performed.

Table 2-4a. Emission Reductions Associated with the Repair of Carbureted Vehicles with "OK" Diagnoses.

System/ Component	Reduction in FTP Emissions (g/mi)			
	HC	CO	NOx	Score
Carb Rebuild/ Replacement	ns[a]	21.91±4.98	ns	2.77±0.78
Fuel Metering System Repair	1.32±0.31	21.30±3.33	-0.27±0.11	3.13±0.56
Ignition System Tune-up Repair[b]	1.10±0.35	ns	ns	1.67±0.65
Other Ignition System Repair[b]	ns	ns	ns	ns
EGR Repair	ns	ns	0.66±0.13	ns
Air Injection Repair	ns	9.44±4.43	ns	ns
Catalyst Replacement	0.85±0.40	ns	0.78±0.14	2.31±0.70
ECU Replacement	1.65±0.63	35.41±7.25	-0.51±0.23	4.85±1.11
Oxygen Sensor Replacement	0.72±0.39	19.53±4.30	ns	2.42±0.69
Other Sensor Replacement/Repair	ns	13.82±7.70	0.43±0.24	2.42±1.19

a Not significant at the 90% level.

b Ignition system "tune-up" repairs include repairs to the distributor cap/rotor, timing, and plugs/wires. All other ignition system repairs were included in the "other" ignition system repair category.

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In comparing the results from Tables 2-4a and 2-4b, several interesting points can be made. First, the effect of ignition system defects was consistent in that only HC emissions were significantly affected. Likewise, EGR defects consistently affected only NOx emissions. Oxygen sensor defects had a significant effect on HC and CO emissions for both carbureted and fuel-injected vehicles. Another point to be made

Table 2-4b. Emission Reductions Associated with the Repair of Fuel-Injected Vehicles with "OK" Diagnoses.

System/ Component	Reduction in FTP Emissions (g/mi)			
	HC	CO	NOx	Score
Injector Replacement	0.68±0.34	10.08±4.66	-0.24±0.12	1.41±0.73
Fuel Metering System Repair	0.56±0.27	7.93±3.68	0.22±0.09	1.36±0.60
Ignition System Tune-up Repair[b]	ns[a]	ns	ns	1.00±0.53
Other Ignition System Repair[b]	0.94±0.49	ns	ns	ns
EGR Repair	ns	ns	0.85±0.10	ns
Air Injection Repair	ns	ns	ns	1.96±1.19
Catalyst Replacement	ns	ns	1.27±0.10	1.59±0.61
ECU Replacement	3.48±0.61	34.83±8.42	ns	6.91±1.32
Oxygen Sensor Replacement	1.46±0.19	29.87±2.61	ns	4.11±0.44
Other Sensor Replacement/Repair	ns	ns	ns	ns

[a] Not significant at the 90% level.

[b] Ignition system "tune-up" repairs include repairs to the distributor cap/rotor, timing, and plugs/wires. All other ignition system repairs were included in the "other" ignition system repair category.

in reference to the tables is that catalyst replacements did not have as large of an effect on FTP reductions as some of the other repairs. This can be explained by noting that engine-out emissions for a properly functioning late-model vehicle are on the order of 2 g/mi HC, 20 g/mi CO, and 2 g/mi NOx. A catalyst with a 90% efficiency for HC and CO and a 70% efficiency for NOx would result in an emission reduction of

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1.8 g/mi HC, 18 g/mi CO, and 1.4 g/mi NOx. On the other hand, a vehicle with a malfunctioning closed-loop fuel control system (e.g., having a bad ECU or oxygen sensor) can have before-repair emissions as high as 10 g/mi HC and 150 g/mi CO, and the repair of those defects can bring emission rates down to certification levels (i.e., 0.41 g/mi HC and 3.4 g/mi CO). Thus, repairing those defects has a much larger effect on the reduction in FTP emissions than does repairing what might be considered the "heart" of the emission control system - the catalyst. (Note that in the test programs analyzed in this study, catalysts were generally not replaced until most other defects were identified and repaired.)

To serve as a check on how well the repairs that were statistically significant accounted for the total emission reduction from repairs, the emission reductions from all statistically significant repairs performed on the vehicles in the repair database were compared to the overall difference in emissions between the baseline and after-repair FTP results for those vehicles. This was done by first multiplying the number of significant repairs in each repair category by the average emission reduction from repair listed in Tables 2-4a and 2-4b. That product was then subtracted from the total before-repair emissions from the repaired vehicles. Dividing that result by the total number of vehicles (more correctly, "repair events," since a single vehicle may have been repaired and FTP tested more than once) gives the average g/mi value when only the significant repairs are considered. For example, there were 541 repair events (with "OK" diagnostics) in the fuel-injected repair database, and those had an average before-repair HC emission rate of 2.06 g/mi and an after-repair emission rate (considering all repairs) of 0.62 g/mi. When only the statistically significant repairs listed in Table 2-4b are considered (i.e., injector replacement, fuel metering system repair, other ignition system repair, ECU replacement, and oxygen sensor replacement), the estimated after-repair emission rate is 0.85 g/mi, based on the calculation shown below.

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$$HC_{After\text{-}Rep.} = [(541 * 2.06\ g/mi) - (82 * 0.68\ g/mi) - (140 * 0.56\ g/mi) - (35 * 0.94\ g/mi) - (23 * 3.48\ g/mi) - (280 * 1.46\ g/mi)] \div 541 = 0.85\ g/mi$$

- (82 * 0.68 g/mi)	Injector Replacement
- (140 *0.56 g/mi)	Fuel Metering System Repair
- (35 * 0.94 g/mi)	Other Ignition System Repair
- (23 * 3.48 g/mi)	ECU Replacement
- (280 * 1.46 g/mi)]	Oxygen Sensor Replacement

Thus, when only the statistically significant component repairs are considered, the calculated HC emission reduction from repair is 84% (i.e., (2.06-0.85)/(2.06-0.62)) of the reduction from all repairs. For CO emissions, the statistically significant component repairs account for 87% of the total emission reduction, and for NOx, the value rises to 92%.

The results presented in Tables 2-4a and 2-4b assume that the change in FTP emissions as a result of repair is independent of the original state of the vehicle. This assumption was tested by segregating vehicles by before-repair emission level prior to performing the regressions. Vehicles were considered "high" emitters if their before-repair FTP emission levels exceeded 1.0 g/mi HC, 15 g/mi CO, or 1.7 g/mi NOx; vehicles with emissions below those levels were considered "normal/moderate" emitters. These values were used because they approximate IM240 levels of 0.8 g/mi HC, 15 g/mi CO, and 2 g/mi NOx. (The FTP levels were calculated from EPA correlation equations developed for MOBILE5a, discussed in Sierra's report "Investigation of MOBILE5a Emission Factors - Evaluation of IM240-to-FTP Correlation and Base Emission Rate Equations" (Sierra, 1994) and from IM240-to-FTP correlations developed by Sierra from the CARB I/M Pilot Project data (Sierra, 1995).) The results of this analysis are summarized in Tables 2-5a and 2-5b for carbureted and fuel-injected vehicles, respectively.

As expected, the benefits from repair of high emitting vehicles are much greater than for normal/moderate emitting vehicles. In addition, it is clear that repair of high emitters drives the analysis when emitter groups are combined (i.e., Tables 2-4a and

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2-4b). Finally, it is interesting to note that catalyst system repairs on normal/moderate emitting fuel-injected vehicles are significant for all pollutants, while those repairs are significant only for NOx and "Score" for the high emitting vehicles.

Table 2-5a. Emission Reductions Associated with the Repair of Carbureted Vehicles with "OK" Diagnoses - Segregated into "High" and "Normal/Moderate" Emitters.

Emitter Category	System/Component	Reduction in FTP Emissions (g/mi)			
		HC	CO	NOx	Score
High	Carb Rebuild/ Replacement	ns[a]	21.73±5.47	ns	2.60±0.86
	Fuel Metering System Repair	1.42±0.36	23.81±3.75	-0.29±0.12	3.47±0.64
	Ignition System Tune-up Repair	1.11±0.40	ns	ns	1.80±0.73
	EGR Repair	ns	ns	0.79±0.15	ns
	Air Injection Repair	ns	9.61±4.82	ns	ns
	Catalyst Replacement	1.05±0.49	ns	0.98±0.17	2.87±0.86
	ECU Replacement	1.77±0.70	37.47±8.08	-0.52±0.25	5.20±1.23
	Oxygen Sensor Replacement	0.83±0.45	23.30±4.88	-0.27±0.15	2.92±0.78
	Other Sensor Replacement/Repair	ns	ns	0.45±0.26	ns
Normal/ Moderate	Carb Rebuild/ Replacement	ns	ns	0.53±0.18	0.81±0.28
	Fuel Metering System Repair	0.27±0.06	5.30±1.03	ns	0.93±0.13
	Air Injection Repair	ns	-5.46±2.28[b]	ns	-0.50±0.28
	Catalyst Replacement	0.53±0.06	6.32±1.02	0.27±0.08	1.43±0.12
	Oxygen Sensor Replacement	-0.14±0.08	ns	0.23±0.11	ns

[a] Not significant at the 90% level.

[b] Due to the small sample size of normal/moderate emitters with air injection system repairs (3), this negative result is driven by a single vehicle. That vehicle had an EGR repair during the same repair event as the air injection repair, and its NOx emissions decreased by over 1 g/mi (thus, it was flagged as an "OK" repair). Its CO emissions increased by 17 g/mi, causing the negative repair effect shown in the table. For calculating the contribution of defective air injection systems to the fleet-average emission rate (presented later in this section), the normal/moderate emitter air injection repair reduction from fuel-injected vehicles (in Table 2-5b) was substituted for the carbureted results shown above.

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Table 2-5b. Emission Reductions Associated with the Repair of Fuel-Injected Vehicles with "OK" Diagnoses - Segregated into "High" and "Normal/Moderate" Emitters.

Emitter Category	System/ Component	Reduction in FTP Emissions (g/mi)			
		HC	CO	NOx	Score
High	Injector Replacement	0.92±0.42	12.70±5.64	0.34±0.15	1.90±0.90
	Fuel Metering System Repair	ns[a]	ns	0.33±0.12	ns
	Ignition System Tune-up Repair	ns	ns	ns	1.37±0.65
	Other Ignition System Repair	1.28±0.62	ns	ns	ns
	EGR System	ns	ns	1.01±0.12	ns
	Catalyst	ns	ns	1.53±0.13	1.30±0.77
	ECU	4.48±0.78	44.47±10.58	ns	8.80±1.66
	Oxygen Sensor Replacement	1.98±0.24	40.20±3.17	0.20±0.09	5.67±0.56
Normal/ Moderate	Injector Replacement	0.08±0.04	2.36±0.71	ns	0.27±0.12
	Fuel Metering System Repair	0.08±0.04	1.18±0.58	ns	0.23±0.10
	Ignition System Tune-up Repair	0.07±0.03	0.83±0.45	ns	0.20±0.08
	Other Ignition System Repair	-0.13±0.06	-2.34±1.02	ns	ns
	EGR System	ns	ns	0.38±0.06	0.29±0.09
	Air Injection	0.22±0.09	5.73±1.52	ns	0.84±0.27
	Catalyst	0.32±0.03	3.02±0.55	0.43±0.06	1.03±0.10
	Oxygen Sensor Replacement	0.08±0.02	2.14±0.36	0.11±0.04	0.38±0.06
	Other Sensor Replacement/Repair	ns	ns	0.31±0.11	0.31±0.18

[a] Not significant at the 90% level.

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EXCESS EMISSIONS VERSUS NATURE OF DEFECT

This study also required an estimate of excess emissions versus the nature of the defects. As described above, the repair database included an assessment of the primary cause of each repaired defect: mechanical failure, electrical failure, malmaintenance, or tampering. These designations were arrived at by evaluating mechanic comments along with the type of repair. For example, replacement of spark plugs and/or wires was generally considered malmaintenance, carburetor rebuilds or replacements were considered mechanical failures, and oxygen sensor replacements were considered electrical failures. Repairs were labeled as tampering if there was a clear indication in the mechanic comments that the component had been tampered, or if a critical emission control component was missing (e.g., the air pump).

The methodology used to quantify the change in FTP emissions by type of defect is similar to the regression technique described above for the analysis of individual components. The arrays of 1s and 0s defined by the term δ_{ij} were constructed for each repair action, but rather than the subscript i referring to a particular component, it referred to the nature of the defect (i.e., mechanical failure, electrical failure, malmaintenance, and tampering). Once each δ_{ij} was matched with the change in FTP emissions from each repair, regressions were performed. The results of that analysis are shown in Table 2-6, which indicates that electrical component failures have the largest influence on the reduction in emissions as a result of repair, particularly for fuel-injected vehicles.

The results in Table 2-6 were combined with the frequency of each type of defect in each of the five databases analyzed in this study to arrive at the fraction of emissions reduced (according to defect type) in the fleet of vehicles receiving repairs. Although there is considerable uncertainty in some of the estimates contained in Table 2-6, this

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gives a reasonable indication of the fraction of excess emissions that are a result of mechanical defects, electrical defects, malmaintenance, and tampering.

Table 2-6. FTP Emission Reductions by Repair Reason.

Fuel System	Repair Reason	FTP Emission Reductions (g/mi)			
		HC	CO	NOx	Score
Carbureted	Mechanical Failure	0.79±0.42	9.16±3.18	0.49±0.10	2.20±0.48
	Electrical Failure	0.92±0.34	23.58±3.95	-0.27±0.12	3.01±0.60
	Malmaintenance	0.84±0.31	13.18±3.57	-0.13±0.11[a]	2.03±0.54
	Tampering	0.75±0.42	7.56±4.93[a]	0.31±0.15	1.82±0.75
Fuel-Injected	Mechanical Failure	0.41±0.20	3.13±2.81[a]	0.72±0.21	1.46±0.44
	Electrical Failure	1.23±0.21	25.26±2.86	-0.07±0.08[a]	3.69±0.45
	Malmaintenance	0.68±0.24	9.42±3.31	-0.04±0.09[a]	1.58±0.52
	Tampering	-0.21±0.56[a]	-1.89±7.66[a]	0.72±0.21	0.32±1.20[a]

[a] Not significant at the 90% level.

The results of that analysis, which was performed for the combined FTP "score," are shown in Table 2-7. As seen in the table, the distribution of excessive emissions across the four defect types differs between carbureted and fuel-injected vehicles. This is not unexpected, since fuel-injected vehicles generally are more reliant on electrical components to control emissions than are carbureted vehicles. This is observed in Table 2-7, which indicates that 50-60% of excessive emissions from fuel-injected vehicles are related to electrical component failure, while only 25-30% of the excessive emissions from carbureted vehicles are related to electrical component failure. It is also interesting to note that the contribution of tampering to excessive emissions from fuel-injected vehicles is very small, but it is much larger for carbureted vehicles.

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Table 2-7. Contribution of Mechanical Failures, Electrical Failures, Malmaintenance, and Tampering to Emission Reductions from Repair.

