On-road remote sensing data is an increasingly popular source of evaluation information for vehicle inspection/maintenance (I/M) programs. This article conducts one such remote sensing data evaluation for the Atlanta, Georgia, I/M program. The reference method involves comparing emissions differences in I/M and non-I/M fleet vehicles with those predicted by a regulatory computer model. Assuming that on-road emissions differences represent observed effectiveness and model-predicted emissions differences represent effectiveness goals, the Atlanta enhanced I/M program appears to be achieving 83% of its targeted emissions reductions. The method compares favorably with other remote sensing evaluation methods in its ability to be applied over time and its relatively small sample size requirement. The chief limitation to the approach is its reliance on a representative non-I/M fleet, which may differ in characteristics for which controls are difficult to locate. Such potential confounding factors include discrepancies in maintenance trends, socioeconomic conditions, and vehicle quality.

EVALUATING VEHICLE INSPECTION/ MAINTENANCE PROGRAMS USING ON-ROAD EMISSIONS DATA

The Atlanta Reference Method

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The 1990 Clean Air Act (CAA) Amendments made sweeping changes in the scope and stringency of vehicle inspection/maintenance (I/M) programs. Driven by persistent growth in vehicle travel and chronic air pollution in the nation's largest metropolitan areas, the legislation requires that enhanced I/M programs employ advanced testing technologies and procedures as a way to

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better ensure the operability of vehicle emission control systems.[1] The law also requires biennial evaluation of enhanced I/M programs and on-road measurement of inspected fleet emissions but does not link together the two requirements (CAA Title I §182c3C, Title I §182c3Bi, Title I §182c3Ci).

In the absence of an explicit legislative linkage, a recent National Research Council report has recommended that I/M programs be evaluated using on-road emissions data collected by remote sensing devices (RSD) (Committee on Vehicle Inspection/Maintenance Programs 2001). RSD use infrared and ultraviolet technology to measure the emissions of in-use vehicles.[2] The National Research Council report cited several advantages of RSD data for I/M evaluation. First, RSD are a cost-effective source of evaluation data compared with the higher per-vehicle costs of advanced dynamometer testing on a small sample of vehicles, the original evaluation approach recommended by federal regulators. RSD data can also capture trends that cannot be discerned through internal inspection records alone, such as motorists avoiding the program and preinspection maintenance behavior. RSD data can also be used for a variety of purposes in addition to I/M evaluation, including mobile source emission inventories, clean-screen programs that exempt low-emission vehicles from subsequent I/M testing, and high-emitter programs that target polluting vehicles for off-cycle inspection and repair.

In response to this growing interest, the U.S. Environmental Protection Agency (EPA) released draft guidance in July 2001 for the use of remote sensing data for I/M program evaluation (U.S. EPA 2001). The document outlines equipment specifications and measurement procedures along with study design techniques and quality control measures. The document also discusses three methodologies for analyzing remote sensing data to determine I/M program effectiveness. The comprehensive method compares the on-road emissions of the vehicle fleet before and after scheduled I/M testing. The step method compares inspected with uninspected model year emissions during the 1st year of a new or upgraded I/M program. The reference method compares the emissions of the vehicle fleet located in an I/M area with that of a distantly located non-I/M area.

This article employs the reference method to evaluate the enhanced I/M program of Atlanta, Georgia. This major metropolitan area in the southeastern United States is home to 13 counties in serious nonattainment of the federal ozone standard.[3] The Atlanta enhanced I/M program was implemented in October 1996 in this 13-county area, replacing a basic I/M program that had been operating in 4 of the 13 counties since the early 1980s. We estimate the effectiveness of the new I/M program by comparing the RSD emissions of a sample of its inspected vehicles with that of a sample of vehicles registered in the Georgia cities of Augusta and Macon. The latter areas have demographics, climate, and fleet characteristics similar to Atlanta's but do not operate an I/M program. The emissions difference in the inspected Atlanta and uninspected Augusta/Macon vehicle fleets are then compared with that predicted by the commonly used EPA MOBILE5b computer model. Viewing model-predicted emissions differences in inspected and uninspected vehicles as the Atlanta I/M program goal and observed on-road emission differences as actual program performance, we estimate I/M effectiveness as the ratio of the two numbers.

