Journal of the Air & Waste Management Association

ISSN: 1096-2247 (Print) 2162-2906 (Online) Journal homepage: http://www.tandfonline.com/loi/uawm20

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To cite this article: Marc Ross , Rob Goodwin , Rick Watkins , Tom Wenzel & Michael Q. Wang (1998) Real-World Emissions from Conventional Passenger Cars, Journal of the Air & Waste Management Association, 48:6, 502-515, DOI: 10.1080/10473289.1998.10463705

To link to this article: https://doi.org/10.1080/10473289.1998.10463705

Published online: 27 Dec 2011.

TECHNICAL PAPER

ISSN 1047-3289 *J. Air & Waste Manage. Assoc.* **48**:502-515

Real-World Emissions from Conventional Passenger Cars

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ABSTRACT

It has long been recognized that vehicles emit more pollutants than allowed under the new car emission standards. Further tightening of the certification standards based on existing test procedures does not directly address the largest sources of emissions. This study attempts to quantify vehicle emissions by source, in order to prioritize future policymaking. Several new sets of data are used in conjunction with regulatory emission models to characterize the lifetime emissions from the average Model Year (MY)93 vehicle. Special attention is paid to two of the largest sources of real-world emissions: (1) high-power driving by cars with properly functioning emissions controls, and (2) cars with malfunctioning emissions controls. Emissions are projected to MY2000 and 2010, based on estimates of the effectiveness of recently adopted and proposed regulatory policies. These new policies are projected to reduce total emissions substantially.

IMPLICATIONS

Despite large reductions in emissions from new cars, many metropolitan areas continue to suffer from poor air quality. Although current regulations have proven successful in reducing emissions from new cars in a standard test, most of the remaining emissions are from sources that may not be successfully addressed by existing policies. Continued emission reductions require new regulatory strategies that focus on the principal remaining sources of "real-world" emissions from cars. Better quantification of the major sources of vehicle emissions is necessary to carry out new regulatory strategies for continued emission reduction.

INTRODUCTION

In spite of important progress in reducing emissions from new vehicles, air quality is far from satisfactory in many major metropolitan areas. Unless vehicle emissions are further reduced, as vehicle travel continues to grow, the progress will be eaten away—about as rapidly as it was achieved. This trend is compounded by the increased use of light-duty trucks, which are not subject to as strict standards as cars. The large discrepancy between the emission certification tests, called the Federal Test Procedure (FTP), and real-world emissions is well-known,[1] and is briefly addressed in the Clean Air Act Amendments of 1990 (CAAA90). While manufacturers have been able to meet the strict certification-test standards in the FTP, limitations in the current regulatory approach permit much higher emissions in real-world driving. Most of these excess emissions come from two regulatory "loopholes": "off-cycle" driving, which is essentially driving at higher power than involved in the FTP (including use of the air conditioner), and malfunction of emissions control systems (ECSs).

The current driving cycles in the FTP were developed over 20 years ago, based on driving conditions in Los Angeles, CA. The initial cycles had rather low maximum speed and acceleration, since vehicles could not be driven at high accelerations on the first generation of dynamometers without slipping. Moreover, the initial cycles were based on typical drivers, underestimating the role of aggressive drivers. The CAAA90 instructed the U.S. Environmental Protection Agency (EPA) to revise the FTP as needed to make it more realistic. The resulting FTP-Revision Project (FTP-RP) has recently led to a new rule that will add a supplement to the FTP that better represents real-world conditions.[2]

Special regulatory initiatives aimed at reducing emissions from ECS malfunction have long been on the books, including "in-use" vehicle emission compliance testing with recalls, and emission control system inspection and maintenance (I/M) programs. Broadly speaking, these efforts, although fairly successful in the late 1970s and early 1980s, are only modestly successful in current conditions; the emissions reductions they achieve are a small fraction of the emissions addressed. In-use testing is unsuccessful because the law states that manufacturers are only responsible for the emissions performance of vehicles that have been "properly maintained and used." In response to this wording, the vehicle recruitment and screening procedures of the in-use tests make the observation of malfunctioning ECS unlikely. The I/M programs are also severely flawed—and in many ways. Efficient identification of malfunctioning vehicles through smog inspections has proven difficult. Perhaps more importantly, proper diagnosis and effective repair also are elusive; it is much easier to make a temporary fix than to identify and repair the underlying cause of malfunction.

Largely as a result of the CAAA90, new policies and technologies are being developed to close these two regulatory loopholes and reduce real-world emissions. EPA's supplemental FTP and associated standards should reduce much of the off-cycle emissions, while new information technologies and associated policies may lead to better identification and diagnosis of ECS malfunctions. However, even with these new policies, real-world emissions will continue to substantially exceed emission standards.

The emissions allocations presented here are largely based on a 1995 report that contains details of many of the calculations.[3] We have made three major changes in our results since that report: the off-cycle emissions are much reduced, based on a reinterpretation of the uncertain data on driving patterns; an additional emissions source, degradation as opposed to outright failure of the ECS, has been quantified; and the NO_x malfunction emissions have been reduced such that our estimates still match the total from MOBILE5a. The analysis starts with a breakdown of the real-world emissions from Model Year (MY) 1993 cars into seven sources. Based on this breakdown, we project the average lifetime emissions for MY2000 and MY2010 vehicles. Finally, we briefly discuss the effectiveness of policies to reduce in-use emissions.

RESULTS

Seven sources of in-use emissions have been established:

1. Properly-functioning warmed-up cars in moderate "on-cycle" driving (where on-cycle refers to driving as represented in the FTP);
2. Cold start for cars with properly-functioning emissions controls;
3. Off-cycle operations of cars with properly-functioning emissions controls (with the focus on driving and use of air conditioning that involves higher power than in the FTP);
4. Normal degradation of emissions control systems (ECS) affecting tailpipe emissions;
5. Malfunction of ECS affecting tailpipe emissions;
6. Evaporative hydrocarbon (HC) emissions from the vehicle, including malfunctioning evaporative emissions controls; and
7. Upstream emissions (from fuel extraction, transportation, refining, and distribution).

All but the last two sources are exhaust emissions.

We examine in some detail the three largest categories not measured in the present certification tests: off-cycle operation of properly-functioning cars, especially high-power driving; degradation of ECS performance; and malfunctioning exhaust ECS. The public-domain measurements analyzed for the first category ("off-cycle") are extensive emissions tests on dynamometers for small sets of vehicles[4] as well as surveys of driving patterns using instrumented vehicles,[5,6] both conducted as part of the FTP-RP. The measurements analyzed for the latter two categories (degradation of ECS and malfunctioning ECS) are a large-scale remote-sensing survey,[7] supplemented by dynamometer surveys of vehicles tested in the condition in which they were received.[8] In both cases, accurate analysis is difficult because the incidence of the problems is small, while the emissions per affected vehicle/event are large. We derive estimates of hot, on-cycle emissions ("source" #1) and cold start emissions (#2) from the FTP-RP, while we rely primarily on EPA's emission factor model MOBILE5a for estimates of evaporative emissions (#6).[9] We exploit a new model created by one of us (Wang) to predict the upstream emissions (#7).[10]

Our estimate of lifetime emissions in grams per mile from MY93 vehicles is shown in Table 1a, while our projection for MY2000 and MY2010 vehicles is shown in Table 2. Figure 1 presents our estimates graphically. The numbers are weighted by their relative occurrence in total driving, so that the sum of emissions from all sources equals our estimate for overall lifetime emission rates for the average car.