Fuel System	Database	Mechanical Failures	Electrical Failures	Malmaintenance	Tampering
Carb.	CTP	46%	25%	22%	7%
	Hammond	33%	28%	32%	7%
	CA I/M Pilot	31%	32%	22%	16%
Fuel-Injected	CTP	21%	63%	17%	0%
	Hammond	26%	55%	19%	0%
	Phoenix	28%	61%	11%	0%
	CARBFI	18%	60%	22%	1%
	CA I/M Pilot	28%	48%	22%	2%

PREVALENCE OF EMISSION CONTROL SYSTEM DEFECTS IN THE FLEET

The incidence of emission control system defects in the fleet, coupled with the emissions impact of repairing those defects, gives an estimate of excessive emissions that can be attributed to specific component failures. The emission reductions associated with the repair of defects were presented previously; below is a description of how the fleet component failure rates were determined.

As discussed above, the manner in which vehicles were selected for each of the five databases analyzed in this section of the report has a bearing on how to translate the results to a fleet basis. The CTP database and the CARBFI database contain vehicles that should fail an I/M short test. However, transient short test data (i.e., IM240) are not available from the vehicles tested nor the fleets from which they were drawn. Thus, it is not possible to project component failure rates in those databases to a fleet basis. On the other hand, the Hammond and Phoenix databases contain IM240 scores that can be used to project the lab results to a fleet basis. Such an approach

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was used by EPA in developing the base emission rate equations for MOBILE5a, and a similar approach was used in this study for projecting sample component failure rates to a fleet basis for both the Hammond and Phoenix databases. Finally, the Pilot Project database contains a randomly selected group of vehicles that reflects the California fleet without the need to re-weight the sample.

Hammond and Phoenix Component Failure Rates

The component failure rates for the Hammond and Phoenix databases were determined by analyzing the "ECOMP" files downloaded from EPA's MICRO database. Those files contain information regarding the baseline condition of each vehicle receiving an FTP. The codes "PASS", "FAIL", or "NA" are logged for 11 separate systems and 85 individual components. The systems and components contained in the ECOMP files were combined in a fashion similar to that described above for the analysis of repair effects so that a more manageable number of system/component combinations could be analyzed. These data were used in conjunction with IM240 scores to determine the fraction of component failures for vehicles passing and failing IM240 cutpoints of 0.8 g/mi HC, 15.0 g/mi CO, and 2.0 g/mi NOx. Failure rates were compiled in this manner so that the results could be extrapolated to the fleet on the basis of IM240 pass/fail rates observed at the I/M lanes in Hammond and Phoenix. The results of this analysis are contained in Tables 2-8a and 2-8b for the Hammond and Phoenix databases, respectively.

The component failure rates listed in Tables 2-8a and 2-8b are very similar for fuel-injected vehicles when the results are extrapolated to the fleet, with the Hammond fleet having slightly higher failure rates. This was expected, as the Hammond I/M lane data represented a non-I/M case (i.e., those data were collected during the initial two years of a biennial I/M program), and the Phoenix I/M data represented an I/M case. Also note that the component failure rates for the carbureted vehicles are much higher than

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for the fuel-injected vehicles. This is because the carbureted fleet is older and, in general, fuel management systems are not as durable on a carbureted vehicle as on a fuel-injected vehicle. Both databases indicate an approximate 25% failure rate for

Table 2-8a. Component Failure Rates for the Hammond Database.

Fuel System	System/ Component	Percent Equipped	FTP Sample - Component Failure Rate			Fleet Failure Rate*
			All Vehicles	IM240 Failures	IM240 Passes	
Carbureted	Carburetor	100.0%	24.0%	25.7%	19.5%	23.1%
	Fuel Metering System	100.0%	73.4%	84.1%	43.9%	67.0%
	Ignition Tune-up	100.0%	69.5%	77.0%	48.8%	65.0%
	Other Ignition	100.0%	14.9%	17.7%	7.3%	13.3%
	EGR	98.7%	44.8%	52.2%	24.4%	40.4%
	Air Injection	100.0%	31.2%	37.2%	14.6%	27.6%
	Catalyst	100.0%	12.3%	14.2%	7.3%	11.3%
	Electronic Control Unit	97.4%	7.8%	10.6%	0.0%	6.1%
	Oxygen Sensors	83.8%	27.9%	36.3%	4.9%	23.0%
	Other Sensors	97.4%	4.5%	6.2%	0.0%	3.6%
Fuel-Injected	Fuel Injector(s)	100.0%	12.6%	20.9%	6.6%	9.5%
	Fuel Metering System	100.0%	18.9%	31.4%	9.9%	14.2%
	Ignition Tune-up	100.0%	48.9%	68.6%	34.5%	41.3%
	Other Ignition System	100.0%	8.2%	13.6%	4.3%	6.2%
	EGR	69.3%	20.2%	34.1%	10.2%	15.0%
	Air Injection	23.3%	3.8%	7.7%	1.0%	2.3%
	Catalyst	100.0%	11.8%	24.6%	2.6%	7.0%
	Electronic Control Unit	100.0%	2.1%	4.1%	0.7%	1.4%
	Oxygen Sensor	100.0%	34.0%	55.0%	18.8%	26.0%
	Other Sensors	99.8%	2.3%	3.6%	1.3%	1.8%

* Since the FTP sample was skewed with high emitting vehicles, the fleet failure rates were calculated by weighting the IM240 passing and failing component failure rates by the IM240 pass and fail rates observed in the fleet.

Table 2-8b. Component Failure Rates for the Phoenix Database.

Fuel System	System/ Component	Percent Equipped	FTP Sample - Component Failure Rate			Fleet Failure Rate*
			All Vehicles	IM240 Failures	IM240 Passes	
Fuel-Injected	Fuel Injector(s)	100.0%	14.4%	21.4%	7.9%	8.8%
	Fuel Metering System	100.0%	14.0%	17.9%	10.3%	10.8%
	Ignition Tune-up	100.0%	45.3%	53.9%	37.3%	38.4%
	Other Ignition System	100.0%	5.3%	9.4%	1.5%	2.0%
	EGR	86.4%	22.2%	34.2%	11.1%	12.6%
	Air Injection	25.9%	2.5%	4.3%	0.8%	1.0%
	Catalyst	100.0%	13.6%	23.9%	4.0%	5.3%
	Electronic Control Unit	100.0%	2.1%	3.4%	0.8%	1.0%
	Oxygen Sensor	100.0%	37.9%	53.0%	23.8%	25.8%
	Other Sensors	100.0%	6.6%	11.1%	2.3%	2.9%

* Since the FTP sample was skewed with high emitting vehicles, the fleet failure rates were calculated by weighting the IM240 passing and failing component failure rates by the IM240 pass and fail rates observed in the fleet.

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oxygen sensors. This is important from the perspective that repair of oxygen sensor failures results in a large decrease in emissions.

The effects of vehicle age on component failure rates were assessed by analyzing data from only 1983 to 1985 model year vehicles. That evaluation revealed similar failure rates for carbureted and fuel-injected vehicles for most components. For example, there was a 17% catalyst failure rate for both carbureted and fuel-injected vehicles, oxygen sensor failures occurred on 25% of the carbureted vehicles and 31% of the fuel-injected vehicles, and EGR failures occurred on 38% of the carbureted vehicles and 31% of the fuel-injected vehicles. However, the fuel metering system failure rate (e.g., idle speed, idle CO, choke adjustments, MAP sensor, etc.) for 1983 to 1985 model year carbureted vehicles was more than double that of the same model year fuel-injected vehicles (69% versus 30%). This reflects, in large part, the greater number of components associated with carburetors relative to fuel injectors.

CARB I/M Pilot Project Component Failure Rates

The California I/M Pilot Project database was also analyzed to determine the fraction of specific component failures in the California fleet. Because the California I/M Pilot Project represents a randomly selected fleet, it was not necessary to re-weight the results to reflect the fleet. A summary of the system/component failure rates from the Pilot Project database is contained in Table 2-9. It is interesting to note that the component failure rates for the California fleet are considerably lower that the Hammond and Phoenix fleets. We believe vehicles in the EPA databases may have been subject to a more thorough inspection and repair protocol than the Pilot Project fleet, with more component failures discovered during the time in which the vehicles were being tested. The differences in failure rates between EPA and CARB data may reflect the thoroughness of the inspections more than real differences in the fleets.

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This can be better understood by noting the purpose of the programs. The CARB I/M Pilot Project was intended to evaluate vehicles under the same time and cost

Table 2-9. Component Failure Rates for the California I/M Pilot Project Database.

Fuel System	System/ Component	Percent Equipped	FTP Sample - Component Failure Rate All Vehicles	IM240 Failures	IM240 Passes	Fleet Failure Rate*
Carbureted	Carburetor	**	14.4%	22.6%	0.0%	14.4%
	Fuel Metering System	**	48.6%	72.0%	7.6%	48.6%
	Ignition Tune-up	**	22.6%	33.3%	3.8%	22.6%
	Other Ignition System	**	4.8%	7.5%	0.0%	4.8%
	EGR	**	39.0%	51.6%	17.0%	39.0%
	Air Injection	**	17.1%	26.9%	0.0%	17.1%
	Catalyst	**	13.0%	20.4%	0.0%	13.0%
	Electronic Control Unit	**	2.1%	3.2%	0.0%	2.1%
	Oxygen Sensor	**	24.7%	36.6%	3.8%	24.7%
	Other Sensors	**	4.8%	7.5%	0.0%	4.8%
Fuel-Injected	Fuel Injector(s)	**	2.8%	7.9%	1.1%	2.8%
	Fuel Metering System	**	14.5%	42.2%	5.6%	14.5%
	Ignition Tune-up	**	8.1%	23.6%	3.0%	8.1%
	Other Ignition System	**	2.0%	5.6%	0.7%	2.0%
	EGR	**	8.1%	24.7%	2.6%	8.1%
	Air Injection	**	2.2%	5.6%	1.1%	2.2%
	Catalyst	**	5.6%	18.0%	1.5%	5.6%
	Electronic Control Unit	**	1.4%	4.5%	0.4%	1.4%
	Oxygen Sensor	**	13.4%	39.3%	4.8%	13.4%
	Other Sensors	**	0.6%	2.3%	0.0%	0.6%

* Since the CARB Pilot Project fleet was randomly selected, there was no need to re-weight the sample; thus, columns 4 and 7 are equal.

** The percent of vehicles equipped with each system/component could not be determined from the Pilot Program database.

constraints as in an operating I/M program. On the other hand, although the vehicles in the EPA projects were selected from I/M fleets, those programs were more research oriented, and time and cost constraints were generally not imposed.

OVERALL IMPACT OF SPECIFIC DEFECTS ON FLEET-AVERAGE EMISSIONS

By combining the component failure rates calculated above with the FTP reductions from repair of those defects, it is possible to estimate the impact that defective components have on the fleet-average emission rate. This was performed for the Hammond, Phoenix, and Pilot Project databases by first determining the fraction of

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IM240 passing and failing vehicles (based on 0.8 g/mi HC, 15.0 g/mi CO, and 2.0 g/mi NOx cutpoints) in the fleet of vehicles from which the vehicles receiving FTPs were drawn. The system/component failure rates listed in Tables 2-8 and 2-9 were then used in combination with the IM240 pass/fail rates to arrive at the component failure rates for the fleet. The benefits of repairing the defects were then determined by multiplying the fraction of defects by the reduction in FTP emissions associated with the repair of those defects. This is best illustrated with an example, which is provided below.

Consider ECU defects in fuel-injected vehicles in the Hammond database. As noted in Tables 2-4b and 2-5b, repair of ECU failures results in the greatest FTP reduction of any component. However, because the fraction of ECU failures in the fleet is relatively low, the overall impact on fleet-average emissions is not as significant as the repair effects might indicate. To calculate the effects on the fleet-average emission rate of ECU defects, the first step was to estimate the baseline emission rate for the fleet being analyzed. As noted above, the sample selection process in Hammond was biased toward high emitting vehicles. The FTP data collected in Hammond were re-weighted to a fleet basis by noting that 20% of the 1981 and later model year fuel-injected vehicles failed the 0.8/15/2 HC/CO/NOx IM240 cutpoints at the I/M lane. Since vehicles tested at the I/M lane were randomly selected, it is reasonable to assume that this is the failure rate for the Hammond fleet. The fleet-average FTP emission rate was then calculated by determining the average FTP levels for passing and failing IM240 vehicles in the sample that received FTPs, and weighting these results by 80/20. For HC emissions, passing vehicles averaged 0.42 g/mi, while failing vehicles averaged 2.84 g/mi. Combining these values resulted in a baseline fleet-average HC level of 0.90 g/mi.

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From Table 2-8a, 4.1% of the IM240 failing vehicles had ECU failures, while only 0.7% of the IM240 passing vehicles had ECU failures. Since the Hammond fuel-injected fleet consists of 20% IM240 failures, the fleet contains 4.1% x 20%, or 0.82% high emitting vehicles with ECU failures. From Table 2-5b, repairing a defective ECU on high emitting vehicles results in an average HC decrease of 4.48 g/mi. (The effect of ECU repair is not significant for normal/moderate emitting vehicles.) Thus, the overall contribution to the fleet-average HC emission rate of defective ECUs is:

$$HC_{ECU} = 0.0082 * 4.48 = 0.04 \text{ g/mi}$$

which is 0.04/0.90, or 4% of the fleet-average emission rate.

The above calculations were carried out for each database, system/component, and pollutant. The results are shown in Tables 2-10, 2-11, and 2-12 for the Hammond, Phoenix, and CARB I/M Pilot Project fleets, respectively. Several key points, detailed below, can be made in reference to the results presented in Tables 2-10 to 2-12.

- For carbureted vehicles, the primary contributor to excess emissions is defective fuel metering systems (including the carburetor and related components), which contribute 35-36% to the fleet-average emission rate (i.e., the FTP "score"). That is followed by defective oxygen sensors, which account for 10-11% of the fleet-average emissions.

- For fuel-injected vehicles, defective oxygen sensors are the primary cause of excess emissions, contributing 22-23% to fleet-average emissions in the Hammond and Pilot Project fleets, and 15% to the Phoenix fleet. Other types of failures contribute less to the fleet-average emission rate, primarily because the frequency of failure is much lower than for oxygen sensors.

- The small contribution of defective catalysts to excess emissions is somewhat surprising. However, the fraction of defective catalysts in the fleet is relatively low and, as discussed previously, the benefit of repair is limited if all other systems on the vehicle are functioning properly. In addition, the regression analysis performed to determine the effects of repair indicated that catalyst system repairs of high emitters were significant only for NOx and the weighted FTP "score." Even if the HC value calculated by the regression analysis were used (i.e., 0.33 g/mi), the contribution to fleet-average HC emissions would go only from 1% to 2.5%. Under an optimistic scenario of a 1.5 g/mi HC reduction for each defective catalyst on

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high-emitting vehicles,* the contribution to the fleet-average emission rate only increases to 9%, less than half of the contribution due to defective oxygen sensors.