This section provides background on I/M programs, including an overview of I/M program operations, the evolution of such programs in the United States, and a history of I/M programs in Atlanta. The second section reviews current enhanced I/M evaluation approaches (including the RSD methods outlined in recent EPA guidance) and their respective strengths and weaknesses. The third section describes reference method data sources and methodology. The fourth section reports the results of the reference method. The fifth section discusses the results, with particular attention paid to their caveats. The sixth section presents our conclusions about the reference method results for Atlanta and how it compares with other evaluation methodologies using remote sending data.

VEHICLE I/M PROGRAMS

Vehicle I/M programs involve scheduled testing of a vehicle's tailpipe and evaporative emissions to determine the effectiveness of its emission controls.[4] Inspections can be provided by decentralized test-and-repair networks, which allow service stations and automotive repair shops to perform emissions tests and repair failed vehicles, or by centralized test-only networks, in which a limited number of centrally operated facilities perform testing as the sole service. Depending on program design, the test may be performed annually or biennially, while the vehicle idles or is placed on a treadmill-like dynamometer that induces slight acceleration to mimic the engine stress of on-road driving conditions.

Motorists must repair failed vehicles, composing the maintenance component of the program. Vehicles with repair costs above a set amount may qualify for a waiver—an exemption from further repair and testing—provided that attempted repairs show some emissions improvement and are not triggered by tampering. Compliance is typically verified through the presence of a vehicle windshield sticker received after passing the test or through the vehicle registration process that requires an emissions certificate.

EVOLUTION OF U.S. VEHICLE I/M PROGRAMS

The 1970 CAA was the first legislation to address I/M programs, giving states the option to implement them and delegating responsibility for program oversight and guidance to the U.S. EPA.[5] I/M programs were not required until the 1977 CAA Amendments, which mandated them for states persistently not complying with federal air quality standards. EPA's first guidance for I/M programs addressed the minimum emission reductions required for such programs, as well as implementation requirements and time frames (U.S. EPA 1978). However, the general nature of this guidance resulted in I/M programs that varied significantly in design and enforcement (I/M staff in U.S. EPA's Office of Transportation and Air Quality, personal conversation with author, 26 September 2001).

In the late 1980s, with CAA reauthorization looming ahead in 1990, experts were attributing more than half the ozone-causing emissions and nearly all the carbon monoxide (CO) pollution in U.S. cities to the automobile (Bryner 1995). The EPA responded to this assertion by citing improper testing and poor-quality control in decentralized test-and-repair programs, the most common program design (Inspection/Maintenance Program Requirements 1992). EPA believed that improper testing sometimes stemmed from an inherent conflict of interest in test-and-repair programs: Emissions inspectors might be tempted to falsely pass a regular customer's vehicle or a vehicle that did not pass after repairs (Inspection/Maintenance Program Requirements 1992). Decentralized test-and-repair networks also have a greater number of geographically dispersed test stations that are operated independently of one another. As a result, EPA asserted, it was more difficult for administering agencies to ensure that test technicians were properly trained and that tests were competently and honestly performed (Inspection/Maintenance Program Requirements 1992).

These shortcomings led Congress to expand the requirements for automobile I/M programs in the CAA Amendments of 1990 (Title I §182). The CAA Amendments define two I/M program types, basic and enhanced. Basic I/M programs apply to moderate and marginal ozone nonattainment areas. The performance standard of basic I/M programs require light-duty vehicles of a certain age to be inspected using a simple idle test. Enhanced programs apply to serious, severe, and extreme ozone nonattainment areas with urbanized populations of 200,000 or more and to all metropolitan statistical areas with populations of 100,000 or more in the Northeast Ozone Transport Region. Enhanced I/M program areas must use improved test technologies and test procedures; conduct centralized testing, unless the state demonstrates that decentralized testing is equally effective; inspect cars annually, unless a state demonstrates that less frequent testing is equally effective;[6] and deny vehicle registration to motorists who fail to comply with inspection requirements (Title I §182c3C).

