On-Road Evaluation of Inspection/Maintenance Effectiveness

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This study presents an evaluation of inspection and maintenance (I/M) programs in terms of their effect on motor vehicle carbon monoxide (CO) and hydrocarbon (HC) exhaust emissions as measured on-road by remote sensing technology. The results show that the performance of past I/M programs at several monitored locations has been less effective than predicted by the U.S. Environmental Protection Agency. The emissions from I/M and non-I/M vehicles measured in Tucson, AZ, and in rural Colorado show no statistically significant difference. An apparent I/M effect observed in El Paso, TX, and in Denver, CO, is smaller than predicted. Comparisons of CO emissions by vehicle age for several years at the same locations in Chicago and Denver show no evidence that the Chicago centralized I/M program was more effective than the Denver decentralized I/M program.

Introduction

Legislation has been enacted by the U.S. Government to require further reduction of mobile source emissions in order to improve ambient air quality (*1*). Regulated exhaust emissions include carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter. Vehicle emissions inspection and maintenance (I/M) programs have played a central role in mobile source emissions reduction strategies. Most populous regions of the country have been required to implement I/M programs with the intent of on-road vehicle emissions reduction through the identification and repair of vehicles that do not meet exhaust emission standards. Through 1994, the I/M test was typically a measurement of tail pipe emissions at idle and at 2500 rpm with no load on the engine. Inspections were performed in either centralized or decentralized stations, annually or biennially. The U.S. Environmental Protection Agency (EPA) claimed that states which had an I/M program could take a computer-modeled credit for considerable reductions in on-road vehicle emissions (*2*). The centralized I/M programs were generally predicted to be more effective than the decentralized programs (*3*). However, the basis for projecting that I/M programs benefit ambient air quality has become increasingly uncertain (*4*).

These programs have been criticized for several reasons: (i) a test of the operation of unloaded engines is not representative of on-road emissions (*5*); (ii) even though the no-load test used with a high cut point may be good at identifying high emitters, with the same cut point it becomes a poor tool for verification of proper repair (*6*); (iii) the TECH/MOBILE models, on which I/M program benefit estimates are based, use limited statistical analysis and significantly underestimate urban on-road emissions (*7*); (iv) cheating has taken place either by the tester, vehicle owner, or both, including vehicle owners tampering with their vehicles before and after scheduled testing (*8, 9*); and (v) the test results have shown poor repeatability, thus allowing a vehicle tested several times to eventually pass without any repair (*10–13*).

In a multi-factorial analysis of I/M effectiveness, Scherrer and Kittelson concluded that the centralized emissions testing system adopted in Minnesota in 1991 had a negligible impact on urban ambient CO (*14*), even though at least 80% of urban ambient CO is from mobile sources. It has been reported that the reduction of emissions by a centralized I/M program in Tucson (*15*) and a decentralized I/M program in Los Angeles (*16*) were far less than the U.S. EPA's computer model predicted. Lawson (*17, 18*) showed that the various centralized, decentralized, biennial, and "enhanced" I/M programs investigated in California and other locations have done little to reduce in-use emissions from the motor vehicle fleet. One study in Denver (*19*) showed that the age-weighted non-I/M vehicle fleet had a significantly 13% higher CO emissions than the age-weighted I/M vehicle fleet based on the calculation of average emissions of the age-weighted fleets. However, a statistical analysis on the HC data from the same data base showed that there was no significant difference between the HC emissions from I/M and non-I/M vehicles (*20*). An analysis of EPA's survey data for ambient CO reductions over the decade from 1983 to 1992 in different regions by Manhard (*21*) shows that the overall mean CO reduction for 19 centralized I/M regions (36%) was not significantly different from the mean CO reduction for 47 decentralized I/M regions (33%). As a result of these studies, several states intend to stop implementation of their I/M programs and seek other alternatives (*22*).

This paper presents simultaneous comparisons of on-road emissions by model year at locations within I/M program regions, from vehicles registered within and without the I/M program areas in several U.S. cities.

Experimental Section

Instrumentation. Development of remote sensing technology by the University of Denver with the capability to accurately measure CO and HC exhaust emissions of many thousands of vehicles per day provides a practical approach to routinely characterize on-road vehicle emissions. The system has been used to measure the emissions of more than 1 million vehicles at over 30 locations around the world. The details of the instrument system are described elsewhere (*23, 24*).