The overall impact on the fleet-average emissions of the repairs listed in Tables 2-10 to 2-12 is summarized in Table 2-13. That table shows that the baseline fleet-average emission rate for the fuel-injected vehicles is much lower than for carbureted vehicles, and that the fractional reduction from repair is larger for carbureted vehicles.

Table 2-10. Contribution of Defective Components to the Fleet-Average Emission Rate for the Hammond Database.

Fuel System	System/Component	Contribution to FTP Emissions			
		HC	CO	NOx	Score
Carbureted	Carb Rebuild/Replacement	ns[a]	11%	2%	7%
	Fuel Metering System Repair	34%	42%	-13%	29%
	Ignition Tune-up	24%	ns	ns	13%
	Other Ignition Repair	ns	ns	ns	ns
	EGR System	ns	ns	21%	ns
	Air Injection System	< 1%	8%	ns	< 1%
	Catalyst	5%	< 1%	8%	4%
	ECU	5%	8%	-3%	5%
	Oxygen Sensor	8%	17%	-5%	10%
	Other Sensors	ns	ns	1%	ns
Fuel-Injected	Injector Replacement	5%	5%	-2%	3%
	Fuel Metering System Repair	< 1%	< 1%	2%	< 1%
	Ignition Tune-up	2%	2%	ns	8%
	Other Ignition Repair	3%	-1%	ns	ns
	EGR System	ns	ns	11%	< 1%
	Air Injection System	< 1%	< 1%	ns	< 1%
	Catalyst	< 1%	< 1%	9%	3%
	ECU	4%	3%	ns	2%
	Oxygen Sensor	25%	37%	-1%	22%
	Other Sensors	ns	ns	< 1%	< 1%

[a] Repair effects were not significant for these systems/components.

* This is the approximate reduction in HC emissions associated with the replacement of a totally dead or missing catalyst on an otherwise properly functioning vehicle.

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Table 2-11. Contribution of Defective Components to the Fleet-Average Emission Rate for the Phoenix Database.

Fuel System	System/Component	Contribution to FTP Emissions			
		HC	CO	NOx	Score
Fuel Injected	Injector Replacement	4%	6%	-1%	3%
	Fuel Metering System Repair	2%	2%	< 1%	1%
	Ignition Tune-up	5%	5%	ns	6%
	Other Ignition Repair	1%	-1%	ns	ns
	EGR System	ns	ns	8%	2%
	Air Injection System	< 1%	< 1%	ns	< 1%
	Catalyst	2%	2%	5%	3%
	ECU	2%	2%	ns	1%
	Oxygen Sensor	18%	31%	2%	15%
	Other Sensors	ns	ns	< 1%	< 1%

[a] Repair effects were not significant for these systems/components.

Table 2-12. Contribution of Defective Components to the Fleet-Average Emission Rate for the CARB I/M Pilot Project Database.

Fuel System	System/Component	Contribution to FTP Emissions			
		HC	CO	NOx	Score
Carbureted	Carb Rebuild/Replacement	ns[a]	11%	< 1%	6%
	Fuel MeteringSystem Repair	34%	39%	-9%	29%
	Ignition Tune-up	12%	ns	ns	6%
	Other Ignition Repair	ns	ns	ns	ns
	EGR System	ns	ns	17%	ns
	Air Injection System	< 1%	6%	ns	< 1%
	Catalyst	7%	< 1%	9%	6%
	ECU	2%	3%	-1%	2%
	Oxygen Sensor	10%	19%	-4%	11%
	Other Sensors	ns	ns	1%	ns
Fuel-Injected	Injector Replacement	3%	3%	-1%	2%
	Fuel Metering System Repair	< 1%	< 1%	4%	< 1%
	Ignition Tune-up	< 1%	< 1%	ns	3%
	Other Ignition Repair	3%	-1%	ns	ns
	EGR System	ns	ns	7%	< 1%
	Air Injection System	< 1%	< 1%	ns	< 1%
	Catalyst	< 1%	< 1%	8%	3%
	ECU	8%	5%	ns	4%
	Oxygen Sensor	32%	42%	-2%	23%
	Other Sensors	ns	ns	< 1%	< 1%

[a] Repair effects were not significant for these systems/components.

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Table 2-13. Effect of Correcting All Repairable Defects on Fleet-Average Emissions.

Fleet	Fuel System	Repair Status	FTP Emissions (g/mi)			
			HC	CO	NOx	Score[a]
Hammond	Carbureted	As-Received After-Repair Reduction (%)	2.66 0.64 76%	36.08 4.73 87%	1.41 1.24 12%	7.67 2.36 69%
	Fuel-Injected	As-Received After-Repair Reduction (%)	0.90 0.53 41%	12.99 6.89 47%	0.91 0.73 21%	3.12 1.89 39%
Phoenix	Fuel-Injected	As-Received After-Repair Reduction (%)	0.50 0.33 34%	6.22 3.35 46%	0.80 0.67 16%	1.92 1.33 31%
CA I/M Pilot	Carbureted	As-Received After-Repair Reduction (%)	1.93 0.67 66%	28.67 6.56 77%	1.50 1.30 14%	6.30 2.75 56%
	Fuel-Injected	As-Received After-Repair Reduction (%)	0.62 0.33 47%	9.56 4.63 52%	0.94 0.79 17%	2.52 1.63 35%

[a] Score = HC + NOx + CO/10

To put the estimates contained in Table 2-13 into perspective, it is useful to compare those results with the emission reductions expected in an enhanced I/M program. Based on MOBILE5a, an enhanced I/M program is expected to result in an approximate 35% reduction in HC and CO, and a 13% reduction in NOx. For the most part, the estimates presented in Table 2-13 are greater than the MOBILE5a estimates of enhanced I/M reductions. This is due to three factors: (1) the MOBILE5a enhanced I/M benefits are for the entire on-road fleet, while the results in Table 2-13 are just for light-duty cars and trucks (which would be subject to an enhanced I/M program); (2) the MOBILE5a estimates account for post-repair deterioration; and (3) the MOBILE5a estimates account for cost-waivered vehicles and non-complying vehicles that do not participate in the program.

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Another way to look at the results in Table 2-13 is to compare the after-repair emission levels to the emission standards, i.e., are there excess emissions remaining after repairing all of the significant defects. For example, assuming that the vehicles in the Hammond program were certified to 0.41 g/mi HC, 3.4 g/mi CO, and 1.0 g/mi NOx, Table 2-13 indicates that excess emissions remain after repair (i.e., the after-repair values are above the standard), except for NOx in the fuel-injected group. This is shown graphically in Figure 2-2, which shows the baseline and after-repair FTP emission rates (normalized by the emission standards) for the Hammond fuel-injected fleet. Although significant emission reductions occur as a result of repair, HC and CO emissions are still above the emission standards. The only fleet that was consistently below the emission standards after repair is the Phoenix fleet. That is primarily the result of its relatively low baseline (i.e., before-repair) emission rates.

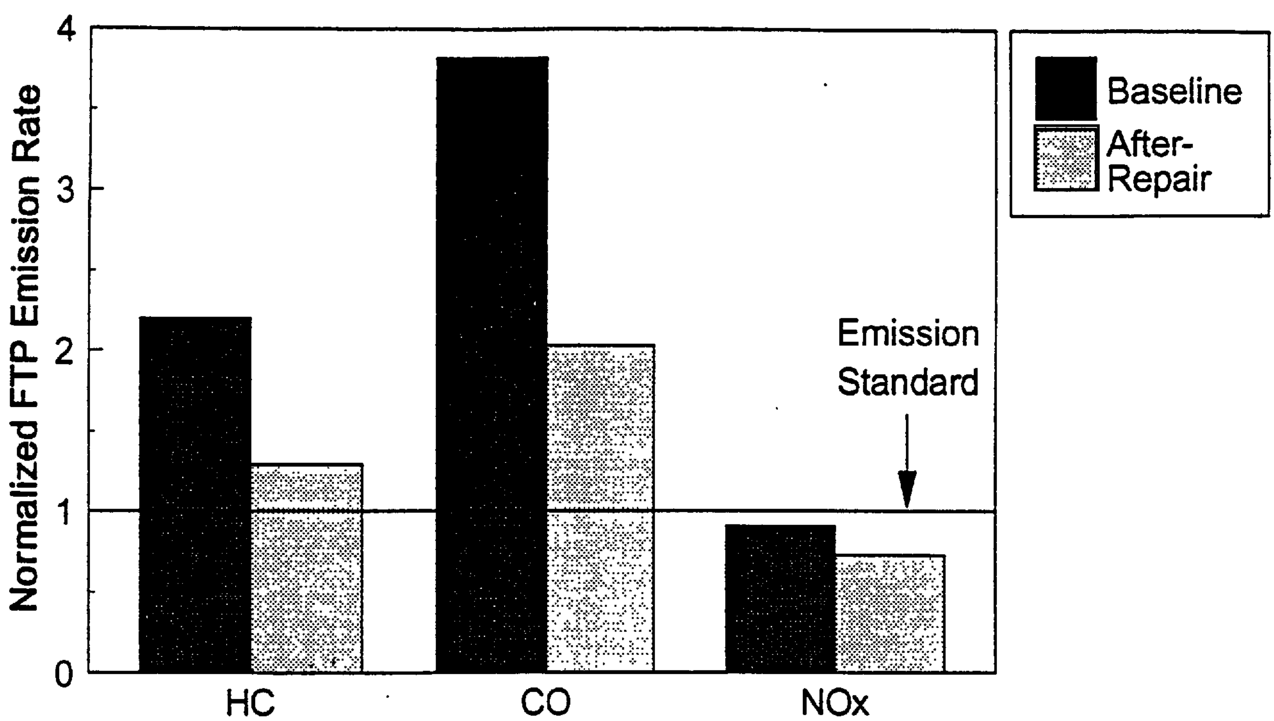

Figure 2-2. The Effect of Repairing Identified Defects in the Hammond Fuel-Injected Fleet Relative to the Emission Standards.

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PCV SYSTEM DEFECTS

Although not part of the scope of work for this project, data were available from the EPA "ECOMP" files on the failure rates of PCV systems. Using those failure rates, coupled with an estimate of the emissions increase from PCV failures, it is possible to calculate the impact of PCV failures on fleet-average HC emissions. For the Hammond database, 5.8% of the fuel-injected vehicles were labeled as having defective PCV valve assemblies, and 13.8% of the carbureted vehicles had defective PCV valve assemblies. (These estimates include extrapolation of IM240 pass/fail vehicles to the fleet.) Assuming that a defective PCV valve causes a 1.2 g/mi HC emission increase (the MOBILE5a tampering offset for late-model, light-duty vehicles), the fleet-average HC emission rate would increase by 0.07 g/mi for fuel-injected vehicles and 0.17 g/mi for carbureted vehicles. This represents 8% and 6% of the baseline exhaust HC emission rate for fuel-injected and carbureted vehicles, respectively.

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Section 3
REVIEW OF CARB'S OBDII ANALYSIS

In September 1989, the California Air Resources Board adopted regulations requiring more advanced emission control system monitoring capability to be incorporated into on-board diagnostic systems. Those regulations, termed "OBDII," contain specific requirements for monitoring of the catalyst, oxygen sensor, and EGR system, among others. The Technical Support Document prepared for that regulation contained a fairly detailed assessment of the effects of repairing defects in those components (CARB, 1989). However, because the data used to prepare that analysis were from one of CARB's standard in-use surveillance programs, they are subject to the biases normally experienced with surveillance programs (i.e., individuals with intentionally tampered or poorly maintained vehicles may be less likely to offer their vehicles for testing). Additionally, because the data used in CARB's OBDII analyses were collected seven to eight years ago, the 1981 and later model year vehicles were tested at a lower average age relative to the Hammond, Phoenix, and California I/M Pilot Project data sets analyzed in the previous section. Thus, a lower defect rate would be expected. Nonetheless, these data provide a lower bound on the frequency of emission control system component failure in the California fleet, and the after-repair data give an indication of the magnitude of excess emissions resulting from component failure.

The CARB OBDII analysis was limited in scope to three exhaust emission control components because those components were specifically required to be monitored by the OBDII system.* Other components and systems, such as the ignition system, were not evaluated by CARB. Given the significance of other emission control systems in contributing to excessive exhaust emissions (as demonstrated in the previous section),

* An evaluation of the benefits of monitoring the evaporative emission control system was also included in CARB's OBDII analysis; however, issues related to evaporative emissions were not addressed in this study.

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this is a shortcoming of the OBDII analysis. However, the results obtained using the OBDII database and CARB's methodology provide a cross-check of the results obtained using the regression analysis presented in Section 2.

The discussion below summarizes the data presented by CARB in its evaluation of the emission reduction potential of identifying and repairing defective catalysts, oxygen sensors, and EGR systems.

DATABASE DESCRIPTION AND SUMMARY STATISTICS

The data used in CARB's analysis to support the OBDII regulations came from its ninth light-duty surveillance program. Only 1981 and later model year passenger cars equipped with three-way catalyst systems were used in the evaluation. A total of 494 vehicles were included in the final database - 260 carbureted and 234 fuel-injected. A summary of the baseline emission rates for that fleet is contained in Table 3-1. As shown in the table, the fleet used for the OBDII analysis is a relatively "clean" group of vehicles, particularly when compared to the databases analyzed in Section 2 of this report (see Table 2-1). It is interesting to note, however, that the fuel-injected vehicles in this database and in the California I/M Pilot Project database have nearly the same mean emission levels (the I/M Pilot Project fuel-injected vehicles averaged 0.62 g/mi HC, 9.54 g/mi CO, and 0.94 g/mi NOx). On the other hand, the Pilot Project carbureted vehicles have much higher mean FTP values than those observed in Table 3-1 (the I/M Pilot Project carbureted vehicles averaged 1.92 g/mi HC, 28.60 g/mi CO, and 1.50 g/mi NOx).

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Table 3-1. Baseline FTP Emission Levels of the CARB OBDII Database.

Fuel System	Sample Size	Mean Mileage	Mean FTP Emission Rate (g/mi)		
			HC	CO	NOx
Carbureted	260	57,500	0.78	10.76	0.98
Fuel-Injected	234	51,800	0.64	8.77	0.94

COMPONENT FAILURE RATES

Baseline component failure rates were calculated from data presented in the above-referenced Technical Support Document. In that report, all vehicles with suspected catalyst failures, oxygen sensor failures, and EGR system failures are tabulated, and each failure is categorized according to whether it would have a high likelihood of detection by an OBDII system, a moderate likelihood of detection, or whether it would be unlikely to be detected by an OBDII system. In general, failures were classified as having a high or moderate likelihood of detection if there was a discernible decrease in emissions as a result of repair. For this analysis, the high and moderate likelihood failures were also considered to be true component failures. The failure rates observed in this fleet of vehicles are summarized in Table 3-2. Because surveillance vehicles are randomly selected, weighting factors to translate the sample results to a fleet basis are not necessary. In fact, as discussed above, surveillance data generally under-represent the fraction of high emitting vehicles in the fleet. This is particularly evident when comparing the results of Table 3-2 to the CARB I/M Pilot Project database, which, for example, had oxygen sensor failure rates of 24.7% and 13.4% for carbureted and fuel-injected vehicles, respectively.