The totals in Table 1a are the weighted average of both summer and winter conditions. Table 1b shows the incremental emissions by the season when the exceedances are critical: winter conditions for CO, summer conditions for HC and NO_x. The causes of these incremental emissions are:

1. The longer time before catalyst lightoff during winter conditions increases cold start CO emissions. We estimate this increase to be 1 g/mi at 20 °F.
2. Higher than average evaporation during summer conditions increases HC emissions. Some of this increase is offset by decreases in stabilized and degradation HC emissions. Evaporative emissions

Table 1a. Sources of emissions (grams per mile) for a MY93 car, weighted average over vehicle life.

	CO		HC		NO_x	
Source[a]	**Est.**	**Stnd.**[b]	**Est.**	**Stnd.**[b]	**Est.**	**Stnd.**[b]
(1) Hot moderate driving[c]	0.98		0.090		0.201	
(2a) 70 °F cold start[c]	0.66		0.071		0.070	
(2b) 20 °F cold start[c]	1.66		0.178		0.091	
Subtotal[c]	3.3		0.34		0.36	
(3) Off-cycle[c]	2.8		0.05		0.24	
(4) Degradation	2.1		0.21		0.43	
(5) Malfunction	6		0.6		0.45[e]	
Subtotal, exhaust emissions	14.2	3.4	1.2	0.41	1.5	1.00
(6) Evaporation[d]	0		0.5		0	
(7) Upstream	0.063		0.098		0.315	
TOTAL	14		1.8		1.8	

Note: The sources are weighted by the relative occurrence in total driving, so that the average per-car emissions are shown.
[a] All are exhaust emissions except (6) and (7); [b] 1993 federal standard. The standard legally applies to the sum of (1) and two times (2a) (one cold start); [c] Properly-functioning cars; [d] MOBILE5a estimate. 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) through (4).

are estimated to increase HC 0.3 g/mi on days when the high temperature is 95 °F rather than the mid-80s we assume for the Table 1a estimates.

3. Heavier than average loads on the engine (due to air conditioning, construction, vacation travel, etc.) during summer conditions increase NO_x emissions. We estimate that these conditions add an additional 0.2–0.3 g/mi to the Table 1a NO_x emissions.

Table 1a shows that total emissions of CO and HC are four to five times the 1993 tailpipe standards, while those for NO_x are approximately twice the U.S. standard and four to five times the California standard. These totals are consistent with those of MOBILE5a, which are 19, 1.9, and 1.5 g/mi for CO, HC, and NO_x, respectively, for conditions similar to those assumed

Table 1b. Incremental seasonal peak emissions (grams per mile) for a MY93 car.

Source	**Winter CO**	**Summer HC**	**Summer NO_x**
(1,2) Hot stabilized + cold start	1.0	-0.11	-0.02
(3) Off-cycle	0	0	0.15
(4) Degradation	0.6	-0.05	0.14
(6) Evaporation		0.3	
TOTAL	1.6	0.14	0.26

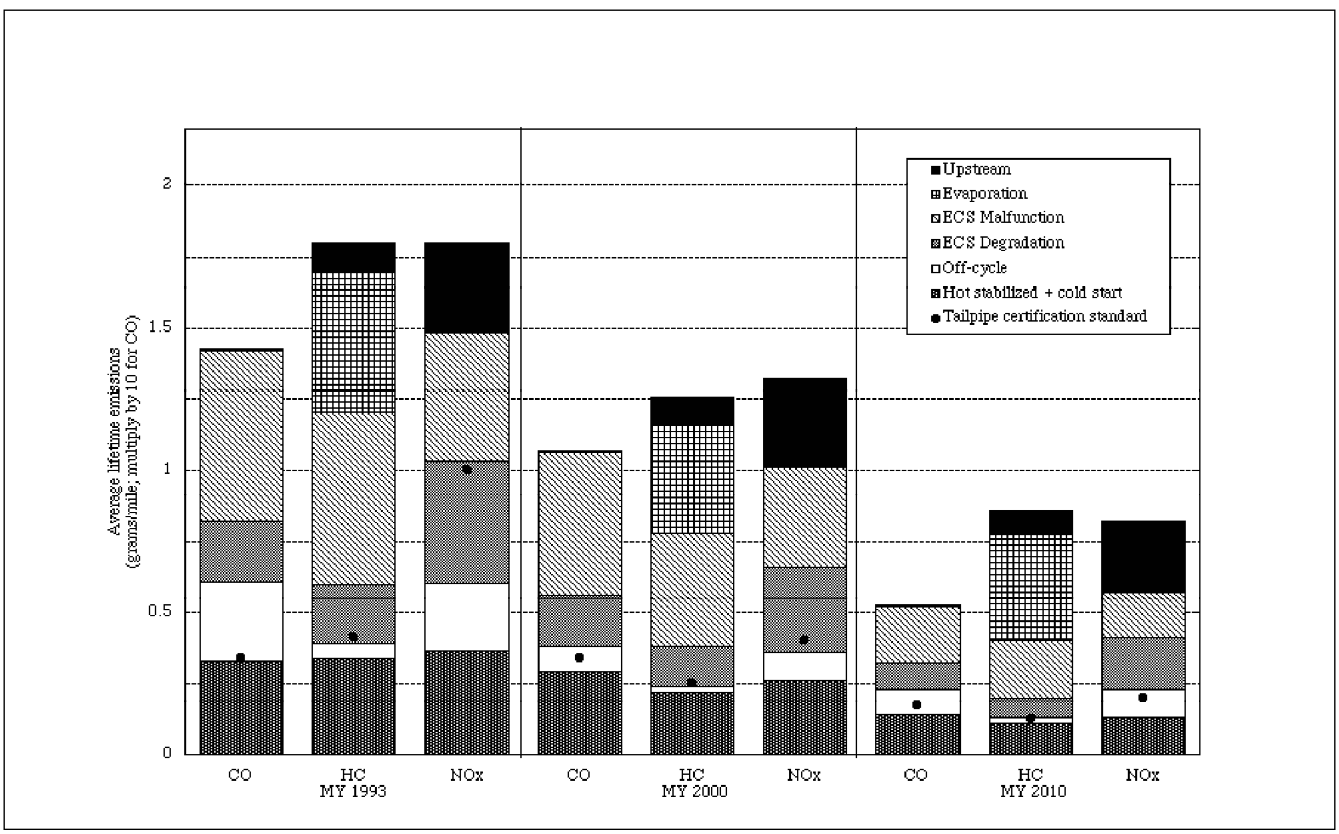

Figure 1. Estimated and projected lifetime emissions for the average MY1993, MY2000, and MY2010 vehicle.

Table 2. Predicted sources of emissions (grams per mile) for a MY2000 and MY2010 car, weighted average over vehicle life.

