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Reducing emissions from in-use vehicles: an evaluation of the Phoenix inspection and maintenance program using test results and independent emissions measurements☆

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Abstract

Various federal regulations require states to evaluate the effectiveness of their vehicle inspection and maintenance (I/M) programs in reducing in-use emissions. One method to evaluate program effectiveness is to compare initial and final program test results of individual vehicles. Unscheduled emissions measurements, from remote sensing measurement or roadside pullover testing, can also be used to provide an independent assessment of program effectiveness. We compared emissions reductions from the Arizona IM240 program measured by program data and a large set of remote sensing measurements. Remote sensing measurements indicate smaller emission reductions from the program than those calculated directly from program test results. We discuss some possible causes of the differences obtained from the two sets of measurements. Published by Elsevier Science Ltd.

Keywords: Evaluation; Inspection and maintenance; Vehicle emissions; Vehicle repairs

1. Introduction

The Clean Air Act Amendments of 1990 required many urban areas with poor air quality to adopt ‘Enhanced’ vehicle emissions inspection and maintenance (I/M) programs, and to conduct biennial evaluations of such programs. EPA published a rule in 1992 that required Enhanced I/M programs to perform IM240 tests on a random sample of 0.1% of the vehicle fleet to be used in program evaluations[1]. Although EPA did not provide details on how this fleet should be analyzed in an evaluation, an analysis published by EPA in 1997 suggests one approach (Glover and Brzezinski, 1997). The method is to compare the initial emission test result of an individual vehicle with any subsequent test of that vehicle, and then aggregate to get fleet emission reductions. The difference between the initial and final test results represents an estimate of the initial tailpipe emission reduction due to vehicle repair. This initial program benefit will decrease over time as tailpipe emissions of these tested vehicles increase due to the aging of most and the malfunction of emissions controls of a few.

There are several advantages and disadvantages of using I/M program test results to evaluate the effectiveness of the program in reducing emissions. One advantage of using program test data is the sheer number of vehicles tested; the emissions of virtually every vehicle reporting for testing can be tracked to estimate program effectiveness, and effectiveness can be analyzed on many subsets of vehicles (by model year, type, program result, etc.) However, there are disadvantages of basing a program evaluation solely on program data. As discussed later, most vehicles are tested over different durations of the IM240 test, and emissions of different test durations are not comparable unless adjustments are made. (Alternatively, the analysis can be conducted on a small random sample of vehicles given the full IM240 test, as in Glover and Brzezinski, 1997). In an

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[1] In January 1998 EPA allowed states to use a mass emission transient test, or METT, equivalent to the IM240 in program evaluation.

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I/M program vehicles that fail their initial test are repaired or adjusted and then retested until they pass. However, because emissions of an individual vehicle can be highly variable (Knepper et al., 1993; Bishop et al., 1996; Wenzel et al., 2000), some of these failing vehicles may pass a retest without any repairs being made. Once a vehicle passes an inspection no attempt is made to determine the durability of any repairs made to the vehicle, or the resulting emission reductions. Some vehicle owners find ways to avoid complying with I/M program requirements; program data cannot be used to estimate the number of such vehicles, and their emissions. Finally, some vehicles receive legitimate repairs that reduce their emissions prior to I/M testing; an evaluation based on program test results does not include any of the emissions reductions the program may induce prior to vehicle testing.

Independent emissions data can be used to overcome some of these limitations, and to supplement an evaluation based on program test results. There are several benefits of using independent emissions data. One is that the test is unscheduled, so that drivers and repair technicians cannot make temporary adjustments immediately prior to testing in order to get a vehicle to pass the test. Another is that such data can measure emissions from vehicles that are either ineligible for the I/M program, or are eligible but are avoiding the program. Independent emissions data can be collected in several ways, including measurement of emissions as vehicles drive by a roadside remote sensor, and roadside I/M testing of randomly selected vehicles. Roadside pullover tests are much more expensive than remote sensing measurement, and the number of vehicles tested is relatively small. Because participation in such programs typically is voluntary, they are sensitive to recruitment bias. Remote sensing measurement, on the other hand, is inexpensive, so a larger sample of vehicles can be measured. If the remote sensing program is used for evaluation purposes only, there is no incentive to avoid driving by the sensors, and therefore the program should have relatively low recruitment bias[2].

The advent of advanced on-board diagnostic computer systems on 1996 and newer vehicles, which inform the operator of emission malfunctions when they occur, will eventually lead to the majority of emission repairs being performed prior to initial I/M inspections. Therefore, program test results will be even less useful in evaluations of the effect of I/M programs on emissions from newer vehicles. As a result, independent emissions measurements, such as those made by roadside remote sensing instruments, will become increasingly important to evaluate I/M program effectiveness.

We used both program test results and a large database of remote sensing measurements to evaluate the effectiveness of the Arizona Enhanced I/M program. In the first section we discuss results of our evaluation using program test data, followed by results using remote sensing data. We then discuss some possible causes of the discrepancy in the results obtained using the two methods.

2. Evaluation using IM240 data

The Arizona Enhanced I/M program is a centralized program that required biennial IM240 testing for model year 1981 and newer vehicles under 8500 pounds gross vehicle weight. The IM240 test involves placing a vehicle on a treadmill-like device called a dynamometer, and driving it through a standard 240-second speed/time trace (or driving cycle) fashioned after the test procedure used to certify that new vehicles meet tailpipe emission standards[3]. Vehicles from earlier model years, and all-wheel drive vehicles, are subject to a two-speed idle test. Vehicles from the current and two previous model years are exempted from testing. No I/M test is required when vehicles are sold or change ownership. The I/M testing is managed by a single contractor that operates ten stations throughout the Phoenix metropolitan area. Vehicles that fail the I/M test are required to have their vehicle repaired and pass a subsequent test at one of the centralized test stations. Vehicle owners may apply for a one-time waiver from further testing if they make $450 worth of qualified repairs. US EPA considers the Phoenix IM240 program the model I/M program, noting that it ‘most closely resembles’ EPA’s recommended program design (US EPA, 1998). In fact, in a recent guidance document EPA recommends that states use the Phoenix program as a benchmark for the determination of the effectiveness of their own I/M programs (US EPA, 1998).

2.1. Method

We started with a database of over 850 000 vehicles with an initial IM240 test between January 1996 and June 1997. We matched these I/M test records with a database of over 4 million remote sensing measurements of 1.2 million vehicles measured between January 1996 and August 1997 at numerous sites in the Phoenix area. The match was based on the vehicle license plate in each datafile. The result was a database of 451 000

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[2] One advantage of roadside pullover testing over remote sensing is that visual inspections of tampered controls and evaporative HC emission controls can be performed during the roadside test. Also, because the roadside tests attempt to mimic the conditions of the program tests, the vehicle load at the time of emission measurement is known and is similar to that of vehicles tested in the I/M program.

[3] In January 2000 the IM240 test was replaced with a shorter test, the IM147.

Table 1
Average tailpipe emissions and percent reduction from I/M test results, 1996–1997 IM240 Fleet (Vehicles with both IM240 test result and remote sensing measurement)

Type	Number	Unweighted average emissions per vehicle (adjusted grams per mile)[a]						Percent reduction		
		HC		CO		NOx		HC	CO	NOx
		Initial	Final	Initial	Final	Initial	Final			
Cars	255 569	0.58	0.49	8.45	6.91	1.18	1.08	15.4	18.3	8.5
LDT1	123 193	0.76	0.67	10.95	9.73	1.48	1.38	12.6	11.1	6.3
LDT2	33 579	0.95	0.79	13.10	11.27	2.28	2.18	16.0	14.0	4.5
All	412 341	0.67	0.57	9.58	8.11	1.36	1.26	14.5	15.3	7.2
All (VMT-weighted)								13.0	13.5	6.3

[a] Fast-pass/-fail emissions adjusted to full IM240 emissions using LBNL method.

vehicles with both an IM240 record and at least one remote sensing measurement, or about half of the vehicles reporting for IM240 testing during this period[4].

In the original Arizona Enhanced program, the cleanest vehicles were allowed to 'fast-pass' the IM240 test after only 30 s of testing, while the dirtiest vehicles could 'fast-fail' after only 94 s of testing. Consequently, very few vehicles were given the full IM240 test (although 2% of vehicles reporting for testing were randomly selected to receive a full IM240 test, as were some other samples of vehicles for other research purposes). The IM240 test measures the mass of pollutants emitted by the vehicle; results are expressed in terms of total grams of pollutant, or grams of pollutant per mile driven. Because not all vehicles were driven over the same duration of the IM240 test, emissions results expressed in grams per mile are not necessarily comparable across vehicles. In order to account for vehicles tested over different durations of the IM240, we estimated the full test emissions of vehicles that were fast-passed or fast-failed, by applying adjustment factors to their measured emissions. We developed the factors from a database of second-by-second emissions of 4864 vehicles given a full IM240 in Phoenix between 1991 and 1994, conducted by the Automotive Testing laboratory for EPA. This sample of vehicles is not representative of the Phoenix in-use fleet; 98% of the sample is passenger cars, with very few of 1983 and older, and 1993 and newer; however, this was the best sample of second-by-second emissions data available to us at the time. To derive our factors we first calculated the ratio of the emissions at each second to the emissions for the full IM240, for each pollutant for each vehicle. Then we averaged these ratios over the entire fleet of vehicles, to obtain a single adjustment factor for each pollutant at each second of the IM240[5].

