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Characterization of Recent-Model High-Emitting Automobiles

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ABSTRACT

In-use vehicles which are high emitters make a large contribution to the emissions inventory. It is not known, however, whether high-emitting vehicles share common emissions characteristics. We study this by first examining laboratory measurements of second-by-second engine-out and tailpipe emissions from a small number of MY90-97 high-emitting vehicles. We distinguish high-emitter types by the behavior of six ratios in low- and moderate-power driving: the engine-out emissions indices (engine-out pollutant to fuel-rate ratios) and the catalyst pass fractions (tailpipe to engine-out ratios) for CO, HC, and NOx. Four general types of high emitter are observed: 1) fuel-air ratio excessively lean, 2) fuel-air ratio excessively rich, 3) partial combustion such as misfire, and 4) severe deterioration in catalyst performance in vehicles where malfunctions of Types 1, 2 or 3 are not predominant. We also find that these behaviors may be chronic, or may only occur transiently. The second step is to determine the prevalence of the four different types of high emitter in the on-road fleet. For this we analyze IM240 tailpipe emissions from a large sample of cars measured in the Arizona inspection and maintenance program. We find that all four types of failure are observed with roughly comparable probabilities.

INTRODUCTION

Several independent analyses have found that about half of the on-road emissions by automobiles may be from the small fraction of vehicles that are high emitters [1-4]. Although there are many potential technical causes of failed or malfunctioning emissions controls, there has been relatively little study of the distribution of these technical causes in the fleet of in-use vehicles [5-7]. Probably the most useful work is a comprehensive analysis of several datasets on the effectiveness of repairing specific components, which identifies components most likely to fail [8,9].

In the nature of investigations of high-emitters, the emphasis has been on carbureted vehicles and early-model fuel-injected vehicles. In the present analysis, we focus on newer model years, presenting information on model-year 1990 and later vehicles with sophisticated computer-controlled fuel-injected engines.

First, we identify the types of high emitters in hot-stabilized operation, and draw rough conclusions about the physical mechanisms underlying each, based on detailed second-by-second testing of engine-out and tailpipe emissions on a sample of in-use vehicles at the University of California, Riverside. In particular, we distinguish high-emitter types by the behavior of six ratios in low- and moderate-power driving: the engine-out emissions indices (engine-out pollutant to fuel-rate ratios) and the catalyst pass fractions (tailpipe to engine-out ratios) for CO, HC, and NOx. Thus our determinations of the causes of high emissions are based on detailed comparisons of fuel rate, and engine-out and tailpipe emissions, rather than on mechanical inspection or any subsequent emissions reductions due to component repairs and/or replacements.

Second, we estimate the frequency of occurrence of each type of malfunction in the in-use fleet, based on analysis of results from the inspection and maintenance (I/M) program in Arizona. The distribution of three-pollutant "profiles" in the I/M data enables estimation of the on-road probabilities for each type of high emitter observed in the laboratory measurements made at UC Riverside.

HIGH EMITTER TYPES IN THE NCHRP DATA

A major emissions measurement has been recently completed at the College of Engineering Center for Environmental Research and Technology (CE-CERT) at the University of California at Riverside, funded by the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board. The primary purpose is to develop a modal, or driving-dependent, emissions model [10, 11]. Both engine-out and tailpipe emissions of some 300 vehicles have been measured second-by-second on three driving cycles, including the Federal Test Procedure (FTP) cycle and a modal cycle developed at CE-CERT for modeling purposes (the

Modal Emission Cycle, or MEC). The vehicles have been recruited for emission model development; i.e., in accordance with their relative contribution to the emission inventory, rather than according to their frequency on the road. The emissions of roughly fifteen MY1990 and later high-emitting cars and a similar number of high-emitting light-duty trucks are among the vehicles recruited and measured. (The number of high emitters depends on the cutpoints used to define high emissions.) Sixteen of these high-emitters are analyzed in this paper. The NCHRP project is the first to specifically recruit high-emitters for such second-by-second measurements of both tailpipe and engine-out emissions.

The recruitment of high-emitting vehicles of MY1990 and later is difficult because the fraction of such vehicles in the fleet is low (at least at current vehicle ages). In the NCHRP project vehicles suspected of being high emitters were specifically recruited in a non-random fashion, so the overall frequency of high emitters, and the frequency by type of failure, in the on-road fleet is not known from these data. (It should be clear that the identification of one or two vehicles of a particular model as high emitters in this project has no statistical significance.)

To address the issue of real-world frequency of the high emitters, we categorize the several types of high emitters measured in the project according to their emissions characteristics, and make a correspondence between these types of high emitter and the distribution of high emitters with similar tailpipe-emission profiles observed in Arizona's on-going I/M program. The Arizona program covers essentially all light-duty vehicles in the Phoenix area (although the number of high emitters may be underestimated because there is a tendency for people to not register their vehicles, or register them elsewhere, if they think that they won't pass the I/M test [12]). We thus determine weights to assign to the NCHRP high-emitter types which may reasonably reflect the representation of those kinds of high emitters on the road.

The characterization of the NCHRP high emitters might be done using simulation-model parameter fits to the measurements, or simply from bag data. But emissions in distinct driving modes will be used here because it is a simple approach which reveals aspects of the physical mechanisms of emissions control system (ECS) failure. (Note that careful inspection of the tested vehicles by a professional mechanic was not a part of the NCHRP project.)

We focus our study on vehicles which are high emitters in low- to moderate-power driving. An example of what we call moderate power is a 50 mph cruise on a level road without unusual load, but with throttle fluctuations. Such a power level requires a fuel rate of about 0.7 grams per second for small sedans, and about twice that for large sedans and most light trucks. This power level is characteristic of the IM240 driving cycle used in the Arizona I/M program and the 505-second cycle used for bags 1 and 3 of the Federal Test Procedure (FTP), as shown in Table 1. Such moderate power modes are also found in the MEC. The maximum fuel rates achieved in throttle fluctuations during the MEC are also shown in parentheses and are seen to be less than the maxima in the regulatory cycles.

Table 1. Modes of the MEC Considered

Mode	**Avg speed (mph)**	**Avg (Max) Fuel Rate (g/s) small sedan**	**Avg (Max) Fuel Rate (g/s) large sedan**
MEC:			
low power	20, 35	0.4 (0.7)	0.6 (1.2)
mod. power	50	0.7 (1.1)	1.3 (2.0)
IM240		0.7 (2.1)	1.2 (3.5)
FTP Bag 2		0.4 (1.3)	0.8 (2.2)
FTP Bag 3		0.6 (2.1)	1.0 (3.5)

We will compare emission rates in the MEC, and Arizona IM240 measurements (as well as referring to analyses of earlier FTP measurements). As seen in Table 1, the average and maximum power levels in FTP bag 2 are substantially less than in the IM240 cycle, while bag 3 and IM240 have similar power levels. On the other hand, bag 3 starts after a 10 minute soak which modestly increases CO and HC totals for the bag. The IM240 is supposed to begin with the vehicle hot, but there is evidence that in practice vehicles often may have cooled off somewhat or the engine block may not have been fully warmed up [13]. Power levels and vehicle conditioning in the selected modes of the MEC are most comparable to those of FTP bag 3 and the IM240 cycle.

EMISSIONS BEHAVIOR IN CLOSED-LOOP AND COMMAND ENRICHMENT – Accurate control of the fuel-air ratio in closed-loop operation is critical to effective emissions control. It is likely that most high emitters among MY1990 and later vehicles are caused or created by some form of fuel-air ratio control problem.

In closed-loop operation with a three-way catalyst, the electronic control module manages the injection of fuel so as to essentially maintain stoichiometry (the optimum ratio of air to fuel, about 14.7:1) to maintain combustion while minimizing emissions. In vehicles with three-way catalysts, the ratio is made to swing back and forth between slightly rich and slightly lean, at about 1 Hz or faster, in order to automatically adjust the oxygen level on catalyst surfaces so that exhaust CO and HC are oxidized while NO is simultaneously reduced. The time dependence of the fuel-air ratio in a typical properly-functioning vehicle is schematically shown in Figure 1. As shown, for proper operation the fuel-air ratio oscillates around stoichiometric:

$$\left| \langle\phi\rangle - 1 \right| < \Delta\phi \qquad \text{(Eq. 1)}$$

Here, ϕ is the fuel-air ratio compared to its stoichiometric value. In fact, eq(1) should hold with substantial overlap. For many vehicles with malfunctioning ECS the fuel-air management isn't working properly, so this inequality doesn't hold, even at moderate power. In these conditions, the vehicle is likely to be a high emitter.

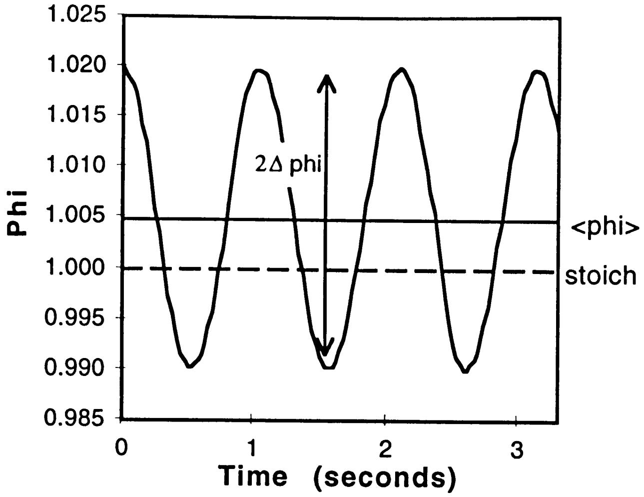


Figure 1. Illustrative Example of Oscillations in Fuel-Air Ratio in Closed-Loop Operation

In Table 2, six emissions ratios measured in the NCHRP project are shown with typical values that have been observed for modern *properly-functioning* vehicles in hot-stabilized operation (specifically, MY91-93 vehicles tested by manufacturers as part of the FTP Revision Project [14,15]). We distinguish three fuel-air ratio regions: *stoichiometric*, where eq(1) is satisfied; *rich*, where $\phi > 1$ beyond that described by Figure 1; and *lean*, where $\phi < 1$ beyond that described by Figure 1.

Table 2. Average Emission Ratios for Low-Emitting Vehicles, Stoichiometric and Rich Operations

Variable	Operating Range	
	Stoichiometric	**Enrichment**
EICO	≈ 0.08	0.1 to ~1.0
EIHC	≈ 0.015	≈ 0.015
EINOx	≤ 0.05, lower at low power	≤ 0.05, declines with enrichment
CPFCO	≤ 0.1	quickly → 1.0
CPFHC	≤ 0.1	gradually → ~0.7
CPFNOx	0.02 to 0.2	quickly → ~0.7

In stoichiometric operation one observes that:

- The CO emission index, or EICO (the ratio of mass of CO that leaves the engine to fuel input mass), varies around 0.08, from perhaps 0.02 to 0.15.
- EIHC depends somewhat on details of engine design and fuel and lubricant composition, since it comes from cylinder surfaces and crevices; but it lies between 0.01 and 0.02 in rich as well as stoichiometric operation.
- EINOx, the engine-out NOx-to-fuel mass ratio, varies with power and with EGR system. The typical maximum value observed is 0.05.
- We designate catalyst activity using catalyst pass fractions, or CPFi: the mass ratio of pollutant i output from the catalyst to pollutant i input to it (i.e. the tailpipe to engine-out ratio). The three catalyst pass fractions vary considerably from one vehicle model to the next and with the details of operation.

