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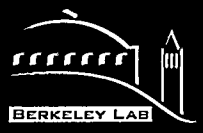

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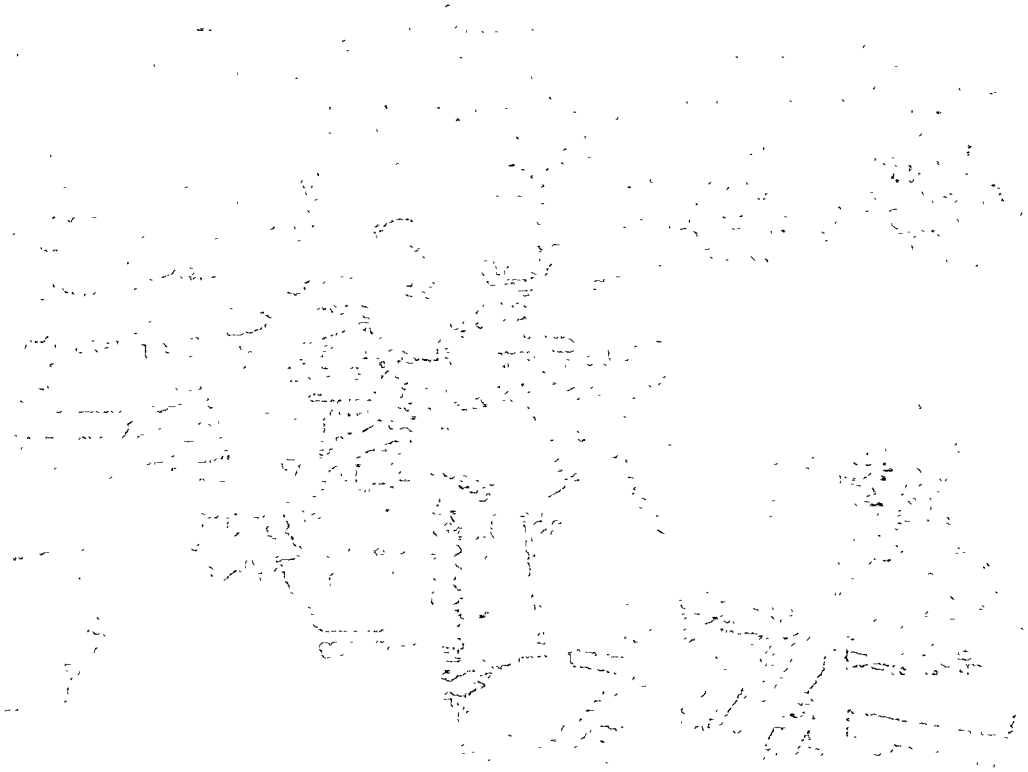
Real-World Emissions from Model Year 1993, 2000, and 2010 Passenger Cars

M. Ross, R. Goodwin, R. Watkins, M.Q. Wang, and T. Wenzel
Energy and Environment Division

November 1995



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REAL-WORLD EMISSIONS FROM MODEL YEAR 1993, 2000, AND 2010 PASSENGER CARS

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Brief Overview

Automotive emissions of carbon monoxide (CO), hydrocarbons (HC), and nitrogen oxides (NO_X) are major contributors to metropolitan air pollution in the US. Important progress has been made in the past quarter century to reduce these emissions, but in some regions much more progress is needed. Moreover, increased driving will destroy even the progress that has been made unless the emissions in grams per mile of driving are reduced further.

Exhaust emissions may be viewed as consisting of three major sources: on-cycle, off-cycle, and malfunction emissions. On-cycle emissions are those emissions occuring under the driving conditions in the new car certification tests, while off-cycle emissions are caused by driving at higher power than required by the tests. Malfunction emissions are caused by the malfunction of on-board emissions control systems (ECS). Two other sources of real-world emissions from vehicles are fuel-related: fuel evaporation and upstream fuel processing. This report estimates the contribution of all six of these sources, but focuses on the two sources that are the result of "loopholes" in the current emissions control program: off-cycle and malfunction emissions.

We determine the average lifetime grams-per-mile (g/mile) emissions of a model-year (MY) 1993 car through detailed analysis of emission measurements from a variety of data sources. CO and HC emissions are about five times higher than test levels, and NO_X may be about twice as high. We then predict the g/mile emissions for MY2000 and MY2010 conventional gasoline-fueled cars. Significant reductions are possible from regulatory changes and improved technology.

Off-cycle emissions occur in part because of the sensitivity of NO_X to power, and in part due to a practice called command enrichment, the injection of excess fuel (beyond that needed for combustion) at high power. Supplemental regulatory tests have been proposed by the Environmental Protection Agency to motivate improvements in ECS design to further reduce NO_X, and to limit the frequency and strength of command enrichment. Assuming effective regulations are adopted in this area, we forecast reductions of about two-thirds for all three pollutants.

Malfunction emissions occur in modern cars because some models do not have robust ECS. This is a new insight; current regulations are based on the assumption that ECS malfunction is fundamentally the fault of individual owners, drivers, or mechanics, caused by either poor maintenance or disconnection of ECS components. This assumption is less convincing with today's modern cars, which require little maintenance and provide little incentive to tamper.

This result supports mounting criticism that inspection and maintenance (I&M, or smog check) programs aimed at repairing malfunctions in individual vehicles are stop-gap at best. In contrast, if new information technologies, such as remote sensing and on-board diagnostics, are developed and used to identify malfunction-prone models and to motivate the design and manufacture of models with robust ECS, then substantial emissions reductions can be achieved. Our prediction of a two-thirds reduction of malfunction emissions is based on the fact that most, and perhaps all, manufacturers have virtually eliminated malfunctions in at least some of their models.

Policies to reduce off-cycle and malfunction emissions are discussed, including suggestions for regulators and manufacturers to evaluate their emissions programs in terms of real-world emissions, measured from in-use, rather than laboratory-tested, vehicles. Although non-automotive emission sources also need attention, the potential reductions in automotive loophole emissions are probably among the most cost-effective for our metropolitan areas.

Real-World Emissions from Model Year 1993, 2000 and 2010 Passenger Cars

1. Introduction and Summary

1.1. History

Air pollution by cars and light trucks is a major problem in metropolitan areas in the United States and around the world. Much of the discussion of this issue is based on the emissions per vehicle mile as determined under somewhat artificial testing conditions. The pollutants actually emitted vary considerably with the particular vehicle and the way it is driven, but the average emissions per mile are much higher than the test values. This report concerns the sources and levels of excess emissions, and the potential for reducing them.

The history of automotive emissions regulation reveals remarkable success in reducing the emissions of carbon monoxide (CO), hydrocarbons (HC) and oxides of nitrogen (NO_X) from new automobiles — as measured in certification tests. The grams-per-mile (g/mile) standards for these tests are stringent, with 96% reductions mandated in comparison to the estimated pre-control (mid-1960s) levels for CO and HC; and 75% reductions mandated for NO_X. Powerful new technologies have been developed and incorporated into every new vehicle in order to accomplish these reductions. Most noteworthy are the catalytic converter and closed-loop engine controls; the latter includes sensors before and after the engine proper, and computer analysis of the information leading to real-time control of fuel injection, with the principal objective of maintaining just the right chemical balance of fuel and air.

During the same period that tailpipe emission standards were reduced by 96% compared to unregulated emissions, the "real-world" g/mile emissions of CO and HC were reduced by roughly 75%. Since vehicle miles traveled increased by about a factor of 2 during that period, total automotive emissions declined by roughly 50% (national average). If the real-world exhaust emissions had matched the standards then a reduction of total automobile exhaust emissions of roughly 90% would have been achieved over the past twenty-five years. Nevertheless, the 50% reduction in total automobile exhaust emissions is an important achievement, quite noticeable in some metropolitan areas where pollution is dominated by cars and light trucks.

Ambient air quality measurements confirm that our nation's air has improved. For the ten-year period from 1983 to 1992 the national average of the "second highest non-overlapping 8-hour average CO concentration" (an EPA measure of ambient air quality regarding CO) dropped by 34%. Since emissions of CO are usually dominated by cars and trucks, one must agree with the EPA, at least in the case of this pollutant, that "this indicates that the Federal Motor Vehicle Control Program has been effective on the national scale, with controls more than offsetting growth during this period (USEPA 1993)."

The effect of auto emissions regulations on ambient HC, NO_X and ozone concentrations is less clear, due to the more complex atmospheric chemistry of these species and because the motor vehicle contribution to overall HC and NO_X emissions is proportionally less than it is for CO. However, the EPA has reported a 21% decrease in the national average "second highest daily maximum one-hour ozone concentration" from 1983 to 1992 (USEPA 1993). In addition, over the same period, the population exposure to unhealthy levels of ozone in Los Angeles was cut in half (Lents and Kelly 1993).

In spite of this important progress, air quality is far from satisfactory in many major metropolitan areas. Moreover, vehicle travel continues to grow, so that, unless the g/mile emissions are further reduced, the progress will be eaten away — about as rapidly as it was achieved. The large discrepancy between the regulatory tests, called the Federal Test Procedure (FTP), and real-world emissions is well known (Calvert et al. 1993). It is a major focus of planning to continue the reductions in automobile pollution (Clean Air Act Amendments of 1990 — CAAA90); but while manufacturers have been able to meet the strict certification-test standards in the FTP, two major loopholes in the approach based on those tests are causing the much higher emissions in real world driving. The loopholes are "off-cycle" driving, essentially driving at higher power than is represented in the FTP, and malfunction of emissions control systems (ECS). Primarily due to these loopholes, average emissions of CO and HC by cars on the road are about five times greater than the new-car tailpipe standards, and NO_X emissions are estimated to be about twice as high (USEPA 1994b).

Special regulatory initiatives aimed at closing the malfunction loophole have long been on the books: "in-use" testing with manufacturer recalls, as well as vehicle inspection and maintenance (I&M) programs. Broadly speaking, these efforts have not been successful; the emissions reductions they achieve are a small fraction of the emissions addressed. More particularly, in-use testing is unsuccessful because the law states that manufacturers are only responsible for the emissions performance of vehicles which have been "properly maintained and used"; and in response to this wording, the vehicle recruitment and screening procedures of the in-use tests make the observation of malfunctioning ECS unlikely. This is one of the key issues for this report. The I&M programs are also severely flawed. Efficient identification of malfunctioning vehicles through smog inspections has proven difficult. Making lasting and effective repairs is even more difficult: diagnosis can be complicated, and it appears to be much easier to make a temporary fix than to identify and repair the underlying problem.

Better policies are needed *and are in the works*, largely as a result of the CAAA90. We refer to EPA's proposed supplemental certification tests which we project would close much of the off-cycle loophole if adequately implemented; and radical new information technologies to identify ECS malfunctions, which will, if implemented intelligently and with vigor, lead to closure of much of the malfunction loophole. Emissions from these sources will not be eliminated, however.

1.2. Analytical Results

We project the average lifetime real-world g/mile emissions (exhaust, evaporative and fuel distribution system) associated with conventional gasoline-fueled cars for model years (MYs) 1993, 2000 and 2010. The emissions analyzed are three criteria pollutants: CO, HC and NO_X. Average lifetime emissions are those of cars about halfway into their lifetime mileage. Light trucks are not considered. The climate of the Northeast states is assumed.

We have two purposes in this report: 1) to delineate the current sources of real-world emissions, and the potential for reducing them, in order to inform the debate over policies to reduce emissions from conventional vehicles; and 2) to provide a standard of comparison for alternative-technology vehicles. Conventional vehicles are taken to be gasoline-fueled vehicles propelled by internal-combustion engines of the present configuration. Alternative vehicles fall into two classes in terms of this report: Those which are intrinsically clean at the vehicle (e.g. battery-electric or hydrogen fueled fuel cell vehicles) and those which are combustion-based and depend for low emissions certification on powerful ECS. For analysis of the latter, this report has a special use. The same loopholes of off-cycle driving and malfunctioning ECS will probably contribute to real-world emissions of these alternative vehicles, and insights can be obtained by studying these emissions in conventional vehicles.

The approach in this report is to categorize the sources of real-world emissions, estimate their relative contributions for model year 1993 vehicles, and then to consider the technical and regulatory improvements likely to be made in order to reduce each type of emissions. The well-established sources of real-world emissions are:

1) properly-functioning warmed-up (hot-stabilized) cars in moderate on-cycle driving (where on-cycle means driving that is represented in the FTP),
2) cold start for cars with properly-functioning emissions controls,
3) evaporation from the vehicle, including malfunctioning evaporation control,
4) off-cycle operations with properly-functioning emissions controls (with the focus on driving that involves higher power than occurs or is emphasized in the FTP),
5) malfunctioning emissions control systems (ECS) affecting tailpipe emissions, and
6) upstream emissions (from fuel extraction, transportation, refining and distribution).

All are exhaust emissions except evaporation (3) and upstream emissions (6).

We examine in some detail two of the largest emissions sources not measured in the certification tests: off-cycle (4) and malfunction (5) emissions. We make use of some relatively new data: a) sets of dynamometer data involving both moderate and aggressive driving, with detailed emissions and vehicle-operation measurements; b) measurements on instrumented cars recording how cars are driven in ordinary use (i.e. "in-use" vehicles); c) a large set of 1991 remote-sensing measurements, recording emissions concentrations from identified in-use vehicles; and d) emissions collected from in-use vehicles tested on a dynamometer "as received," rather than being screened before testing. These data sets are briefly described in section 3. Accurate analysis of off-cycle and malfunction emissions is difficult because the incidence of the problems is small, while the emissions per affected vehicle or event are large.

Table 1.1. Sources of emissions (g/mile) for an average MY93 car, over vehicle life[a]

Source[b]	CO	HC	NO_X
1) Hot, On-Cycle[c]	0.983	0.090	0.201
2a) 70°F summer cold start[c]	0.663	0.071	0.070
2b) 20°F winter cold start[c]	1.658	0.178	0.091
Subtotal	3.304	0.339	0.362
3) Evaporation[d]	0	0.5	0
4) Off-cycle[c]	7.9	0.12	0.3
5) Malfunction	6	0.6	0.8[e]
6) Upstream	0.063	0.098	0.315
Total	17	1.7	1.8
1993 tailpipe standard	3.4	0.41	1.0

a) The sources are weighted so that the average per-car emissions are shown. See the discussion of distance-weighted incremental emissions at the beginning of Appendix A.
b) All are exhaust emissions except (3) and (6).
c) Properly-functioning cars.
d) MOBILE 5a estimate.
e) The NO_X malfunction estimate is simply the difference between the total exhaust NO_X emissions estimated by MOBILE5a and our estimate of sources (1)+(2a)+(2b)+(4).

Table 1.1 shows for MY93 that total emissions of CO and HC are about five times the tailpipe standards and NO_X is about twice the standard. It also shows that in moderate driving with properly functioning ECS, exhaust emissions satisfy the standards. (Legally, row (1) plus two times row (2a) should be compared with the standard.) Manufacturers design vehicles to test at roughly half the standard. (The test values for NO_X are even lower than this relative to the standard, because the California standard is lower.) We predict that vehicles will continue to be able to meet increasingly strict standards in certification tests, as is shown below in table 1.2.

High-power driving leads to high CO emissions because at high power — generally meaning power levels that exceed the maximum power levels in the FTP — vehicles are designed to command a rich fuel-air mixture, which requires that the ECS be overridden. One consequence is that when one attempts to drive low-power vehicles as if they were high-power cars, their ECS may be overridden for long stretches of driving, making low-power vehicles some of the worst polluters on the road. Off-cycle emissions of NO_X are also high because of the sensitivity of NO_X formation to temperature inside the engine cylinders, and therefore power. Assuming the proposed new FTP testing rules are adopted in an effective form, we predict reductions in off-cycle emissions in table 1.2 and figures 1.1, 1.2 and 1.3 below. (See section 5.4 and Appendix section B.4.)

Vehicles with malfunctioning ECS are the source of almost half of each of the pollutants (table 1.1). The measurement of CO associated with malfunction is far superior to that of the other pollutants. For it, we find malfunction emissions to be strongly vehicle-model dependent. Interpretation of this result will be highly controversial because the emissions community embraced the concept (primarily from study of 1970s and early '80s-model year cars) that ECS failures are due to abuse by individual owners and mechanics (Beaton et al. 1995). The data on more-modern models do not support this concept, and call for an entirely different viewpoint. With 2- to 5-year old popular cars of Asian manufacturers, observed in the 1991 remote-sensing survey in California, malfunctions are rare in several mid-price models, but frequent in many less-expensive models of each of the manufacturers. Different ways of examining these data support our view that the responsibility is fundamentally the manufacturers', not that of the individual owner or mechanic. (See section 5.5 and Appendix section B.5.)

The impact of ECS malfunctions is large. In the 1991 survey, roughly one-fourth of the vehicle models from MY87-89 have a high probability for malfunctioning ECS. Among the models in the worst quartile, some 10% to 30% of the cars are malfunctioning. For these models, the average car (averaged

Table 1.2. Sources of emissions (g/mile) for MYs 2000 and 2010 cars, average over vehicle life

	CO		HC		NO_X	
Source	MY2000	MY2010	MY2000	MY2010	MY2000	MY2010
Hot, on-cycle + cold start[a]	2.9	1.4	0.22	0.11	0.26	0.13
Evaporation[b]	0	0	0.37	0.37	0	0
Off-cycle[a]	2.4	2.4	0.036	0.036	0.1	0.1
Malfunction	5	2	0.4	0.2	0.6	0.3
Upstream	0.063	0.055	0.097	0.085	0.31	0.25
Total	10	6	1.1	0.8	1.3	0.8
Tailpipe standards	3.4	1.7[c]	0.25[d]	0.125[c]	0.4	0.2[c]

a) Properly functioning cars.
b) MOBILE5a prediction.
c) Tier 2 standards.
d) Non-methane hydrocarbons.

Table 1.3. Seasonal emissions (g/mile) for MY93

	Winter CO	Summer HC	Hot summer HC	Hot summer NO_X
Seasonal increment	1.0	0.3	0.6	0.2
Adjusted total	18	2.0	2.3	2.0

over malfunctioning and properly-functioning cars) pollutes about 10 times as much as a properly-functioning car. Some other models, including popular models, are found to have extremely low malfunction rates. That is the basis for our prediction that the manufacturers could meet a tough standard for robustness of ECS. Our prediction that they *will* meet such a standard is based on the environment that will be created *if* the new technologies to identify malfunctions, remote sensing and on-board diagnostics (OBD), continue to be vigorously pursued; and recalls based on them enacted. The two kinds of instrumentation are rapidly improving in their capabilities, and in a few years should be flooding us with good information. The predictions for reduced malfunction emissions are shown in table 1.2.

The totals in table 1.1 are averages over summer and winter conditions. Winter (20°F average) CO emissions are 1 g/mile higher than the total in table 1.1, as shown by the difference between rows (2b) and (2a). Summer HC emissions are higher than the total shown in table 1.1 because the 0.5 g/mile evaporative emissions, row (3), is the average of 0.1 and 0.9 g/mile rates for winter and summer, respectively. Taking into account that HC cold start summer emissions are reduced compared to winter, the summer HC emissions total is 0.3 g/mile higher than the table 1.1 total. This is shown in table 1.3 along with results for hot summer days.

Hot summer days are critical times for pollution in most regions. Although lifetime-average g/mile emissions are indicators for this problem, special factors on hot summer days affect the g/mile emissions. Two emissions sources are particularly important: 1) extra NO_X is associated with heavier than average loads on the engine (air conditioning, construction, vacation travel). We estimate extra emissions of 0.2 g/mile at these times with MY93 cars. This excess should be reduced to about 1/3 that level with MY2000 cars as a result of EPA's proposed rulemaking for a supplemental FTP. 2) extra HC is associated with higher than average evaporation rates. Evaporative emissions are estimated to increase 0.3 g/mile on a day when the temperature is 95°F rather than the 86°F we assumed. New instrumentation for measuring vehicular evaporation and more realistic evaporative tests in the proposed rulemaking should help reduce the excess, but we do not predict major reductions. On the other hand, fuel vapor-pressure regulation has been fairly effective. The vapor pressure could be reduced further in the summer in the Northeast, to values now mandated in California and some Southern states.

Before discussing the results further, we stress that both the analysis of MY93 emissions and the prediction of emissions reductions involve substantial uncertainties. For MY93, the biggest uncertainties are associated with lack of data on: a) the extent and nature of the NO_X emissions we have labeled malfunction, b) CO and HC emissions in cold start from vehicles with malfunctioning ECS, and c) emissions from real-world, properly-functioning cars in on-cycle driving. For (a), we simply show NO_X malfunction emissions as the difference between the emissions we are able to estimate and the total predicted by EPA's emission factor model MOBILE5a (USEPA 1994b); there is, however, no evidence for such large NO_X malfunction emissions in the "as-received" survey (section 4.5). For (c) our data is for very clean cars; the "as-received" survey suggests that in-use vehicles emit about twice as much (due to deterioration as distinguished from malfunction). In addition, due to lack of accurate data, the predicted reductions in all three pollutants associated with ECS malfunction (tailpipe) are based on analysis of CO alone. Moreover, the latter is based on remote sensing data for MY87-89 vehicles, taken

Figure 1.1. Sources of CO emissions for model years 1993, 2000 and 2010 cars, average over vehicle life

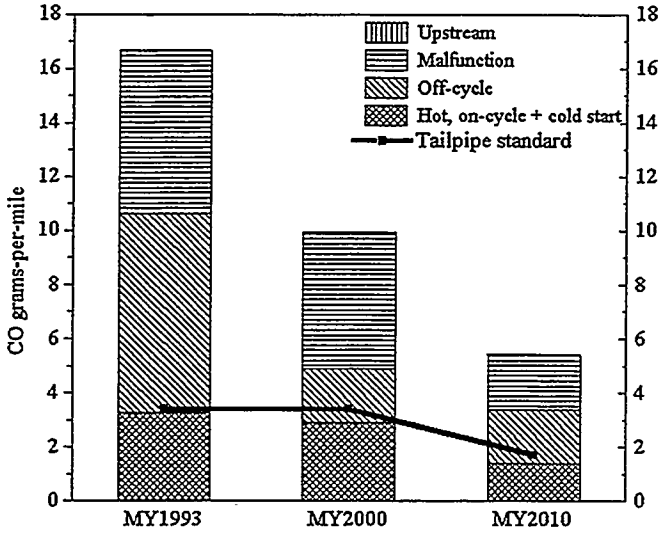
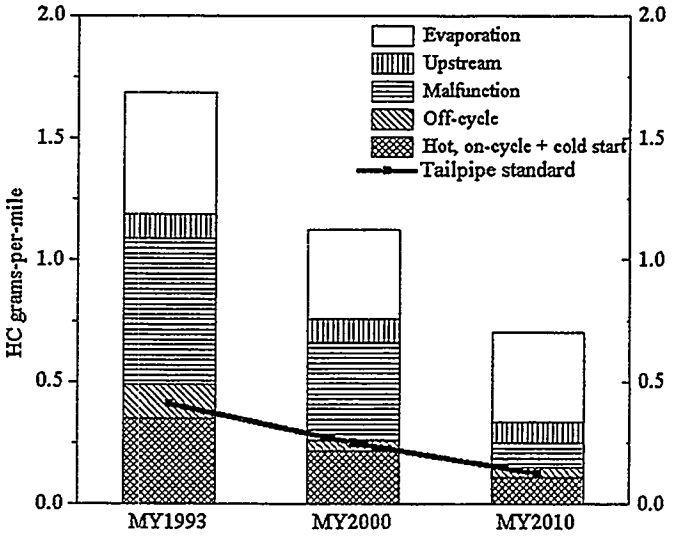


Figure 1.2. Sources of HC emissions for model years 1993, 2000 and 2010 cars, average over vehicle life

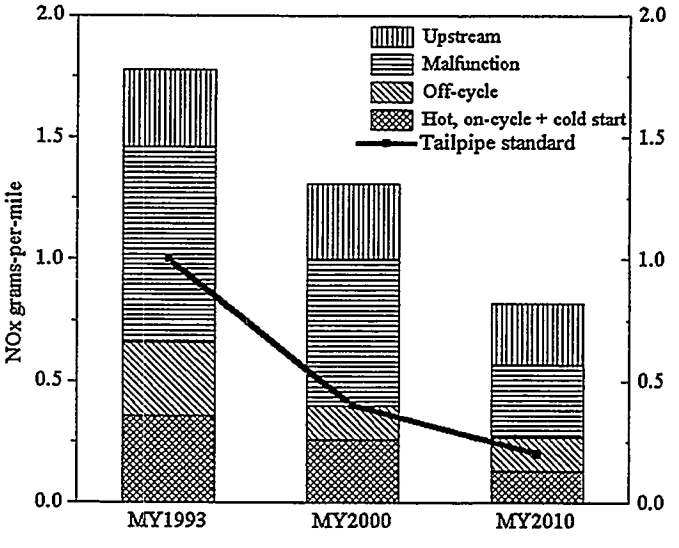


in 1991. This is far from ideal; one would prefer to examine cars over a longer age span; but the analysis must be based on modern fuel-injected cars, which, we decided, limits us to MY87 and later. Another prediction, for evaporation, is not based on fresh information, but is simply taken from the nominal forecast in MOBILE5a. Of course all predictions are uncertain. The ones we have singled out here appear to us to have the largest g/mile uncertainties.

What influence might these uncertainties have on our predictions? In spite of the serious data problems, we believe the predictions of *relative* reductions for 2010 to be fairly robust, because the physical opportunities are fairly well defined, and they are similar in percentage terms for all major sources except evaporative HC. (The reductions for 2000 could, however, be much smaller than shown.) *It is the policy-related uncertainties that are probably the most critical.* If the proposed rulemaking on off-cycle emissions doesn't lead to meaningful regulations, and/or if the development and use of improved information technologies to detect ECS failures and make ECS more uniformly robust are not pursued with vigor, then the progress is likely to be much smaller.

The results in tables 1.1 and 1.2 are summarized graphically in figures 1.1, 1.2, and 1.3. The predicted MY2000 emissions are 60%, 65% and 72% of real-world MY93 emissions for CO, HC and NO_X, respectively. The reductions in malfunction emissions are small because there is not a lot of time changes in the approach to malfunction emissions to affect lifetime emissions for MY2000. The reductions could well be much smaller than we predict for MY2000. For MY2010 we project that

Figure 1.3. Sources of NO_X emissions for model years 1993, 2000 and 2010 cars, average over vehicle life



lifetime average emissions of CO will be reduced to 1/3 of MY93 levels, and those for HC and NO_X to about 1/2 and 2/5, respectively, of MY93 levels.

1.3. Policy Implications

In the light of our analyses, we draw a number of conclusions about policy:

1) In connection with the core of the regulatory program, compliance testing of new vehicles, we stress the importance of developing instrumentation and information to support this effort. The failure to make an adequate effort to improve instrumentation and information in the 1980s badly served the manufacturers, regulators and public. Better information leads not only to more-effective regulation, but, if well-handled, can also lead to simpler regulations.

2) We find that forecasts by the regulatory emission factor models MOBILE and EMFAC are not based on detailed analysis relevant to the regulatory scenarios which are named, and so can be misleading. For example, in MOBILE5a a scenario called California LEV program has no malfunctioning vehicles.

3) The potential for effective I&M programs is dubious in our view, because they are based on two doubtful assumptions: that ECS failures are fundamentally the individual's responsibility, and that essentially all malfunctioning cars can be repaired effectively at a moderate price.

4) The remote sensing and OBD technologies now in development, and "as-received" dynamometer testing of in-use vehicles, are all highly promising as tools that could be used in efforts to reduce malfunction emissions.

5) Although the public information that *should* become available from these new technologies might bring about changes in design and manufacture that greatly reduce malfunction emissions, to insure this a recall program based on real-world observation of excessive number of high-emitters is needed. It may be appropriate to balance changes in other regulations against the new regulations aimed at loophole reduction.

6) The loophole emissions are roughly proportional to fuel use; as a result, vehicles with improved fuel economy would have major real-world emissions benefits and should be supported for that reason.

7) As an alternative to the increasing variety of regulatory initiatives, we suggest that the manufacturers try a proactive role. They could commit to reduction of *real-world* emissions, as determined through the new instrumentation now becoming available. (Good instrumentation would be critical.) If real-world emissions could be adequately measured at reasonable cost, they could provide the basis for simpler regulations.

These policy recommendations are briefly explained and discussed in section 6.

There are two broad policy approaches to reduction of vehicular emissions in the near term; and they are highly controversial: The emphasis of the official national approach embodied in the CAAA90 is to require new vehicles to perform better, i.e. with lower g/mile, in the laboratory-like tests to which they now are subject for emissions certification. There are various standards, such as Tiers 1 and 2 nationally, and Low and Ultra-Low Emission Vehicles in California. These new vehicle standards are complemented by I&M programs and in-use testing, aimed, in principle, at keeping ECS functional, or repairing them if necessary. The justification for this approach is that the regulatory structure of the past two decades has led to substantial emissions reductions, and the various players are used to it; so it should be continued in

a strengthened version. If this program is regarded as defining g/mile emissions goals, then the means for carrying them out have been inadequate. On the other hand, one can regard this program based on the certification tests as a *means* to reduce real world emissions. In this view, real-world emissions will continue to be substantially higher than the test limits, but that is acceptable as long as progress is made.

New regulatory initiatives (required or study items in the CAAA90), which have not yet received widespread attention among non-specialists, are the basis of the second approach. They emphasize closing the loopholes in the old approach rather than creating yet cleaner vehicles in the original certification test. These new initiatives are: a) EPA's proposed supplement to the new-vehicle certification test aimed at sharply reducing off-cycle emissions, and b) radically-improved information technologies to identify ECS malfunctions (remote sensing, OBD, and "as-received" in-use tests), with regulatory mechanisms to reduce them accordingly — primarily through improvements in new vehicles, rather than through repair of existing vehicles. The argument for this change in emphasis is that the emissions associated with the loopholes are larger than those measured in the certification test (table 1.1, figures 1.1-1.3). Moreover, the sources of the loophole emissions are different, so that, in the absence of effective targeted measures, little further emissions reduction will be achieved by stricter standards on conventional vehicles under the old certification tests.

These two approaches are not necessarily in conflict with each other, so why not pursue them simultaneously? We are concerned that there may be high costs to an unfocused campaign which includes some relatively ineffective policies. The regulations may be poorly carried out because of the lack of focus and limited budgets of the agencies. In addition, very strict NO_X certification test standards may inhibit rather than encourage technical development (section 6.6). Perhaps most important, there might be political penalties from trying to do so many different things, especially ineffective things.

The analysis presented in this report suggests emphasizing the second approach. Our analysis concludes that these policies will reduce the emissions associated with the two loopholes by about two-thirds. *We recommend that these policies be vigorously pursued, including strong support for development and use of instrumentation to create better publicly-available information on real-world emissions.* To help assure these reductions, we suggest that the manufacturers and regulators propose that emissions regulations be changed to a basis of real-world data (sections 6.5 and 6.7).

In contrast, the policies of the first approach, increasingly strict standards for new conventional vehicles and I&M programs, either do not directly address the loopholes or have been found only marginally effective against them; and they are costly. *In terms of conventional-vehicle emissions, we suggest that these policies be de-emphasized.* This is our opinion; the analyses in this report do not directly address these policies.

The other issue is that, even if successful, the second approach will not fully close the loopholes. Would this partial success be good enough for 2010? While we are impressed with the progress projected for conventional cars, we do not draw a conclusion on this. A third approach aimed at reduction of vehicular emissions in the longer term comes in here. This policy focus is creating and marketing vehicles which are intrinsically clean at the vehicle (e.g. electric or hydrogen fuel-cell vehicles) or vehicles that *might* be much cleaner through use of new propulsion technology (hybrid drivetrains with much higher energy efficiency, and/or alternative energy such as natural gas or methanol). Some of these may prove successful as vehicles as well as having much lower test emissions and suffering much less, or not at all, from ECS malfunction. In this approach, radically lower test standards are viewed as goals for real-world alternative vehicles. These standards would force industry to bring new propulsion technology to the market. (The emissions from such alternative technology vehicles are beyond the scope of the report.)

Areas which suffer from especially severe urban-air quality problems, such as Southern California, will continue to experiment with intrinsically clean vehicle technologies. We are enthusiastic about the opportunities, but in this report we do not analyze these technologies nor address policies to encourage them. *We hope, however, that our prediction of real-world emissions from conventional vehicles manufactured at that time will help people evaluate potential new propulsion technologies and policies to encourage them.*

2. Emissions Regulations

2.1. An Informal History of Tailpipe Exhaust Emissions Regulation up to 1990

The tailpipe mass emission rates (grams of pollutant emitted per mile driven, or g/mile) of three pollutants are currently regulated as part of the effort to achieve healthful air quality across the US: hydrocarbons (HC), oxides of nitrogen (NO_X), and carbon monoxide (CO). The history of automobile exhaust regulations begins essentially in the early 1950s, when Professor A. J. Haagen-Smit of the California Institute of Technology first suggested that HC and NO_X, two by-products of fossil fuel combustion, react in the atmosphere in the presence of sunlight to form photochemical smog. Smog was becoming an increasing health concern in southern California, and political pressure was mounting to do something about it (Krier 1977).

After more than a decade of debate over the contribution of automobiles to the air pollution problem, the first tailpipe exhaust standards in the country were applied to the 1966 model year (MY) vehicles sold in California. Following the lead of California, The Motor Vehicle Air Pollution Control Act of 1965 (Public Law 89-272) authorized the federal government to set motor vehicle emission standards nationwide. The first federal standards limited CO and HC exhaust concentrations from MY68 cars sold in the US. The Air Quality Act of 1967 (PL 98-148) mandated uniform auto emission standards throughout the country with the exception of California, which was allowed to continue setting its own, stricter standards. Subsequent federal standards have more or less followed the California standards (compare tables C.1 and C.2).

The 1970 Clean Air Act Amendments (CAAA70, PL 91-604) marked a major change in federal automobile emissions regulation and set the tone for current policies. "The automotive targets [in the CAAA70] were acknowledged by all to be beyond the existing technological capabilities of the automobile manufacturers; the targets were specifically designed to be 'technology forcing.' The authors of the act had learned a lesson from the experience of the 1950s and early 1960s: that they could not rely on the good will of the automobile companies or on market forces alone for the development of technology to deal with this problem. They saw the setting of strict emission standards as the way to force that development (White 1982)."

Although the CAAA70 called for reducing emissions from a wide range of mobile as well as stationary pollution sources, it is noteworthy that only automobile and truck standards were singled out and *specified quantitatively* in the law. This was probably due in part to the contentious relationship which had developed between the auto industry and the federal government during the formative years of auto pollution regulations. For example, in 1955 American automobile manufacturers entered into a cross-licensing agreement that allowed them to share technological developments in the area of air pollution controls with each other. Ostensibly, the agreement was to expedite the introduction of air pollution control measures into new vehicles; but the Justice Department found evidence that the agreement was discouraging competition between the manufacturers and was delaying the introduction of potentially expensive new equipment. In 1969, a consent decree allowed the automobile industry to avoid litigation by agreeing to end the cross-licensing agreement without admitting any wrongdoing (Senate Hearings 1973).

In another example, the EPA reported in July, 1972, that some MY73 cars were being equipped with devices that were designed to turn off pollution control measures when the cars were driven under conditions not represented in the Federal Test Procedure (FTP). The FTP (described in section 2.3 below) is the procedure for measuring compliance with emission standards, which is performed under

highly controlled, laboratory conditions. "Specifically, it was reported that emission control systems would shut off when the engine was idling, when the outside air temperature was below the minimum test level of 68 degrees, or when major accessories such as air conditioning units were operated (Senate Committee Print 1973)." Here, the auto industry obeyed the letter of the law, but not the spirit. Federal regulations were changed to prohibit the use of "...an auxiliary emission control device [AECD] that reduces the effectiveness of the emission control system under conditions which may reasonably be expected to be encountered in normal vehicle use, unless...[t]he need for the AECD is justified in terms of protecting the vehicle against damage..." (40 CFR 86.094-2). (This exception allows for the use of command enrichment of the fuel-air mixture introduced into the engine, which severely reduces the effectiveness of the catalyst, but which may be necessary to protect the engine and catalyst from overheating during high-power episodes.)

Due to claims by the auto industry in the early '70s that they could not meet the planned 1975 emissions standards in time, the 1975 standards were waived by the EPA and were eventually put off until MY80 and MY81 in the CAAA77 (PL 95-95). In addition, the NO_X standard was relaxed. However, EPA Administrator William D. Ruckelshaus allowed California to maintain its more strict 1975 standards, all but requiring the auto industry to use catalysts on MY75 vehicles sold in California. Ruckelshaus intended that California would be a proving ground for in-use catalyst technology (Senate Hearings 1973).

The federal tailpipe standards for CO and HC for MY81-93 called for g/mile emissions only 4% of the pre-control levels. However, actual in-use emissions are very roughly one-fourth of pre-control levels. Meanwhile, vehicle miles have roughly doubled since 1970, so that total motor vehicle emissions (grams, rather than g/mile) have been reduced by one-half, or perhaps less. The story for NO_X is similar but much less dramatic. The revised standards in the CAAA90 (PL 101-549) were a response to the persistent air pollution problems in the US and the perception that reductions in automobile emissions would be cost effective (Waxman 1991).

The emissions standards (both evaporative and tailpipe) from 1968 through 1993 did force many technological innovations that have reduced emissions and, in some cases, improved fuel economy (although some early engine re-calibrations reduced fuel economy). Among these innovations are: positive crankcase ventilation; ignition timing controls; exhaust gas recirculation (EGR); catalytic converter systems; fuel injection systems; activated charcoal canister; computer-based sensors and engine controls (Black 1991).

2.2. Regulations for the Mid- and Late-1990s

The CAAA90 provide for two tiers of emission standards (table 2.1). Tier 1 standards are to be phased into the fleet over the years 1994 to 1996, and call for a 35% reduction in tailpipe HC (chiefly in the form of non-methane hydrocarbons) and a 60% reduction in NO_X compared to MY93 standards. The Tier 1 CO standard remains unchanged from the 1993 level. (The 1993 standards are sometimes referred to as "Tier Zero" standards.) Tier 2 standards are scheduled to take effect in MY2003 vehicles and would cut the Tier 1 standards for all three pollutants in half. The Tier 2 standards can be waived by the EPA administrator if they are found to be not technologically feasible, not cost effective, or unnecessary.

Low Emission Vehicle Initiative. The California Air Resources Board (CARB) has established a low-emission vehicles/clean fuel program to further reduce mobile source emissions in California during the mid- and late-1990s. CARB defines four vehicle types in addition to conventional vehicles (CVs): transitional low-emission vehicles (TLEVs), low-emission vehicles (LEVs), ultra-low-emission vehicles

Table 2.1. Federal passenger car tailpipe emission standards at 50,000 miles (g/mile)

Model Year	Total HC	Non-Methane HC	CO	NO_X
1981-93	0.41	—	3.4	1.0
1994[a]	—	0.31	3.4	0.76
1995[a]	—	0.27	3.4	0.52
1996-2000	—	0.25	3.4	0.4
2003 and on[b]	—	0.125	1.7	0.2

a) The Tier 1 standards established in the CAAA90 are: 0.25 g/mile for non-methane HC, 3.4 g/mile for CO, and 0.4 g/mile for NO_X. The amendments require 40% of an automaker's produced passenger cars must meet these standards for 1994 model year, 80% for 1995 model year, and 100% thereafter. Fleet average standards for non-methane HC and NO_X were calculated with the phasing-in schedule. To calculate the average of non-methane HC from THC and non-methane HC, a conversion factor of 0.85 from THC to non-methane HC is assumed. There are additional standards for vehicles between 5 years/50,000 miles and 10 years/100,000 miles.

b) The Tier 2 standards established in the CAAA90 for 2003 model-year vehicles may be implemented if EPA concludes the need for further mobile source emission reductions.

(ULEVs), and zero-emission vehicles (ZEVs). The emission standards for these five vehicle types is shown in table 2.2 (CARB 1989a, 1989b).