To estimate the effectiveness of the Phoenix program, we compared the initial and last test of each vehicle with an initial test from January 1996 through June 1997 (similar to the method described in Glover and Brzezinski, 1997). To do this we first matched all vehicle I/M tests by vehicle identification number (VIN). For vehicles with subsequent retests, we took the last retest through June 1997 as the final test of the vehicle. For vehicles that passed their initial test, and vehicles that failed their initial test but did not receive a retest, we assumed that their emissions were equivalent to those measured during their initial test. We excluded from our analysis 25 000 vehicles (or 5.5% of all unique vehicles) with subsequent tests coded as initial tests[6].

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[4] This subset of vehicles was representative of the overall fleet reporting for I/M testing, as we obtained the same percentage emission reductions from the subfleet as the overall fleet. We cannot determine how representative this subfleet was of the entire on-road fleet measured by remote sensing, however, because we did not have access to vehicle registration records that would identify the age and type of vehicles measured by remote sensing but not participating in the I/M program.

[5] Researchers from Resources for the Future (RFF) have developed a more sophisticated set of adjustment factors, based on second-by-second emissions from a more representative sample of vehicles (Ando et al., 1999). To ensure that the use of our adjustment method does not bias our results, we also report results using the method more recently developed by RFF. We achieved comparable results using each adjustment method.

[6] There are several reasons why a vehicle may have multiple initial tests within a 2-year period (in order of likely frequency): (1) a prospective buyer may voluntarily test a vehicle prior to purchase; (2) subsequent tests of vehicles that were not passed within 5 months of the initial test are coded as initial tests; (3) vehicles for sale by dealers that are not fleet-licensed must be tested every 90 days; (4) some repeat initial tests are for research purposes only; and (5) a small number of audit vehicles are covertly run through the system periodically (personal communication with Frank Cox, Arizona Department of Environmental Quality). Vehicles that received a voluntary off-cycle test (from cause 1 above) had slightly higher emissions during their initial I/M test than the overall fleet. And all vehicles which did not pass a second test in 5 months (cause 2 above), by definition, failed their initial I/M test, and therefore had higher initial emissions than the average vehicle. Therefore exclusion of these vehicles understates the baseline emissions of the I/M program, and perhaps the emission reductions from the program.

Table 2
Average tailpipe emissions and percent reduction from I/M test results, 1996–1997 random 2% IM240 fleet (Vehicles with both full IM240 test result and remote sensing measurement)

Type	Number	Unweighted average emissions per vehicle						Percent reduction		
		HC		CO		NOx		HC	CO	NOx
		Initial	Final	Initial	Final	Initial	Final			
Cars	4366	0.58	0.49	9.10	7.51	1.17	1.07	15.6	17.5	8.5
LDT1	2006	0.81	0.70	12.66	11.20	1.58	1.45	14.0	11.5	8.5
LDT2	599	1.01	0.81	13.54	11.26	2.44	2.27	19.5	16.8	6.9
All	6971	0.68	0.58	10.51	8.90	1.40	1.28	15.5	15.3	8.3
All (VMT-weighted)								14.7	14.2	7.5

We also excluded 13 000 vehicles (or 2.9% of all unique vehicles) that passed their initial emissions test but received a subsequent retest, presumably because they failed their initial visual inspection.

2.2. Results

Table 1 shows the average initial and final emissions, in adjusted grams per mile, of passenger cars, light duty trucks less than 6000 pounds gross vehicle weight (LDT1), and light duty trucks between 6000 and 8500 pounds gross vehicle weight (LDT2) tested on the IM240 in the 18 months from January 1996 through June 1997. The table also shows the percentage emissions reduction for each vehicle type, and for the fleet as a whole, as measured by comparing the initial test with the final test of each vehicle. The table suggests that the Phoenix IM240 program reduced emissions of the fleet by 15% for HC and CO, and 7% for NOx[7]. The percentage reduction in CO and NOx appears to be substantially larger for cars than for light duty trucks. (This analysis does not consider evaporative HC emissions, and therefore may understate the program's effectiveness in reducing total HC). These percentage reductions do not account for older vehicles being driven fewer miles each year than newer vehicles, or for trucks being driven more or fewer miles than cars of the same age. We also weighted the percent emissions reduction by annual mileage assumptions by vehicle type and age recently developed for EPA's MOBILE6 model (Acurex Environmental Corporation, 1997). These weighted emissions reductions are shown in the last row of Table 1. The table indicates that weighting the emissions reductions by estimates of annual vehicle mileage slightly lowers the percent reduction in overall fleet emissions.

We conducted a similar analysis of the 2% of vehicles that were randomly selected to receive a full IM240 test from January 1996 through April 1997. Using the method described above, we were able to match nearly 7000 vehicles in the 2% random sample with remote sensing measurements. Table 2 shows that the estimates of emissions reductions from the program using the vehicles given a full IM240 test are slightly higher than the estimates using adjusted emissions of all vehicles tested. This suggests that our method of adjusting fast-pass/−fail test results to full IM240 equivalents is not substantially biasing our general results.

As mentioned above, EPA conducted a similar study to estimate the effectiveness of the Arizona IM240 program, using the random sample of vehicles receiving the full IM240 in 1995. In that study EPA also presented the MOBILE5 prediction of program effectiveness. Table 3 compares the Arizona program effectiveness as predicted by MOBILE5 with the EPA estimate, and our two estimates, based on program test results for passenger cars (the percent reductions are VMT-weighted). Our results from analyzing all cars, and the random sample of cars, tested in 1996–1997 are similar to the results from EPA's analysis. All three analyses suggest that, for the 1996–1997 Phoenix IM240 program, MOBILE5 accurately predicts CO emissions reductions, over-predicts HC emissions re-

Table 3
Comparison of MOBILE5 estimate of Arizona IM240 program benefit with estimates from three analyses, based on initial and final I/M tailpipe test results

Analysis	Cars	Percent reduction		
		HC	CO	NOx
1995 MOBILE5		16.9	16.2	16.7
1995 AZ IM240 (random sample)	7647	14.3	16.2	7.6
1996-97 AZ IM240 (all tests)	255 569	14.1	16.7	7.4
1996-97 AZ IM240 (random sample)	4366	14.9	16.3	7.7

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[7] We achieved comparable results for all vehicles reporting for I/M testing, including those not measured by remote sensing. Using the RFF adjustment method, the overall percentage emission reductions were slightly less, 13% for HC and CO, and 6% for NOx.

Table 4
Number of IM240 vehicles by I/M result

I/M result	Number	Percent of total	Percent of initial fails
1) Initial pass	373 496	90.6	
2) Fail–pass	25 984	6.3	66.9
3) No-final-pass	7738	1.9	19.9
4) No-second-test	5123	1.2	13.2
Subtotal 3 and 4	12 861	3.1	33.1
Total	412 341	100.0	100.0

ductions by up to 20%, and over predicts NOx emissions reductions by a factor of two[8].

As discussed above, we determined the final I/M result of each vehicle initially tested in the 18-month period. We grouped vehicles into four groups, based on their first and last emissions test (we did not consider whether vehicles passed or failed the visual or functional I/M tests):

1. vehicles that passed their initial test, and are not retested (‘initial-pass’);
2. vehicles that failed their initial test, but passed a subsequent retest, including vehicles that passed a retest without any repairs being made (‘fail-pass’)[9];
3. vehicles that failed their initial test and failed all subsequent retests through the period analyzed (‘no-final-pass’); and
4. vehicles that failed their initial test and had no retest in the period analyzed (‘no-second-test’).

We frequently treated groups 3 and 4 as a single group — no-final-pass vehicles. This group includes vehicles that were waived after completing $450 worth of repairs.

Table 4 shows the number and distribution of vehicles by I/M result. No-final-pass and no-second-test vehicles are first shown separately, and then grouped together and shown in italics. Table 4 indicates that 9.4% of all vehicles failed their initial IM240 emissions test; the failure rate was slightly higher for passenger cars (11%) than for light duty trucks (7%). Of the vehicles that failed their initial IM240 test, only 67% received a final passing test through June 1997; 33% did not receive a final passing test through June 1997. The percentage of no-final-pass cars was greater than the percentage of no-final-pass trucks (36% for cars, 27% for LDT1, 23% for LDT2).

One reason for the large number of no-final-pass vehicles may be that insufficient time is allowed for a vehicle to pass a subsequent retest. We examined the no-final-pass rate as a function of how many months the no-final-pass vehicles had to obtain a passing test. Fig. 1 shows the no-final-pass rate, expressed as the fraction of all vehicles that fail their initial test, as a function of the date of their initial test. The no-final-pass rate was quite high for vehicles that received their initial test in June 1997; this is because our analysis is restricted to an 18-month period, and these vehicles had only 1 month in which to obtain a passing test. The no-final-pass rate was consistent for all vehicles tested before March 1997. This suggests that nearly all vehicles that obtained a final passing test did so within 4 months. (Arizona actually requires that subsequent tests of vehicles that do not obtain a passing test within 5 months of an initial fail be coded as initial tests. As noted above, we have excluded these vehicles with multiple initial tests from our analysis[10]). The figure indicates that about 30% of all vehicles that failed their initial test did not receive a passing test, regardless of how many months they had to obtain a passing test.