In high-power operations, most vehicles command fuel enrichment; i.e. the fuel-air control system goes open loop and ϕ is commanded to be in a range roughly 1.05 to 1.20 (i.e. 5 to 20 percent rich). Since command enrichment results in massive increases in tailpipe CO emissions and some increase in HC, and will, moreover, be coming under regulation with the Supplemental FTP, manufacturers have begun to reduce the use of this technique.

The emissions ratios behave in predictable ways when the fuel-air ratio goes rich (right-hand column, Table 2):

- EICO increases strongly with enrichment (as shown by eq(2), below); CPFCO is sensitive to even slight enrichment and increases rapidly toward 1.0 with increasing enrichment.
- EIHC is essentially independent of enrichment as such because at the high cylinder temperatures excess fuel is converted to CO and H_2; however, it increases due to other kinds of incomplete combustion, such as from cylinder misfire. CPFHC increases slowly with increasing enrichment.
- EINOx is moderately suppressed by the cooling effect of enrichment; CPFNOx may be reduced with slight enrichment, but increases rapidly with stronger enrichment in most modern vehicles (although it does decline in a few models).

In decelerations during closed-loop operation the fuel-air ratio often goes lean, often very lean in major decelerations. Lean excursions are normal, although large engine-out HC puffs may occur. If catalyst performance has deteriorated, then tailpipe HC puffs associated with these lean excursions can be substantial [16].

FUEL-AIR RATIO DATA – As suggested by Figure 1, ϕ (the fuel-air ratio relative to stoichiometric) would need to be known to much better than 2% accuracy to be useful for our purposes here. Fuel-air ratios based on emission measurements and chemistry are not accurate enough for this purpose. For this reason we use the emissions ratios listed in Table 2 as indicators of improper fuel management.

As an alternative to calculating ϕ from tailpipe measurements and chemistry, one can estimate it from a linear formula for EICO:

$$\mathrm{EICO} \approx 0.08 + 3.6(1 - 1/\phi), \text{ or}$$
$$\phi = 1 + (\mathrm{EICO} - 0.08)/(3.5 - \mathrm{EICO}) \qquad \text{(Eq. 2)}$$

It is likely that ϕ calculated using eq(2) is not grossly in error. Eq(2) is not however useful in lean conditions.

DEFINITION OF HIGH AND LOW EMITTERS – For this paper, we define high emitters in the NCHRP project as vehicles which exceed FTP bag 3 emissions cutpoints in grams per mile (gpm); the selected cutpoints are shown in Table 4 below. With the chosen cutpoints, high emitters exceed the emissions of typical properly-functioning MY 1990-1993 vehicles by more than a factor of about 2.5. These are rather tight cutpoints for "high emitters"; we choose them because MY90 and later high emitters proved hard to recruit for testing.

For our analysis we also need cutpoints below which we consider a vehicle to be a low emitter. For this purpose we examine three sets of measurements, as summarized for cars in Table 3. The measurements are: 1) NCHRP, for MYs 90-93 measured in 1996-97 (mostly California cars). We calculate average emissions for properly-functioning cars by excluding the 10% highest emitters. 2) FTP Revision Project measurements on new MY91-94 49-state vehicles with 50,000 mile laboratory-aged catalysts [17]. 3) American Automobile Manufacturers Association in-use survey from which we select MY 1991-92 cars with odometer readings from 40,000 to 60,000 miles, measured in 1995-96 [18]. Again, we take the average emissions of the 90% cleanest cars (sorted for each pollutant separately).

Table 3. Emissions from Properly-Functioning Cars at 50,000 miles in Three Studies: FTP Bag 3 (gpm)

dataset	MYs	n^a	CO	HC	NOx
NCHRP	1990-93	24	2.7	0.22	0.35
FTP-RP	1991-94	23	1.5	0.16	0.33
AAMA in-use	1991-92	57	2.5	0.21	0.22

a) number of vehicles measured in the subset considered. See text for definition of each subset.

The low cutpoints adopted are shown in Table 4. We regard these low cutpoints to be representative of properly-functioning in-use vehicles at 50,000 miles and age 4 to 5 years. Roughly two-thirds of properly-functioning vehicles will emit less than the low-emitter cutpoints chosen.

Table 4. Cutpoints for High and Low Emitting Vehicles in the NCHRP Project: FTP Bag 3 (gpm)

	CO	HC	NOx
Low Emitters			
cars	3	0.2	0.4
trucks	4	0.3	0.7
High Emitters			
cars	6	0.5	1.0
trucks	10	0.8	1.5

HIGH-EMITTER TYPES – Below we consider the four types of high emitters observed in NCHRP project measurements

Type 1. Operates Lean at Moderate Power – In the first type of high emitter, the fuel-air ratio is chronically lean or goes lean in transient operation calling for moderate-power. An average 2% or more lean is likely to saturate the catalyst with oxygen. The examples from the NCHRP data are vehicles 103 (1993 Sundance), 202 (1997 Windstar), and 295 (1990 Astro).

The characteristics of the six ratios for vehicle 202 at low and moderate power are shown in Table 5. The effect on the CPFs is striking, while that on the engine-out emissions is slight. While vehicle 202 operates consistently lean, vehicle 103 goes lean in moderate-power transients (i.e. with throttle fluctuation). Vehicle 295 also goes lean during transients, and shows considerable catalyst deterioration as well.

Table 5. Average Emission Ratios at Moderate Power for Type 1 (Vehicle 202)

Variable	Range, Comment
EICO	≈ 0.08 or less, normal
EIHC	≈ 0.02, normal
EINOx	≤ 0.1, slightly > normal
CPFCO	≈ 0.01, almost zero, < normal
CPFHC	≈ 0.01, almost zero, < normal
CPFNOx	roughly 0.5 to 1.0, much > normal

The behavior of a high NOx emitter over a portion of the MEC (Figure 2a) is compared with that of a normal NOx emitter (Figure 2b). The tendency of vehicle 202 to run lean for long stretches is seen in Figure 2a. In driving at 50 and 65 mph, phi is frequently about 0.9, and the tailpipe NOx rate is high, reaching 0.1 or 0.2 grams per second. Vehicle 136, a normal NOx emitter, operates at stoichiometry during the cruise sections, resulting in very low tailpipe NOx levels. (The strong acceleration at approximately 110 to 120 seconds involves power beyond FTP levels which we do not consider here.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 6: very high NOx tailpipe emissions, and low CO and HC emissions, relative to emissions of clean vehicles. The profile is in the form of CO/HC/NOx levels in terms of the two cutpoints for each, with L, M and H standing for: below the low cutpoint, medium or in between, and above the high cutpoint, respectively. The low and high cutpoints for trucks are shown for comparison, from Table 4.

Table 6. FTP Bag 3 gpm Tailpipe Emissions for Type 1 Vehicles, and Truck Cutpoints

Test Vehicle	CO	HC	NOx	profile
103 (car)	1.7	0.05	1.1	LLH
202 (truck)	0.4	0.04	2.9	LLH
295 (truck)	4.0	0.90	1.8	MHH

A physical failure mechanism leading to Type 1 behavior is not so easy to pinpoint. Improper signal from the oxygen sensor or improper functioning of the electronic engine control are possibilities.

Type 2. Operates Rich at Moderate Power – In the second type of high emitter, the fuel-air ratio is chronically rich or goes rich in transient moderate-power operation. The EIHC remains normal. Under these conditions, the CO emission index and catalyst pass fraction are high, resulting in high tailpipe CO emissions. Examples from the NCHRP testing are three cars, 113 (1990 Sentra), 125 (1990 Spirit), and 136 (1993 240 SX).

The measurements on vehicle 113 at low and moderate power are summarized in Table 7. The high EICO and CPFCO occur in moderate-power transients (i.e. with throttle fluctuation). Relative to properly-functioning vehicles, EIHC is unaffected and EINOx is slightly low. The behavior of vehicle 136 is similar. Vehicle 125 shifts from stoichiometric to steady highly-enriched operation for long periods in a manner apparently unrelated to the driving. Vehicles 43 and 277 show transient enrichment, but their strong deterioration of catalyst performance leads us to categorize them as Type 4 below.

Table 7. Emission Ratios at Moderate Power for Type 2 (Vehicle 113)

Variable	Range, Comment
EICO	> 0.15, 2 or more times normal
EIHC	≈ 0.015, normal
EINOx	≈ 0.02, < normal
CPFCO	roughly 0.5 to 1.0, much > normal
CPFHC	≈ 0.05 to 0.2, somewhat > normal
CPFNOx	≈ 0.01, < normal

The behavior of a high CO emitter over a portion of the MEC (Figure 3a) is compared with that of a normal CO emitter (Figure 3b). The tendency of vehicle 136 to run somewhat rich when there are throttle variations at moderate power is shown in Figure 3a in the 60- to75-second segment, where EICO reaches levels of 0.2 to 0.3. The great sensitivity of CPFCO to these rich excursions is evident. A normal CO emitter, vehicle 103 (Figure 3b) shows much lower EICO and CPFCO in this segment of the MEC. (Again we do not focus on the strong accelerations at the beginning and end of the sequence shown.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 8: high CO, and low to medium HC and NOx, relative to emissions of clean vehicles. The low and high cutpoints for cars, from Table 4, are shown for comparison. (For car 113, the CO is taken as high although the measurement comes in slightly below the high cutpoint.)

There are many possible failure mechanisms resulting in enrichment during closed loop operation; however the mechanism here must also leave the engine-out HC emissions index in its normal range of 0.01 to 0.02. Thus there can be enrichment but not misfire. One example which meets the characteristics is a leaking exhaust line which brings in oxygen before the oxygen sensor, resulting in the sensor calling for more fuel from the injectors.