	CO		HC		NO_x	
Source	**MY2000**	**MY2010**	**MY2000**	**MY2010**	**MY2000**	**MY2010**
(1,2) Hot stabilized + cold start[a]	2.9	1.4	0.22	0.11	0.26	0.13
(3) Off-cycle[a]	0.9	0.9	0.02	0.02	0.10	0.10
(4) Degradation	1.8	0.9	0.14	0.07	0.30	0.18
(5) Malfunction	5	2	0.4	0.2	0.35	0.16
(6) Evaporation[b]	0	0	0.37	0.37	0	0
(7) Upstream	0.063	0.055	0.097	0.085	0.31	0.25
TOTAL	11	5	1.25	0.86	1.32	0.82
Tailpipe standards:						
Tier 1 2000, Tier 2 2010	3.4	1.7	0.25[c]	0.125[c]	0.4	0.2

[a] Properly-functioning cars. [b] MOBILE5a prediction. [c] Nonmethane hydrocarbons (U.S. EPA Tier 1 & 2).

off-cycle driving and vehicles with malfunctioning emissions controls. Off-cycle driving accounts for 20% of CO, 3% of HC, and 13% of NO_x emissions. Degradation emissions are roughly one-sixth of each of the pollutants. Vehicles with malfunctioning ECS are the source of about one-third of each of the pollutants. In the next sections, we discuss the methodology used to develop the estimates and predictions of the seven emission sources.

Table 3. Estimates of the three factors for warmed up, FTP (bag 2) style driving, MY93 cars.

Pollutant	(1) Fuel Rate	(2) Emissions Index	(3) Catalyst Pass Fraction	(4) (2) * (3)	(5) Tailpipe Emissions (g/sec)	(6) Tailpipe Emissions (g/mi)
CO	0.602	0.095	0.074	0.00703	0.00423	0.95
HC	0.602	0.025	0.032	0.00008	0.00048	0.11
NO_x[a]	0.684	0.013	0.179	0.00233	0.00159	0.4
NO_x[b]	0.493	0.033	0.052	0.00172	0.00085	0.2

Note: A car with EGR will have a lower NO_x emissions index but a higher catalyst pass fraction relative to a car without EGR, as the table indicates. The higher tailpipe emissions rate from cars with EGR shown in the table is a result of multiplying the average values of two highly variable factors, NO_x emissions index and catalyst pass fraction, from a small sample of cars. In particular the catalyst pass fraction for NO_x varies from 3 to almost 30% for these cars (in stoichiometric operation averaged over several driving cycles in the FTP-RP), so the estimate for average tailpipe NO_x for cars with EGR is highly uncertain.

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

here but without downstream emissions. (As stated in the table notes, the agreement for NO_x is by assumption.) The tailpipe standard legally applies only to the emissions shown in row 1 plus two times those in row 2a. (Evaporative HC emissions are subject to a separate standard, and are determined using a separate test procedure; upstream emissions are regulated in part by evaporative HC controls on fueling hoses and on-board vehicles.) As shown in Table 2, we predict that vehicles will continue to be able to meet increasingly strict standards for on-cycle tailpipe emissions (hot stabilized plus cold start) using the current FTP.

The two largest sources of real-world emissions are

ON-CYCLE EMISSIONS OF HOT PROPERLY-FUNCTIONING CARS

Current Vehicles (MY1993)

Present-day vehicles incorporate a sophisticated emissions control system (ECS) to meet the stringent standards associated with the FTP. The test involves a cold start cycle (bag 1) and warm cycles: hot stabilized (bag 2) and warm start (bag 3). The emission factors in row 1 of Table 1a were calculated from FTP (bag 2) and (bag 3) data for the MY91–93 cars contained in the FTP-RP database. These are clean cars with catalysts nominally aged to about half their useful lives. In Table 3, average emissions as measured in the FTP-RP are shown, for illustration, for FTP bag 2, which is low-power driving.

The tailpipe emissions in grams per second are shown as products of three factors in Table 3: the fuel rate, in grams per second; the engine-out emissions index, which is the dimensionless ratio of g/sec of pollutant to g/sec of fuel use; and the catalyst pass fraction, which is the fraction of pollutant that passes through the catalyst without conversion. We dissect the bag emission rates into these physically-based factors to help develop an understanding of how technological changes will affect emissions.

The tailpipe emissions in column 5 are converted from grams per second into grams per mile by multiplying by 224 seconds per mile (based on the average speed of 16 mph in bag 2). Column 6 shows typical tailpipe emission rates in grams per mile. (The tailpipe rates in Table 3 differ from those shown in Table 1a, row 1, which also include the contributions from warm starts (bag 3)).

Future Vehicles (MY2000 and MY2010)

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 certification-test emissions. The average

Table 4. Headroom in meeting FTP test standards. FTP emissions with 70 °F cold start of the MY91–93 cars in the FTP-RP (g/mile).

	CO	HC	NO_x
MY91–93 cars (FTP-RP)	2.3	0.23	0.34
MY91–93 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

emissions of the clean vehicles tested in the FTP-RP are shown in Table 4. A comparison with the national and California standards shows that, on average, clean vehicles are designed to pass the FTP well below the most stringent 1993 standards (federal for CO, California for HC and NO_x). (Note particularly that these federal cars met the California standard for NO_x, 0.4 g/mi. This indicates that practical differences between California and "49-state" vehicles were small at this time.) Thousands of new car certification tests documented in the 1990–1993 EPA Test Car Lists,[11] as well as studies of in-use cars recruited and tested by GM in the late 1980s,[12–14] confirm that g/mile tailpipe test emissions declined consistently during the 1980s and early 1990s. Since national standards remained fixed during that period, headroom steadily increased.

Moreover, car 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 these test emissions through further improvements in control systems to more accurately control the fuel-air ratio; this results in substantially lower tailpipe emissions. Some of this can be accomplished relatively easily and at reasonable cost, as demonstrated by the better-performing engines of today. Meeting ultralow emissions standards (from properly-functioning vehicles in moderate driving) is more difficult, but will also be achieved, for instance 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 ultra low emission vehicle (ULEV) production vehicle.[15]

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

Our prediction concerns both how many low emission vehicles (LEVs) are produced and how much headroom the manufacturers decide to have between certification-test emissions and the regulatory limits. For the prediction we assume, on the basis of performance of the more successful cars in the FTP, that the emissions measured in certification tests will average 60% of the 50,000-mile regulatory limits in effect in MY2000 (Tier 1 standards) and MY2010 (assumed to be the proposed Tier 2 standards). Including the 20 °F cold start to represent winter experience, we obtain the top row of emissions in Table 2.

COLD START EMISSIONS OF PROPERLY-FUNCTIONING CARS

Current Vehicles (MY1993)

Cold start emissions averaged over summer and winter conditions are shown in line 2 of Table 1a. Emissions are relatively high for two stages when a vehicle is started with the engine at ambient temperature. First, for purposes of drivability, the fuel-air mixture is commanded to be rich, for perhaps half a minute, depending on ambient temperature (similar to the use of a choke in older vehicles). This acts primarily to increase CO emissions. Second, it takes 2 min or so for the catalytic converter in the exhaust stream to warm up to the point that it is converting pollutants. For a similar time, while the engine block is cold, HC emissions are high. 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 compared to warmed-up, stoichiometric operation. Based on FTP-RP data, we find that about two-thirds of the cold start emissions at 70 °F are associated with this first stage. The duration 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 problems 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; 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. Oxygenated fuels appear to reduce CO emissions on the order of 15%.[16,17] 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 two-thirds compared to MY93 cars.

Prediction of cold-start emissions is especially uncertain because the frequency and duration of stops with the engine off, and the consequences of these stops, are uncertain.

