Costs, Emissions Reductions, and Vehicle Repair: Evidence from Arizona

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ABSTRACT

The Arizona I/M program provides one of the first opportunities to examine the costs and effectiveness of vehicle emission repair. This paper examines various aspects of emission reductions, fuel economy improvements, and costs of repair, drawing data from over 80,000 vehicles failing the I/M test in Arizona between 1995 and the first half of 1996. We summarize the wealth of repair data from the Arizona program and highlight its limitations. Because missing or incomplete cost information has been a serious shortcoming for evaluation of I/M programs, we develop a method for estimating the costs of repair when those costs are not reported. We find surprising evidence that almost one quarter of all vehicles that take the I/M test are never observed to pass the test. Using a statistical analysis, we provide some information about the differences between the vehicles that pass and those that do not. Older, more polluting vehicles are much more likely to never pass the I/M test, and their expected costs of repair are much higher than those of new cars. The paper summarizes the evidence on cost and emission reduction in the Arizona program, comparing costs and emission reductions for both cars and trucks. Finally, we examine the potential for more cost-effective repair, first through an analysis of tightening I/M cutpoints, and then by calculating the cost savings of achieving different emission reduction goals when the most cost effective repairs are made first.

Key Words: I/M, repair, emissions, mobile sources

Journal of Economic Literature Classification Numbers: Q25, R48

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Amy Ando, Virginia McConnell, and Winston Harrington*

1. INTRODUCTION

Since the early 1980s, air quality management authorities in the U.S. have struggled to develop effective and politically acceptable inspection and maintenance (I/M) programs to control emissions from motor vehicles. I/M was—and still is—perceived as a key element in any attempt to reduce vehicle emissions to improve air quality in polluted urban areas. Unfortunately, these programs were generally found to be ineffective in reducing emissions, and one of the most important new sections of the 1990 Amendments to the Clean Air Act directed the EPA to develop an "Enhanced I/M" program to overcome the apparent inadequacies of first-generation I/M programs. However, the focus of these efforts was concentrated far more on the "inspection" than on the "maintenance"—identifying vehicles in need of emission repair; that is, rather than on the repair itself.

The Enhanced I/M regulations were the result of an EPA research program on emission repair, which involved repair of a sample of vehicles in EPA's own laboratories by specially trained mechanics. This research effort had a number of characteristics with important implications for later use in regulatory decision-making. First, the sample of vehicles repaired was small (N = 266) and, since recruitment was voluntary, non-random (although the Agency was successful in examining a wide range of model-years). Second, the Agency's mechanics were able to bring into compliance most, but not all, of the vehicles; for the remainder the Agency simply presumed that further repair would do the trick. Third, the sample excluded vehicles that showed evidence of tampering (Harrington et al., 1998). On the basis of its studies, the Agency concluded that nearly all vehicles could be successfully repaired at modest cost (USEPA, 1992;). However, the Agency's conclusions were called into question shortly thereafter by a handful of studies of repairs done at actual auto repair shops. These studies suggested that repair was quite costly and often was unable to return vehicles to compliance (California IM Review Committee, 1994; Cebula, 1994; Lodder and Livo, 1994). These studies were based on data sets that were small or selected by unknown, and possibly undesirable, criteria.

In this paper we use a data set that circumvents many of the problems encountered by earlier repair studies. These data are from the Arizona I/M program, the first of the new Enhanced I/M programs to be implemented. For approximately 80,000 vehicles that failed the initial I/M test during 1995 and early 1996, we have emission test results before and after repair. We also have information on the parts that were repaired , and the costs of repair.

We use these data to examine various aspects of repair under the Arizona I/M program. We explore test failure rates by model year and, for failed vehicles, identify the vehicle characteristics that are associated with successful repair. We quantify the relationships among pollutants in test results and in post-repair emission-rate changes. We devise a method of compensating for missing cost data. Using the resulting figures, we estimate per-vehicle repair costs and improvements in

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emission rates and fuel economy, and assess the sensitivity of those costs and improvements to a relaxation of program cutpoints. Finally, we illustrate the scope and importance of variation in the cost-effectiveness of vehicle repair.

2. THE ARIZONA I/M PROGRAM AND THE DATA

The data for this analysis are from the Arizona I/M program, which has had since 1995 a biennial centralized enhanced vehicle emission inspection program in place for Maricopa County (Phoenix). The program requires all post-1980 vintage light duty vehicles to take the newly-developed IM240 emissions test. This dynamometer test measures pollutant levels for HC, CO and NOx in grams/mile in vehicle exhaust over a driving cycle that reflects urban commuter travel. A vehicle fails the tailpipe test if any of its emission rates exceeds the emission "cutpoint" for that pollutant.

In addition to the tailpipe test, Arizona's program conducts pressure tests to ensure against leaks, so that evaporative emissions are not excessive.[1] Unfortunately, there is no accepted measurement of evaporative emissions, so it is not possible to determine the emission reductions achieved by the evaporative tests. The Arizona program also screens for vehicles with emission control systems that have been tampered with. Failure of the overall I/M test results from failure of any one of the three components—the IM240 test, the evaporative tests, and the tampering inspection. Vehicles that fail the tailpipe or evaporative emission tests must be repaired regardless of the results of the tailpipe test.

No vehicle can be registered until the I/M test is passed. Each time a vehicle comes back for a retest, its owner must submit a repair summary which shows, for that round of repair, the changes that were made to the vehicle and the costs of those repairs. In some cases, a vehicle requiring repair expenditures over $450 may get a waiver from the state exempting it from further repairs regardless of test outcome. However, all tampering problems must be remedied regardless of cost.

Our dataset consists of all vehicle tests and repairs for the 17-month period from January1995 through May 1996. We work with a very large sample of 82,786 vehicles[2] that failed the tests over this period, of which just over two-thirds are cars and the rest light duty trucks. Some vehicles were retested and (presumably) repaired more than once, giving 110,584 rounds of repair. This data set is a rich source of information on how I/M works in the real world. However, it has a number of important complicating factors.