CARB has developed a sales-weighting and emissions credit system for introducing these four new vehicle types into the California market during the 1990s. (CARB, 1990) This program is being considered by other states, by the Northeastern states in particular.

Other regulatory initiatives. Two other initiatives are the focus of much of this report, improvement in the Federal Test Procedure and possible efforts to strengthen the various efforts aimed at deterioration or failure of emissions controls. These will be discussed as needed in later sections. We begin with the procedures.

2.3. The Testing Procedures

Federal Test Procedure. The EPA certifies the emissions performance of new cars under highly controlled conditions specified in the Federal Test Procedure (FTP). Details of the FTP are published in the Code of Federal Regulations (40 CFR 86) and have remained essentially unchanged since 1975.

As part of the FTP, cars are driven on a chassis dynamometer using a prescribed speed-time sequence (a driving cycle) while the associated exhaust is captured sequentially in three separate bags for

Table 2.2. California tailpipe emission standards for five passenger car vehicle types at 50,000 miles[a] (g/mile)

	CV	TLEV	LEV	ULEV	ZEV
NMOG[b]	0.25[c]	0.125	0.075	0.040	0.0
CO	3.4	3.4	3.4	1.7	0.0
NO_X	0.4	0.4	0.2	0.2	0.0

a) Higher (less stringent) standards were established at 100,000 miles.

b) NMOG (non-methane organic gases) are non-methane HC + ketones + aldehydes + alcohols.

c) Emission standard of non-methane HC.

analysis. A dynamometer is a kind of treadmill for cars consisting in the newest models of a large (48 inches in diameter) steel roller, or in older models of smaller (8.65 inches in diameter) twin rollers on or between which the vehicle drive wheels rest. The dynamometer is capable of providing variable resistance to the drive wheels, depending upon speed, thus simulating the loads that the vehicle would experience when driven on a road.

The FTP driving cycle was developed in the late '60s to be representative of a commute to work in the city of Los Angeles. However, dynamometers of the '60s were not able to handle accelerations greater than about ±3.3 mph/sec, so that the maximum acceleration in the FTP was limited to this value (Kruse and Huls 1973). As a result, FTP driving has been artificially restricted, requiring only moderate power output from cars, with essentially no command enrichment. See section 4.4 below.

As mentioned, three bags of exhaust are collected during the FTP: 1) The cold start, 2) hot stabilized driving, and 3) the hot start. The cold start bag is intended to measure the elevated tailpipe emissions that occur during the first several minutes of driving after start-up following an overnight rest, or "soak," when the vehicle engine and catalytic converter have cooled to ambient temperatures of around 70°F (section 4.2). Bag 2 represents warmed-up, or hot stabilized, driving during which the emissions control system is fully functional, and bag 3 determines emissions levels during the several minutes following start-up after the vehicle has soaked for only 10 minutes (section 4.1).

The manufacturers measure and report to the EPA the g/mile emissions for CO, HC, and NO_X in each bag, multiplied by distance-weight factors (table A.3), and added together to compare to the standards (40 CFR 86.144-94).

Supplemental Federal Test Procedure. The CAAA90 directed the EPA to revise the FTP as necessary to more accurately reflect the manner and conditions under which cars are actually being driven. In February, 1995, the EPA published a Notice of Proposed Rulemaking to revise the FTP (USEPA 1995b), called the Supplemental FTP (SFTP).

The SFTP includes three additional bags. These new bags are intended to measure tailpipe emissions from five kinds of driving behavior not represented in the original FTP: aggressive driving episodes, rapid speed fluctuations, driving behavior immediately following start-up, driving with the air conditioner on, and intermediate duration soaks of about an hour (USEPA 1995b). The EPA proposes to combine the new bag g/mile pollutant measurements (using suitable weighting factors) with the original FTP for comparison with the emission standards.

Selective enforcement auditing. EPA and CARB use a "selective enforcement auditing" program to spot check vehicle emissions. Every year, EPA and CARB determine which engine families to audit for compliance with emissions standards. They select vehicles from the end of the assembly line and bring them to laboratories for testing. If at least 40% of these vehicles fail the standards, an engine family failure is defined. Then EPA or CARB can stop the production of that engine family and order the manufacturer to recall the vehicles already produced. About 10 years ago there were some engine family failures, and some of these resulted in recalls. Recently there have been virtually no engine family failures defined under this program.

Deterioration tests. Before a manufacturer starts production of a given MY engine family, it must submit an emission certification application to EPA or CARB. In the application form, the manufacturer presents results of emissions testing: rates at about 4000 miles and emission deterioration rates. EPA or CARB determines whether the engine family meets the 50,000- and 100,000-mile standards.

To generate emission deterioration rates, manufacturers have to run sample vehicles on dynamometers to accumulate mileage. Recently, EPA and CARB have begun to allow manufacturers to run engines rather than vehicles to age emission control components, then installing the component on a vehicle to test emissions at high mileage. If a manufacturer determines that there are no significant changes in engine and vehicle designs between the current model year and the previous model year for the same engine family, the manufacturer can carry over the deterioration rates generated for the previous model year.

In-use tests. EPA and CARB also use "in-use" tests and associated recalls to try to make sure that in-use vehicles meet standards during their first 50,000 or 100,000 miles. Each year, EPA and CARB select some engine families to conduct in-use tests. Through state databases, they select some owners of vehicles of the selected engine families. The selected vehicles usually have 30,000 to 50,000 miles accumulated. The selected owners are asked to bring their vehicles to laboratories. It is a voluntary program. A visual inspection of recruited vehicles is conducted to make sure that no "tampering" or abuse have occurred and that vehicles have been "properly maintained" (e.g. from records of regular oil changes). After this screening, the "properly maintained and used" vehicles are conditioned and then tested for compliance with emissions standards. Perhaps 20 to 25 vehicles in a given family are tested in California. If a number of vehicles within an engine family fail the in-use tests, a recall can be instituted. As a result of negotiations between EPA or CARB and manufacturers, recall rates are lower than engine family failure rates.

One of the key issues for this report is that the in-use testing procedures do not identify vehicle models with high probability for malfunctioning emissions controls. Malfunctioning vehicles tend to be screened out by the procedures or are not identified because of the recruitment process and the small number of vehicles tested. Yet vehicles with malfunctioning emissions controls are responsible for almost half the total emissions. A careful review of the causes of, or responsibility for, malfunctions is needed. Thoughtful analyses of practical measures to sharply reduce malfunction emissions are needed. An initial discussion of these issues is presented in this report.

3. The Principal Sets of New Measurements Used in this Study

This study relies on many previously-published analyses, which in turn are based on many measurements. However, several new results are presented here that are based on recent public-domain measurements. We describe these data sets briefly. (In these data and in figures and tables in this report, particular vehicles are sometimes named. They are simply representative vehicles for which good measurements are available.)

3.1. High-Acceleration Test by California Air Resources Board

CARB tested 10 vehicles on a dynamometer in a high-acceleration cycle designed to examine the effects of fuel enrichment at high power. The cycle involves ten high-power episodes with useful differences in intensity and duration, simulating a variety of driving conditions. Emissions and dynamometer data are collected second by second. These are rear-wheel drive vehicles, MYs 1988-90 (Cicero and Long 1993).

3.2. Steady-State Data Collected by Office of Mobile Sources, USEPA

These data involve dynamometer tests of 29 hot stabilized cars and light trucks, model years 1990-92. Each vehicle is measured at about 60 operating (fixed engine speed and power output) points, averaging over about 1 minute for each point. For each point much data is available, such as vehicle speed, engine speed, dynamometer torque, throttle opening, manifold vacuum, engine-out and tailpipe emissions of CO_2 and criteria pollutants, temperatures, and air-fuel ratio. The data have some problems, but are good for study of command enrichment strategies and of engine-out emissions (Koupal 1995).

3.3. Manufacturer's Data for the FTP Revision Project (FTP-RP)

These data involve dynamometer tests of 27 vehicles, model years 1991-94, 11 of which are Tier Zero (pre-1994) cars. The measurements are second-by-second, and use a modern electrodynamic large-diameter (48-inch) dynamometer. Several different driving cycles are used, involving high-power driving as well as the moderate driving of the FTP. For each second, much data is available, including engine speed, vehicle speed, manifold vacuum, throttle position, air-fuel ratio, engine-out and tailpipe emissions, exhaust volume, and temperatures. In addition, for some vehicles data are available for two electronic management schemes for the engine: the vehicle with its "production chip" for managing air-fuel ratio, and a "non-enrichment chip" which avoids command enrichment (section 4.4), although some enrichment still occurs. These data are rather good in terms of timing, with only small differences between the chemical measurements at the emissions analyzer, and the mechanical measurements at the dynamometer. These data have just become publicly available (Haskew et al. 1994).

In addition, data has recently been made available from a joint EPA/industry study of the effects of real (not simulated, as in the current FTP) air conditioning load on tailpipe emissions. Six Tier 1 vehicles and one TLEV were tested at GM's AC Rochester facility over the current FTP and the high-power cycle of the proposed supplemental FTP (USEPA 1995).

3.4. Air Resources Board Remote-Sensing Data Compilation

There are now several large remote-sensing data sets. The data we use were collected by the University of Denver at 13 sites in California on 29 days in May-July 1991, and are available from

California's Air Resources Board. The remote sensing technique involves measurement of absorption of infrared light across a single lane of traffic, behind each vehicle just after it passes. The vehicle is identified by videotaping its license plate. The sites are primarily expressway ramps and an urban boulevard closed down to one lane by the police. Rough descriptions of the type of driving at each site are provided. There are approximately 90,000 vehicles in the sample. Some 60,000 vehicles are different, and there are about 30,000 repeats. The data involves measurement of CO and total hydrocarbons concentrations and of the VIN of each vehicle; one can determine most of the vehicle model information from the latter. This large sample permits one to look for statistical correlations involving high-emission concentrations, with vehicle age, technology, and model (CARB 1994).

3.5. Joint EPA/Industry Driving Behavior Survey

In February and March of 1992, the EPA in conjunction with the automobile industry recruited and instrumented over 300 vehicles in Atlanta, Spokane and Baltimore, recording real-world driving behavior over a span of several days. A majority of the vehicles were outfitted with "three-parameter" instruments that recorded second-by-second observations of vehicle speed, engine speed, and manifold absolute pressure along with the time and date of the observations. Approximately 60 vehicles were outfitted with "six-parameter" instruments that also measured equivalence ratio (the observed fuel-air ratio divided by the stoichiometric fuel-air ratio), throttle position and coolant temperature. It should be noted that the six-parameter instrumentation required vehicles with certain modern technologies, so that the fleet recruited for the six-parameter study does not necessarily accurately represent the overall fleet. These surveys include mostly urban driving with *average* speeds between 20 and 30 mph. (USEPA 1994a; LeBlanc et al. 1994; Kishan, et al. 1993; DeFries and Kishan 1992)

3.6. Air Resources Board "As-Received" Dynamometer Measurements

In 1993 and 1994, CARB tested "in-use" vehicles as they were received, without any of the screening or modification that characterizes most in-use testing (Gammariello & Long 1993). These are bag data including 78 MY87 and later cars. Tests were made using both the FTP and Unified Cycle (a driving pattern including high power episodes roughly corresponding to actual driving in Los Angeles). The key feature of these data from our perspective is that there are 8 to 10 high emitting MY87 and later cars in the tail of the emissions distribution (for FTP bag 2). This enables examination of some features of malfunction emissions based on measurement technology quite different from remote sensing.

4. Emissions of Model-Year 1993 Cars

The emissions analysis is organized according to the six physical categories listed in section 1.2. The following summarizes our results. Details are presented in Appendix A.

4.1. On-Cycle Emissions of Hot Properly-Functioning Cars

Cars are certified for emissions performance using a driving pattern specified in the Federal Test Procedure (FTP). Present-day vehicles incorporate an emissions control system in order to meet the stringent emissions standards associated with the FTP. The heart of the system is a three-way catalytic converter. To be effective the catalyst must be hot and the fuel-air mixture must be stoichiometric, i.e. have the chemical balance that would permit complete combustion, in order for the catalyst to be able to transform the residues in the exhaust into inert molecules. To help achieve the stoichiometric ratio, there is an oxygen sensor in the exhaust line whose signal is used to adjust the amount of fuel injected into the engine.

The driving in the FTP, or "on-cycle" driving, is moderate. The highest acceleration rate is 3.3 mph/sec, only about half of what is occasionally encountered in real-world driving, and the highest speed is 57 mph. It involves both a cold start cycle (next subsection) and warmed-up vehicle/catalyst cycles (the subject of the present subsection).

The emission factors in row (1) of table 1.1, correspond to warmed-up engine and catalyst and moderate driving for properly-functioning MY93 cars. They are calculated from FTP stabilized running (bag 2) and hot start (bag 3) data for the MY91-93 cars contained in the FTP-RP database. (Identical standards applied during these three years.) We dissect these emission-rates into physically-based factors, to help develop an understanding of potentials for change.

The tailpipe emissions in grams per second ($TP_{g/s}$) are the product of three factors:

$$TP_{g/s} = FR \cdot EI \cdot CPF \qquad (1)$$

The fuel rate (FR) is in g/s. The engine-out emissions index (EI) is the dimensionless ratio of g/s of pollutant to g/s of fuel use. The catalyst pass fraction (CPF) is the fraction of pollutant which passes through the catalyst without conversion; it is also dimensionless, pollutant out (g/s) to pollutant in (g/s).

Estimates of the three factors in equation (1) for tailpipe emissions are shown in table 4.1 for warmed-up, moderate driving. These are for an average 1991-1993 MY passenger car, nominally about half way through its life. The data of the Federal Test Procedure Revision Project (FTP-RP), on which

Table 4.1. Estimates of the three factors in equation (1) for warmed up, FTP (bag 2) style driving

Pollutant	(1) FR	(2) EI	(3) CPF	(4) EI x CPF	(5) $TP_{g/s}$	(6) $TP_{g/mile}$
CO	0.602	0.095	0.074	0.00703	0.00423	0.948
HC	0.602	0.025	0.032	0.00080	0.00048	0.108
NO_x[a]	0.684	0.013	0.179	0.00233	0.00159	0.356
NO_x[b]	0.493	0.033	0.052	0.00172	0.00085	0.190

a) Cars in the FTP-RP equipped with EGR.
b) Cars in the FTP-RP without EGR.

the table is based, involves vehicles in excellent condition with catalysts aged under laboratory conditions.

The tailpipe emissions in column (4) are converted into g/mile from g/s by multiplying by 224 seconds-per-mile (i.e. an average speed of 16 mph in the FTP bag 2). Column (5) in table 4.1 shows typical tailpipe emission rates in g/mile for warmed-up, on-cycle driving of a MY93 car. In comparing the results in table 4.1, column (5), and table 1.1, row (1), it should be noted that the emissions rates in table 4.1 do not include the contributions from hot starts and the distance-weights that go into the results of table 1.1, row (1). (See Appendix A and table A.3.) This accounts for the differences in the two tables.

Properly-functioning, in-use cars pollute more than the relatively clean vehicles used in the FTP-RP, perhaps twice as much when measured over the same cycle. (See Appendix, section A.1.) In mid-life, typical engines have deposits on the cylinder walls; their valves are not like new; and the catalytic converters have probably deteriorated more than the laboratory-aged catalysts installed in the FTP-RP cars. We do not, however, make a correction for this deterioration (An, Barth & Ross 1995).

4.2. Cold Start Emissions of Properly-Functioning Cars

Cold start emissions averaged over summer and winter conditions are shown in line (2) of table 1.1. Emissions are relatively high when a vehicle is started with the engine at ambient temperature because there are two stages without the benefit of substantial emissions control: First, for purposes of drivability, the fuel-air mixture is commanded to be rich, for perhaps half a minute, depending on ambient temperature. (This is like the use of a choke in older vehicles.) Second, it takes two minutes or so for the catalytic converter in the exhaust stream to warm up to the point that it is converting pollutants. These times are shorter when the ambient temperature is high, and longer when the ambient temperature is low. For model years before MY94, there was no regulatory motivation to limit cold start emissions at ambient temperatures well below 70°F. Starting with MY94, cars must meet modified CO standards for a 20°F cold start test.

Command enrichment of the fuel-air mixture (in the first stage of a cold start) leads to extremely high CO emissions, because the engine-out emissions index and the catalyst pass fraction both increase for CO. (See subsection 4.4 below.) Based on FTP-RP data presented in Appendix A (section A.2), we find that about 2/3 of the cold start emissions at 70°F are associated with this first stage. The period of this command enrichment is associated with moderate warming of the intake manifold and the engine coolant and so is sensitive to ambient temperature. As a result, CO emissions are very high in cold start at low ambient temperatures, creating serious winter air quality conditions in several metropolitan areas.

These high CO conditions have led to the requirements for oxygenated fuels in winter. This is an ineffective policy in the long term compared to improvement of on-board emissions controls. Currently, oxygenated fuels with oxygen content ranging from 2% to 3.5% by volume are required in wintertime in most states. With increased oxygen content in gasoline, combustion tends to become lean, and thus CO emissions can be reduced. However, newer cars with oxygen sensors combined with closed-loop systems automatically adjust air/fuel ratio and emit far less CO than do older cars. Consequently, as the vehicle fleet turns over, the impact of a mandated oxygenated fuels program on CO emissions will diminish over time. Emissions impacts of oxygenated fuels were analyzed for 20 1989 MY cars in the Auto/Oil Air Quality Improvement Research Program, showing that oxygenated fuels reduced CO emissions by less than 15% (1991). A remote sensing study by Bishop and Stedman [1990] in the Denver area showed a 16% reduction in CO from older models as a result of oxygenated fuel use. On the other hand, we find in this report that improved on-board controls and associated steps in design and manufacture to reduce CO

emissions in high-power driving and from malfunctioning emissions control are likely to achieve, in time, much larger reductions in overall CO emissions, on the order of 70% compared to MY93 cars.

4.3. Evaporation

There are several sources of evaporative emissions from the vehicle. Some are associated with heating of the fuel and fuel vapor: by ambient heating and by the heat generated by vehicle operation. There are also refueling emissions, vapors that escape from the vehicle's fuel tank due to displacement by gasoline during refueling.

Technology for reducing evaporative emissions includes: redesigned fuel tanks to account for fuel expansion; overfill protection in the fuel tank filler neck; pressure/vacuum relief valve in the fuel tank sealer cap; and an activated charcoal canister to store fuel vapors which may be periodically purged and burned in the engine (Black 1991). In addition, gas station fuel pumps in ozone non-attainment areas have been fitted with vapor recovery systems. If these systems malfunction, evaporative emissions are high (section 5.3).

Gasoline with higher Reid vapor pressure (RVP) evaporates faster than does gasoline with lower RVP under the same atmospheric conditions. To control evaporative emissions, RVP of gasoline sold in the summertime has been regulated. In particular, California started to regulate gasoline RVP in 1971. There, gasoline RVP was, is, and will be regulated below 9 psi from 1971 to 1991, below 7.8 psi between 1992 and 1995, and below 7 psi after 1996 (CARB 1991). Nationwide, EPA began to regulate gasoline RVP in 1989. Depending on the area and the month, gasoline RVP was required below 10.5 psi, 9.5 psi, or 9 psi between 1989 and 1991 (USEPA 1989). After 1991, gasoline RVP has been limited to 9 psi or 7.8 psi (USEPA 1990). Studies have shown that gasoline RVP regulations have been very cost-effective in reducing HC emissions (Wang 1995).

4.4. Off-Cycle Operations of Properly-Functioning Cars, High and Moderate Power Driving

The concern with off-cycle driving is the incremental emissions associated with the distribution of power (i.e. the fractions of time at various engine power levels) being much higher in practice than in the FTP. There is both: 1) driving at higher power than occurs in the FTP ("high power") and 2) a shift toward higher power within the power range of the FTP ("moderate power"). The emissions consequences can be large (German 1995).

Under certain driving conditions, command enrichment occurs: The emissions control system is overridden and the fuel-air ratio is increased. As just discussed, when the engine is cold, the fuel injectors are instructed, for a brief period, to introduce excess fuel in order to improve combustion stability. When high power is required of the engine, the fuel injectors are also instructed to introduce excess fuel. Engine operations in which command enrichment usually occurs and the degree of enrichment are analyzed in detail in the Appendix, section A.4.

The principal rationale for command enrichment at high power is protection of the catalyst from overheating. Enrichment also: increases the maximum power available from the engine by about 3 to 5%, curbs the increase in engine-out NO_X emissions in high-power episodes, helps provide a smooth knock-less response when the throttle is opened wide, and helps cool the engine.

Enrichment is usually commanded in three high-power driving situations involving properly-functioning vehicles:

1) at high absolute power in hard-acceleration episodes of roughly 5 to 15 seconds, such as entering an expressway at low speed and quickly coming up to speed, accelerating in a high-speed lane change, and climbing short hills at high speed,

2) when relatively high power is momentarily called for at low engine speeds, such as when coming out of a curve, or accelerating rapidly, in urban driving , and

3) in sustained relatively high-power driving in non-acceleration situations such as: a) low power-to-weight vehicles at high speed, b) long hill climbing at high speed, and c) trailer pulling.

During command enrichment very high CO and HC emissions occur, much higher than those for moderate driving. The effect is strongest for CO, and is illustrated in figure 4.1, where 500 seconds of moderate driving is followed by 7 high-power episodes with command enrichment, each lasting about 10 seconds. Each episode alone produces much more CO emissions than the 500 seconds of moderate driving. During these enrichment episodes the mass of CO emitted is almost as large as the mass of fuel consumed. The figure shows two curves: One curve represents CO tailpipe emissions with the engine-control microprocessor chip in the normal production vehicle, and the other curve shows the CO emissions from the same vehicle driven over the same driving cycle (the HL07 cycle) with a chip that

Figure 4.1. Effect of command enrichment on total tailpipe CO emissions (sample MY94 car in the FTP-RP)

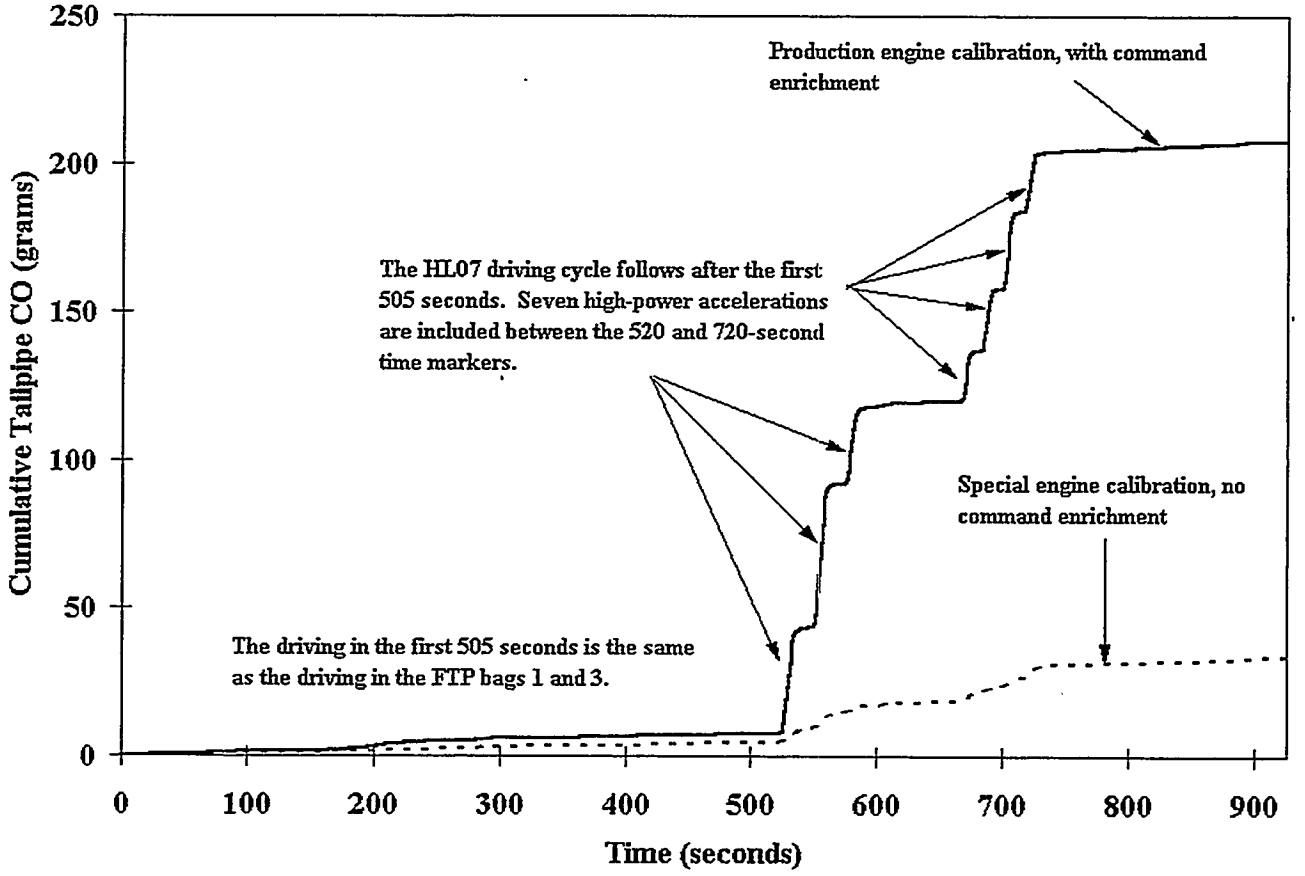


Table 4.2. Estimates of the three factors in equation (1) in illustrative high-power driving with command enrichment

	(1) FR	(2) EI	(3) CPF	(4) $TP_{g/s}$	(5) Ratio of high-power-to-FTP tailpipe emission rates
CO	4.7	0.60	0.97	2.7	~500
HC	4.7	0.019	0.54	0.047	~100
NO_X†	4.7	0.015	0.34	0.023	~20

†) Near wide open throttle EGR no longer functions (unless the vehicle is equipped with an EGR pump), so that both cars with and cars without EGR have similar engine-out NO_X emissions index at high fuel rates.

does not command the air-fuel ratio to go rich under any conditions.

The behavior of tailpipe HC emissions is similar to that of CO during command enrichment, although the relative increase over stoichiometric operation is smaller.

To estimate the emissions associated with command enrichment, it is necessary to model a) emissions, given command enrichment, b) the enrichment strategy of typical vehicles (e.g. the strength of enrichment as a function of engine power and speed), and c) the frequency of high-power driving or other driving that leads to command enrichment. There are a wide variety of enrichment strategies built into vehicles, ranging from strong enrichment essentially everywhere outside the conditions tested in the FTP to enrichment only at the most extreme engine speed and power; however it is possible to talk about a typical strategy for the estimate to be made here (An and Ross 1995, Koupal 1995).

In table 4.2, tailpipe emission rates in g/s ($TP_{g/s}$) are calculated for an illustrative example of high power driving, and are compared in column (5) to the results for the FTP-style driving shown in table 4.1, column (4). The fuel rate (FR) is in g/s, the emissions index (EI) is the ratio of engine-out pollutant (g/s) to fuel use (g/s), and the catalyst pass fraction (CPF) is the ratio of pollutant exiting the catalyst in the tailpipe exhaust (g/s) to pollutant entering the catalyst (g/s). The factors by which the emissions rates (g/s) increase are about one order of magnitude for NO_X, two orders for HC and three orders for CO.

On the basis of the driving pattern surveys recently completed by EPA and the auto industry in Spokane, Atlanta and Baltimore, we estimate the CO and HC emissions associated with command enrichment to be 7.3 and 0.12 grams per average mile of driving, respectively, from the three causes of command enrichment just listed. This is shown in the summary table 1.1, above. The contribution of command enrichment to excess NO_X emissions is small, and is included in the estimate for NO_X at moderate power immediately below.

These estimates for the extra emissions that occur in the relatively rare instances of command enrichment in properly-functioning cars are uncertain for two major reasons: 1) The enrichment strategies for different engines and vehicle models vary strongly. 2) The patterns of driving involved occur only 1 to 5% of the time and so are difficult to determine accurately.

Excess emissions arise in off-cycle situations from other causes than command enrichment. Of prime interest is excess NO_X in moderate-power driving. NO_X formation increases rapidly with increased temperature in the cylinders. As a result, engine-out NO_X emissions are very low below a threshold fuel rate and increase rapidly above it. That is, NO_X emissions are sensitive to vehicle operation which involves extra power, but where the extra power is not so high as to command enrichment. (The increase

in NO_X with fuel rate is inhibited by enrichment, i.e. by its cooling effects.) These moderate-power situations arise in off-cycle driving associated with: air conditioner use, grades at moderate speed, heavy loads (like passengers and luggage beyond the FTP's 300 lbs), high speeds (but without high acceleration), etc.

The combined incremental effect of the various sources of off-cycle NO_X is estimated to be:

0.35 g/mile in summer, and

0.25 g/mile in other seasons,

or an annual average of 0.3 g/mile (Appendix, section A.4).

4.5. Malfunctioning Exhaust Emissions Controls

This category comprises excess emissions from vehicles whose emissions controls are not properly functioning (as distinguished from normal degradation). It is both the largest and the least well-understood source of emissions. We make an independent contribution in this area on the basis of analysis of remote sensing data. Two important examples of malfunctioning emissions controls are substantial damage to the catalyst, and failure of the oxygen sensor which provides feedback for control of the fuel-air ratio. The catalyst can be damaged, for example, by exposure to prolonged high temperatures (and reducing atmosphere) These conditions are associated with prolonged high-power driving, e.g. in mountain driving or trailer pulling. They can also be the secondary result of inadequate performance of fuel-air ratio controls or of engine misfire. The oxygen sensor can, for example become disconnected or be operating improperly.

One way to estimate the role of emissions from malfunctioning cars is from the MOBILE5 model, which is based on extensive comparisons with emissions from in-use vehicles, even though it—and all in-use emissions data—must be questioned in terms of how representative they are, with respect to the kinds of driving and vehicles involved (USEPA 1994b). Although malfunctioning vehicles are not identified as such within MOBILE5, since we independently project the exhaust emissions from properly-functioning vehicles, we can project the incremental malfunction emissions by simple subtraction. These results are shown in table 1.1, above, only for NO_X. For the other two pollutants we estimate the malfunction emissions from direct measurement. (The two methods roughly agree.)

The second way we estimate the incremental malfunction emissions uses remote sensing data (section 3.4), supported by the "as-received" dynamometer data (section 3.6). The basic remote-sensing data takes the form of a snapshot of pollutant concentration just beyond the tailpipe of an on-road vehicle, combined with information about the vehicle model involved. A sample data set is shown for CO in figure 4.2. There are about 3000 observations of MY87 fuel injected cars. The distribution shown is the cumulative fraction of vehicles observed at the CO concentration in question or at higher concentration. The key to the distribution is that it has two parts. The first is a central peak, with about 90% of the cars, whose average CO concentration agrees essentially with the dynamometer data for properly-functioning cars discussed in section 4.1, above. The second part is the tail at high CO concentrations, with about 10% of the cars, whose average CO concentration is about 50 times that for properly-functioning cars. These are the cars taken to have malfunctioning emissions control systems. There are uncertainties about the remote sensing data, but checks, such as restricting the analysis to cars observed at least two — or at least three — times, and comparison with the "as-received" dynamometer measurements, show that our essential results are valid. (See section 5.5 for further discussion and Appendix sections A.5 and B.5 for details.)

The criterion we adopt for malfunction with respect to CO is 1% or greater concentration, essentially CO concentration greater than about 20 times that measured for properly functioning cars (section 4.1 and Appendix, table A.13). The HC data and their analysis is much more uncertain than that for CO. For HC we rely primarily on the fact that the high CO emitters in the remote-sensing and the as-received dynamometer data are largely the same cars as the high HC emitters in each set of data. (Details are given in Appendix section A.5.) Representative results for CO emissions by cars with malfunctioning emissions controls are shown in table 4.3.

One result is that for CO, for cars halfway through average lifetime mileage (at age about 4 years), two-thirds of the CO emissions come from vehicles with malfunctioning emissions controls even though only about one-tenth of the cars are malfunctioning. This is for warmed-up moderate driving. We estimate that the fraction of emissions from malfunctioning cars in cold start is about one-fifth as great as for properly-functioning cars, although we have very limited information. We find the weighted incremental malfunction emissions to be 4.1 times the emissions for moderately-driven properly-functioning cars. (That is, these are the incremental emissions of the average car due to the large emissions of a small number of malfunctioning cars.) This factor multiplies the warmed-up rate (0.98 g/mile from table 1.1) plus one-fifth the cold-start rate (0.2 x 2.32 g/mile). That is the basis for the entry of 6 g/mile: [4.1 x (0.98 + 0.2 x 2.32)] for CO malfunction in table 1.1.

Figure 4.2. Stephens plot of distribution of CO emissions from MY87 fuel-injected vehicles (CARB 1991 remote sensing data)

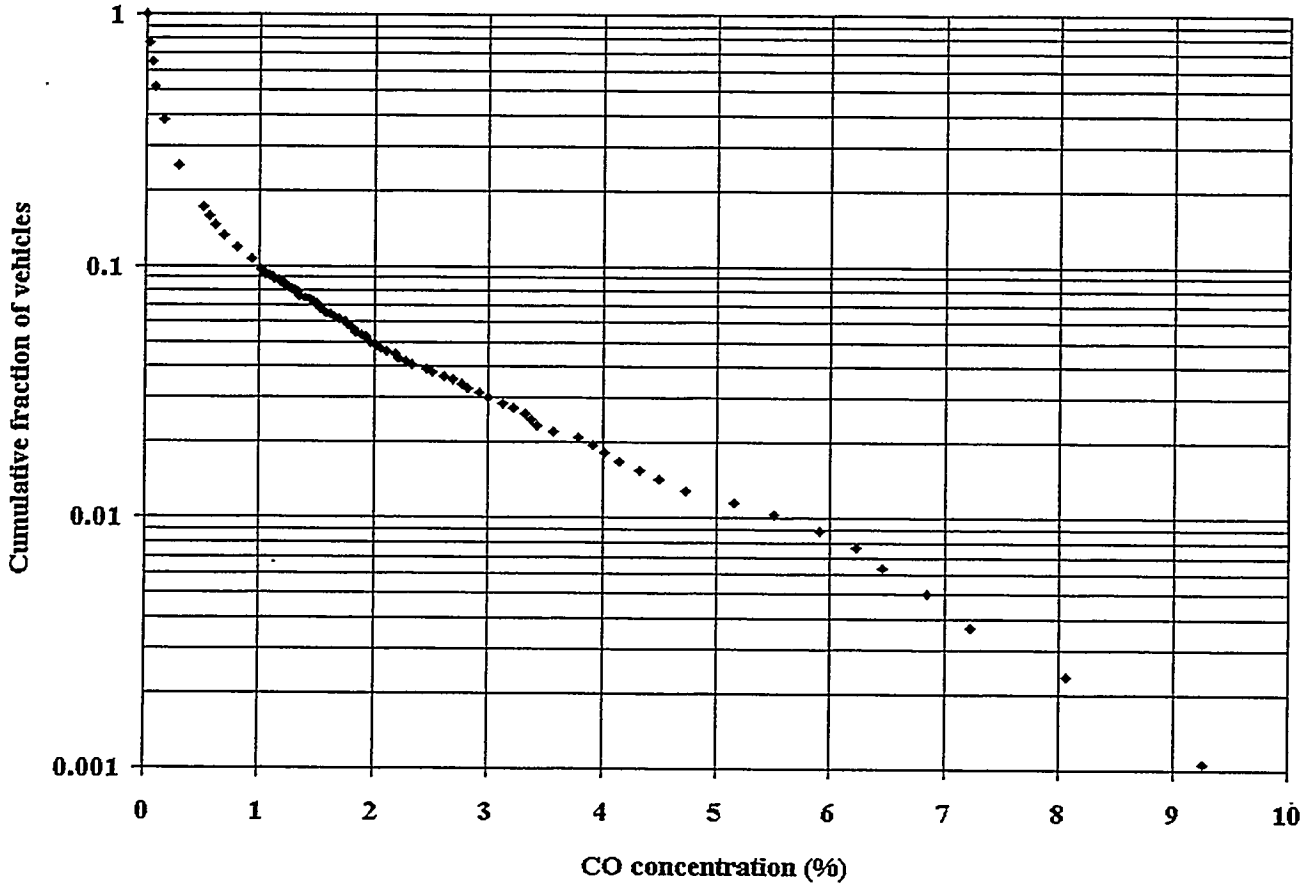


Table 4.3. Occurrence of CO malfunctions — MYs 87 and 90, fuel-injected cars, measured in May-July 1991

Vehicle group	Malfunctioning vehicles (percent)	Percent of observed emissions
MY87 CO malfunctions	8.4	64
MY90 CO malfunctions	5.6	57

For HC, the incidence of malfunctions is taken to be the same as that for CO, as indicated above (Appendix A, section 5). Thus, the incremental malfunction emissions in moderate driving are taken to involve the same factors times the emissions from properly-functioning cars. That is the basis for the entry of 0.6 g/mile: [4.1 x (0.09 + 0.2 x 0.25)] for HC malfunction in table 1.1.

4.6. Upstream Emissions

When comparing emissions among gasoline vehicles and electric vehicles, emissions of up-stream energy production facilities for gasoline vehicles are often ignored, even though up-stream power-plant emissions for electric vehicles are considered. In this report, we estimate up-stream emissions as well as vehicular emissions in order to put gasoline vehicles into a complete fuel cycle perspective (DeLucchi et al. 1994).

Fuels are burnt for crude oil recovery, crude transportation, crude refining, and gasoline transportation, storage, and distribution. Fuel combustion during these processes produce emissions. In addition, gasoline evaporates during transportation, storage, and distribution. One of us has recently developed a fuel-cycle model to calculate fuel-cycle emissions of gasoline vehicles as well as alternative fuel vehicles (Wang 1995b). The documentation is not yet final.

In the model, energy consumption is first calculated for a fuel production stage. Then, with the calculated energy consumption and emission factors in grams per million Btu of energy consumed, emissions in grams per gallon of gasoline produced are calculated for the fuel production stage. Emission factors of fuel combustion for various combustion processes used in the fuel-cycle model are derived from various sources, including EPA's AP-42 documents. Finally, using the fuel economy of gasoline vehicles, upstream emissions in grams per gallon are converted into grams per mile driven. The model results for MY93 passenger cars are shown in table A.13 below and in row (6) of table 1.1.

5. Prediction of Emissions for Model-Year 2000 and 2010 Vehicles

The prediction of lifetime emissions is organized according to the same six sources of the preceding section. Details are presented in the Appendix, section B.

5.1. On-Cycle Emissions of Hot Properly-Functioning Cars

Manufacturers meet the current test standards with room to spare — called "headroom" — as a result of *continuing improvements in engine and emissions controls* and their desire to avoid costly recalls based on excessive test emissions, so that vehicle-to-vehicle variations and the differences between national and California standards are not troublesome. If one considers the FTP with the original 70°F cold-start test, then the average emissions as tested are shown in Table 5.1. One sees that the cars test at about 60% of the national standard except that the NO_X test value is low enough to meet the California standard. The trend of decreasing g/mile tailpipe emissions during the '80s and early '90s even while the national standards remained fixed — that is, steadily increasing headroom — is evident in the studies of thousands of *in-use* cars recruited and tested by GM in the late '80s (Haskew and Gumbleton 1988; Haskew, Garrett and Gumbleton 1989; Haskew and Liberty 1991), and it is consistent with results of thousands of new cars tested and documented in the 1990-1993 EPA Test Car Lists (Murrell, unpublished analysis).

Moreover, car designers/manufacturers have the capability to meet the various new standards for emissions — from properly-functioning vehicles in moderate driving — in a timely fashion. They can substantially reduce emissions through further improvements in control systems which keep the fuel-air ratio closer to stoichiometric; this results in substantially smaller catalyst pass fractions than the averages for MY93. Some of this can be accomplished relatively easily and at reasonable cost, as demonstrated by the better-performing engines of today. Meeting ultra-low emissions standards (from properly-functioning vehicles in moderate driving) is more difficult, but can be achieved by accurately controlling the variations (especially in fuel-air ratio) among the cylinders and from cycle to cycle. This is a more sophisticated step in terms of equipment design, software and quality of manufacture; but it has been accomplished by Honda in their recently announced ULEV production vehicle (American Honda Motor Company 1995).