Future Vehicles (MY2000 and MY2010)

Cold-start emissions from properly functioning vehicles is another area where more stringent certification-test 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. This will primarily reduce CO cold start emissions.

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 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 preheated catalysts might be required.

Table 5. Estimates of the three factors in eq 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 (g/sec)
CO	4.7	0.6	0.97	2.7	~500
HC	4.7	0.019	0.54	0.047	~100
NO_x [a]	4.7	0.01	0.34	0.023	~20

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

OFF-CYCLE OPERATION OF PROPERLY-FUNCTIONING CARS

Current Vehicles (MY1993)

A study of driving behavior confirms what has long been suspected: The FTP is not representative of real-world driving.[5,6] 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. The emissions consequences can be large.[18]

Under certain driving conditions, fuel enrichment is commanded: the emissions control system is overridden and fuel injectors are instructed to introduce excess fuel. This strategy is adopted in most current vehicle models when high power is required, as well as when the engine is cold in order to improve combustion stability. Enrichment at high power may also be used to protect the engine and catalyst from overheating, increase power output (by about 5%), curb the increase in engine-out NO_x emissions in high-power episodes, and provide a smooth knock-less response when the throttle is opened wide.

During command enrichment, high CO and HC emissions occur.[19] The effect is strongest for CO and is illustrated in Figure 2, where cumulative emissions are

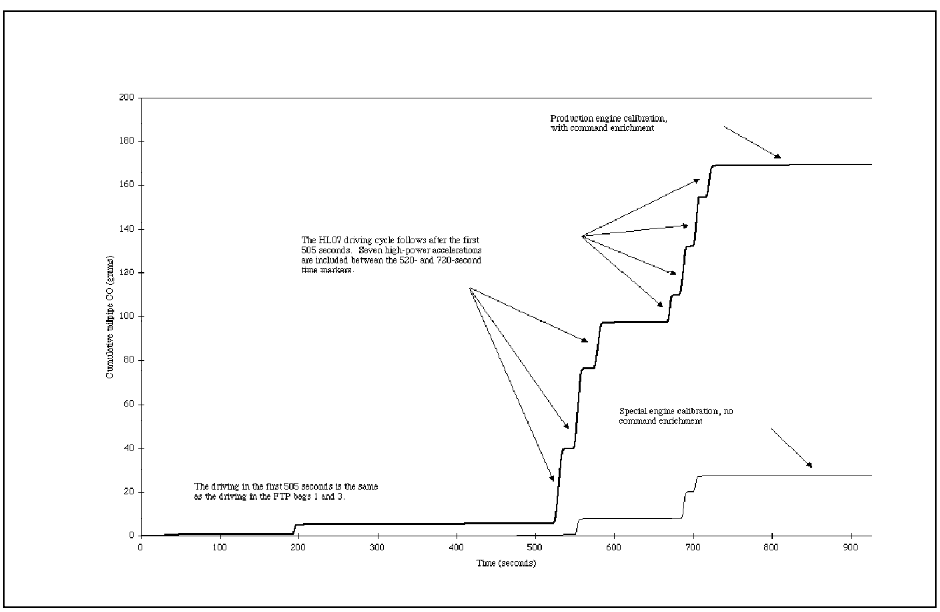

Figure 2. Effect of command enrichment on total tailpipe CO emissions (a sample MY1994 car from the FTP-RP).

shown for 500 seconds of moderate driving followed by seven brief, high-power episodes with command enrichment. Each episode alone produces much more CO than the 500 sec 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: tailpipe emissions with the normal engine-control microprocessor chip, and the emissions from the same vehicle driven over the same cycle (the HL07 cycle) with a chip that does not command enrichment.

The behavior of tailpipe HC emissions is similar to that of CO during command enrichment, but the relative increase over stoichiometric operation is much smaller. Enrichment sharply reduces the effectiveness of the catalyst in oxidizing HC, but does not have much of an effect on engine-out HC emissions.

The instantaneous fuel rate, emission index, and catalyst pass fraction for an illustrative event of very high power in the FTP-RP are shown in Table 5. Tailpipe emission rates in g/sec (TP g/sec) are calculated and are compared to the results for the FTP-style driving shown in Table 3. Very high-power driving results in emission rate increases of roughly 1 order of magnitude for NO_x, 2 orders for HC, and 3 orders for CO.

On the basis of the FTP-RP driving-pattern survey, we estimate the CO, HC, and NO_x emissions associated with command enrichment to be 2.8, 0.05, and 0.09 grams per average mile of driving, respectively, as shown in the summary Table 1 above. (More detail of our analysis of off-cycle emissions of MY93 cars can be found in references 20 and 21.)

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, and (2) the patterns of driving involved occur only 3–6% of the time and so are difficult to determine accurately.

Excess emissions arise in off-cycle situations from causes other than command enrichment. Of prime interest is the incremental NO_x in extra-power driving. NO_x formation increases rapidly that increased temperature in the cylinders. As a result, engine-out NO_x emissions are essentially zero below a threshold fuel rate and increase rapidly above it. That is, NO_x emissions are sensitive to vehicle operation that involves extra power, but where the extra power is not so high as to command enrichment. (The cooling effects of enrichment inhibit NO_x formation.) These extra-power situations arise in driving associated with air conditioner use, moderate acceleration, under-inflated tires and replacement tires of high rolling resistance, grades at moderate speed, heavy loads (like passengers and luggage beyond the FTP's 300 lbs), etc. The contribution from air conditioning can be estimated from dynamometer measurements of emissions with and without air conditioning in the FTP-RP. Continuous operation of the air conditioning, as on an extremely hot sunny day, results in 0.2 grams per second added fuel use, and roughly 0.2 g/mi incremental NO_x in urban driving. Typical air conditioning in summer would contribute about half that. The NO_x from other extra-power operation can be crudely estimated based on the real-world fuel economy being approximately 15% poorer than measured.[22] The combined incremental effect of the various sources of NO_x at extra power (without command enrichment) is estimated to be 0.2 g/mi in summer and 0.1 g/mi in other seasons, or an annual average of 0.15 g/mile.

Future Vehicles (MY2000 and MY2010)

New rules, involving test cycles with higher-power driving, as well as actual air conditioning and an additional evaporation test, require a supplemental FTP.[2] This should lead both to on-board controls that delay enrichment and to reduced levels of enrichment. Manufacturers can avoid enrichment in most brief high-power episodes by introducing timers to delay command enrichment for a few seconds, and they can minimize the level of enrichment needed to protect the engine and catalyst from overheating. These measures have already been adopted in some vehicles.

Such measures will delay command enrichment, as well as reduce the level of command-enrichment emissions in long high-power episodes. Some cars, such as the Mercedes 420 SEL, have already eliminated most enrichment. However, it is difficult to avoid enrichment altogether, especially in low-power cars that are driven at wide-open throttle for long periods, or in most cars driven at high speed on long grades or pulling a trailer.

On the basis of the opportunity to delay command enrichment and to reduce the enrichment level, we predict that the CO emissions from this source are likely to be reduced 70% by MY2000, from 2.8 to 0.9 g/mi, and the HC emissions from 0.05 to 0.02 g/mi.