I/M IN ATLANTA

Atlanta's first I/M program was established in 1981, covering the three ozone nonattainment area counties of Fulton, Cobb, and DeKalb and implemented in a decentralized test-and-repair network. The fast-growing Gwinnett County was added in 1986. Testing was originally required for the latest 10 model year vehicles but was expanded in 1986 to include the latest 12 model years. Inspections were conducted on an annual basis.

In response to the 1990 CAA Amendments, the Georgia legislature revisited emissions testing in 1992.[7] This legislation enabled the Georgia Department of Natural Resources to upgrade Georgia's I/M program to an enhanced program, bringing it into compliance with the 1990 CAA Amendments and new federal I/M regulations. This enhanced version of the program received limited implementation in October 1996,[8] with emission inspections required only for those vehicles migrating to the Atlanta I/M program area. The new program commenced in January 1997, with biennial emissions testing required of all vehicles from the 1975 model year to 2 years of age.[9] The new program also spanned the 13-county nonattainment area, incorporating 9 new counties that were not subject to the previous basic I/M program. This study focuses on the first 2 years of the Atlanta enhanced I/M program, during which time vehicles were inspected using a two-speed idle testing procedure that measures emissions under idle and at a 2,500 revolutions per minute engine speed.[10]

ENHANCED I/M PROGRAM EVALUATIONS

Three types of data currently dominate the evaluation of enhanced I/M programs: I/M records, which document the results of each inspection; roadside pullovers, which administer emissions tests to vehicles of randomly selected willing motorists; and remote sensing data, which measure on-road vehicle emissions. This section reviews evaluations employing each data type, along with the strengths and weakness of each.

EMISSIONS INSPECTION RECORDS

The most common source of biennial evaluation data is emissions test records generated by I/M programs (James Lindner of U.S. EPA's Office of Transportation and Air Quality, personal conversation with author, 26 September 2001; see also http://www.epa.gov/otaq/epg/progeval.htm). I/M test records provide a cost-effective source of evaluation data because they are routinely generated and easily accessible. Because I/M records cover the entire inspected vehicle population, statistical conclusion validity is generally not an issue: Evaluators can control for a variety of vehicle characteristics that influence emissions. The availability of odometer data in most I/M records is also advantageous, enabling evaluators to control for the influence of mileage on emissions. A final advantage stems from I/M protocols, which are designed to correlate with the Federal Test Procedure[11] and to facilitate quality control.

However, I/M records suffer from weaknesses that limit their reliability as the sole indicator of program performance. Chief among these is the inability to parcel out fraudulent testing behavior, particularly when inspectors substitute clean-emitting vehicles for unrepaired high-emitting ones on the retest (Wenzel, Gumerman, et al. 2000). I/M records may also underestimate program effectiveness by missing preinspection maintenance performed by some motorists to lower I/M test failure risks. Although it is difficult to quantify the impact of such maintenance, it is expected to yield artificially low baseline emissions and thus underestimate program effectiveness. Generally speaking, these weaknesses speak to the role of I/M records as an internal, not an independent, source of evaluation data.

Evaluations employing I/M records also make tradeoffs between internal validity and representativeness of the data. The inspection process employs highly controlled conditions to ensure that vehicles are measured under consistent circumstances (e.g., engine stress, vehicle speed, and temperature). Although these controls reduce confounding influences on emissions, they represent only a fraction of driving conditions that typify on-road driving. Consequently, the ability to extrapolate I/M test emissions to on-road emissions is limited.

To estimate I/M effectiveness, some evaluations calculate the average emissions difference between the initial and final test scores on failing vehicles and assume that the difference is attributable to the I/M program. Three studies used this approach to evaluate different time periods of the Arizona enhanced I/M program. Two of these studies (Wenzel 1999; Glover and Brzezinski 1997) estimated a 14% reduction in CO, a 15% reduction in hydrocarbons (HC), and a 7% reduction in nitrogen oxides (NOx). The third study (Ando, McConnell, and Harrington 1999), focusing on repaired vehicles, estimated emission reductions of 8%, 8%, and 14% for CO, HC, and NOx, respectively.