In other words, low- and ultra-low emissions can be achieved in new production vehicles when tested under laboratory conditions that simulate moderate driving (including vehicles with "aged" components). That is a challenge the manufacturers can and will meet, albeit with some cost.

Prediction. The prediction concerns both how many LEV vehicles are produced and how much headroom the manufacturers decide to have between certification test emissions and the regulatory limits.

Table 5.1. Headroom in meeting FTP test standards. FTP emissions with 70°F cold start of the federal Tier Zero cars (MY91-93) in the FTP-RP (g/mile)

	CO	HC	NO_X
Tier Zero cars as tested	2.31	0.23	0.34
National standards	3.4	0.41	1.0
California 92 standards	7.0	0.39	0.4
California 93 standards	3.4	0.35	0.4

For the prediction we assume that the emissions measured in certification tests will be at 60% of the 50,000-mile regulatory limits, Tier 1 for MY2000 and Tier 2 for MY2010. Including the 20°F cold start to represent winter experience, we obtain the top row of emissions in table 1.2.

5.2. Cold Start Emissions of Properly-Functioning Cars

Cold-start emissions from properly-functioning vehicles is another area where new standards can and will be met. The automotive engineering community has been doing a lot of successful work on cold-start emissions; and manufacturers are meeting the new standard for cold-start emissions at 20°F. The approach to reduction of emissions in the first, or enrichment, stage of cold start is more-sophisticated sensors and control of the fuel-air mixture which enables good response even when the engine is cold. For example, a 1993 Mercedes in the FTP-RP requires no enrichment in cold start at 70°F.

Reducing the second stage emissions will usually involve the addition of a close-coupled catalytic converter (one placed close to the exhaust manifold, so that it heats up rapidly). The catalyst can be formulated so that it resists damage from the increased temperatures which would normally occur in this position. This general kind of technology is already in use in some vehicles. If the stiffer Tier 2 standards are adopted for cold start, more drastic measures such as pre-heated catalysts might be required.

5.3. Evaporation

Vehicular evaporative emissions can be controlled through lower gasoline RVP and installed on-board canisters which absorb evaporative emissions. Evaporative emissions in gasoline service stations due to vehicle refueling can be controlled by the so-called Stage-II technology which returns vapors from vehicle gas tanks to underground storage tanks during refueling, or by on-board canisters which absorb vapors from gas tanks. Currently, Stage-II technology is required in many ozone non-attainment areas. Beginning in 1998, on-board canisters will be required for controlling refueling emissions. The canisters can be designed to integrate with the canisters that are currently installed for controlling diurnal and hot soak evaporative emissions. To control running loss emissions, CARB has established a running loss emission standard of 0.05 grams per mile for 1995 MY cars. EPA will be likely to follow CARB's requirement.

As part of the extensive Auto/Oil study, 300 light-duty vehicles were recruited from an I&M inspection line in the Phoenix area in 1993 and tested as received (e.g. with gasoline unchanged and missing or loose gas caps unchanged) for evaporative emissions (Brooks et al. 1995). Using approximately the same evaporative standard as applies in the FTP, 46 vehicles, or 15%, exceeded the standard. (This criterion is relatively less demanding than the criterion for malfunctioning exhaust ECS adopted in this report.) The emissions from these 46 vehicles accounted for over 70% of the total evaporative emissions.

The high evaporative emitters were repaired where possible. For MY87 and newer vehicles, there were twenty high emitters. Of these, 17 were diagnosed of which 7 were gas cap problems. Of these 7, 3 were cap failures, 2 missing caps and 2 loose caps. The other 10 were miscellaneous equipment failures and included the only 2 very high emitters; all but one involved tank vapors.

The test used for this Auto/Oil study, and in the FTP, involves placing a warmed-up vehicle in a sealed room, with the temperature at about 100°F, for an hour (called a hot soak). A less costly, less complicated "pressure/purge" test, required by EPA in enhanced I&M programs, identified 12 of these 20 high emitters.

Prediction. As this kind of information is collected, especially from vehicles recruited randomly and tested as received, one can expect certain kinds of evaporative malfunctions to be identified and avoided in future models — through design improvements. Because of the small number of vehicles on which this kind of testing has been carried out, there is no evidence, of the kind we have for malfunctions-associated exhaust emissions, that some vehicle models are highly successful at avoiding evaporative emissions from malfunctioning fuel systems. On the basis of the variety of malfunctions identified in the Auto/Oil study just discussed, and considering the difficulty of acquiring extensive data on randomly selected in-use vehicles, we find the MOBILE5 prediction of only 25% reduction in evaporative emissions by MY2010 to be reasonable. This is the prediction shown in table 1.2.

5.4. Off-Cycle Operations of Properly-Functioning Cars, High and Moderate Power Driving

Proposed new rules, involving test-cycles with higher-power driving, are likely to be incorporated into a supplemental FTP as briefly discussed in section 2.3 (60 FR 7404). This should lead to controls that delay enrichment and to reduced levels of enrichment. That is, it is practical for the manufacturers to avoid enrichment in most brief high-power episodes; they can adopt timers to delay command enrichment for a few seconds; and they can minimize the level of enrichment needed to protect the catalyst from overheating. These are all measures which have been adopted in some vehicles, especially European vehicles.

Such measures will: 1) partially reduce command-enrichment emissions in major high-power episodes lasting roughly 10 seconds, 2) eliminate command-enrichment emissions in brief accelerations of a second or two, but 3) not substantially reduce command-enrichment emissions from lengthy high-power driving. Some cars have already eliminated most of (1) and all of (2), such as the Mercedes 420 SEL. It is difficult to avoid enrichment altogether in high-power episodes; the high temperatures involved increase engine-out NO_X emissions, and in long episodes damage the catalyst.

On this basis, we predict that the CO emissions from this source are likely to be reduced from 7.9 g/mile to 2.4 g/mile, and the HC emissions from 0.12 to 0.04 g/mile. (See Appendix section B.4 for details.)

In addition, NO_X at moderate power should be reduced in response to the supplemental FTP. There are two basic lines of attack: reduction of engine-out emissions using exhaust gas recirculation (EGR) and increased catalyst efficiency for tailpipe conversion of NO_X. We have not tried to analyze the effectiveness of EGR beyond observing that engine-out NO_X is substantially lower in cars with EGR. We do find that the average catalyst pass fraction in stoichiometric operations is much lower for some cars than for others. The pattern is not related to price but to general design choices; it tends to be that cars with high engine-out NO_X have very low catalyst pass fraction, and vice versa. The best half of the cars in this respect have an average catalyst pass fraction under 4%, about one-third of the average for the whole group. On this basis we predict that the NO_X emissions from moderate-power stoichiometric operations will be reduced by two-thirds by MY2010, as a result of the proposed rulemaking.

It is also possible, given the anti-regulatory views in the new Congress in Washington, that these proposed FTP revisions will be postponed, greatly weakened or dropped. We consider this a less-likely outcome, but still worthy of consideration. In this case, there would probably still be some reductions in command enrichment, as suggested by the enrichment strategies in some newer engines, but the reductions would be much less.

5.5. Malfunctioning Exhaust Emissions Controls

The nature of malfunctions. The issue here is not simply the high average emissions observed by the remote-sensing detectors, but the association of high emissions with particular vehicles. Our analysis is based on the assumption, which is supported by the data, that most cars are characterized by properly-functioning ECS, albeit with some deterioration, and the rest by severely malfunctioning ECS.

Almost half of the CO, HC and NO_X emissions are due to malfunctioning emissions controls. In the past, the responsible EPA offices have stated that many of these failures are due to "tampering", i.e. (presumably) deliberate disabling of emissions controls or related parts (USEPA 1991). This is important, as much of the testing analysis and policymaking presumes tampering. Without making a judgment on the validity of the tampering claim for earlier models, we conclude that the claim is, in any case, out of date. We have not seen any evidence that computer-controlled vehicles of the post-carburetor, post-leaded-gasoline era suffer from a substantial amount of deliberate disabling of emissions controls. (There is one troubling technology however: electronic engine control chips for sale as substitutes for the production chips, which deliberately restrict emissions controls.)

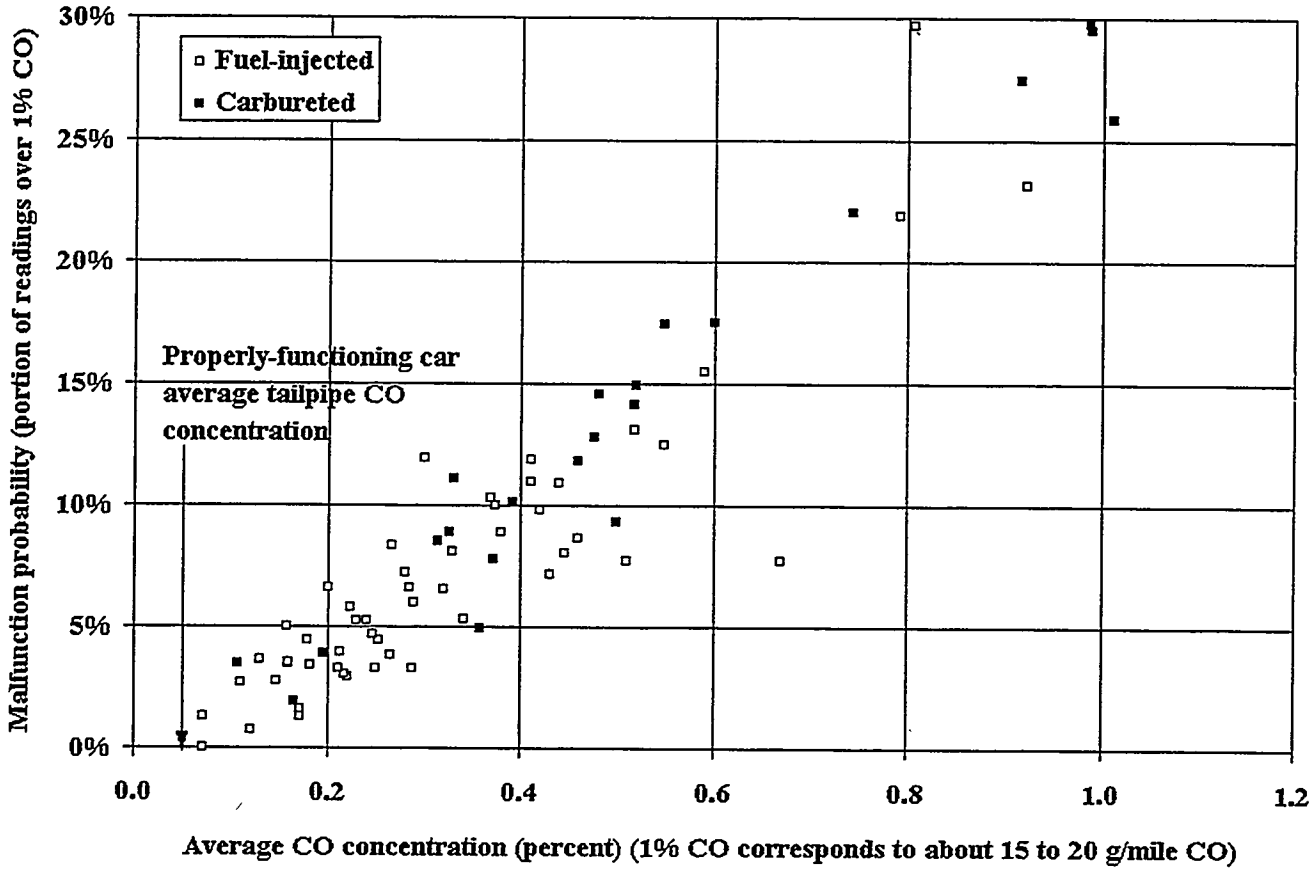
Malfunctioning emissions controls lead to very high emissions. For example, catalyst failure increases the catalyst pass fraction from a few percent to near 100%. (Compare columns (3) in tables 4.1 and 4.2.) Failure of fuel-air controls increases CO emissions even more. (Compare columns (2) in tables 4.1 and 4.2.) The emissions of vehicles with malfunctioning emissions controls are roughly comparable to those of the pre-regulation era (before the late '60s). The latter levels are estimated to be (in g/mile) 84, 11, and 4, for CO, HC, and NO_X, respectively (AAMA 1994). Using this rule of thumb, if 8.4% of cars are malfunctioning with respect to CO (table 4.3), then the CO emissions due to malfunction are estimated to be about 7 grams per mile, which is roughly correct (table 1.1).

The probability of malfunctions. The emissions due to malfunctioning vehicles is the product of the probability that vehicles malfunction and the level of emissions per malfunctioning vehicle. (See Appendix section B.5 for details.) As just suggested, the second factor (in g/mile) does not vary strongly with the vehicle or emissions control technology. The first factor is perhaps the most important issue for this report: the probability for vehicles to have severely malfunctioning ECS.

Analyzing the remote sensing data for CO, we find that the probability of malfunction is strongly correlated with vehicle model. For each model, the probability for malfunction is shown in figure 5.1, against the average CO concentration for all cars of the model. (Malfunction is defined here as CO concentration >1%.) Shown are the 76 individual MY-models from MY87-89 with more than 50 vehicles measured. Since the measurements were made in June 1991, the cars are 2 to 5 years old. The spread in malfunction probability is very large, with six MY-models in the sample having none or only one high-emitter (bottom left of the figure), and five having more than 25% high emitters (upper right of the figure). The apparent intercept on the x-axis, at about 0.07% concentration, is roughly consistent with expectations for properly functioning cars of 0.054%. (See Appendix table A.13.)

Of the models shown in figure 5.1, five less-expensive models (14 MY-models) of Asian manufacturers have very high malfunction rates. The average malfunction rate in this group is 22%. (The malfunction criterion is greater than 1% CO concentration.) Meanwhile, corresponding popular mid-price models of these manufacturers tend to have low malfunction rates; *for some models very low malfunction rates.* We have decided not to publish a list of the vehicle models and their malfunction rates, because the list of models is limited by statistics and for that reason might be misinterpreted, and because this is a new application of remote sensing and publication of lists should wait for critical review of the methods. Nevertheless we will name two models to make the result quite clear: Nissan Maximas

Figure 5.1. Malfunction probability vs average CO concentration, 76 MY87-89 models with over 50 different vehicles observed in the 1991 CARB Remote Sensing Data



show extremely low ECS malfunction rates for all three MYs 1987-89. Corresponding Nissan Sentras all show high rates. (This is simply an illustration. We have no reason to believe that current Nissans are any better or worse than current models of other manufacturers.) There are three major possibilities for this kind of result:

1) The result is wrong, due to inadequate statistics, to model-dependent driving behavior, or to some difficulty associated with the remote-sensing methodology. We have looked at these possibilities and find the evidence to be strongly against them; some further comments on remote sensing are needed.

   Remote sensing surveys to date have been criticized as too uncertain for identifying cars with malfunctioning ECS for the purpose of requiring those vehicles to be inspected more thoroughly and repaired. That dispute is not of concern here: Our use of the remote sensing data is completely different, and is less demanding. For our research purposes we need to determine reliable statistical ratios, not assure the accuracy of individual identifications of vehicles as high-emitters. For example, one of our critical results is that the data shows 22% of cars from five 1987-89 models to have CO concentrations in excess of 1% — in single passes by the remote sensor. Many of these may be misidentifications as high emitters, and many of the 78% observed to have concentrations below 1% in single passes may be

misidentifications as low emitters. When we tighten the criterion to consider only vehicles (of these models) for which three or more remote sensing measurements were obtained, the fraction of vehicles with average CO concentrations in excess of 1% is essentially unchanged at 21% (Appendix section B.5, table B.3). This means that the original 22% malfunction rate is robust, even though individual vehicle measurements may be rather inaccurate. In addition, the CARB survey of in-use vehicles, with dynamometer tests of the vehicles as they were received, supports the remote-sensing results in detail, although the "as-received" survey has poor statistics.

2) Owners of the less-expensive cars abuse them, while owners of the popular mid-price cars take good care of their cars, such that over 20% of the former have malfunctioning ECS in 2 to 5 years, while almost none of the latter do. In the past there has been some evidence to support this kind of concept: surveys of older-models than those under discussion showed extensive "tampering" or lack of maintenance; and one might believe that is more likely in low-price vehicles, especially after the first owner.

   Unfortunately for this argument, vehicles and their ECS have become much more sophisticated since most of the published tampering surveys, making deliberate tampering unlikely. Neglective abuse remains a possibility. Relevant to this we find that, among the five inexpensive Asian models, MY89 cars (only 2 to 3 years old) nevertheless have a high malfunction rate of 20%. There is, in addition, no evidence for large consistent differences in malfunction rates between corresponding low- and popular mid-price domestic models. It is our conclusion that abuse does not explain the striking differences observed between the less-expensive and mid-price Asian vehicles, and among some other models. By implication, abuse is not important for most 2 to 5 year-old cars of these model years. On the other hand, we haven't studied yet older cars; for them abuse might be an important factor in ECS malfunction.

3) Flaws in design and/or manufacture are much more probable in certain models than in others. The notion of model-dependent, or technology-dependent, component failures is well established for components other than ECS. We conclude that ECS suffer the same kind of difficulty.

Approaches to reduce malfunction emissions. Three basic approaches are being tried to reduce malfunction emissions: 1) identification of individual vehicles with malfunctions, 2) repair of malfunctions in these vehicles, and 3) reduction in the frequency of malfunctions in future vehicles, i.e. through more-robust emissions controls. (Approach (3) could also include recalls to try to fix in-use vehicles.) By far the largest efforts are going into identification. Attempts to strengthen vehicle inspection programs in areas where ambient pollution exceeds standards have been in the news a great deal (e.g. Wald 1994). Installation of on-board diagnostic equipment is another major program for identifying malfunctions. In addition, remote sensing of malfunctioning vehicles is being introduced for identification.

Even though EPA is retreating on the proposed expansion of inspection (smog check) programs, strong technological progress is being made with the other two identification technologies: The new generation of on-board diagnostic instrumentation will be effective in identifying malfunctions, and will be formally implemented in California cars by MY96, although it may take time to work out the bugs. The information provided by remote sensing is also being improved. By the late '90s, identification of malfunctioning vehicles with these two technologies will be a powerful tool. But will identification of problems lead to progress in repairs or in robustness of emissions controls?

At present, there is no reason for optimism about repair of malfunctioning emission controls. The record is poor. This is not surprising, because many of the repairs are neither easy nor cheap. Often it is easier to make a superficial repair, which yields satisfactory test results at the time but does not work for long. For example, tuning the engine for the purpose can yield good results in a simple emissions test, without solving the problem; or replacing a failed catalyst often yields good temporary results, but if the failure was caused by another faulty component, the catalyst will fail again later. Unlike performance repairs, the driver doesn't know whether emissions-control work has been successful, because cars usually perform adequately even when emission controls don't. This not only leads to faulty repairs, but sometimes to fraud. Moreover, large-scale success on repairs is made unlikely by the complexity of the institution. There are about 60,000 general automotive repair shops, including 26,000 auto and truck dealers.

We are much more optimistic about the eventual role of more robust emissions control systems in reducing malfunction emissions. Up to the present, a barrier to reducing malfunctioning emissions controls has been the weakness, in the regulations, of manufacturer responsibility with respect to malfunction. Manufacturer responsibility in this general area is to avoid excessive deterioration of components in "properly-maintained and used" vehicles. We believe that in response to this wording, regulatory tests in this area of concern, 50,000 mile certification tests and in-use tests, were designed in a way that makes identifying malfunction-prone models unlikely.

Robustness of emissions controls is likely to see substantial improvement in the future, because the new instrumentation technologies, remote sensing and on-board diagnostics, should provide a great deal of information about malfunctions to all parties. In addition, different management of in-use testing could provide highly valuable information on vehicle models with a propensity for malfunctioning ECS, as evidenced by the recent CARB "as-received" measurements. Well-disseminated results by vehicle model would likely change manufacturer priorities. We recommend, in addition, modifications in regulations to help this change occur. With this move to increase manufacturer priority in one area, we recommend regulatory balance, consideration of reduced priorities in other emissions-related regulations. (See section 6.5.) In our judgment, MY2000 is too soon for major progress on increasing the robustness of emissions controls to have been made; great progress should be made by MY2010.

Prediction. The basis for our predictions of malfunction emissions of all three pollutants are the assumptions that the probability and consequences of ECS malfunction are not affected by the introduction of advanced automotive technology as such, but by the quality of design and manufacture, and that the latter can be estimated using the 1991 data on the incidence of CO malfunctions in MY87-89 fuel-injected models. (See Appendix section B.5 for details.) We have found that many vehicle models are already rather robust against malfunction. The level of malfunction that the best models achieved in MY87-89 forms the basis of our prediction. *Manufacturers can, and in our opinion will, bring all their models up to the ECS robustness standard already met by many of their models.*

We assume for MY2000 that all models will be as robust as those of MY87-89 which had malfunction frequency under 16%. This reduces the average frequency of malfunction found for 54 fuel-injected MY-models studied from 7.4% to 5.7%, a reduction of incremental malfunction emissions from that assumed for MY93 of 23%. (While we are working from actual data on the incidence of ECS malfunctions, the progress we predict is simply a judgment. We also assume that the average emissions of a car with malfunctioning ECS will be the same as for MY87-89, roughly the emissions rates for pre-control cars.)

For MY2010, we predict that the average frequency of malfunction will correspond to that of the best quartile of MY87-89 models studied (which had frequency of malfunction under 3.5%). This

reduces the average frequency of malfunction found for the 54 MY-models studied from 7.4% to 2.6%, a reduction of malfunction emissions from that assumed for MY93 of 65%.

An increased incidence of successful repairs is not taken into account in these predictions. Although we believe that OBD will be helpful in this respect, in the overall picture we believe repair will be much less important than making ECS more robust.

As with the predicted reductions in off-cycle emissions, we believe the greatest uncertainty in the MY2010 prediction to concern the policies influencing improvements and applications of the remote sensing and OBD technologies, and use of as-received testing of in-use vehicles. Negative policies could slow the development and applications; the results might be kept secret; this would probably greatly reduce the predicted progress.

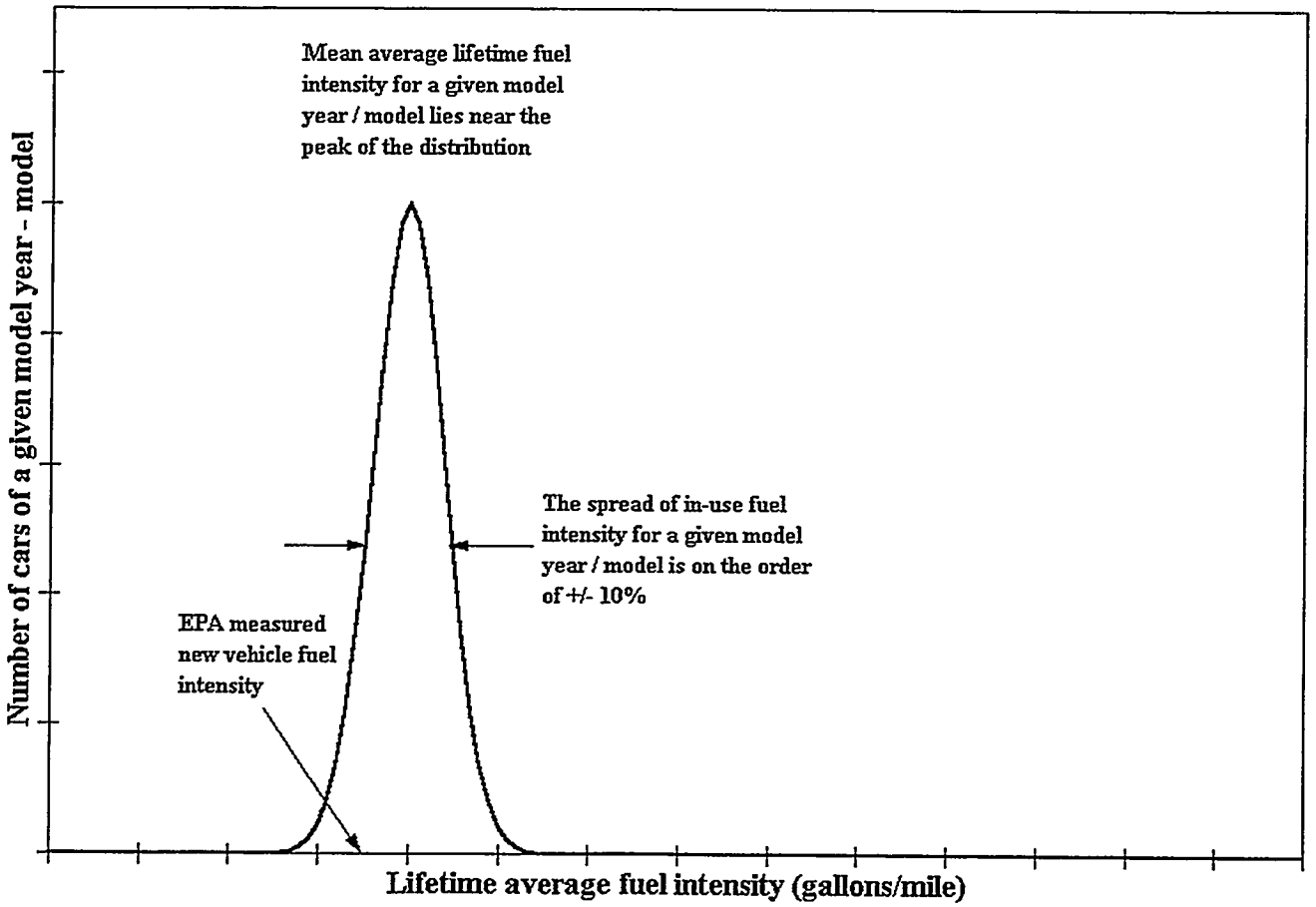
6. Implications

6.1. The Federal Test Procedure

Adequate information is necessary to achieve regulatory goals like substantially reduced emissions from light-duty vehicles. Adequacy of information regarding real-world emissions performance is a key issue for this study.

The importance of information is illustrated by comparing vehicular fuel use and emissions. Fuel use is much more predictable than emissions, so the information system created in the '70s for fuel use standards, especially the measurement of vehicle fuel economies, has proved accurate enough to enable meaningful discussion and policy making: *You don't have to be a specialist to understand quantitative information on fuel use* — in the sense that various measures (like mean, median and mode) approximately agree. Unfortunately, the distribution of emissions from different vehicles of the same model is highly variable and much less predictable. In particular, a small fraction of vehicles of any model typically contribute most of the emissions, because their ECS fails and/or because of the way the vehicle is driven. In a sense, the average vehicle doesn't have average emissions, so there is a great deal of confusion and room for misrepresentation. *You have to be a specialist to understand quantitative information on emissions* — because the distribution of emissions from vehicles of any particular model

Figure 6.1. Distribution of lifetime average fuel intensity for a typical car model



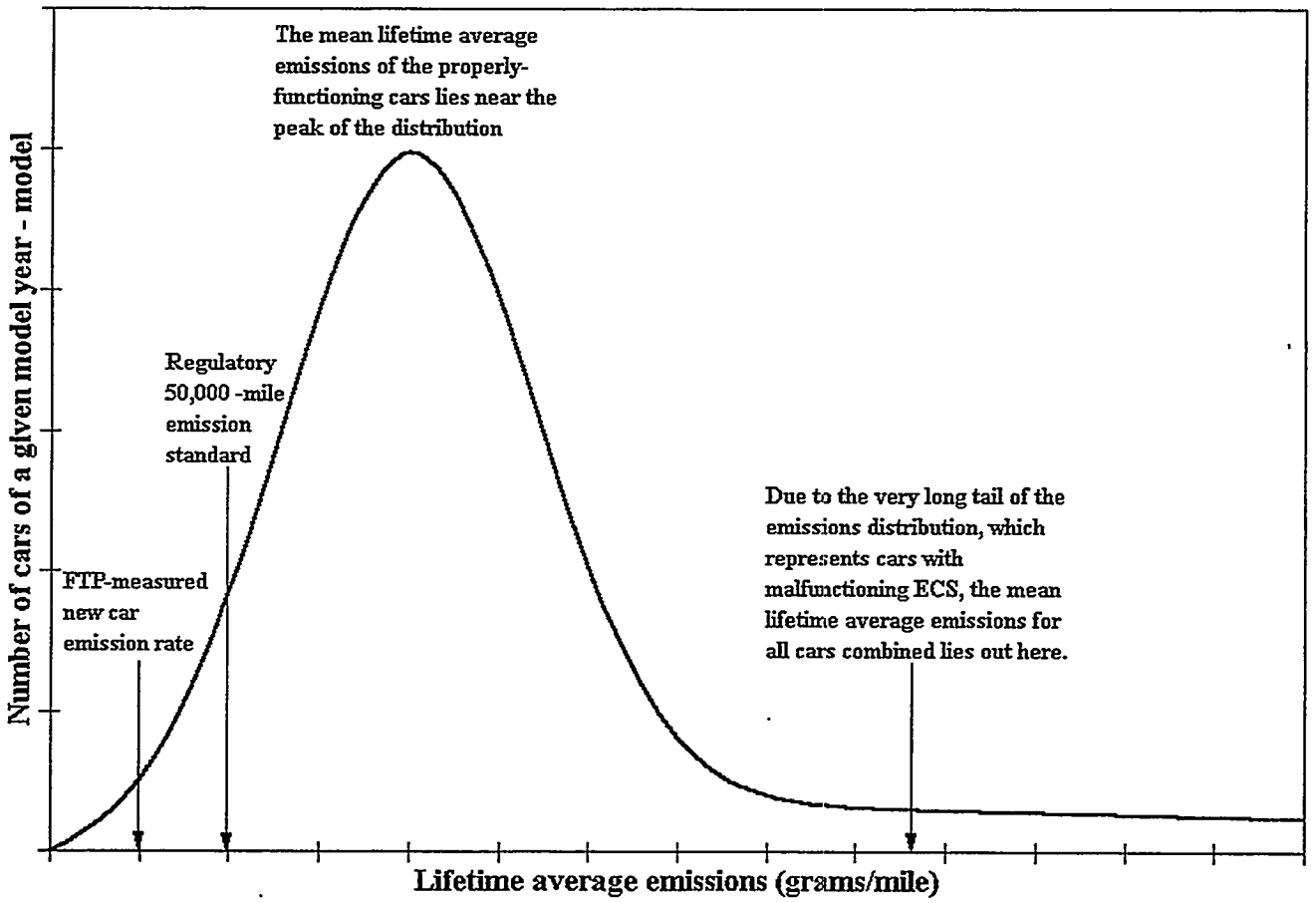
is so highly skewed.

This qualitative difference between fuel use and emissions is illustrated by figures 6.1 and 6.2. In the figures, vehicles manufactured to be the same (i.e. of the same model) are compared. The frequency of vehicles (y-axis) is shown as it depends on their lifetime average fuel use (figure 6.1) and emissions (figure 6.2).

It's a cliché about society's problems that "the problem isn't lack of technology, it's institutional" (or behavioral). Not so in this case. The critical lack has been accurate emissions-measurement instrumentation. Although a start was made in the '70s to create adequate information technology, instrumentation R&D was largely neglected in the '80s (an exception being Prof. Donald Stedman's development of remote sensing). A decade was lost. Now in the mid '90s, primarily as a result of Clean Air Act Amendments of 1990 and initiatives in California, the needed information and technology is beginning to be available. We should have really adequate information technology by the end of the decade.

Emissions ratings of vehicles as determined in the FTP have been a major source of mischief, or confusion, for the two reasons that are the focus of this report: 1) the importance of emissions from off-cycle driving, and 2) the importance of vehicles with malfunctioning emission-control-systems (ECS). As shown in this report, driving at relatively high power is important for emissions and is not represented in the FTP cycles. As a result of requirements in the Clean Air Act Amendments of 1990, a substantial

Figure 6.2. Distribution of lifetime average emissions for a typical car model



supplement to the FTP has just been proposed by EPA to remedy this defect. The emissions-certification process also includes a durability test for ECS degradation and follow-up tests of cars in-use; but the way these tests are designed and administered they have failed to find that some vehicle models are malfunction prone — with major emissions consequences.

It is not surprising that emissions tests designed in the '70s, prior to extensive experience with modern ECS, fail to accurately sample enough of the emission-related experience of vehicles in the real world. What is not satisfactory was the delay in the development of instrumentation and in research on emissions. Congress, the regulators, the industry and the environmental groups should have recognized this instrumentation and information need.

It should be known that any major regulatory initiative will need improvement. Certainly that pattern is established here with Clean Air Act Amendments in 1970, 1977 and 1990. The lesson is that regulatory initiatives must be backed by R&D on information technology and by programs of measurement and analysis. Moreover, the citizen groups which help to pass such legislation should not regard its passage as the time to declare victory and turn away to other projects. They need to participate, for the long haul, in the continuing technical and institutional issues that underlie the potential success of a regulatory initiative.

These comments do not mean that regulations must become more complicated in response to the increased information we call for. Alternative forms of achieving regulatory goals, that are based on real world-performance and are simpler, *are only feasible with good instrumentation of reasonable cost.* If real-world emissions could be adequately sampled through surveys with remote sensors or with on-board equipment (with acceptable accuracy and cost), then emissions compliance by manufacturers might be based on actual in-use performance rather than new vehicle tests. This might enable simpler regulations. The instrumentation is not yet sufficiently developed to consider this application.

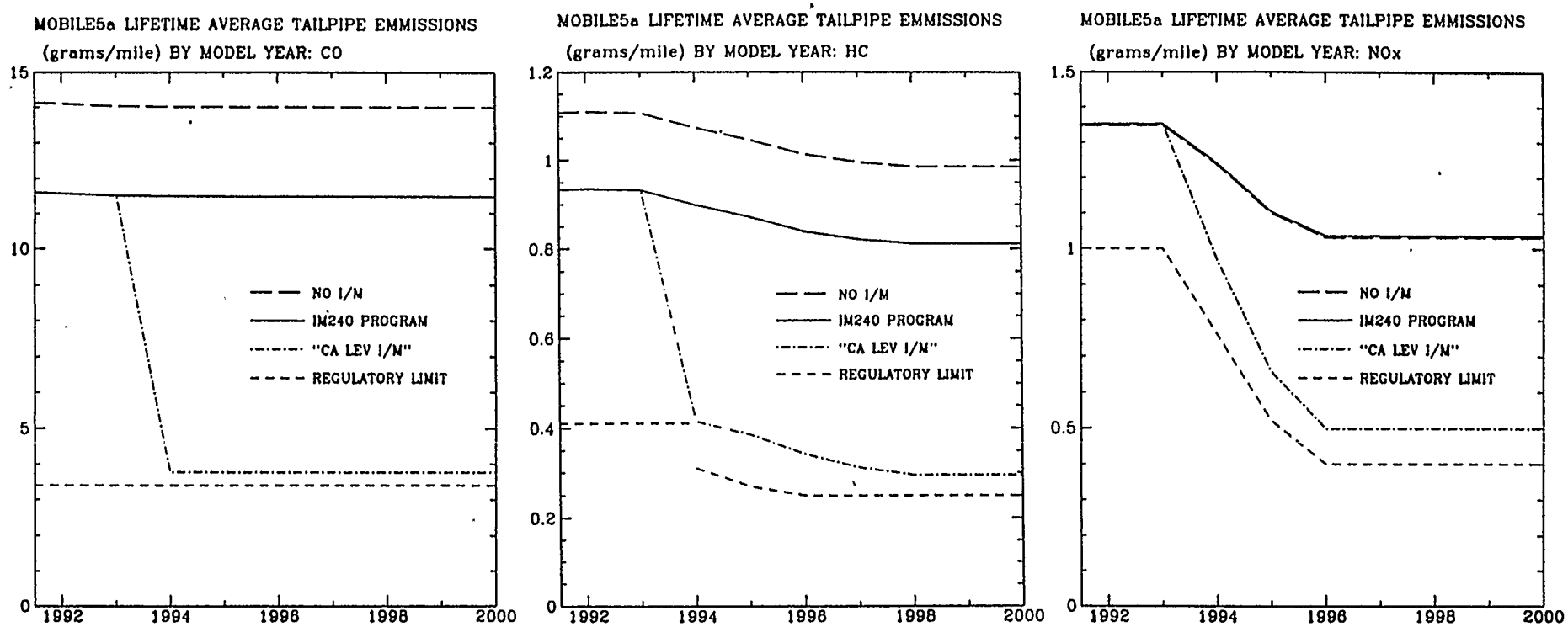
6.2. MOBILE and EMFAC

A great deal of work lies behind the current versions of these emission-factor models designed for regional air quality planning purposes. In their latest versions, MOBILE and EMFAC represent fairly accurately the total emissions of average vehicles in average driving. For example, the independent analysis of remote sensing and other data in this report for CO and HC emissions is roughly consistent with MOBILE5a predictions for 1993 cars. (We are not able to verify the NO_X prediction, however.)

The concern we have is that these models can be misleading about the future. They are not adequately organized according to the physical sources of emissions. Instead, future scenarios are simplistic, although nominally under user control. MOBILE5a offers users unconvincing stories for inspection and maintenance programs. In figure 6.3 three MOBILE5a forecasts are shown: with and without an I&M 240 program, and with an I&M program described as associated with the California LEV program, in which all malfunctions disappear! We believe the two I&M-program forecasts, with their large benefits, to be misleading.

It *is* reasonable to argue, as we have here, that when production vehicles are introduced that are designed to meet stricter certification test standards, such as the LEV, or even ULEV, standards, they will pass the certification tests. If the manufacturers' experts are given a high priority to design and produce vehicles that pass the proposed laboratory tests, the technology and manufacturing skills are there, at reasonable cost in most cases, to do it.

Figure 6.3. MOBILE5a predictions for three regulatory scenarios



On the other hand, it is not reasonable to argue that vehicles will simply become robust against ECS failures, and even more unbelievable, that it can become the norm that vehicles with such failures are effectively repaired (as discussed further in 6.3 below). (Although we disagree with the optimism about reducing malfunction emissions for the near term, for the longer term we project that remote sensing and OBD should lead — through a process in which information forces technical and institutional improvement — to major reductions in malfunction emissions.) The lesson is that users of these emission-factor models must be aware that the modeling of the future is formal, not realistic.

6.3. Inspection and Maintenance Programs (I&M).

The manufacturers' legal responsibility for the robustness of emissions controls *applies only to vehicles that have been "properly maintained and used."* (The laboratory-like 50,000-mile durability tests may help to reduce some ECS failures, but there is no evidence on the point.) Instead of policies aimed at the design and manufacture of vehicle models with more-robust ECS, the current regulatory focus is identifying and repairing *individual vehicles* with emissions. This focus on individual vehicles is based on two assumptions: 1) most ECS failures are fundamentally caused by the individual user or the individual mechanic; and 2) essentially all malfunctioning cars can be repaired effectively and at a moderate price. We strongly question these assumptions.

Our results show that the frequency of ECS failure is strongly dependent on vehicle model. Figure 5.1, above, shows that the average fuel-injected model studied, at average vehicle age about 3.5 years, has a frequency of ECS failure of 7.4%; but that models in the top quartile have an average failure frequency of only 2.6%, and in the top half a failure frequency of only 4%. This shows that, fundamentally, individual owner/drivers and mechanics are not responsible for most of the failures. Instead, vehicle models with unsatisfactory design or quality control are responsible, and also, possibly, vehicle models characterized by unsatisfactory service arrangements. *We must set aside the notion that "tampering" or other abuse by owners/drivers/mechanics is the root cause of ECS failures in current-technology vehicles*, even if it may have been in the day of simple control systems, carburetors, cheap leaded gasoline, and pervasive use of air pumps in the exhaust line.