In addition, NO_x at extra power (without command enrichment) should be reduced in response to the supplemental FTP. There are two main approaches to improved NO_x control: reduction of engine-out emissions using exhaust gas recirculation (EGR), and increased catalyst efficiency for 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 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. In the FTP-RP, the best half of the cars in this respect have an average catalyst pass fraction under 4%, approximately one-half of the average for the whole group. On this basis, we predict that the NO_x emissions from moderate-power closed-loop operations will be reduced by one-half by MY2010, as a result of the new rule. (Thus, off-cycle NO_x emissions are estimated to be 0.3 × 0.09 + 0.5 × 0.15 = 0.10 g/mi.)

EMISSIONS DUE TO DEGRADATION OF ECS COMPONENTS

Properly-functioning, in-use cars pollute more than the relatively clean vehicles tested in the FTP-RP, roughly twice as much when measured over the same cycle. In mid-life, typical engines have deposits on the cylinder walls; their valves have deposits and are worn; and the oxygen sensors and catalytic converters may have deteriorated more than the laboratory-aged components installed in the FTP-RP cars. Thus, our estimates for emissions, based on measurements of these clean vehicles should be increased to account for degradation of ECS components. Degradation characterizes properly-functioning cars and is relatively modest; we separately consider component malfunction or failure below.

In the 1991 remote-sensing survey in California discussed below, excluding the vehicles categorized as malfunctioning, the average CO emissions rate for MY87 is roughly two times the rate for hot running vehicles, as determined above from the FTP-RP data set (FTP bag 2). This result is supported by recent analysis of Phoenix, AZ, IM240 data, where the average properly-functioning car emits two to three times as much as for a low-mileage car.[23,24] (The average in the latter case refers to MY90 cars measured in 1995 with 50,000–60,000 miles.)

The incremental emissions associated with degradation are taken to be equal to the running emissions (Table 1a, source 1). Degradation is also assumed to increase cold-start emissions, but not as much, since degradation would have a small relative effect when there is enrichment. In cold-start, the degradation emissions are assumed to be half the source 2 emissions. Degradation is assumed not to apply to the enrichment emissions in off-cycle driving, but to the NO_x emissions at extra power without command enrichment. The results are shown as source 3 in Table 1a. (Thus, the MY1993 degradation NO_x emissions are estimated to be 0.20 + (0.07 + 0.09)/2 + 0.15 = 0.43 g/mi.) Degradation emissions expressed as the factors just discussed are assumed to be unchanged for the predictions.

The allocation of emissions between degradation and malfunction emissions is sensitive to the cutpoints chosen to separate them, so the separate quantities are more uncertain than the sum.

MALFUNCTIONING EXHAUST EMISSIONS CONTROLS

This category comprises excess emissions from vehicles whose emissions controls are not functioning properly (as distinguished from degradation). It is both the largest and the least understood source of emissions.

It has been well documented that a substantial portion of CO and HC emissions are due to a small number of high-emitting vehicles with malfunctioning emissions controls.[7,25–27] Two important examples of malfunctioning emissions controls are improper fuel metering and failure of the oxygen sensor, which provides feedback for control of the fuel-air ratio.[28] There appear to be at least five possible causes of failure of such components: (1) extensive high power driving of a vehicle; (2) outright tampering of the ECS (by owner or mechanic); (3) inadequate maintenance (by owner); (4) improper repairs (by owner or mechanic); and (5) poor initial ECS design or manufacture. Component failures can also result from a combination of two or more of these causes.

Current Vehicles (MY1993)

Malfunctioning emissions controls lead to very high emissions. For example, a properly functioning catalyst converts all but a few percent of engine-out emissions (Table 3, column 3); catalyst failure would allow nearly all engine-out emissions to exit the tailpipe unconverted, resulting in an order of magnitude increase in tailpipe emissions. The emissions of vehicles with malfunctioning emissions controls are very roughly comparable to those of the pre-regulation era (before the late 1960s), estimated to be (in g/mi over the FTP) 84, 11, and 4, for CO, HC, and NO_x, respectively.[29] Using this rule of thumb, if 8% of cars are CO-malfunctional (Table 6), the average CO emissions due to malfunction would be approximately 7 g/mi, which compares well with our estimate of 6 g/mi in Table 1.

We estimate the incremental malfunction emissions primarily on the basis of remote- sensing data collected by the University of Denver for the California Air Resources Board in 1991.[7] (More detail of our analysis of emissions from malfunctioning cars can be found in reference 30.) The remote sensor directs an infrared beam across a single

Table 6. Occurrence of CO malfunctions in MY1987 through MY1991 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%

lane of traffic, at the height of an automobile's tailpipe. As a vehicle passes the beam, the instrument measures the absorption of infrared light to determine CO, HC, and CO_2 concentrations in the exhaust. Because of limitations in the HC measurements, we base our analysis on the CO measurements only. The vehicle is identified by videotaping its license plate, later crosschecking license plate numbers with vehicle identification numbers (VINs), and then decoding VINs to obtain technical information on individual vehicles. Most of the observations are from sites selected to minimize the number of readings taken from vehicles operating with cold catalysts or under fuel enrichment.

A sample data set is shown for CO in Figure 3 (this figure is based on a methodology developed in reference 26). The distribution shown is the cumulative fraction of 2,600 MY87 fuel-injected cars observed by CO concentration (for cars with multiple measurements, we use a randomly selected measurement for each car). The key to the distribution is that it has two parts. The first is a central peak, with approximately 90% of the cars, whose average CO concentration is slightly higher than that inferred from the dynamometer data for the clean cars tested in the FTP-RP. The second part is the tail at high CO concentrations, with about 10% of the cars, whose average CO concentration is about 40 times that for the clean cars tested in the FTP-RP. We take the cars in the tail to have malfunctioning emissions control systems.

The criterion we adopt for malfunctioning vehicles is greater than 1% CO concentration. Although remote sensors measure emissions in terms of total exhaust concentration, rather than mass (grams), the concentration results can be approximately converted to grams per mile. These criteria are lower than the cut points used in previous analyses of remote sensing data, where higher cut points have been used to reduce the probability of misidentifying an individual vehicle as a high emitter. Our malfunctioning vehicle criteria are essentially 15–20 times those expected for clean, properly-functioning cars, based on bag 2 emissions from the FTP-RP dynamometer tests. Representative results for emissions by fuel-injected cars with malfunctioning emissions controls are shown in Table 6.