Table 8. FTP Bag 3 gpm Tailpipe Emissions for Type 2 Vehicles, and Car Cutpoints

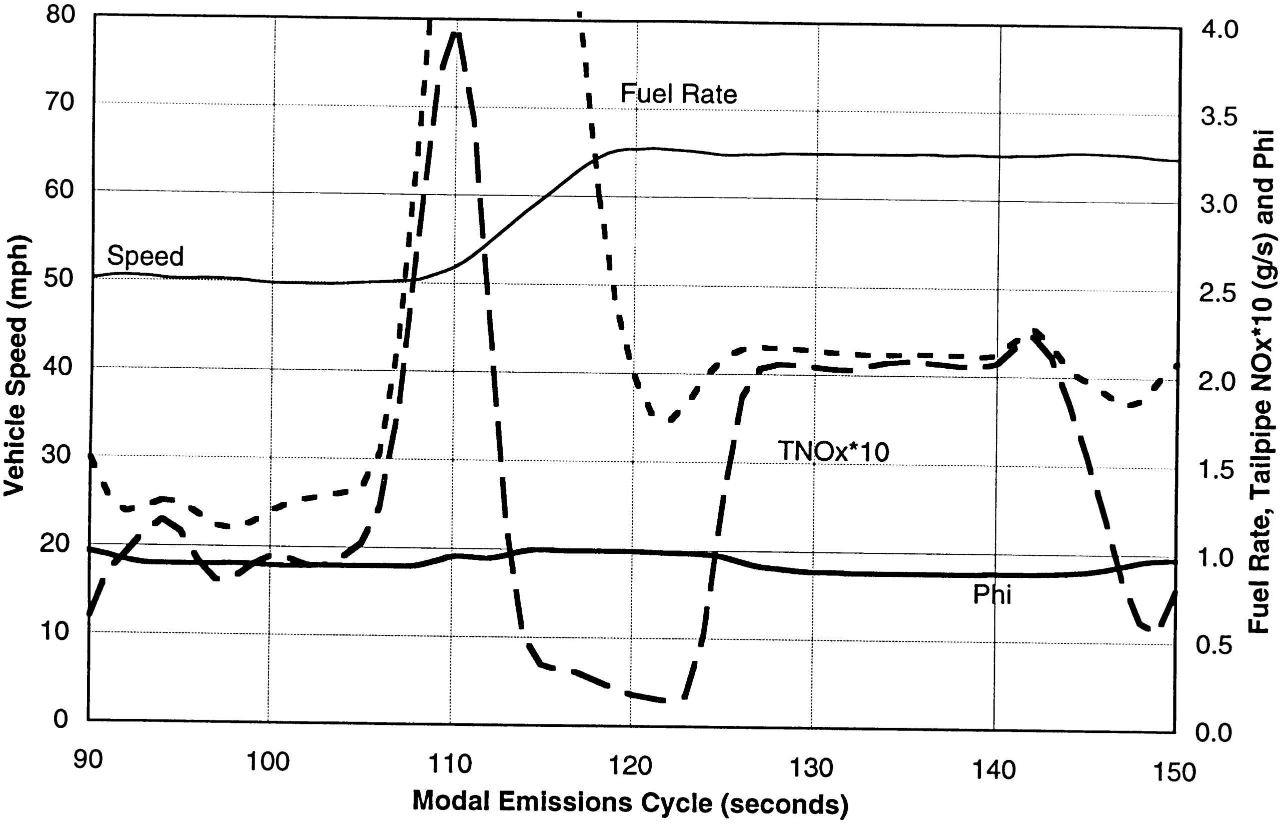
Test Vehicle	CO	HC	NOx	profile
113 (car)	5.9	0.21	0.24	HML
125 (car)	6.4	0.34	0.57	HMM
136 (car)	6.8	0.17	0.17	HLL

Type 3. High Engine-Out Hydrocarbon Emissions Index – The third type of high emitter involves a high engine-out emission index for HC and mild enrichment, as evidenced by high EICO and CPFCO. Catalyst performance is also poor. The examples are vehicles 178 (1992 S-10 pickup), 209 (1994 Caravan), and 273 (1992 Corsica). The characteristics of vehicle 209, whose second-by-second EIHC is consistently high, are shown in Table 9.

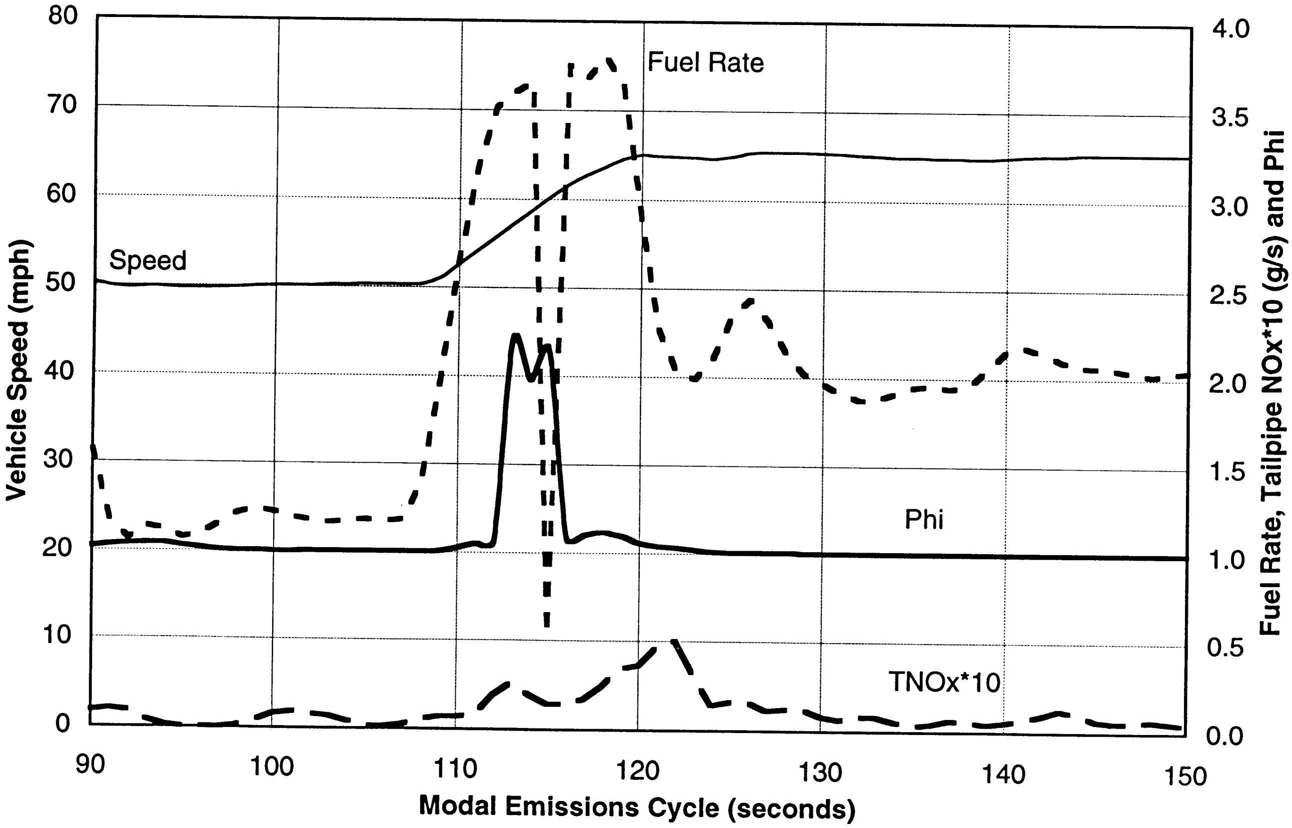
Table 9. Emission Ratios for Type 3 (Vehicle 209)

Variable	Range, Comment
EICO	> 0.15, 2 or more times normal
EIHC	≈ 0.15, roughly 10 times normal
EINOx	≈ 0.02, < normal
CPFCO	roughly 0.5 to 1.0, much > normal
CPFHC	≈ 0.05 to 0.2, slightly > normal
CPFNOx	≈ 0.01, essentially zero

The characteristics of vehicle 178 are shown in Table 10. In this case, high EIHC is a transient effect, with puffs of HC every time the fuel-air ratio declines, even in cases where it remains rich.