In addition, we believe that widespread effective repair of failed ECS as the norm is inconceivable as a near-term possibility. There are no near-term programs that offer hope for effective repairs for *most* vehicles. The achievement of widespread effectiveness in repairing ECS will be truly difficult. The problems of many jurisdictions, a diffuse service industry with tens of thousands of repair organizations, and high-tech repair work which often must be done without immediate feedback, are well known.

[Immediate feedback is often lacking because ECS are complicated and because it's hard to measure emissions accurately. An interesting analog is found in the buildings sector, in, e.g., the quality of installing insulation vs that of installing floor tile. The workman installing insulation often doesn't know if he's done a good job, and neither does the customer; a poor job is often done. With floor tile, both can easily see if the job is good, at least on the surface, and therefore a good job is usually done. With the improvements now coming in instrumentation (remote sensing, OBD, and possibly low-cost on-board measurement of actual emissions), it would be possible to improve on this lack of feedback; but it would take many years.]

Improving the inspection part of I&M, including separating inspection from maintenance facilities, does not hold much promise for widespread effective repairs. Moreover, EPA's inspection programs, either existing or enhanced, will probably not be justified for modern vehicles, in competition with the new identification technologies.

6.4. Remote Sensing and OBD Technologies; As-Received Dynamometer Surveys

One of the most important changes in the arena of automotive emissions is the development of new technology for identifying malfunctions in emissions controls. Not only do these new technologies promise to leave inspection (smog-check) programs behind, the information beginning to be gathered is changing our fundamental perception of the problem and of the means to reduce it.

As just discussed, remote-sensing data shows that most ECS failures strongly correlate with vehicle model, and are thus fundamentally the responsibility of the manufacturer (at least for vehicles 2 to 5 years old). Apparently, better design and manufacture yield vehicles with much less frequent ECS malfunctions. Much larger surveys than that analyzed here, using improved remote sensing instrumentation, are already being undertaken. These should be able to unambiguously identify most vehicle models with excessive frequencies of high emitters. (We have discussed elsewhere the distinction between remote-sensing data accurate enough for the task here of evaluating vehicle models from the more-demanding task of identifying individual vehicles in need of repair — section 5.5 and Appendix B section 5.) For something effective to be done, regulatory agencies would have to overcome their reluctance to identify models with high frequency of ECS malfunction. This may require changing the wording that only holds manufacturers responsible for vehicles "properly maintained and used." Another option is to verify the identification of malfunction-prone models by testing in-use vehicles on dynamometers, using procedures designed to identify models with high probability of malfunctioning ECS, like CARB's "as-received" survey. Because of the small number of vehicles measured in dynamometer surveys, to be effective, well-designed surveys would be needed.

Unfortunately these identifications will be made perhaps three or more years after a model year was manufactured. Nevertheless, through recall or warranty mechanisms, or simply as a result of the information becoming public, manufacturers will be motivated and should be able, especially with the aid of OBD, to identify the flaws involved. Such flaws should then be avoidable in future models, as well as being partially corrected in existing vehicles through well-designed recalls. The data show that most manufacturers, probably all, already meet excellent standards for ECS robustness in some of their MY87-89 vehicles.

Much of the attention given to the new identification technologies has been directed at schemes for repair/enforcement; that is, to notifying people that their vehicle's ECS needs repair, combined with some kind of enforcement to try to achieve successful repairs. We are skeptical about the effectiveness of any such system based on individual vehicle identification, as compared with identifying problems with models and addressing them specifically. On the other hand, OBD and other instrumentation is clearly promising for improving the capabilities of repair work. Such programs based on identification of individual vehicles for repair, based on OBD, could be tried out in limited jurisdictions.

A more important option in our view is the creation of recall/warranty programs to address vehicle models with excessive frequencies of high emitters.

6.5. A Recall Program for Excessive ECS Malfunctions

Manufacturers contend with an enormous variety of concerns in successfully designing, manufacturing and selling vehicles. Although they prefer to make cleaner vehicles, and have ongoing efforts directed towards this, their environmental priorities are, to a large extent, set by regulators. In our view, the regulators' priorities have not been well-chosen in some important aspects of automotive emissions. In our view, I&M and enforcement aimed at the individual should receive lower priority. Robustness of ECS should receive high priority — where it now has essentially none. Along with this it

is essential that more research be carried out to enhance the accuracy of real-world measurement of the incidence of ECS malfunctions.

As far as ECS robustness is concerned, the regulatory change we propose is that, after a suitable period to develop the needed instrumentation and information, a vehicle recall program be established based on excessive frequency of ECS failure as demonstrated by real-world emissions. In particular, large-scale surveys using remote sensing with up-graded technology could be used, perhaps on the scale the recent survey by the California Bureau of Automotive Repair in the Sacramento area. In terms of our analysis of a 1991 remote-sensing survey, we conclude that the approximately 90,000 observations was adequate for analysis of about 35 car models, or 75 MY/models in MYs 87-89. With one or two million observations, all popular models/engine families would be adequately tested. One would want better remote sensing technology than used in 1991; and the technology is being substantially improved.

For purposes of illustration, consider a regulatory standard in terms of the 1991 remote-sensing results. One might start with a standard based on the best one-half of the MY87-89 fuel-injected models, i.e. that models experiencing more than 7% ECS malfunction frequency be subject to recall. (For CO, a 1.0% concentration remote sensing cutpoint, or a 10 g/mile FTP-bag 2 cutpoint could be used.) Later one might establish a stricter standard roughly corresponding to the top quartile of MY87-89 vehicles, and define models with excessive malfunctions as those having more than, say, 3% malfunctioning vehicles.

We suggest that such a recall program be introduced first in California. We also suggest that the I&M and ULEV programs be reviewed, in the interest of regulatory balance.

6.6. Emissions and Fuel Economy

Emissions rates (g/mile) are commonly thought to be uncorrelated with fuel economy. After all, the allowed emissions rates do not depend on fuel economy. (In Europe, they have depended on engine size, with larger engines allowed higher emissions. This encourages manufacturers to use better emissions controls on high fuel economy vehicles, often a cost effective option for society.) However, when emissions controls are shut off or fail, then tailpipe emissions tend to follow fuel use, since the engine-out emissions are roughly proportional to fuel use. (See sections A.1 and A.4.)

Evaporative and upstream emissions are also essentially proportional to fuel use (DeLucchi et al. 1994), so, although tailpipe emissions from properly-functioning vehicles in moderate driving tend to be related to regulatory limits, most of the real-world emissions are roughly proportional to fuel use. This is a broad generalization; specific changes in technology may tend to increase or decrease the off-cycle or malfunction emissions discussed in this report. Nevertheless, policies that encourage large improvements in fuel economy, such as the Partnership for a New Generation of Vehicles (PNGV), are also likely to have the benefit of greatly reduced real-world pollution.

The PNGV has a goal of up to a factor of three increase in fuel economy. Success in developing a gasoline- or diesel-based vehicle with a factor of three increase in fuel economy might well also involve reduction by a factor of three in the corresponding real-world emissions, compared to MY93 cars. Our reasoning on this is preliminary; but it is that the vehicle would be designed to meet a tough certification standard for tailpipe emissions. Whatever this would be, the vehicle's off-cycle, malfunction, evaporative and upstream emissions would probably be lower in rough proportion to its fuel consumption. If such a vehicle were based on another, "cleaner" form of energy, then its real-world emissions would probably be smaller still.

There is another important connection between emissions and fuel economy. Stringent regulation of NO_X emissions in the certification tests (as with Tier 2 and LEV standards) may not only be a relatively ineffective policy — in terms of the regulatory loopholes discussed in this report — but might also prevent development work on a variety of lean-burn engines which have promise for high fuel economy and, perhaps, good real-world emissions, even though their test emissions of NO_X are not very low with current technology. Modern direct-injection diesels, new direct injection stratified charge (DISC) spark-ignition engines (Yamaguchi 1995) and fuel-injected two-stroke engines are all of considerable interest, although the performance capabilities of mature versions remain to be seen. These standards and the way they are implemented should be carefully thought out; it would be a mistake to stifle this engine-development work in the US for minor regulatory objectives.

6.7. An Emissions-Reduction Strategy for the Manufacturers

What kind of alternative to the burgeoning variety of federal and state regulatory initiatives might the manufacturers offer? The results of this study suggest that the manufacturers should make a commitment to sharply reduce *real-world emissions*, i.e. emissions from malfunctions and off-cycle driving, in addition to meeting reasonable standards in conventional certification tests.

This commitment *should address the actual emissions performance of the fleet, as determined by a statistically sound procedure for surveying emissions from vehicles in the real world.* While it is not obvious what procedure should be used, with the advent of highly-sophisticated remote sensing, OBD instrumentation, inexpensive direct on-board measurement of emissions, and new evaporation instrumentation, the research community should be able to suggest a sound cost-effective methodology. The manufacturers could commit to: 1) certification-test emissions they feel are appropriate, 2) elimination of off-cycle emissions at roughly the level indicated by the Proposed Rule Making (60 FR 7407), 3) participation in large surveys to identify rates of ECS malfunction, 4) more than 50% reductions in the incidence of ECS-failures observed in present vehicles, and 5) enhanced capability for effective repairs. The results of this report suggest that these commitments would be achievable with reasonable effort.

On the basis of the analysis in this report, these achievements would reduce real-world automotive emissions by more than one-half from their present level. In our opinion, an offer to make that much further progress would merit very serious consideration.

7. Acknowledgments

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Technical Appendices

A. The Sources of Excess Emissions, a Quantitative Assessment for Model Year 1993 Cars

Measurements showing that real-world motor vehicle emissions far exceed regulatory levels are many and varied. There are dynamometer tests of "in-use" vehicles recruited from the smog check lane in Hammond, Indiana, sampling of air along and above highways (Hlavinka, et al. 1988; Zweidinger, et al. 1988), measurements of pollutant concentrations in tunnels in Los Angeles and on the Pennsylvania Turnpike (Pierson et al. 1990; Gertler 1994), remote sensing of the composition of air behind vehicles (Bishop et al. 1990; Naghavi et al. 1993), and computer modeling of observed ambient air quality (Harley et al. 1993). There are problems of interpretation with all of this information; however, careful evaluation over the years has led to regulatory models of emissions "inventories", MOBILE5a and EMFAC7F, which appear to describe total average emissions per mile by light-duty vehicles with fair accuracy.

These total "real-world" emissions rates for model year (MY) 93 cars, according to MOBILE5a, are shown in table A.1 (USEPA 1994b). These are lifetime (winter and summer) averages, for CO, and for HC and NO_X. The temperatures chosen are appropriate to the Northeastern states. Note that the CO and HC emissions rates are about five times the 1993 tailpipe regulatory maxima of 3.4 and 0.41 grams-per-mile (g/mile), respectively; while the NO_X emissions are somewhat higher than the regulation 1.0 g/mile.

Our focus is average g/mile emissions from a given MY over its lifetime. Our approach is to analyze the emissions in terms of their physical sources.

The well-established sources of emissions are:

1) properly-functioning warmed-up (hot-stabilized) cars in moderate on-cycle driving (on-cycle means driving that is represented in the FTP),

2) cold start for cars with properly-functioning emissions controls,

3) evaporation from the vehicle, including malfunctioning evaporation controls,

4) off-cycle operations with properly-functioning emissions controls (off-cycle is driving behavior, conditions or loads that are not represented in the FTP — we focus on off-cycle driving that involves higher power than represented in the FTP),

Table A.1. MOBILE5a lifetime average (for summer and winter†) g/mile emissions, MY93 cars

Criteria pollutants	MOBILE5a	Tailpipe Standard
CO	19	3.4
HC, tailpipe	1.4	0.41
HC, evaporation	0.5	
NO_X	1.5	1.0

†) MOBILE5a assumptions: RVP = 9.0; winter temperatures: daily high = 37°F, low = 22°F; summer temperatures: daily high = 86°F, low = 68°F.

5) malfunctioning emissions control systems (ECS) affecting tailpipe emissions, and

6) upstream emissions (from fuel extraction, transportation, refining and distribution).

All are exhaust emissions except (3) and (6).

The estimates of emissions from these sources, made below, serve two purposes: to establish a base line for projections to future vehicles, and to establish a source structure in order to help evaluate the effects of new tests/regulations and new technology.

Part of the total average exhaust emissions is due to on-cycle driving and part due to off-cycle; some is from properly-functioning cars and some from malfunctioning cars. How are the emissions rates for these different modes to be combined? Consider mode i, for which the average tailpipe emissions rate in g/s is $TP_{g/s}^{i}$, and time and length of trip are t_i seconds and x_i miles, respectively. The total average per-mile emissions summing over modes, $TP_{g/mile}$ in g/mile, is:

$$TP_{g/mile} = \left[\sum_i TP_{g/s}^{i} \cdot t_i\right] \Big/ \sum_i x_i = \sum TP_{g/mile}^{i} \cdot (x_i/x).$$

Here

$$TP_{g/mile}^{i} = TP_{g/s}^{i} \cdot (3600/v_i)$$

is the tailpipe emission for mode i in g/mile, $v_i/3600$ is $x_i/(t_i \times 3600)$ — vehicle speed in mph, and x is the total distance, Σx_i. Thus the emissions per unit distance for each mode, $TP_{g/mile}^{i}$, are combined using the distance weights x_i/x as *illustrated* in the following table. The distance weight is the fraction by distance of driving in each mode. In this table and the next, TP_i refers to tailpipe g/mile emissions in mode i.

Mode, i	Distance weight, x_i/x	Tailpipe emissions in mode i, TP_i	Contribution of mode i to average emissions
(1) Properly-functioning cars, on-cycle	0.87	TP_1	$0.87 \times TP_1$
(2) Properly-functioning cars, off-cycle	0.05	TP_2	$0.05 \times TP_2$
(3) Malfunctioning cars, on-cycle	0.08	TP_3	$0.08 \times TP_3$
Total	1.0		$0.87 \times TP_1 + 0.05 \times TP_2 + 0.08 \times TP_3$

An alternative way of viewing the contribution of the various sources to total average exhaust emissions is to start with a base emissions rate and to calculate the additional incremental emissions rates due to the other modes. In this method, all driving modes have a base emission rate equivalent to the on-cycle emissions from properly-functioning cars, so that this mode has a distance-weight of 1.0. Then, the additional, incremental emissions due to mode i is the distance weight for mode i times the difference between the tailpipe emissions rate in mode i and the tailpipe emissions rate for on-cycle driving, properly-functioning cars. The total average exhaust emissions rate is the same for both methods, as is illustrated in the following table. We choose the incremental emissions approach for presenting our results in this report.

Mode, i	Distance weight, x_i/x	Incremental tailpipe emissions in mode i, TP_i	Incremental contribution of mode i to average emissions
(1) Properly-functioning cars, on-cycle	1.0	TP_1	$1.0 \times TP_1$
(2) Properly-functioning cars, off-cycle	0.05	$TP_2 - TP_1$	$0.05 \times (TP_2 - TP_1)$
(3) Malfunctioning cars, on-cycle	0.08	$TP_3 - TP_1$	$0.08 \times (TP_3 - TP_1)$
Total	>1.0		$0.87 \times TP_1 + 0.05 \times TP_2 + 0.08 \times TP_3$

The estimated contributions of the six sources to the overall average g/mile emissions during an average MY93 car's life are summarized in table A.2. All the sources are seen to be important, at least for some emissions. The malfunction emissions are generally the largest; unfortunately the malfunction contributions are also rather uncertain.

A.1. On-Cycle Emissions of Hot Properly-Functioning Cars

The manufacturers determine the g/mile emissions for CO, HC and NO_X in each bag of the FTP (section 2.3), multiply these values by distance-weight factors (table A.3), and add them together to compare to the standards, and these results are checked by the EPA (40 CFR 86.144-94). For example, the frequency of cold starts assumed in the analysis behind the FTP is equivalent to assigning 20.7% of miles driven to the cold start bag.

Table A.2. Sources of emissions (g/mile) for an average MY93 car, over vehicle life[a]

Source[b]	CO	HC	NO_X
1) Hot, On-Cycle[c]	0.983	0.090	0.201
2a) 70°F summer cold start[c]	0.663	0.071	0.070
2b) 20°F winter cold start[c]	1.658	0.178	0.091
Subtotal	3.304	0.339	0.362
3) Evaporation[d]	0	0.5	0
4) Off-cycle[c]	7.9	0.12	0.3
5) Malfunction	6	0.6	0.8[e]
6) Upstream	0.063	0.098	0.315
Total	17	1.7	1.8
1993 tailpipe standard	3.4	0.41	1.0

a) The sources are weighted so that the average per-car emissions are shown. See the discussion of distance-weighted incremental emissions above.
b) All are exhaust emissions except (3) and (6).
c) Properly-functioning cars.
d) MOBILE 5a estimate.
e) The NO_X malfunction estimate is simply the difference between the total exhaust NO_X emissions estimated by MOBILE5a, 1.5 g/mile, and our estimate of sources (1)+(2a)+(2b)+(4).

Table A.3. Regulatory (FTP) distance-weights for hot and cold driving

	Bag 1 Cold Start	Bag 2 Stabilized	Bag 3 Hot Start
Time (sec)	505	866	505
Distance (miles)	3.59	3.86	3.59
Distance-weight	0.207	0.518	0.275

The emission rates shown in the first two rows of table A.2 are obtained from FTP bag data for 16 1991-1993 MY (Tier Zero) cars aged to roughly halfway through their useful lives under laboratory conditions in the FTP-RP. The average g/mile rates for CO, HC and NO_X for each bag (table A.4) are multiplied by the appropriate distance-weights (table A.5). The weighted average bags 2 and 3 are combined and entered in the first row of table A.2 — hot, moderate driving.

Emissions as the product of three factors. We now dissect the exhaust emission rates into physically-based factors, to help develop an understanding of potentials for change. The tailpipe emissions in grams per second ($TP_{g/s}$) are the product of three factors:

$$TP_{g/s} = FR \cdot EI \cdot CPF \qquad (A1)$$

Table A.4. FTP bag data for Tier Zero cars in the FTP-RP (g/mile)

	Bag 1		Bag 2		Bag 3	
	Avg.	St. Dev.	Avg.	St. Dev.	Avg.	St. Dev.
CO	6.404	2.017	1.124	1.037	1.459	0.826
HC	0.684	0.193	0.090	0.054	0.157	0.083
NO_X	0.675	0.231	0.212	0.189	0.332	0.241

The fuel rate (FR) is in g/s. The emissions index (EI) is the dimensionless ratio of g/s of engine-out pollutant to g/s of fuel use. The catalyst pass fraction (CPF) is also dimensionless, pollutant out (g/s) to pollutant in (g/s).

Estimates of these factors are shown in table A.6 for FTP bag 2 type driving. These are for an average 1991-1993 passenger car. (The FTP-RP data on which the table is based involves vehicles in excellent condition but with most catalysts aged on engine-dynamometers to 50,000 miles.)

Table A.5. FTP distance-weighted bag data (g/mile)

	(1) Bag 1	(2) Bag 2	(3) Bag 3	(4) =(2)+(3)	(5) FTP Total	(6) 1993 Standard
CO	1.326	0.582	0.401	0.983	2.31	3.4
HC	0.142	0.047	0.043	0.090	0.23	0.41
NO_X	0.140	0.110	0.091	0.201	0.34	1.0

Table A.6. Estimates of the three factors in equation (A1) for warmed up, FTP (bag 2) style driving

	(1) FR	(2) EI	(3) CPF	(4) EI *x* CPF	(5) $TP_{g/s}$	(6) $TP_{g/mile}$
CO	0.602	0.095	0.074	0.00703	0.00423	0.948
HC	0.602	0.025	0.032	0.00080	0.00048	0.108
NO_x[a]	0.684	0.013	0.179	0.00233	0.00159	0.356
NO_x[b]	0.493	0.033	0.052	0.00172	0.00085	0.190

a) Cars in the FTP-RP equipped with EGR.
b) Cars in the FTP-RP without EGR.

The tailpipe emissions in table A.6, column (5), are converted into g/mile (column(6)) from g/s by multiplying by 224 seconds-per-mile (i.e. 866 seconds/3.86 miles in the FTP bag 2 — see table A.3).

The factors in table A.6 are obtained as follows:

1) The fuel rate (FR) is the average over the cars in the FTP-RP during bag 2 of the FTP.

2) The engine-out emissions index (EI) is taken from the FTP-RP data (table A.7). Shown are the ratios of total engine-out emissions to total fuel use over bag 2 of the FTP. As will be discussed in section 4 immediately below, the average emissions index is not highly sensitive to the driving, or fuel use, in moderate driving, except, perhaps, for NO_X.

   In on-cycle stoichiometric operations, the air-fuel ratio varies slightly and the CO emissions index varies from second to second; however the average emissions index yields adequate results.

   For HC, the steady-state emissions index tends to be somewhat smaller than these averages based on total emissions over the cycle, because driving transients cause puffs of HC with some cars. These puffs considerably increase total engine-out HC emissions in variable-speed driving with these cars, particularly with manual transmissions.

   The NO_X rates vary considerably in the FTP-RP data, depending particularly on the use of EGR (see figure A.1). For this reason, the average engine-out NO_X emissions index is calculated separately for cars with and without EGR.

3) The stoichiometric catalyst pass fractions are estimates based on the FTP-RP data; they are extremely sensitive to the vehicle (for example, see figure A.1). The average NO_X catalyst pass fraction is calculated separately for cars with and without EGR in the FTP-RP data and the results are shown in table A.7.

Notes of caution on accuracy. There are two general reasons for being uneasy about the results

Table A.7. Hot, stabilized (FTP bag 2) emission factors for Tier Zero cars in the FTP-RP

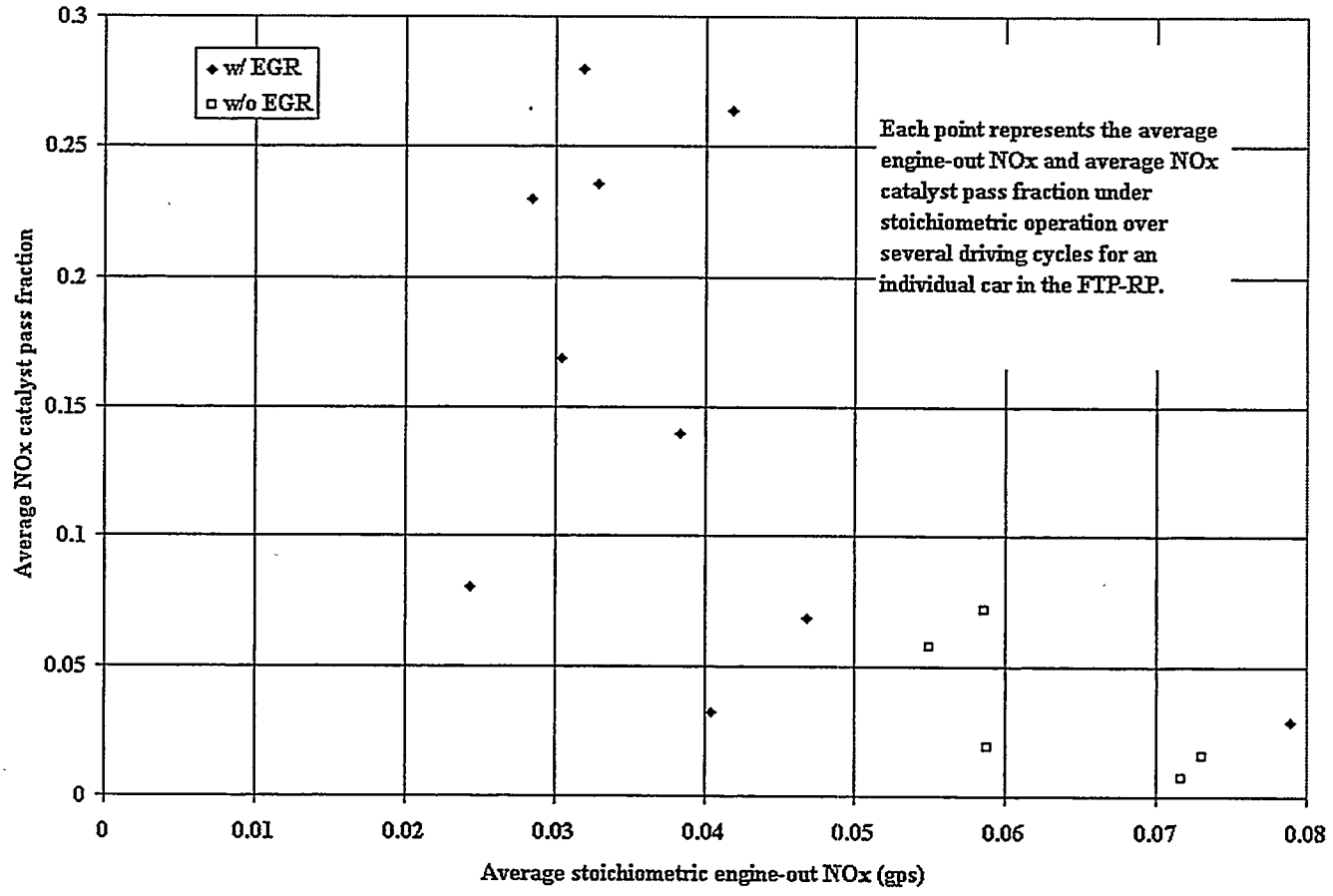
		CO		HC		NO_X with EGR			NO_X without EGR		
	FR	EI	CPF	EI	CPF	FR	EI	CPF	FR	EI	CPF
Avg.	0.602	0.095	0.074	0.025	0.032	0.684	0.013	0.179	0.493	0.033	0.052
St. Dev.	0.151	0.021	0.047	0.015	0.026	0.151	0.007	0.154	0.046	0.005	0.029

obtained here for on-cycle driving of properly functioning cars: 1) The bag weights shown in table A.3 and used in table A.5 correspond to the frequency of cold and hot starts per mile of driving. New data, including the driving behavior survey based on instrumented vehicles which is analyzed in this report, suggests that average trips are shorter, so starts are more frequent. We have, however, not studied the question of how much engine and catalyst cooling occurs with various parking times at various ambient temperatures, and so feel not prepared to evaluate such corrections. We do not believe this issue is important to our overall results.

The second issue may be more serious. A variety of arguments and measurements suggest that typical properly-functioning cars pollute more (as measured in the same dynamometer tests) than observed in the FTP-RP data with its relatively clean vehicles. In mid-life, typical engines have deposits on the cylinder walls; their valves are not like new; and the catalytic converters have probably deteriorated more than the laboratory-aged catalysts installed in the FTP-RP cars. Unfortunately, any quantitative assessment of the emissions associated with this additional deterioration depends on the distinction made between malfunctioning and properly-functioning cars, and this distinction is somewhat arbitrary at present.

We examine two data sets which bear on this issue: remote sensing data on model year 87-89 cars as observed in 1991, and FTP bag data for a similar group of in-use cars tested "as-received" (see section A.5). They suggest that the emissions of properly-functioning cars in hot-stabilized driving are over 2

Figure A.1. Average NO_X catalyst pass fraction vs average engine-out NO_X for cars in the FTP-RP



times greater than those measured in the FTP-RP for CO, only slightly greater for HC and about two times greater for NO_X. (The effect of deterioration on cold start emissions is much less, because most cold-start emissions occur during the initial period when the engine is running rich and the catalyst is not converting pollutants.) This factor of two may overstate the effect however. It is uncertain because it depends on the selection of a boundary between deteriorated and malfunctioning emissions control systems, and because the cars studied are several years older than those in the FTP-RP measurements.

While a factor of two would be a substantial correction to the hot on-cycle emissions of table 1, an extra 1 g/mile CO would not be large compared to the totals. We do not include this correction in our final results.

A.2. Cold Start Emissions of Properly-Functioning Cars

Emissions are relatively high when a cold vehicle is started because there are two stages without the benefit of substantial emissions control: First, for purposes of drivability, the fuel-air mixture is commanded to be rich, for, perhaps, half a minute, depending on ambient temperature. Second, it takes two or three minutes for the catalytic converter in the exhaust stream to warm up to the point that it is converting pollutants. These times are shorter when the ambient temperature is high, and longer when the ambient temperature is low. For model years before MY94, there was no regulatory motivation to limit cold start emissions at ambient temperatures well below 70°F. Starting with MY94 cars must meet modified CO standards for a 20°F cold start test.

Command enrichment of the fuel-air mixture (in the first stage of a cold start) leads to extremely high CO emissions, because the engine-out emissions index and the catalyst pass fraction both increase for CO. Moreover, the time of this first stage is sensitive to the ambient temperature. As a result, CO emissions have been very high in cold start at low ambient temperatures, creating serious winter air quality conditions in several metropolitan areas.

Dissecting the 70°F cold start. We can estimate the components of the 70°F cold start (FTP bag 1) CO emissions from the FTP-RP data. The average time for the first stage, enrichment, of the 70°F cold start for cars in the FTP-RP is 33 seconds and the average air/fuel ratio during this time is 13.0. Predicting the average engine-out CO from figure A.2 (0.48 grams CO per gram of fuel), taking the catalyst pass fraction to be 1, and the fuel rate to be 0.9 g/s, we obtain:

First stage: $33 \cdot 0.48 \cdot 1 \cdot 0.9 = 14$ grams CO.

For the second stage, catalyst light-off, the average time before catalyst light-off from the start of the test cycle is 115 seconds, the average catalyst pass fraction during this time is 0.9, and the CO/fuel ratio is 0.095 (table A.7) while the average stoichiometric fuel rate is 0.8 g/s. We obtain the emissions:

Second stage: $(115-33) \cdot 0.095 \cdot 0.9 \cdot 0.8 = 6$ grams CO.

For the third stage, the remainder of the 505 seconds of the cold start test (bag 1 of the FTP), when the air-fuel ratio is stoichiometric and the catalyst has reached light-off temperatures, we obtain:

Third stage: $(505-115) \cdot 0.095 \cdot 0.074 \cdot 0.8 = 2$ grams CO.

The total of the three stages is 22 g. Dividing 22 g by 3.6 miles, the distance driven in bag 1, we obtain 6.1 g/mile, consistent with column 1 of table A.5.

This same three-stage cold start analysis may also be applied to HC emissions. The engine-out emissions index of HC is approximated as 0.025 (table A.7) regardless of air-fuel ratio, so that the first 33 seconds of enrichment with a catalyst pass fraction of 1 yields:

First stage: $33 \cdot 0.025 \cdot 1 \cdot 0.9 = 0.74$ grams HC.

For the second stage, catalyst light-off, the average time before catalyst light-off from the start of the test cycle is 115 seconds, the average catalyst pass fraction during this time is taken to be 0.9, while the average stoichiometric fuel rate is 0.8 g/s. We obtain the emissions:

Second stage: $(115-33) \cdot 0.025 \cdot 0.9 \cdot 0.8 = 1.5$ grams HC.

For the third stage, the remainder of the 505 seconds of the cold start test (bag 1 of the FTP), when the air-fuel ratio is stoichiometric and the catalyst has reached light-off temperatures, we obtain:

Third stage: $(505-115) \cdot 0.025 \cdot 0.032 \cdot 0.8 = 0.25$ grams HC.

The total of the three stages is 2.5 g HC. Dividing 2.5 g by 3.6 miles, the distance driven in bag 1, we obtain 0.69 g/mile, consistent with column 1 of table A.5.

The 20°F cold start. Here, the key fact is that for CO the first or enrichment stage dominates, even at 70°F, which explains the sensitivity of cold start CO emissions to ambient temperature in cars up to this time. The cause of increased HC during cold starts is predominantly the time during which the catalyst is too cold to be effective. Unfortunately, we cannot provide estimates of the 20°F emissions in detail because we do not have data on the time and degree of enrichment in current vehicles at low ambient temperatures. A study was performed, however, for two modern European cars by Laurikko and Nylund (1993) indicating that the catalyst took three times longer to light-off for tests performed at -6°F than at the standard 70°F — this effect alone (without considering longer or more severe cold start enrichment) would roughly double the cold start CO and triple the cold start HC emissions at -6°F compared to 70°F.

The numbers in row (2) of table A.2 are constructed from FTP cold start bag 1 data in the FTP-RP database. The temperature of the FTP cold start is about 70°F, representative of a summertime cold start, but we also want to predict average emissions for winter conditions in the Northeast states. We therefore assume that half the lifetime cold starts occur in winter and half in summer, and we estimate the winter cold start emissions by applying scaling factors to the summer average cold start emissions. The CO and HC entries are calculated as follows:

$$\text{TPCO}_{\text{g/mile}} \text{ cold start @ } 20°\text{F} = 2.5 \cdot \left(\text{TPCO}_{\text{g/mile}} \text{ cold start @ } 70°\text{F}\right)$$

$$\text{TPHC}_{\text{g/mile}} \text{ cold start @ } 20°\text{F} = 2.5 \cdot \left(\text{TPHC}_{\text{g/mile}} \text{ cold start @ } 70°\text{F}\right).$$

Physically, the factor of 2.5 represents the increase in CO and HC emissions in wintertime cold starts due to longer periods of start-up enrichment and longer times until catalyst light-off (this factor is adopted from MOBILE5a predictions).

A similar formula is used for NO_X, except that the wintertime factor from MOBILE5a is 1.3, due essentially to the longer times until light-off.

$$\text{TPNOx}_{\text{g/mile}} \text{ cold start @ } 20°\text{F} = 1.3 \cdot \left(\text{TPNOx}_{\text{g/mile}} \text{ cold start @ } 70°\text{F}\right).$$

An important issue not addressed in this analysis is the probability that in the real world there are more-frequent cold starts per mile of driving than in the FTP (i.e. a greater distance weight for bag 1 in table A.3).

A.3. Evaporation

There are several sources of evaporative emissions: 1) diurnal emissions, the vapors that escape from a vehicle fuel tank due to expansion and contraction of fuel and vapors, caused by temperature changes over the course of a day. 2) Hot soak emissions, the evaporation from a vehicle fuel tank and system at the end of a trip due to the build-up of heat in the tank during vehicle operation. 3) Running losses, the evaporative emissions from a vehicle fuel system during vehicle operation. During operation, fuel evaporates because of heat transfer from engine compartments and exhaust system to the fuel system. 4) Resting losses, the emissions from vehicle fuel systems occur via vapor permeation into non-metallic components and vapor migration allowed by the evaporative control system (e.g. via open-bottom canisters). In addition, there are refueling emissions, vapors that escape from the vehicle fuel tank due to displacement of vapor in the tank by gasoline during refueling.

The estimate of evaporative emissions shown in table A.2 is from MOBILE5a. It includes malfunctions in evaporative emissions control such as leaks or holes in the fuel system. (An investigation of these malfunctions is briefly reviewed in section 5.3.) The temperatures and RVP assumed are for the Northeast states and are shown in the note to table A.1.

A.4. Off-Cycle Operations of Properly-Functioning Cars, High and Moderate Power Driving

Present-day vehicles incorporate an emissions control system in order to meet the stringent emissions standards based on the FTP. The heart of the system is a three-way catalytic converter in the exhaust line. To be effective the catalyst must be hot and the fuel-air mixture must be stoichiometric. Under certain conditions, command enrichment occurs: the emissions control system is overridden and the fuel-air ratio is increased. As discussed just above, when the engine is cold, the fuel injectors are instructed, for a brief period, to introduce excess fuel in order to improve combustion stability. When high power is required of the engine, the fuel injectors are also instructed to introduce excess fuel. The main rationale is protection of the catalyst from overheating. (See figure B.1, below.) Enrichment also increases the maximum power available from the engine by a few percent. When high torque is called for by the driver at low engine speeds, overheating is not a serious problem, but there is sometimes command enrichment, probably as an anti-knock strategy. Emissions associated with command enrichment (other

Table A.8. Estimates of the three factors in equation (A1) in illustrative high-power driving with command enrichment

	(1) FR	(2) EI	(3) CPF	(4) $TP_{g/s}$	(5) Ratio of high-power-to-FTP tailpipe emission rates
CO	4.7	0.60	0.97	2.7	~500
HC	4.7	0.019	0.54	0.047	~100
NO_X†	4.7	0.015	0.34	0.023	~20

†) Near wide open throttle EGR no longer functions (unless the vehicle is equipped with an EGR pump), so that both cars with and cars without EGR have similar engine-out NO_X emissions index at high fuel rates.

than in cold start) in properly-functioning cars, is the main subject of this section. NO_X from moderate-power stoichiometric operations is also discussed.

During command enrichment, very high CO and HC emissions occur, at a much higher rate than those estimated above for moderate driving. To estimate the emissions associated with command enrichment, it is necessary to model a) the emissions rate, given command enrichment, b) the enrichment strategy of typical vehicles (e.g. the strength of enrichment as a function of engine speed and power), and c) the frequency of high-power driving or other driving that leads to command enrichment (Barth and Norbeck 1994). Data from the CARB high-acceleration test, EPA Steady State study, FTP Revision Project and the EPA six-parameter driving survey, described briefly in section 3, yield rough quantitative descriptions of (a), (b) and (c).

In table A.8 the three factors discussed above for on-cycle driving (table A.6), are presented in an illustration of high power driving (roughly as at the peaks in the CARB high-acceleration test). The rate of CO emissions (g/s) increases by roughly three orders of magnitude, and that of HC by two orders, as can be seen in column (5) of table A.8. NO_X increases by an order of magnitude.

The following discussion includes cites to the sources of the factors in table A.8.

Emissions, given command enrichment. The engine-out emissions index of CO is taken from the FTP-RP. Typical behavior is shown in figure A.2 for a sample MY93 car in the FTP-RP. The y-axis is emissions index — the engine-out CO to fuel mass ratio. The x-axis is the fraction of fuel in excess of stoichiometric, $1 - \phi^{-1}$, where ϕ is the equivalence ratio (the actual fuel-air ratio divided by the fuel-air ratio at stoichiometry). The CO emissions index is linear in the excess fuel fraction, as seen. The intercept and slope vary slightly from vehicle to vehicle, but they vary remarkably little. From the FTP-RP database, we calculate for CO:

$$\text{CO EI} = (3.59 \pm 0.17) \cdot (1 - \phi^{-1}) + (0.08 \pm 0.01) \qquad \text{(A2)}$$

At high enrichment, the CO emissions index is given by basic chemical analysis to be:

Figure A.2. CO emissions index vs $1-\phi^{-1}$ for a sample MY93 car

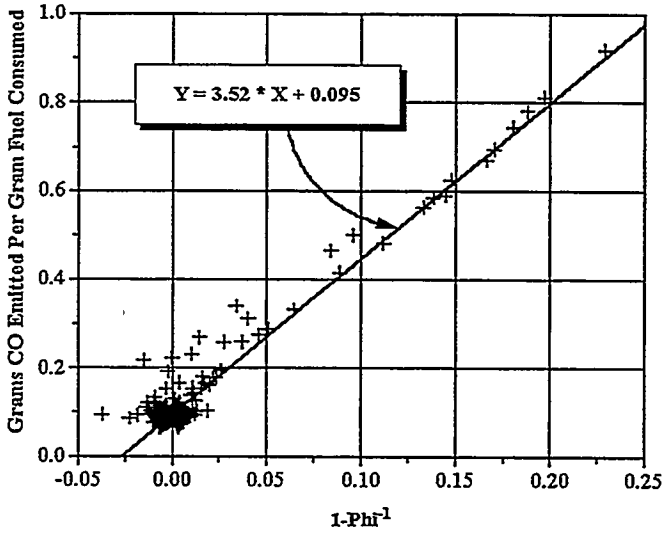
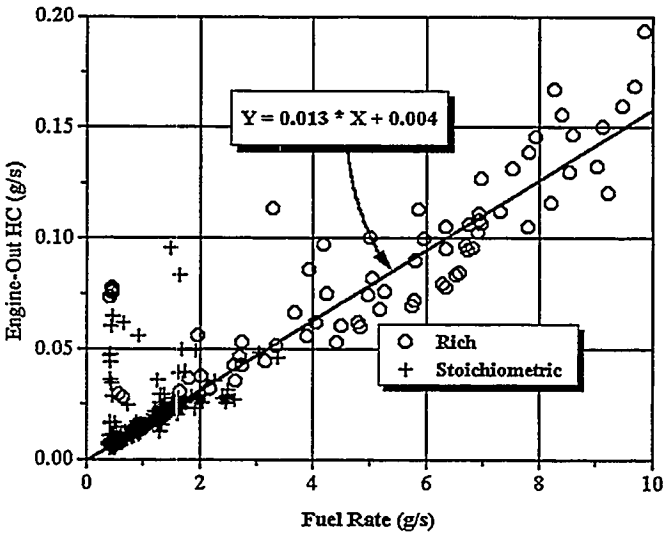


Figure A.3. Engine-out HC vs fuel rate for a sample MY93 car



$$\text{CO EI} \approx 4 \cdot \left(1 - \phi^{-1}\right).$$

That is, the CO engine-out emissions index is roughly proportional to the fractional excess fuel, with the coefficient independent of the vehicle (An and Ross 1995).