First, although all vehicles are supposed to be repaired to meet Arizona's I/M cutpoints (see Appendix B), we find that about 22 percent of vehicles that fail their initial tests do not have passing emission rates as of their last tests. This could happen for several reasons. A number of vehicles were simply still trying to comply with the cutpoints when our sample period ended. Some may have received waivers (although the number of waivers reported by the Arizona Department of Environmental Quality in 1997 was only 4 percent of failed vehicles)[3] and others may have been scrapped or sold outside of the region covered by the I/M program. Still other vehicles may be

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1. Evaporative emissions consist of fuel that vaporizes and escape from the vehicle. Modern vehicles have several components designed to minimize fuel loss through evaporation, and evaporative tests examine some of these components.
2. There were initially 135,734 failing vehicles out of a total of 995,904 tested vehicles during the entire 17 month period. We cleaned the data extensively, dropping vehicles that were plagued by any of a number of random data problems. For example, some had bogus license numbers, or multiple "initial tests." We also dropped failing vehicles which had no retests at all because we had no repair information for them.
3. Personal communication, Rick Day, Arizona Department of Environmental Quality, April 1, 1998. We have not yet received data from Arizona enabling us to identify the vehicles in our sample that received waivers.

improperly registered or registered outside the region but still driven in it, an outcome especially problematic for the I/M program. It is difficult to make an accurate assessment of the success of the I/M program without being able to identify the ultimate fate of all the tested vehicles.[4]

Second, the raw emissions data reported by the Arizona program are not consistent across tested vehicles. Like many states, Arizona's test protocol allows for vehicles to "fast-pass" in less than the full 240 seconds of the test. In addition, Arizona is the only state that permits vehicles to fast-fail. Vehicles can fast-pass the test starting at second 31, and they can fast-fail any time after second 93. The resulting emission-test results (in grams/mile) cannot be directly compared. To make the results consistent across vehicles, we have forecast full 240-second readings from the fast-pass or fast-fail results for each vehicle.[5]

Third, vehicles that fail the tampering or evaporative tests are not identified specifically but are, presumably, those vehicles that fail the overall test without failing the tailpipe test for any pollutant. Although the dataset contains data fields to indicate tampering or evaporative failure, those fields are filled with missing data. Thus, we can distinguish tampering or evaporative failures from tailpipe test failures, but we cannot distinguish them from each other. Furthermore, any vehicle that fails for both tailpipe and tampering or evaporative emissions is counted as a tailpipe failure.

Fourth, the information on vehicle repairs, including cost and parts repaired, are self-reported by motorists and not verified by test inspectors. Furthermore, many rounds of repair have reported costs equal to zero. While zero or trivial costs can occur, there are other explanations, including warranty repair or home repairs by do-it-yourself mechanics. Reported zeroes could also indicate missing data. We can not determine which of these explanations pertains to any given car. For analysis of repair, the proper treatment of zero cost depends on what question is being asked. The cost of a round of repair would be zero from the perspective of a vehicle owner if the vehicle is still under warranty. It might also be zero if the repair were done at home, depending on the opportunity cost of the owner's time and the utility received from successful repair. However, in order to determine the full cost of repair, we want to know the costs of all the repairs that were done, regardless of who performed and paid for them. To that end, we develop a method for imputing costs for repairs with zero reported costs but non-zero numbers of reported repairs. We discuss that method and the results that emerge from its use in the next section of this paper.

Motor-vehicle repair may yield benefits through improved fuel economy. In its regulatory impact analysis (RIA) for the Enhanced I/M rule, for example, EPA estimated that fuel economy for failed vehicles would improve on average by 12.6 percent (USEPA, 1992). Using the same method as EPA, we calculate the fuel economy changes among failed vehicles in Arizona,[6] where we found estimated fuel economy improvements to be much smaller than EPA's estimates—about 3.5 percent.

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4. Some recent studies have attempted to identify the extent to which vehicles are avoiding I/M but still driven in I/M regions (Stedman et al. ,1998 and McClintock, 1999).

5. Using the 2 percent random sample of vehicles in Arizona that have full 240 second tests, we estimated a separate equation for each pollutant for each second of the test, which we then used to forecast the full 240 second reading. For a detailed discussion of the methods used and the resulting equations, see Ando, Harrington and McConnell (1998).

6. We use a carbon mass-balance equation supplied by EPA to estimate mpg. Our forecasted 240-second readings of HC, CO, and CO_2 emission rates are the inputs used. The equation is:

$$mpg = 2421/((.866*HCgram/mile) + (.429*COgram/mile) + (.273* CO_2gram/mile)).$$

We get a small number of unreasonable outliers when we use this method to estimate fuel economy. EPA staff explained to us that these very high estimates of fuel economy may be the product of measurement errors for CO_2. CO_2 levels are only read in I/M programs to determine whether there are leaks in the exhaust pipes or if the exhaust funnel has been attached incorrectly, so these readings may be less accurate than those of the emission rates of the other pollutants. Thus, we discard vehicles with fuel economy estimates above the 99th percentile for their vehicle type (car, small light trucks, medium light trucks). The mean initial fuel economy for the remaining vehicles is 20.5 mpg.

Figure 1
Failure Rates of Vehicles by Model Year

Percent of failed vehicles that do not later pass

Percent of all vehicles that fail initial test
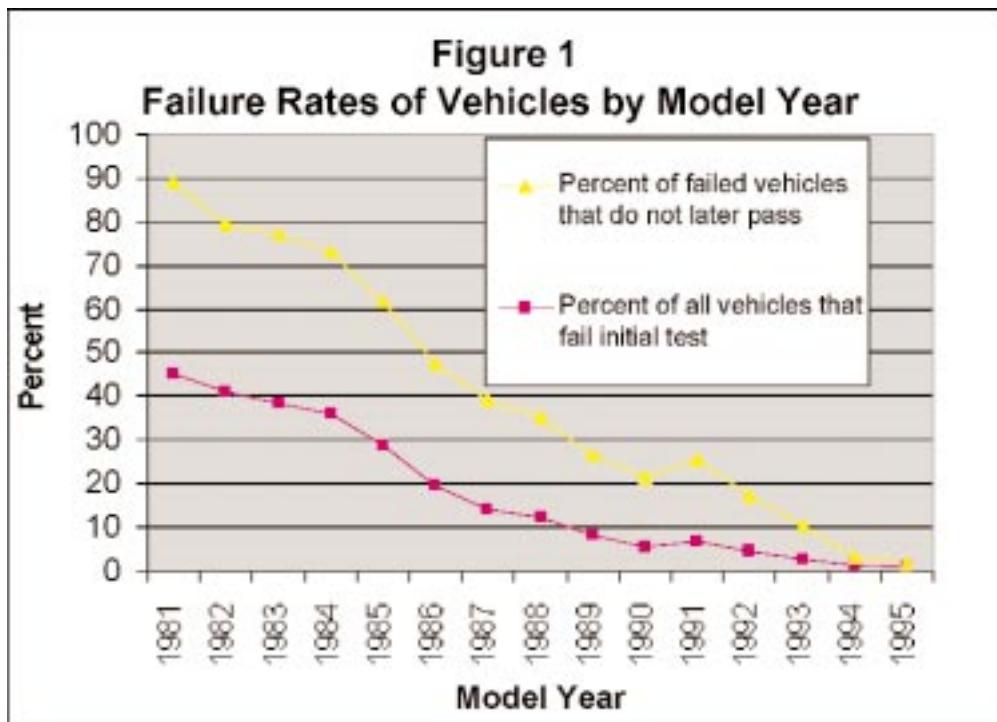
Model Year