Sierra Research (1998) also compared initial and final emission results for failed vehicles in AirCare, the Canadian Vancouver/British Columbia emissions testing program. This study estimated I/M emission reductions of 13% CO, 9% HC, and 4% NOx. Replacing initial emission results of failed inspections with EPA model predictions of an untested fleet's emissions, the researchers estimated 16%, 20%, and 14% emission reductions for CO, HC, and Nox, respectively. The latter emission differences are thought to be higher than the former because model predictions, as opposed to initial inspection results, are not influenced by preinspection maintenance behavior.

The Colorado enhanced I/M program was twice evaluated using inspection records. The first analysis, comparing final test scores for vehicles inspected in 1997 with the new program's first 2,138 initial inspection test scores in 1995, indicated CO emission reductions in the range of 30% to 34% (Environ 1998). The second analysis compared failed vehicles' initial and final inspection results from 1998 that had been converted to Federal Test Procedure scores. The comparison, which normalized repair benefits to the entire inspected fleet, suggested that CO had been reduced by 8% and HC by 6%, with NOx increasing by 1% (State of Colorado Office of the State Auditor 2000). Although the study results seem contradictory, they cover different time frames, make divergent assumptions (about deterioration rates, the fate of vehicles with final failures), and employ different measures in estimating I/M effectiveness.

One weakness in attributing before-after emission differences to I/M is the potential for regression-to-the-mean emissions behavior, in which a portion of I/M failures will register lower emissions on the final inspection without repair.[12] This phenomenon is driven by tremendous test-to-test emissions variability, the presence of vehicles with marginally failing emissions, and variance in environmental conditions favorable to test performance. Without verifying repairs, the emissions differences between initial and final test scores may overestimate program effectiveness.

ROADSIDE EMISSION INSPECTIONS

Used primarily in California, roadside emissions tests are administered with the aid of law enforcement officers who randomly pull vehicles over and ask motorists to voluntarily submit their vehicles to an emissions inspection. Volunteer license plate numbers are then used to query the I/M program database to determine those vehicles with and without an inspection in the past 12 months. Recently inspected and uninspected vehicle emissions are then compared to estimate the emission reductions due to enhanced I/M. Roadside emissions estimates of 1999 enhanced I/M program effectiveness indicate emission reductions of 13% for CO, 14% for HC, and 6% for NOx (California Air Resources Board 2000).

As with I/M program data, roadside pullovers enable the collection of odometer data for mileage estimates. In contrast with I/M program data, the spontaneity of roadside inspections precludes fraudulent test results that overestimate effectiveness as well as preinspection maintenance behavior that underestimates program effectiveness. However, because roadside emissions tests employ a portable version of official inspection procedures, they sacrifice real-world driving conditions. Furthermore, the approach is costly and generates limited data, requiring as many as four technicians and one law enforcement officer to measure approximately 25 vehicles per day (Wenzel, Gumerman, et al. 2000, III-8). Self-selection bias is a risk because the test is voluntary and tends to yield a 10% refusal rate (Wenzel, Gumerman, et al. 2000, III-8).[13]

REMOTE SENSING DATA FROM ON-ROAD VEHICLES

A second source of data for evaluating I/M program effectiveness, the one used in this study, is from RSD that measure the emissions of vehicles while they are being driven. The advantage of in-transit measurement is the ability to observe a vehicle's emissions under typical driving conditions, which cannot be as easily captured by traditional controlled emissions testing procedures. Remote sensors can measure a large number of vehicles, an important attribute given the need to control for tremendous emissions variability due to vehicle type, age, make and model, and emission control technology. A final advantage stems from the unscheduled nature of the measurement, which precludes preinspection and fraudulent maintenance behavior that can occur when motorists (as with I/M tests) know when a measurement will occur.

In contrast with the highly controlled parameters of the emissions inspection, the physical circumstances of remote sensing data collection are only approximated through sampling site characteristics (e.g., moderate grades to ensure vehicles operate under only a slight engine load and sampling sites that avoid residential areas to minimize inflated emissions from cold engines). Another drawback is that remote sensors capture a split-second emissions reading that may not reflect a vehicle's typical emissions, making larger sample sizes a requirement to average out random emission fluctuations and to profile emissions aggregated within vehicle type (cars vs. trucks) and model year.