The database we used for our analysis does not identify vehicles that exceeded the cost repair limit without passing the test, and received a temporary waiver from I/M requirements. Arizona DEQ reports that the waiver rate is about 4% of all vehicles that failed their initial test. If we assume that all of the vehicles that received a waiver are classified as no-final-pass vehicles in our classification scheme, then the percentage of 1997 initial fail vehicles that never completed I/M testing is reduced from 30% to about 26% of all vehicles that failed their initial test.

Another possibility to explain the high number of no-final-pass vehicles is that the VIN of a passing retest of these vehicles was entered incorrectly into the database, and therefore the passing retest was not matched with the initial test. After matching vehicle by license plate, rather than VIN, we found that only three of the no-final-pass vehicles had a subsequent retest with an invalid VIN; each of these vehicles failed the retest (one vehicle had two retests with invalid VINs, and failed both). Overall program effectiveness, expressed in terms of tons per day of emission reduced, can vary dramatically depending on the assumptions made regarding how many no-final-pass vehicles are induced by the

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[8] EPA obtained the results in Table 3 after substantially modifying the MOBILE model. An earlier analysis by EPA predicted even higher reductions in HC and CO emissions, in excess of 30% (Harrington et al., 2000).

[9] Presumably emissions controls malfunctions were identified and repaired for most of these vehicles; however, it is possible that a number of these vehicles passed a retest without any permanent repairs being made.

[10] Of the 25 000 vehicles with multiple initial tests within the 18-month study period, 88% were apparently voluntarily tests upon a pending ownership change (first initial test was a pass, or second initial test was within 5 months of first initial test). The remaining 12% failed their initial test and did not pass a retest within the next 5 months; one-third of these failed their final I/M test, and should be classified as no-final-pass. Therefore, including the vehicles with multiple initial tests in the analysis would not affect the no-final-pass rate.

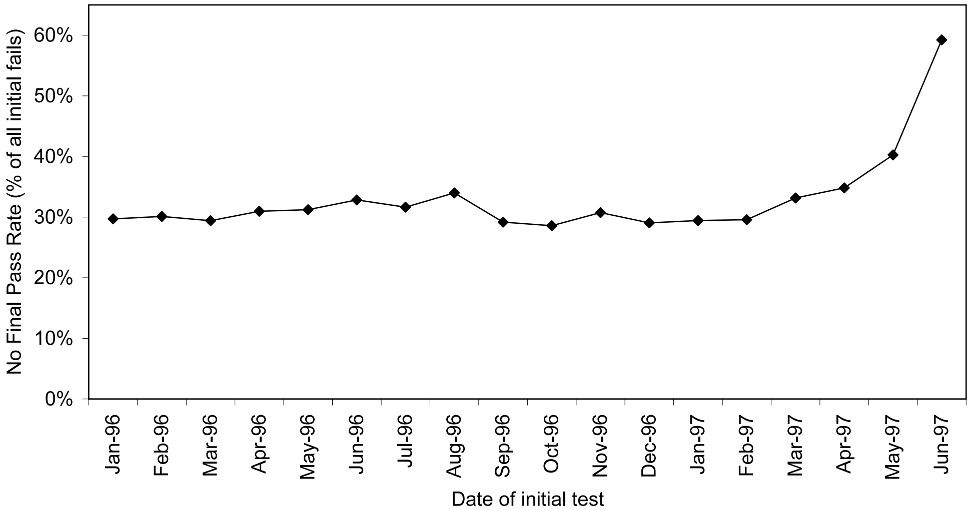

Fig. 1. No final-pass rate by date of initial test, 1996–1997 Arizona IM240.

Table 5
Average IM240 emissions and percent reduction by I/M Result, unweighted by annual VMT

I/M result	Unweighted average emissions per vehicle (adjusted grams per mile)						Percent reduction		
	HC		CO		NOx		HC	CO	NOx
	Initial	Final	Initial	Final	Initial	Final			
1) Initial-pass	0.46	0.46	6.61	6.61	1.18	1.18	0.0	0.0	0.0
2) Fail–pass	2.35	0.90	34.12	12.02	3.16	1.67	61.7	64.8	47.3
3) No-final-pass	3.16	2.89	45.24	41.23	2.91	2.72	8.7	8.9	6.5
4) No-second-test	3.20	3.20	47.35	47.35	2.75	2.75	0.0	0.0	0.0
Subtotal 3 and 4	3.18	3.01	46.08	43.67	2.85	2.73	5.2	5.2	4.0
Total	0.67	0.57	9.58	8.11	1.36	1.26	14.5	15.3	7.2

program to leave the I/M area, and the emissions of vehicles used as their replacements (if any).

Table 5 shows the average initial and final emissions by I/M result for all vehicles. As noted above, we assumed that the 'final' emissions of vehicles with no second test, the initial-pass and no-second-test vehicles, were the same as their initial emissions. Initial emission reductions of the fail–pass vehicles were dramatic: HC and CO emissions of these vehicles were initially reduced by over 60%, while NOx emissions were reduced by 47%. The percent reduction of CO and NOx emissions was somewhat greater for cars (68 and 49%, respectively) than for light duty trucks (59 and 45%, respectively). Presumably, much of this reduction was due to actual repairs made to vehicles; however, it is possible that initially failing vehicles passed a retest without any repairs having been made[11]. In addition, the emissions of no-final-pass vehicles also were reduced somewhat, from 7 to 9%, presumably from partial repairs made to some vehicles in this group.

Some of the differences in average emissions by I/M result are attributable to different vehicle age distributions in each of the vehicle groups. For instance, more newer vehicles were in the initial-pass group, while more older vehicles were in the fail–pass and no-final-pass groups. Figs. 2–4 present the average passenger car emissions by I/M result and model year. The initial emissions of the initial-pass cars are compared with the initial and final emissions of the fail–pass and the no-final-pass (including no-second-test) groups.

The figures demonstrate that, for the most part, both initial and final HC and CO emissions were lower for newer vehicles than for older vehicles. This trend is due to a combination of better emissions control technology on newer vehicles, less aging and mileage accumulation of newer vehicles, and more stringent 1/M standard (or cut points) for newer vehicles. (For example, the sharp decrease in HC emissions between model year 1990 and 1991 cars, most notable for fail–pass and no-final-pass vehicles, was likely due to more stringent IM240 cut

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[11] For example, a vehicle could fail its initial I/M test because it was not properly warmed up prior to testing, and pass a retest simply by warming the engine and catalyst prior to the retest. Or a vehicle could have an intermittent component malfunction which may result in sporadically high emissions, causing it to fail an initial I/M test but not a subsequent retest.

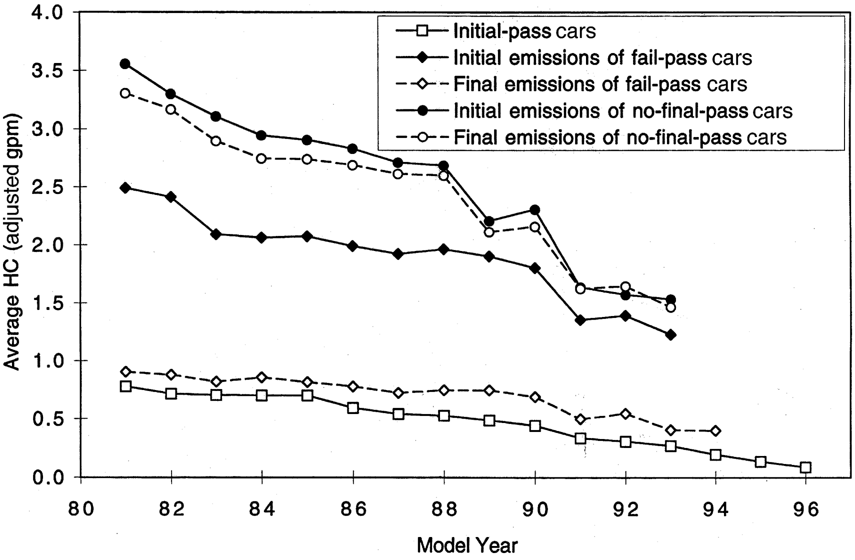

Fig. 2. Average passenger car HC/CO/Nox emissions by model year and I/M result, 1996–1997 Arizona IM240.

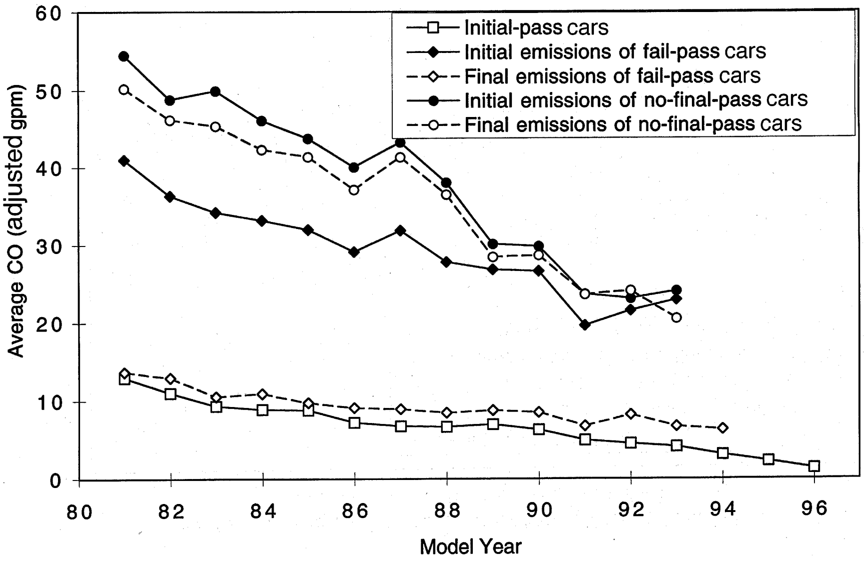

Fig. 3. Average passenger car HC/CO/Nox emissions by model year and I/M result, 1996–1997 Arizona IM240.