Figure 1 and Tables 1 through 3 provide some summary information about the Arizona repair data. Figure 1 shows failure rates for vehicles by model year. The probability that a vehicle of a given model year will fail the initial test increases monotonically with vehicle age except between 1990 and 1991 model years. The failure rate is actually lower for 1990 vehicles than for the newer 1991 model year because the cutpoint to which light duty cars were subject for the 1990 model year was less stringent than for the 1991 model year. Failure rates are low for new vehicles, and reach about 20 percent for vehicles 10 years old, and 40 percent for vehicles 15 years old. Figure 1 also shows the percentage of failed vehicles in each model year that were not repaired to meet the cut-points as of the last test results in the data set. As vehicles get older, this percentage also gets larger. This is evidence these vehicles are not simply still mired in the repair-and-retest process; if what we were observing were only incomplete testing sequences, then there would be little difference among model years. We return to this point in a more formal selection model below.

Table 1. Combinations of Pollutants Initially Failing Tailpipe Test

Combination of Pollutants	% of Initial Failures
None	19.92
HC only	16.09
CO only	6.24
NOx only	33.75
HC and CO	16.27
CO and NOx	.27
HC and NOx	6.34
HC, CO, and NOx	1.11
Total	100.00

Failures can occur for many reasons, ranging from faulty spark plugs to broken catalysts, and different emission system problems affect emission rates for the three pollutants in different ways. Table 1 shows the distribution of failures among all possible combinations of the pollutants. The largest number of failures were of NOx emissions only. The "none" category refers to vehicles that did not have tailpipe emission rates in excess of any of the cutpoints but still failed the test. This category represents a large share of the total failures—about 20 percent—and we assume these vehicles are either tampered vehicles or evaporative emis-

Table 2. Emission-Rate Reductions and Fuel-Economy Improvements

Test Result Change	Mean	Standard Deviation
*HC (g/m)	.82	1.62
*CO (g/m)	12.35	32.56
*NOx (g/m)	.92	1.85
*MPG	.76	2.73

Note: N = 82,786.

Table 3. Correlation Coefficients Among Emission-Rate Reductions and Fuel-Economy Improvements

	*HC (g/m)	*CO (g/m)	*NOx (g/m)	*MPG
*HC (g/m)	1.0			
*CO (g/m)	0.63	1.0		
*NOx (g/m)	-0.16	-0.37	1.0	
*MPG	0.28	0.40	-0.04	1.0

sion failures. This assumption is consistent with the fact that the most common repair reported for these vehicles was replacement of a missing or damaged gas cap. As noted above, we cannot distinguish evaporative failures from tampering, for the pertinent data fields only contain missing values.

Table 2 summarizes the improvements we observed in emission rates and fuel economy as a result of repair of vehicles failing at least one tailpipe test. That is, evaporative emission repairs are excluded, because evaporative emission reductions cannot be calculated. The changes in pollution rates are calculated as the initial readings minus the results given by the last observed test; the change in fuel economy is the final minus the initial result. The table shows that emission rates fall on average, but there are some vehicles that have increased measured emission rates after repair, and those increases are sometimes large. Similarly, while fuel economy improves on average with repair, it may decline for some vehicles.[7]

Table 3 highlights the interrelationships among the pollutants and between the pollutants and fuel economy. Changes in HC and CO are positively related and both are inversely related to changes in NOx emissions. Improvements in HC and CO appear to be correlated with improved MPG, but improvements in NOx emissions and MPG are barely correlated. The correlations suggest that a policy instrument aimed only at one pollutant could induce changes in emission rates of the others. This feature of auto repair complicates optimal-policy design.

3. COSTS AND EMISSION REDUCTIONS FROM REPAIR UNDER CURRENT PROGRAM

There is a great deal of controversy over the size of the emission reductions and vehicle-repair expenditures generated by current I/M programs. We examine the evidence from the Arizona program regarding both of these. First, we present statistics on emission reductions and costs of repair, both with and without imputed values for repairs that are reported to be free. Next, we explore the

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7. With only a single emission measurement before and after repair, it is impossible to disentangle the fuel economy improvement from the emission test measurement error for an individual vehicle. The average improvement for all vehicles is estimated with considerable precision, however.

likelihood that the vehicles we observe being repaired to meet the cutpoints are not a representative sample of all vehicles that take the initial IM240 test, and discuss the implications of that sample selection. Finally, we use the data to explore the likely effects on both repair costs and emission reductions of changing the cutpoints that some vehicles are required to meet.

Costs and Reductions of Emissions from the Arizona Program

Vehicle-repair costs are not the full costs of the I/M program. Indeed, repair costs have been estimated to be only about one third of the overall costs of an I/M program.[8] However, the numbers involved are not trivial. In January 1996 alone, even a crude glance reveals repair expenditures totaling almost $600,000. This facet of the program is big enough to warrant a more detailed analysis.

As discussed earlier, the repair and cost data reported by motorists to the Arizona I/M program are incomplete in a number of ways. For many observations, vehicles appearing for retests report zero costs (59 percent) or no repairs (29 percent). A large fraction (31 percent) report specific repairs performed but no expenditures.[9] It seems likely that repairs on vehicles still under warranty or performed at home could involve no out-of-pocket expenditures, and yet still entail implicit costs such as the value of time or other resources that should be counted when evaluating the I/M program. Thus, we develop a method to estimate or impute costs for the rounds of repair that have some repairs but no costs reported.

Cost imputation is done using coefficients from an ordinary least squares regression equation. The equation is estimated using a sample of all the rounds of repair for which cost information was not missing. In this equation, cost is a function of the parts repaired (there were 26 possible types of parts), features of the repair (which round it is, how many parts were fixed, and whether the repair can be identified as having been performed in a shop), and vehicle age.

The estimated coefficients (and corresponding standard errors) of the cost imputation equation are given in Table 4. Shop repairs are reported to be more expensive than those that may have been done at home. The large positive constant term and the even larger coefficient for the shop-repair dummy suggest economies of scale in repair. In addition, the coefficient on the square of the number of parts fixed is negative, suggesting economies of scope. The most expensive single item to repair, on average, is a catalytic converter, followed by a carburetor. On the other hand, common repairs such as adjusting the air-to-fuel mixture, the timing, or the idle speed seem to be relatively cheap.