One result is that, for cars of average lifetime mileage (at an age of about four years), the incremental

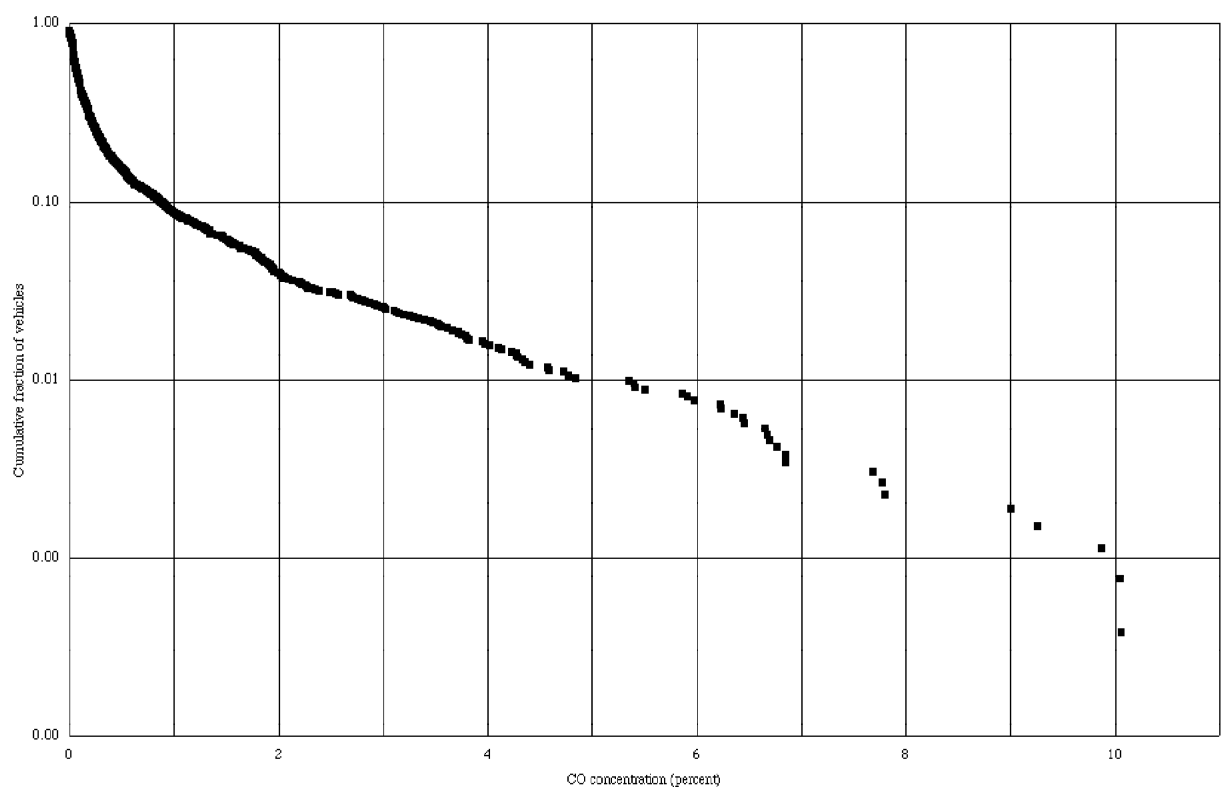

Figure 3. Distribution of CO emissions from MY1987 fuel-injected cars, from remote-sensing data.

CO emissions from vehicles with malfunctioning emissions controls are over four times the emissions from properly functioning cars in certification tests, even though only about one-tenth of the cars are malfunctioning. This factor is based on the difference in average emission concentrations from properly functioning and malfunctioning cars (from the remote-sensing data), divided by the average emissions of clean cars (from the FTP-RP), and weighted by the fraction of malfunctioning cars in the fleet [(2.79–0.14) / 0.054 × 0.084 = 4.1]. The factor of 4 is for warmed-up moderate driving; we estimate that the fraction of emissions from malfunctioning cars in cold start is about one-fifth as large, although this is based on very limited information. Therefore, in Table 1, we calculate the incremental malfunction emissions to be 4.1 times the on-cycle warmed-up emissions from clean, properly functioning cars (0.98 g/mi from Table 1) plus one-fifth the annual average cold-start rate (2.32 g/mi), resulting in an incremental CO malfunction rate of 6 g/mi [4.1 × (0.98 + 0.2 × 2.32)].

We determine the incremental HC malfunction emissions in moderate driving using the same factors applied to CO, times the HC emissions from properly functioning cars (0.09 and 0.25), resulting in an estimate of 0.6 g/mi HC [4.1 × (0.09 + 0.2 × 0.25)].

NO_x was not measured in the same remote-sensing survey. In limited-statistics dynamometer measurements (LDVSP-12),[8] analyzed by An et al.,[31] and in preliminary analysis of the high-statistics IM240 data from Phoenix,[23] we do not observe a tail in the distribution like the one shown in Figure 3. Thus, estimating the number of high NO_x emitters is especially sensitive to the NO_x cutpoint assumed to separate the degraded from the malfunctioning vehicle. Selecting what we feel is a reasonable cut point (2.0 grams per mile NO_x, the EPA-recommended final IM240 composite standard), the contribution of malfunction to NO_x is substantial. This is seen in both the life-cycle analysis of LDVSP and the Phoenix IM240 data. The level of malfunction emissions that brings our estimated total NO_x into agreement with the total from MOBILE5a is 0.45 g/mi (Table 1a). The IM240 data shows NO_x emissions from a typical malfunctioning car to be about 4 g/mi, and a probability of malfunction of about 5% (i.e., a 5% ECS failure rate), combining to yield malfunction emissions of 0.2 g/mi for the average car. Since IM240 is low-power driving, an estimate of about 0.4 g/mi, from the malfunction source in average driving, may be reasonable.

The above analysis is primarily based on 1991 remote-sensing measurements. Preliminary analysis of 1995 IM240 data shows that malfunction emissions remain a major, but reduced, source for MY1991–93.[23] Unfortunately, since a different measurement technique is involved, and only one year of data are currently available, we have not yet been able to quantitatively evaluate the dependence of malfunction emissions on improving vehicle technology (holding vehicle age constant).

Future Vehicles (MY2000 and MY2010)

The emissions due to malfunctioning vehicles are the product of the probability that vehicles malfunction and the level of emissions per malfunctioning vehicle. As one can see in Table 6, the second factor does not vary strongly with the age of the vehicle or emissions control technology. The *probability* for vehicles to have severely malfunctioning emissions control systems, rather than the emission *rate* of malfunctioning vehicles, is the most important factor in the relative contribution to total malfunction emissions. Therefore, how malfunction probability may depend on vehicle characteristics (fuel system or emission control technology, or initial ECS design), and how it may be affected by policy, becomes critical.

The probability of malfunctions. Because there are major uncertainties in the HC remote-sensing data, our projections of malfunction emissions are based on the CO readings. Perhaps the most important finding of this analysis is that the probability of malfunction based on CO emissions is strongly correlated with vehicle model. We looked in detail at 76 MY-models (e.g., 1987 Nissan Sentras) from MY87–89 for which at least 50 vehicles were observed by the remote sensor (for vehicles of each domestic manufacturer, we grouped individual vehicles by engine family). The probability for malfunction (CO concentration greater than 1%) against the average CO concentration for all cars of the model is shown in Figure 4 for the 76 MY-models. Since the measurements were made in the summer of 1991, the cars are two to five 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 consistent with expectations for properly-functioning cars (0.05%), based on the FTP-RP dynamometer data. The figure demonstrates that average CO concentration for a MY-model correlates well with the malfunction probability for that MY-model. This is because only a few high emitters have a large effect on the average concentration for the entire group of vehicles.

Of the MY-models shown in Figure 4, five less-expensive models (14 MY-models) of Asian manufacture have especially high malfunction rates. The average malfunction rate of this group is 22%, while only 6% of all other MY-models are malfunctioning. Cars from these five models represent nearly 60% of the malfunctioning cars from all of the 76 MY-models analyzed, and nearly 30% of the malfunctioning cars from the entire data set of MY87–89 cars. Most of the vehicles of the five worst models use carbureted fuel systems (two models are exclusively carbureted and one model is predominantly carbureted; the remaining two models switched to exclusively fuel-injected vehicles in MY88). All of the cars from the five worst models have small engines (1.6 l or less). However, a few models with carburetors or small engines have very low malfunction rates. In addition, some domestic engine families from certain MYs have failure rates similar to the five Asian models. However, these domestic engines do not have consistently high malfunction rates over the three model years studied.