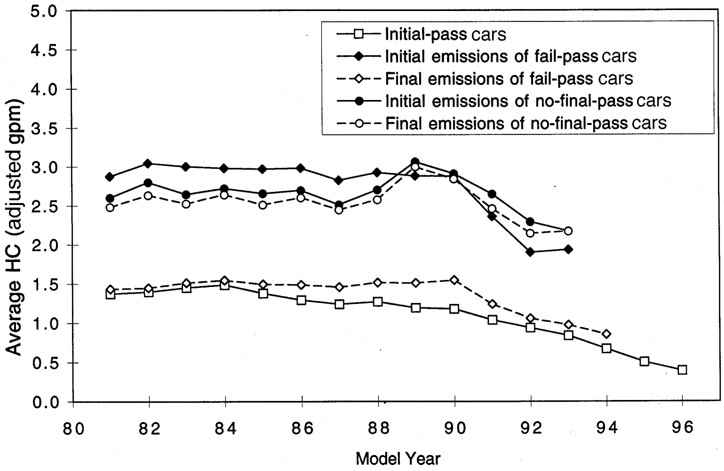

Fig. 4. Average passenger car HC/CO/Nox emissions by model year and I/M result, 1996–1997 Arizona IM240.

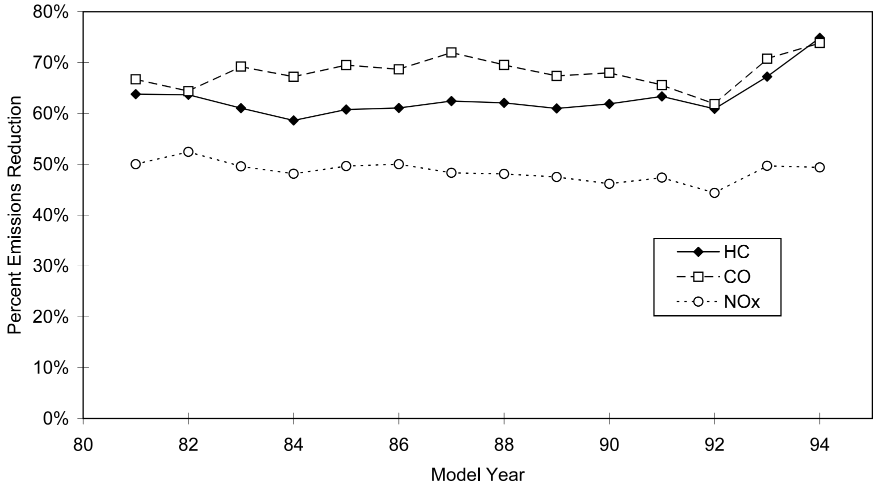

Fig. 5. Percent emission reduction by model year fail–pass passenger cars, 1996–1997 Arizona IM240.

points applied to model year 1991 and newer vehicles.) Initial NOx emissions were fairly steady for 1990 and older cars; however, for 1991 and newer cars, NOx emissions were lower for newer cars. It is not clear why the trend in initial CO emissions of fail–pass and no-final-pass cars increased for 1992 and newer cars.

The figures show that fail–pass vehicle emissions were dramatically reduced by the program, to a level slightly higher than that of initial-pass vehicles. For the most part no-final-pass vehicles had higher initial and final emissions than fail–pass vehicles of the same age. However, older fail-pass vehicles had higher initial NOx emissions than older no-final-pass vehicles.

The percent reduction in emissions of all fail–pass passenger cars was 62% for HC, 68% for CO, and 49% for NOx. Fig. 5 presents the percent emissions reduction for each pollutant, by model year, for fail–pass cars. The figure suggests that the percentage emissions reductions of model year 1981 through 1992 fail–pass cars were fairly consistent by model year. HC and CO emission reduction percentages were slightly higher for 1993 and newer cars than for older cars.

Analysis of similar data from passenger cars given a full IM240 test reveals comparable results. However, older initial-pass cars tended to have higher full test emissions (observed in the random sample) than short test emissions adjusted to full test equivalents (estimated from the entire sample of cars). Similarly, the final emissions of fail–pass cars were higher in the random sample than in the entire sample of cars. This was probably because the method we used to adjust emissions of fast-pass cars to full test emissions underestimated full test emissions, as mentioned above. Because the random sample of cars given the full-test tended to have higher final emissions, the percent reductions in emissions from the fail–pass cars given a full IM240 were somewhat lower than that for the entire sample of cars, only 56% for HC, 58% for CO, and 42% for NOx[12].

3. Evaluation using remote sensing data

We next evaluated the effectiveness of the Arizona IM240 program by examining the remote sensing measurements of the 412 000 vehicles with matched I/M test results. Remote sensors direct a beam of infrared light across a roadway. A series of filters measure the concentrations of CO, HC and CO_2 in the exhaust of passing vehicles. A video camera placed alongside the remote sensor records each vehicle's license plate, which is stored together with the emissions measurement. The license number can be used to retrieve information about each vehicle (age, type and perhaps mileage) from registration or I/M records (Bishop et al., 1996). One concern about the use of remote sensing data is that the vehicle driving condition (or load) at the time of measurement is unknown. To address this issue, remote sensors typically are sited to measure emissions from vehicles under a known driving condition, often while driving uphill under moderate load.

3.1. Method

The remote sensing data were collected by the state's initial contractor, Hughes Technical Services Company, to identify suspected high emitting vehicles for more

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[12] When we used the RFF adjustment method rather than our adjustment method, the emission reductions for fail–pass cars were very similar to those in the random sample: 56% for HC, 60% for CO, and 41% for NOx.

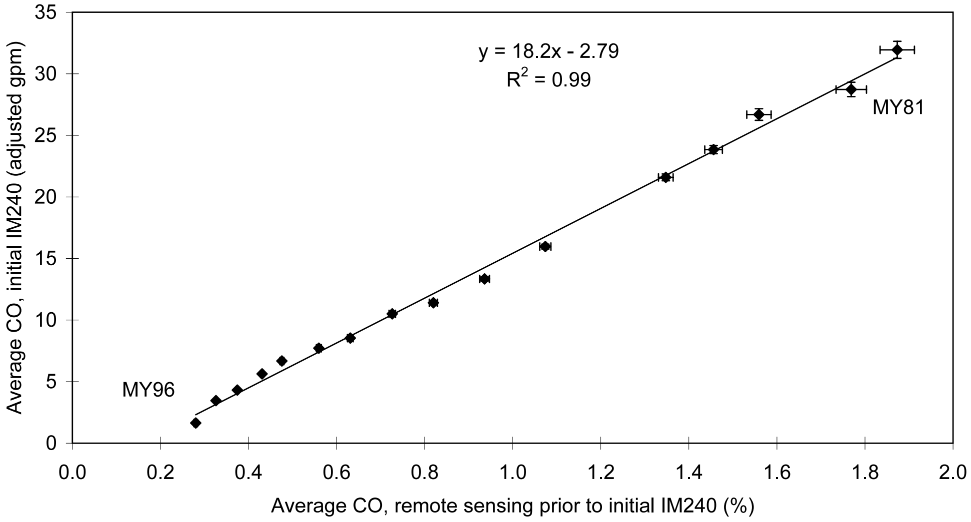

Fig. 6. Average remote sensing and IM240 CO by MY for 264 000 vehicles, 1996–1997 Arizona.

frequent I/M testing, so there is an incentive for drivers to avoid driving past the sensors (the program has since been terminated). To increase the likelihood of measuring emissions from high emitting vehicles, Hughes used an extensive network of over 100 remote sensing sites; as discussed above, however, even with this extensive network, only half of the fleet reporting for IM240 testing was measured by remote sensing over an 18-month period. The Arizona remote sensing data were collected before the development of instrumentation to measure vehicle NOx emissions; only CO and HC measurements were made during the study period. In addition, because vehicle speed and acceleration were not recorded until October 1996, speed and acceleration measurements are available for only half of the emissions measurements. Also the data were collected before protocols on data collection and reporting had been established. For instance, the software developed by Hughes excluded emissions measurements of vehicles with measured accelerations over 3 mph/s, excluded otherwise invalid measurements (rather than including them with flags), and rounded all negative measurements to zero. Reviewers of the Hughes remote sensor instrument used in Arizona have identified several potential problems with the data. These include bias in emissions, speed and acceleration measurements; inefficient site selection; and imperfect matching of measured data to vehicle license plates (Rendahl, 1997; Pokharel et al., 1999). We did not attempt to correct for any of these potential problems with the remote sensing data, as discussed below.