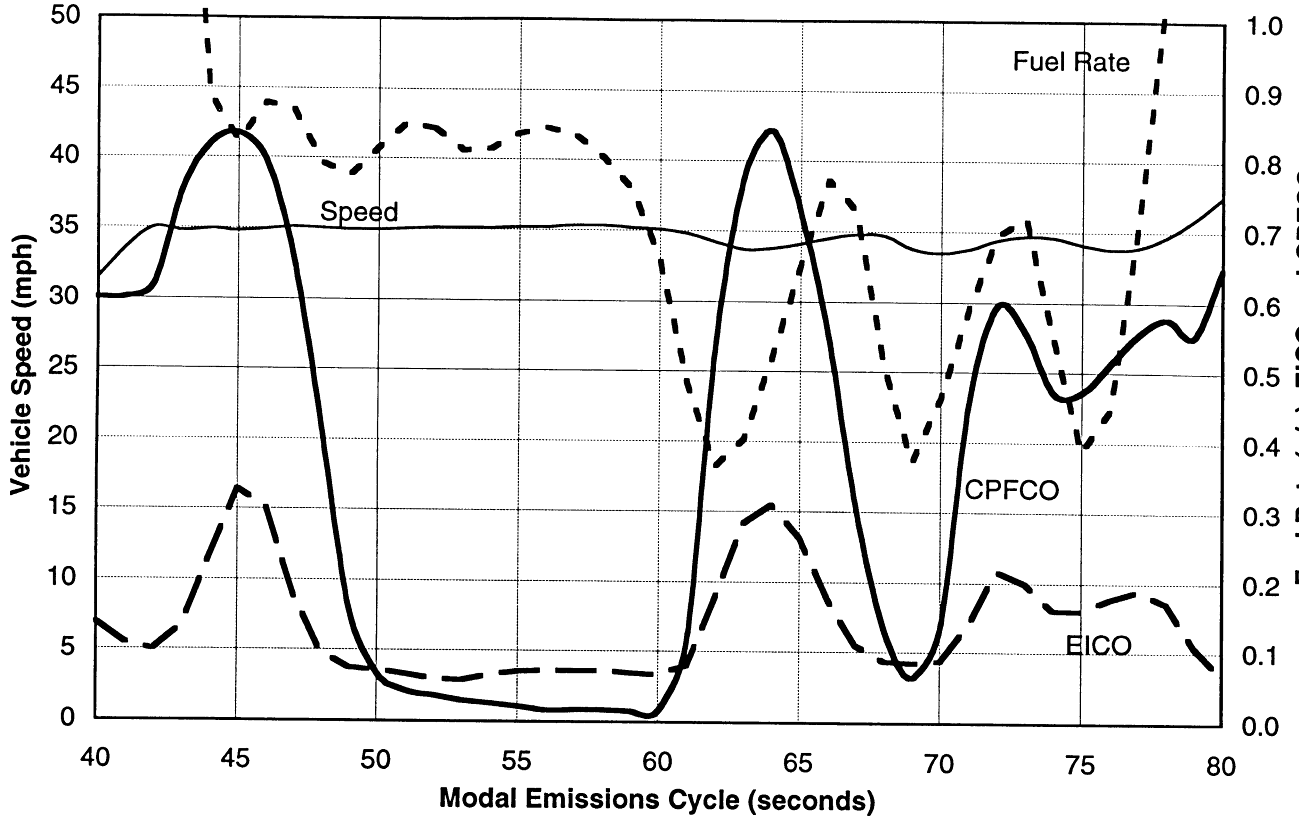


(a) Vehicle 202 (High NOx Emitter): Fuel Rate, Tailpipe NOx, and Phi

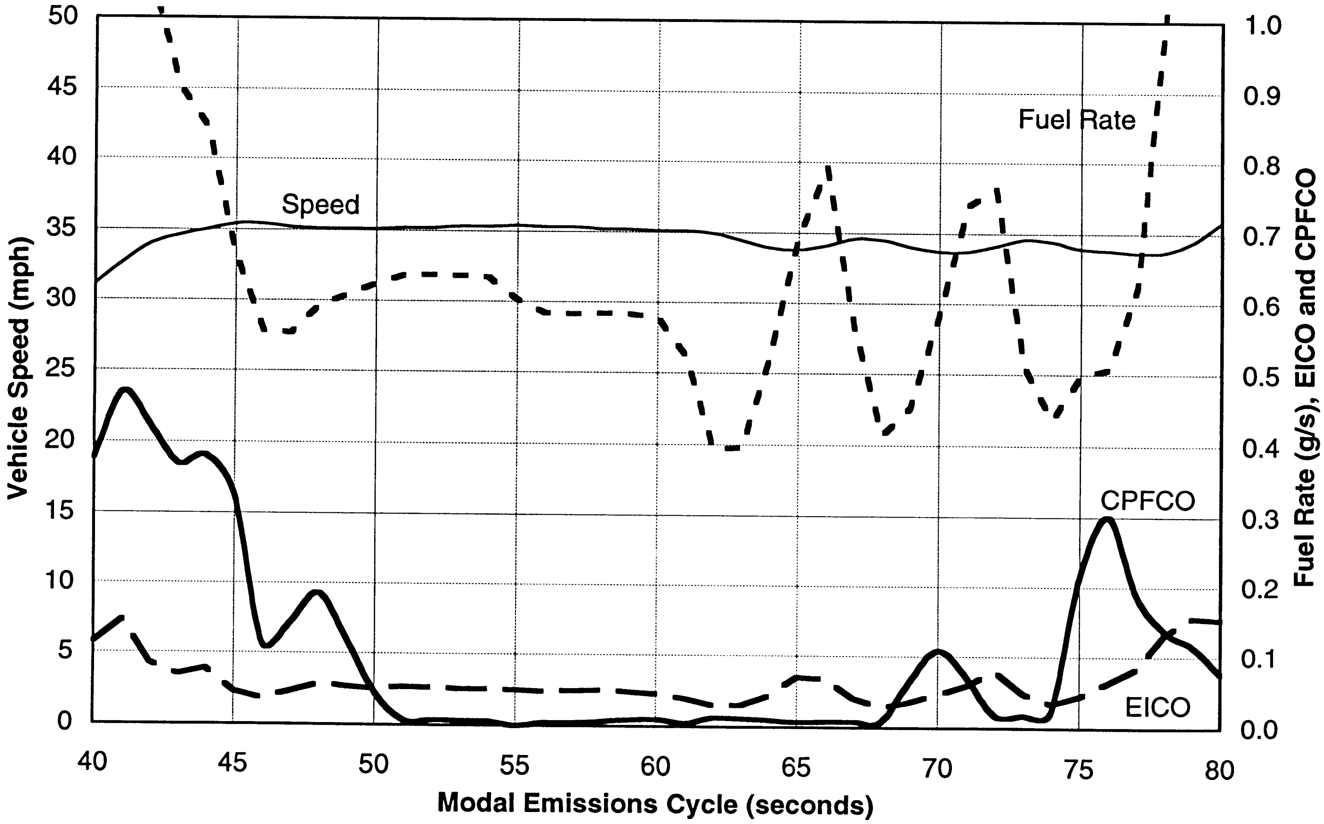


(b) Vehicle 136 (High NOx Emitter): Fuel Rate, Tailpipe NOx, and Phi

Figure 2.



(a) Vehicle 136 (High CO Emitter): Fuel Rate, Engine Out CO and CO Catalyst Pass Fraction



(b) Vehicle 103 (High CO Emitter): Fuel Rate, Engine Out CO and CO Catalyst Pass Fraction

Figure 3.

Table 10. Emission Ratios for Type 3 (Vehicle 178)

Variable	Range, Comment
EICO	≈ 0.15, slightly over normal
EIHC	≈ 0.05, roughly 3 times normal
EINOx	< 0.02, < normal
CPFCO	roughly 0.5, much > normal
CPFHC	≈ 0.1 to 0.3, > normal
CPFNOx	≈ 0.5, much > normal

The behavior of a high HC emitter over a portion of the MEC (Figure 4a) is compared with that of a normal HC emitter (Figure 4b). The tendency of vehicle 178 to have HC emissions indices exceeding 0.1 at times other than major decelerations is shown in Figure 4a. The effect seems to be associated with throttle fluctuations between seconds 70 and 80 of the MEC (the relatively low EICO values at these times suggest that the increase in EIHC is not due to enrichment; an example of enrichment can be seen between seconds 40 and 45, at the end of an acceleration). Figure 4b shows that a properly-functioning engine of current technology maintains EIHC in the 0.01 to 0.02 region, except after major accelerations or decelerations. (The figure also shows small EIHC excursions above this value during transients.)

The FTP bag 3 tailpipe emissions profile for these vehicles is shown in Table 11: moderate to slightly-high tailpipe CO, very high HC, and moderate to low NOx relative to properly-functioning vehicles. The key aspect of the profile is the very high HC.

Table 11. FTP Bag 3 gpm Tailpipe Emissions for Type 3 Vehicles

Test Vehicle	CO	HC	NOx	profile
178 (truck)	4.5	1.2	0.80	MHM
209 (truck)	11.4	2.1	0.06	HHL
273 (car)	9.8	1.7	0.90	HHM

Excess EIHC is probably caused by incomplete combustion in one or more cylinders, from many physical mechanisms such as a bad spark plug or partial obstruction of an injector resulting in too little fuel injected into the cylinder. There are many possible mechanisms. Oxygen levels in the exhaust are observed to be correspondingly high (2.5 grams of excess oxygen per gram of excess engine-out fuel). Catalyst performance is also poor, and not only when EIHC is high. Perhaps the catalyst deterioration results from the history of high engine-out HC emissions.

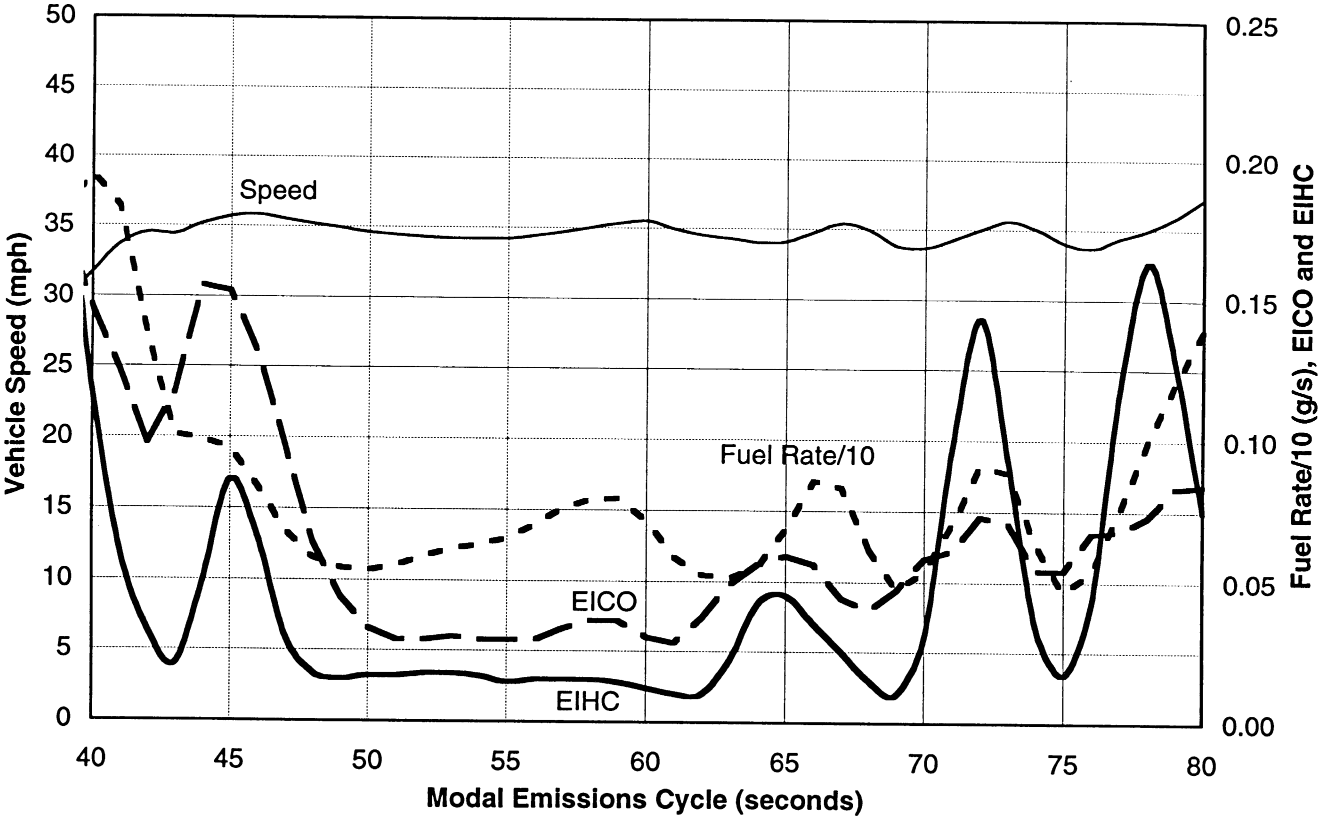
<u>Type 4. Poor Catalyst Performance for All Three Pollutants at Moderate Power</u> – High tailpipe emissions of all pollutants typifies Type 4 high emitters. This type involves more than one behavior, with 1) chronically poor catalyst performance, due to burned-out or missing catalyst, or 2) transiently poor catalyst performance, e.g. a catalyst pass fraction of 0.3 or more in moderate-power driving. Type 4 malfunction is distinguished from Type 3 because EIHC is normal, or only slightly high, and from Type 1 because there is no or only slight enrichment at moderate power.

There are seven vehicles of this type. Two vehicles, 42 (1990 Grand Am) and 71 (1992 Corolla), have burned-out catalysts. Five, 43 and 150 (both 1992 Dakotas), 77 (1992 Tercel), 254 (1992 Elantra), and 277 (92 Fox) are more complex examples of poor, highly-variable, catalyst performance; emissions characteristics for three of these vehicles are shown in Table 12. Vehicles 77 and 150 are similar in their relatively good fuel control and normal EIHC. Vehicle 43 and especially 254 and 277 have poor fuel control. Vehicle 277 could be classified as Type 2, with its considerable transient enrichment. Vehicle 254 could be classified as Type 3, being somewhat similar to 178; its EIHC is about twice normal.