The engine-out emissions index of hydrocarbons is obtained from the FTP-RP data. An illustration is shown for a particular high-power cycle and car in figure A.3. (Note that, unlike figure A.2, the y-axis is now emissions rate in g/s and the x-axis is fuel rate in g/s.) The HC emissions are roughly proportional to fuel use, for stoichiometric and rich mixtures, so the emissions index is roughly constant, with:

$$\text{HC EI} \approx 0.01 \text{ to } 0.02.$$

The hydrocarbons emitted appear primarily to be residuals from walls (e.g. out-gassing from lubricants) and crevices (Cheng et al. 1993; Min et al. 1994; Norris and Hochgreb 1994; Boam et al. 1995). However, if the mixture goes too lean, then large HC emissions can occur from a different mechanism, incomplete combustion. This sometimes occurs during rapid decelerations and may be seen in figure A.3 as the points that stretch vertically upward at very low fuel rates.

For NO_X, there is a threshold in fuel rate below which the emissions are negligible. Then the engine-out emissions increase rapidly from low- to moderate-power driving conditions (see figure A.4). If it were not for command enrichment under high load conditions, engine-out emissions of NO_X would be much higher still (figure A.5). Command enrichment actually reduces the engine-out emissions index of NO_X at a given fuel rate compared to stoichiometric operation at the same fuel rate. This is to be expected due to the high-temperature sensitivity of NO_X formation (i.e. the cooling effect of a rich mixture) and the increased competition for available oxygen by the excess fuel. The cluster of stoichiometric points above 3 g/s fuel rate in figure A.5 were obtained using a special electronic engine control chip that did not command enrichment under any conditions. Using the production engine chip, the operating points above 3 g/s caused command enrichment (for this car).

The engine-out NO_X emission indexes shown in tables A.6 and A.8 are averages over driving

Figure A.4. Threshold effect of engine-out NO_X for a sample MY93 car with EGR

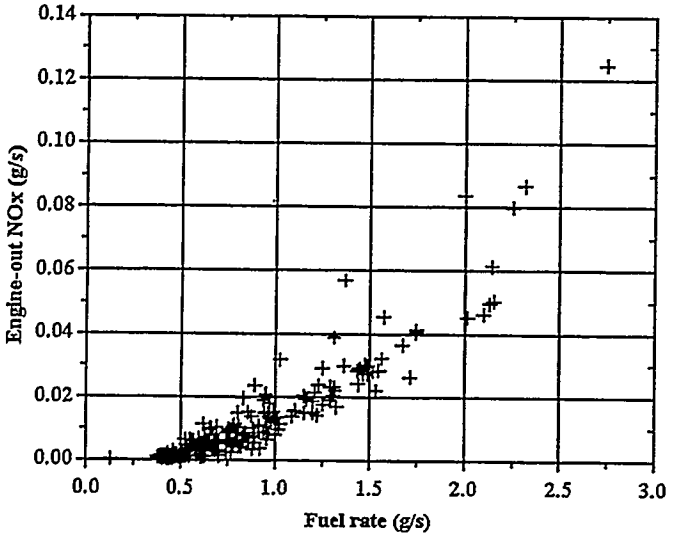
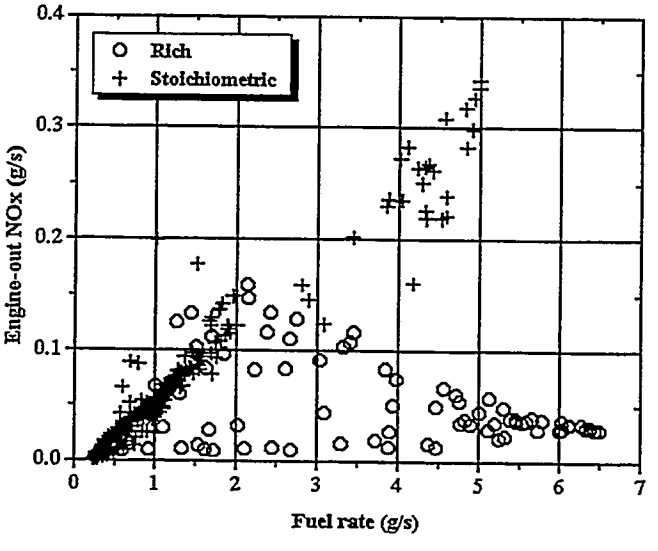
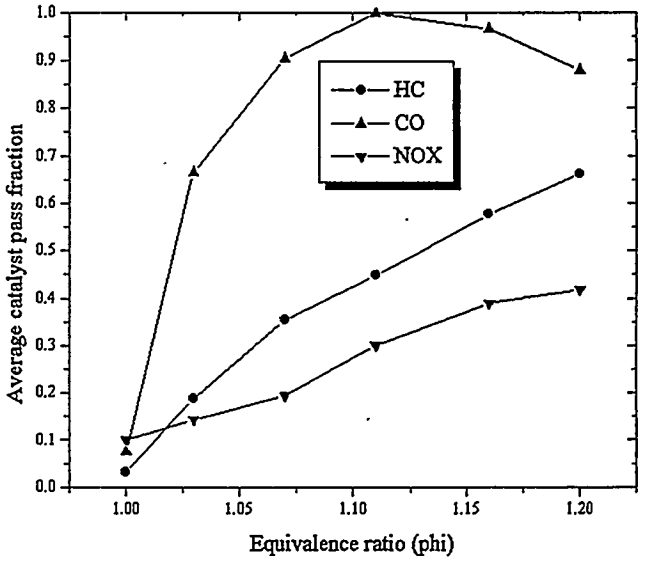


Figure A.5. Engine-out NO_X vs fuel rate for a sample MY93 car without EGR



cycles, and the second-by-second, as well as the vehicle-by-vehicle, rates vary substantially.

Figure A.6. Average catalyst pass fraction vs equivalence ratio for cars in the FTP-RP



The catalyst pass fractions at high power, (i.e. with enrichment) are taken from the FTP-RP data. (see figure A.6 — an equivalence ratio of 1 is stoichiometric operation and values greater than 1 are progressively richer.) Each point in figure A.6 represents the average catalyst pass fraction over hundreds or thousands of cumulative seconds at the given equivalence ratio for the cars in the FTP-RP. The increases in pass fractions with increasing equivalence ratio are expected from the chemistry of CO and HC conversion: Reactions that convert CO are inhibited at low oxygen levels, so the catalyst passes nearly all the CO that enters it. (The apparent decrease in CO pass fraction for phi greater than 1.12 shown in figure A.6 is probably due to data mismatches between engine-out and tailpipe CO emissions measurements, and is not physically accurate.) Hydrocarbon concentrations, which are much lower than those for CO, continue to experience some catalytic oxidation in the presence of enrichment, but much less than at stoichiometry. The increase in NO_X catalyst pass fraction with enrichment is not expected from simple chemistry, but may be due to increased mass flow at high fuel rates, which decreases the residence time in the catalytic converter for reactions to occur. NO_X is converted to N_2 by oxidation-reduction reactions that do not require oxygen in the exhaust stream. The qualitative behavior of these catalyst pass fractions during enrichment are not sensitive to the vehicle.

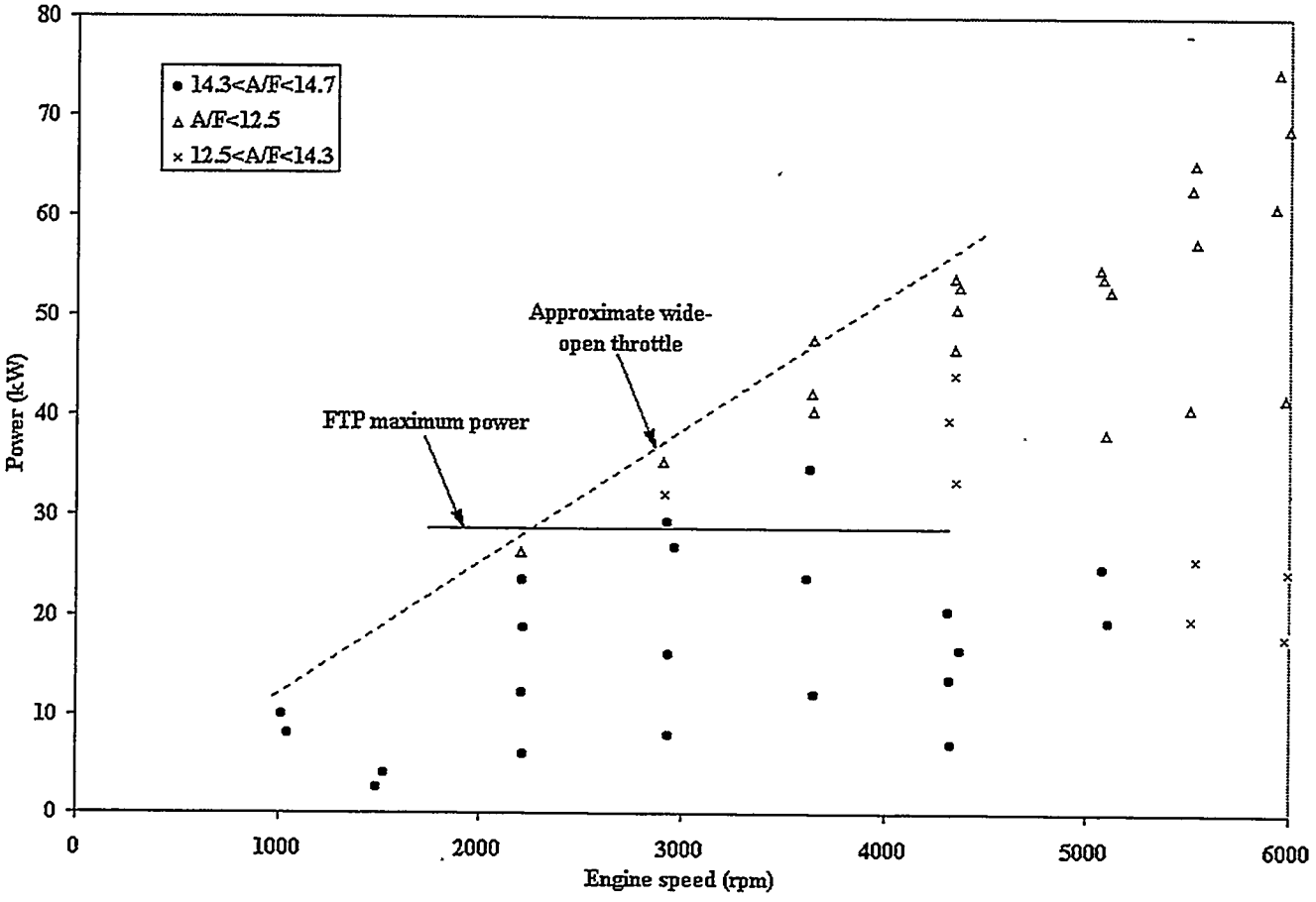
Enrichment strategy. In figure A.7 a fairly typical command-enrichment strategy is shown for a sample MY91 car (EPA Steady State data). The engine is seen to operate stoichiometrically (closed loop) at low to moderate power and engine speed (dark circles). One sees that, for moderate engine speeds, as wide-open-throttle is approached, enrichment (a low air-fuel ratio) is commanded ("x" and, especially, triangle). At high engine speeds, command enrichment is stronger and more pervasive. The maximum level of enrichment reached corresponds, for most of the cars tested, to 20-25% excess fuel, an air-fuel ratio of about 11.5.

For most cars for which data are available (EPA Steady State data, FTP-RP and CARB High Acceleration Tests), the threshold for ramping up the enrichment, at engine speeds like 2500 rpm and above, is at, or slightly above, the maximum power required in the FTP. (Note the solid line in figure A.7, and see An and Ross 1995.) In other words, in many cases the manufacturers' vehicle design conforms to the letter of the law, but there has been little or no effort to avoid command enrichment beyond that point.

A variable we call the power factor, which has been used by Harry Watson and by EPA analysts, is used here as a surrogate for power output:

$$\text{power factor} = \Delta v^2/\Delta t \ \ (\text{in mph}^2/\text{s}).$$

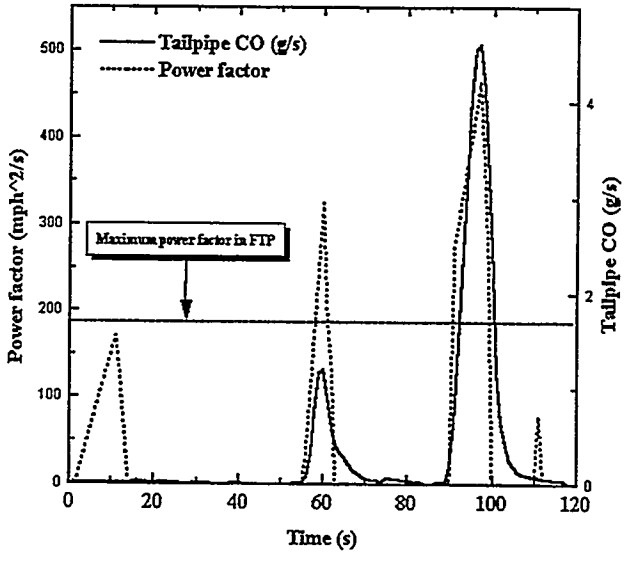
Figure A.7. Air fuel ratio dependence on power and engine speed for a sample MY91 car



The power factor is the rate of change of the square of the instantaneous speed of the vehicle from one second to the next, and it is proportional to the time rate of change of the kinetic energy of the vehicle per unit mass. The maximum value of the power factor in the FTP is 192 mph^2/sec.

This threshold for command enrichment as a function of power factor is illustrated for a particular car in figure A.8 in terms of CO, which as just discussed is sensitive to enrichment (CARB High Acceleration Test data). Three separate high-power episodes are shown: one weaker, one slightly stronger, and one much stronger than the maximum encountered in the FTP (Ross 1994). Each episode is about 10 seconds in duration. The pulses of CO emission associated with each episode are shown with the power-factor

Figure A.8. CO emissions in three high-power episodes

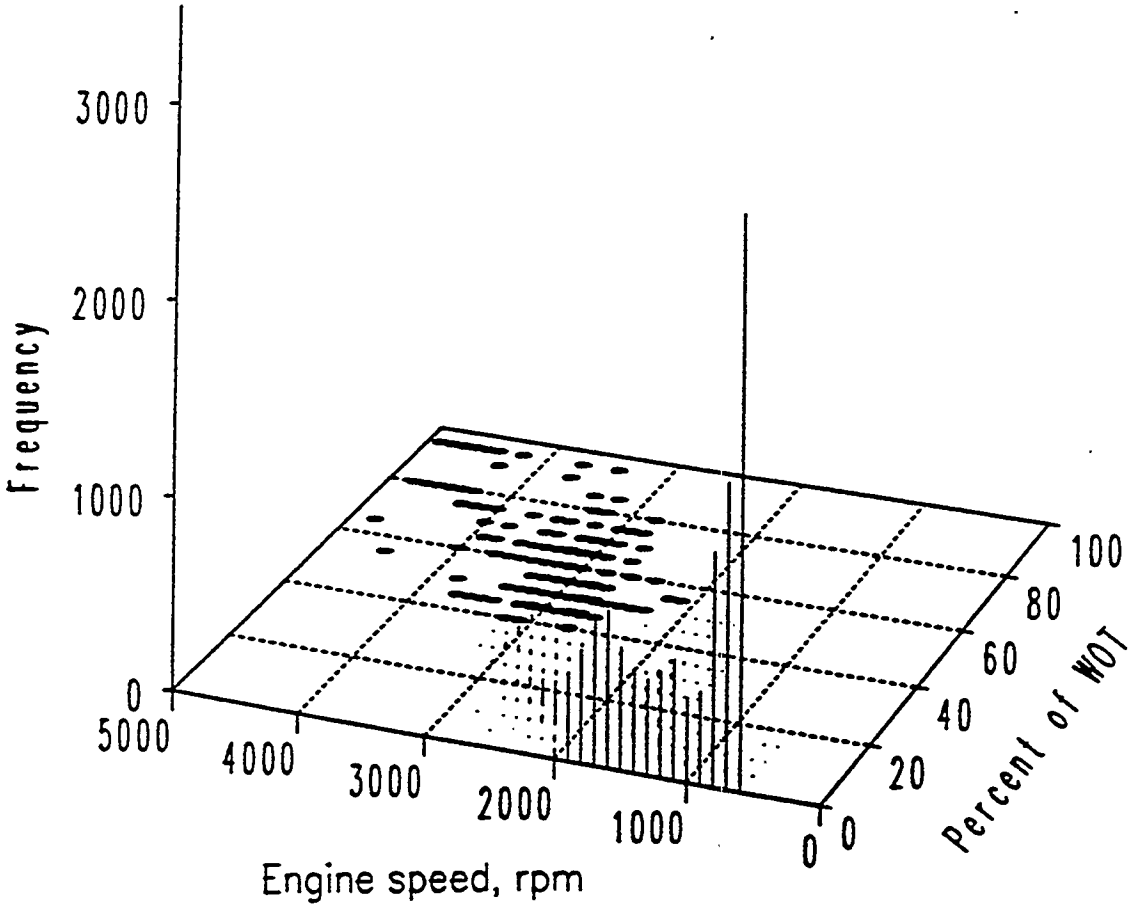


curves. The emissions are negligible for the weakest episode, and about 30 grams total for the strongest episode.

For many cars, command enrichment also occurs at lower engine speeds, as low manifold vacuum is approached. This is illustrated by the triangle at 2200 rpm in figure A.7. At low engine speeds this does not require very high throttle opening, i.e. the accelerator pedal on the floor. These episodes will usually be brief. (There are also a few cars for which enrichment is commanded only at very high engine speed, near wide-open throttle.)

The relationship between engine operation and command enrichment as it may occur in typical driving is illustrated by records of travel of instrumented cars driven in the Los Angeles area (Kelly & Groblicki 1993; St. Denis et al. 1994). Figure A.9 (Kelly and Groblicki 1993) shows that the lion's share of time driving was in the "FTP" part of the engine map: moderate engine speeds and away from wide-open throttle; it is stoichiometric, i.e. closed loop. The dark points show times of command enrichment, or open-loop driving. Relatively little time in enrichment is involved. The range of engine speeds in enrichment is large, including both high-power-high-engine-speed driving and high-torque driving with engine speeds well below 3000 rpm. There is no time spent in the upper left portion of the engine map because with an automatic transmission down shift occurs if one depresses the accelerator pedal far enough. At low power and high engine speed, bottom right of figure A.9, there is also no time spent.

Figure A.9. Frequency distribution of throttle position and engine speed combinations for a modern production vehicle driven in Los Angeles (Kelly and Groblicki 1993)



Driving patterns. The most important driving patterns in which command enrichment occurs are probably: 1) at high absolute power in hard-acceleration episodes lasting, perhaps, 5-15 seconds, 2) when high torque is demanded for one, or a very few, seconds, at lower engine speeds (roughly 2500 rpm), and 3) in sustained relatively high-power driving by moderate drivers with: a) low power/weight vehicles at high speed, b) hill climbing, and c) trailer pulling. Brief enrichment has also been observed during decelerations for one vehicle in the FTP-RP — this is presumably not commanded enrichment but is instead due to momentary mismatches between the air intake and fuel delivery rates. For our calculation, we do not disaggregate the three contributions to command enrichment listed above. Instead, we look at the combined effect of two regimes of enrichment: "mild" and "severe", defined below.

We analyze the six-parameter driving surveys to determine the distance weights for the enrichment driving modes and combine these with emission rates determined from the FTP-RP to estimate average emissions due to off-cycle, high-power driving. First we consider the three-parameter driving survey to generate a picture of the frequency of high-power driving.

Figure A.10 shows the distribution of power factor for the three-parameter, three-city instrumented driving data. The figure shows that approximately 1% of the 9 million seconds of recorded in-use driving involved power factors greater than the FTP maximum.

Figure A.10. Power factor distribution for three-parameter in-use driving data

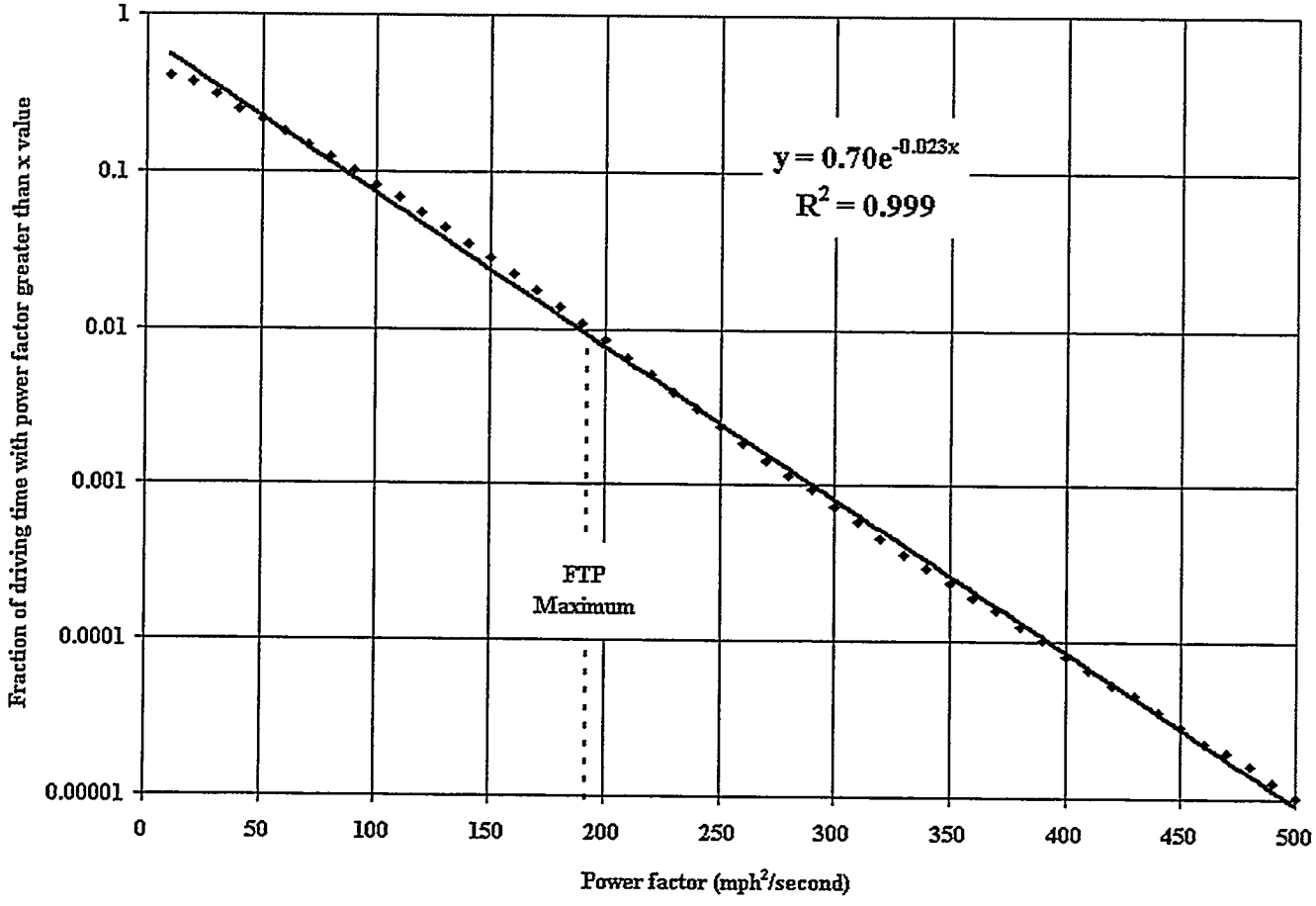
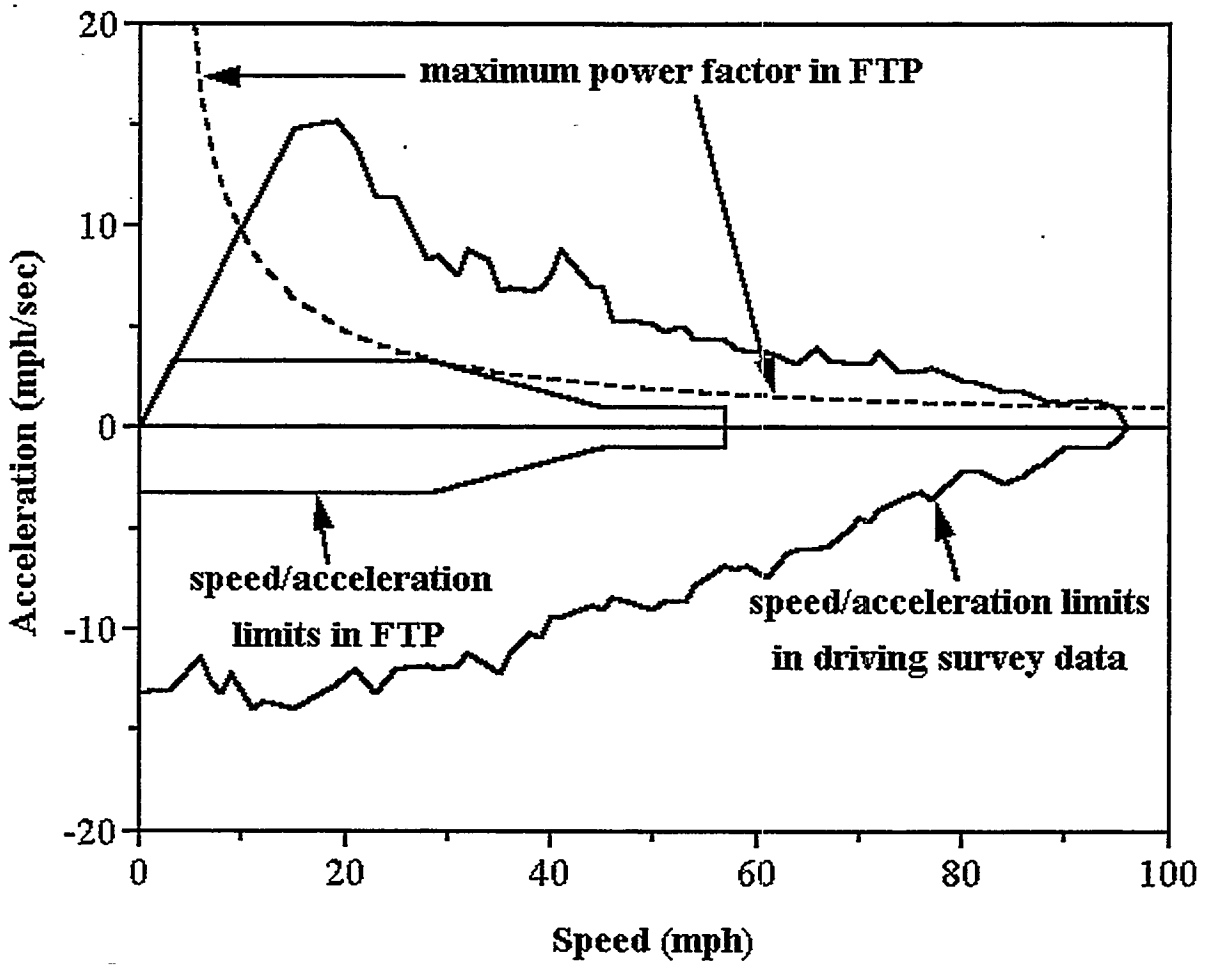


Figure A.11. FTP driving compared to real-world driving in the three-parameter driving data



The "space" for driving that is outside the FTP (in terms of speed and acceleration) is shown in a Watson diagram, figure A.11 (Milkins and Watson 1983). In this figure second-by-second in-use speed/acceleration combinations are plotted in two dimensions, with the speed on the x-axis and acceleration on the y-axis. The outer envelope is defined by the extremes observed in the three-paramater instrumented vehicle survey; the inner envelope shows the extremes of the FTP. The off-cycle driving occurs primarily between the FTP and survey envelopes. This space is occupied about 15% of the time (9% in the upper quadrant and 6% in the lower). In addition, a line is plotted representing the combination of speed and acceleration that results in the maximum power factor in the FTP — all points above and to the right of this line exceed the maximum power factor in the FTP. As mentioned above and indicated by figure A.10, about 1% of the in-use driving time exceeds the maximum power factor in the FTP.

Results for CO and HC. Analysis of the EPA/Industry six-parameter in-use driving data indicates that, for the cars and drivers surveyed, approximately 4.8% of the total miles driven were in mild enrichment ($1.03 \leq \phi < 1.12$) at an average speed of 27 mph and average fuel rate of 2.6 g/s. 1.2% of the total miles driven were in severe enrichment ($\phi \geq 1.12$) at an average speed of 31 mph and average fuel rate of 3.7 g/s. This includes all times when the engines were running except for the first 60 seconds after starts, to avoid counting cold start enrichment. [The choice of mild and severe enrichment regimes employed here follows that used by LeBlanc, et al. (1994).] ϕ averaged 1.06 during the mild enrichment

Table A.9. Average tailpipe CO emissions due to command enrichment

Enrichment mode	(1) FR	(2) EI	(3) CPF	(4) $3600/v_i$	(5) TP†	(6) TP - TP_1	(7) x_i/x	(8) Incremental TP
Mild	2.6	0.3	0.8	133	83.0	79.7	0.048	3.8
Severe	3.7	0.8	1.0	116	343	340	0.012	4.1
Total								7.9

†) Here and in table A.10 TP is tailpipe emissions in g/mile.

events and 1.19 during the severe enrichment events. Some of the enrichment events observed in the driving data are likely not due to command enrichment but are instead associated with highly transient operation (e.g. hard decels) and low fuel rates. We do not expect the non-command enrichment events to contribute significantly to average emissions. However, we do not attempt to quantify the fraction of observed enrichment due to non-command enrichment. Using this information we estimate the incremental contribution (discussed at the beginning of Appendix A) of command enrichment to average CO and HC emissions in tables A.9 and A.10.

Fuel rates were not measured in the driving surveys. Instead we estimate the second-by-second fuel rate in the data. For the cars where the mass air flow (MAF) was recorded:

$$FR = MAF \cdot \frac{\phi}{14.6} \cdot \frac{1000}{3600} \qquad \text{(A3)}$$

here 14.6 is the stoichiometric air-fuel ratio, MAF is measured in kg/hr and FR is in g/s. For cars where the manifold absolute pressure (MAP) was recorded:

$$FR = 0.67 \cdot MAP \cdot V \cdot \frac{N}{(2 \cdot 60)} \cdot \frac{1000}{(287 \cdot 293)} \cdot \frac{\phi}{14.6} \qquad \text{(A4)}$$

here MAP is measured in kPa, V is the engine displacement in liters, and N is the engine speed in rpm. The factor of 1/2 takes into account that there is one induction for every two revolutions; the factor of 1/60 converts rpm to rps; the factor of 1000 converts kPa into Pa; 287 is the universal gas constant for dry air in units of J/kg-K; and 293 is the average ambient air temperature in degrees K. The factor of 0.67 was determined empirically by applying equation (A4) to measurements in the FTP-RP and correlating the results with the measured fuel rate. Physically, the factor of 0.67 represents an average

Table A.10. Average tailpipe HC emissions due to command enrichment

Enrichment mode	(1) FR	(2) EI	(3) CPF	(4) $3600/v_i$	(5) TP	(6) TP - TP_1	(7) x_i/x	(8) Incremental TP
Mild	2.6	0.019	0.25	133	1.64	1.30	0.048	0.062
Severe	3.7	0.019	0.65	116	5.30	4.96	0.012	0.060
Total								0.12

volumetric efficiency over the engines and cycles observed in the FTP-RP. V for each car in the six-parameter survey is known. This method is similar to that used by LeBlanc, et al. (1994) to calculate exhaust mass flows for the six-parameter driving survey.

The engine-out CO emission indexes (0.3 and 0.8) are calculated using fraction of fuel in excess of stoichiometric values of 0.06 and 0.19, respectively, in equation (A2). The engine-out HC emissions index is taken from table A.8. The catalyst pass fractions for CO and HC are estimated from figure A.6 at the appropriate equivalence ratios. Seconds per mile driven in the given mode are calculated from the average speeds (27 and 31 mph). TP_1 is the g/mile emissions due to on-cycle driving of properly-functioning cars (3.3 g/mile for CO and 0.34 g/mile for HC — see subtotals in table A.2).

These estimates for the extra emissions that occur in the relatively rare instances of command enrichment in properly-functioning cars are particularly uncertain for two major reasons: 1) The enrichment strategies for different engines and vehicle models vary strongly. 2) The patterns of driving involved only occur a few percent of the time and so are difficult to determine accurately.

NO_X from Moderate-Power Stoichiometric Operation. Currently, the FTP accounts for the extra power requirements imposed by air conditioner use by increasing the dynamometer load 10% over the measured road load at 50 mph (using the "coast down" method). However, this method underestimates actual air conditioner loads, particularly at low speeds, and the EPA has proposed changes in the FTP to improve this test (60 FR 7404). In addition, road grades are not simulated at all in the FTP. These loads, among others discussed below, are potentially significant off-cycle sources of NO_X emissions, since the instantaneous engine-out NO_X emissions, particularly in cars with EGR, experience a threshold in fuel rate, or load, below which the emissions are very low and above which they increase rapidly (see figure A.4).

The engine-out, stoichiometric NO_X emissions ($EONO_X$), in g/s, are approximately of the form:

$$EONO_X = C \cdot \left(FR - FR_{th}\right) \quad \text{for } FR > FR_{th}$$

$$EONO_X = 0 \text{ for } FR \le FR_{th} \qquad \text{(A5)}$$

Here C is dimensionless, and FR_{th}, in g/s, is the fuel rate threshold. Both constants may be determined empirically for each vehicle and averaged. For the cars we studied in the FTP-RP we find, approximately:

$$EONO_X = 0.071 \cdot (FR - 0.27) \text{ for cars without EGR}$$

$$EONO_X = 0.035 \cdot (FR - 0.50) \text{ for cars with EGR}$$

$$EONO_X = 0 \text{ if the difference in the parenthesis} \le 0. \qquad \text{(A6)}$$

The values of C and FR_{th} vary relatively little for the cars in the FTP-RP without EGR, but they vary considerably for cars with EGR.

As a result, NO_X emissions are sensitive to vehicle operation which involves extra power, i.e. when vehicle operation moves up the NO_X ramp shown in the equations above, but where the extra power is not so high as to command enrichment. These moderate-power situations arise in off-cycle driving associated with: air-conditioner use, grades at moderate speed, heavy loads (like passengers and luggage beyond the FTP's 300 lbs), high speeds (but without high acceleration), etc.

For this analysis, tailpipe emissions in g/mile are calculated using equation (A1), re-expressed as follows:

$$TP_{g/mile} = EO \cdot CPF \cdot 3600/v \tag{A7}$$

here EO are the engine-out emissions (of CO, HC or NO_X) in g/s, and v is the vehicle speed in mph.

For CO and HC, $\Delta EO \approx C\ \Delta FR$. Under stoichiometric conditions, the coefficient C is given in table A.7 (EI) for CO and HC.

For NO_X we must take into account the threshold behavior found in equation (A5). We also find a strong correlation between C in equation (A5) and CPF (figure A.1). Therefore, analyzing the cars in the FTP-RP, we find the following average with respect to NO_X for stoichiometric conditions:

$$\langle C \cdot CPF \rangle \approx 0.006$$

so that equation (A7) becomes, for tailpipe NO_X in g/mile,

$$TPNO_X \approx \langle C \cdot CPF \rangle \cdot \left(\langle FR \rangle - FR_{th} \right) \cdot 3600/\langle v \rangle, \text{ and} \tag{A8}$$

$$\Delta TPNO_X \approx 0.006 \cdot 3600 \cdot \left\{ \left(\frac{\langle FR \rangle - FR_{th}}{\langle v \rangle} \right)_1 - \left(\frac{\langle FR \rangle - FR_{th}}{\langle v \rangle} \right)_2 \right\} \tag{A9}$$

Here equation (A9) estimates the incremental NO_X in real-world driving (quantity in first parenthesis) due to stoichiometric driving at average loads higher than contained in the FTP (second parenthesis). We calculate the average stoichiometric ($0.97 < \phi < 1.03$) fuel use rate in the six-parameter driving survey to be 1.04 g/s using equations (A3) and (A4). The average speed is 27 mph. The result is $\Delta TPNO_X \approx 0.2$ g/mile. Including the incremental NO_X from enrichment and air conditioning (year long average) we obtain $\Delta TPNO_X \approx 0.3$ g/mile.

In making this estimate we assume that the driving behavior and cars in the six-parameter driving survey is representative of the average modern car on the road, and that the emissions behavior of the cars in the FTP-RP is also representative. In this calculation we are interested in the difference of two quantities that are roughly equal and are determined from independent sources of information, so that small changes (uncertainties) in the factors that go into the calculations can substantially alter the result. Nevertheless, we believe that the result is roughly correct, and we support this conclusion by estimating the individual incremental contribution of air conditioning, grade, high acceleration at low speeds, and high speed cruises to tailpipe NO_X emissions below.

We can estimate FR in g/s using a simple model of engine energy performance (Ross and An 1993):

$$FR = \left(k \cdot N \cdot V + P_b/\eta \right)/LHV \tag{A10}$$

Here, k is the engine frictional characteristic, the fuel energy consumption (in kJ) to overcome engine frictions at zero power output, per revolution and per liter of displacement (about 0.22 kJ/revolution-liter in current cars); N is engine speed in rps; V is displacement in liters; P_b is engine power output in kW; η is a measure of the indicated efficiency (about 0.40); and LHV is the lower heating value of the fuel (44 kJ/g for typical gasoline).

Table A.11. Estimates of NO_X emissions in off-cycle modes (assuming stoichiometry)

Mode	Change in fuel rate (g/s unless stated otherwise)	Change in tailpipe NO_X emissions (g/mile)
air conditioning (summer)	$P_{AC}/(\eta \cdot LHV)$	0.1 (includes 50% duty factor)
grade	$\theta \cdot M \cdot g \cdot (0.477 \cdot v)/(\eta \cdot \varepsilon \cdot LHV)$	$\approx 10\theta$ (speed independent)
2% grade		0.2
average grade		0.08
hard acceleration	$M \cdot (0.447^2 \cdot \Delta v^2/\Delta t)/(2\eta \cdot \varepsilon \cdot LHV$	$\approx 0.43a$ (speed independent)
a = 5 mph/s		0.7 (compared to a = 3.3)
high speed	Δ(FR) (kJ/mile)	
80 mph	≈ 1000	0.14
100 mph	≈ 2500	0.34

Therefore, the fuel-rate increment due to an additional loads is (neglecting the increase in N in higher-power modes):

$$\Delta(FR) = \Delta(P_b)/(\eta \cdot LHV)$$

We apply equations (A9) and (A10) to NO_X emissions in four modes involving excess power compared to the FTP in table A.11. Here, P_{AC} is the air conditioner load, θ is grade; M is vehicle mass in metric tonnes; g is acceleration due to gravity (9.8 m/s2); ε is transmission efficiency ($\approx$ 0.85); a is acceleration (mph/s), and the factor of 0.447 converts mph to m/s. The estimates require brief discussion.