In order to impute a cost to a round of repair with zero reported costs but repairs listed as having been conducted, we simply plug values for the dependent variables into this equation and calculate the implied cost. We refer to costs that include imputed costs for seemingly false zeroes as "complete" costs. There are two indications that this is a reasonable approach to this particular problem of missing data. First, the R^2 statistic for the cost imputation equation, which is one measure of goodness-of-fit, is .22; this is a respectable fit for a regression performed on cross-sectional data. Second, the mean cost estimates one gets using our imputation technique are broadly similar to the mean non-zero reported costs when the means are calculated for two categories of repair.[10]

Cost statistics from Arizona provide perhaps the best direct estimate of the costs of repair in an ongoing I/M program. As such, they provide a useful benchmark against which to compare I/M repair-cost estimates developed elsewhere in the literature. Of these estimates, we know of only two

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8. Repair costs in Arizona are about 29 percent of the total I/M cost or about 36 percent of the cost not counting estimated fuel economy benefits. For more information see Harrington, McConnell and Ando (1999).

9. See Appendix A for a detailed breakdown of the numbers of rounds of repairs that have missing values for these data.

10. See Appendix A for the actual costs. The two types of repair are repair of a vehicle that failed the test for at least one of the three pollutants, and repair of a vehicle that seems only to have failed due to tampering.

Table 4. Cost Imputation Equation

Independent Variable	Coefficient	Standard Error
Constant	34.61	2.90
2nd round of repair	4.14	1.85
3rd round of repair	3.69	3.07
4th+ round of repair	3.22	4.24
vehicle age	-2.19	.22
shop repair	54.96	1.66
(# parts fixed)2	-1.53	.04
Dummy variables indicating repair performed:		
inlet restrictor	-.46	3.31
gas cap	5.59	2.73
Timing	9.42	1.72
air intake system	20.48	2.05
vacuum leaks	19.57	1.78
air/fuel mixture	14.26	1.89
idle speed	10.94	1.92
spark plug wires	23.31	2.15
spark plugs	33.96	1.94
spark plug contacts	29.84	2.29
Carburetor	87.81	1.82
oxygen sensor	83.04	2.25
throttle sensor	62.86	3.45
Temperature sensor	30.01	4.66
ambient sensor	18.96	5.88
barometric sensor	13.92	6.31
maf sensor	62.78	6.53
rpm sensor	-18.70	8.65
electronic control module	84.58	6.08
egr system	64.27	1.67
electrical problems	74.90	3.17
coolant system	52.81	3.62
positive crankcase ventilation	24.65	2.26
Evaporative emissions system	27.43	2.47
air injection system	40.69	2.35
catalytic converter	134.35	2.51

Note: The dependent variable is total repair costs. The R^2 is .2234, N=44,881.

that purport to be derived from a more or less random sample of failed vehicles or which may not have been completely repaired because of tight limits on required expenditure.[11] The first and most important is the set of assumptions used by the EPA in the RIA of the Enhanced I/M rule:

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11. Other studies that do not meet these two criteria are the "undercover car" study sponsored by the California I/M Review Committee (1994) and two studies conducted by oil companies that selected particularly dirty vehicles (Cebula 1994, and Lodder and Livo 1994).

Table 5. Average Repair Costs, Fuel Economy Costs, and Emission Reductions for Vehicles Repaired in the Arizona Program 1995-96

Mean per-vehicle values of:	All Failing Vehicles (N=82,786)	Failed Vehicles Repaired to Meet the Cutpoints (N=64,403)
Complete repair costs ($)[a]	123.02	119.53
Fuel economy costs ($)[b]	-34.83	-46.16
Total costs ($)[c]	88.19	73.36
Emission-rate improvements (g/mile)		
HC	0.82	0.98
CO	12.35	14.92
NOx	0.92	1.12

a. Complete repair costs include imputed costs for rounds with repairs reported but costs given as zero. Both non-tampering and tampering repairs are included.
b. The fuel economy costs presented here are the present discounted value of two years' worth of costs.
c. Total costs are the sum of complete repair costs and fuel economy costs.

> The overall average repair cost for transient failures is estimated to be $120. Average repair costs for pressure and purge test failures are estimated to be $38 and $70, respectively. Repairs for NOx failures are estimated to cost approximately $100 per vehicle. Data from the Hammond test program indicate that it would be very rare for one vehicle to need all three of these repair costs. (USEPA 1992, p. 84)[12]

The EPA excluded tampered vehicles from its sample and thus provided no estimate of the cost of repairing such vehicles.

Second, the 1994 California Pilot Project in Sacramento, California repaired about 200 vehicles at an average cost of $215, with no further breakdown by type of repair (see Patel et al., 1996). Here, too, tamper-related repairs were not conducted.

Table 5 summarizes the average costs and emissions reductions associated with Arizona's current program. For each vehicle in the sample, we add up the complete costs of all of its rounds of repairs, and calculate the change in emission rates for each vehicle from its initial to its last observed test. We also derive estimates of the costs (which on average turn out to be negative) associated with repair-induced changes in fuel economy. To that end, we assume that gasoline costs $1.00 per gallon, and that each vehicle travels a number of miles each year equal to the age-specific annual mileage rates used in EPA's emissions inventory model.[13] We also assume that repairs last for two years (the time between required I/M tests in the Arizona program),[14] which implies that fuel economy benefits (as

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12. It is not clear how these estimates were generated. We obtained EPA's repair dataset but were unable to reproduce their results with respect either to costs or emission reductions. Indeed we found that some vehicles were not repaired to the specified cutpoints, but additional repairs were nonetheless projected to achieve compliance. For further details see Harrington, McConnell, and Cannon (1998).

13. The MOBILE Model. These same annual mileage assumptions by vehicle model year are also used to calculate total tons of pollution in the costs and simulation results below.

14. There is little evidence on the duration of emission repairs. Using a dataset of Arizona vehicles that had returned after two years for the renewal of their I/M certification, Wenzel (1998) found that vehicles requiring repair during the first I/M renewal period were more likely to fail the first emission test during the second period, compared to a vehicle of the same vintage that passed the test during the first period. In other words, the duration of some emission repairs for some, but not all, vehicles is less than two years. Thus an average of two years is not an unreasonable assumption.

well as emission reductions) persist that long. Thus, the fuel economy costs presented here are the present discounted value of two years' worth of changes; a discount rate of 5 percent is applied to second-year costs. Finally, means of all these quantities are calculated over the 82,786 failing (and 64,403 failing and subsequently repaired) vehicles in 17 months of test data.

The average cost of repairing vehicles in Arizona seems to be almost the same as the EPA estimate for tailpipe repairs. This similarity, however, is somewhat misleading. While the EPA study, like the California Pilot Project, did not include tampering repairs, the data from Arizona include many repairs of vehicles that exceeded no tailpipe cutpoints but failed the test, we presume, because of tampering or evaporative emissions. As Appendix A makes clear, the Arizona data suggest that such repairs are much cheaper than repairs of vehicles that failed the transient tailpipe test (IM240). Thus, we need to exclude such rounds of repair from our estimation of mean repair costs in order to have a number that is comparable to the EPA estimate for tailpipe repair.