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TABLE 1

Comparison of Emissions from I/M and non-I/M Fleets Measured in Tucson, El Paso, and Ute Pass

location (date)	fleet	no. of vehicles	mean % CO[a]	mean % HC[a]	av model year
Tucson (Feb 1994)	centralized-I/M	10 529	1.07	0.078	84.7
	non-I/M	304	0.81	0.075	86.7
			(1.00)	(0.086)	(84.7)
El Paso (Mar 1993)	decentralized-I/M	13 312	1.19	0.071	86.2
	non-I/M	797	1.41	0.083	85.4
			(1.31)	(0.078)	(86.2)
Ute Pass (Jan 1989)	decentralized-I/M	1 071	1.98	NA[b]	82.4
	non-I/M	3 240	2.10	NA	82.3
			(2.09)		(82.4)

[a] The % CO and % HC values in parentheses are the non-I/M fleet average after the vehicle age distribution has been adjusted to match the corresponding I/M fleet age distribution. [b] NA, not applicable.

The technique has been validated by means of blind comparisons with vehicles of known emissions, which show that remote sensing measurements accurately reflect the instantaneous vehicle exhaust emissions (*25, 26*). Studies by the California Air Resources Board (CARB) show that the remote sensing CO readings are correct within ±5% of the values reported by an on-board gas analyzer and within ±15% for HC (*27*).

Sample Collection and Treatment. The data sets used for the present study were collected in Tucson, AZ; El Paso, TX; Ute Pass, CO; Denver, CO; and Chicago, IL, by means of remote sensing. The survey sites in Tucson were selected around the intersection of Alvernon Way and 22nd Street (*28*). Several directions, approaching the intersection and leaving, were sampled on different days. The intersection was level, traffic light-controlled, and generally showed high traffic density. The traffic flow was fairly continuous at 15–30 mph. The majority of the vehicles were under either light acceleration or cruising at about 25 mph through the intersection and then accelerating. However, some vehicles under hard acceleration were also observed, especially after they passed the intersection. The measurements in El Paso, TX (*29*), were carried out at several highway on-ramps with a slight uphill grade. The vehicles were thus traveling under load but not strongly accelerating due to the heavy traffic. The speeds varied between 25 and 40 mph. The data from Ute Pass, CO (*30*), were collected at Ute Pass road (U.S. Highway 24) west of Colorado Springs and 2 mi within the boundary of El Paso County at about 7400 ft above sea level. Measured vehicles were on their way upgrade from work in Colorado Springs to their homes in western El Paso or eastern Teller County. The sampling site in Denver was set up at a tightly curved, 4% uphill grade ramp between southbound I-25 and southbound Speer Boulevard near downtown Denver. The measurements in Chicago (*31*) were carried out at the straight, uphill, traffic light-controlled on-ramp from Central Avenue to eastbound I-290 (Eisenhower Expressway). The sites and sampling time periods were chosen to minimize the probability of measuring vehicles in a cold-start driving mode.

Only those measurements with all parameters valid and proper calibrations for CO, CO_2, and HC were used as data for the analyses. However, in the case of simultaneous measurements at the same location for vehicles within and without an I/M program, calibration errors and the influence of different driving modes are irrelevant to this I/M effectiveness analysis. In these studies, the ratio of vehicles passing compared to vehicles measured with complete emissions data varied between 0.75 and 0.96. A further 20–35% did not give valid in-state license plates. These "missed" vehicles should not effect this analysis suince there is no reason why I/M or non-I/M area vehicles (after age correction) should be more or less missed by the sytem.

Results

Comparison of I/M Vehicles with Non-I/M Vehicles. Table 1 shows an analysis of three data sets comparing those vehicles registered in non-I/M zip codes to the vehicles registered in I/M-required zip codes, leaving out those zip codes that are partially in the I/M program. In Tucson, the vehicles registered to zip codes included in the Arizona centralized inspection and maintenance program had average exhaust CO and HC concentrations higher than those vehicles registered to zip codes not included in the I/M in 1994. However, the average age of the non-I/M vehicles was 2 years younger than the I/M vehicles. For the El Paso data set, the vehicles with Texas license plates (decentralized I/M required at the time) were lower emitters but about 1 year younger than the vehicles with New Mexico license plates (no I/M required at the time). There were no HC data available for the vehicles measured at Ute Pass, CO, in January 1989. The average % CO and vehicle age were similar for the vehicles registered in El Paso County (decentralized I/M required at the time) and the vehicles registered in Teller County (no I/M required at the time).