Remote sensing data have been used in three ways to evaluate I/M programs. The first method averages the emissions of vehicles measured before initial and after final I/M testing, with the difference attributed to I/M program effectiveness. Dubbed the "comprehensive method" in recent EPA evaluation guidance, emissions differences can also be generated for various subfleets, such as vehicles initially failing and ultimately passing I/M testing versus failing vehicles that never receive a final pass. This approach enables a variety of I/M-related analyses, such as deterioration rates of I/M repairs, the influence of pre-I/M repairs on emissions baselines, and a comparison with estimates based on I/M records alone. The major disadvantage to this approach is the enormous volume of on-road data required to measure a representative sample of vehicles before and after I/M testing. Sample size requirements hinge on the probability of measuring vehicles on-road within a specific time period of I/M testing, a probability that fluctuates with testing frequency and the distribution of sampling throughout the year.

The comprehensive method was used in California in 1996 to compare the on-road emissions of 3.5 million vehicles 30 to 90 days before with up to 90 days after their basic I/M test (Klausmeier and Weyn 1997). For those vehicles that failed their initial smog check and then passed, both CO and HC emission differences registered at 20%. Normalizing this result to the entire fleet yielded an estimated 9% emissions reduction in HC and CO. A second evaluation, of the Arizona enhanced I/M program in 1997, analyzed 4 million remote sensing measurements on 1.2 million vehicles in the Phoenix I/M area (Wenzel 1999). The results indicated a 7% reduction in CO and an 11% reduction in HC.

One weakness in the comprehensive method is the potential seasonal effects that result from the year-round testing required to obtain adequately sized samples. Users of this method have also tended to rely on a few high-volume sites, yielding a large number of repeat vehicles that lower the fraction of unique vehicles that could be reached at a greater number of sites.

A second I/M evaluation approach using remote sensing, known as the Step Method, compares inspected and uninspected vehicles during the 1st year of a new or upgraded program. The uninspected vehicles compose an internal control group against which to compare the emissions reductions of the inspected vehicles. Because the method applies to the early phases of a new or improved program, it can be used only once to assess program effectiveness.

A remote sensing study of the Colorado enhanced I/M program compared odd- (inspected) and even- (uninspected) model-year vehicles during the end of the 1st year of a new biennial enhanced I/M program (Stedman et al. 1997). At that point in program history, all odd-model-year vehicles should have been inspected, whereas all even-model-year vehicles had no reason to be inspected. This timing rendered even-model-year vehicles the untested control group against which to compare the odd-model-year vehicle emissions. The comparison of odd- and even-model-year emissions suggested that Colorado's enhanced I/M program had reduced CO between 5% and 9%, whereas HC and NOx showed no improvement.

Three factors limit the generalizability of the Colorado study results to enhanced I/M program effectiveness. Remote sensing took place in a single location, which avoids any confounding socioeconomic or physical influences at different sites but limits generalizability to the overall fleet. Furthermore, vehicles traveling past the remote sensing site were decelerating, which does not represent typical driving conditions and is not the optimal condition for measuring CO (Environ 1998, 2-19). A third limitation was that the study measured vehicles transitioning from an annual basic I/M program to an enhanced I/M program, rendering it an evaluation of incremental program effectiveness and not a complete estimate of enhanced I/M program performance.