That exclusion gives us transient-test repair costs per vehicle equal, on average, of about $151. This is quite a bit higher than the estimate put forth by EPA, especially considering that the "cutpoints" to which the vehicles were being repaired were more lenient in Arizona than in the EPA labs. We note that EPA used only 266 vehicles in its repair study; that may simply have been too small a sample to yield an accurate prediction of the costs that obtain in a working I/M program. Our estimate is, on the other hand, a bit lower than the average cost of repair found in the California Pilot Project of over $200. This may be, at least in part, because the cutpoints to which vehicles were to be repaired were substantially tighter in the Pilot Project than in Arizona.[15]

Costs may be subject to variability due to differences in mechanic ability, pricing patterns, and repair strategy. To examine this issue, we were able to link about half of the failing vehicles in our sample to the repair shops that performed the repairs. Restricting the analysis to only those shops for which there are at least 50 observations of vehicle emissions repairs, we find that the performance of repair shops is quite variable, with the rate of successful first-time repair varying between 39 and 91 percent. The average repair cost across shops varied between $56 and $291 per vehicle.[16]

The estimates of emission-rate improvements in Arizona are much smaller than both the emission reductions obtained by mechanics in EPA's laboratory studies and the reductions assumed by EPA in the RIA. The vehicles in EPA's repair data set showed average improvements of 1.9 g/mi for HC and 32 g/mi for CO (NOx was not observed in these studies), compared to 0.82 g/mi for HC and 12.35 for CO in Arizona. The differences in average emission reductions arise in part because the cutpoints were set at much more lenient levels in Arizona's program than those used in the EPA labs. EPA's assumption that emission reductions would be larger than we observed in the Arizona program would also help explain why EPA's estimates of fuel economy improvements were larger than ours (12.6 percent vs. 3.5 percent). Compared to the Arizona results, in other words, EPA had predicted lower repair costs for a more stringent program.

Several caveats about these estimated emissions reductions are in order. First, both the EPA lab results, which are based on emissions estimates using the Federal Test Procedure (FTP) and the IM240 test (which is a segment of the FTP) results from Arizona, may not accurately capture actual emissions or emissions changes because they are based on a driving cycle that differs from real-world driving conditions. Recent evidence shows that typical urban driving includes high acceleration rates not found in either the FTP or IM240 tests. Second, because the IM240 test, like any test,

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15. See Harrington, McConnell and Cannon (1998), Appendix B for the comparison of the California Pilot Project cutpoints to the Arizona cutpoints.

16. The correlation between repair cost and retest success is 0.46. There were about 40 repair facilities with at data for at least 50 repaired vehicles.

Table 6. Expected Costs of Repair in Arizona I/M For an I/M Cycle

Model Year	(1) Probability that vehicle will fail initial test (percent)	(2) Average costs of repair for failing vehicles imputed costs ($/vehicle)[a]	(3) Average costs of repair for failing vehicles Reported costs only ($/vehicle)	(4) Expected costs of repair for failing vehicles ($/vehicle) (1)x(2)	(5) Average income of owner (in national sample)
1981	45.4	132	91	60	$38,400
1982	41.2	140	96	58	35,500
1983	38.5	148	103	57	39,000
1984	35.9	153	104	55	40,800
1985	28.8	155	106	45	41,700
1986	19.8	145	99	29	44,100
1987	14.2	142	96	20	46,000
1988	12.2	150	101	18	47,300
1989	8.1	144	99	12	48,000
1990	5.6	134	90	7	51,200
1991	6.8	152	95	10	52,000
1992	4.4	138	79	6	53,600
1993	2.6	130	63	3	54,900
1994	1.2	80	38	1	57,400
1995	1.0	62	24	.59	61,000

Sources: Columns 1, 2, 3, 4, 5: Arizona Enhanced I/M Data Base, 1995–1996
Column 6: 1995 Nationwide Personal Transportation Survey
Note:
a. Includes both the expenditures reported by motorists and our imputations of costs when repairs are made but costs are not reported. For late-model vehicles these imputations include warranty repairs and therefore overstate the burden on the motorist.

is subject to error, some motorists are aware that even if they fail an initial test, they may pass simply by testing the vehicle again without making any repairs. Data from the Arizona program shows that 10% of vehicles were retested within two hours of the initial test, and about half of these reported no repair costs. To the extent immediate retesting is occurring, changes in emissions from test lane data will overstate emission reductions from the program.

Expected Repair Costs by Model Year

Average repair costs do not vary a great deal by vehicle model year as shown in Table 6 (column 3). We show both repair cost estimates with imputed costs included and also the raw reported repair costs. We found that even the distributions of repair costs within each model year are similar, with about 20 percent of most model year vehicles having repair costs over $200, except for the two most recent model years tested. Column 4 of Table 6 shows the expected costs of repair by model year, which is the probability of failing (column 2) times the average cost for vehicles that do fail (column 3). The expected costs show substantial

variation across model years, primarily because of the difference in failure rates. While the expected costs are not terribly high, they are much higher for older vehicles, and these are vehicles more likely to be held by low income households. Column 6 provides confirmation of this, showing average income of households who own each model year from household and vehicle data from the National Personal Transportation Survey (1995).

Characteristics of Successfully Repaired Vehicles

To estimate total repair expenditures required to bring all failed vehicles in Arizona into compliance with the cutpoints, it is tempting simply to multiply the mean repair costs from Table 5, $119.53 per vehicle, by the number of failed vehicles. However, the estimates in Table 5 include only those vehicles that were repaired to pass the I/M test, and there is no guarantee that the vehicles we do observe being successfully repaired to pass are just like the ones we do not. If the two groups of cars are qualitatively different from one another, then cost estimates derived for the former group may not be applicable to the latter.

Table 5 provides some hints that the two groups may be qualitatively different. Vehicles we observe passing a retest have their emission rates reduced more by repair than those that have not attained compliance by the end of our sampling period, yet these passing vehicles seem to have less money spent on their repair. In order to explore the distinctions between the two types of vehicles more carefully, we conduct an empirical exploration of whether observable vehicle characteristics seem to influence the likelihood that a failed vehicle passes the test by the end of our sampling period.

To that end, we estimate a probit equation, in which the dummy dependent variable Z equals 1 if and only if the vehicle passes the test.[17] The probit model posits a latent variable, which is a score representing the tendency of the vehicle to be repaired successfully. γ is specified as a linear combination of the effects of observable characteristics W, plus a disturbance term reflecting the influence of the unobserved variables:

$$Z^* = \gamma W + \mu \tag{1}$$

where μ is distributed standard normal. The variable Z is observed if and only if $Z^* > 0$.