Since age differences could obscure differences in exhaust emissions, the non-I/M fleet emissions by model year were normalized to have the same vehicle distribution by model year as the corresponding I/M fleet. The average exhaust concentrations of the adjusted fleet were then calculated. The results, shown as the values within parentheses in Table 1, suggest that the I/M fleet had 9% and 5% lower average CO emissions than the equivalent age non-I/M fleet for the El Paso and Ute Pass data, respectively, while in Tucson the I/M fleet had 7% higher CO emissions than the age-corrected non-I/M fleet. For HC emissions, the I/M fleet was 9% lower emitting on average than the equivalent age non-I/M fleet in both Tucson and El Paso.

To further determine the difference between the means of the I/M and non-I/M fleets, the average emissions in each model year for each of the I/M and non-I/M fleets are calculated and plotted as shown in Figures 1–3. Non-I/M fleets in Tucson and El Paso show more scatter than the I/M fleets because of the relatively small numbers in older model years. As an experiment, a hypothesis *t*-test was performed on the Ute Pass data to determine the statistical significance of the mean difference between the I/M and

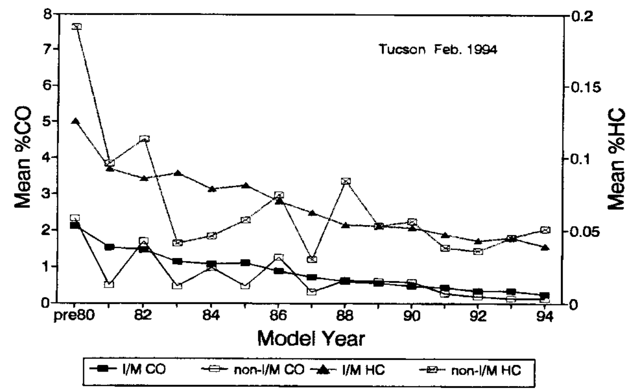

FIGURE 1. Comparison of mean % CO and mean % HC by model year for the I/M and non-I/M vehicles from Tucson data collected in February 1994. Lines connecting the points are to guide the eye only. As discussed in the text, the differences are not statistically significant.

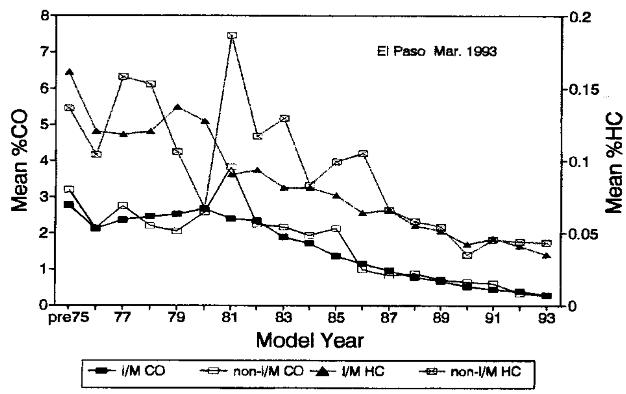

FIGURE 2. Comparison of mean % CO and mean % HC by model year for the I/M and non-I/M vehicles from El Paso data collected in March 1993. As discussed in the text, the differences are not statistically significant.

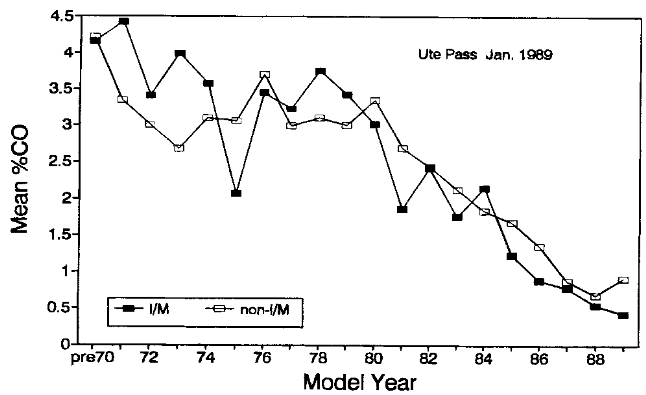

FIGURE 3. Comparison of mean % CO by model year for the I/M and non-I/M vehicles from Ute Pass data collected in January 1989. As discussed in the text, the differences are not statistically significant.