A typical auto air conditioner, when on, might impose a load of 4 kW on the engine. Referring to the expressions for $EONO_X$, equation (A6), we assume one is on the NO_X ramp (above the fuel rate threshold FR_{th}) when the air conditioner is off. Based on an analysis in a Department of Transportation report (DoT 1990), we assume that the air conditioner is on half the time in summer months. Most new cars have air conditioners. The result is incremental NO_X emissions by a typical car of about 0.1 g/mile during the summer due to air conditioning. This estimate is consistent with excess NO_X emissions due to actual air conditioner use as measured by AC Rochester as a part of the FTP-RP (USEPA 1995a). Such excess NO_X emissions in urban driving in summer are of course critical to ozone formation.

A DoT survey of road grades reported in an EPA study (USEPA 1980) shows uphill grades of 0.5 to 1%, 1 to 3%, and 3 to 5%, and above 5%, for 10, 12, 7 and 3% of nationwide driving, respectively. For an average vehicle, climbing a 2% grade at 25 mph requires an incremental 3.3 kW at the wheels. Assuming the DoT grade survey applies to both urban and highway driving, the weighted average engine power required for road grades is about 1.5 kW in urban driving and 2.8 kW in highway driving. This implies incremental tailpipe NO_X slightly under 0.1 g/mile.

Hard accelerations, exceeding the 3.3 mph/s maximum in the FTP, may not cause enrichment if the vehicle speed is low. As an example, we make an estimate in table A.11 of NO_X emissions for an acceleration of 5 mph/s compared to 3.3 mph/s. The g/mile emissions rate is seen to be high, but such accelerations occur only a small fraction of the time.

In level driving with a typical car the fuel rate (g/s) increases almost a factor of 2 at 60 mph compared to 25 mph (USEPA 1995a). This brings most cars onto the $EONO_X$ ramp. Then as one drives faster, NO_X emissions rise. In table A.11 we take the change in fuel rate in kJ/mile from figure 2 of An

and Ross (1993b). It is mainly driven by air drag and grows as the square of the speed. One can see that very high NO_X emissions can result from steady driving at autobahn speeds.

Emissions From Congestion. When the engine is on but the vehicle isn't moving, g/mile emissions rise accordingly. We estimate a typical fuel rate in vehicle idling of 0.3 g/s, based on equation (A10). With air conditioning the fuel rate might be about 0.5 g/s, when it's on. These estimates are for a typical car; some vehicles probably have substantially lower or higher idle fuel rates. Nevertheless, according to the threshold in equation (A6), these estimates suggest that NO_X emissions are not a primary concern with congestion, except perhaps for cars without EGR and air conditioning on.

For CO and HC, consider a trip with duration time t_0 and speed v_0. Now consider a trip with more congestion such that the duration is $t_0 + \Delta t$, with the added time spent idling. Similar to equation (A7) we estimate the added tailpipe emissions (g/mile) as:

$$\Delta TP = C \cdot FR \cdot CPF \cdot \Delta t \cdot 3600/(t_0 \cdot v_0)$$

For illustration, assume congestion doubles the trip time; and assume v_0 is the FTP overall speed of 19.6 mph. Without air conditioning, the added g/mile emissions are then 0.4 and 0.03 for CO and HC, respectively. With air conditioning, they are 0.7 and 0.06, respectively. It would seem that excess emissions from idling, due to congestion, are relatively low with properly-functioning vehicles.

A.5. Malfunctioning Exhaust Emissions Controls

This category comprises excess tailpipe emissions from vehicles whose emissions control systems (ECS) have failed or are strongly malfunctioning, involving *large departures* from normal emissions performance. In addition to ECS malfunction in a narrow sense, high emissions rates can result from poor engine performance, such as misfire, and we include that in the malfunction category. (EPA Tampering Surveys (USEPA 1991) have used the term malfunctioning in the restricted sense of those vehicles which have non-performing, but not "tampered", emissions controls, we adopt the term malfunctioning for the general category.) The term high emitter is also used; it is somewhat more general than a vehicle with malfunctioning ECS, since it may include a vehicle under command enrichment (properly-functioning) or with cold catalyst.

Malfunction emissions deduced using MOBILE5a. MOBILE5 is based on extensive measurement of emissions from vehicles in-use, even though it - and all emissions data - must be questioned in terms of how representative they are, in terms of the kind of driving and the vehicles involved. Although malfunctioning vehicles are not identified as such within MOBILE5, since we independently project the emissions from properly-functioning vehicles, we can estimate the modeled malfunction emissions by simple subtraction.

For MY93 cars, our MOBILE5a run shows g/mile lifetime average tailpipe emissions for CO, HC, and NO_X of 19, 1.4 and 1.5, respectively. (See note to table A.1 for summer/winter temperature and RVP assumptions.) Comparing with the other direct emissions shown in table A.2 for properly-functioning cars and subtracting, we obtain malfunction emissions of 9, 0.4, and 0.8 g/mile, for CO, HC, and NO_X respectively. This is the result for NO_X shown in table A.2, because we do not estimate NO_X malfunction emissions directly.

Identification of malfunctioning vehicles on the basis of remote sensing. Remote sensing is an extremely promising tool for several purposes; most important for our analysis is the very large number of vehicles that are measured, and the absence of a vehicle-recruitment process, other than choice of site,

that might bias the sample. The data we analyze for CO and HC was collected in California in 1991, as discussed in section 3 (CARB 1994).

Remote sensing measurements show that a relatively small fraction of vehicles have extremely high emissions rates, such that most CO, much HC, and perhaps much NO_X comes from this source. This general state of affairs is perplexing; it means that measurement of a typical vehicle will usually be misleading. In a sense there is no typical vehicle. The state of affairs has been confirmed by dynamometer measurements at the roadside on vehicles identified as high emitters through remote sensing, even though some cars so-identified by remote sensing are not found to be high emitters on the dynamometer cycle (McAlinden 1994; CARB 1994).

This state of affairs, with a small number of vehicles contributing most emissions, is not addressed by the "in-use" emissions tests of cars recruited for the purpose by EPA, CARB and others. In these tests high emitters are typically omitted by the recruitment process, by deliberate exclusion of vehicles in poor condition and even of outliers, and by the limited statistics. (See section 2.3.) This divergence of perspectives is historical. There has been a focus by regulators on "tampering", and the wording in legislation appears to place the responsibility for malfunctions on individual owners/drivers and servicing. The in-use testing serves a perceived legal purpose rather than being an attempt to collect unbiased information.

We make the case here that vehicle design and quality of manufacture are responsible for most of the malfunctions in modern cars (perhaps essentially all, at least up to an age of 4 or 5 years). In judging this case, the reader must be aware of the limitations of the remote sensing data on which we base the case. Remote sensing may misidentify particular vehicles as malfunctioning for several reasons: the vehicle may have been started recently so the engine/catalyst may be cold; the driver may have momentarily called for high power and caused command enrichment; the actual emissions may have been too small to measure accurately but still yield a high pollutant concentration, since concentration is based on a ratio. (The latter is particularly a problem at a moment when a vehicle is using little fuel, e.g. when the driver's foot lifts off the pedal.) In addition, hydrocarbon measurements are difficult to interpret because the hydrocarbons involve a large number of species with different infrared signatures, as discussed further below.

Previous studies indicate that on-road emissions, and therefore remote sensing measurements, for an individual vehicle can be highly variable (not surprising, since the measurement is essentially a snapshot). Stephens found that the correlation between remote sensing measurements and a roadside IM240 (dynamometer) test was poor for both CO ($r^2 = 0.34$) and HC ($r^2 = 0.39$); the correlation improves for CO when emissions for two or more remote sensing readings from the same vehicle are averaged ($r^2 = 0.68$) (Stephens 1994a). Averaging four or more remote sensing CO readings for an individual car only raises the r^2 to 0.77, which is still not excellent correlation. So remote sensing has not been a perfect technique for identifying the individual vehicle as malfunctioning. (It is important for more general considerations to keep in mind that remote sensing technology has improved since the 1991 measurements we analyze, and is continuing to be improved.)

These are important caveats. They call into question the use of remote sensing — at least in its early '90s form — for identifying cars to be brought in for more detailed inspection and repair. In other words, while the general remote-sensing result on the major role of malfunctions is correct and broad quantitative measures are reasonably accurate, one has to be careful about conclusions deduced from small, specially selected, samples. We attempt to overcome this limitation by analyzing the percentage of high-emitters for large samples of vehicles, and by studying the emissions of cars for which there are multiple readings. (See section B.5)

Figure A.12. Average CO emissions, by MY and fuel system

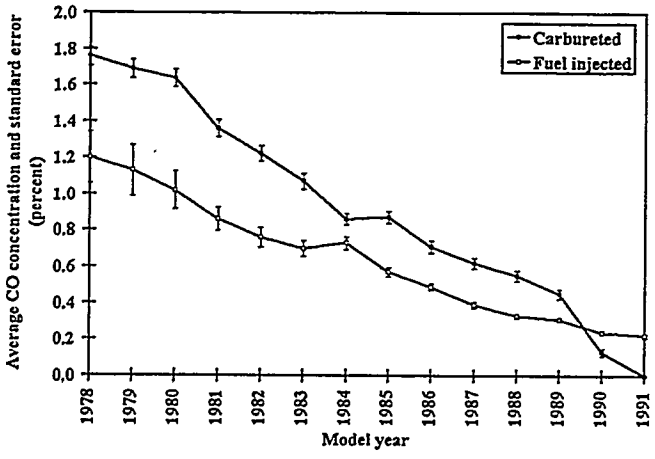
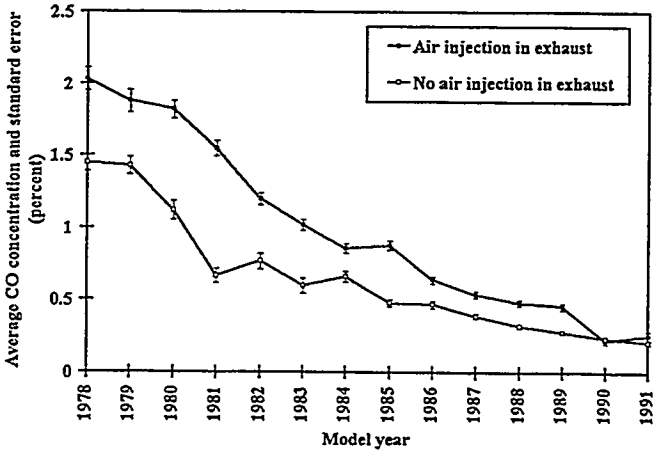


Figure A.13. Average CO emissions by MY and exhaust air injection



Choice of Sample. The first step in using the remote sensing data is to choose a criterion for labeling vehicles as having malfunctioning ECS (m-cars), distinguishing them from those that are properly-functioning (p-cars), in order to make projections of future malfunction emissions. The form of our analysis is due to Stephens (1994b).

Our goal here is to describe lifetime emissions for MY93 cars, but the analysis is based on 1991 remote sensing data. We need to distance our analysis from older vehicle technology which was quite different in terms of emissions from 1993 technology. Carburetion and, often, air injection in the exhaust were used in older vehicles. Figures A.12 and A.13 show that these technologies tend to increase average in-use CO emissions measured in the survey studied here (CARB 1991 Remote Sensing Survey). Modern vehicles avoid these technologies by using a combination of fuel injection and improved emission control systems Figures A.14 and A.15 show the use of carburetion and air injection decreasing in modern vehicles (data again from the CARB 1991 survey under study here). The use of carburetion

Figure A.14. Number of readings by fuel system and MY

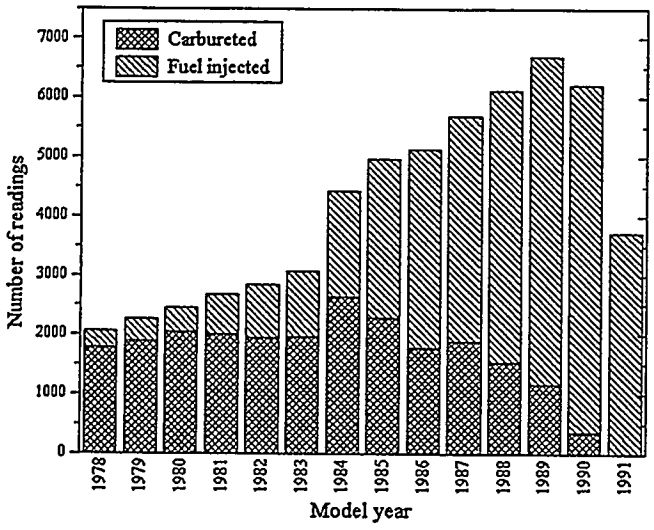
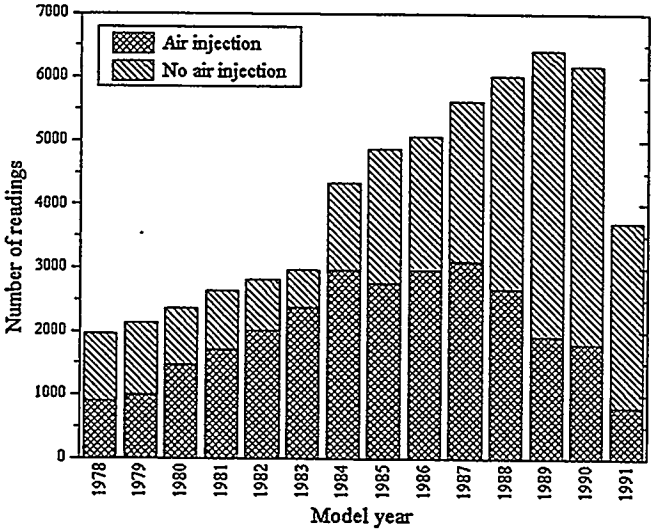


Figure A.15. Number of readings by air injection system and MY



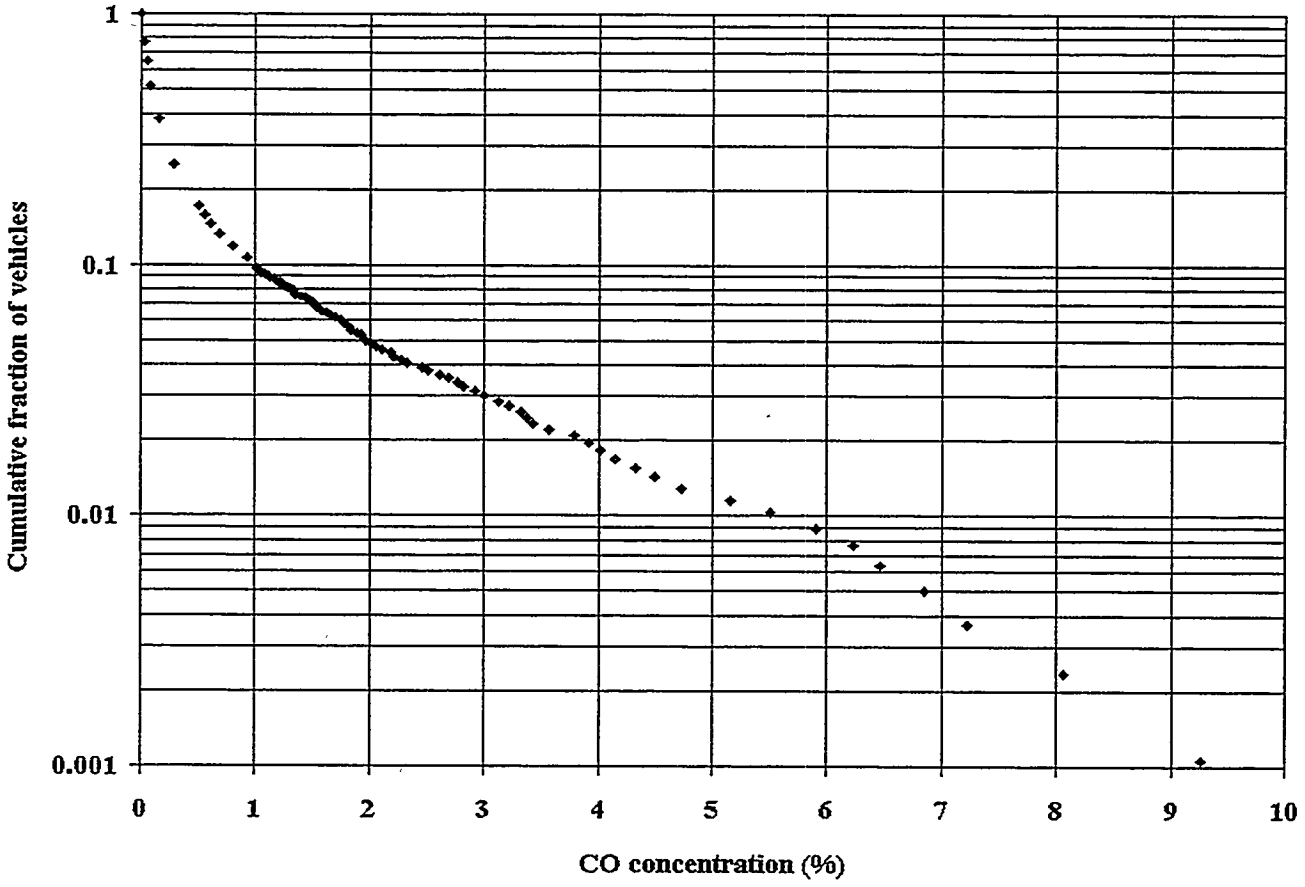
essentially disappeared with MY90 (Murrell, et al. 1993). Air pumps were still in use in MY93 in about 15% of models.

In addition, vehicle tampering rates are higher for older vehicle technologies. This is because specific components common in older cars, such as fuel inlet restrictors and air injection systems may have restricted performance and were relatively easy to disable. The unavailability of leaded fuel, as well as sophisticated engine design with computer controls that improves emissions as well as performance, reduce the incentive to tamper with modern vehicles. (See section B.5.)

By focusing on relatively late-model vehicles we reduce the role of older technologies that tend to be associated with high in-use emissions as well as tampering. However, we need data on cars at least two to five years into their driving life for a study of the incidence of ECS malfunction. Emissions data from late-model (post MY90) vehicles that have been driven three to five years would be ideal for our purposes. However, we are limited at this time to the 1991 measurements in hand. We focus on MY87 and later vehicles, restricting our critical analyses to fuel-injected cars .

CO emissions from malfunctioning cars. We plot the data as the cumulative fraction of vehicles, CFV, with respect to CO concentration (Stephens 1994b). (See figure A.16.) The distribution is seen to consist of two parts: a central peak at low concentration and a tail going to high concentrations. It is reasonable to hypothesize that the low-concentration peak represents vehicles with properly-functioning

Figure A.16. Stephens plot of distribution of CO emissions from MY87 fuel-injected vehicles (CARB 1991 Remote Sensing Data)



emissions controls (p-cars), while the tail consists of vehicles with malfunctioning emissions controls (m-cars). We show below that the central peak has average emissions concentration in rough agreement with the dynamometer data on the ratio grams-of-pollutant to grams-of-fuel from properly-functioning cars in moderate driving.

One approach to carrying out the separation into p-cars and m-cars quantitatively is simply to identify all observations above a certain concentration cutpoint, which we take as 1% for CO. Table A.12 shows the results, with the simple 1% CO cutpoint, for five model years. These results have the qualitatively correct behavior:

1) The percent of m-cars is higher for older cars. The MY87 cars are about 4.5 years old; the MY91 cars about 0.5 years old. (That is, these are cars observed in June 1991.)

2) The average emissions concentration per m-car is about 50 times higher than that those per average p-car of 0.05 to 0.06% (estimated in the next subsection). High levels of CO are associated with fuel enrichment.

The relatively high frequency of m-cars among the very newest cars and their relatively high emissions, as shown for MY91 in table A.12, is surprising, but was also noted by Stephens, whose remote sensing survey was conducted at the same time at some of the same sites (Stephens 1994b). There was an experimental problem with the data on the MY91 cars: Some license numbers, apparently observed on older cars, were identified with new vehicles by the motor vehicle bureau by the time it processed the information to provide the VINs. (See section 3.) In addition to these, there may also be up to a few percent of vehicles which have malfunctioning ECS when new or almost new.

In most cars, the ratio of CO to fuel is expected to rise by a factor of about 100, going from stoichiometric to high-power operation with an air-fuel ratio of about 12. (Compare tables A.6 and A.8.) Thus, to explain the factor of 50 increase here, the level of enrichment characteristic of the average emissions per malfunctioning vehicle in this data would be an air-fuel ratio of about 13.0. This may be typical of default air-fuel ratios, which can come into use, for example, if the oxygen sensor fails.

Obviously the 1% concentration criterion identifies a larger fraction of malfunctioning cars than using the customary high cutpoint in some remote sensing studies. For our research purposes this is desirable. The identification of the *residual* as p-cars, works moderately, but only moderately, well. With this identification the average p-car CO emission, measured by remote sensing, is roughly twice that from the dynamometer data, as shown immediately below.

Table A.12. Occurrence of CO malfunctions, fuel-injected cars

	MY91	MY90	MY89	MY88	MY87	MY87-89
Average CO concentration, all cars	0.22%	0.25%	0.30%	0.32%	0.36%	0.33%
Malfunctioning cars						
Percent	4.9%	5.6%	7.3%	7.2%	8.4%	7.6%
Average CO concentration	2.65%	2.52%	2.61%	2.63%	2.79%	2.67%
Percent of total CO	59%	57%	63%	59%	64%	62%
Properly-functioning cars						
Percent	95.1%	94.4%	92.7%	92.8%	91.6%	88.6%
Average CO concentration	0.09%	0.11%	0.12%	0.14%	0.14%	0.13%
Percent of total CO	41%	43%	37%	41%	36%	38%

The average concentration of p-cars from dynamometer data. The tailpipe CO-to-fuel ratio (grams-CO/grams-fuel) measured on the FTP-RP dynamometer tests of p-cars in bag 2 type driving (table A.6, column 4) is r = 0.0070. The corresponding CO concentration, conc (in %), is:

$$\text{conc} = \left[2800/(363 - 6.8 \cdot \text{conc})\right] \cdot r$$

where 2800g/gal is roughly the average density of gasoline. We obtained the factor in the denominator by regression involving the (grams CO/gallon of fuel) and CO concentration in the remote sensing data set. Thus, for p-cars, one predicts, based on the dynamometer data:

p-car CO concentration (%) = 0.054.

The analysis of the dynamometer data (FTP bag 2 type driving) is summarized for CO and HC in table A.13. Considering their independence, this FTP-RP dynamometer result for CO is in fair agreement with, but smaller than, the remote sensing results (next to bottom row of table A12). There are several reasons why the two would be expected to disagree somewhat, mostly in the direction observed: California p-cars are allowed higher CO emissions; the actual difference is small however. Actual degradation of the ECS in p-cars is probably more rapid in the observed vehicles than the FTP-RP vehicles (as indicated by the "as-received" dynamometer data and discussed in section A.1); in addition the mileage may be higher for the MY87 vehicles. There may also be systematic error in the remote sensing measurements at small concentration (in either direction). Taking the p-cars to be the

Figure A.17. Stephens plot of distribution of HC emissions from MY87 fuel-injected vehicles (CARB 1991 Remote Sensing Data)

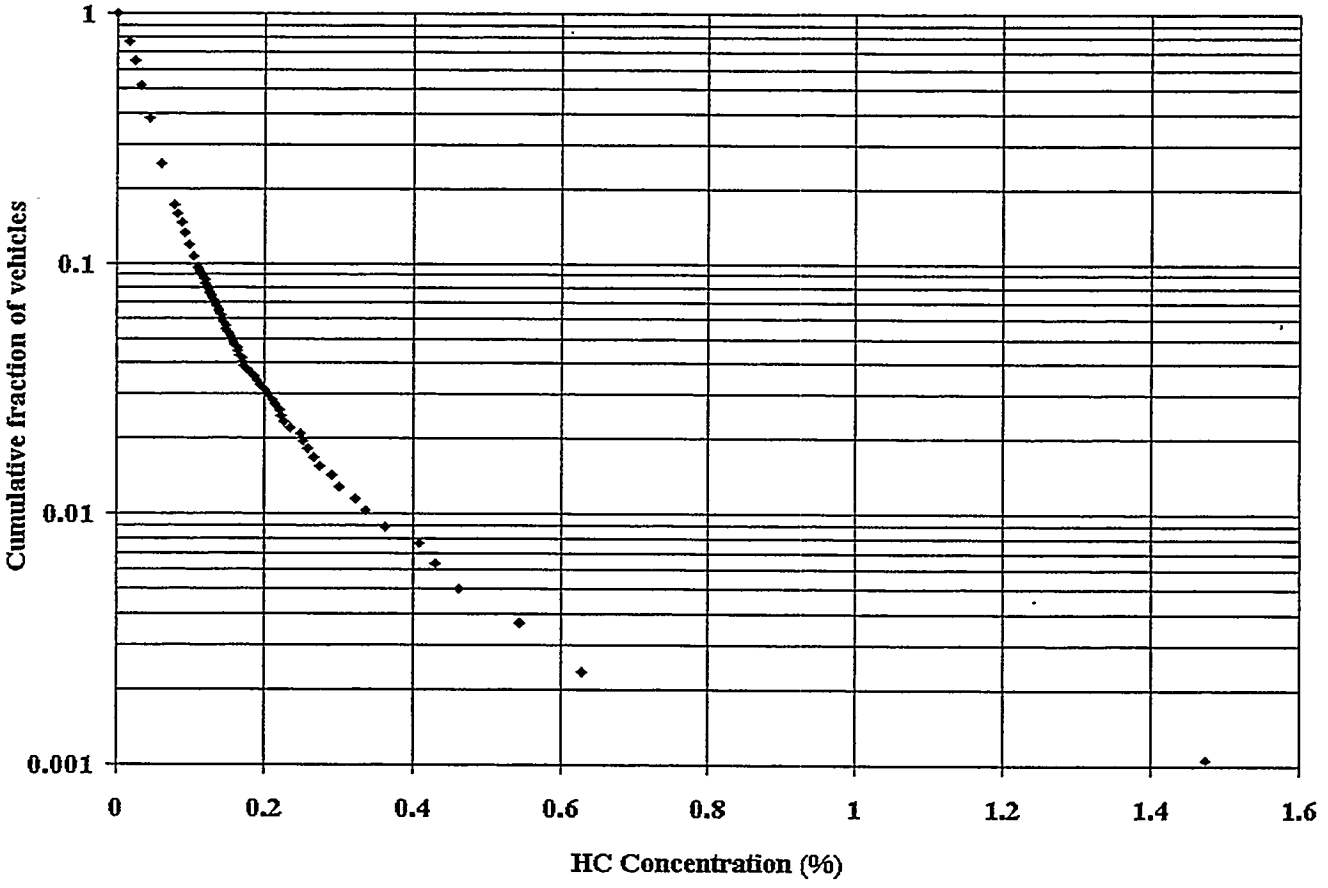


Table A.13. Pollutant concentration for properly functioning cars — FTP-RP dynamometer data

	$g_{pollutant}/g_{fuel}$, Table A.6	conversion factor at low concentration	concentration (%)
CO	0.0070	7.7	0.054
HC	0.00080	4.9	0.0039

residual in the remote-sensing data after identifying the m-cars with a particular cutpoint may exaggerate p-car emissions; in effect, the cutpoint may be too high.

For HC the corresponding results are:

$$\text{conc} = [2800/(572 - 146 \cdot \text{conc})] \cdot r,$$

and

p-car HC concentration (%) = 0.0039.

HC emissions from malfunctioning cars. The data for HC is much poorer than that for CO. One powerful indication of this is that the average HC concentration found by the General Motors group at the same site and time (Stephens 1994b) is much smaller than found by the University of Denver group (the data we are using), e.g. 0.014 and 0.042%, for MY87 cars, respectively. The CO measurements by the two groups are, instead, quite consistent. The difficulties with accurate determination of HC concentrations are associated with the low concentration of HC and the large number of species and their different infrared signatures (Stephens 1994c; Butler et al. 1995). The mixture of species varies with different gasolines and with the emissions mechanism (e.g. with misfire or fuel enrichment). A related challenge to accurate analysis of high HC emitters is the lack of a clear transition from central peak to tail. (See figure A.17.) As a result of these limitations, we do not attempt to extract information directly from the HC remote-sensing data. Instead we rely on the CARB "as-received" dynamometer data.

The CARB "as-received" dynamometer survey. We study dynamometer bag measurements by CARB on 78 MY87 and later cars recruited in 1993-4. One purpose is to test the validity of the malfunction-emissions results from remote sensing. Another purpose is to analyze HC emissions from m-cars. This dynamometer data involves only one-hundredth as many cars as the remote sensing data analyzed here, and the sample may be biased because the vehicles had to be recruited. The results are valuable, nevertheless, because the measurement technique is quite different, involving emissions over a cycle instead of at an instant; and the measurements are accurate for HC and NO_X as well as for CO.

The Stephens plot for CO emissions in FTP bag 2 by the 78 cars, figure A.18, speaks for itself. It is highly similar to fig. A.16 from remote sensing. The fraction of malfunctioning vehicles, taken as the tail of the distribution, is roughly 10%, and the average malfunction emissions are about 25 times those from the FTP-RP of 1 g/mile, comparable to the ratio of about 50 found from the remote sensing data. Moreover the particular vehicle models among these high emitters strongly overlap the high-malfunction-probability models identified by the remote sensing study (discussed in section B.5). The "as-received" data includes some carbureted cars.

The main difference between figures A.16 and A.18 is the narrower central peak of the bag data, showing that there is less fluctuation in the bag data than in the remote sensing data. The break between the central peak and tail is seen to occur at about 10 g/mile (FTP bag 2); this corresponds to about 10 times the emission rate for the FTP-RP sample (bag 2) as seen in table A.4, or a CO concentration of 0.5%. This suggests that 0.5% might, in principle, be a better cutpoint for the malfunction designation than 1.0%. Fortunately for our analysis, the total malfunction emissions are not sensitive to this cutpoint,

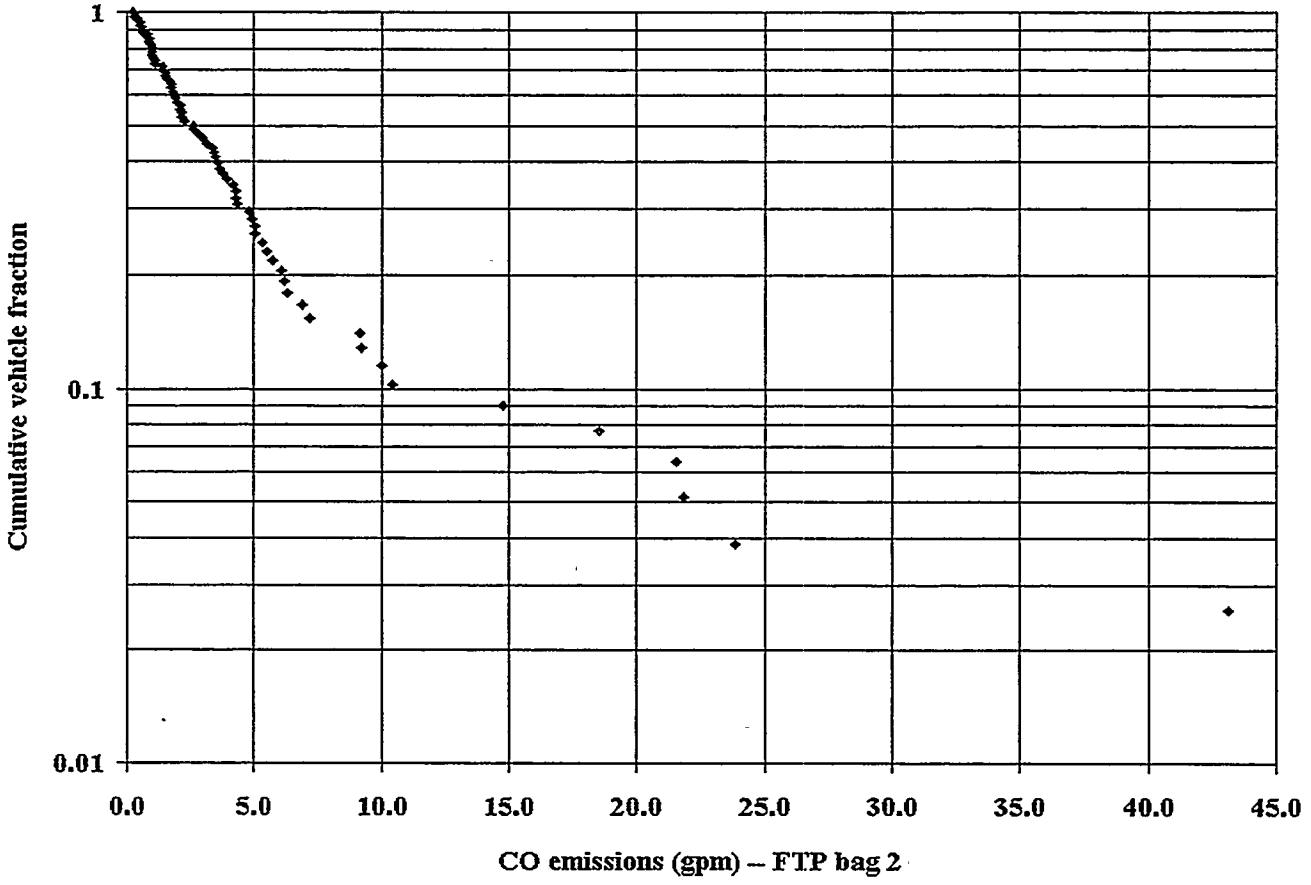
even while determination of the percent of malfunctioning cars is. The tail may also drop more rapidly in the dynamometer than the remote-sensing data, but the statistics of the former are inadequate.

This dynamometer data also enables accurate determination of the emissions of properly-functioning cars. Using a 10 g/mile cutpoint for p-cars, the average CO emissions are 2.5 times the average emissions (for the same bag) for the FTP-RP sample, similar to the discrepancy found with the remote-sensing data (as discussed in section A.1). The HC and NO_X bag 2 emissions from these data are about 1.7 times the FTP-RP emissions.

One of the troubling questions about the remote sensing data has been whether most of the high emitters identified by the method might simply be properly-functioning vehicles in transient command enrichment. These dynamometer results show that interpretation to be incorrect, because in FTP bag 2, less than one second in a thousand is in enrichment in the FTP-RP sample. (The sites selected for the remote sensing survey and the results for vehicles with multiple readings (section B.5) also argue against such an interpretation.)

Beyond confirming the essential results we obtain from remote sensing on CO, the as-received dynamometer data enables comparison of CO, HC and NO_X. The HC distribution, figure A.19, is similar

Figure A.18. Stephens' plot of CO emissions (CARB "as-received" dynamometer data — MY87 and later cars)

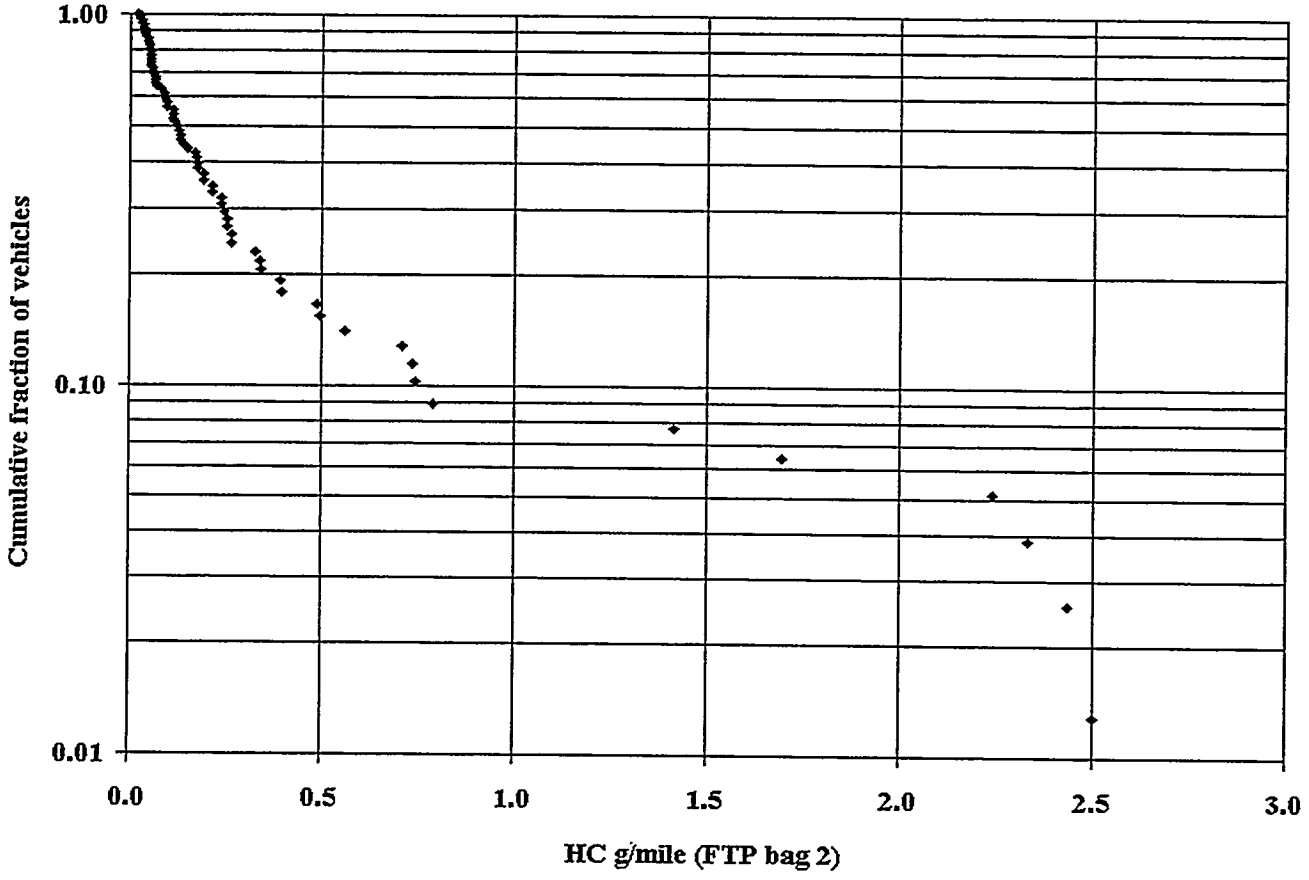


to, but more definitive with respect to the malfunction tail, than from remote sensing, fig. A.17.

When the high CO emitters and high HC emitters are put on a scatterplot (figure A.20), this shows that the same fraction of vehicles have malfunctioning ECS by an HC- as by a CO-criterion. (This is not so clear in the remote sensing data, where one might use a relatively high cutpoint and think there is a smaller proportion of high HC emitters than high CO emitters.) Indeed the overlap among individual high emitting vehicles is almost complete, such that almost all of the high CO emitters are high HC emitters. The dotted lines in figure A.20 are rough suggestions for the transition from p-cars to m-cars according to CO or HC criteria; they are chosen by inspecting figures A.18 and A.19. (The break point in the HC distribution is not, however, clear.) The CO criterion at 10 g/mile corresponds to about 0.5% concentration. The HC criterion at 0.4 g/mile corresponds to about 0.02% concentration.

There is a hint in figure A.20 of some moderately high HC emitters that are low CO emitters. Misfire can cause major engine-out emissions of HC. The degree to which the engine-out exhaust is oxidized by the catalyst depends on details. In addition, strong puffs of HC are associated with lean air-fuel mixtures that occur as transients in some properly functioning cars. The remote sensing data also suggests that there are a few high HC emitters that are low CO emitters. Some 10 to 15% of the high HC emitters appear to be p-cars in terms of CO (with CO concentration < 0.1%).