We model the likelihood of successful repair as a function of the independent variables listed in Table 7. The date on which the vehicle's initial test occurred is coded such that zero corresponds to January 1, 1960, and each subsequent day increments the variable by one unit. There are three vehicle-type categories into which a given vehicle may fall; dummy variables are included for light- and medium-duty trucks, with ordinary cars as the default category. As in Table 1, there are eight combinations of pollutant failures that a vehicle might have suffered in its initial test (here, the default category is "none", with dummy variables included for the others.) We include three variables to capture how badly a vehicle initially fails the test for a given pollutant. For each pollutant a vehicle fails, these measure the gaps between the vehicle's initial pollution rates and the standards it must meet for those rates. Finally, we control for the age of the vehicle (in years) at its initial test, and the duration of that initial test in seconds (this ranges from 31 to 240).

The results from estimation of the probit equation (Table 7) are consistent with the various reasons we might expect some vehicles to have difficulty passing the test. (Note that a positive coefficient for a variable in Table 7 indicates that an increase in the value of the explanatory variable makes the vehicle more likely to pass the test.) If the initial test was too recent, an owner may simply be less likely to have had time to successfully repair and retest the vehicle during the data-collection period. Vehicles that failed only the evaporative or tampering portions of the test are easier to diagnose and bring up to code than vehicles that exceed the cutpoint for at least one pollutant. Furthermore, it seems that (at least for HC and NOx) vehicles that fail by a wide margin are more likely to have final observed tests that are failures, either because the repairs are more time-consuming (and not complete by the end of our sampling period), or because the costs of bringing such a

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17. See Greene (1990) for a detailed explanation of estimating the probit.

Table 7. Results from Probit Analysis of Successful Repair[a,b]

Explanatory Variable	Coefficient	Standard Error	Significance[c]
Date of initial test	-.00010	.000043	*
Light truck	.036	.017	*
Medium-duty truck	.23	.027	*
Fail HC only	-.48	.028	*
Fail CO only	-.26	.035	*
Fail NOx only	-.11	.029	*
Fail HC and CO only	-.54	.032	*
Fail CO and NOx only	-.29	.11	*
Fail HC and NOx only	-.51	.035	*
Fail HC, CO, and NOx	-.63	.056	*
(HC g/m, initial – cutpoint)*(failed HC)	-.12	.0057	*
(CO g/m, initial – cutpoint)*(failed CO)	-.00062	.00035	
(NOx g/m, initial – cutpoint)*(failed NOx)	-.15	.0073	*
Age at initial test	-.067	.0023	*
Length of initial test (seconds)	-.014	.00011	*
Constant	5.1	.56	*

a. The dependent variable = 1 if vehicle is observed to be repaired to pass.
b. There were 82,786 observations, and the log-likelihood value is 25,833.849
c. Asterisk indicates significantly different from zero at the 5% level.

vehicle into compliance is high enough to induce the owner to drive illegally, scrap the car, or sell it out of the area. Finally, older cars are more likely to linger without being fixed; this may reflect the fact that older cars are better candidates for scrap anyway, and thus are more commonly pushed into the junkyard by impending IM240 repairs.

Thus, our sample of successfully repaired vehicles is not a random subsample of all the vehicles that failed the Arizona I/M test. If one wants to apply cost estimates from that subsample to a broader group of vehicles in need of emission-related repair, then steps need to be taken to correct the estimated means for sample-selection bias.[18]

Emission Reduction and Cost under Different Cutpoints

An important issue for the future of I/M programs is whether the cutpoints used in the emissions test should be weakened or tightened. Tighter cutpoints increase emission reductions, but do so at a cost both in terms of increased repair costs and inconvenience costs associated with multiple repairs. Here we try to shed light on how changing the emission-rate cutpoints in Arizona would have influenced repair-related costs and associated emission-rate reductions, at least for one group of vehicles.

Cars from the 1990 and 1991 model years were manufactured to meet the same engine-certification emission standards, and use similar technologies to accomplish their pollution-control goals (EEA, 1997). However, the cutpoints in Arizona were much stricter for the 1991 model year than for the 1990 model year as Table 8 shows. It is, therefore, not surprising that the failure rate on initial tests is lower for the 1990 cars than the 1991 cars, even though failure rates usually rise as vehicles age (see Table 1 for failure rates by model year).

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18. See Greene (1990) pp. 740-747 for details of Heckman's well-known two-step estimator for correcting sample-selection bias.

Table 8. Emission-Rate Cutpoints and Initial-Test Failure Rates for Passenger Cars in Arizona I/M, Model Years 1990 and 1991

Model Year	Cutpoints (grams/mile)			Number of Failures per 100 Initial Tests
	HC	CO	NOx	
1990	2.0	30	3.0	5.55
1991	1.2	20	2.5	6.82
Ratio of 1991 to 1990 values	.60	.67	.83	1.23

Table 9. How More Stringent Standards Affect Costs and Emission Reductions

Cutpoints Imposed	No. of vehicles repaired	Total Costs ($1000)			Emission Reductions (tons over two years)[a]		
		Repair	Fuel Economy[a]	Repair & Fuel Economy	HC	CO	NOx
1991 Cutpoints	1872	295	-57	238	29.43	421.8	38.82
1990 Cutpoints	1092	185	-39	146	20.61	325.9	27.84
Percent change associated with tightening the cutpoint	71%	60%	46%	63%	43%	29%	39%

a. We assume that repairs and the associated fuel economy benefits last two years, and that the discount rate is 5 percent. Thus, reported reductions are $1.95 \times$ one-year's-worth of emission reductions. The second year of fuel economy benefits is discounted as well.

We examine the importance of cutpoints by comparing the actual emission reductions and costs for 1991 vehicles with a simple simulation of what the results would have been if the vehicles had been subject to 1990 cutpoints. In this simulation we assume the vehicle is only repaired if it has emissions exceeding the 1990 cutpoints. This analysis is performed only on the subset of 1991 cars that initially failed the 1991 cutpoints for at least one of the tailpipe pollutants.[19] We assume this group of vehicles is subject to the looser 1990 cutpoints and determine the costs and emissions reductions from repair for just the vehicles that would have failed those cutpoints.

Table 9 shows the results of this analysis. The looser 1990 cutpoints mean that fewer vehicles will fail and get repaired: 1,092, compared to 1,872 under the tighter cutpoints. Repair costs (net of fuel economy benefits) are about 60 percent higher when the tighter cutpoints are applied, compared to an increase in emission reductions of 30 to 40 percent. These results fit with expectations that the costs of reducing emissions will rise quickly as I/M programs try to attain marginal improvements in emissions with stricter cutpoints. This analysis is only suggestive because it deals with just one model year and simulated results instead of actual cutpoint changes (1991 model year vehicles were only repaired to one set of cutpoints and we do not know if the same repairs would have been made if the cutpoints were different). As I/M programs in the future begin to tighten standards to which vehicles must comply, it will be important to assess the costs and effectiveness of such changes.