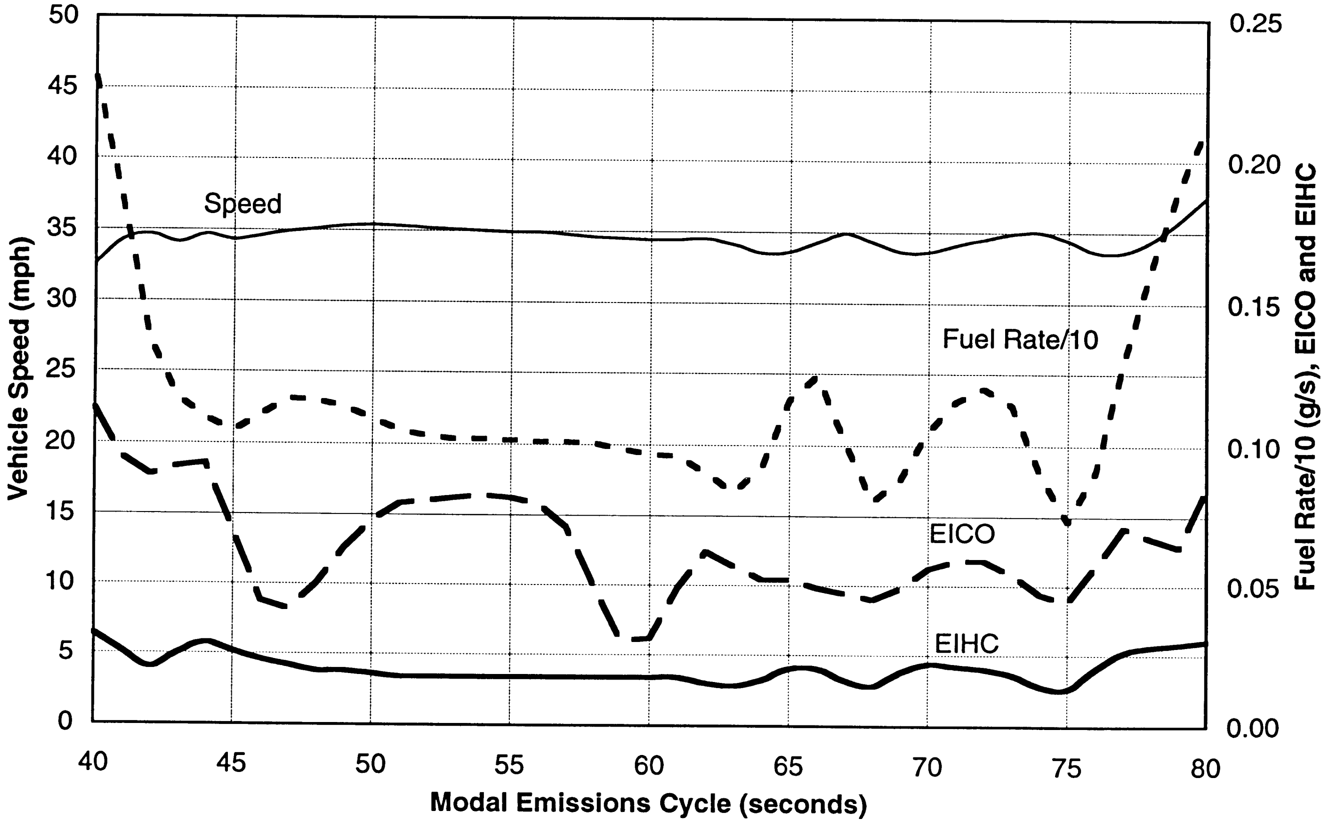
Table 12. Emission Ratios for Type 4 (Vehicles 43, 77 & 150)

Variable	Range, Comment
EICO	up to 0.15, normal or slightly higher
EIHC	up to 0.025, normal or slightly higher
EINOx	< 0.05, normal
CPFCO	0.3 to 0.6, well above normal
CPFHC	≈ 0.2 or 0.3, above normal
CPFNOx	0.2 to 0.6, well above normal

The behavior of a vehicle with high emissions of all pollutants over a portion of the MEC (Figure 5a) is compared with that of a normal emitter (Figure 5b). Figure 5a illustrates strong if variable catalyst deterioration for vehicle 254, with CPFs of about 0.4 in moderate driving. This deterioration does not seem to be caused by excursions in phi, although we cannot be sure because the measurement of phi may not be accurate enough for this purpose. In contrast, Figure 5b shows that a normal emitter (vehicle 248) has CPFs of essentially zero in the same segment of the MEC (although CPFs do increase with excursions in phi).

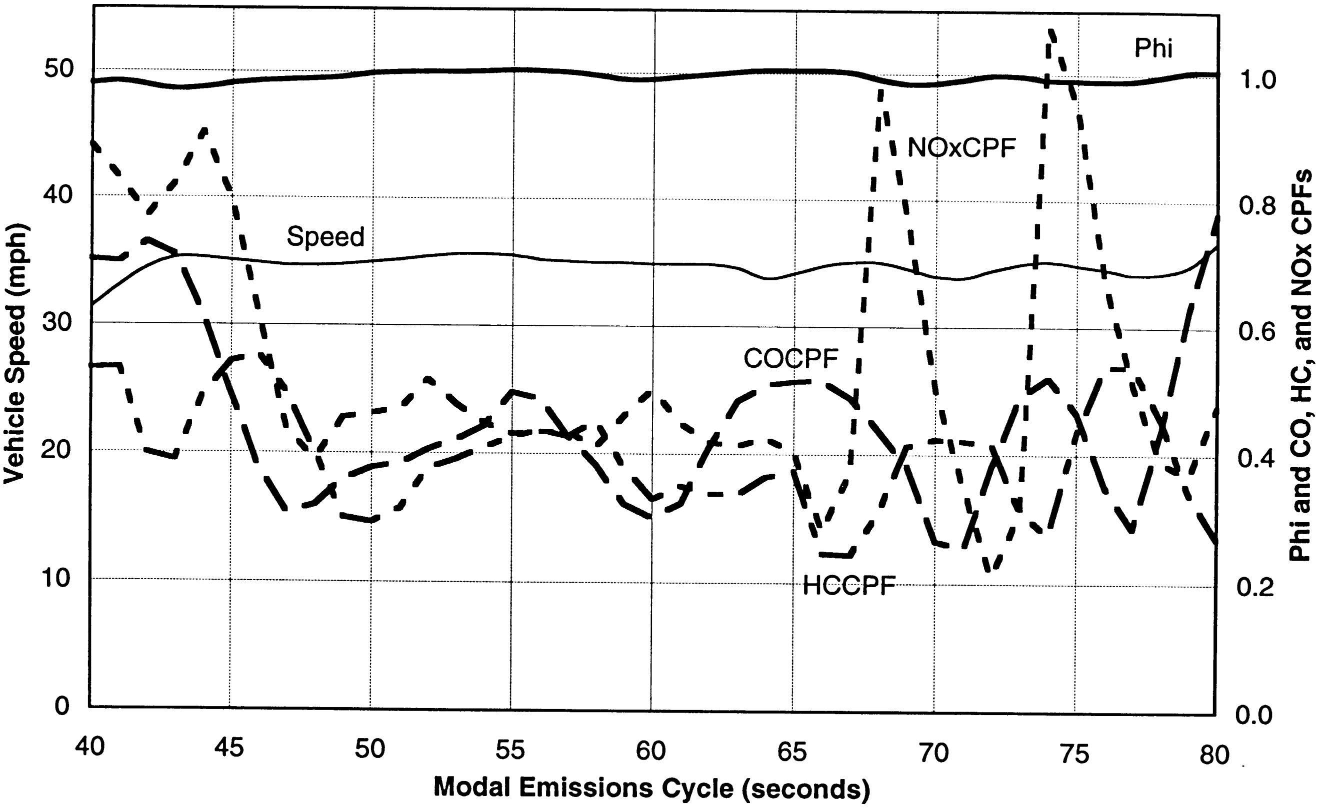


(a) Vehicle 178 (High HC Emitter): Fuel Rate, Engine Out CO and HC

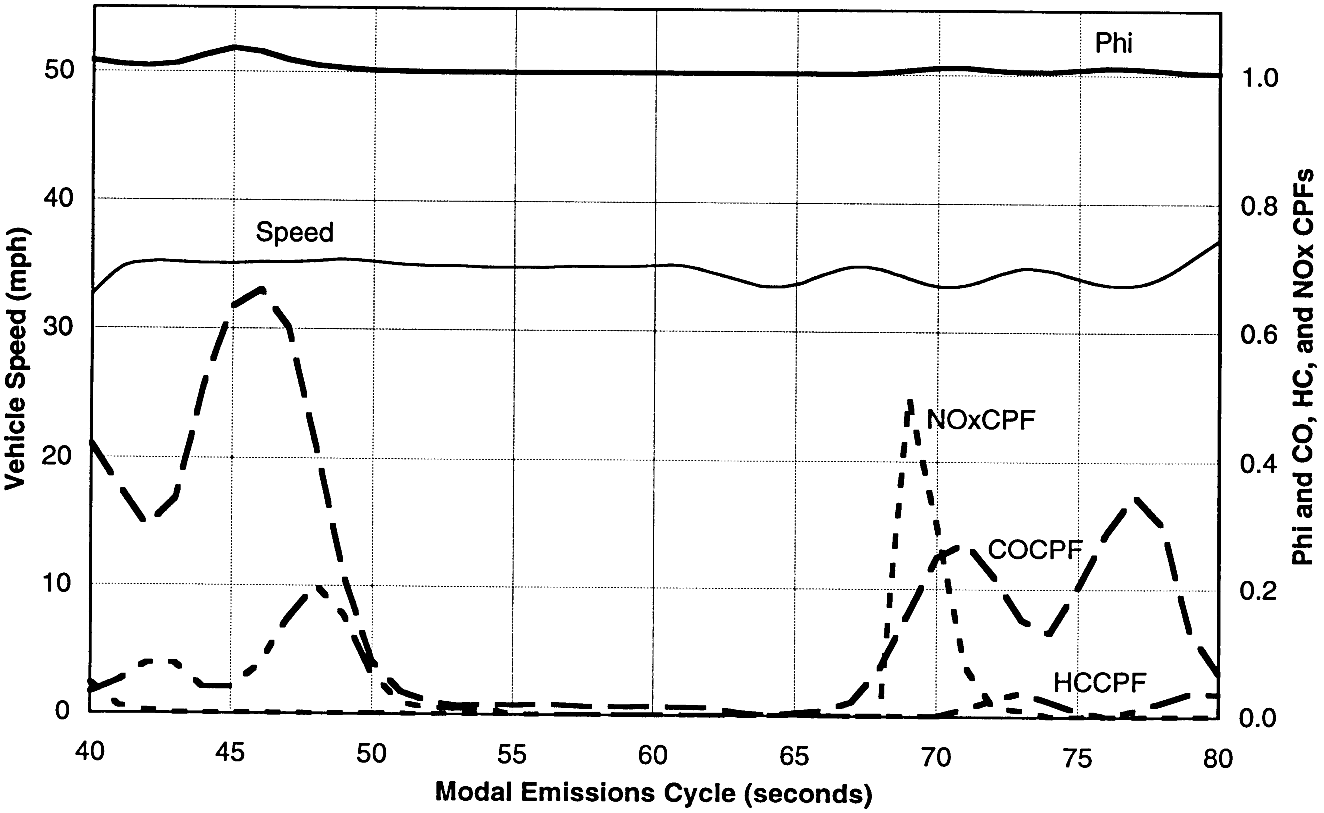


(b) Vehicle 295 (Normal HC Emitter): Fuel Rate, Engine Out CO and HC

Figure 4.