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Table 3-2. Baseline Component Failure Rates for 1981 and Later Model Year Vehicles in the OBDII Database.

Fuel System	Component	Number Equipped	Number Fail	Mean Mileage	Failure Rate	
					Component	Fleet
Carb.	Catalyst	260	19	76,500	7.3%	7.3%
	O_2 Sensor	212	10	77,900	4.7%	3.8%
	EGR System	258	17	67,700	6.6%	6.5%
Fuel-Injected	Catalyst	234	7	82,200	3.0%	3.0%
	O_2 Sensor	234	24	64,100	10.3%	10.3%
	EGR System	178	7	71,000	4.1%	3.8%

EFFECT OF COMPONENT REPAIR

The FTP emission reductions as a result of component repair were calculated in a manner much different than the analysis of the five databases presented in the previous section of this report. For this analysis of the OBDII database, CARB's methodology of classifying vehicles according to emitter regime was extended so that the baseline and after-repair emission results were estimated based on the distribution of vehicles among regimes before and after repair. In this way, the reductions from individual component repairs were calculated. A brief description of that methodology is contained below, followed by a summary of the reductions from repair of individual components and the effect on the fleet-average emission rate of repairing those failing components.

Methodology

The methodology used in CARB's OBDII analysis was based on several models developed to estimate the benefits of inspection and maintenance programs (Sierra, 1991; EPA, 1985). In that approach, vehicles are stratified by emitter category or

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"regime" (i.e., normals, moderates, highs, very highs, and supers), and vehicles migrate among regimes as a result of repair. For each of the vehicles listed as having a high or moderate likelihood of detection by an OBDII system, the before-repair and after-repair emitter categories (for HC, CO, and NOx) were tabulated. In addition, CARB listed the mean emission level of the emitter regimes, so it was possible to construct an estimate of the before- and after-repair mean emission level of those vehicles identified as having emission control system defects.

For vehicles receiving multiple repairs between FTP tests, CARB made a determination as to whether the full benefit of repair should be ascribed to the component repair of interest, or whether only partial benefit should be ascribed (e.g., by assigning the vehicle's after-repair status to one regime higher than it would normally be assigned solely on the basis of its FTP score). That determination was generally based on the results of intermediate Hot-505 test scores. For example, consider a vehicle in the high emitter regime that received an oxygen sensor repair and a fuel-injection system repair between FTPs, and the after-repair FTP placed the vehicle in the normal emitter regime. If intermediate Hot-505 test results indicated that both repairs had a significant effect on emissions, then that vehicle would be placed in the after-repair moderate emitter regime for the purposes of calculating the benefit of the oxygen sensor repair. In this way, CARB attempted to de-couple the effects of multiple repairs. This made it possible in this analysis to estimate the repair effects of individual component repairs by simply comparing the baseline and after-repair emissions calculated from the regime distributions presented by CARB.

Average Emission Reductions from Individual Repairs

Using the methodology described above, average FTP emission reductions from the repair of catalysts, oxygen sensors, and EGR systems were calculated. The results are presented in Table 3-3. For both carbureted and fuel-injected vehicles, catalyst system

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repairs are responsible for the largest FTP reductions. This is different from the results presented in Section 2, which indicated that ECU and oxygen sensor repairs had the greatest FTP reductions for fuel-injected vehicles and fuel system repairs had the greatest FTP reductions for carbureted vehicles. Several factors are likely responsible for these differences, but the one that has the most pronounced influence on the results is the way in which CARB "sequenced" catalyst system repairs when more than one repair was performed on a single vehicle. For example, vehicle 215 had before-repair HC emissions that put it in the super emitter category. After repair, which included an oxygen sensor replacement and an ignition system tune-up, it was in the very high emitter category for HC. A test of the catalyst revealed that it had low activity, so CARB assumed the catalyst benefit for that vehicle to be from the super category down to the high category, or a reduction of 5.14 g/mi (from 6.30 g/mi to 1.16 g/mi). It would have been more appropriate for CARB to assign the vehicle to the very high emitter group before catalyst repair and the moderate level after repair. This would have resulted in a reduction of 1.99 g/mi HC (from 2.58 g/mi to 0.59 g/mi), which is a much more reasonable estimate of the effects of catalyst replacement when other emission control and fuel system components are functioning properly.

Table 3-3. Reduction in FTP Emissions as a Result of Repair Based on the CARB OBDII Database.

Fuel System	Component	FTP Reduction (g/mi)			
		HC	CO	NOx	Score[a]
Carbureted	Catalyst	1.60	21.09	0.99	4.70
	O_2 Sensor	0.51	2.22	0.09	0.82
	EGR System	-0.20	-1.95	1.18	0.79
Fuel-Injected	Catalyst	0.73	9.40	1.07	2.74
	O_2 Sensor	0.59	9.74	0.09	1.65
	EGR System	0.0	2.23	1.45	1.67

[a] Score = HC + NOx + CO/10

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Fleet-Average Emission Reductions

The component failure rates in Table 3-2 were combined with the FTP reductions from repair listed in Table 3-3 to estimate the effect of component failure on the fleet-average emission rate. For example, the fuel-injected fleet is estimated to have an oxygen sensor failure rate of 10.3%; repairing those defects results in an average decrease in FTP HC emissions of 0.59 g/mi. Therefore, the overall impact of defective oxygen sensors on the fleet-average HC emission rate of the OBDII fleet is:

$$HC_{O2\ Sensor} = 0.103 * 0.59\ g/mi = 0.06\ g/mi$$

Thus, oxygen sensor failures contribute 0.06/0.64 or 9.4% to the fleet-average HC emission rate of the OBDII fuel-injected fleet. The contribution of the remaining component failures to the fleet-average emission rates for HC, CO, NOx, and the weighted FTP "score" is summarized in Table 3-4.

Table 3-4. Contribution of Defective Components to the OBDII Fleet-Average Emission Rates.

Fuel System	Component	Contribution to Fleet-Average Emissions			
		HC	CO	NOx	Score[a]
Carbureted	Catalyst	15.1%	14.3%	7.3%	12.0%
	O_2 Sensor	2.5%	0.8%	0.0%	1.1%
	EGR System	-1.7%	-1.2%	7.9%	1.8%
Fuel-Injected	Catalyst	3.4%	3.2%	3.4%	3.3%
	O_2 Sensor	9.4%	11.4%	1.0%	6.9%
	EGR System	0.0%	0.8%	4.6%	2.0%

[a] Score = HC + NOx + CO/10

Comparing the results in Table 3-4 to the results computed in Section 2 of this report, defective catalysts were estimated to contribute approximately 3% to the fuel-injected vehicle, fleet-average FTP-weighted emission rate (i.e., "score," as defined above) for

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both methodologies. In contrast, defective oxygen sensors were estimated to contribute 7% to the fleet-average FTP score using the OBDII database, while the regression analysis indicates a 22% effect. Finally, EGR failures were projected to contribute 5% to the fuel-injected vehicle, NOx fleet-average emission rate using the CARB OBDII database and 11% using the Hammond database. The difference between the results was expected, as the data used in CARB's analysis were collected seven to eight years ago. Because all of our analyses are focussed on 1981 and later models, lower defect rates would be expected for datasets with a lower average vehicle age. In fact, the average age of the vehicles in the OBDII database was 4.4 years, while the average age of the Hammond vehicles was 4.8 years. More importantly, the fraction of high mileage vehicles (i.e., over 100,000 miles) was much higher in the Hammond database (12.4%) compared to the OBDII database (3.9%).

Although the OBDII database provides an alternative estimate of the effect that catalyst, oxygen sensor, and EGR system failures have on fleet-average emissions, it likely underestimates their impact, and the results in the previous section are more reflective of the effect of component failure on fleet-average emissions.

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Section 4

REVIEW OF EPA AND CARB RECALL DATA

As part of this study, a limited review of EPA and CARB recall data was conducted to estimate the effects of recall actions on fleet-average emissions. EPA data were used to determine the number of vehicles subject to recalls each year, and the CARB data were used to provide a rough estimate of the average emission benefit from a recall repair. The discussion that follows describes the EPA and CARB data from which these estimates were made.

Beginning in 1983, EPA has compiled a list each year of vehicles that are subject to emission control system recall actions. Those lists contain the manufacturer, model year, engine family designation, affected models, the emission problem, and the number of vehicles recalled (based on production volume). A summary of the information contained in the 1994 calendar year recall list is shown in Table 4-1. Several points can be made in reference to the table. First, more than half of the recalls were voluntary, i.e., they were not required as a result of EPA or CARB recall testing. Voluntary recalls are generally initiated by vehicle manufacturers if a specific part or component is found to have a high percentage of warranty claims, or if a problem is found independently by the manufacturer. The effect on emissions of these voluntary recalls is likely to be less than EPA- or CARB-influenced recalls, which are based on the results of emissions testing of vehicles in customer service. Second, the recalled vehicles range in age from new to eight years of age. It is a little surprising that vehicles beyond the five-year/50,000-mile warranty period would be recalled, but these could be vehicles where the defect was identified before the warranty period ended and the resolution (which, for influenced recalls, is usually decided by mutual agreement between the manufacturer and EPA) was protracted. Finally, the most common types of defects and components on the 1994 recall list included oxygen sensors, catalysts, evaporative control systems, and the computer control system.

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Table 4-1. Summary of EPA's 1994 Recall List.

Model Year	Recall Type*	Manufacturer	Cal/ Fed	Model	Engine Disp (ltr)	Engine Family	Excessive Pollutant HC	CO	NOx	Recall Reason if not Exhaust Emissions	Number Recalled
86	I	Chrysler	F	Many	2.2L turbo	gcr2.5v5faax		x	x		166,206
90	I	Chrysler	F	Jeep Wrangler	4.2L High	lam4.2t2hea4		x			1,400
88	I	Chrysler	F	Many	2.2L High	jcr2.5v5fbe6		x			5,264
93	V	Chrysler	F	Grand Cherokee	5.9L	pcr5.9t5fey4				Spark Plug Spec	4,855
93	V	Chrysler	C	Grand Cherokee	5.9L	pcr360t5fhb2				Spark Plug Spec	
90	V	Chrysler	C	Grand Wagoneer	5.9L	lam5.9t2hlex				Carburetor	780
90	V	Chrysler	C	Dodge Ram*	5.2 & 5.9L	lam5.9t2hlex			x		13,715
89	V	Chrysler	C	Jeep many	2.5L	kam150t5lad9				O2 Sensor/PCV	4,487
90	V	Chrysler	C	Jeep many	2.5L	lam150t5ladx				O2 Sensor	1,306
90	V	Chrysler	C	Jeep Wrangler	4.2L	lam258t2hea8	x	x		PCV Solenoid	4,764
89	V	Chrysler	F	Cher, Com, Wran	2.5L	kam2.5t5lad8				O2 Sensor	9,242
88	I	Ford	F	Ranger	2.0L	jfm2.0t2gmf2			x		27,612
88	I	Ford	F	Taurus/Sable	3.0L High	jfm3.0v5fegx		x			20,500
89	I	Ford	F	Taurus/Sable	3.0L High	kfm3.0v5feg0		x			
90	I	Ford	F	Taurus/Sable	3.0L High	lfm3.0v5feg1		x			
86	I	Ford	F	T-bird,Cgr,XR4TI	2.3L turbo	gfm2.3v5fgk3		x			91,765
87	I	Ford	F	T-bird,Cgr,XR4TI	2.3L turbo	hfm2.3v5fgk4		x			
88	I	Ford	F	T-bird,Cgr,XR4TI	2.3L turbo	jfm2.3v5fgk8		x			
89	I	Ford	F	T-bird,Cgr,XR4TI	2.3L turbo	kfm2.3v5fgk9		x			
94	V	Ford	F/C	Tempo, Topaz	2.3 & 3.0L					Canister Hose	230
90	V	Ford	F	T-bird, Cgr	3.8L	lfm3.8v5feg5				ECU Ign Timing	3,400
91	I	GM	F	Saturn SC & SL2	1.9L	m4g1.9m8nvb7	x	x			28,850
92	V	GM	B	Lumina FFV	3.1L	n1g3.1m8nvb7				Circuit Board	1,265
93	V	GM	B	Lumina FFV	3.1L	p1g3.1m8mpbx		x			403
93	V	GM	B	Lumina FFV	3.1L	& p1g3.148mpbx		x			
92-94	V	GM	F/C	LDT	4.3L					PCV Line Freezes at Low Temp.	1,543
95	V	GM	B	S/T Trucks	4.3L	s3g4.319gfej				Misfire	837
95	V	GM	B	S/T Trucks	4.3L	& s3g4.329gfgj				Misfire	
95	V	GM	B	Many	3.8L	s1g3.8v8gfec				Powertrain Module	29,783
90	V	Hyundai	C	Excel, Mitsu Precis	1.5L	lhy1.5v5fca6				Catalyst	16,000
90	V	Hyundai	C	Sonata	2.4L	lhy2.4v5fcd0				Catalyst	
90	V	Hyundai	C	Sonata	3.0L	lhy3.0v5fca3				Catalyst	
90	I	Isuzu	F	Geo Storm	1.6L	lsz1.6v5fcb6		x			54,231
94	V	Mitsubishi	F	Montero	3.5L	rmt3.58jgaea				Tune-up Label	1,361
91	V	Mitsubishi	C	3000GT, Stealth	3.0L	mmt3.0v5fc17				High Evap Emissions	4,023
91	V	Mitsubishi	C	3000GT, Stealth	3.0L	& mmt3.0v5fc28				High Evap Emissions	
91	V	Mitsubishi	F	3000GT, Stealth	3.0L	mmt3.0v5ff12				High Evap Emissions	18,932
91	V	Mitsubishi	F	3000GT, Stealth	3.0L	& mmt3.0v5ff23				High Evap Emissions	
92	V	Mitsubishi	F	Colt Vista,Eagle Summit	1.8L	nmt1.8v5ff45				Tune-up Label	24,458
92	V	Mitsubishi	C	Colt Vista,Eagle Summit	1.8L	nmt1.8v5fc4x				Tune-up Label	
93	V	Mitsubishi	F	Colt Vista,Eagle Summit	1.8L	pmt1.8v5ff47				Tune-up Label	
93	V	Mitsubishi	C	Colt Vista,Eagle Summit	1.8L	pmt1.8v5fc41				Tune-up Label	
89	I	Suzuki	F	Many	1.0L	lsk1.0v5ffc2		x			3,827
94	V	Volkwgn	C	Audi 100	2.8L	rad2.8v8gfea				Tune-up Label	1,599
94	V	Volkwgn	F	Audi 100	2.8L	rad2.8v8gbea				Tune-up Label	
94	V	Volvo	B	850	2.4L	rvv2.4hgfea				O2 Sensor	10,150
										Total =	552,788

* I = Influenced - Voluntary recall after EPA investigation.
V = Voluntary - Voluntary recall without EPA investigation.