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19. We exclude all of the vehicles that were shown as failing but do not have emissions that exceed any of the cutpoints. We also exclude trucks from this analysis.

Table 10. Summary Statistics on Repair Costs

	Statistic	Complete repair costs[a,b]	Raw repair costs[a,c]
Summary statistics	Mean	123.02	75.19
	Standard Deviation	161.60	147.28
	Minimum	0.00	0.00
	Maximum	3708.00	3609.00
Correlation coefficients of costs with improvements in:	ΔHC (g/m)	0.14	0.11
	ΔCO (g/m)	0.12	0.09
	ΔNOx (g/m)	0.10	0.07
	ΔMPG	0.03	0.03

Note: N = 82,786.

a. Costs are summed across all of each vehicle's rounds of repair.

b. Complete repair costs include imputed costs for rounds with repairs reported but costs given as zero.

c. Raw repair costs are strictly as reported.

Table 11. Costs and Total Pollution Reduction by Vehicle Type

|	Cars	Light trucks 1	Light trucks 2
Number of vehicles	57,559	18,691	6,536
Mean repair costs per vehicle[a]	$129	$110	$109
Mean Tons emissions[b] reduced per vehicle			
HC	.006	.009	.013
CO	.097	.115	.162
NOx	.007	.010	.012

a Costs include imputed costs for rounds with repairs reported but costs given as zero.

b Repairs are assumed to last two years.

Cost-Effective Repair

Table 2 showed great variation in the emission-rate and fuel-economy changes induced by vehicle repair. As Table 10 shows, no matter whether raw or complete repair-cost data are considered, there is tremendous heterogeneity in the amount of money motorists spend trying to repair their vehicles to pass the I/M test. In addition, repair expenditures are only very weakly correlated with improvements in emission rates and fuel economy. These features of the data raise the possibility that some repairs are simply more cost-effective than others. To evaluate the overall cost-effectiveness of the Arizona I/M program, we would have to consider all of the costs, not just the repair costs (see Harrington, McConnell and Ando, 1999 for such an analysis).

Table 11 provides an example of one dimension along which cost-effectiveness seems to vary in our data. Repair costs are lower and emission reductions are greater for all three pollutants for trucks compared with cars. For example, by aggregating costs and emission reductions by vehicle type, we find that almost 43 percent of the emission reductions of HC and 39% of NOx reductions come from lighttruck repair, even though lighttruck owners incur only about 27 percent of all repair expenditures. Further, repairs appear to be most cost-effective for the heavier class of trucks, although they make up only about one quarter of all trucks in the repair dataset. It would appear

Figure 2
Cost- Effective Emission Reduction from Re[
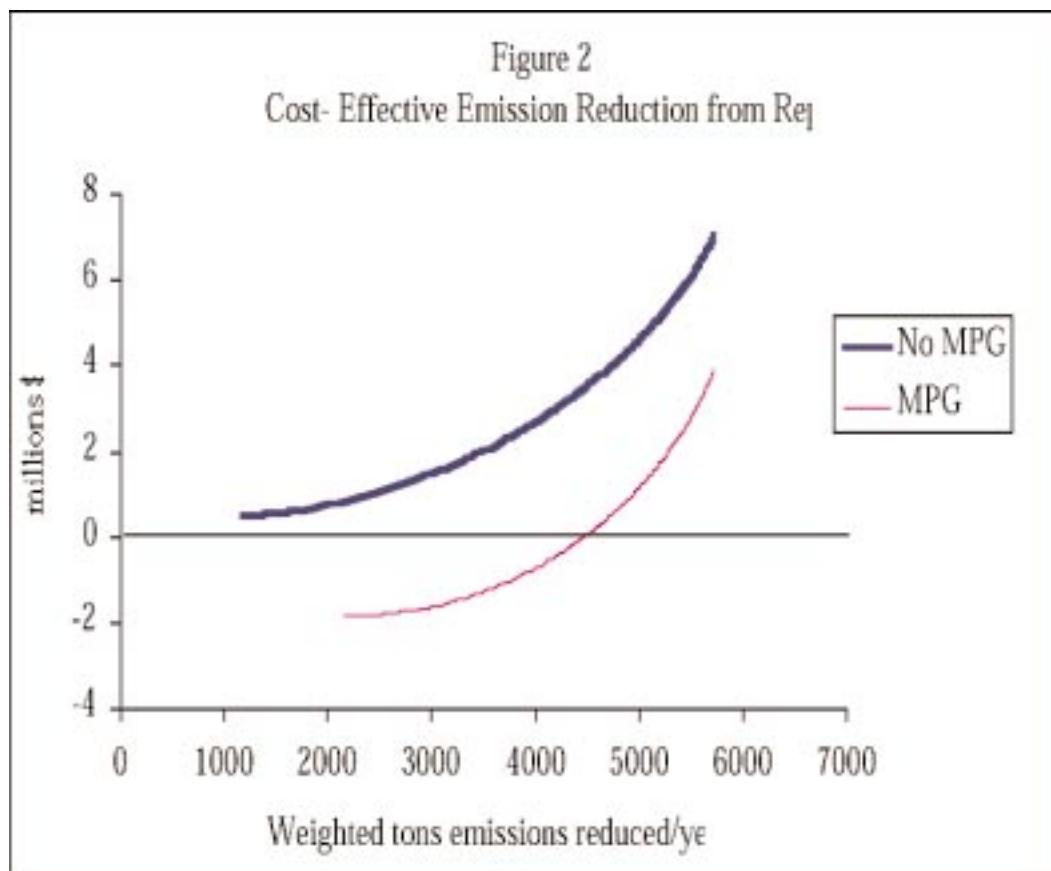
from these results that future attempts to further reduce vehicle emissions could most cost-effec-
tively come from tightening light truck cutpoints.[20]

Figure 2 represents an effort to illustrate more completely the potential importance of paying
attention to variation in cost-effectiveness of repairs. We first rank the repairs that actually occurred
in the Arizona I/M program according to their cost-effectiveness. We then construct the graphs in
Figure 1 by assuming that repairs are performed in decreasing order of cost-effectiveness. We then
track the cumulative total costs and emission reductions that occur as a result of the repair as those
repairs get less and less cost-effective. Emission reductions, measured along the horizontal axis are
measured as a weighted average of the annual reductions in tons of HC, CO and NOx. The weights
are taken from the literature on the relative damage from the three pollutants[21]; other weights yield
very similar results. In the top line, the monetary values of improvements in fuel economy associ-
ated with repairs are not included in the analysis; in the lower line, those values are included in total
costs.