(a) Vehicle 254 (High CO, HC, and NOx Emitter): Phi and CO, HC, and NOx CPFs



(b) Vehicle 248 (Normal CO, HC, and NOx Emitter): Phi and CO, HC, and NOx CPFs

Figure 5.

The FTP bag 3 tailpipe emissions profile for all of these vehicles is shown in Table 13: in almost all cases all three pollutants are high, relative to clean car levels.

Table 13. FTP Bag 3 GPM Tailpipe Emissions for Type 4 Vehicles

Test Vehicle	CO	HC	NOx	profile
42 (car)	11.6	2.1	5.4	HHH
43 (truck)	10.4	0.7	2.5	HMH
71 (car)	9.2	1.6	1.9	HHH
77 (car)	7.1	1.0	1.7	HHH
150 (truck)	8.8	1.9	2.8	MHH
254 (car)	11.9	1.7	3.5	HHH
277 (car)	24.6	1.7	1.5	HHH

This type of high emitter may be associated with a burned-out catalyst, as observed in two of the vehicles here; but transiently bad catalyst performance is also observed. It is difficult to distinguish between two possible basic causes of the latter. The first involves greatly deteriorated performance of the catalyst, presumably due to severe operating conditions in the past. A second possible cause is poor closed-loop control of the fuel-air ratio, such that it doesn't conform to the needed pattern (illustrated in Figure 1), but at a level of failure too detailed to be observed directly here.

Summary – The CO/HC/NOx tailpipe emissions profiles for the 16 high-emitters measured in the NCHRP project and analyzed here, using the cutpoints of Table 4 to define the boundaries for High, Medium and Low, are shown in Table 14. We include MMH vehicles as both Type 1 and Type 4 high emitters, as discussed below.

Table 14. High-Emitter Types by FTP Bag 3 Profile

High-Emitter Type	CO/HC/NOx profile
1: lean	LLH, LMH, (MMH)
2: rich	HML, HMM
3: misfire	HHL, MHM, MHL, HHM
4: catalyst problem	HHH, MHH, (MMH)

An essential point is that these are general categories. Each "type" identified corresponds to more than one detailed behavior; for example, we observe both transient and chronic behavior for each type. And each type covers more than one disparate *physical* malfunction.

EMISSION PROFILES IN THE ARIZONA IM240 DATA

Because the high emitting vehicles recruited for testing under the NCHRP project are not representative of the in-use fleet, we analyze data from the Arizona I/M program to get a sense of the prevalence of each type of high emitter.

The IM240 test was recently introduced in several non-attainment areas, including the Phoenix area, as part of an enhanced inspection and maintenance (I/M) program. The test involves a 4-minute dynamometer cycle with speeds up to 57 mph, with an average speed of 30 mph. The IM240 power levels are similar to those in FTP bag 1 or 3, and involve the same maximum specific power, as shown in Table 1. To reduce costs and waiting, the 240-second test is terminated early by the Arizona contractor for vehicles with relatively low or high emissions. For short tests, we calculate an adjusted gpm; our adjustment is different than that used in Arizona [19].

DEVELOPMENT OF EMISSION PROFILES – Using the IM240 data, we create CO/HC/NOx profiles based on high, medium and low categories for each pollutant, as we did with FTP bag 3 measurements on the 16 NCHRP vehicles. The profiles again depend on choice of low-emitter and high-emitter cutpoints. (Because of differences between the two measurement programs, as discussed below, these IM240 cutpoints are not the same as those for the bag 3 measurements.) We consider several alternative sets of cutpoints; two of these sets, which differ in the definition of high-emitters, are shown in Tables 15 and 16.[1] Among MY1990-93 cars as measured in 1995, the cutpoints of Table 15 yield 10% high emitters (vehicles with at least one H); almost half of the non-high emitters are classified as LLL. The cutpoints of Table 16 yield 25% high emitters.

Table 15. High High-Cutpoints for Profiling the IM240 High Emitters

Range		CO (gpm)	HC (gpm)	NOx (gpm)
high	H	>20	>1.2	>2.5
medium	M	6 to 20	0.4 - 1.2	1.2 - 2.5
low	L	<5	<0.5	<1.2

Table 16. Low High-Cutpoints for Profiling the IM240 High Emitters

Range		CO (gpm)	HC (gpm)	NOx (gpm)
high	H	>15	>0.8	>2.0
medium	M	6 to 15	0.4 - 0.8	1.2 - 2.0
low	L	<5	<0.5	<1.2

Almost all of the Arizona IM240 high emitters occur in eight profiles, depending on the choice of cutpoints. The

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[1] The high cutpoints shown in Table 15 are the cutpoints currently in use in the Arizona I/M program for MY1991 and newer cars. The high cutpoints in Table 16 are the final cutpoints originally proposed for the Arizona program (and not adopted due to the finding of inconsistent vehicle preconditioning [13])

profile distributions found are shown in Table 17. With three pollutants and three emissions levels, H, M and L, there are nineteen possible profiles of high emitters (i.e. vehicles with at least one H). Just eight in Table 17 have an incidence of 5% or more; only 10% of the vehicles fall in the other eleven profiles. A characteristic of most of the missing profiles is that they do not obey a tight correlation between CO and HC (independent of the NOx level).

The distribution of a sample of vehicles among the high emitter profiles is shown in Figure 6. The vehicles all have at least one H, i.e. with one of the pollutants high. The dashed lines mark the boundaries of the emitter profiles, using the cutpoints in Table 15. The lower left quadrant of the figures represents the LLx emitter profile (low CO and HC, with unspecified NOx emissions), while the upper right quadrant contains cars in the HHx profile. The three level of NOx emissions are denoted in the figures using different symbols. One sees patterns: 1) There are no HLx and few LHx vehicles; i.e. HC and CO are strongly correlated. 2) High CO is correlated with low-to-moderate NOx. 3) There is a group of vehicles with high NOx and low-to-moderate CO and HC. These general tendencies are expected, but we are surprised by their pervasiveness in a very large sample. Part of the explanation is that high CO only occurs with enrichment, which enhances HC and suppresses engine-out NOx.

Care must be taken in interpreting the figure, since the restriction of at least one H strongly influences its appearance. Figure 7 is a similar scatterplot using the same cutpoints, but including vehicles with two medium-level pollutants, in order to clarify the structure near the medium-to-high transition in HC for medium CO. The distribution is smooth across this boundary. One sees, for example, that there are many MML vehicles, with medium CO, but on the high side, which probably have similar malfunctions to those classified as HML, i.e. with high CO.

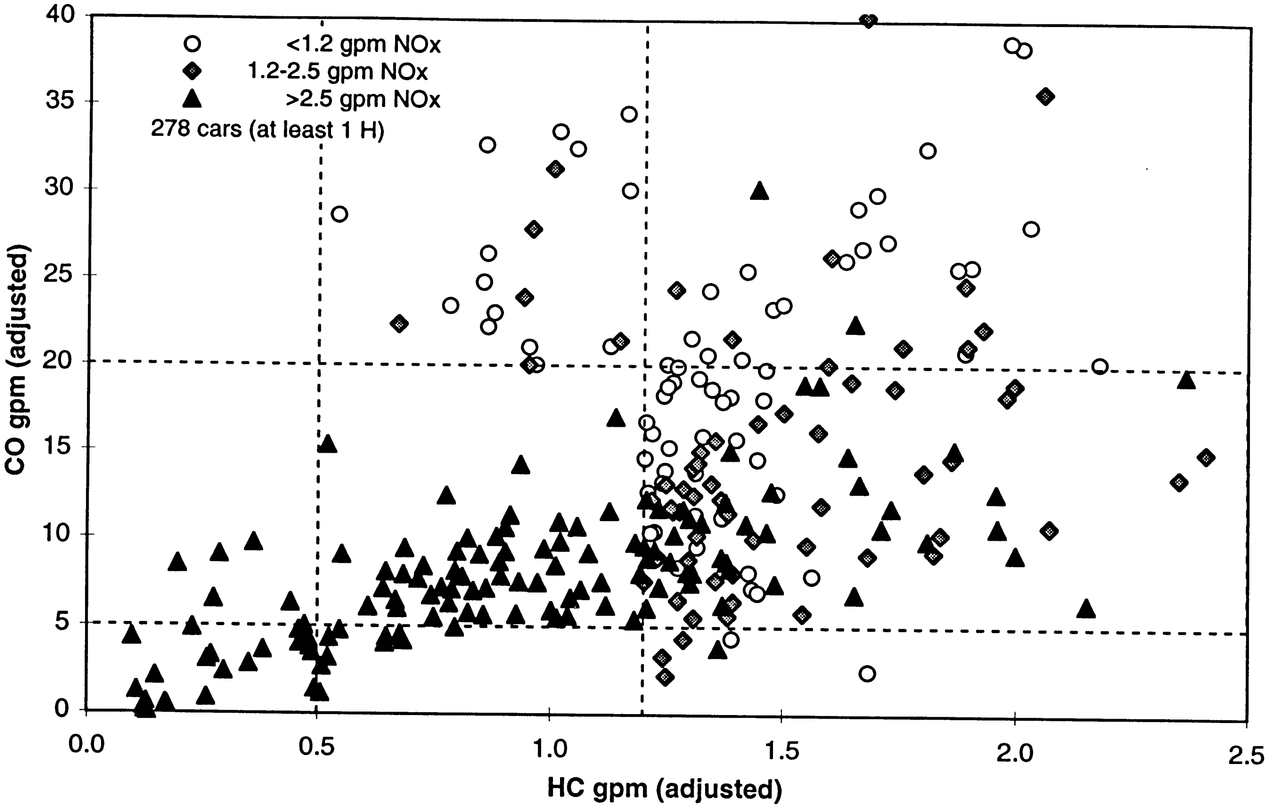

Figure 6. Distribution of High Emitters by Emission Profile (CO/HC/NOx), 278 Cars with at Least 1 H (MY90-93 Cars, 1995 AZ IM240)

Table 17. Distribution of High Emitters by Profile: Arizona IM240, MY1990-1993 Cars[a]

	Percent high emitters	
Profile: CO/HC/NOx	**high cutpoints[b]**	**low cutpoints[c]**
HHH	1	3
HHM	5	5
HMH	0	0
MHH	11	18
HMM	2	1
MHM	17	12
MMH	20	10
HHL	10	10
HML	11	5
HLM	0	0
MHL	6	8
MLH	2	4
LHM	1	2
LMH	4	4
HLH	0	0
LHH	0	2
HLL	0	2
LHL	0	1
LLH	7	13

a) since we base the emission profile on our adjusted gpm results from the IM240 data, some cars classified as high emitters in this analysis actually were passed by the AZ I/M contractor (were passed in Phase 2 of test).
b) See Table 15. c) See Table 16.