A third approach using remote sensing data (the one used in this study) compares the on-road emissions of vehicles registered in an I/M area to that of vehicles registered in non-I/M areas. The non-I/M area serves as a surrogate untested fleet. The validity of this approach relies on the selection of a non-I/M area comparable in fleet age, a well-documented contributor to vehicle emissions; climate, which can accelerate emission control equipment deterioration; and demographics, which influences the age, quality, and maintenance of the vehicle fleet. This approach was originally applied to the basic I/M program operating in 4 counties of the 13-county Atlanta ozone nonattainment area, with the 9 nonattainment counties without I/M composing the untested fleet (Rodgers, DeHart-Davis, and Lorang 1999). The analysis indicates that car and truck emissions for CO were 15% and 10% higher, respectively, in the uninspected 9-county fleet than in the inspected 4-county basic I/M fleet. The study is limited by its inability to control for differences in mileage and socioeconomic conditions between the two vehicle fleets.[14]

I/M PROGRAM EVALUATION COMPONENTS

This study employs an I/M program evaluation method that compares the on-road emissions differences observed in inspected and uninspected vehicles with the same emissions differences predicted by a U.S. EPA mobile emissions model. The model-predicted emissions difference represents the goal of the I/M program, a reasonable assumption given that states use the model to generate the emission reduction credit received for automobile emissions testing programs. The emissions difference observed in on-road inspected and uninspected vehicles is assumed to reflect I/M program performance, an assumption rendered plausible only by the comparability of the inspected and uninspected fleets. We will devote attention in the next section to answering the comparability question.

This section describes the collection of data used in the evaluation. It details the Continuous Atlanta Fleet Evaluation (CAFE), the remote sensing study of on-road Georgia vehicles that provides on-road emissions data of inspected and uninspected vehicles. The TECH5 subroutine of EPA's MOBILE5b emissions model, from which we extracted predicted emission factors, is also discussed. The last section outlines the algorithm that combines data from CAFE and TECH5 to generate effectiveness estimates for the Atlanta enhanced I/M program.

ON-ROAD EMISSIONS DATA

CAFE provides the on-road emissions data used to represent, inter alia, Atlanta enhanced I/M program performance. CAFE uses RSD to measure annually the emissions of approximately 300,000 in-use vehicles in the 13-county I/M program area, as well as two cities more than 75 miles from Atlanta that do not require vehicle emissions testing.[15] The study is an ongoing effort started in 1993 to collect vehicle emissions data for assessing a variety of trends, including fleet turnover, emission control deterioration, and socioeconomic impacts of mobile source control strategies.

RSD measure the emissions of passing vehicles remotely and unobtrusively so motorists are minimally aware of the equipment and do not alter their natural driving behavior. To that end, the remote sensing instrumentation is housed in a van parked on the roadside along with a video camera. An infrared light source and its generator are placed on the opposite side of the road or on the median to create a beam of light that traverses the road. When a passing vehicle breaks the beam, it triggers a measurement of HC, CO, and NOx in the exhaust. Simultaneously, a video camera records the vehicle's license plate, which is automatically scanned into the database of emissions measurements.

After data collection, remote sensing measurements are merged with vehicle registration records using the vehicle license plate. The resulting database allows various characteristics of measured vehicles to be identified, including vehicle identification number,[16] make, model year, and vehicle type. License plates are also linked with I/M records to identify vehicles with prior emission inspections.

RSD sampling sites are selected to ensure physically consistent but demographically diverse characteristics. Single straight lines of traffic with an average 35 miles per hour velocity are sought to facilitate single vehicle measurements and speeds that maximize measurement opportunities. Driver behavior and driving maneuvers are also observed at each site to ensure that remote sensing measurements would not be biased high by acceleration or low by coasting. Finally, notations are made during the site visits regarding any obvious or suspected diurnal patterns that affect the traffic volume. If distinct variations are found to exist in sites ultimately selected, sampling times are scheduled to account for those diurnal patterns. U.S. census tract data and traffic count reports inform the selection of different income ranges and land uses.

The remote sensing sites relevant to this study reside within the 13-county Atlanta I/M program area as well as the Georgia cities of Augusta and Macon. The latter locales do not require emissions testing and thus provide an uninspected vehicle fleet to serve as a control group. These cities were chosen after a review of census data and registration records revealed them to have characteristics—median household income, population density, and fleet distribution—more similar to Atlanta's than did three other Georgia cities considered.[17]