Others have noted that remote sensing measurements of individual vehicles may not correlate well with the I/M test results of those vehicles (Radian International, 1996). However, the correlation between average remote sensing measurements and average I/M test results by vehicle model year for a fleet of vehicles is fairly good; Stedman et al. report r^2 values of 0.96, 0.97, and 0.97 for HC, CO, and NOx, respectively (Stedman et al., 1997). This strong correlation on a fleet basis suggests that remote sensing measurements can be used to characterize the in-use emissions of a fleet of vehicles, and therefore can be used to evaluate I/M program effectiveness. The average remote sensing CO emissions by model year of Arizona vehicles correlate very well with average IM240 CO emissions by model year. Fig. 6 compares average remote sensing and IM240 emissions of 264 000 vehicles with at least one remote sensing measurement within 1 year prior to the vehicle's initial IM240 test. Each point in the figure represents the average emissions for a given model year of vehicles. We used the initial IM240 test result for the IM240 emissions of each vehicle. Multiple remote sensing measurements of the same vehicle were averaged across individual vehicles[13]. Fig. 6 indicates an r^2 of 0.99 for CO emissions under the two measurement techniques. The correlation is not as good for HC, particularly for the newest vehicles. Although Fig. 7 indicates a r^2 of 0.99 for remote sensing and IM240 HC measurements of 1981 to 1990 vehicles, there is a deviation in the regression line for 1991 and newer vehicles.

We have identified several potential causes for the poor correlation for HC emissions from new vehicles: there is one reason the IM240 readings may be too low, and three reasons the remote sensing measurements may be too high. The IM240 HC emissions may be too low due to our method for adjusting fast-pass/fast-fail emissions to full test emissions. Both our and the RFF method for adjusting short test emissions underpredict

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[13] When we analyzed all remote sensing measurements (that is multiple measurements per vehicle), regardless of when the next (or previous) IM240 test occurred, we observed the same trends as in Figs. 6 and 7.

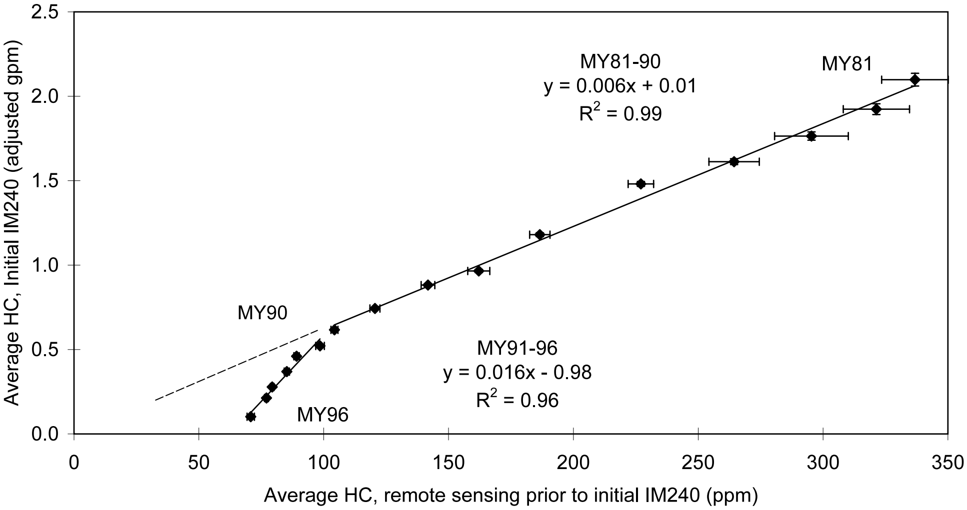

Fig. 7. Average remote sensing and IM240 HC by MY for 264 000 vehicles, 1996–1997 Arizona.

emissions from vehicles fast-passed after only 30 s of testing (Ando et al., 1999). Since the fraction of vehicles fast-passed was higher for newer vehicles than older vehicles (ranging from 30% for 1981 vehicles to 75% for 1995 vehicles), any bias in our method to estimate full test emissions of fast-pass vehicles should affect fleet average emissions of newer vehicles more than those of older vehicles. When we compared remote sensing and IM240 average emissions by model year using 28 000 measurements of vehicles given a full IM240 we saw similar trends in average emissions by model year as in Figs. 6 and 7; this indicates that our method of adjusting emissions of fast-pass/fast-fail vehicles to full test emissions is not the cause of the deviation of new vehicle HC emissions in Fig. 7[14].

On the other hand, the remote sensing HC measurements for new vehicles may be too high, for several reasons. First, the Arizona remote sensing contractor, Hughes, converted all negative emissions measurements to zero; this raises average emissions of HC and CO, and particularly affects the newer model years with more clean vehicles. Second, about half of the vehicles with speed measurements were under deceleration at the time of measurement; since decelerations can result in elevated HC emission concentrations, large numbers of decelerating vehicles will also raise average HC emissions[15]. Third, two field evaluations of the Hughes sensor have found that it consistently over-estimated both CO and HC emissions (Rendahl, 1997; Pokharel et al., 1999).

We attempted to quantify how much of the high remote sensing HC emissions for newer vehicles can be attributed to the first of these, the conversion of negative HC measurements to zero. We used a separate data set of remote sensing measurements made by the California Air Resources Board at 35 sites in Los Angeles in 1997, using the same Hughes instrument, to estimate the effect of converting all negative HC measurements to zero (negative emissions measurements were retained in this data set). This conversion has little effect on CO emissions and HC emissions from older vehicles, but overstates HC emissions of 1996 vehicles by 20%.

Many remote sensing databases include a large number of measurements of vehicles under deceleration. Deceleration in and of itself is not a valid reason to invalidate a remote sensing emissions measurement; depending on the grade of the measurement site, and the vehicle speed, a decelerating vehicle may be under positive load. Jimenez et al. have proposed a method for calculating the vehicle load under which individual remote sensing measurements are made, in order to screen for analysis measurements that are made under negative, very low, or very high vehicle load (Jimenez et al., 1998). They propose the metric vehicle specific power, or VSP, to identify the relative load under which a remote sensing measurement is made. VSP is calculated based on instantaneous vehicle speed and acceleration; average rolling resistance, aerodynamic drag, and inertial resistance values for the light duty vehicle fleet; and roadway grade at the remote sensing site. Unfortunately, we were unable to obtain information on the roadway grade of the over 100 Arizona sites where Hughes made their remote sensing measurements, so we could not screen individual measurements by VSP. As a result, we utilized all remote sensing measurements made at each site, regardless of recorded

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[14] Adjusting the fast-pass/fast-fail vehicle HC emissions using the RFF method did not remove the deviation from emissions measured by remote sensing for newer model years.

[15] However high HC emission *concentrations* during vehicle deceleration do not translate into high HC *mass* emissions, as total mass output of all gasses is low during deceleration.

Table 6
Average emissions and percent reduction, vehicles measured by remote sensing up to 3 months before initial IM240 or up to 3 months after final IM240[a]

Type	Number of measurements	Distribution	Unweighted average emissions per vehicle				Percent reduction	
			HC (ppm)		CO (%)		HC	CO
			Before I/M	After I/M	Before I/M	After I/M		
Cars	84 766	61%	122	109	0.71	0.65	10.4	8.5
LDT1	42 826	31%	133	116	0.74	0.70	13.1	4.6
LDT2	11 936	9%	130	114	0.65	0.62	12.7	4.5
All	139 528	100%	126	111	0.71	0.66	11.5	6.9

[a] 140 000 remote sensing measurements both before and after I/M test, of 206 000 vehicles (only 20% of vehicles were measured by remote sensing both before and after I/M test).

speed and acceleration[16], with the understanding that this may introduce bias in our results.

We conclude that a combination of the three factors described above accounts for the large overstatement of HC emissions from newer vehicles in the Hughes remote sensing data from Arizona. Because of the limitations with the HC remote sensing data, particularly for newer model years, we must be careful to account for vehicle age when evaluating program effectiveness in reducing HC emissions, as measured by remote sensing.

We compared average remote sensing emissions of vehicles measured up to 90 days before their initial IM240 with average emissions of vehicles measured up to 90 days after their final IM240. There were 206 000 such vehicles in our database, with 140 000 measurements both before and after I/M testing (but not necessarily of the same vehicles). We checked the IM240 results of this subset of vehicles measured under both systems, and found that the IM240 results of the 206 000 vehicles were the same as those of the 412 000 vehicles. Multiple remote sensing measurements of individual vehicles were averaged to obtain a single remote sensing emissions value for each vehicle before and/or after IM240 testing.

3.2. Results

Table 6 shows average remote sensing emissions before and after IM240 testing, and percent emissions reduction, by vehicle type; these results can be compared with the results based on IM240 test results and presented in Table 1. The remote sensing data indicate a smaller reduction in HC emissions, 11.5% as opposed to 14.5% from the IM240 data, and a much smaller reduction in CO emissions (7% as opposed to 15%). Table 7 shows the average remote sensing and emissions reductions by IM240 result (and can be compared with the results from the IM240 data presented in Table 5). Remote sensing emissions of fail–pass vehicles were reduced by only 38% for HC and 29% for CO, as opposed to the 62 and 65% reductions in Table 5. And the remote sensing data indicate larger reductions in emissions from no-final-pass vehicles than the IM240 data (20% as opposed to 5%). The distribution of vehicles by type and I/M result was very similar for those with remote sensing measurements before and after IM240 testing, indicating that the remote sensing results were not influenced by a bias in the two fleets measured before and after IM240 testing.