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To prepare an estimate of the direct effect of recalls on fleet-average emissions, it was first necessary to determine the total number of vehicles subject to recall. The recall lists from 1983 to 1994 were obtained from EPA, and the total number of vehicles recalled each calendar year was compiled. The results are shown in Table 4-2. Because it was desired to estimate the total VMT from those vehicles in 1995, several assumptions had to be made regarding the number left in the fleet in 1995 and their annual mileage accumulation rates. Although the age at which vehicles are recalled varies widely, this analysis assumed that, on average, vehicles were recalled at three years of age. (This is the timeframe when recall testing is normally conducted by EPA and CARB.) Thus, if the vehicles recalled in 1994 were three years old, there would be 96.4% of their original numbers remaining in the fleet, based on EPA's scrappage curve used in the MOBILE5a dynamic registration preprocessor (EPA, 1994). Similarly, vehicles recalled during 1993 were assumed to be four years old, and 94.5% of those were assumed to still be in the fleet. This calculation continued for all vehicles recalled back to the 1983 calendar year, and the results are also contained in Table 4-2. To determine the average mileage driven by recalled vehicles in 1995, the MOBILE5a annual mileage accumulation rates (which are a function of age) were applied to the remaining vehicles.

Table 4-2. Number of Vehicles Subject to EPA Recall Action by Calendar Year (Including Voluntary Recalls).

Recall Year	Vehicles Recalled	Fraction Remaining	Total Remaining	Average Annual VMT	Total VMT
1983	2,751,660	0.412	1,133,684	6,987	7.92E+09
1984	2,076,190	0.481	998,647	7,386	7.38E+09
1985	2,140,520	0.553	1,183,708	7,807	9.24E+09
1986	1,561,540	0.625	975,963	8,254	8.06E+09
1987	3,170,847	0.693	2,197,397	8,726	1.92E+10
1988	3,383,642	0.755	2,554,650	9,225	2.36E+10
1989	4,921,810	0.809	3,981,744	9,751	3.88E+10
1990	2,615,493	0.855	2,236,247	10,310	2.31E+10
1991	2,326,339	0.893	2,077,421	10,899	2.26E+10
1992	2,979,176	0.923	2,749,779	11,552	3.18E+10
1993	2,013,315	0.945	1,902,583	12,180	2.32E+10
1994	552,788	0.964	532,888	12,875	6.86E+09
Total:	30,493,320		22,524,709		2.22E+11

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Summing across all recall calendar years, the total VMT driven by recalled vehicles in 1995 was estimated to be 2.2 x 10^{11} miles. However, this is an optimistic assessment because it assumes that recall repairs were performed on all vehicles.

The total mileage driven by the U.S. fleet was estimated by assuming a fleet-average annual mileage accumulation rate of 10,000 miles, and a light-duty fleet population of 176 million (based on 1993 and 1994 issues of AAMA Facts & Figures). The fraction of VMT traveled by recalled vehicles in 1995 was then calculated as 2.2 x 10^{11}/(176 million $*$ 10,000) = 12.5%.

To determine the change in emissions from a typical recall action, the mean excess emission rates (i.e., the tested FTP value minus the certification standard) from 65 CARB recall tests were used. Those tests were conducted from 1983 to 1993 and covered model years from 1980 to 1991 (CARB, 1995). The results of that analysis yielded average excess emissions of 0.13 g/mi HC, 2.54 g/mi CO, and 0.19 g/mi NOx. Although those numbers at first appear low, it should be recognized that not all recalls are strictly for tailpipe emissions. Vehicles can be recalled for things such as incorrect information on tune-up labels, evaporative control system defects, etc. Also, not every emissions-related recall affects all three pollutants. Finally, those estimates are likely conservative (i.e., high) because they represent only vehicles that were subject to an influenced recall. As discussed above, voluntary recalls make up over half of the recall actions, and the effect on emissions of those recalls could be less than for an influenced recall because the recalled components do not necessarily result in vehicles exceeding emission standards. Unfortunately, emissions data on voluntary recalls were not identified in this project.

To determine the fleet-average baseline emission rate, the MOBILE5a model was run for January 1, 1995, under a "basic" I/M scenario at 750F. This resulted in light-duty

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gasoline vehicle emission rates of 1.22 g/mi HC, 14.8 g/mi CO, and 1.61 g/mi NOx. Assuming that (1) all vehicles subject to recall get repaired, (2) a recall repair results in a constant offset in emissions over the remaining life of the vehicle, and (3) the excess emissions calculated above are a reasonable representation of the benefit of a recall repair, the overall impact of those repairs on the fleet-average HC emission rate is:

$$Recall_{HC} = (12.5\% * 0.13 \text{ g/mi})/1.22 \text{ g/mi} = 1.3\%$$

Performing the same calculation for the other pollutants results in recall actions accounting for 2.1% of fleet-average CO emissions and 1.5% of fleet-average NOx emissions.

These results indicate that the direct impact of recalls on fleet-average emissions is very small. Since vehicles selected for recall testing are well-maintained vehicles with less than 50,000 miles, this indicates that the majority of excess emissions in the fleet result from maintenance problems or defects that occur beyond the "useful life" of the vehicle. As an example, data from the Hammond program indicated that fuel-injected vehicles had an 11% oxygen sensor failure rate for vehicles with less than 50,000 miles. For vehicles with more than 50,000 miles, the oxygen sensor failure rate increased to 40%.

The contribution to the fleet-average weighted FTP "score" of recall repairs versus non-recall repairs (discussed in Section 2 of this report) is illustrated in Figure 4-1 for the Hammond database (carbureted and fuel-injected vehicles combined). The emission levels have been normalized by the emission standard to which these vehicles were certified (i.e., 0.41 g/mi HC + 1.0 g/mi NOx + 3.4 g/mi CO/10), which is also shown in the figure. Figure 4-1 indicates that recall actions have a small impact on fleet-average emissions, but if all identifiable defects are repaired, emissions are within 25% of the certification standard. The level of emissions remaining above the standards may be

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attributable to general aging and deterioration of emission control components that would not necessarily be positively identified as a defect.

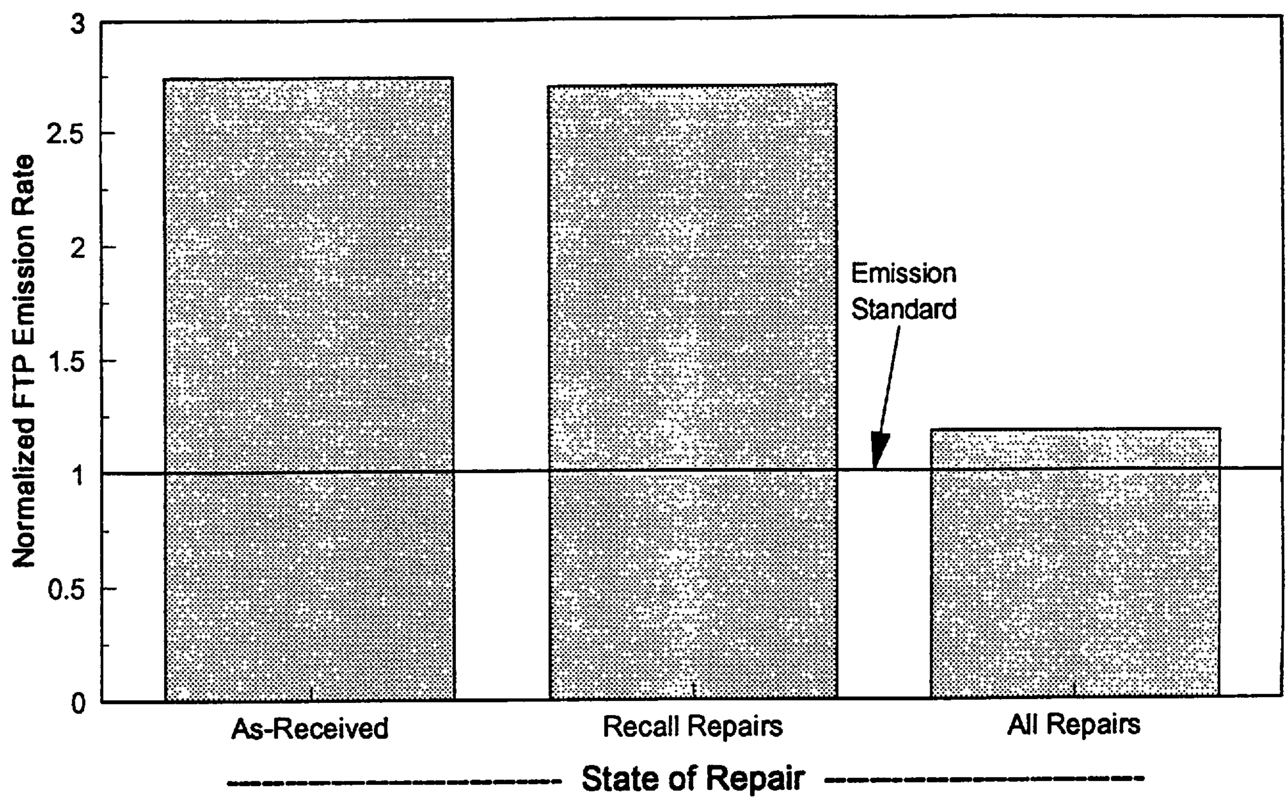

Figure 4-1. Contribution of Repairable Defects Relative to the Fleet-Average Emission Standard (HC + NOx + CO/10) for the Hammond Database.

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Appendix A

REGRESSION RESULTS FOR ANALYSIS OF FTP REDUCTIONS FROM REPAIRS

Components included in the regression variables (see the table on the next page for the system and component codes) were:

COM1 - Carburetor replacement/rebuild (system 2, component 2)

COM2 - Fuel metering system repairs for carbureted vehicles (system 2, components 2-25; system 11, component 9)

COM3 - Fuel injector replacement (system 3, component 3)

COM4 - Fuel metering system repairs for fuel-injected vehicles (system 3, components 2, 6-43; system 11, component 9)

COM5 - Ignition system tune-up repairs (system 4, components 2-3, 5-6)

IGN2 - Other ignition system repairs (system 4, components 4, 7-23)

COM6 - EGR system repairs (system 5, components 2-14)

COM7 - Air injection system repairs (system 8, components 2-15)

COM8 - Catalyst replacement (system 9, components 3-7)

COM9 - ECU replacement (system 10, component 2)

COM10 - Oxygen sensor replacement (system 11, component 2)

SENS2 - Other sensor replacement/repair (system 11, components 10-21)

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Table A-1. System and Component Codes Used to Standardize Repair Data from the CTP, Hammond, Phoenix, CARBFI, and California I/M Pilot Project Databases.

1 Air Induction
- 2 air door
- 3 air filter
- 4 air cleaner housing - ach
- 5 cold air duct
- 6 hot air duct
- 7 intake manifold
- 8 turbocharger - tc
- 9 charge air cooler - cac
- 10 supercharger - sc
- 11 sensor / switch / solenoid
- 12 hoses / vacuum lines
- 13 gasket / seal
- 14 wire / harness / fuse
- 15 other

2 Carburetion
- 2 carburetor assembly
- 3 idle mixture adj. limiting device
- 4 idle mixture
- 5 idle speed
- 6 idle speed control isc
- 7 throttle/throttle controls
- 8 throttle position sensor - tps
- 9 mixture control solenoid - mcs
- 10 mixture control solenoid - mcs, cmds
- 11 choke adjustment (notches)
- 12 choke adjustment (vacuum break)
- 13 choke adjustment limiting device
- 14 choke heater
- 15 choke (misc.)
- 16 early fuel evaporation - efe (electric)
- 17 engine coolant temp. sensor - ects
- 18 intake air temperature sensor - iats
- 19 vacuum diaphragms
- 20 fuel pump
- 21 fuel filter
- 22 hoses
- 23 gasket / seal
- 24 wire / harness / fuse
- 25 other

3 Fuel-Injection
- 2 air flow sensor
- 3 injector(s)
- 4 diesel injector(s)
- 5 diesel fuel supply pump
- 6 throttle body - tb
- 7 throttle controls
- 8 throttle position sensor - tps
- 9 fuel pump
- 10 fuel filter
- 11 fuel distributor
- 12 fuel pressure regulator
- 13 fuel delivery/return line
- 14 fuel pump relay - fpr
- 15 diesel fuel injection pump
- 16 diesel fuel heater
- 17 diesel speed governor
- 18 diesel smoke puff limiter - spl
- 19 diesel glow plugs
- 20 diesel water separator
- 21 inertia fuel shutoff switch - ifss
- 22 idle speed control - isc
- 23 idle air control valve - iacv
- 24 iacv hoses
- 25 cold start valve
- 26 early fuel evaporation - efe (electrical)
- 27 engine coolant temp. sensor - ects
- 28 cam position sensor (smpi)
- 29 crankshaft position sensor - cps
- 30 manifold surface temp. sensor - msts
- 31 intake air temperature sensor - iats
- 32 diesel fast idle solenoid
- 33 diesel cold start solenoid
- 34 diesel altitude control solenoid
- 35 hoses

3 Fuel-Injection (Continued)
- 36 hoses (air flow sensor & throttle body)
- 37 hoses (vac hoses, pressure regulator, ect)
- 38 gasket / seal
- 39 wire / harness / fuse
- 40 other
- 41 idle CO
- 42 idle speed
- 43 aux. air regulator

4 Ignition
- 2 distributor assembly (cap & rotor)
- 3 ignition timing
- 4 ignition timing limiting device
- 5 spark plugs and / or wires
- 6 spark plugs and / or wires
- 7 breakerless pickup (all types)
- 8 ignition module
- 9 spark timing control module
- 10 coil/coil pack
- 11 dwell / points
- 12 vacuum advance assembly
- 13 spark delay devices
- 14 knock sensors - ks
- 15 engine speed sensor
- 16 camshaft position sensor
- 17 crankshaft position sensor - cps
- 18 engine coolant temperature sensor - ects
- 19 thermal vacuum switch - tvs
- 20 hoses
- 21 gasket / seal
- 22 wire / harness / fuse
- 23 other

5 EGR
- 2 egr valve assembly
- 3 egr filter
- 4 egr spacer plate
- 5 egr function sensor - egrs
- 6 egr function control - egrc
- 7 delay solenoid/valve
- 8 vacuum amplifier
- 9 vacuum reservoir
- 10 engine coolant temperature sensor - ects
- 11 thermal vacuum switch - tvs
- 12 hoses / vacuum lines
- 13 wire/harness/fuse
- 14 other

6 PCV
- 2 pcv valve or orifice
- 3 pcv filter
- 4 oil filler cap
- 5 hoses
- 6 wire / harness / fuse
- 7 other

7 Evaporative Control
- 2 canister
- 3 canister filter
- 4 canister purge solenoid / valve
- 5 fuel filler cap
- 6 fuel restrictor
- 7 fuel tank
- 8 fuel line (supply/return)
- 9 vapor separator
- 10 pressure relief valve
- 11 rollover valve
- 12 anti siphon valve
- 13 hoses / vacuum lines
- 14 gasket / seal
- 15 wire / harness / fuse
- 16 other