FREQUENCY OF OCCURRENCE OF TYPES OF HIGH EMITTERS – All but three of the eight important IM240 profiles (Table 17) are included in the list of profiles identified among the NCHRP/Riverside high emitters (Table 7); the three are MMH, LMH and MHL. The differences between the two sets of percentages in Table 17 show where there are sensitivities to the high cutpoints used.

High emitters from the NCHRP project (FTP bag 3) are plotted in Figure 8 for comparison with the sample of the Arizona IM240 high emitters in Figures 6 and 7. Figure 8 has the same axis scales as Figures 6 and 7, but the dashed lines reflect the lower cutpoints used for the FTP tests.

In Figure 9 we present rough boundaries for the IM240 profiles for the four types of high emitter identified among the NCHRP vehicles. As seen, we assign about one-third of IM240 category MMH to Type 4 and two-thirds to Type 1, all of LMH to Type 1, and all of MHL to Type 3. The resulting frequencies as percentages of all high emitters are shown in Table 18.

Table 18. Distribution of IM240 Profiles of MY90-93 Cars, Based on Cutpoints of Table 15

High Emitter Type	**Profile**	**Percent of High Emitters**	**Percent of All Cars**
1: Runs Lean	LLH, LMH, (MMH)	24	2.4
2: Runs Rich	HML, HMM	14	1.3
3: Misfire	HHL, MHM, MHL, HHM	33	3.3
4: Bad Catalyst	HHH, MHH, (MMH)	19	1.9
Other high emitters		9	0.9

CAVEAT – There are several important differences between IM240 bag emissions as measured and those of FTP bag 3 analyzed above:

- The sample of vehicles is quite different. IM240 test results of over 135,000 MY90-93 passenger cars were analyzed; these vehicles represent roughly half of the registered vehicles in the Phoenix area (the program is a biennial program, where testing is required every two years and upon vehicle sale). These data are much more representative of the in-use fleet than the 300 vehicles tested under the NCHRP program. In addition, the Arizona data are dominated by 49-state vehicles with somewhat different emissions controls than for California vehicles. Moreover, the measurements in Arizona used here were made in 1995, while those at UC Riverside were made in 1996-97. In addition, the IM240 sample used consists of cars only, while the NCHRP data contains both cars and light trucks.
- The conditioning of the vehicles (i.e. the block and catalyst temperatures prior to testinig) is somewhat different. This is probably not a big effect for high emitters. As an extreme comparison, when one compares the NCHRP FTP bag 2 and bag 3 data one finds that bag 2 HC and CO emissions are only moderately lower, in spite of the full warm-up and lower power requirements of bag 2.
- Most important, we are comparing carefully controlled FTP measurements carried out on 300 vehicles in a laboratory setting with relatively inexpensive measurements on over one hundred thousand vehicles. The equipment and procedures are different; and the CE-CERT group at Riverside has found that it is not a routine matter, even in their laboratory setting, to obtain accurate results. We find that the Arizona IM240 measurements tend to exaggerate the emissions of low- and medium- emitting vehicles, a subject we will explore in a different report. (This does not mean that the Arizona measurements fail to satisfy their purpose, the identification of high emitters.)
- Another problem with the IM240 analysis is that about half of the IM240 tests analyzed were ended after 31 seconds of driving, because the cars met low "fast pass" emission cutpoints. And most of those

tested more than 31 seconds were also given a shortened test. Only about 2% of the tested cars were given the full IM240 test; most of these cars were randomly recruited to receive the full test. Although we make adjustments to make the shortened test emission results roughly comparable to those of a full IM240 test, these adjustments are rather simplistic and may affect our results.

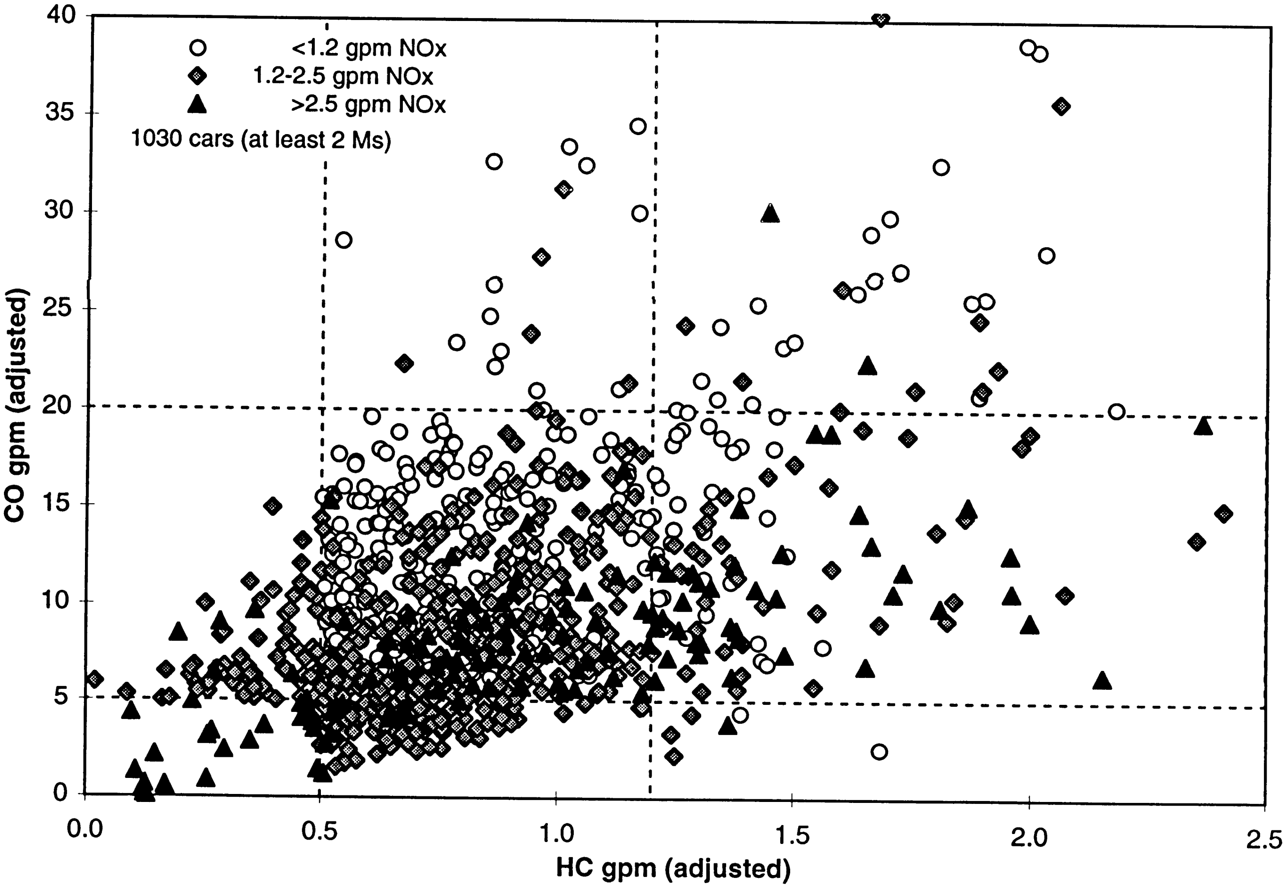

Figure 7. Distribution by Emission Profile (CO/HC/NOx), 1030 Cars with at Least 2 Ms (MY90-93 Cars, 1995 AZ IM240)

All of these differences between the FTP and IM240 testing may affect the accuracy of mapping FTP high emitter types to IM240 emission profiles.

DISCUSSION

Generally speaking, the four types of high emitters identified from the emission ratios are roughly equally represented in the Arizona I/M fleet. Type 1 (runs lean) occurs in 24% of vehicles while Type 2 (runs rich) occurs in only 14%. It is possible that there has been a shift in the distribution of high emitters from high CO to high NOx emitters, as we have moved from carbureted to sophisticated computer-controlled fuel-injected vehicles. Also, earlier I/M programs using idle emissions tests virtually ignored NOx emissions, so high emitters may have been previously repaired to reduce CO and HC at the expense of NOx emissions.

For many people, the study of emissions-control malfunction concerns component malfunction. While our study does not directly address individual components, we do get some information on what components may affect the different types of high emitters. As just mentioned, we find that relatively small fuel control deviations from stoichiometry characterize about 40% of the high emitters. Another group (33%) can be roughly characterized as cylinder misfire (Type 3). Catalyst malfunction in the absence of one of the other malfunctions (Type 4) has a relatively low probability at 19%. However, catalyst malfunction is an important but subsidiary problem in many Type 2 and 3 vehicles. So the statement that replacing the catalyst will improve the emissions performance in one-half or more of vehicles is in agreement with our data. But the improvement might be temporary in many vehicles because uncorrected conditions of frequent enrichment or misfire might cause swift catalyst degradation.

In the NCHRP sample, we did not find excessive lean operation to be associated with catalyst degradation. We have not gone further in attempting to pinpoint component failures from the NCHRP data. The data are rich; we hope that others will study it to discover more.

LIMITATIONS – There are several analytical and measurement limitations to this study. Most have been mentioned, but they are worth a reminder: a) Accurate measurement of fuel-air ratio is difficult, so much of what we conclude about this critical aspect of emissions control is inferred. b) The sample of NCHRP vehicles is small, and has been further sliced into many categories. To the extent study results are as important as we think they are, this study should be followed up by one with substantially more tests of modern high-emitters. c) Most of the measurements involved MY1990-93 vehicles, which we have treated as a group. We have not examined changes in vehicular emissions control technologies during the 1990s. d) The use of profiles involves cutpoints, with the attendant sensitivity to choice of cutpoints. We have examined a few sets of cutpoints for the IM240 data and find that the general results hold for these cutpoints. e) Verification of the accuracy of the IM240 measurements at high gpm levels needs to be improved.

APPLICATIONS – The application that led to this work as part of the NCHRP project is the inclusion of high emitters in modal emissions modeling, i.e. inclusion of the dependence on driving pattern of emissions from malfunctioning vehicles. What we have been able to do is a first step. The sample of NCHRP high emitters from MY90 and later is inadequate to accurately determine modeling parameters for the four types each with chronic and transient subclasses. We can nevertheless use a weighted mix of the measured vehicles to create a detailed simulation model of emissions as they depend on operating variables such as speed, acceleration and grade. As an example of what might be found, we note that high emitters of Types 1, 2 and 3 may be less sensitive to power than to transients, while for Type 4 power is the key operating variable.