There were only 3500 vehicles from the random sample given full IM240 tests that also had at least one remote sensing measurement up to 90 days before or up to 90 days after IM240 testing (resulting in 2400 remote sensing measurements both before and after I/M testing). The remote sensing data for these vehicles indicate that overall emissions reductions were only 3%, and reductions for fail–pass vehicles under 30%; however, because of the small number of vehicles involved, these results may not be statistically significant.

Figs. 8 and 9 present average passenger car remote sensing emissions by model year and I/M result, similar to Figs. 2 and 3 developed with IM240 data. There is more year-to-year variability in the remote sensing data than in the IM240 data, especially for the fail–pass and no-final-pass cars, because there are fewer remote sensing measurements than IM240 results for each model year[17]. Fig. 10 presents percent emissions reduction of fail–pass cars, similar to Fig. 5. The figures indicate that emissions of fail–pass cars as measured by remote sensing were reduced much less than as measured by IM240 testing, even for HC from newer cars. CO emissions from fail–pass cars were consistently reduced by 30% for all model years, as opposed to the 60% as measured under IM240 testing (Fig. 5). Percent reduc-

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[16] Although Hughes did exclude all measurements with measured accelerations of 3 mph/s or more.

[17] For example, in Figs. 8 and 9 there are 200 to 700 remote sensing measurements for each model year of the final-pass cars, and only 100 to 500 for each year of the no-final-pass cars. Figs. 2 and 3 include over 1000 IM240 results for most model years of fail–pass cars and over 500 for most years of no-final-pass cars.

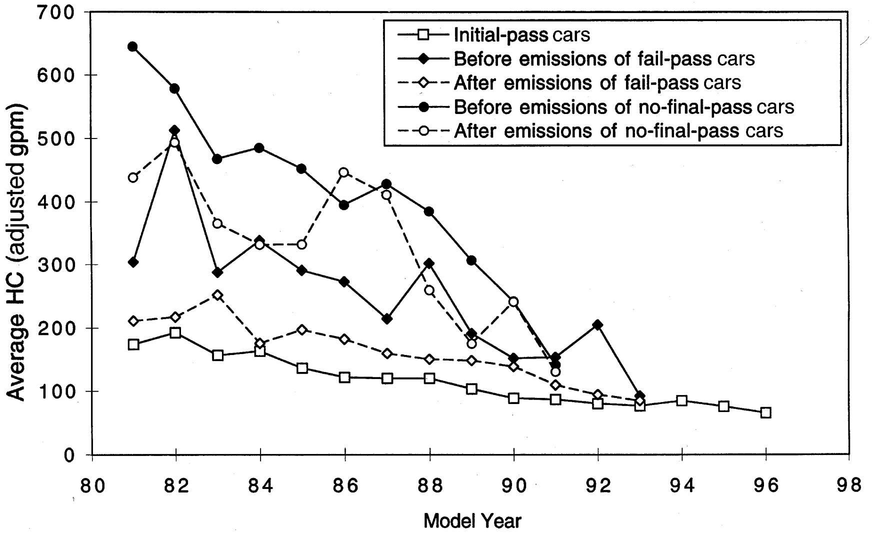

Fig. 8. Average RSD HC emissions for passenger cars by model year and I/M result, up to 90 days before and after I/M test, 1996–1997 Arizona remote sensing.

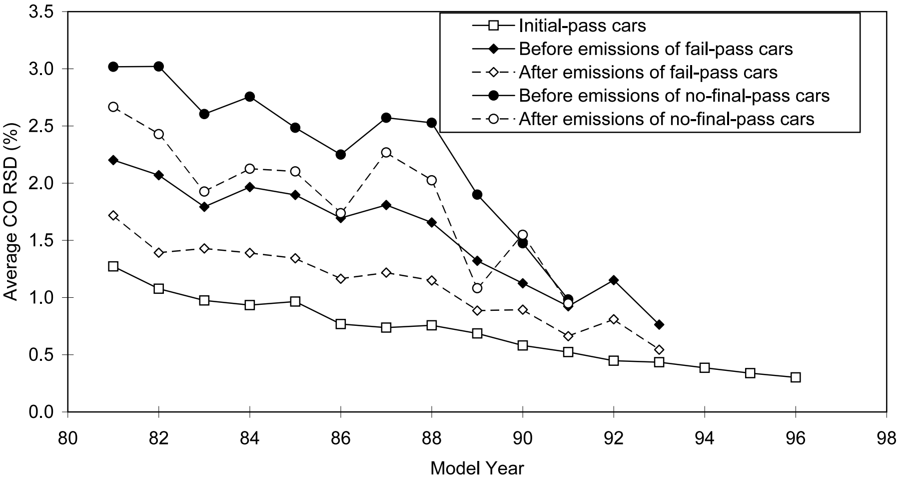

Fig. 9. Average RSD CO emissions for passenger cars by model year and I/M result, up to 90 days before and after I/M test, 1996–1997 Arizona remote sensing.

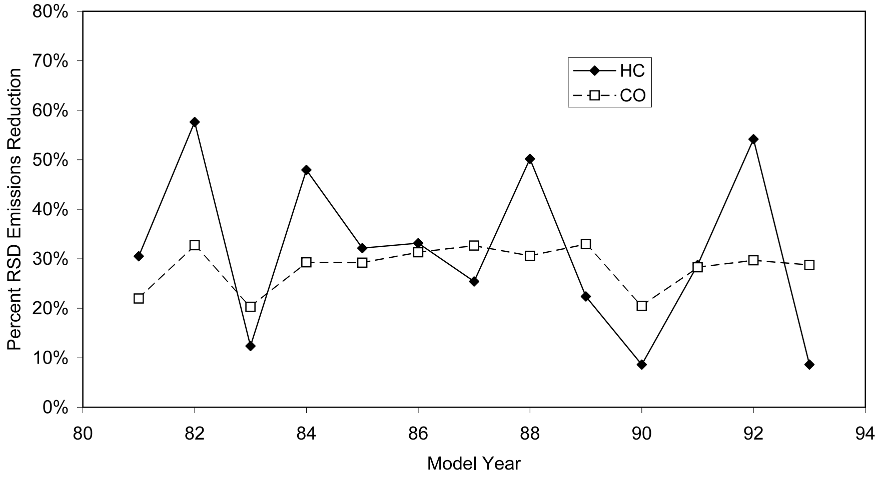

Fig. 10. Percent RSD emission reduction by model year fail–pass passenger cars, 1996–1997 Arizona remote sensing.

Table 7
Average remote sensing emissions and percent reduction by I/M result, unweighted by annual VMT[a]

I/M result	Number of measurements	Distribution of all measurements	Distribution of all fails	Unweighted average emissions per vehicle				Percent reduction	
				HC (ppm)		CO (%)		HC	CO
				Before I/M	After I/M	Before I/M	After I/M		
1) Initial-pass	126 698	90.8%		103	100	0.58	0.59	3.3	−0.9
2) Fail–pass	8298	5.9%	64.7%	295	185	1.70	1.21	37.5	29.2
3) No-final-pass	2663	1.9%	20.8%	420	324	2.44	1.81	23.0	26.1
4) No-second-test	1869	1.3%	14.6%	494	395	2.46	2.31	20.0	6.0
Subtotal 3 and 4	4532	3.2%	35.3%	450	349	2.45	1.99	22.4	18.7
Total	139 528	100.0%	100.0%	126	111	0.71	0.66	11.5	6.9

[a] 140 000 remote sensing measurements both before and after I/M test, of 206 000 vehicles (only 20% of vehicles were measured by remote sensing both before and after I/M test).

tions in HC emissions vary considerably by model year in Fig. 10, but the HC reductions are clearly lower than those in Fig. 5. Figs. 8 and 9 indicated that remote sensing emissions were not brought down as close to the emissions of the initial-pass cars, as was indicated in the IM240 data (Figs. 2 and 3). Also the remote sensing data show larger emission reductions from the no-final-pass cars than the IM240 data.

There are several possible explanations for the difference in emission reductions obtained from the IM240 test results and the remote sensing measurements. We analyze below two of these explanations: that each test measured vehicles under different operating loads, and that each test measured vehicles at different time intervals since their I/M test.

4. Effect of vehicle load on emission reduction

We suspect that part of the difference in repair effectiveness as measured by IM240 testing and remote sensing was due to different vehicle operation under the two tests. The IM240 driving cycle is not particularly rigorous, whereas remote sensing units are typically sited at locations where vehicles are under moderate loads, to give a strong enough emissions signal.

We analyzed second-by-second IM240 emissions measurements of 1000 vehicles with full IM240 tests both before and after repair. We divided the IM240 trace into several modes of distinct vehicle operation, including seconds 159 to 170, the most heavily-loaded section of the IM240 (average VSP over these 10 s is 19 kW per tonne; the average VSP value in remote sensing surveys is typically 10–15 kW per tonne). Although this is the most heavily-loaded segment of the IM240 cycle, and is a bit higher than the average load of most remote sensing studies, it is only considered a moderate load (for example, an acceleration of 3.3 mph/s, the maximum acceleration called for in the IM240, at a speed of 55 mph on a 1% grade results in a VSP of 47 kW per tonne).