8 Secondary Air Injection
- 2 secondary air injection filter
- 3 secondary air injection pump

8 Secondary Air Injection (Continued)
- 4 secondary air bypass valve - sabv
- 5 secondary air anti-backfire valve - sabfv
- 6 secondary air anti-backfire valve - sabfv
- 7 secondary air switching valve - sasv
- 8 secondary air pulse valve - sapv
- 9 drive belt
- 10 upstream injection tube(s)
- 11 downstream injection tube(s)
- 12 hoses / vacuum lines
- 13 gasket / seal
- 14 wire / harness / fuse
- 15 other

9 Exhaust After-Treatment
- 2 thermal reactor
- 3 warm-up oxidation catalyst - wuoc
- 4 warm-up three way catalyst - wutwc
- 5 oxidation catalyst - oc
- 6 three way catalyst
- 7 three way catalyst
- 8 trap oxidizer, continuous - toc
- 9 trap oxidizer, periodic - top

10 Engine Control
- 2 powertrain control module - pcme
- 3 powertrain control module (trans) - pcmt
- 4 body control module - bcm

11 Sensor/Solenoid/Valve
- 2 oxygen sensor - o2s
- 3 oxygen sensor - o2s
- 4 air conditioner sensor - acs
- 5 barometric absolute pressure sensor
- 6 coolant level sensor - cols
- 7 engine coolant temperature sensor - ects
- 8 fuel temperature sensor
- 9 manifold air pressure sensor - map
- 10 manifold vacuum sensor - mvs
- 11 manifold vacuum zone switch - mvzs
- 12 wide open throttle switch - wots
- 13 engine speed sensor
- 14 torque sensor
- 15 cylinder chamber temperature sensor
- 16 catalyst temperature sensor
- 17 thermal vacuum switch - tvs
- 18 vehicle speed sensor - vss
- 19 wire / harness / fuse / vacuum line
- 20 gasket / seal
- 21 other

12 On-Board Diagnostics
- 2 malfunction indicator light - mil
- 3 mil bulb check
- 4 obd system
- 5 diagnostic trouble codes - dtc
- 6 service reminder
- 7 data link connector - dlc
- 8 wire / harness / fuse

13 Engine/Exhaust
- 2 engine block
- 3 cooling system
- 4 coolant fan control
- 5 intake/exhaust valves
- 6 auxiliary vacuum pump
- 7 belt tension
- 8 exhaust manifold
- 9 early fuel evaporation - efe (heat riser)
- 10 mufflers
- 11 exhaust port liner/double walled pipe
- 12 tailpipe
- 13 other
- 14 cylinder compression pressure (psi - xxx.)
- 15 cylinder leak down (percent - xx.x)
- 16 vacuum lines (general)

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Backward Elimination Procedure for Dependent Variable R_HC

Step 0 All Variables Entered R-square = 0.28197841 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	1118.31162403	111.83116240	12.33	0.0001
Error	314	2847.63607597	9.06890470		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	0.66282904	0.45126060	19.56604584	2.16	0.1429
COM2	1.37891116	0.32600452	162.24830751	17.89	0.0001
COM5	1.00097783	0.37454840	64.77208296	7.14	0.0079
COM6	-0.02549988	0.39263682	0.03825154	0.00	0.9483
COM7	-0.14393537	0.39565955	1.20018055	0.13	0.7163
COM8	0.85710408	0.39901388	41.84522924	4.61	0.0325
COM9	1.64598952	0.64301855	59.42401044	6.55	0.0109
COM10	0.67853236	0.39635141	26.57878720	2.93	0.0879
IGN2	-1.05519954	0.72718406	19.09568866	2.11	0.1478
SENS2	0.53302377	0.68919882	5.42449024	0.60	0.4399

Bounds on condition number: 1.825337, 131.6381

Step 1 Variable COM6 Removed R-square = 0.28196876 C(p) = 8.00421788

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	1118.27337249	124.25259694	13.74	0.0001
Error	315	2847.67432751	9.04023596		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	0.65897726	0.44663862	19.67922931	2.18	0.1411
COM2	1.37487048	0.31950633	167.39573894	18.52	0.0001
COM5	0.99782623	0.37080399	65.46373872	7.24	0.0075
COM7	-0.14663683	0.39284454	1.25957627	0.14	0.7092
COM8	0.85614640	0.39811056	41.80887096	4.62	0.0323
COM9	1.64231072	0.63950553	59.62135151	6.60	0.0107
COM10	0.67506678	0.39212163	26.79363562	2.96	0.0861
IGN2	-1.05754563	0.72513736	19.22814676	2.13	0.1457
SENS2	0.52582217	0.67914383	5.41918575	0.60	0.4394

Bounds on condition number: 1.794697, 103.3038

Step 2 Variable COM7 Removed R-square = 0.28165117 C(p) = 6.14310745

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	1117.01379622	139.62672453	15.49	0.0001
Error	316	2848.93390378	9.01561362		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	0.63378033	0.44090638	18.62859245	2.07	0.1516
COM2	1.37151989	0.31894498	166.71242381	18.49	0.0001
COM5	0.98287839	0.36813288	64.26664765	7.13	0.0080
COM8	0.84428503	0.39629953	40.91912644	4.54	0.0339
COM9	1.60111526	0.62905200	58.40733381	6.48	0.0114
COM10	0.65971210	0.38942657	25.87337193	2.87	0.0912
IGN2	-1.08783240	0.71960156	20.60321909	2.29	0.1316
SENS2	0.51553937	0.67766015	5.21789185	0.58	0.4474

Bounds on condition number: 1.773764, 80.89914

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Step 3 Variable SENS2 Removed R-square = 0.28033549 C(p) = 4.71846820

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	1111.79590438	158.82798634	17.64	0.0001
Error	317	2854.15179562	9.00363342		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	0.61684310	0.44005126	17.69133821	1.96	0.1620
COM2	1.39770912	0.31687099	175.18077100	19.46	0.0001
COM5	1.01868535	0.36486897	70.18173159	7.79	0.0056
COM8	0.84829443	0.39600111	41.31599564	4.59	0.0329
COM9	1.60101543	0.62863390	58.40005319	6.49	0.0113
COM10	0.68736142	0.38746921	28.33438018	3.15	0.0770
IGN2	-1.04586813	0.71700742	19.15686158	2.13	0.1456

Bounds on condition number: 1.744769, 62.46968

Step 4 Variable COM1 Removed R-square = 0.27587468 C(p) = 4.66923721

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	1094.10456617	182.35076103	20.19	0.0001
Error	318	2871.84313383	9.03095325		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM2	1.39321506	0.31733513	174.07388362	19.28	0.0001
COM5	1.14387792	0.35430577	94.13182889	10.42	0.0014
COM8	0.85004147	0.39659949	41.48676041	4.59	0.0328
COM9	1.62098386	0.62942524	59.89666784	6.63	0.0105
COM10	0.71646459	0.38749912	30.87319739	3.42	0.0654
IGN2	-0.98618422	0.71682717	17.09309791	1.89	0.1699

Bounds on condition number: 1.64023, 46.02912

Step 5 Variable IGN2 Removed R-square = 0.27156472 C(p) = 4.55404011

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	1077.01146827	215.40229365	23.78	0.0001
Error	319	2888.93623173	9.05622643		
Total	324	3965.94770000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM2	1.31617203	0.31279162	160.34756820	17.71	0.0001
COM5	1.09867808	0.35327249	87.59282892	9.67	0.0020
COM8	0.84646850	0.39714553	41.14049547	4.54	0.0338
COM9	1.64558701	0.63005090	61.77854941	6.82	0.0094
COM10	0.72425488	0.38799952	31.55496934	3.48	0.0629

Bounds on condition number: 1.626127, 32.64309

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_HC

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	COM6	9	0.0000	0.2820	8.0042	0.0042	0.9483	EGR
2	COM7	8	0.0003	0.2817	6.1431	0.1393	0.7092	SECOND AIR
3	SENS2	7	0.0013	0.2803	4.7185	0.5788	0.4474	
4	COM1	6	0.0045	0.2759	4.6692	1.9649	0.1620	CARB RPL/RBLD
5	IGN2	5	0.0043	0.2716	4.5540	1.8927	0.1699	

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Backward Elimination Procedure for Dependent Variable R_CO

Step 0 All Variables Entered R-square = 0.44871048 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	303165.75713329	30316.57571333	25.56	0.0001
Error	314	372472.03756671	1186.21668015		
Total	324	675637.79470000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	21.06603200	5.16097802	19763.57409824	16.66	0.0001
COM2	19.90441296	3.72844904	33806.97801877	28.50	0.0001
COM5	6.23135527	4.28363579	2510.17485371	2.12	0.1468
COM6	-4.24585148	4.49050948	1060.47977374	0.89	0.3451
COM7	8.89808350	4.52507982	4586.74389028	3.87	0.0501
COM8	5.80636667	4.56344270	1920.38249930	1.62	0.2042
COM9	34.02746927	7.35407575	25396.10592226	21.41	0.0001
COM10	17.98271105	4.53299246	18668.28251181	15.74	0.0001
IGN2	-2.30556978	8.31665996	91.16385475	0.08	0.7818
SENS2	13.75331911	7.88223032	3611.44349585	3.04	0.0820

Bounds on condition number: 1.825337, 131.6381

Step 1 Variable IGN2 Removed R-square = 0.44857555 C(p) = 8.07685262

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	303074.59327854	33674.95480873	28.47	0.0001
Error	315	372563.20142146	1182.74032197		
Total	324	675637.79470000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	21.01165938	5.14968731	19690.12111804	16.65	0.0001
COM2	19.74936859	3.68085845	34048.46993310	28.79	0.0001
COM5	6.17818280	4.27306436	2472.47576661	2.09	0.1492
COM6	-4.30769260	4.47838858	1094.29713878	0.93	0.3368
COM7	8.76521787	4.49302894	4501.28386910	3.81	0.0520
COM8	5.81332361	4.55668202	1925.04530605	1.63	0.2030
COM9	34.13431712	7.33319985	25626.23472246	21.67	0.0001
COM10	18.03616102	4.52224914	18813.45854579	15.91	0.0001
SENS2	13.61661837	7.85525518	3553.91747186	3.00	0.0840

Bounds on condition number: 1.821677, 107.8856

Step 2 Variable COM6 Removed R-square = 0.44695590 C(p) = 6.99936294

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	301980.29613976	37747.53701747	31.92	0.0001
Error	316	373657.49856024	1182.46043848		
Total	324	675637.79470000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	20.34999922	5.10293429	18805.09197011	15.90	0.0001
COM2	19.03837130	3.60544977	32970.63453563	27.88	0.0001
COM5	5.63530344	4.23512643	2093.57474975	1.77	0.1843
COM7	8.28483444	4.46465806	4071.71978363	3.44	0.0644
COM8	5.65234064	4.55306865	1822.36294153	1.54	0.2154
COM9	33.52973391	7.30534907	24909.49301835	21.07	0.0001
COM10	17.45848346	4.48166271	17944.08485574	15.18	0.0001
SENS2	12.37348671	7.74729313	3016.27431339	2.55	0.1112

Bounds on condition number: 1.789897, 82.40099

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Step 3 Variable COM8 Removed R-square = 0.44425865 C(p) = 6.53564461

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	300157.93319823	42879.70474260	36.20	0.0001
Error	317	375479.86150177	1184.47905837		
Total	324	675637.79470000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	20.29628701	5.10710455	18707.29870968	15.79	0.0001
COM2	19.42132216	3.59529425	34563.37086075	29.18	0.0001
COM5	5.79968731	4.23666757	2219.66670681	1.87	0.1720
COM7	8.72774871	4.45417712	4547.75319967	3.84	0.0509
COM9	34.30396756	7.28488955	26264.56120298	22.17	0.0001
COM10	17.80610172	4.47672288	18738.92461501	15.82	0.0001
SENS2	12.46745230	7.75353307	3062.55241370	2.59	0.1088

Bounds on condition number: 1.788148, 64.37702

Step 4 Variable COM5 Removed R-square = 0.44097336 C(p) = 6.40685983

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	297938.26649142	49656.37774857	41.81	0.0001
Error	318	377699.52820858	1187.73436544		
Total	324	675637.79470000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	21.91139426	4.97577772	23032.30525329	19.39	0.0001
COM2	21.29614414	3.32878757	48612.62973644	40.93	0.0001
COM7	9.44473185	4.42935045	5400.30763848	4.55	0.0337
COM9	35.41282323	7.24965753	28340.36527246	23.86	0.0001
COM10	19.52814621	4.30224750	24470.93577478	20.60	0.0001
SENS2	13.81744728	7.70112269	3823.55084643	3.22	0.0737

Bounds on condition number: 1.250137, 41.88638

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_CO

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	IGN2	9	0.0001	0.4486	8.0769	0.0769	0.7818	
2	COM6	8	0.0016	0.4470	6.9994	0.9252	0.3368	EGR
3	COM8	7	0.0027	0.4443	6.5356	1.5412	0.2154	CATALYST
4	COM5	6	0.0033	0.4410	6.4069	1.8740	0.1720	IGN TUNE-UP

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Backward Elimination Procedure for Dependent Variable R_NOX

Step 0 All Variables Entered R-square = 0.19626812 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	88.74227730	8.87422773	7.67	0.0001
Error	314	363.40592270	1.15734370		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	-0.16914326	0.16120599	1.27411724	1.10	0.2949
COM2	-0.22048752	0.11646016	4.14835229	3.58	0.0592
COM5	-0.04548019	0.13380172	0.13371606	0.12	0.7342
COM6	0.71628400	0.14026354	30.18167185	26.08	0.0001
COM7	0.23362516	0.14134336	3.16191919	2.73	0.0994
COM8	0.78496387	0.14254164	35.09765949	30.33	0.0001
COM9	-0.54671408	0.22970860	6.55583996	5.66	0.0179
COM10	-0.21201095	0.14159051	2.59484010	2.24	0.1353
IGN2	-0.14555842	0.25977545	0.36336311	0.31	0.5757
SENS2	0.45416827	0.24620580	3.93821443	3.40	0.0660

Bounds on condition number: 1.825337, 131.6381

Step 1 Variable COM5 Removed R-square = 0.19597239 C(p) = 8.11553704

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	88.60856124	9.84539569	8.53	0.0001
Error	315	363.53963876	1.15409409		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	-0.18050654	0.15747997	1.51626973	1.31	0.2526
COM2	-0.23348554	0.10984854	5.21401923	4.52	0.0343
COM6	0.71010695	0.13888591	30.16979371	26.14	0.0001
COM7	0.22916323	0.14053476	3.06876462	2.66	0.1040
COM8	0.78368770	0.14229200	35.00791833	30.33	0.0001
COM9	-0.55432845	0.22829252	6.80443661	5.90	0.0157
COM10	-0.22439669	0.13662921	3.11305632	2.70	0.1015
IGN2	-0.14951212	0.25915032	0.38414089	0.33	0.5644
SENS2	0.44587006	0.24464825	3.83330706	3.32	0.0693