Figure A.19. Stephens' plot of HC emissions (CARB "as-received" dynamometer data — MY87 and later cars)

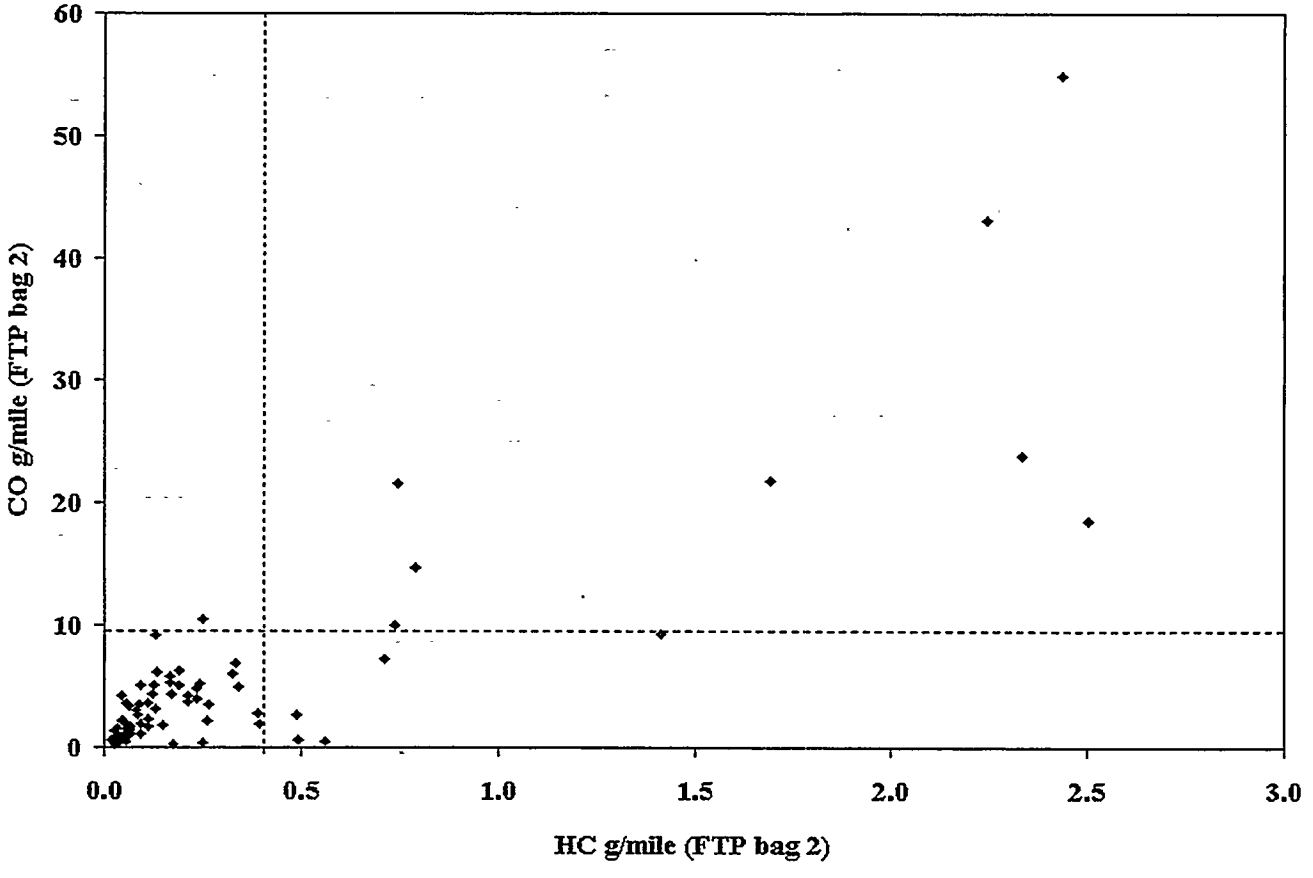


There is no corresponding tail in the NO_X distribution (not shown). Moreover, the high CO and HC emitters are scattered throughout the NO_X distribution. It is premature to draw conclusions about the overall NO_X emissions of cars with malfunctioning ECS. However, one possibility is that these emissions are small, much smaller than the 0.8 g/mile obtained as a difference from MOBILE5 and shown in the summary table A.2.

Results. Consider the CO concentration > 1% criterion to define m-cars, and MY87 cars to define typical lifetime average emissions. From table A.12, x = 2.79% is the average concentration for m-cars, and a = 0.084 is the fraction of cars that are m-cars. Let z be the average concentration for the non m-cars. *The incremental* malfunction emission (as a CO concentration) spread out over all cars is then a(x - z) = 0.22%. (Here to correct for the background we have used z = 0.14. See the discussion at the beginning of Appendix A.) This is 4.1 times the p-car concentration from dynamometer data (table A.13).

This is for hot moderate driving. It is unfortunate that we do not have measurements on malfunction emissions in cold start. We take the corresponding *factor* for cold start to be one-fifth as great. This is an educated guess based on examination of measurements of bag emissions of "as-received" vehicles by CARB (Gammariello & Long 1993). Another approach, which yields the same answer, is to assume that malfunction emissions per car in both cold start and warmed-up operations are

Figure A.20. CO vs HC bag 2 emissions (CARB "as-received" dynamometer data — 78 MY87-92 cars)



roughly the same as the pre-control level, and note that cold start emissions of p-cars are 5 to 6 times higher than in warmed-up driving (table A.4). We thus take the malfunction emissions to be 4.1 times the hot moderate-driving rate for p-cars (0.98 g/mile from table A.2) plus 0.2 times the corresponding amount for cold-starts (2.32 g/mile from rows (2a) + (2b) of table A.2). That is the basis for the entry of 6 g/mile [4.1 x (0.98 + 0.2 x 2.32)] for CO malfunction in table A.2.

For HC the malfunction emissions in hot moderate driving are taken to involve the same factors times the emissions from p-cars. That is the basis for the entry of 0.6 g/mile [4.1 x (0.09 + 0.2 x 0.25)] for HC malfunction in table A.2.

There are elements of these calculations that are rough. Let us compare them with the estimates obtained by subtraction from MOBILE5a (table A.1). The CO estimate adapted from MOBILE5a is roughly 1.5 times the 6 g/mile estimate made here, while the HC estimate adapted from MOBILE5a is two-thirds the estimate made here.

Unfortunately the remote sensing survey we analyze does not have any information on NO_X; we rely entirely on MOBILE5a for it.

A.6. Upstream Emissions

When comparing emissions between gasoline vehicles and electric vehicles, emissions of up-stream energy production facilities for gasoline vehicles are often ignored, even though up-stream power-plant emissions for electric vehicles are considered. In this report, we estimate up-stream emissions, as well as vehicular emissions, for gasoline vehicles in order to put both gasoline vehicles and electric vehicles into a fuel cycle perspective.

Table A.14. Upstream emissions of gasoline production (grams per mile driven with gasoline vehicles)

Model Year	Pollutant	Crude Recovery	Crude Transport	Crude Refining	Gasoline T&S&D	Total
1993	VOC	0.020	0.008	0.007	0.063	0.098
1993	CO	0.013	0.001	0.028	0.020	0.063
1993	NO_X	0.037	0.009	0.215	0.053	0.315
2000	VOC	0.020	0.008	0.007	0.063	0.097
2000	CO	0.013	0.001	0.028	0.020	0.063
2000	NO_X	0.035	0.009	0.213	0.053	0.310
2010	VOC	0.018	0.007	0.005	0.055	0.085
2010	CO	0.011	0.001	0.025	0.018	0.055
2010	NO_X	0.025	0.008	0.172	0.046	0.251

Fuels are burnt for crude recovery, crude transportation, crude refining, and gasoline transportation, storage, and distribution (T&S&D). Fuel combustion during these processes produce emissions. In addition, gasoline evaporates during transportation, storage, and distribution. One of us has recently developed a fuel-cycle model to calculate fuel-cycle emissions of gasoline vehicles as well as alternative fuel vehicles (Wang 1995).

In the model, energy consumption is first calculated for a fuel production stage. Then, with the calculated energy consumption and emission factors in grams per million Btu of energy consumed, emissions in grams per gallon of gasoline produced are calculated for the fuel production stage. Emission factors of fuel combustion for various combustion processes used in the fuel-cycle model are derived from various sources, including EPA's AP-42 documents. Finally, with fuel economy of gasoline vehicles, upstream emissions in grams per gallon are converted into grams per mile driven. Table A.14 below presents our estimated up-stream emissions for the criteria pollutants being considered in this report.

Note: Up-stream emissions of 1993 MY cars were calculated in 1998 calendar year, 2000 MY cars in 2005, and 2010 MY cars in 2015. We assumed 23.8 MPG for 1993 and 2000 MY cars, and 27.2 MPG for 2010.

B. Projection of Lifetime Emissions Per Mile for Model-Years 2000 and 2010

For every physical source of emissions 1 though 6, changes in regulation and technology are taking place. The major regulatory changes have been briefly indicated in the history (section 2). Important details will be given here in each area. In addition, our evaluation of the changes are discussed, and the main assumptions underlying our projection in most of the source areas are explained. The predictions are shown in table B.1.

B.1. On-Cycle Emissions of Hot Properly-Functioning Cars

Automotive engineers, designers and manufacturers have the capability to meet more-stringent standards for emissions from properly-functioning vehicles, in moderate driving, in a timely fashion. They can substantially reduce emissions through improved sensors, better fuel injectors and more uniform performance among engines of a given model, as manufactured, to keep the fuel-air ratio closer to stoichiometric. This results in substantially smaller catalyst pass fractions than the averages for MY93. Some of this can be accomplished relatively easily and at reasonable cost, as demonstrated by the better-performing engines of today. Many of the post 1993 federal and California standards, including LEV standards, can be met in this way.

In addition, more-powerful new technology is in the wings: real-time measurement and control of the cycle-by-cycle performance of individual cylinders. Measurements of performance in each cylinder at each cycle can be made, for example, by pressure sensors in each cylinder, by observing the rotational acceleration of the flywheel, or by measurements in the exhaust manifold. Moreover, fuel injection can be fully controlled cylinder-by-cylinder and cycle-by-cycle with direct injection of fuel into each cylinder. Variation in performance among cylinders and cycle-to-cycle is believed to be an important source of emissions. Their reduction, and other improvements, such as improved catalysts to reduce cold start emissions, should enable meeting the "ultra-low" emissions standards for properly-functioning vehicles in moderate driving. Many of these are development areas, but the Honda ULEV includes some of this technology, and other technologies will be in production soon (American Honda 1995).

In other words, the variety of low and ultra-low emissions standards can be achieved in the laboratory-like tests used for emissions certification. Most, and possibly all, of these improvements can

Table B.1. Sources of emissions (g/mile) for MYs 2000 and 2010 cars, averaged over vehicle life

	CO		HC		NO_x	
Source	MY2000	MY2010	MY2000	MY2010	MY2000	MY2010
Hot, on-cycle + cold start[a]	2.9	1.4	0.22	0.11	0.26	0.13
Evaporation[b]	0	0	0.37	0.37	0	0
Off-cycle[a]	2.4	2.4	0.036	0.036	0.1	0.1
Malfunction	5	2	0.4	0.2	0.6	0.3
Upstream	0.063	0.055	0.097	0.085	0.31	0.25
Total	10	6	1.1	0.8	1.3	0.8
Tailpipe standards	3.4	1.7[c]	0.25[d]	0.125[c]	0.4	0.2[c]

a) Properly functioning cars.
b) MOBILE5a prediction.
c) Tier 2 standards.
d) Non-methane hydrocarbons.

be achieved at moderate cost. We are not at all saying that these are simple challenges, but they are challenges the manufacturers can and will, as appropriate, meet.

Prediction. The prediction concerns both how many LEV vehicles are produced and how much "headroom" the manufacturers decide to have between certification test emissions and the regulatory limits. For the prediction we assume that cars will pass the certification tests (50,000 miles) at 60% of the regulatory limits, Tier 1 for MY2000 and Tier 2 for MY2010. This applies to the present FTP. Including the 20°F cold start to represent winter experience, we obtain the top row of emissions in table B.1.

B.2. Cold Start Emissions of Properly-Functioning Cars

Another source about whose reduction (in properly-functioning vehicles) one can be optimistic, is cold-start emissions. This has been a focus of development by manufacturers in recent years. Manufacturers are meeting the new standard for cold start emissions at 20°F.

In the first stage of a cold start, the engine is cold; and drivability problems have been solved by fuel enrichment and control of spark timing. These lead to high emission rates. With improved real-time information and control with respect to fuel mixture and combustion, the time in enrichment at the initiation of a cold start has already been substantially reduced and will be reduced further.

The catalyst is cold for a period long beyond the initial enrichment. A great deal of effort has been devoted to hastening catalyst light-off. Electrically-heated catalysts were first explored as a solution. Adding a close-coupled catalytic converter in the exhaust line close to the exhaust manifold, so that it heats up rapidly, is a less expensive solution. The catalyst can be formulated so that it resists damage from the increased temperatures which would normally occur in this position. A similar approach is already in use with big engines, more particularly high displacement-to-weight vehicles. Other vehicles, such as the Ford Escort, also use close-coupled catalysts.

If the stiffer Tier 2 standards are adopted for cold start, more drastic measures such as electrically pre-heated catalysts might be required.

B.3. Evaporation

Vehicular evaporative emissions can be reduced through lower gasoline RVP and installed on-board canisters which absorb evaporative emissions. Refueling emissions in gasoline service stations due to vehicle refueling can be reduced by the so-called Stage-II technology which returns vapors from vehicle gas tanks to underground storage tanks during refueling, or by on-board canisters which absorb vapors from gas tanks. Currently, Stage-II technology is required in many ozone non-attainment areas. Beginning in 1998, on-board canisters will be required for controlling refueling emissions. These canisters can be designed to integrate with the canisters that are currently installed for controlling diurnal and hot soak evaporative emissions. To control running loss emissions, CARB has established a running loss emission standard of 0.05 grams per mile for 1995 MY cars. EPA is likely to follow the CARB's requirement. These efforts are being supported by new instrumentation for measuring evaporative emissions (and associated standards) for multiple hot soaks and evaporation while running. Evaporative emissions are measured in a completely sealed flexible-wall shed in which multiple high-temperature excursions, or hot soaks, simulate conditions of cars parked for several days in hot weather — conditions in which the canister becomes full and then releases vapor to the atmosphere.

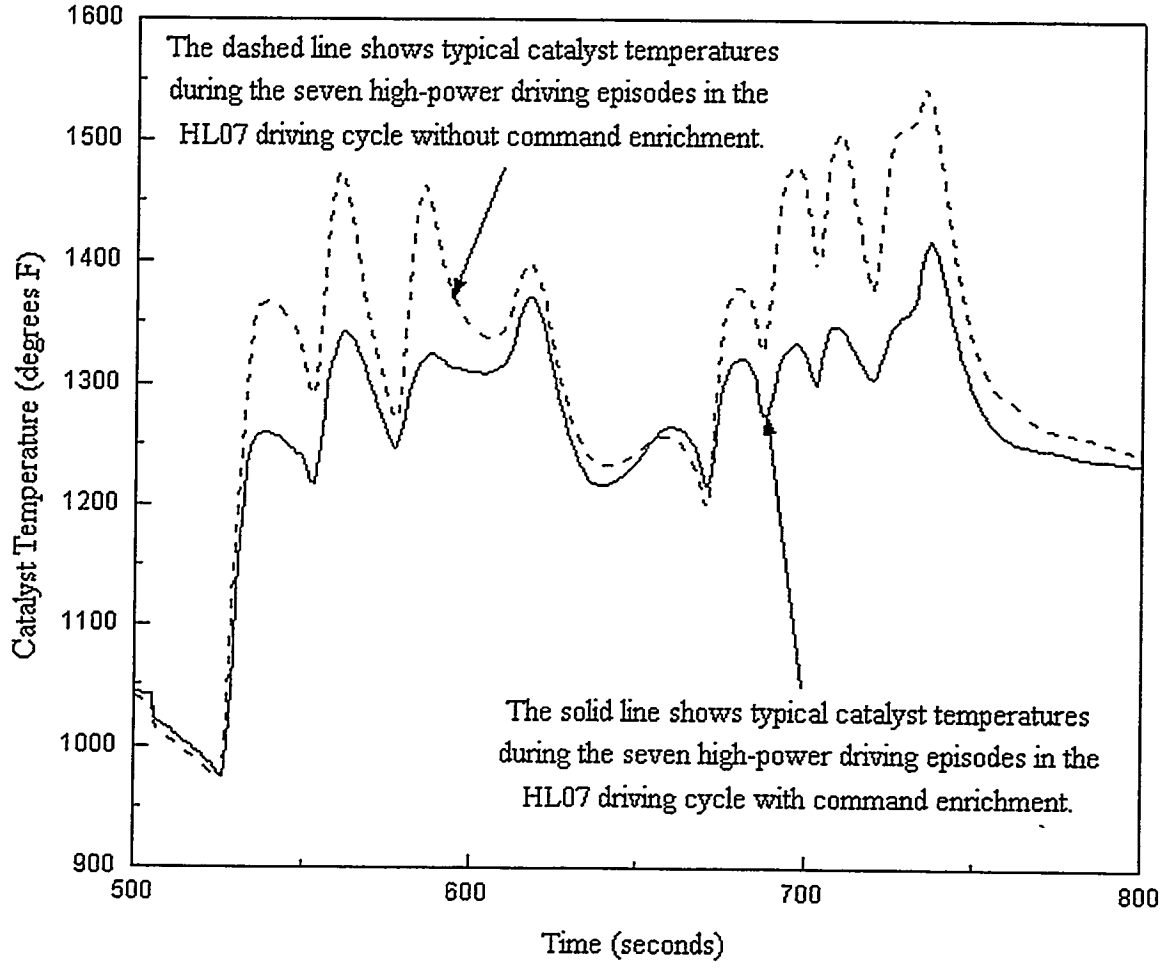
As discussed in section 5.3, malfunctions in the fuel system are responsible for much of the evaporative emissions, and their measurement and diagnosis remains difficult as of this time. For this reason, we feel that the relatively small reduction of 25% forecast in MOBILE5a is reasonable.

B.4. Off-Cycle Operation of Properly-Functioning Cars, High and Moderate Power Driving

Proposed new rules, including a test-cycle with higher-power driving, are likely to be incorporated into a revised Supplemental FTP (section 2.3). It is likely that the SFTP will lead to the introduction of timers onto vehicles that will delay the onset of command enrichment for a period that may be as long as eight seconds during high-power driving. In addition, manufacturers may be able to minimize the level of enrichment needed to protect the catalyst from overheating. These are measures which have been adopted in some vehicles.

Command enrichment as practiced. Starting points for discussion are: 1) the rationales for command enrichment and 2) command enrichment practices. Command enrichment, or the deliberate override of emissions controls and introduction of excess fuel, as increased power is called for by the driver, has several rationales — rationales which seem to depend on the engineer you ask. At any engine speed, the maximum power an engine can produce is perhaps 3% higher than at stoichiometric with a

Figure B.1. Catalyst temperature during high-power driving with and without command enrichment



10% rich fuel-air mixture (Heywood 1988, p 830). Improved drivability when the driver sharply depresses the accelerator pedal with a carbureted engine was also a rationale for command enrichment; and avoidance of knock continues to be a rationale.

There are, in addition, two emissions-related rationales for command enrichment: 1) Catalysts can overheat when engines are operated stoichiometrically at high power. (See figure B.1: The power factor for these enrichment events was approximately two times the FTP maximum.) The catalyst becomes 100° to 150° F hotter without enrichment in high power episodes. This overheating takes only a few seconds. In long high-power episodes the catalyst may become 250°F hotter. The overheating can of course be lessened or delayed by appropriate engineering measures; but it is a serious problem at the highest engine power output. It need not be a problem at low or moderate engine speed or in the first few seconds of an episode of high-power driving. Damage to the engine from overheating is also a possibility.

2) NO_X emissions increase substantially when engines are operated stoichiometrically at high power, because NO_X emissions increase very rapidly with maximum in-cylinder temperature, i.e. with fuel rate when operating stoichiometrically. As figure A.5 shows, fuel enrichment dampens these temperature increases and high-power NO_X emissions.

The details of command enrichment design do not appear to have received high priority by US and Asian manufacturers. One finds that among most US and all Asian vehicles tested (in the public domain) that the enrichment practice is to take advantage of the letter of the law rather than its spirit, as illustrated in figure A.7 above. That is, the threshold for command enrichment is just beyond the driving conditions in the test for emissions certification (FTP), and the degree of enrichment (up to an air-fuel ratio roughly 11.5) is unnecessarily high, mimicking that found with carbureted engines. However, some vehicle/engines exhibit much more caution about command enrichment: the threshold is remote, at the highest engine speed and power, and the degree of enrichment is reduced. This limited enrichment strategy is particularly common in European makes.

Possible changes in enrichment design. As many as three changes might occur as a result of the proposed rulemaking: 1) Command enrichment may be avoided at low engine speeds where power output is not really high even at low manifold vacuum. Immediate response by the engine to the driver's call for power will be achieved with much more accurate fuel delivery and mixing, including knock control (e.g. through spark timing). 2) Enrichment will be delayed a few seconds at high power using a "timer". As indicated by figure B.1, the catalyst heats up quickly, so only a brief delay is likely to be tolerated. 3) The degree of enrichment will be less. Excess fuel of 15%, rather than 20 to 25% is already practiced in several vehicles. All three techniques have already been employed, especially (1) and (3) in European vehicles.

Prediction. In terms of the three kinds of driving patterns discussed in section A.4, these measures will: 1) partially reduce command-enrichment emissions in major high-power episodes, 2) eliminate command-enrichment emissions in brief accelerations, but 3) not substantially reduce command-enrichment emissions from sustained driving, principally in underpowered operations.

Analysis of the EPA six-parameter in-use driving data indicates that approximately 70% of the total enrichment driving time (both mild and severe enrichment modes combined) is contained in events that last 8 seconds or less. Therefore, if the industry adopts 8-second enrichment delay timers in response to the SFTP, command enrichment emissions could be reduced by 70% from 7.9 and 0.12 g/mile to 2.4 and 0.036 g/mile for CO and HC, respectively (table B.1). These reductions apply for both MY2000 and MY2010. This prediction assumes that the distribution of mild and severe enrichment modes does not

Table B.2. USEPA estimated emissions reductions (g/mile) resulting from supplemental FTP

Control area	NMHC reduction	CO reduction	NO_X reduction
High speed/accel	0.055	2.39	0.062
Air conditioning	0.000	0.00	0.091

depend on the duration of an enrichment event and that the degree of enrichment will not change in the future. If severe enrichment is more likely to occur in extended duration enrichment events (i.e. long hill-climbing), which would not necessarily be addressed by the SFTP, then these reductions may be lessened. If, however, the overall degree of enrichment is reduced by automakers in future cars, then these reductions could be increased.

EPA estimates for emissions reductions due to the SFTP are shown in table B.2 (60 FR 7407). Our prediction for CO reduction is approximately two times theirs, while our predictions for HC and NO_X reductions are roughly consistent with theirs. (Compare off-cycle emissions in tables A.2 and B.1.)

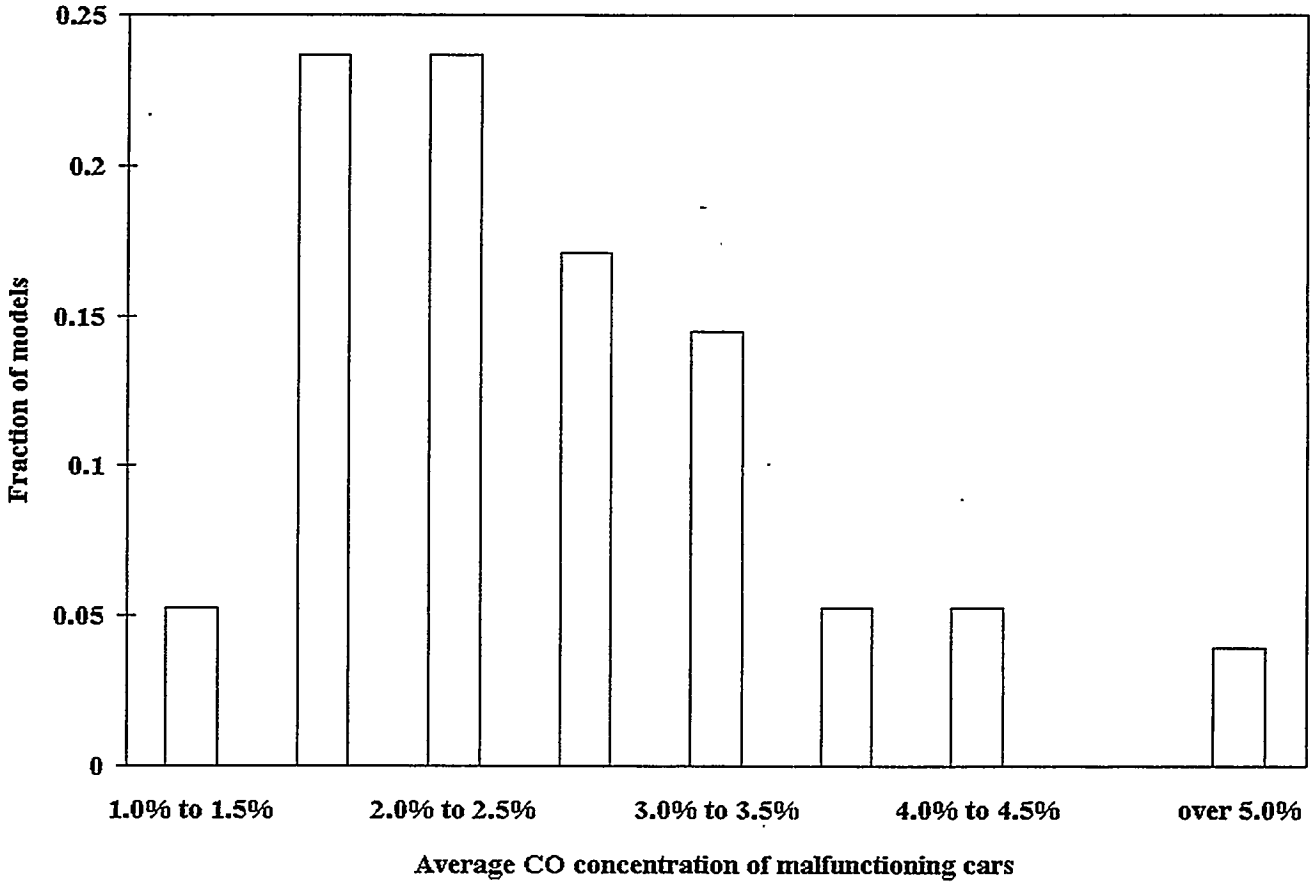
B.5. Malfunctioning Exhaust Emissions Controls

The nature of malfunctions. A substantial portion of CO, HC and, NO_X emissions are due to malfunctioning emissions controls. In the past, the responsible EPA office has stated that these failures are in large part due to "tampering", (presumably) deliberate disabling of emissions controls or related parts (USEPA Tampering Survey 1990). One flaw in the tampering argument is the data that supports it. EPA protocols for visual inspection label some faults as tampering, although they may be due to "natural" causes. Without, however, making a judgment on the validity of the importance of tampering for earlier vehicle models, we conclude that the claim is now out of date. There is no evidence showing that computer-controlled models of the post-carburetor, post-leaded-gasoline eras suffer from substantial deliberate disabling of emissions controls. The CARB Random Roadside Inspection Survey found, for a sample of MY80 and later cars with 3-way catalysts, tampering rates of only 2 or 3% (Rajan 1990 and 1991). They found much higher tampering rates for vehicles with older technology; and we believe tampering rates are almost certainly much lower than this for recent models. Our claim that tampering is relatively uncommon in modern cars is, however, controversial. One reason it is uncertain is that the publicly-available tampering survey data is now five and more years old, and vehicle age (given a fixed MY) is a major determinant of tampering rates. It is important to establish that tampering plays only a minor role in modern cars, because much of the past policy discussion has been motivated by a focus on tampering; we provide evidence in the form of vehicle model dependence, below.

Are emissions control failures fundamentally the result of flaws of design/manufacture, or are they due to actions or mistakes by owner/drivers and in servicing vehicles? In this section we address this question by focusing on malfunctions as they depend on vehicle model. The number of observations in the remote sensing study we use is large enough for an initial study of the dependence of malfunction on vehicle model.

The emissions of cars with malfunctioning ECS (m-cars). Whatever their proximate cause, it is clear why m-cars have very high emissions. For example, catalyst failure increases the catalyst pass fraction from a few percent to near 100%. Failure of fuel-air controls increases CO emissions even more, as seen comparing tables A.6 and A.8. Frequent misfire causes high HC emissions.

Figure B.2. Probability distribution of models, by percent concentration of CO from malfunctioning cars (MY87-89)



In figure B.2 the average CO concentration is shown in terms of the fraction of models in each concentration interval. The criterion for malfunction here is $x > 1\%$, where x is the CO concentration percent. The data are MY-model combinations from MYs 87-89, all the MY-models in the sample having at least 50 cars. In this figure only emissions by m-cars are considered, and each model's average CO concentration for m-cars. Thus, for a randomly selected model, the probability the model's average CO concentration for m-cars falls in a particular percent interval is shown. Averaging over these models, the average CO concentration is 2.6 ± 0.7 % (standard deviation).

The average CO emissions of m-cars are thus found to be rather well defined. The emissions are high, averaging over 40 g/mile — in moderate driving with the engine/catalyst hot, compared to about 1.0 g/mile for p-cars in bag 2 driving (table A.6). The emissions also correspond, as mentioned in section A.4, to operating with an air-fuel ratio of about 13.0.

On the basis of the same remote sensing survey and the "as-received" dynamometer survey, a roughly similar story can be told for HC.

The probability of malfunctions. The incremental emissions due to malfunctioning vehicles is the product of the probability that vehicles malfunction and the level of emissions per malfunctioning vehicle, minus the average on-cycle emissions rate from properly-functioning vehicles, TP_1 (beginning of Appendix A):

$$\text{incremental malfunction emissions} = [\text{probability of malfunction}] \cdot [\text{emissions per m-car}] - TP_1.$$

As suggested by figure B.2, the second factor does not vary strongly, at least with today's emissions control technology. The first factor is perhaps *the most important issue for this report: the probability for vehicles to have emissions control failures*, and how that probability depends on the vehicle model, on improved emissions control technologies and on mitigation programs.

Consider, as for figure B.2, MY-model combinations from 1987-89 with at least 50 cars in our remote sensing sample. The probability for malfunction is shown in figure B.3, against the average CO concentration for all cars of the MY-model. (Malfunction is again defined as CO concentration >1%. There are 76 individual MY-models — 37 different models — shown.) The spread is very large, with six MY-models in the sample having none or only one high-emitter, and five having more than 25% high emitters. The apparent intercept on the x-axis, at about 0.07% concentration, is essentially consistent with expectations for p-cars (table A.11).

The emissions implication of high malfunction probability for a model is clear. Since the emissions per m-car are very high relative to regulatory standards, the average emissions for all cars of a model with substantial probability of malfunction are far higher than the standards. For example, in figure B.3, the average emissions of *all* cars in the group of models with malfunction probability over 15% is

Figure B.3. Malfunction probability vs average CO concentration, 76 MY87-89 models with over 50 different vehicles observed in the 1991 CARB Remote Sensing Data

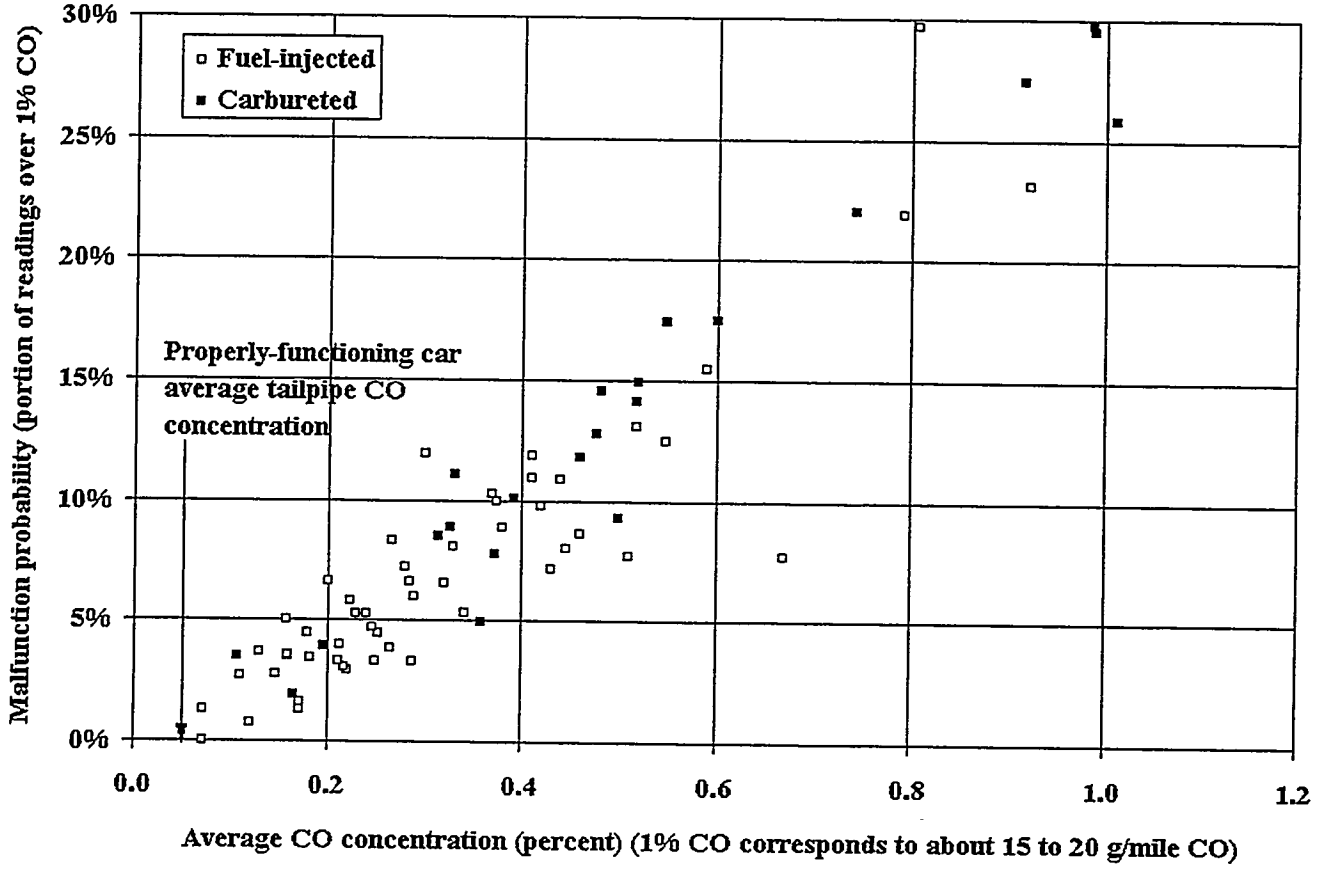


Table B.3. Dependence of CO malfunction probability on the number of remote sensing observations per vehicle — for a group of five MY87-89 models with high malfunction probability

number of observations per vehicle	total cars	cars with x > 1%	malfunction probability
1 or more	2256	519	22.0%
2 or more	669	173	25.9%
3 or more	182	38	20.9%

over ten times the p-car level.

Let us examine the emissions of the best and worst of these models. There are 21 different models in the group with probability of malfunction 7.5% and under. This is the best half, with 38 different MY-models. These include GM and Ford products, one European car and several Japanese-manufacturer vehicles. (Note that the requirement for 50 cars in the sample eliminates many models from consideration. With the California sites involved, most are Asian models. For this reason among others we feel it is premature to name models.) Both luxury cars and popular mid-price vehicles are included, though no bottom of the line vehicles. All but one of the engines in this group are from 2.0 through 3.0 liters. The average probability of malfunction for these 7.5% and under models is 4%. If we consider the best quartile of models, there are nine models (19 MY-models) with an average probability of malfunction of 2.6%.

On the other hand, the worst third of the models (19 MY-models — 11 models) each has probability of malfunction greater than 12%. These are mostly inexpensive models (and, for reasons stated above, almost all Asian cars). Five of the 9 engines are under 2.0 liters.

Since the distribution shown in figure B.3 and its interpretation is critical to our predictions, it is essential to check its validity. There might be some bias in the remote sensing data working against those models that have a high frequency of high emitters. In particular, we may be misidentifying cars observed with momentary high pollutant concentration as malfunctioning. Consider some checks. For almost all the models the probability for malfunction from one MY to the next is found to be strongly correlated. Thus the results shown in figure B.3 are not due to random variation. In addition, we examined whether the poorest models were equipped with carburetors or air pumps. In fact, carbureted models are more likely to have a high proportion of malfunctions. However, the fuel-injected models also include some with high malfunction probability.

Most important, we find that the probability for high emitters in the group of poorest-performing models (five models with two or more adjacent MYs, and each probability greater than 13%) is essentially unchanged when we restrict the sample to vehicles which were observed two or more times, or to vehicles observed three or more times, multiple readings for the same vehicle being averaged (table B.3). This shows that particular vehicles are high emitters, rather than all vehicles of certain models having an unusual propensity for high emissions.

What about the possibility that many cars of the poorest models shown in fig. B.3 happened to be in command enrichment at the instant the remote-sensing observation was made? This is very unlikely to explain the 15 to 30% frequency of high concentrations found for these models. The driving pattern data (section A.4) shows that only 1 to 5 % of driving time is spent in conditions likely to cause command enrichment. Most of the observations were made at a road site narrowed to one lane with cones and with police presence. That many cars in just these models are still in cold-start enrichment is also unlikely. Moreover, the "as-received" dynamometer data, which is not subject to this problem for FTP bag 2, is consistent with the frequency of high CO emitters in the remote sensing data.

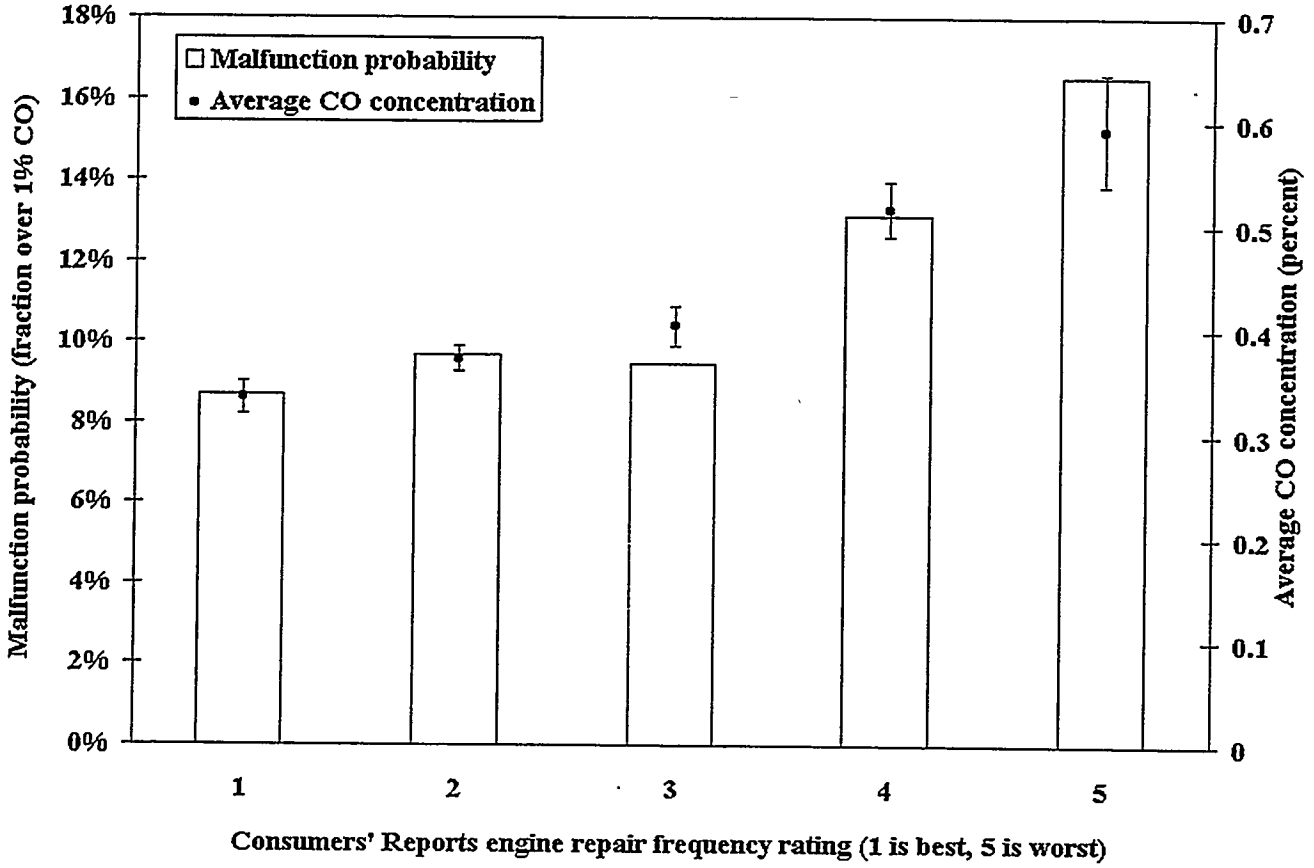
We conclude that the frequency of high emitters in the remote-sensing data is correctly interpreted in terms of the probability of ECS malfunction by vehicle model.