Fig. 11 compares emissions reductions from repair over the full IM240 cycle with reductions over the moderately-loaded segment of the cycle. The figure indicates that vehicle repairs reduced CO emissions over the entire IM240 by nearly 60%, as we found in the earlier analysis of IM240 measurements for the entire fleet. However, CO emissions from the moderately loaded section of the IM240 were reduced by only 34%; this result is comparable to the emission reduction we observed for the entire fleet in the remote sensing data. Therefore, it appears that much of the difference between repair effectiveness as measured by IM240 and RSD may be attributable to the different average loads vehicles are subjected to in each type of test. (Again,

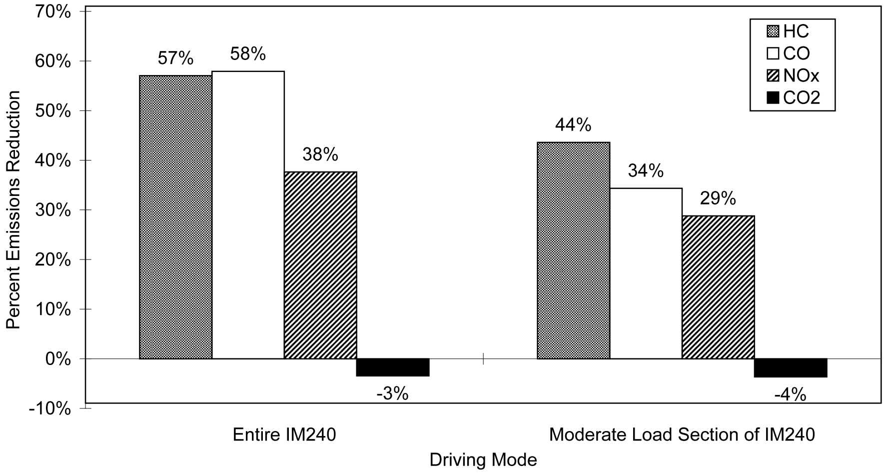

Fig. 11. Emission reductions due to IM240 repairs 1080 vehicles given full IM240 pre- and post-repair, 1996 Arizona IM240.

because we did not have any data on the roadway grade at each of the remote sensing sites, we could not estimate the vehicle load under which each remote sensing measurement was taken. If such information were available we could select a sample of remote sensing measurements with the same distribution of vehicle loads as encountered in the IM240 test, and compare emission reductions under the two tests holding vehicle load constant.).

5. Effect of time since test on emission reduction

Part of the difference in the results from the IM240 and remote sensing data may be due to when each technique measures emissions; the IM240 test measures a vehicle's emissions immediately after meeting I/M requirements, while remote sensing measures emissions days, weeks, or months after a vehicle has met I/M requirements. This feature of remote sensing allows one to estimate the effectiveness over time of repairs made in the I/M program.

We grouped the remote sensing data into several time periods, ranging from 30 to 90 days in duration, both before and after I/M testing in order to study how on-road emissions change over time. For each time period we averaged multiple remote sensing measurements of a single vehicle. Figs. 12 and 13 show how remote sensing emissions by I/M result increased as a vehicle got closer to its scheduled I/M test; these increases are quite dramatic for the fleets of fail–pass and no-final-pass vehicles. This is because at the time of the initial I/M test all of these vehicles failed their test, by definition. As expected, the remote sensing data show a large reduction in emissions of fail–pass vehicles immediately after the final (passing) I/M tests of these vehicles, presumably from repairs to many of the vehicles. Similarly, emissions were reduced somewhat for the no-final-pass fleets as well, presumably from repairs that reduced emissions, but did not cause the vehicles to pass. As each vehicle fleet gets further from its final I/M test, emissions begin to increase.

The remote sensing data indicate how quickly the initial emissions reductions from the I/M program diminished over time. Table 8 compares the initial emission reductions, as measured by the IM240, with the reductions calculated at different times after the final I/M test, as measured by remote sensing. Emission reductions are shown for the overall fleet, fail–pass vehicles, and initial-pass vehicles. The results for CO are striking; remote sensing saw much smaller emission reductions from fail–pass vehicles within 1 month of the final I/M test (36 vs 65%). The reductions continued to diminish, down to 28%, as the vehicles got further away from their final I/M test. Reductions in emissions from the overall fleet similarly decreased, from 12% up to 1 month after I/M testing to 6% over a year after I/M testing. Reductions in emissions from the initial-pass vehicles also decreased over time since I/M testing (negative percentages in Table 8 indicate that emissions were greater than when measured before I/M testing). The trend in reductions in remote sensing HC emissions over time is similar to that of CO emission reductions[18].

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[18] The data in Table 8 for HC emissions 12–15 months after the I/M test appear at first to be inconsistent. The emission reductions from both the initial pass and fail–pass fleets decreased from the previous time period, yet the overall fleet emission reductions did not. This is explained by an increase in emission reductions from the no-final-pass vehicles, which are not shown in Table 8 but can be seen as emission reductions at 12–15 months after the I/M test in Fig. 12. This reduction in no-final-pass emissions may have been due to the highest-emitting of these vehicles being removed from the on-road fleet 12–15 months after their final I/M test.

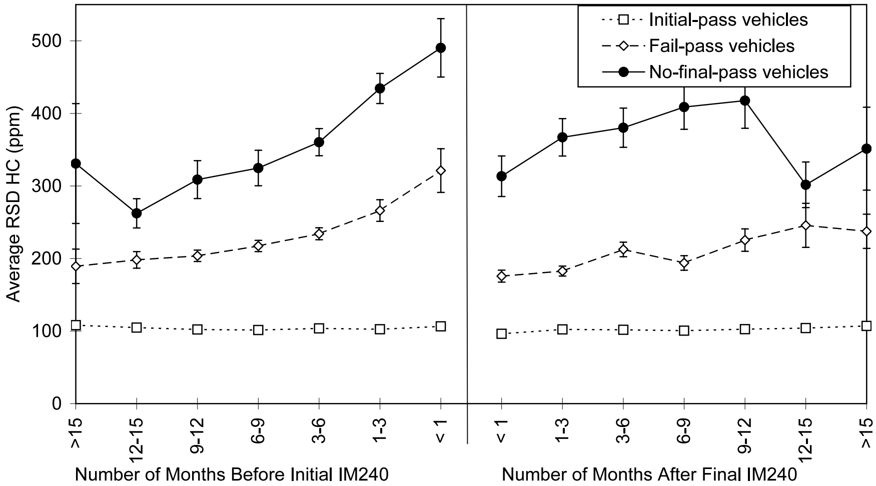

Fig. 12. Average HC RSD emissions by I/M result and time period 1996–1997 Arizona remote sensing.

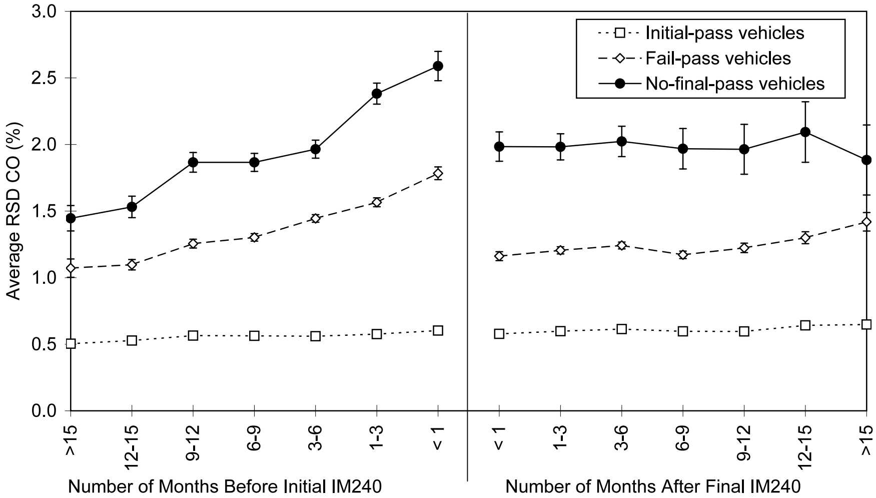

Fig. 13. Average CO RSD emissions by I/M result and time period 1996–1997 Arizona remote sensing.

6. Other possible explanations

There are two other possible explanations for the difference in emission reductions measured by IM240 test results and remote sensing measurements. The first is that some of the apparent emission reduction measured by the IM240 test could have been caused by inherent test-to-test variability of vehicle emissions. Emissions from all vehicles can be variable for a variety of reasons (Wenzel et al., 2000). In addition, some vehicles with an intermittent component malfunction may have relatively high emissions on one test but relatively low emissions on a later test, under the same conditions. Because of vehicle emission variability, some vehicles that pass their initial I/M test, or a subsequent retest, may have higher emissions when tested several days later (by, for example, remote sensing). Another explanation is that a small number of vehicles, with high emissions, may have been improperly passed by falsifying their emissions test. Although this practice is unlikely in a centralized I/M program, the Phoenix I/M testing contractor has fired several inspectors over the years for conducting fraudulent emissions tests (Arizona State Legislature and Vehicle Emissions Inspection Legislative Study Committee, 1999).

7. No-final-pass vehicles

We used the remote sensing data to try to determine what happened to the no-final-pass vehicles that apparently never completed I/M test requirements. If these vehicles were being scrapped or otherwise no longer operated in the I/M area, the removal (and perhaps replacement) of these vehicles should be counted as a positive benefit of the I/M program. However, if these vehicles continued to be operated in the I/M area without meeting I/M requirements, they represent a loophole in

Table 8
Percent reduction in remote sensing emissions by I/M result and time since I/M test

	Percent emission reductions by I/M result					
	HC			CO		
Measurement	Overall	Fail-pass	Initial-pass	Overall	Fail-pass	Initial-pass
IM240	15%	62%	0%	15%	65%	0%
Remote sensing up to 1 month after I/M	19%	46%	10%	12%	36%	4%
Remote sensing up to 3–6 months after I/M	14%	35%	5%	9%	32%	−2%
Remote sensing up to 12–15 months after I/M	14%	24%	2%	6%	28%	−7%

the I/M program and undermine its effectiveness in reducing in-use emissions.