Bounds on condition number: 1.470814, 98.70649

Step 2 Variable IGN2 Removed R-square = 0.19512279 C(p) = 6.44745304

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	88.22442034	11.02805254	9.58	0.0001
Error	316	363.92377966	1.15165753		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	-0.18490285	0.15712937	1.59476176	1.38	0.2402
COM2	-0.24454754	0.10804798	5.89951896	5.12	0.0243
COM6	0.70561934	0.13852147	29.88340868	25.95	0.0001
COM7	0.22019086	0.13952409	2.86829299	2.49	0.1155
COM8	0.78404280	0.14214039	35.04030655	30.43	0.0001
COM9	-0.54796408	0.22778501	6.66464884	5.79	0.0167
COM10	-0.22186452	0.13641447	3.04633867	2.65	0.1049
SENS2	0.43635705	0.24383415	3.68823247	3.20	0.0745

Bounds on condition number: 1.466201, 78.2987

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Step 3 Variable COM1 Removed R-square = 0.19159572 C(p) = 5.82540305

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	86.62965858	12.37566551	10.73	0.0001
Error	317	365.51854142	1.15305534		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM2	-0.25046066	0.10799656	6.20168042	5.38	0.0210
COM6	0.67850255	0.13667418	28.41712880	24.65	0.0001
COM7	0.19308118	0.13769249	2.26730271	1.97	0.1618
COM8	0.78538310	0.14222206	35.16246738	30.50	0.0001
COM9	-0.54861635	0.22792253	6.68056418	5.79	0.0167
COM10	-0.23455969	0.13606971	3.42636823	2.97	0.0857
SENS2	0.45179771	0.24362856	3.96535256	3.44	0.0646

Bounds on condition number: 1.425625, 59.93892

Step 4 Variable COM7 Removed R-square = 0.18658120 C(p) = 5.78446042

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	84.36235587	14.06039264	12.16	0.0001
Error	318	367.78584413	1.15655926		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM2	-0.23992366	0.10789839	5.71852611	4.94	0.0269
COM6	0.70871425	0.13517026	31.79420075	27.49	0.0001
COM8	0.80093922	0.14200401	36.79305009	31.81	0.0001
COM9	-0.49398225	0.22490874	5.57927701	4.82	0.0288
COM10	-0.20975006	0.13511939	2.78699831	2.41	0.1216
SENS2	0.46266106	0.24387506	4.16254566	3.60	0.0587

Bounds on condition number: 1.390199, 43.55197

Step 5 Variable COM10 Removed R-square = 0.18041730 C(p) = 6.19255951

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	81.57535755	16.31507151	14.04	0.0001
Error	319	370.57284245	1.16167035		
Total	324	452.14820000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM2	-0.27153178	0.10619360	7.59499635	6.54	0.0110
COM6	0.66354676	0.13229283	29.22492246	25.16	0.0001
COM8	0.78407466	0.14190033	35.46752753	30.53	0.0001
COM9	-0.50953170	0.22518148	5.94784949	5.12	0.0243
SENS2	0.42737166	0.24334913	3.58290054	3.08	0.0800

Bounds on condition number: 1.325783, 29.48345

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_NOX

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	COM5	9	0.0003	0.1960	8.1155	0.1155	0.7342	IGN TUNE-UP
2	IGN2	8	0.0008	0.1951	6.4475	0.3329	0.5644	
3	COM1	7	0.0035	0.1916	5.8254	1.3848	0.2402	CARB RPL/RBLD
4	COM7	6	0.0050	0.1866	5.7845	1.9663	0.1618	SECOND AIR
5	COM10	5	0.0062	0.1804	6.1926	2.4097	0.1216	O2 SENSOR

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Backward Elimination Procedure for Dependent Variable R_SCORE

Step 0 All Variables Entered R-square = 0.47610784 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	8029.97467055	802.99746706	28.54	0.0001
Error	314	8835.89911145	28.13980609		
Total	324	16865.87378200			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	2.60034104	0.79489643	301.13457953	10.70	0.0012
COM2	3.14859922	0.57425760	845.94547585	30.06	0.0001
COM5	1.57860146	0.65976774	161.09570083	5.72	0.0173
COM6	0.26552335	0.69163053	4.14742197	0.15	0.7013
COM7	0.97995104	0.69695507	55.63143885	1.98	0.1607
COM8	2.22343462	0.70286374	281.59669259	10.01	0.0017
COM9	4.50175902	1.13267844	444.50056240	15.80	0.0001
COM10	2.26581254	0.69817378	296.37528393	10.53	0.0013
IGN2	-1.43044547	1.28093615	35.09205078	1.25	0.2650
SENS2	2.36319092	1.21402508	106.62607037	3.79	0.0525

Bounds on condition number: 1.825337, 131.6381

Step 1 Variable COM6 Removed R-square = 0.47586193 C(p) = 8.14738630

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	8025.82724858	891.75858318	31.78	0.0001
Error	315	8840.04653342	28.06363979		
Total	324	16865.87378200			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	2.64044858	0.78693414	315.95312297	11.26	0.0009
COM2	3.19067367	0.56293932	901.54124498	32.12	0.0001
COM5	1.61141821	0.65332084	170.72908381	6.08	0.0142
COM7	1.00808068	0.69215417	59.52904260	2.12	0.1463
COM8	2.23340673	0.70143238	284.51686309	10.14	0.0016
COM9	4.54006529	1.12674702	455.63319454	16.24	0.0001
COM10	2.30189867	0.69088046	311.53767680	11.10	0.0010
IGN2	-1.40601631	1.27762205	33.98755480	1.21	0.2720
SENS2	2.43817921	1.19658588	116.51651765	4.15	0.0424

Bounds on condition number: 1.794697, 103.3038

Step 2 Variable IGN2 Removed R-square = 0.47384676 C(p) = 7.35519686

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	7991.83969379	998.97996172	35.57	0.0001
Error	316	8874.03408821	28.08238636		
Total	324	16865.87378200			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	2.60149759	0.78640030	307.32191032	10.94	0.0010
COM2	3.08989763	0.55562675	868.47216239	30.93	0.0001
COM5	1.57423902	0.65266463	163.37861247	5.82	0.0164
COM7	0.92284897	0.68803717	50.52094693	1.80	0.1808
COM8	2.23623994	0.70166190	285.24301677	10.16	0.0016
COM9	4.59993183	1.12580887	468.82144070	16.69	0.0001
COM10	2.32943688	0.69065771	319.45535866	11.38	0.0008
SENS2	2.34393102	1.19391576	108.23713743	3.85	0.0505

Bounds on condition number: 1.789897, 82.40099

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Step 3 Variable COM7 Removed R-square = 0.47085131 C(p) = 7.15055205

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	7941.31874686	1134.47410669	40.30	0.0001
Error	317	8924.55503514	28.15317046		
Total	324	16865.87378200			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM1	2.76743075	0.77758653	356.60167443	12.67	0.0004
COM2	3.12508672	0.55570604	890.35093154	31.63	0.0001
COM5	1.67460914	0.64917710	187.33884450	6.65	0.0103
COM8	2.31144620	0.70029889	306.71004936	10.89	0.0011
COM9	4.85426116	1.11112331	537.33986926	19.09	0.0001
COM10	2.42351521	0.68795223	349.38337771	12.41	0.0005
SENS2	2.42240449	1.19398330	115.88417344	4.12	0.0433

Bounds on condition number: 1.766368, 62.71057

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_SCORE

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	COM6	9	0.0002	0.4759	8.1474	0.1474	0.7013	EGR
2	IGN2	8	0.0020	0.4738	7.3552	1.2111	0.2720	
3	COM7	7	0.0030	0.4709	7.1506	1.7990	0.1808	SECOND AIR

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Backward Elimination Procedure for Dependent Variable R_HC

Step 0 All Variables Entered R-square = 0.25974605 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	1526.68295603	152.66829560	18.63	0.0001
Error	531	4350.91544397	8.19381440		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.61420862	0.34065590	26.63704834	3.25	0.0720
COM4	0.44529807	0.27785591	21.04497778	2.57	0.1096
COM5	0.35373155	0.24963137	16.45263184	2.01	0.1571
COM6	-0.30390386	0.28427083	9.36470221	1.14	0.2855
COM7	0.93014545	0.55068399	23.37668699	2.85	0.0918
COM8	0.41217915	0.28527601	17.10518113	2.09	0.1491
COM9	3.45762930	0.61177594	261.73282387	31.94	0.0001
COM10	1.29358445	0.20619331	322.49764436	39.36	0.0001
IGN2	0.84138884	0.49955004	23.24457489	2.84	0.0927
SENS2	0.27290305	0.57037473	1.87578202	0.23	0.6325

Bounds on condition number: 1.49823, 119.3232

Step 1 Variable SENS2 Removed R-square = 0.25942691 C(p) = 8.22892659

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	1524.80717401	169.42301933	20.71	0.0001
Error	532	4352.79122599	8.18193839		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.61608262	0.34038644	26.80338313	3.28	0.0709
COM4	0.44291569	0.27760989	20.82708455	2.55	0.1112
COM5	0.36572944	0.24818866	17.76692146	2.17	0.1412
COM6	-0.29958905	0.28392177	9.10983888	1.11	0.2918
COM7	0.93385561	0.55023020	23.56822186	2.88	0.0902
COM8	0.41305256	0.28506336	17.17845314	2.10	0.1479
COM9	3.47327461	0.61045856	264.86347178	32.37	0.0001
COM10	1.29729707	0.20589788	324.81144222	39.70	0.0001
IGN2	0.83904032	0.49916380	23.11722578	2.83	0.0934

Bounds on condition number: 1.483112, 97.89937

Step 2 Variable COM6 Removed R-square = 0.25787698 C(p) = 7.34072123

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	1515.69733514	189.46216689	23.15	0.0001
Error	533	4361.90106486	8.18367930		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.58401704	0.33906329	24.27940851	2.97	0.0856
COM4	0.42251939	0.27696558	19.04540835	2.33	0.1277
COM5	0.33551978	0.24655806	15.15466897	1.85	0.1741
COM7	0.88181236	0.54807350	21.18475083	2.59	0.1082
COM8	0.37101993	0.28229645	14.13618634	1.73	0.1893
COM9	3.41681488	0.60817377	258.30697676	31.56	0.0001
COM10	1.27885773	0.20517679	317.93372214	38.85	0.0001
IGN2	0.80740806	0.49831580	21.48450990	2.63	0.1058

Bounds on condition number: 1.463376, 76.78083

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Step 3 Variable COM8 Removed R-square = 0.25547189 C(p) = 7.06594780

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	1501.56114880	214.50873554	26.18	0.0001
Error	534	4376.03725120	8.19482631		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.60053578	0.33906094	25.70762813	3.14	0.0771
COM4	0.43641129	0.27695224	20.34800955	2.48	0.1157
COM5	0.35877572	0.24608973	17.41802354	2.13	0.1455
COM7	0.90125995	0.54824672	22.14561888	2.70	0.1008
COM9	3.43524245	0.60842607	261.23953843	31.88	0.0001
COM10	1.32558108	0.20221107	352.16198231	42.97	0.0001
IGN2	0.82953519	0.49837039	22.70413274	2.77	0.0966

Bounds on condition number: 1.455839, 59.0831

Step 4 Variable COM5 Removed R-square = 0.25250843 C(p) = 7.19170056

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	1484.14312526	247.35718754	30.12	0.0001
Error	535	4393.45527474	8.21206593		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.64411923	0.33809556	29.80616013	3.63	0.0573
COM4	0.55104209	0.26583584	35.28538870	4.30	0.0387
COM7	0.90046409	0.54882282	22.10654636	2.69	0.1014
COM9	3.46780767	0.60865512	266.57528028	32.46	0.0001
COM10	1.42113183	0.19149634	452.27252879	55.07	0.0001
IGN2	0.93867747	0.49323360	29.74266663	3.62	0.0576

Bounds on condition number: 1.250335, 40.18764

Step 5 Variable COM7 Removed R-square = 0.24874727 C(p) = 7.88965603

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	1462.03657890	292.40731578	35.49	0.0001
Error	536	4415.56182110	8.23798847		
Total	541	5877.59840000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	0.67826076	0.33798678	33.17532242	4.03	0.0453
COM4	0.55760458	0.26622494	36.13901903	4.39	0.0367
COM9	3.47794732	0.60958359	268.16410396	32.55	0.0001
COM10	1.45557203	0.19064258	480.22940567	58.29	0.0001
IGN2	0.94011968	0.49401069	29.83422625	3.62	0.0576

Bounds on condition number: 1.235312, 28.25606

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_HC

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	SENS2	9	0.0003	0.2594	8.2289	0.2289	0.6325	
2	COM6	8	0.0015	0.2579	7.3407	1.1134	0.2918	EGR
3	COM8	7	0.0024	0.2555	7.0659	1.7274	0.1893	CATALYST
4	COM5	6	0.0030	0.2525	7.1917	2.1255	0.1455	IGN TUNE-UP
5	COM7	5	0.0038	0.2487	7.8897	2.6920	0.1014	SECONDARY AIR

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Backward Elimination Procedure for Dependent Variable R_CO

Step 0 All Variables Entered R-square = 0.32294678 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	400145.78720277	40014.57872028	25.33	0.0001
Error	531	838899.82609723	1579.84901337		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.68804321	4.73021245	6627.14426459	4.19	0.0410
COM4	6.86034238	3.85819670	4995.03382274	3.16	0.0760
COM5	4.74159235	3.46628201	2956.21641616	1.87	0.1719
COM6	-4.09187022	3.94727177	1697.71672585	1.07	0.3004
COM7	8.54440164	7.64657895	1972.62502418	1.25	0.2643
COM8	-1.61941298	3.96122925	264.04069029	0.17	0.6828
COM9	34.93443255	8.49487760	26718.29366389	16.91	0.0001
COM10	28.80442977	2.86311837	159902.60563723	101.21	0.0001
IGN2	0.92382044	6.93655338	28.02226598	0.02	0.8941
SENS2	3.42204577	7.91999675	294.94239741	0.19	0.6659

Bounds on condition number: 1.49823, 119.3232

Step 1 Variable IGN2 Removed R-square = 0.32292416 C(p) = 8.01773731

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	400117.76493678	44457.52943742	28.19	0.0001
Error	532	838927.84836322	1576.93204580		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.71363211	4.72194343	6673.20892254	4.23	0.0402
COM4	6.84039598	3.85172796	4973.52439222	3.15	0.0763
COM5	4.80595388	3.42925881	3097.21710322	1.96	0.1617
COM6	-4.06015186	3.93644147	1677.60587165	1.06	0.3028
COM7	8.54007086	7.63944745	1970.66149784	1.25	0.2641
COM8	-1.60619100	3.95632752	259.90993636	0.16	0.6849
COM9	34.96461718	8.48401053	26783.54983022	16.98	0.0001
COM10	28.82783326	2.85508120	160768.16454340	101.95	0.0001
SENS2	3.41168160	7.91229982	293.18685518	0.19	0.6665