We examine the data in several ways to ensure that the limitations of remote-sensing measurements were not biasing our results, including averaging remote-sensing readings from cars with multiple readings; examining only cars with three or more remote sensing readings; controlling for vehicle operation by analyzing data collected at sites where accelerations were not observed; and using a more stringent malfunction definition (3% CO concentration).

Each of these tests confirm our initial results, including the vehicle-model dependence. In addition, we examine MY87–89 high emitters from four sets of dynamometer data, including the LDVSP-12.[8] Although these data sets are much smaller than our remote-sensing data set, they provide a more accurate picture of the emissions of an individual car. The same models that were identified by remote sensing as having a high malfunction probability tend to fail dynamometer tests as well. Thirteen percent of all cars tested in the LDVSP have CO emissions in excess of 10 g/mi in bag 2 of the FTP, while seven of the 19 cars from the five Asian models exceed 10 g/mi CO. When the four sets of dynamometer data are combined, 19% of the five Asian models are high CO emitters, while only 3% from all other models are high emitters. The dynamometer data, therefore, confirm our finding from the remote-sensing data: that cars from a few models have over 4 times the malfunction probability of all other cars.

Approaches to reduce malfunction emissions. In the past, the responsible EPA offices stated that ECS failures are in large part due to “tampering,” that is, (presumably) deliberate disabling of emissions controls or related parts.[32] This is important, as much of the analysis and policy discussion

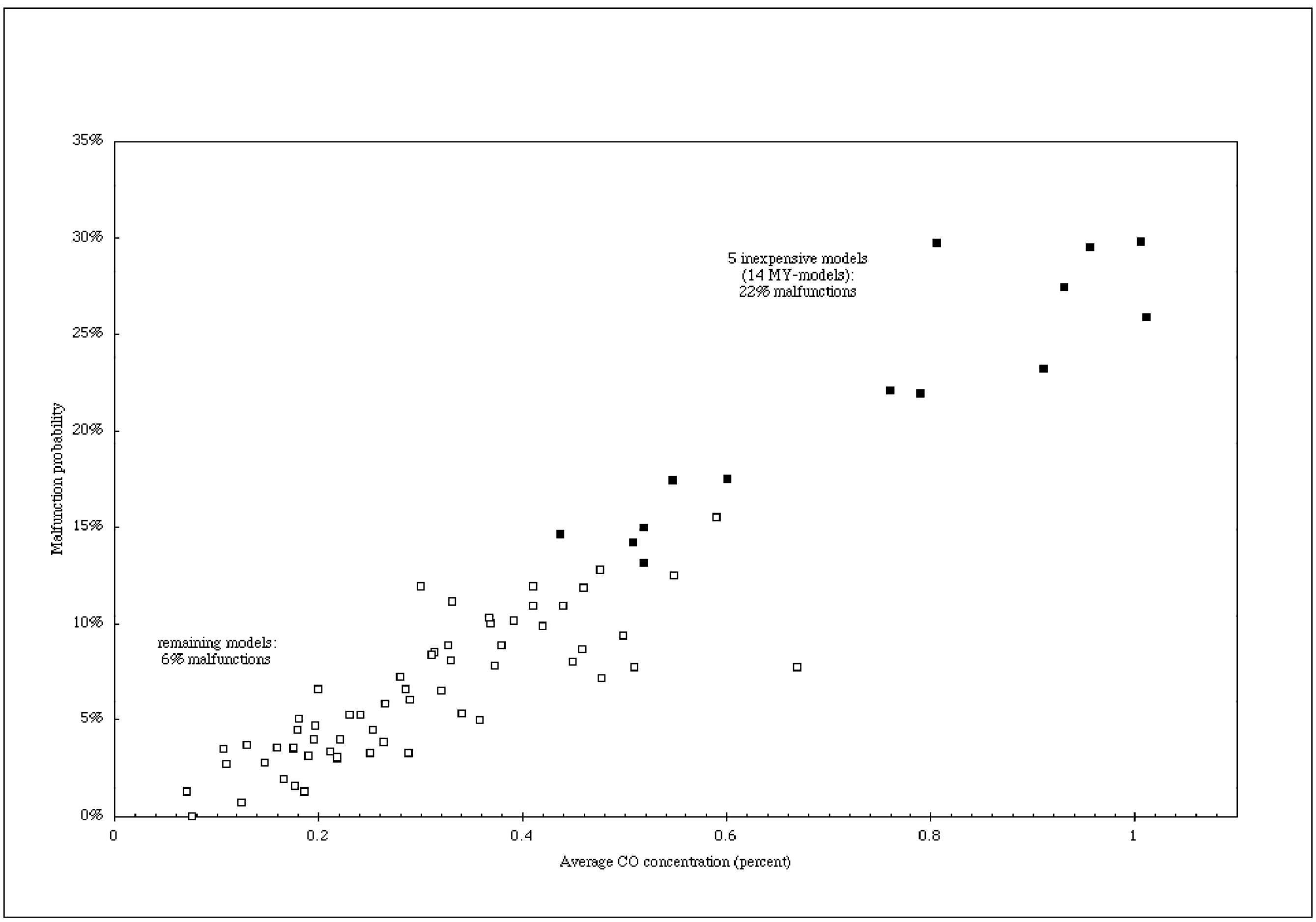

Figure 4. Malfunction probability vs. average CO concentration for 76 MY1987-89 MY-models with over 50 individual vehicles, from remote-sensing data.

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.

Three basic approaches are being tried to reduce malfunction emissions: (1) identification of individual vehicles with malfunctions; (2) repair of malfunctions in individual vehicles; and (3) reduction in the frequency of malfunctions in future vehicles, that is, through more durable emissions controls. By far the largest efforts are currently devoted to identification of individual malfunctioning vehicles. Attempts to enhance vehicle I/M programs using a more thorough dynamometer test (the IM240 and Acceleration Simulation Mode, or ASM) in areas where ambient pollution exceeds standards have been in the news.[33] Installation of on-board diagnostic equipment (OBD) is another major program for identifying malfunctions. In addition, remote sensing of malfunctioning vehicles is being introduced for identification of individual malfunctioning vehicles.

Even though the EPA is retreating on requiring IM240 tests as part of enhanced I/M, strong technological progress is being made with two other identification technologies. The new generation of OBD instrumentation, fully implemented in all MY96 vehicles, will be effective in identifying malfunctions, although it may take time to work out bugs. The information provided by remote sensing is also being strikingly improved. By the late 1990s, 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 the durability of emissions controls?

At present, there is no reason for optimism about the repair of malfunctioning emission controls. The record is poor. This is not surprising because neither proper diagnosis nor lasting repair is easy or cheap. It is costly to test emissions from a vehicle under power at a repair facility. Moreover, it is often easier to make a superficial repair, which yields satisfactory test results at the time but does not endure. As an extreme example, 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 repairs have been successful because cars usually perform adequately even when emission controls do not. This not only leads to faulty repairs, but sometimes to fraud. Moreover, the complexity of the repair industry makes large-scale success in repairing vehicles unlikely: throughout the United States, there are about 60,000 general automotive repair shops, including about 23,000 auto and truck dealers. Some hope may be offered by OBD regulations, which were developed to improve the performance of I/M programs by alerting drivers to an emissions control problem, as well as by assisting mechanics in diagnosing a problem.