We calculated the distribution of remote sensing measurements by I/M result and time period, to see if the fraction of no-final-pass vehicles in the fleet measured by remote sensing decreased more rapidly than that of fail–pass vehicles.

Fig. 14 shows the fraction of the no-final-pass and fail–pass vehicles of the fleet over time. Nearly half of the no-final-pass vehicles were no longer driven in the I/M area 6 months after their I/M test, and two-thirds were no longer driven 15 months after I/M testing. Only about one-third of the fail-pass vehicles were no longer driven in the area after 15 months. The no-final-pass vehicles were removed from the I/M area faster than the fail–pass vehicles. However, about one-third of the no-final-pass vehicles continued to be driven in the I/M area 15 months after their last I/M test. These vehicles may have been legally re-registered outside of the I/M area, but their emissions were still affecting urban air quality. (Arizona state law requires that even vehicles that are registered outside of the I/M area, but often operated within the I/M area, are required to participate in the I/M program).

We looked at how the model year distribution of vehicles changed over time to determine if the I/M program was inducing the oldest vehicles, and therefore those likeliest to be high emitters, to leave the I/M area. We compared the model year distribution of remote sensing measurements taken 1 month after I/M testing with the distribution of measurements taken over 15 months after I/M testing. The distributions are remarkably similar, indicating that the oldest vehicles were being removed from the I/M area at roughly the same rate as the newest vehicles. A strength of remote sensing is that it measures vehicles that are driven frequently, and contribute relatively more to area emissions, than vehicles that are driven relatively infrequently (frequently driven vehicles are more likely to be driven past the remote sensors than those driven infrequently). It is possible that the program induced older, infrequently driven vehicles to be permanently removed from the I/M area at a faster rate than newer, infrequently driven vehicles. However, the remote sensing data indicate that this was not the case for vehicles that most contribute to area emissions, the vehicles that were frequently driven.

8. Effect of pre-test repairs

A survey conducted in the Phoenix area found that one-third of vehicle owners planned to bring their vehicle in for a tune-up prior to their next scheduled I/M test (Behavior Research Center, 1999). We used the remote sensing measurements to estimate the magnitude of emissions reductions due to vehicle maintenance, adjustments, or repairs prior to the initial I/M test. Fig. 15 indicates that fleet CO emissions increased steadily until about 3 weeks prior to the initial I/M test, when they decreased dramatically. Without accounting for changes to vehicles prior to testing, the remote sensing data indicate that the Phoenix program resulted in an 8% reduction in CO emissions up to 1 week after the final IM240 test (B in the figure). However, if post-test emissions are compared with emissions 3 weeks before testing (A in the figure), the remote sensing data indicate that the program reduced CO emissions by 18% from the level measured 3 weeks prior to the initial IM240 test[19]. We see similar effects of pre-inspection repairs on remote sensing HC emissions. We suspect that most of the repairs leading to this reduction in emissions were induced by the upcoming I/M inspection. Evaluations that do not account for this reduction immediately prior to the initial test, therefore, will under-estimate I/M program effectiveness.

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[19] One could extrapolate the emissions trend from 6 to 3 weeks prior to the IM240 test in Fig. 15 to immediately prior to the initial IM240 test, and estimate an even larger emissions reduction from pre-test repairs than reduction A shown in the figure.

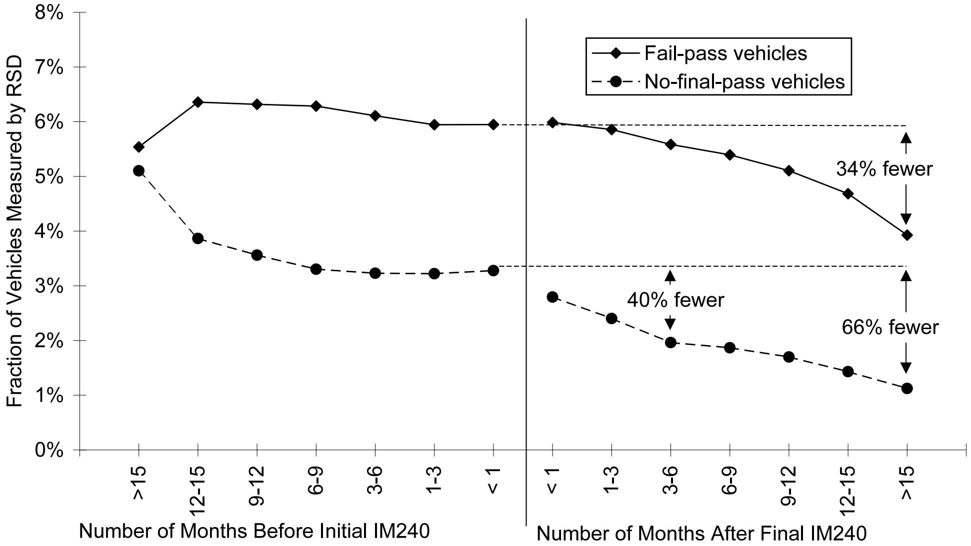

Fig. 14. Fraction of vehicles measured by RSD 1996–1997 Arizona remote sensing.

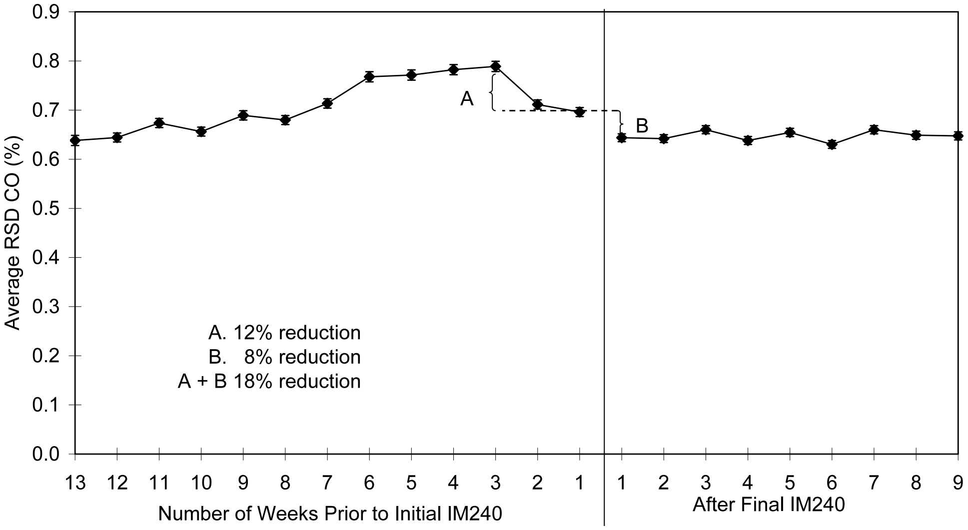

Fig. 15. Average CO RSD emission by time period 1996–1997 Arizona remote sensing.

9. Conclusions

Comparison of initial and final exhaust emission test results from the 1996–1997 Phoenix IM240 program suggests that the program achieved the same initial percentage reduction in CO and HC emissions as predicted by MOBILE5; however, NOx emissions reductions were only half as large as predicted by MOBILE. Emissions of vehicles that failed initial testing, but passed a retest, were reduced dramatically, but were not brought down to the level of vehicles that passed their initial test.

Remote sensing data indicate smaller reductions from the program than the program test results. One probable cause is the different distribution of loads that vehicles are measured under in IM240 and remote sensing measurement. Repairs reduced vehicle emissions measured over moderate loads by a smaller percentage than emissions measured over the full IM240. Another possibility is that the emission reductions measured by remote sensing decreased as time elapsed from the vehicles passing their IM240 test, likely due to deterioration of the repairs made to the vehicles. Both causes, as well as test-to-test variability in vehicle emissions and perhaps test fraud, could contribute to explaining the different results. Evaluation of I/M programs based solely on I/M test results from a single inspection cycle can only estimate the initial emission reductions from the program. Individual vehicles should be tracked over more than one I/M cycle to estimate the deterioration of repairs, and vehicle emissions, over a longer time period (two or more years).

A potential problem with the Arizona program is that 30% of the vehicles that failed initial testing never passed a subsequent retest; remote sensing data indicate that one-third of these vehicles continued to be driven in the Enhanced I/M area more than 1 year after failing the I/M test. The distribution by model year of no-final-pass vehicles seen by remote sensing did not change over a 15-month period, indicating that the vehicles which the program induced to leave the I/M area were not disproportionately drawn from the oldest model years. Perhaps better enforcement of vehicle registration would reduce the numbers of vehicles not completing program requirements.

Finally, it appears that many vehicle owners got their vehicle repaired or adjusted in the weeks before they brought it in for their I/M test. Emission reductions resulting from these repairs must be included to estimate the full benefits of an I/M program. A large number of remote sensing measurements are necessary to quantify any reductions in emissions due to repairs or adjustments immediately prior to an initial I/M test.

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