Probability of malfunction and frequency of repair. We compare the probability of malfunction by MY-model with Consumers Union's survey of frequency of repair, focusing on three repair categories: engine, fuel system and exhaust system (Consumers Union 1994). In each category, the rating runs from 1 to 5, increasing with increasing repair frequency. The data by MY-model (MYs 87 to 89 with more than 50 cars for each MY-model), is shown in figure B.4 for engine repairs, the category with the strongest correlation.

When we compare malfunction probability with all three repair categories, the overall correlation is weak, with only 7% of the variation in probability of malfunction associated with the frequency of repair (linear regression). The regression slope is 0.008. In other words, as the combined repair rating changes from 3 to 15, the probability of malfunction increases by 0.09, or 9 points. This is some of the effect one would like to explain, but not most of it. We can conclude that having one's car repaired does not directly cause most of the ECS failures. There may nevertheless be a strong association: Problems that lead to a vehicle being taken in for repair may be associated with problems that lead to ECS malfunction.

Probability of malfunction and "in-use" testing. EPA and CARB have in-use testing programs for

Figure B.4. High emitters vs engine repair frequency, MY87-89 models with more than 50 different vehicles in the 1991 CARB Remote Sensing Data



vehicles with roughly 30 to 50 thousand miles, aimed at checking the certification tests of new vehicles, and at determining whether a vehicle should be recalled for repairs or changes in their ECS. We conclude that these testing programs do not tend to identify vehicles with malfunctioning ECS.

Consider again the five poorest models (14 MY-models) with over 13% malfunction probability for at least 2 consecutive years (MYs 87-89). Of these 14 MY-models, 7 were tested in CARB's in-use program, but only one was recalled (CARB 1995). In fact, the program is not designed to pick-up vehicles of a given model that are unusual; and models with high frequency of high emitters are not found. (See section 2.3.) Instead of finding some models with *average* emissions an order of magnitude higher than regulatory limits, as indicated by the remote-sensing results here, the in-use tests find all models to have average emissions comparable to the regulatory limits.

The recent CARB dynamometer survey of vehicles as-received confirms the remote-sensing results, with roughly 10% of the cars 5 years old and less malfunctioning (section A.5). (This includes both carbureted and fuel-injected cars.) The malfunction criterion for CO is greater than 10 g/mile in the FTP bag 2, where new vehicles with aged catalysts test at 1 g/mile. This survey represents a major departure for "in-use" testing.

Perhaps the most serious barrier to reduction of the probability of malfunctioning emissions controls is the weakness of manufacturer responsibility with respect to malfunction *in the regulations*. Manufacturers must avoid excessive deterioration of components in vehicles "properly-maintained and used," as interpreted by the regulators. Vehicles are subject to recall to correct failures in properly-maintained-and-used vehicles, and to repair failures under warranty. Failures in vehicles that haven't been shown to have been properly maintained and used are not legally the manufacturers' responsibility. The way these regulations have played out in practice gives low priority to manufacturer responsibility for malfunctioning ECS, as such. (On the other hand, manufacturers are involved in identification and repair activities.)

Approaches to reduce malfunction emissions - identification. Three basic approaches are being tried to reduce malfunction emissions: 1) identification of individual vehicles with malfunctions, 2) repair of malfunctioning vehicles, and 3) reduction in the frequency of malfunctions in future vehicle models. By far the largest efforts are going into identification. Costly vehicle inspection programs in areas where ambient pollution exceeds standards are in the public eye. Attempts by EPA to strengthen them, introducing an improved test, the dynamometer test IM240, have been in the news recently. Installation of on-board diagnostic equipment is also a major program for identifying malfunctions. In addition, remote sensing of malfunctioning vehicles is being introduced for identification, some roadside testing being required by the Clean Air Act Amendments of 1990.

Considerable attention has been paid to Inspection and maintenance (I&M) programs as a way to reduce malfunctions. These programs need to be evaluated in terms of modern vehicles, with fuel injection and after the temptation to use cheaper leaded gasoline had disappeared. In our view, the focus on deliberate tampering, and the judgment that inspection is an effective tool against tampering, are largely irrelevant to modern vehicles.

Within the context of I&M, we believe a focus on maintenance, or, more properly, repair, is needed. The Michigan Roadside study, in which 47 high emitters, recruited from roadside inspection, were repaired by the Big Three, demonstrated that successful repairs on modern vehicles can be complex and costly; and difficult to do satisfactorily (McAlinden et al. 1994).

Even though EPA is retreating on the proposed expansion of IM240 inspection programs, strong technological progress is being made with the other identification technologies. The potential for remote

sensing to become a powerful identification tool is excellent. The technology is being rapidly improved to: interpret observations more cleanly, include simultaneous measurement of velocity and acceleration, and perhaps to measure exhaust temperature. The velocity/acceleration measurement allows identification of vehicles likely to be in command enrichment, and the exhaust measurement might allow identification of cold catalysts. In this way, misidentification of malfunctioning vehicles should be sharply reduced.

OBD technology is also being rapidly improved and installed. It is quite different in function from remote sensing in that it provides records relating to the state of emissions control over time (even though no emissions measurements as such are made). This information may provide good diagnostic information for recalls and repairs. By the late '90s, identification of malfunctioning vehicles will be a powerful tool. But will identification of problems lead to progress in repairs or to robustness of ECS?

Approaches to reduce malfunction emissions - repair. At present, there is no reason for optimism about repair of malfunctioning emission controls. The record is poor (Austin and Rubenstein 1994; Lawson 1994; Herbert 1995). This is not surprising, because many of the repairs on modern vehicles are neither easy nor cheap. Unlike repairs relating to vehicle performance, the repair worker often doesn't know whether ECS work has been successful; and the driver doesn't know. This not only leads to faulty repairs, but sometimes to fraud. [Identification of the malfunction by type might be used to help encourage/enforce effective repairs. Second generation OBD might be effective for this, giving repair people immediate and accurate feedback on ECS function.]

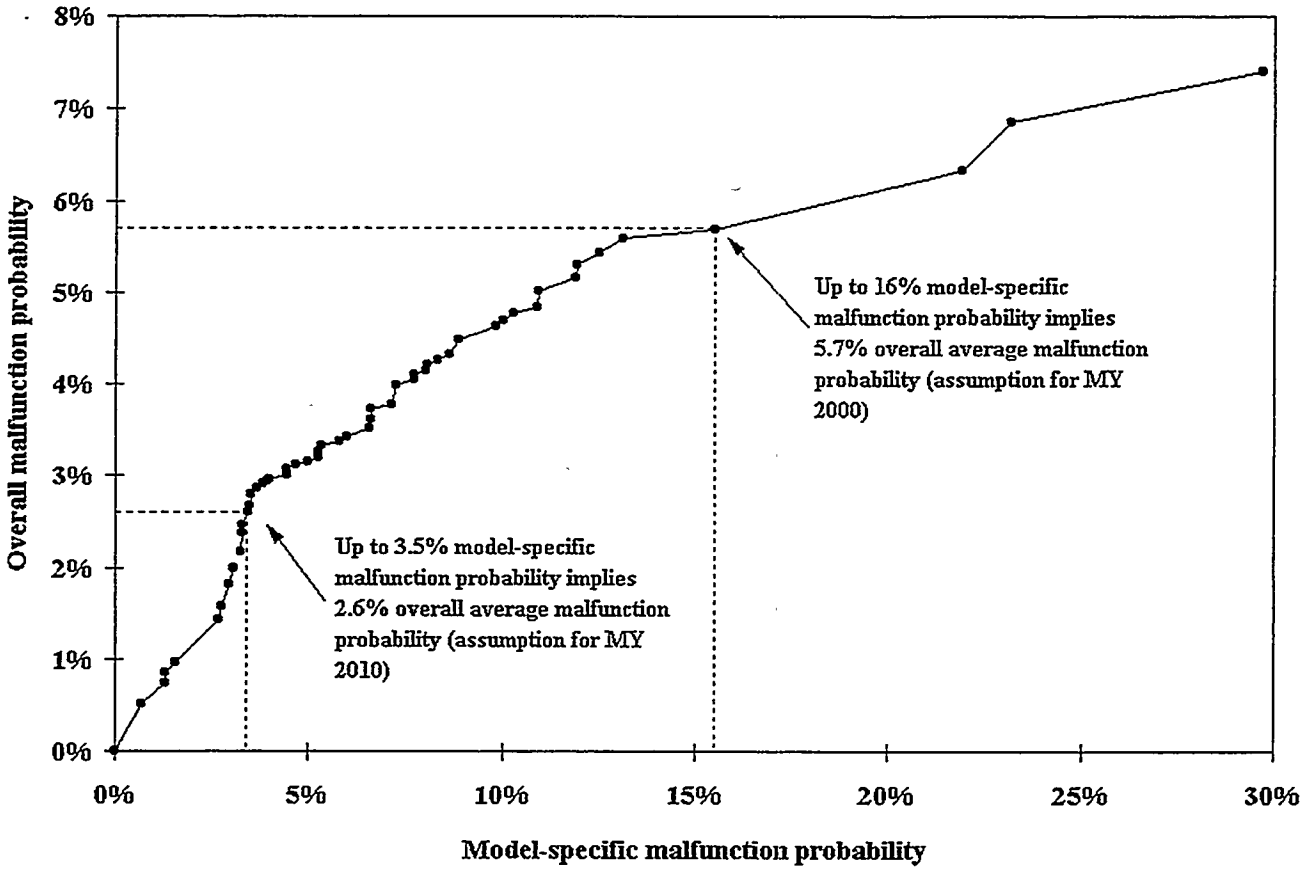
We are not optimistic about inspection programs, remote sensing, or OBD as part of repair enforcement schemes. There are about 60,000 general automotive repair shops, including 26,000 auto and truck dealers. In our view, much better information on the causes of malfunctions in modern vehicles and protocols for their repair will be needed before any even modestly optimistic conclusions can be drawn about the effectiveness of repairs.

Approaches to reduce malfunction emissions - robust ECS in new vehicles. We are much more optimistic about the eventual role of more-robust emissions control systems in reducing malfunction emissions. The central issue in improving ECS robustness is the weakness of connection between identification of failures and the design and manufacture of more-robust emissions controls in new models. This is not a focus of regulations and may not be a priority of manufacturers at present. Much more powerful identification technologies, and well-developed and public identification of results by vehicle model, would change this, however. In our judgment, MY2000 is too soon for most of this progress to have been made, simply because there is little time to establish the information and to improve the design and manufacture. Substantial progress will probably be made by MY2010.

Predictions. The effects of the various potential identification/enforcement/repair programs on the malfunction emissions of an entire MY are the first issue. For the reasons just discussed, our prognosis for major reductions in malfunction emissions through repair programs is poor. Progress in repair effectiveness, for a MY as a whole, will be slow, with little progress by MY2000, and slightly more progress by MY2010.

We are much more optimistic about improving the robustness of ECS. The manufacturers form a far simpler and more capable institution than the repair network. We have shown that many vehicle models are already rather robust against malfunction. The level of malfunction that the best models achieved in MY87-89 forms the basis of our prediction. *Manufacturers can, and probably will, bring all their models up to the ECS robustness standard already met by many of their models.*

Figure B.5. Effect of capping model-specific malfunction probability, based on 54 MY87-89 fuel-injected models with over 50 different vehicles observed in the 1991 CARB Remote Sensing Data



The motivation for this progress depends on 1) improvements in instrumentation for observing malfunctions, 2) carrying out large surveys and promulgating the results, and, 3) modestly strengthened regulatory initiatives. The instrumentation is moving ahead rapidly. Measurements will follow. The connection between new vehicles and this improved information without some modification in regulations is less clear. The reduction of vehicle emissions is motivated by regulations, and the regulations do not have any focus on robustness against ECS malfunction. (We have discussed the lack of connection between the 50,000-100,000 mile certification tests, and the in-use tests, on the incidence of malfunctions.) The connections between vehicle designers on the one hand, and repairmen and other surveyors of emissions-control failure on the other, are weak, as far as we can tell. Two things should change this: 1) information on malfunctions by MY-model should be pouring in, and 2) regulators, perhaps with manufacturer cooperation, should move to require vehicle recalls on the basis of excessive frequency of malfunction. We discuss recall/warranty policy in section 6.5.

The associated emissions reduction will happen gradually. We predict that malfunction emissions of all three pollutants will be reduced in proportion to the average probability of malfunctions, and that the latter can be estimated from the CO data on the MY87-89 models studied. In figure B.5 the results for fuel-injected MY-models shown in figure B.3 are re-plotted to show the average probability of malfunction for all MY-models whose malfunction probability is less than a given level. For MY 2000 we assume that vehicles will be redesigned to avoid being extremely malfunction-prone, in particular that all MY-models will have the probability of malfunction of those models up to 16%. This reduces the

average frequency of malfunction found for the 54 MY-models studied from 7.4% to 5.7%, a reduction of malfunction emissions from that assumed for MY93 of 23%. While we are working from actual data on the incidence of ECS malfunctions, the progress we predict is simply a judgment.

For MY2010, we predict that the average frequency of malfunction will correspond to that of the MY87-89 models studied which had frequency of malfunction up to 3.5%. This reduces the average frequency of malfunction found for the 54 MY-models studied from 7.4% to 2.6%, a reduction of malfunction emissions from that assumed for MY93 of 65%. These two reductions, 23% and 65%, are used to predict the malfunction emissions in table B.1.

The greatest uncertainty about these predictions is not in their practicality or modest cost, but in the motivation to carry them out. At the present time there may be some reluctance on the part of regulators to identify the vehicle models that are prone to malfunction. This needs to be turned around and procedures changed in order that manufacturers put a high priority on ECS robustness. If, in spite of the potentiality of new information sources (large remote sensing surveys, OBD surveys, and as-received testing of in-use vehicles), the information is suppressed, then much less progress will be made than we predict.

Another important question is: Will the emissions of malfunctioning LEV vehicles be as high as those for conventional cars, or will they be correspondingly lower? If properly-functioning emissions controls greatly reduce emissions, then their failure will greatly increase emissions from the control values. We have found that emissions from m-cars are roughly consistent with pre-control levels (roughly 80 g/mile for CO and 10 g/mile for HC, including cold start). Our opinion is that *LEV vehicles with malfunctioning emissions controls are likely to have roughly the same emissions as standard vehicles with malfunctioning controls.* In other words, the relative increase when a LEV malfunctions will be much higher than for today's vehicles.

C. Federal and California Tailpipe Emission Standards

Tables C.1 and C.2 summarize the past, current, and future emission standards for passenger cars nationwide and in California. Table C.3 lists the CARB low-emission vehicle program's proposed standards. These are all standards defined in terms of laboratory-like tests — the FTP — on representative vehicles.

Table C.1. Federal passenger car tailpipe emission standards at 50,000 miles (units: g/mile, otherwise as noted)

Model Year	Test Type	Total HC	Non-Methane HC	CO	NO_X
1968-69[a]	7-mode[b]:				
	50 - 100 CID	410 ppm	—	2.3%	—
	101 - 140 CID	350 ppm	—	2.0%	—
	Over 140 CID	275 ppm	—	1.5%	—
1970-71	7-mode[b]	2.2	—	23	—
1972	CVS-72[c]	3.4	—	39	—
1973-74	CVS-72[c]	3.4	—	39	3.0
1975-76	CVS-75[d]	1.5	—	15	3.1
1977-79	CVS-75[d]	1.5	—	7.0	2.0
1980	CVS-75[d]	0.41	—	7.0	2.0
1981-93	CVS-75[d]	0.41	—	3.4	1.0
1994[e]	CVS-75[d]	—	0.31	3.4	0.76
1995[e]	CVS-75[d]	—	0.27	3.4	0.52
1996-2000	CVS-75[d]	—	0.25	3.4	0.4
2003 and on[f]	CVS-75[d]	—	0.125	1.7	0.2

a) Before 1970, standards were established in pollutant concentration in exhaust gases by weight.
b) This test procedure contains seven driving modes each of which is separated from each other.
c) This is the LA-4 driving cycle with a cold start.
d) This is the federal test procedure that contains the LA-4 cycle and a hot start of the first 505 seconds of the LA-4 cycle.
e) The Tier 1 standards established in the 1990 Clean Air Act Amendments are: 0.25 g/mile for non-methane HC (NMHC), 3.4 g/mile for CO, and 0.4 g/mile for NO_X. The amendments require 40% of an automaker's produced passenger cars must meet these standards for 1994 model year, 80% for 1995 model year, and 100% thereafter. Fleet average standards for NMHC and NO_X were calculated with the phasing-in schedule. To calculate the average of NMHC from THC and NMHC, a conversion factor of 0.85 from THC to NMHC was assumed. There are additional standards for vehicles between 5 years/50,000 miles and 10 years/100,000 miles.
f) The Tier 2 standards established in the 1990 Clean Air Act Amendments for 2003 and on model-year vehicles may be implemented if EPA concludes the need for further mobile source emission reductions.

Table C.2. California passenger car tailpipe emission standards at 50,000 miles (units: g/mile, otherwise as noted)

Model Year	Test Type	Total HC	Non-Methane HC	CO	NO_X
1966-67[a]	7-mode[b]	275 ppm	—	1.5%	—
1968-69[a]	7-mode[b]:				
	50 - 100 CID	410 ppm	—	2.3%	—
	101 - 140 CID	350 ppm	—	2.0%	—
	Over 140 CID	275 ppm	—	1.5%	—
1970	7-mode[b]	2.2	—	23	—
1971	7-mode[b]	2.2	—	23	4.0
1972	7-mode[b]	1.5	—	23	3.0
	CVS-72[c]	3.2	—	39	3.2[g]
1973	CVS-72[c]	3.2	—	39	3.0
1974	CVS-72[c]	3.2	—	39	2.0
1975-76	CVS-75[d]	0.9	—	9.0	2.0
1977-79	CVS-75[d]	0.41	—	9.0	1.5
1980	CVS-75[d]	0.41[h]	0.39[h]	9.0	1.5
1981	CVS-75[d]:				
	Option A[i]	0.41	—	3.4	1.0
	Option B[i]	0.41	0.39	7.0	0.7
1982	CVS-75[d]:				
	Option A	0.41	0.39	7.0	0.4
	Option B	0.41	0.39	7.0	0.7
1983-92	CVS-75[d]	0.41	0.39	7.0	0.4
1993	CVS-75[d]	—	0.334[j]	3.4	0.4
1994	CVS-75[d]	—	0.25[k]	3.4[l]	0.4[l]
1995-96	CVS-75[d]	—	0.235	3.4	0.4
1997	CVS-75[d]	—	0.204	3.4	0.348
1998	CVS-75[d]	—	0.160	3.4	0.298
1999	CVS-75[d]	—	0.117	3.4	0.248
2000	CVS-75[d]	—	0.075	3.4	0.2
2001	CVS-75[d]	—	0.073	3.315	0.2
2002	CVS-75[d]	—	0.072	3.23	0.2
2003 and on	CVS-75[d]	—	0.070	3.145	0.2

a) Before 1970, standards were established in pollutant concentration in exhaust gases by weight.
b) This test procedure contains seven driving modes each of which is separated from each other.
c) This is the LA-4 driving cycle with a cold start.
d) This is the federal test procedure that contains the LA-4 cycle and a hot start of the first 505 seconds of the LA-4 cycle.
e) The Tier 1 standards established in the 1990 Clean Air Act Amendments are: 0.25 g/mile for non-methane HC (NMHC), 3.4 g/mile for CO, and 0.4 g/mile for NO_X. The amendments require 40% of an automaker's produced passenger cars must meet these standards for 1994 model year, 80% for 1995 model year, and 100% thereafter. Fleet average standards for NMHC and NO_X were calculated with the phasing-in schedule. To calculate the average of NMHC from THC and NMHC, a conversion factor of 0.85 from THC to NMHC was assumed. There are additional standards for vehicles between 5 years/50,000 miles and 10 years/100,000 miles.
f) The Tier 2 standards established in the 1990 Clean Air Act Amendments for 2003 and on model-year vehicles may be implemented if EPA concludes the need for further mobile source emission reductions.

g) Hot 7-mode test.
h) When applicable, manufacturers may choose to certify vehicles to either the THC or NMHC standard.
i) For MY81, manufacturers may choose either Option A or Option B for their entire certified vehicle fleet. The option chosen in 1981 must be retained for MY82.
j) Calculated average standard. For MY93, 40% of an automaker's produced cars must meet 0.25 g/mile for NMHC, and the remaining 60% of the cars meet 0.39 g/mile for NMHC.
k) Beginning with MY94 vehicles, non-methane organic gases (NMOG) will be regulated. NMOG consists of NMHC, ketones, aldehydes, and alcohols. Beginning in MY94, manufacturers will be required to meet fleet average NMOG standard for each model year. CARB establishes five vehicle types: conventional vehicles, transitional low-emission vehicles, low-emission vehicles, ultra-low-emission vehicles, and zero-emission vehicles. Emission standards of NMOG, CO, and NO_X were established for each vehicle type. Manufacturers may choose to produce any mix of the five vehicle types as long as the fleet average NMOG standard for each year and CO and NO_X standards for each vehicle type are met.
l) Since the actual mix of the five vehicle types produced by vehicle manufacturers after 1993 is determined by manufacturers (and therefore is unknown), and since each vehicle type is subject to a different CO or NO_X standard, the actual industrial average standards for CO and NO_X after 1993 are unknown. The standards presented here were calculated with CO and NO_X standards for each vehicle type weighted by CARB's assumed sales mix of the five vehicle types from 1994 to 2003.

Low Emission Vehicle Initiative. The California Air Resources Board (CARB) has established a low-emission vehicles/clean fuel program to further reduce mobile source emissions in California during the mid- and late-1990s. CARB defines four vehicle types in addition to conventional vehicles (CVs): transitional low-emission vehicles (TLEVs), low-emission vehicles (LEVs), ultra-low-emission vehicles (ULEVs), and zero-emission vehicles (ZEVs). The emission standards for these five vehicle types is shown in table C.3 (CARB 1989a, 1989b).

Table C.3. California tailpipe emission standards for five passenger car vehicle types at 50,000 miles[a] (g/mile)

	CV	TLEV	LEV	ULEV	ZEV
NMOG[b]	0.25[c]	0.125	0.075	0.040	0.0
CO	3.4	3.4	3.4	1.7	0.0
NO_X	0.4	0.4	0.2	0.2	0.0

a) Higher (less stringent) standards were established at 100,000 miles.
b) NMOG (non-methane organic gases) are NMHC + ketones + aldehydes + alcohols.
c) Emission standard of NMHC.

CARB has developed a sales-weighting and emissions credit system for introducing these four new vehicle types into the California market during the 1990s (CARB 1990). This program is being considered by other states, and it is being considered by the Northeastern states in particular.

References

AAMA, *Motor Vehicle Facts and Figures 94*, American Automobile Manufacturers Assoc., 1994.

American Honda Motor Company, Inc., "Honda First to Have Gasoline Engine Verified at ULEV Exhaust Levels," Press Release, Jan. 6, 1995.

An, Feng, Matthew Barth and Marc Ross, "Vehicle Total Life Cycle Exhaust Emissions," Society of Automotive Engineers, Warrendale PA, 951856, 1995.

An, Feng, and Marc Ross, "Carbon Monoxide Modeling for High Power Episodes," Proceedings of the 5th CRC On-Road Vehicle Emissions Workshop, Coordinating Research Council, Atlanta, GA, April 1995.

An, Feng, and Marc Ross, "Model of Fuel Economy with Applications to Driving Cycles and Traffic Management", *Transportation Research Record* 1416, p105, 1993.

Austin, Thomas C. and Gary S. Rubenstein, letter to the editor, *J. Air Waste Manage. Assoc.*, **44**, 446-447, 1994.

The Auto/Oil Air Quality Improvement Research Program, *Emissions Results of Oxygenated Gasolines and Changes in RVP*, Technical Bulletin No.6, Sept., 1991.

Barth, Matthew J., and Joseph M. Norbeck, "A Power-Demand Approach to Estimating Vehicle Emissions," Presented at the 4th CRC On-Road Vehicle Emission Workshop, March 16-18, Coordinating Research Council, Atlanta, GA, 1994.

Beaton, Stuart P., Gary A. Bishop, Yi Zhang, Lowell L. Ashbaugh, Douglas R. Lawson, and Donald H. Stedman, "On-Road Vehicle Emissions: Regulations, Costs, and Benefits," *Science*, **268**, pp. 991-993, May 19, 1995.

Bishop, Gary A., et al., "A Cost Effectiveness Study of Carbon Monoxide Emissions Reduction Utilizing Remote Sensing," *J. Air Waste Manage. Assoc.*, **43**, 978-988, 1993.

Bishop, Gary A., and Donald H. Stedman, "On-Road Carbon Monoxide Measurement Comparisons for the 1988-1989 Colorado Oxy-Fuels Program," *Environmental Science and Technology,* **24**, no 6, pp 843-847, 1990.

Black, Frank M., "Control of Motor Vehicle Emissions—The US Experience," *Critical Reviews in Environmental Control*, **21(5,6)**, 373-410, 1991.

Boam, Denis J., Thomas A. Clark, and Kenneth E. Hobbs, "The Influence of Fuel Management on Unburnt Hydrocarbon Emissions During the ECE 15 and US FTP Drive Cycles," Society of Automotive Engineers, 950930, 1995.

Brooks, David J., et al., "Real-World Hot Soak Evaporative Emissions — A Pilot Study", Society of Automotive Engineers, 951007, 1995.

Butler, James, Christine Gierczak, Paula Liscombe, Jon Lesko, and Donald New, "Factors Affecting the NDIR Measurement of Exhaust Hydrocarbons," CRC 5th On-Road Vehicle Emissions Workshop, 1995.

CARB, California Air Resources Board, Mobile Source Division, "Summary of In-Use Vehicle Emissions Compliance Testing and Recalls Implemented in 1994 (with a historical summary of in-use testing since 1983)," February, 1995.

CARB, California Air Resources Board, Research Division, On-Road Remote Sensing of CO and HC Emissions in California, prepared by Donald Stedman, Gary Bishop, Stuart Beaton, James Peterson, Paul Guenther, Ian McVey, and Yi Zhang, Contract NO. A032-093, February, 1994.

CARB, California Air Resources Board, *Proposed Regulations for California Phase 2 Reformulated Gasoline, Technical Support Document*, Sacramento, California, October 4, 1991.

CARB, California Air Resources Board, *Proposed Regulations for Low-Emission Vehicles and Clean Fuels,* Technical Support Document, Sacramento, CA, August, 1990.

CARB, California Air Resources Board, "Announcement of Public Consultation Meeting to Discuss Potential Regulations for Gasoline and Clean Fuels/Low-Emission Vehicles," Sacramento, CA, Sept. 29, 1989a.

CARB, California Air Resources Board, "Low-Emission Vehicles/Clean Fuels and New Gasoline Specifications, Progress Report," Sacramento, CA, December, 1989b.

Calvert, J. G., J. B. Heywood, R.F. Sawyer and J. H. Seinfeld, "Achieving Acceptable Air Quality: Some Reflections on Controlling Vehicle Emissions," *Science,* **261**, 37-45, 1993.

Cheng, Wai K., Douglas Hamrin, John B. Heywood, Simone Hochgreb, Kyoungdoug Min, and Michael Norris, "An Overview of Hydrocarbon Emissions Mechanisms in Spark-Ignition Engines," Society of Automotive Engineers, 932708, 1993.

Cicero-Fernandez, Pablo, and Jeffrey Long, "Modal Acceleration Testing on Current Technology Vehicles," Presented at the specialty conference on *The Emission Inventory: Perception and Reality*, Pasadena, CA, 1993.

Consumers Union, *Consumer Reports 1994 Buying Guide*, frequency of repair records, 1987-1992, p 178ff, 1994.

DeFries, T. H., and S. Kishan, Light-Duty Vehicle Driving Behavior: Private Vehicle Instrumentation, Draft Final Report, Radian Corporation, RCN 254-036-90-06, August 24, 1992.

DeLucchi, Mark A., David L. Greene and Michael Quanlu Wang, "Motor Vehicle Fuel Economy: The Forgotten Hydrocarbon Control Strategy?," *Transportation Research*, **28A**, no 3, pp 223-244, 1994.

DoT, Federal Regulations Needing Amendment to Stimulate the Production and Introduction of Electric/Solar Vehicles, a report to Congress by the US Department of Transportation, National Highway Traffic Safety Administration, DoT HS 807 526, NRM-212, 1990.

Fox, Jonathan W., John B. Heywood, and Gregory McRae, "Aggregate Vehicle Emission Estimates for Evaluating Control Strategies," Society of Automotive Engineers, 940303, 1994.

Gammariello, Robert T. and Jeffrey R. Long, "An Emissions Comparison Between the Unified Cycle and the Federal Test Procedure", California Air Resources Board, El Monte CA, 1993.

German, John, "Observations Concerning Current Motor Vehicle Emissions," Society of Automobile Engineers, 950812, 1995.

Gertler, Alan W., "Summary of Recent Tunnel Studies in the Fort McHenry and Tuscarora Mountain Tunnels", Proceedings of the 4th CRC On-Road Vehicle Emissions Workshop, Coordinating Research Council, Atlanta, GA, 1994.

Harley, R. A., et al., "Photochemical Modeling of the Southern California Air Quality Study," *Environmental Science and Technology*, **27**, no 2, pp 378-388, 1993.

Haskew, Harold M., and Thomas F. Liberty, "In-Use Emissions with Today's Closed-Loop Systems," *Society of Automotive Engineers*, 910339, 1991.

Haskew, Harold M., David P. Garrett, and James J. Gumbleton, "GM's Results — The EPA/Industry Cooperative Test Program," *Society of Automotive Engineers*, 890185, 1989.

Haskew, Harold M., and James J. Gumbleton, "GM's In-Use Emission Performance Past, Present, Future," *Society of Automotive Engineers*, 881682, 1988.

Haskew, Harold M., Kevin Cullen, Thomas F. Liberty, and William K. Langhorst, "The Execution of a Cooperative Industry/Government Exhaust Emission Test Program," *Society of Automotive Engineers*, 94C016, 1994. (CDROM of data may be obtained from Jim Markey at the USEPA National Vehicle and Fuel Emissions Laboratory, 2565 Plymouth Rd., Ann Arbor, MI 48105)

Herbert, Jesse, "The New Automobile Inspection and Maintenance Programs: Effectiveness, Efficiency, and Potential Impacts on Motorists and Air Quality", Society of Automotive Engineers, 951045, 1995.

Heywood, John B., *Internal Combustion Engine Fundamentals*, McGraw Hill, 1988.

Hlavinka, M. W., and J. A. Bullin, "Validation of Mobile Source Emission Estimates Using Mass Balancing Techniques," *J. Air Pollution Control Assoc.*, **38**, no 8, pp 1035-1039, 1988.

Kelly, N. A., and Peter J. Groblicki, "Real-World Emissions from a Modern Production Vehicle Driven in Los Angeles," *J. Air Waste Manage. Assoc.*, **43**, pp 1351-1357, 1993.

Kishan, Sandeep, Timothy H. DeFries, and Christophe G. Weyn, "A Study of Light-Duty Vehicle Driving Behavior: Application to Real-World Emission Inventories," Society of Automotive Engineers, 932659, 1993.

Koupal, John, "Real-Time Simulation of Vehicle Emissions Using VEMISS," Presented at the 5th CRC On-Road Vehicle Emissions Workshop, CRC, Atlanta, GA, April, 1995.

Krier, James E., *Pollution and Policy: A Case Essay on California and Federal Experience with Motor Vehicle Air Pollution 1940-1975*, University of California Press, Berkeley, CA, 1977.

Kruse, R. E. and T. A. Huls, "Development of the Federal Urban Dynamometer Driving Schedule," Society of Automotive Engineers, 730553, 1973.

Laurikko, Juhani and Nils-Olof Nylund, "Regulated and Unregulated Emissions from Catalyst Vehicles at Low Ambient Temperatures," Society of Automotive Engineers, 930946, 1993.

Lawson, Douglas, letter to the editor, *J. Air Waste Manage. Assoc.*, **44**, pp 447-451, 1994.

LeBlanc, David C., Michael D. Meyer, F. Michael Saunders, and James A. Mulholland, "Carbon Monoxide Emissions from Road Driving: Evidence of Emissions Due to Power Enrichment," presented at the 73rd TRB meeting, Washington, D.C., Jan. 11-15, 1994.

Lents, James M., and William J. Kelly, "Clearing the Air in Los Angeles," *Scientific American*, pp 32-39, October, 1993.

McAlinden, Ken, et al., "Michigan Roadside Study: Analysis of Repairs on High Emission Vehicles," Proceedings of the 4th CRC On-Road Vehicle Emissions Workshop, Coordinating Research Council, Atlanta, GA, 1994.

Milkins, Eric, and Harry Watson, "Comparison of Urban Driving Patterns," Society of Automotive Engineers, 830939, 1983.

Min, Kyoungdoug, Wai K. Cheng, and John B. Heywood, "The Effects of Crevices on the Engine-Out Hydrocarbon Emissions in SI Engines," Society of Automotive Engineers, 940306, 1994.

Murrell, J. Dillard, Karl H. Hellman and Robert M.Heavenrich, "Light Duty Automotive Technology and Fuel Economy Trends Through 1993," US Environmental Protection Agency, Office of Mobile Sources, Ann Arbor, MI, 1993.

Naghavi, B., and P. R. Stephen, "Remote Sensing, Means, Medians, Extreme Values: Some Implications for Reducing Automobile Emissions," Transportation Research Board, 931007, 1993.

Norris, Michael G., and Simone Hochgreb, "Novel Experiment on In-Cylinder Desorption of Fuel fro the Oil Layer," Society of Automotive Engineers, 941963, 1994.

Pierson, W. R., Alan W. Gertler, and R. L. Bradow, "Comparison of the SCAQS Tunnel Study with other On-Road Vehicle Emission Data," *J. Air Waste Manage. Assoc.*, **40**, pp 1495-1504, 1990.

Rajan, Sudhir C., Report on the ARB/BAR 1990 Random Roadside Inspection Survey, CARB Technical Report, MS #91-06, 1991.

Rajan, Sudhir C., Report on the ARB/BAR 1989 Random Roadside Inspection Survey, CARB Technical Report, MS #90-14, 1990.

Ross, Marc, "Automobile Fuel Consumption and Emissions: Effects of Vehicle and Driving Characteristics," *Annual Review of Energy and Environment*, **19**, pp. 75-112, 1994.

Ross, Marc, and Feng An, "The Use of Fuel by Spark Ignition Engines," Society of Automotive Engineers, 930329.

Senate Committee Print, "The Impact of Auto Emission Standards," Report of the Staff of the Subcommittee on Air and Water Pollution to the Committee on Public Works United States Senate, Serial No. 93-11, U.S. Government Printing Office, Washington, D.C., 1973.

Senate Hearings, "Decision of the Administrator of the Environmental Protection Agency Regarding Suspension of the 1975 Auto Emission Standards," Hearings before the Subcommittee on Air and Water Pollution of the Committee on Public Works United States Senate, Serial No. 93-H9, U.S. Government Printing Office, Washington, D.C., 1973.

St. Denis, Michael J., Pablo Cicero-Fernandez, Arthur M. Winer, James W. Butler, and Gerald Jesion, "Effects of In-Use Driving Conditions and Vehicles/Engine Operating Parameters on "Off-Cycle" Events: Comparison with Federal Test Procedure Conditions," *J. Air Waste Manage. Assoc.*, **44**, 31-38, 1994.

Stephens, Robert D. et al., "Real-World Emissions Variability as Measured by Remote Sensors", Society of Automotive Engineers, Warrendale PA, 940582, 1994a.

Stephens, Robert D., "Remote Sensing Data and a Potential Model of Vehicle Exhaust Emissions," *J. Air Waste Manage. Assoc.*, **44**, pp 1284-1292, 1994b.

Stephens, Robert D., Patricia Mulawa, Michael Giles, Kenneth Kennedy, Peter Groblicki, Steven Cadle, John Duncan, Kenneth Knapp, "An Experimental Evaluation of Remote Sensing Based Hydrocarbon Measurements: A Comparison to FID Measurements," Final Report to CRC, Contract VE-11-4, September, 1994c.

USEPA, Final Technical Report on Air Conditioning for the Federal Test Procedure Revisions, Notice of Proposed Rulemaking, Office of Mobile Sources, US Environmental Protection Agency, Jan. 1995.

USEPA, Preliminary Technical Report, EPA's Survey of In-Use Driving Patterns, Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor MI, 1994a.

USEPA, Users Guide to MOBILE5 (Mobile Source Emission Factor Model), Office of Mobile Sources, U.S. Environmental Protection Agency, Ann Arbor MI, 1994b.

USEPA, Motor Vehicle Tampering Survey - 1990, Office of Air and Radiation, U.S. Environmental Protection Agency, Washington DC, 1991.

USEPA, National Air Quality and Emissions Trends Report, 1992, Office of Air and Radiation, US Environmental Protection Agency, Research Triangle Park, NC, EPA 454/R-93-031, 1993.

USEPA, "Volatility Regulations for Gasoline and Alcohol Blends Sold in Calendar Years 1992 and Beyond," *Federal Register*, **55**, No. 112, pp.23658-23667, 1990.

USEPA, "Volatility Regulations for Gasoline and Alcohol Blends Sold in Calendar Years 1989 and Beyond," *Federal Register*, **54**, No. 54, pp.11868-11884, 1989.

USEPA, Passenger Car Fuel Economy: EPA and Road, a report to Congress by the Motor Vehicle Emission Lab., US Environmental Protection Agency, Ann Arbor, MI, EPA 460/3-80-010, 1980, p117 ff.

Wald, Matthew L., "EPA to Allow Flexibility in Auto Emission Testing," New York Times, December 10, 1994.

Wang, Michael Q., "Mobile Source Emission Control Cost-Effectiveness: Issues, Uncertainties, and Results", Argonne National. Lab., submitted to *Transportation Research*, 1995.

Wang, Michael Q., "Criteria Pollutant, Greenhouse Gas, and Energy Model (CPGEM) for Transportation Fuel Cycles," Argonne National Lab, 1995.

Waxman, Henry A., Gregory S. Wetstone, and Philip S. Barnett, "Cars, Fuels, and Clean Air: A Review of Title II of the Clean Air Act Amendments of 1990," *Environmental Law*, **21**, 1947, 1991.

White, Lawrence J., *The Regulation of Air Pollutant Emissions from Motor Vehicles*, American Enterprise Institute for Public Policy Research, Washington, D.C., 1982.

Yamaguchi, Jack, "Mitsubishi DI Gasoline Engine Prototype," *Automotive Engineering*, pp 25-29, Sept. 1995.

Zweidinger, R. B., et al., "Detailed Hydrocarbon and Aldehyde Mobile Source Emissions from Roadway Studies," Environmental Science and Technology, 22, no 8, pp956-962, 1988.