While a first step, such modeling of high emitters would constitute a major improvement in modal modeling; and it should also contribute to emissions inventory modeling. An issue of interest not yet been studied, but accessible in the NCHRP data, is emissions from modern high emitters at high power levels (beyond the FTP range).

Another application is to help achieve more-durable emissions control through the categorization. The three-pollutant profiles obtained in high-statistics and low-bias recruitment measurement surveys may enable one to focus on important high-emitter problems among recent vehicles. For example, through this research we have begun to be able to a) accurately assess the role of throttle fluctuation and driving with frequent speed adjustment, and b) throw light on catalyst degradation as a result of failure of other controls in contrast to severe driving.

In this paper our focus is categorization of high emitters. We do not address the issue of the total contribution of high-emitting modern vehicles to the emissions inventory. This result depends on assumed cutpoints. A full and fair evaluation of the role of modern high emitters in the emissions inventory is critically important, and requires a different study than the categorization analysis carried out here.

FINAL COMMENT – We believe that systematic measurement surveys with high-statistics and low-bias recruitment could be extremely useful for programs to assess in-use durability of emissions controls in modern vehicles. Such surveys could be based on IM240, remote sensing, on-board diagnostics or some other technique. Until now, in-use testing programs by regulatory agencies and the manufacturers have been severely weakened by possible biases in recruiting high emitters and by poor statistics. As a result of these problems, the nation does not have convincing evidence one way or the other on the importance of high emitters among modern vehicles. We believe that careful analysis of I/M data collected by states can shed light on the real-world emissions of modern vehicles.

CONCLUSION

In this study we examine second-by-second pollution outputs, including engine-out emissions, of vehicles which are high-emitters in low-to moderate-power driving (within the FTP range). We use these detailed emissions data to infer possible causes of emission control system malfunction.

We observe four different patterns, or types, of emissions control malfunction: 1) fuel-air ratio excessively lean, 2) fuel-air ratio excessively rich, 3) partial combustion such as misfire, and 4) severe deterioration in catalyst performance in vehicles where malfunctions of Types 1, 2 or 3 are not predominant. For many vehicles, more than one malfunction is observed; we characterize the malfunction by the one which is the most important to the high emissions. In addition, for all four types of high emitter two further categories are observed: transient and chronic. Transient high emitters are extremely sensitive to vehicle speed variations, or throttle fluctuations; their emissions control performance may be good in steady low-power driving. Chronic high emitters have roughly steady patterns of emissions control failure.

We then relate the types of high emitters, as defined by the analysis of emissions ratios, with 3-pollutant profiles of tailpipe emissions (expressed as high, medium, or low tailpipe emissions of CO, HC and NOx, or, for example, HLM). The correspondences allow us to relate the detailed analysis of a small number of high emitters to bag data for a large number of vehicles tested in the IM240 program in the Phoenix Arizona area, to determine the distribution of high emitter types within the on-road fleet. The emission cutpoints are chosen so that the resulting emission profiles are consistent with the emissions ratios; however, we cannot definitively demonstrate the validity of using tailpipe emissions alone to characterize high emitter types.

We find that CO and HC emissions are correlated; if one is high the other is not low. And CO and NOx are negatively correlated; if one is high, the other is not high. All four types of high emitters--improper fuel control (lean or rich operation), misfire, and catalyst deterioration--are observed in the NCHRP testing, and are roughly equally represented in the Arizona I/M fleet.

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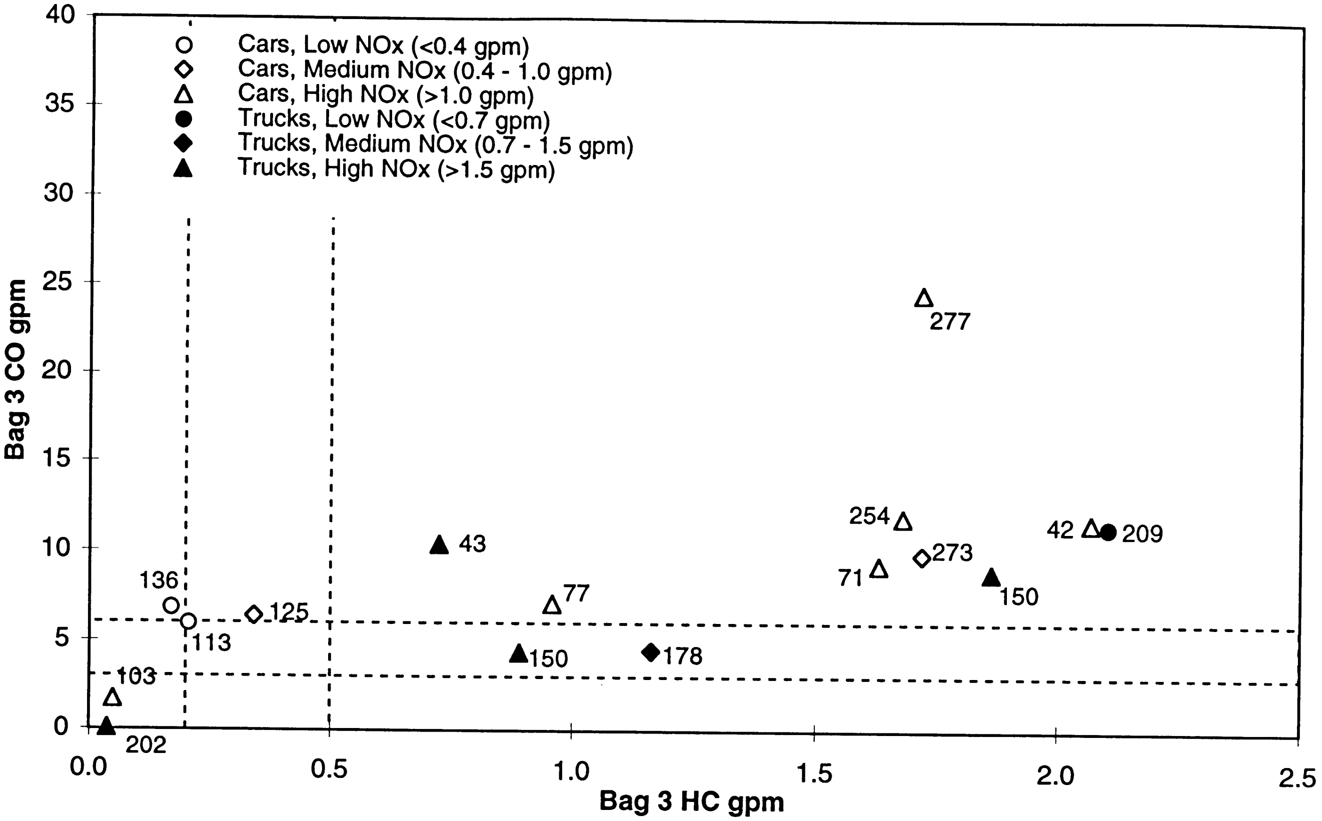

Figure 8. Distribution by High Emitter Type, MY90-96 Vehicles, 1996-97 NCHRP FTP

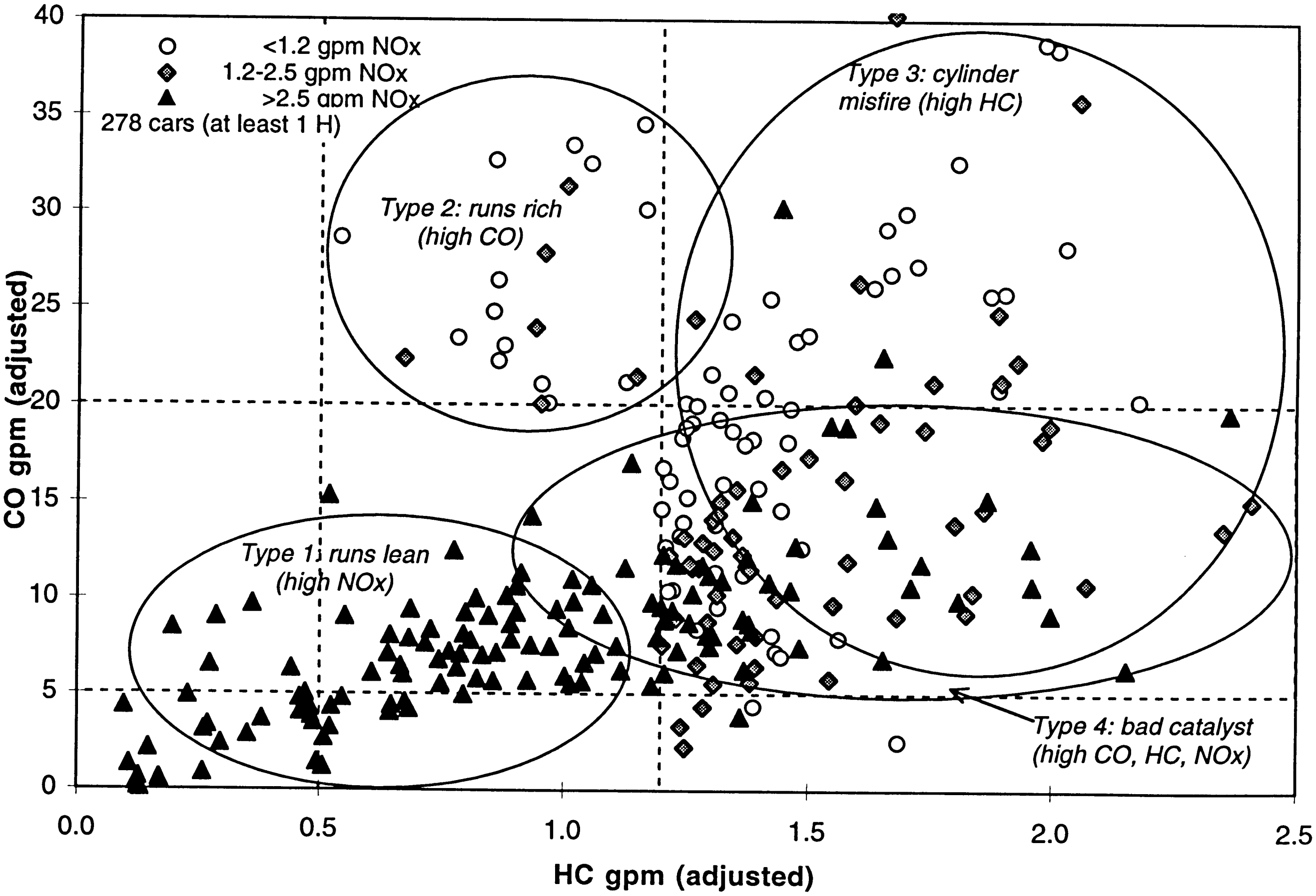

Figure 9. Distribution by Emission Profile and Type, MY90-93 Cars, 1995 AZ IM240

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