non-I/M fleets based on the paired data presented in Figure 3 by using

$$t = \frac{M_d\sqrt{n-1}}{S_d}$$

where M_d is the mean difference between the paired values of means in different model years, S_d is the standard deviation of the differences, and $(n-1)$ is the degrees of freedom. After the average emissions from older model years are aggregated to form bins of comparable size to the newer model years, analysis shows that the calculated t values for CO is 0.15 for the Ute Pass data set. Since 0.15 is less than the corresponding critical value $|t|$ at a significance level of 0.05, the hypothesis of $\text{mean}_{I/M} = \text{mean}_{non\text{-}I/M}$ could not be rejected at a significance level of 0.05 (two tailed).

TABLE 2

Comparison of Average % CO Emissions Measured in Denver and Chicago

	Denver		Chicago	
year of measurement	mean % CO (Denver)	av age	mean % CO (Chicago)	av age
1989	1.03	6.66	1.17	6.44
1990	NA[a]	NA	1.07	6.51
1991	0.80	6.47	NA	NA
1992	0.64	6.42	1.04	6.80
1994	0.53	6.53	NA	NA

[a] NA, not applicable.

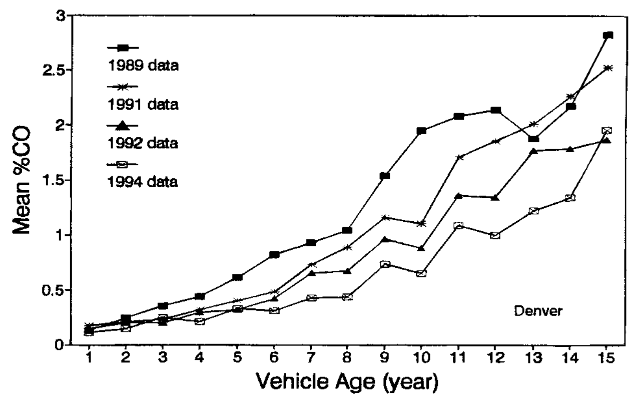

FIGURE 4. Comparison of mean % CO by vehicle age for 1989, 1991, 1992, and 1994 from Denver data, where vehicle age = (measurement year) − (model year). As discussed in the text, the differences are statistically significant.

Comparison of CO Emission Profiles at the Same Locations in Chicago and Denver Year after Year. Table 2 represents a comparison of the average % CO emissions measured at the ramp from Central Avenue to I-290 in Chicago and at the ramp from southbound I-25 to eastbound Speer Boulevard in Denver during 1989−1994. The reduction of CO emission in Denver (0.11% CO per year on average) is higher than the one in Chicago (0.04% CO per year on average), and the average CO emission for the Denver fleet in a given year is lower than the corresponding one for the Chicago fleet. However, note that the Chicago fleets were getting slightly older during the years. Also, the data from Chicago are more likely to include vehicles in power enrichment than the measurements made in Denver (*31*).

Figures 4 and 5 show the comparison of mean % CO segregated by vehicle age for the data sets collected in Denver and Chicago, respectively. One can see the similar overall nature of the resulting emissions profiles at the same location year after year regardless of the different average emission levels and reduction rates between the two locations. The average fleet emission increases smoothly as the age increases for all data sets.

The statistical significance of the mean difference between the different samples was determined by a paired

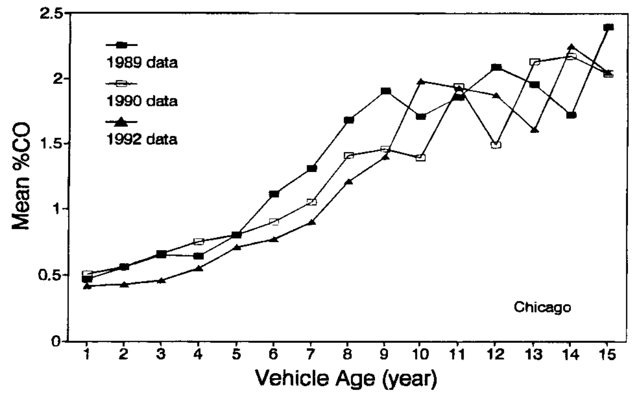

FIGURE 5. Comparison of mean % CO by vehicle age for 1989, 1990, and 1992 from Chicago data, where vehicle age = (measurement year) − (model year). As discussed in the text, the differences are not statistically significant.