The far right end of both lines shows the total costs and total amount of emission reductions that
actually occurred during the 1995 to early 1996 period as a result of repair in the Arizona I/M pro-
gram. The rest of each line shows costs and emission reductions if only the most cost-effective

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20. The average of the repaired trucks is slightly newer than for cars, but this does not appear to account for the cost dif-
ferences. There is not a great deal of difference in cost of repair between new and older vehicles. See Harrington et al
(1999) for more detail.

21. The weights used for Figure 2 are 1.0 for HC, 0.1 for CO and 2.5 for NOx. These are based on damage estimates
from Small and Kazimi, 1995.

repairs were done to achieve a given level of emissions reductions. The figure makes clear that a large share of the emission reductions from the I/M program could potentially be achieved at a relatively small fraction of the cost.[22] For example, if fuel economy benefits are not accounted for (the top line in Figure 2), about 5,000 weighted tons of reduction can be achieved for approximately 4.6 million dollars. This is roughly 87 percent of the emissions reductions under the current program at 65 percent of the cost. The implication is that I/M policy could profitably be redesigned to promote cost-effective repairs and avoid mandating the completion of repairs that accomplish relatively little emission reduction per dollar spent. How this can be done in practice will be a challenge for policy-makers. Simply changing cutpoints in the test is unlikely to have much impact on cost-effectiveness of repairs. Some type of fee on the emissions rate of each car would have the desired result if repair technicians are relatively good at predicting emission reductions from repair and the associated costs. When confronted with paying a fee or getting the vehicle repaired, motorists will undertake repairs only when the expected costs of repair are less than the fee; this will ensure that only cost-effective repairs are made. There are technical and political barriers to fees, however, which must be overcome before they can be used extensively for reducing emissions from motor vehicles (Ando, Harrington and McConnell, 1998).

4. CONCLUSIONS

We have examined the cost and effectiveness of emission repair in the Arizona Enhanced I/M program. We find that the average cost of repairs is $123 per repaired vehicle. When we exclude vehicles for which any tamper-related repairs are done, however, we find an average repair cost of $199. On the basis of comparative before-and-after emission tests, the average emission reduction resulting from these repairs is 0.82 g/mi for HC, 12.35 g/mi for CO and 0.92 g/mi for NOx. When these emission reductions are averaged over the entire fleet, they amount to a 14 percent emission rate reduction for HC and CO and an 8 percent emission reduction for NOx. These emission reductions are somewhat smaller than EPA's original estimates, and the costs are somewhat higher. The cutpoints used in Arizona were much less stringent than those used in the EPA estimate, so the discrepancy in emission reductions is smaller than it looks, but the discrepancy in costs is larger.

The average cost and emission reductions tell only a part of the story for several reasons. First, there are large differences in repair costs across individual vehicles. Costs for individual cars range from large negative numbers (the fuel economy benefits more than outweigh the costs of repair) to positive net costs of over $400. The higher-cost repairs are more likely to fall on low income vehicle owners whose vehicles are more likely to have higher failure rates.

Second, we find that a surprisingly large fraction of the vehicles in our sample—about 22 percent of those failing their initial test—do not show a passing test record. These vehicles may be sold outside the region, or scrapped, or some may still be in the process of completing the I/M cycle. However, there are some vehicles that go through a number of rounds of repair without passing the test, indicating that repairing to pass may be difficult for some vehicles. In our statistical analysis we find that non-passing vehicles are more likely to be cars than trucks (cars face tighter cutpoints than trucks), to be older, and to fail the test for multiple pollutants. This analysis provides more evidence that at least some vehicles may be difficult to repair and that is why they are not passing the I/M

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22. The potential cost savings from cost-effective repair could be exaggerated in Figure 2 if there are measurement errors in either the emissions reductions or the cost estimates. The most cost-effective repairs could be those with the lowest cost and the greatest emission reduction, both of which could be measured with error.

test. More work needs to be done to track the non-passing vehicles to determine their impact on I/M effectiveness.

Our results all suggest that it is critical to consider costs and cost-effectiveness in designing I/M policy. Because there is great variation in costs and effectiveness of repair across vehicles, costs could be reduced if there were better targeting of which vehicles get tested and which repaired. Clearly, relatively new vehicles are less likely to fail so they should be tested less frequently, and older vehicles that are more likely to fail can be tested more frequently. California's high-emitter profiling policy attempts to do exactly that—to target those vehicles for more frequent testing that are most likely to have high emissions. EPA's Clean Screen program allows states to exempt certain model years from testing (EPA, 1998). On the other hand, uniform policies such as those that tighten cutpoints across the board are unlikely to be cost-effective, both because of the differential impact on vehicles and because there is evidence that average costs rise more than in proportion to emissions reductions with stricter I/M cutpoints.

Finally, we find encouraging evidence that some of the data problems inherent in collecting repair cost estimates in an ongoing I/M program may be manageable. We provide a way of statistically estimating repair costs when costs are not reported but the repairs performed are known. The costs estimated using our method are consistent with the evidence we do have of reported repair costs. Information about the costs of repair are critical for assessing cost-effective improvements to I/M programs and for exploring more cost-effective alternative ways of reducing vehicle emissions.

APPENDIX A

Average Costs by Round of Repair

This table shows the mean costs, both reported and complete, for different types of repair rounds. Each round of repair in that data is categorized in three ways: the vehicle failed the previous test for at least one of the three major tailpipe pollutants, or did not; some parts were reported as having been repaired, or none were; and non-zero repair costs were reported, or not. The rounds of repair for which the second column in Table 6 is zero are of vehicles which fail the I/M test even though none of the pollutant rates exceed the cutpoints. We assume these failures are due to tampering or evaporative test failure.

Table A-1

Vehicle fails tailpipe test (no=0, yes=1)	Non-zero repair costs reported (no=0, yes=1)	Specific repairs reported (no=0, yes=1)	# of Rounds	Mean reported costs (no imputed costs)	Mean complete costs (using imputed costs for reported costs of $0)
0	0	0	5,543	$0	$0
		1	5,952	$0	$48
	1	0	13	$43	$43
		1	5,703	$38	$38
1	0	0	25,479	$0	$0
		1	27,977	$0	$131
	1	0	739	$109	$109
		1	39,178	$151	$151

APPENDIX B.

Arizona Inspection and Maintenance Program Cutpoints (grams per mile)

	HC	CO	NOx
LDV, 1981-82	2.0	60.0	3.0
LDV, 1983-90	2.0	30.0	3.0
LDV, 1991+	1.2	20.0	2.5
LDT1 and LDT2, 1979-83	7.5	100.0	7.0
LDT1 and LDT2, 1984-87	3.2	80.0	7.0
LDT1 and LDT2, 1988-90	3.2	80.0	3.5
LDT1 and LDT2, 1991+	2.4	60.0	3.0

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