We are much more optimistic about the eventual role of more durable emissions control systems in reducing malfunction emissions. One of our key findings is that some models studied in the remote-sensing data (Figure 4) have essentially no high emitters. For example, mid-price (not just luxury) models of some of the same Asian manufacturers with high malfunction probability models have low malfunction probability. For some models with several hundred vehicles in the sample, the malfunction rates are extremely low. Thus, manufacturers have demonstrated that they can produce durable ECSs that continue to function, whether or not maintenance and use have been "proper," at least up to a vehicle age of five years—the limit of our analysis.

In our view, the durability of emissions controls is likely to be substantially improved in the future through the utilization of remote sensors and OBD, not to identify individual vehicles for further testing and repair, but to identify entire vehicle models with high malfunction probabilities. The ECS flaws can then be diagnosed and corrected in future vehicles. Wide dissemination of this information might spur manufacturers to improve the ECS durability of all their models to the level already met by the best of their models. If not, regulators could assess penalties to force such improvement.

Prediction for MY2000 and MY2010. Our predictions of future malfunction emissions of all three pollutants are based on the incidence of CO malfunctions in MY87–89 models. In our judgment, MY2000 is too soon to see much progress on increasing the durability of emissions controls; however, we believe that substantial progress will be made by MY2010. We assume, rather arbitrarily, for MY2000 that all models will be as durable as MY87–89 fuel-injected models, which have malfunction frequencies of 16% or lower. This reduces the average frequency of malfunction for the 54 fuel-injected MY-models from 7.4 to 5.7%, a 23% reduction. We assume, quite reasonably, that the average emissions of a car with a malfunctioning ECS will be the same as those from MY87–89, essentially the emission rates of pre-control cars. Therefore, the 23% reduction in malfunctions will lead to a 23% reduction in malfunction emissions by MY2000.

For MY2010, we predict that the average frequency of malfunction will correspond to that of the best quartile of MY87–89 fuel-injected models studied, those with a frequency of malfunction of 3.5% or lower. This assumption is based on the fact that the six largest manufacturers (by sales) all have at least one model or engine family in this group. This reduces the average frequency of malfunction found for the 54 fuel-injected MY-models from 7.4 to 2.6%, a 65% reduction in malfunctions and malfunction emissions from that estimated for MY93.

These predictions do not assume an increase in the successful repair of malfunctioning vehicles. Although we believe that OBD will improve mechanics' ability to properly diagnose the causes of ECS malfunction, in the overall picture we believe that improving ECS durability will be much more effective than repair of individual vehicles.

Although substantial progress in reducing malfunction emissions is technically possible, continued improvements of remote-sensing and OBD technologies, as well as efforts to gather and disseminate performance information, and perhaps enforcement of new durability requirements, are necessary to ensure that our predicted reductions are achieved. Without such actions, reduction of malfunction emissions may take much longer.

OTHER SOURCES

We examine two other sources of emissions briefly in our study: fuel evaporation and upstream emissions. Evaporative emission levels in Table 1 are taken from MOBILE5a. A recent study[34] indicates that, as with exhaust emissions, most evaporative emissions come from a few vehicles with high evaporative emissions. Our predictions of evaporative emissions from future vehicles in Table 2 are also based on MOBILE5a. However, improved information technologies and more aggressive actions to reduce fuel vapor pressure could lead to greater reductions than the 25% reduction predicted by MOBILE5a.

When comparing emissions from gasoline vehicles with 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. We estimate upstream emissions as well as vehicular emissions in order to put gasoline vehicles into a complete fuel cycle perspective. The estimates and predictions in Tables 1 and 2 are based on a model recently developed by one of us.[10]

DISCUSSION

Uncertainties in the Analysis

Both our allocation of MY93 emissions by source and our prediction of emissions reductions involve substantial uncertainties. The biggest uncertainties are associated with lack of data on (a) the extent and nature of the NO_x emissions we have attributed to malfunctioning ECS; (b) the lack of malfunction data on the most modern cars and the lack of a consistent time series for malfunction emissions; (c) the dependence of malfunction emissions on driving pattern, such as higher power and cold start; (d) the dependence of NO_x emissions on air conditioning; and (e) average driving patterns across the United States. For (a), we simply determine NO_x malfunction emissions as the difference between the emissions estimate for the other sources and the total predicted by MOBILE5a. For (b), our estimates are based on late 1980s, not early 1990s, cars. Recent data suggest, however, that malfunction emissions have been declining as vehicle technology improves. For (c), our estimates are based on simplistic assumptions that could be modified when major sources of malfunction are categorized and the corresponding emissions dependence on driving simulated, a possible achievement of current research at the University of California-Riverside.[35] For (d), we have had to rely on the limited data on emissions during air conditioner use from the FTP-RP. For (e), our estimates are based on instrumented vehicle data from Spokane and Baltimore. Uncertainties in both these data themselves and their applicability to the whole country are cause for concern.

In addition, the predicted reductions in all three pollutants associated with ECS malfunction are based on our analysis of CO alone, due to a lack of accurate data on HC and NO_x emissions associated with ECS malfunction. Moreover, the prediction of CO malfunction emissions is based on remote-sensing data for MY87–89 fuel-injected cars, taken in 1991 (i.e., two- to five-year-old vehicles). This is far from ideal; one would prefer to examine high-mileage, older cars with modern fuel and emissions control technologies. Finally, our estimates of evaporative emissions are not based on new information, but are simply taken from the nominal forecast in MOBILE5a. Of course, all predictions are uncertain; the ones just singled out appear to us to be the most problematic.

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.

Policy Implications

When all sources are considered, real-world emissions from cars exceed tailpipe standards by a large margin. Clearly, policies are needed to address the largest sources of emissions, off-cycle driving and cars with malfunctioning emissions controls. A new policy has been adopted to regulate off-cycle emissions; it will be phased in, coming into full effect for MY2002. However, the future of malfunction emissions is hard to predict accurately. New technologies are being adopted that provide information on malfunction emissions. If the development of improved information technologies is not actively pursued, or if these technologies are used solely to identify individual vehicles rather than expose and correct carline design flaws, then the reductions in malfunction emissions may be much smaller than we predict. We predict that, with the implementation of the off-cycle policy and adoption of modest new policies built on the information technologies, real-world emissions will be reduced by more than half by MY2010.

Even if real-world emissions are reduced by more than half in 2010, they will still substantially exceed new car standards. Policies to do even better should be considered. However, any such policies should be considered in light of the progress being made in the entire fleet of conventional vehicles.

ACKNOWLEDGMENTS

This work was supported in part by the Energy Foundation; the Laboratory Directed Research and Development Program of Lawrence Berkeley National Laboratory under the U.S. Department of Energy, Contract No. DE-AC03-76SF00098; and Lockheed Martin Energy Research, Oak Ridge National Laboratory, under a contract with the Federal Highway Administration of the U.S. Department of Transportation. Our gratitude goes out to many, but especially John German of the U.S. EPA, who assisted in the analysis of the FTP-RP data, and Bob Stephens of GM, who provided guidance in the analysis of the remote-sensing data.

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