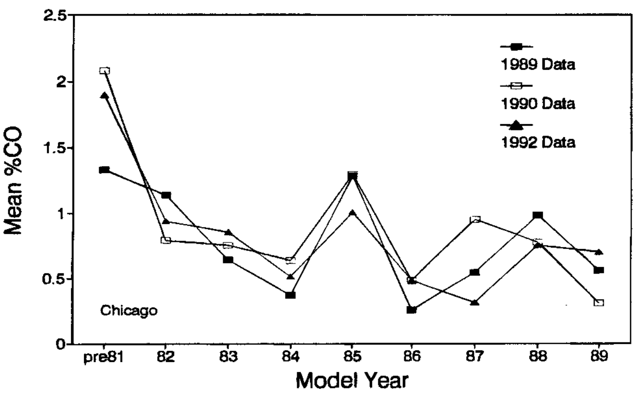

FIGURE 6. Comparison of mean % CO by vehicle model year for the same 130 vehicles measured in 1989, 1990, and 1992 at the same location in Chicago. As discussed in the text, the differences are not statistically significant.

t-test based on the mean % CO data as a function of vehicle age. The *t* values obtained are 1.51, 0.56, and 2.01 for paired samples of 1989 and 1990, 1990 and 1992, and 1989 and 1992 Chicago fleets, respectively. Compared with the critical value ($|t| = 2.14$ for $n = 15$ at significance level $\alpha = 0.05$), the three calculated values of *t* are all less than this. However, the *t* for the 1989 and 1992 data pair is very close to the $|t|$, which indicates that the mean % CO emissions have been reduced but not significantly. The calculated *t* values for paired samples collected in Denver are all greater than the critical value, thus different levels for the mean % CO emissions as a function of vehicle age for the 1989, 1991, 1992, and 1994 Denver fleets are statistically significant at $\alpha = 0.05$. It is possible that the effect observed clearly in Denver is obscured by the power enrichment effect observable in the larger intercept for 1-year-old vehicles in Chicago.

Comparison of Emissions characteristics of the Same Vehicles Year after Year. During the measurements in 1989, 1990, and 1992 in Chicago, a subset of 130 vehicles was identified by license plate and verified by VIN, which had been measured in all 3 years. This subfleet was not necessarily measured the same number of times in each of the 3 years. A comparison of the differences in mean emissions of this subfleet as a function of model year, shown in Figure 6, illustrates that the effect of aging on a small fleet of vehicles is not significant compared to the natural variability of the means of any randomly chosen small fleet. In other words, the emission level of a fleet of vehicles will increase detectably as the fleet ages only when the fleet contains a large enough number of vehicles.

Discussion

An emission difference between I/M and non-I/M vehicles can arise from either of two causes. Either the I/M program is operating in the anticipated manner to reduce emissions or vehicles with high on-road emissions, even though driving in an I/M area, are finding ways to register at a non-I/M address. This study in Tucson comparing the emissions from vehicles in regions with an I/M program and vehicles in nearby regions without an I/M program shows that the Arizona centralized I/M program is not as effective as expected. The studies in El Paso and Ute Pass illustrate the same result as in Tucson, but for decentralized I/M programs. This result confirms earlier, independent evaluations in Minneapolis (*14*), Tucson (*15*), Los Angeles (*16*), and Denver (for HC) (*20*). Although there were some differences between average emissions from I/M and non-I/M vehicles, the results of these studies disagree with the U.S. EPA computer modeling. According to Wolcott and Kahlbaum of the EPA (presented at 1990 Mobile Source Clean Air Conference in Boulder, CO), the predicted reduction for vehicle CO emissions by I/M programs in 1992 would be 35% in Arizona, 25% in El Paso, and 24% in California and Colorado. None of the studies, including the CO study in Denver (*19*), reaches the U.S. EPA modeled reductions.