Bounds on condition number: 1.469108, 97.39755

Step 2 Variable COM8 Removed R-square = 0.32271439 C(p) = 6.18225299

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	399857.85500043	49982.23187505	31.75	0.0001
Error	533	839187.75829957	1574.46108499		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.66560399	4.71676146	6611.53192706	4.20	0.0409
COM4	6.79796773	3.84729211	4915.63699881	3.12	0.0778
COM5	4.72572912	3.42087730	3004.65480441	1.91	0.1677
COM6	-4.28592870	3.89390518	1907.44081546	1.21	0.2715
COM7	8.49694224	7.63272173	1951.18480220	1.24	0.2661
COM9	34.92738213	8.47686557	26729.65853010	16.98	0.0001
COM10	28.64165543	2.81580220	162901.04696833	103.46	0.0001
SENS2	3.39191075	7.90594858	289.80961674	0.18	0.6681

Bounds on condition number: 1.46423, 77.05847

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Step 3 Variable SENS2 Removed R-square = 0.32248050 C(p) = 4.36569433

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	399568.04538369	57081.14934053	36.31	0.0001
Error	534	839477.56791631	1572.05537063		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.68840258	4.71285745	6643.60164331	4.23	0.0403
COM4	6.76925934	3.84377023	4875.68126580	3.10	0.0788
COM5	4.87335850	3.40092606	3227.97512318	2.05	0.1525
COM6	-4.23182766	3.88888839	1861.54193731	1.18	0.2770
COM7	8.54347920	7.62611806	1973.01470427	1.26	0.2631
COM9	35.12115201	8.45835590	27104.00282521	17.24	0.0001
COM10	28.68827624	2.81155423	163675.55325963	104.12	0.0001

Bounds on condition number: 1.449415, 60.0479

Step 4 Variable COM6 Removed R-square = 0.32097810 C(p) = 3.54399802

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	397706.50344638	66284.41724106	42.15	0.0001
Error	535	841339.10985362	1572.59646702		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.19346000	4.69166556	6038.39034914	3.84	0.0506
COM4	6.46786414	3.83443813	4474.40821682	2.85	0.0922
COM5	4.37364916	3.37036040	2648.21044595	1.68	0.1950
COM7	7.77620994	7.59475936	1648.63765416	1.05	0.3063
COM9	34.27504512	8.42399152	26033.79757013	16.55	0.0001
COM10	28.33865853	2.79361740	161823.65909249	102.90	0.0001

Bounds on condition number: 1.422989, 44.00458

Step 5 Variable COM7 Removed R-square = 0.31964753 C(p) = 2.58753930

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	396057.86579222	79211.57315844	50.37	0.0001
Error	536	842987.74750778	1572.73833490		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	9.48915796	4.68297978	6457.54231439	4.11	0.0432
COM4	6.52539644	3.83419934	4555.34107541	2.90	0.0894
COM5	4.37117587	3.37051156	2645.21753304	1.68	0.1952
COM9	34.36345976	8.42392888	26171.03240215	16.64	0.0001
COM10	28.63740598	2.77846379	167076.10490409	106.23	0.0001

Bounds on condition number: 1.422989, 31.43602

Step 6 Variable COM5 Removed R-square = 0.31751264 C(p) = 2.26188761

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	393412.64825918	98353.16206480	62.46	0.0001
Error	537	845632.96504082	1574.73550287		
Total	541	1239045.6133000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	10.07607015	4.66402002	7349.69255709	4.67	0.0312
COM4	7.92897307	3.68062057	7308.01462149	4.64	0.0317
COM9	34.82318253	8.42180943	26923.63645789	17.10	0.0001
COM10	29.86874150	2.61286367	205782.27682898	130.68	0.0001

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Bounds on condition number: 1.213903, 18.34777

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_CO

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	IGN2	9	0.0000	0.3229	8.0177	0.0177	0.8941	
2	COM8	8	0.0002	0.3227	6.1823	0.1648	0.6849	CATALYST
3	SENS2	7	0.0002	0.3225	4.3657	0.1841	0.6681	
4	COM6	6	0.0015	0.3210	3.5440	1.1841	0.2770	EGR
5	COM7	5	0.0013	0.3196	2.5875	1.0484	0.3063	SECONDARY AIR
6	COM5	4	0.0021	0.3175	2.2619	1.6819	0.1952	IGN TUNE-UP

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Backward Elimination Procedure for Dependent Variable R_NOX

Step 0 All Variables Entered R-square = 0.38463783 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	347.75709740	34.77570974	33.19	0.0001
Error	531	556.35860260	1.04775631		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.22830108	0.12181563	3.68018986	3.51	0.0615
COM4	0.24774241	0.09935889	6.51399706	6.22	0.0130
COM5	0.04128140	0.08926604	0.22407666	0.21	0.6439
COM6	0.85278799	0.10165281	73.74009144	70.38	0.0001
COM7	0.13967233	0.19691986	0.52711089	0.50	0.4785
COM8	1.29278339	0.10201225	168.27017979	160.60	0.0001
COM9	-0.15893143	0.21876582	0.55299465	0.53	0.4679
COM10	-0.11373398	0.07373296	2.49297231	2.38	0.1235
IGN2	0.10652492	0.17863481	0.37258947	0.36	0.5512
SENS2	0.18179052	0.20396110	0.83235395	0.79	0.3732

Bounds on condition number: 1.49823, 119.3232

Step 1 Variable COM5 Removed R-square = 0.38438999 C(p) = 8.21386333

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	347.53302074	38.61478008	36.91	0.0001
Error	532	556.58267926	1.04620804		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.22421794	0.12140543	3.56847420	3.41	0.0653
COM4	0.26015038	0.09559694	7.74781013	7.41	0.0067
COM6	0.85803084	0.10094397	75.58978115	72.25	0.0001
COM7	0.13834408	0.19675338	0.51724322	0.49	0.4823
COM8	1.29530962	0.10179059	169.41425316	161.93	0.0001
COM9	-0.15701446	0.21856488	0.53992894	0.52	0.4728
COM10	-0.10392884	0.07056654	2.26930338	2.17	0.1414
IGN2	0.11804228	0.17675945	0.46658197	0.45	0.5045
SENS2	0.19126539	0.20277946	0.93077114	0.89	0.3460

Bounds on condition number: 1.332716, 91.45683

Step 2 Variable IGN2 Removed R-square = 0.38387392 C(p) = 6.65917868

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	347.06643877	43.38330485	41.51	0.0001
Error	533	557.04926123	1.04512057		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.22005392	0.12118217	3.44625312	3.30	0.0699
COM4	0.26007203	0.09554717	7.74315593	7.41	0.0067
COM6	0.86322919	0.10059107	76.96614957	73.64	0.0001
COM7	0.13750989	0.19664714	0.51104484	0.49	0.4847
COM8	1.29754581	0.10168261	170.18386622	162.84	0.0001
COM9	-0.15269167	0.21835544	0.51105671	0.49	0.4847
COM10	-0.09888711	0.07012506	2.07825723	1.99	0.1591
SENS2	0.19183980	0.20267222	0.93638695	0.90	0.3443

Bounds on condition number: 1.317462, 72.71303

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Step 3 Variable COM7 Removed R-square = 0.38330868 C(p) = 5.14693030

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	346.55539393	49.50791342	47.42	0.0001
Error	534	557.56030607	1.04412042		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.21577480	0.12096964	3.32199712	3.18	0.0750
COM4	0.26032555	0.09550076	7.75837125	7.43	0.0066
COM6	0.86940813	0.10015426	78.67905281	75.35	0.0001
COM8	1.29847341	0.10162530	170.45629060	163.25	0.0001
COM9	-0.15263009	0.21825091	0.51064464	0.49	0.4846
COM10	-0.09456447	0.06981863	1.91541952	1.83	0.1762
SENS2	0.19363331	0.20255900	0.95413021	0.91	0.3395

Bounds on condition number: 1.307224, 56.21367

Step 4 Variable COM9 Removed R-square = 0.38274388 C(p) = 3.63429997

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	6	346.04474929	57.67412488	55.29	0.0001
Error	535	558.07095071	1.04312327		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.21983557	0.12077249	3.45617356	3.31	0.0693
COM4	0.25741564	0.09536450	7.60032289	7.29	0.0072
COM6	0.86300284	0.09968694	78.17781496	74.95	0.0001
COM8	1.29760922	0.10156925	170.25464734	163.22	0.0001
COM10	-0.09869325	0.06953534	2.10135483	2.01	0.1564
SENS2	0.18572826	0.20214676	0.88055816	0.84	0.3586

Bounds on condition number: 1.297877, 41.72318

Step 5 Variable SENS2 Removed R-square = 0.38176993 C(p) = 2.47472264

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	5	345.16419113	69.03283823	66.20	0.0001
Error	536	558.95150887	1.04281998		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.21733083	0.12072416	3.37958699	3.24	0.0724
COM4	0.25847715	0.09534364	7.66426008	7.35	0.0069
COM6	0.86763340	0.09954498	79.22150720	75.97	0.0001
COM8	1.29881003	0.10154608	170.59814802	163.59	0.0001
COM10	-0.09376234	0.06931784	1.90799002	1.83	0.1767

Bounds on condition number: 1.290146, 29.61857

Step 6 Variable COM10 Removed R-square = 0.37965960 C(p) = 2.29574724

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	4	343.25620111	85.81405028	82.16	0.0001
Error	537	560.85949889	1.04443110		
Total	541	904.11570000			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	-0.24335618	0.11927312	4.34789866	4.16	0.0418
COM4	0.22420767	0.09198690	6.20481374	5.94	0.0151
COM6	0.84701081	0.09844648	77.31385239	74.02	0.0001
COM8	1.27244228	0.09973441	170.00664479	162.77	0.0001

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Bounds on condition number: 1.134228, 17.80056

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_NOX

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	COM5	9	0.0002	0.3844	8.2139	0.2139	0.6439	IGN TUNE-UP
2	IGN2	8	0.0005	0.3839	6.6592	0.4460	0.5045	
3	COM7	7	0.0006	0.3833	5.1469	0.4890	0.4847	SECONDARY AIR
4	COM9	6	0.0006	0.3827	3.6343	0.4891	0.4846	ECU
5	SENS2	5	0.0010	0.3818	2.4747	0.8442	0.3586	
6	COM10	4	0.0021	0.3797	2.2957	1.8296	0.1767	O2 SENSOR

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Backward Elimination Procedure for Dependent Variable R_SCORE

Step 0 All Variables Entered R-square = 0.36808186 C(p) = 10.00000000

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	10	11881.68075654	1188.16807565	30.93	0.0001
Error	531	20398.31456146	38.41490501		
Total	541	32279.99531800			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	1.35508384	0.73760311	129.65420894	3.38	0.0667
COM4	1.37901683	0.60162580	201.83012252	5.25	0.0223
COM5	0.86886240	0.54051280	99.26355032	2.58	0.1085
COM6	0.13912756	0.61551568	1.96267271	0.05	0.8213
COM7	1.92591129	1.19236513	100.21985937	2.61	0.1069
COM8	1.54340882	0.61769213	239.83777447	6.24	0.0128
COM9	6.79207199	1.32464412	1009.96399731	26.29	0.0001
COM10	4.06059061	0.44645881	3177.71824626	82.72	0.0001
IGN2	1.04008164	1.08164768	35.51918401	0.92	0.3367
SENS2	0.79731875	1.23500039	16.01140831	0.42	0.5188

Bounds on condition number: 1.49823, 119.3232

Step 1 Variable COM6 Removed R-square = 0.36802106 C(p) = 8.05109144

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	9	11879.71808384	1319.96867598	34.42	0.0001
Error	532	20400.27723416	38.34638578		
Total	541	32279.99531800			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	1.36989912	0.73402964	133.55938736	3.48	0.0626
COM4	1.38855654	0.59960816	205.64421920	5.36	0.0209
COM5	0.88248816	0.53666150	103.69106408	2.70	0.1007
COM7	1.94993519	1.18655910	103.55856928	2.70	0.1009
COM8	1.56288057	0.61110987	250.80571266	6.54	0.0108
COM9	6.81775751	1.31858343	1025.16154787	26.73	0.0001
COM10	4.06902464	0.44449989	3213.37761719	83.80	0.0001
IGN2	1.05483292	1.07871379	36.66733312	0.96	0.3286
SENS2	0.80617444	1.23327744	16.38554589	0.43	0.5136

Bounds on condition number: 1.479594, 95.86641

Step 2 Variable SENS2 Removed R-square = 0.36751345 C(p) = 6.47763280

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	8	11863.33253794	1482.91656724	38.71	0.0001
Error	533	20416.66278006	38.30518345		
Total	541	32279.99531800			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	1.37679930	0.73355932	134.93615821	3.52	0.0611
COM4	1.38238662	0.59921169	203.87127718	5.32	0.0214
COM5	0.91921607	0.53342538	113.74842919	2.97	0.0854
COM7	1.96310948	1.18575038	104.99292655	2.74	0.0984
COM8	1.56724899	0.61074495	252.23989394	6.59	0.0106
COM9	6.86637698	1.31577659	1043.15422815	27.23	0.0001
COM10	4.08077650	0.44389751	3237.26123825	84.51	0.0001
IGN2	1.04924107	1.07810021	36.28188561	0.95	0.3309

Bounds on condition number: 1.463376, 76.78083

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Step 3 Variable IGN2 Removed R-square = 0.36638948 C(p) = 5.42210697

	DF	Sum of Squares	Mean Square	F	Prob>F
Regression	7	11827.05065234	1689.57866462	44.11	0.0001
Error	534	20452.94466566	38.30139450		
Total	541	32279.99531800			

Variable	Parameter Estimate	Standard Error	Type II Sum of Squares	F	Prob>F
COM3	1.40973923	0.73274185	141.77190132	3.70	0.0549
COM4	1.36220016	0.59882297	198.19812176	5.17	0.0233
COM5	0.99569503	0.52757928	136.42432381	3.56	0.0597
COM7	1.96426067	1.18569115	105.11620457	2.74	0.0982
COM8	1.58733087	0.61036609	259.04112251	6.76	0.0096
COM9	6.90688875	1.31505294	1056.55725389	27.59	0.0001
COM10	4.10950938	0.44289274	3297.59580732	86.10	0.0001

Bounds on condition number: 1.433972, 59.43799

All variables left in the model are significant at the 0.1000 level.

Summary of Backward Elimination Procedure for Dependent Variable R_SCORE

Step	Variable Removed	Number In	Partial R**2	Model R**2	C(p)	F	Prob>F	Label
1	COM6	9	0.0001	0.3680	8.0511	0.0511	0.8213	EGR
2	SENS2	8	0.0005	0.3675	6.4776	0.4273	0.5136	
3	IGN2	7	0.0011	0.3664	5.4221	0.9472	0.3309	

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