As claimed by the U.S. EPA, centralized I/M programs are stricter on testing quality and the prevention of test cheating and therefore should have a greater reduction in emissions than decentralized I/M programs. Unfortunately, a comparison of the reduction of CO emissions between Chicago and Denver and a comparison of ambient CO concentration data in centralized and decentralized I/M regions show no evidence to support the claim. Chicago and Denver are comparable because of the similar metropolitan status and similar average fleet ages. However, the I/M programs implemented in the two locations were different. The I/M program in Chicago was annual and centralized before 1990 and then became biennial for new vehicles. The I/M program in Denver was annual and decentralized. If the observed effect in Denver is attributed to the decentralized I/M program, then the centralized I/M program in Chicago is not doing as well as the EPA predicted. The same comparison was applied to 1989 and 1991 data sets collected at southbound Long Beach Boulevard one block north of the junction with Norton in Lynwood, Los Angeles (*16*). The result is the same as in Chicago, but the average fleet age in Los Angeles was 2.5 years older than in Chicago, and the I/M program in Los Angeles was decentralized and biennial. Data from the two most recent EPA tampering surveys (*32, 33*), which are publicly available, reveal that there is little if any difference in the percent of tampered vehicles on the road in regions with centralized, decentralized, or no I/M program. It is clear that I/M programs, regardless of whether centralized or decentralized, annual or biennial, have very limited impact toward reducing tampering from the in-use fleet (*34*).

The comparison of CO emissions from the same 130 vehicles measured year after year in Chicago shows that the differences of the mean % CO for each model year in all 3 years fluctuate little except for the pre-1981 vehicles. Since these are the same vehicles, most with the same owners, measured each year, MOBILE models would predict uniform year to year deterioration. However, the observation reflects that the prediction of emission deterioration with age from I/M programs is rather poor because the model calculations have not been compared to on-road vehicle emission data. It is apparent that the model year to model year differences in maintenance status of the gross polluters is a much larger effect than the year to year deterioration for this small set of vehicles. Of the 130 vehicles, only two changed ownership during the years. Both vehicles increased emissions dramatically after their change in ownership. A vehicle that is up for sale has lost its value to its owner who, therefore, may not pay proper attention to its maintenance. In contrast, owners who keep their vehicles for several years may be more prone to good maintenance than the average, accounting for their small changes in emission level.

Inherently, emissions measurement from in-use vehicles is a more complete and accurate source of information than computer modeling for evaluating I/M effectiveness. Besides remote sensing, random roadside pullover surveys have also been used to measure tail-pipe emissions and vehicle tampering (*35, 36*). It has been reported that emissions measured in voluntary random roadside surveys are generally higher than measurements on the same vehicle during a scheduled I/M test (*37*). However, these random roadside surveys are not truly random if significant fractions of motorists pulled over are allowed voluntarily to leave. For example, about 30% of the vehicles pulled over refused the test for one reason or another in a 5-day survey during July 15−19, 1991, in various northern California locations. Remote sensing measurements revealed that the average on-road CO and HC emissions of those vehicles that refused inspection were more than double those of the vehicles that volunteered for inspection (*16*). Thus, the results from the roadside surveys may be biased low because the small fraction of high-emitting vehicles is under-represented. Using biased information could significantly underpredict overall on-road fleet emissions or artificially overpredict I/M effectiveness.

The U.S. EPA has proposed an enhanced I/M program that would require an IM240 dynamometer test under varying engine loads for 240 s and would test NO_x and evaporative emission system function. Ironically, the IM240 is derived from Federal Urban Dynamometer Driving Schedule (FTP), which both the EPA and CARB have stated does not represent real-world driving and emission patterns (*38, 39*). Moreover, the pressure/purge test of vehicle evaporative emissions controls systems, which is the key part to provide more than 90% of the predicted benefits of IM240 versus idle/2500 testing for HC emissions control (*40*), apparently:

"cannot work on a high percentage of vehicles and should be dropped because of lack of accessibility of the vapor storage canister on some models; the potential for breaking hoses on older cars (causing additional pollution); and a check valve in the systems of some models which prevents the test from being performed" (*41*).

This proposed enhanced I/M program is not an idle but a dynamometer test, thus more complicated and expensive. Since it has been demonstrated that the effectiveness of basic I/M programs is very questionable, there is no solid scientific base to presume success of the enhanced I/M programs in reducing on-road emissions, the goal which they were originally supposed to meet.

Underlying this entire discussion is the need for a more effective approach than the current I/M programs to reduce in-use vehicle emissions. Since on-road motor vehicle emissions are statistically γ-distributed (*42*), a cost-effective strategy might be a combination of in-use surveillance for high emitters, rapid identification, loaded mode verification, and diagnosis together with mandated and verified repair for problem correction (*43*).

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