PREDICTED EMISSION FACTORS

We used TECH5, an auxiliary component of EPA's MOBILE5b computer model of mobile emission factors, to predict emissions differences in inspected and uninspected vehicles.[18] TECH5 generates emission factors based on, among other influences, I/M program type and inspection frequency. In using TECH5, we altered one of its key assumptions: that inspected vehicles have been tested regularly since their introduction into the fleet as new vehicles. Two features of the Atlanta enhanced I/M program make this assumption problematic. First, enhanced emissions testing had been in place for only one full cycle (2 years) in 1998, the evaluation year. Second, vehicles registered in the nine Atlanta counties, which were not covered under the previous basic I/M program, were new to emissions testing during 1998. Given these characteristics, the use of MOBILE5 emission factors in this analysis would significantly underestimate expected Atlanta enhanced I/M program effectiveness. To make predicted emission factors reflect current program characteristics, we extracted from TECH5 predicted emission factors from vehicles that had undergone a single enhanced emissions test in a biennial two-speed idle testing program.

Although MOBILE5b and its TECH5 subcomponent are used to benchmark on-road emissions differences, the model is not without limitations. Chief among these are estimated emission factors from small samples of laboratory-derived emissions data, optimistic repair effectiveness assumptions, and little model validation using real-world emissions data (Harrington, McConnell, and Cannon 1998). Nonetheless, all states except California use the model to estimate emission reductions from I/M and other mobile source policy programs for state implementation plan credit. Thus, the model's use in this study reflects more common evaluation practice and less our regard for its accuracy and validity.

EVALUATION ALGORITHM

We estimated Atlanta enhanced I/M program effectiveness by comparing EPA model-predicted emission differences with observed emission differences in inspected and uninspected vehicles. The comparison yields a percentage that represents the proportion of expected emission reductions actually achieved by the program. The formula for estimating I/M effectiveness is as follows:

$$\text{Effectiveness} = \frac{\sum_{ij}\left[\left(O_{n_{ij}} - O_{m_{ij}}\right)/O_{n_{ij}}\right]\left(P_{n_{ij}}\right)\left(C_{ij}\right)\left(VMT_{ij}\right)}{\sum_{ij}\left(P_{n_{ij}} - P_{m_{ij}}\right)\left(C_{ij}\right)\left(VMT_{ij}\right)}$$

where

- O_m and O_n are the average on-road CO emissions observed for a particular model year and vehicle type for I/M program and non-I/M program vehicles, respectively;
- P_m and P_n are the model-estimated emission factors for I/M program and non-I/M program vehicles for a given model year and vehicle type;
- C_{ij} is the fraction of the Atlanta fleet of that model year and vehicle type observed by CAFE; and
- VMT_{ij} is the average annual vehicle miles traveled by model year and vehicle type in the I/M program area.

The formula normalizes predicted and observed emissions differences in I/M program and non-I/M program vehicles by model year to the on-road fleet fraction and average annual mileage of that model year. This exercise enables the different units of measurement between on-road and predicted emissions—exhaust CO percentage versus grams per mile of CO—to be put in ratio form.

ANALYSIS

This section reports the results of the reference method for evaluating the Atlanta enhanced I/M program during its first 2 years of operation. The evaluation uses remote sensing emissions data collected in 1998 and emission factors predicted for the 1998 fleet by an EPA computer model. The 1998 calendar year represents the end of the first full cycle of enhanced two-speed idle testing, by which time all covered odd- and even-model-year vehicles should have been inspected.

Because the reference method involves direct comparisons between on-road data and EPA's MOBILE model, we restrict the data in several ways to obtain an "apples to apples" comparison. First, only 1981 to 1996 model year vehicles are included in the analysis. Although the Atlanta enhanced I/M program inspected back to the 1975 model year during 1998, low sample sizes among on-road vehicles precluded us from valid statistical analysis on this segment of the vehicle population. Furthermore, the absence of EPA model predictions for these model years meant there would be no comparison with the EPA model. The 1997 and 1998 model years are not included because these vehicles were exempt from testing in 1998.

The second data restriction is the use of only vehicles registered in the nine counties of the I/M program area not covered by the previous basic emissions testing program. As discussed previously, the extracted TECH5 emission factors are based on a fleet that has undergone a single cycle of enhanced emissions testing. Vehicles registered in the previous four-county basic I/M area do not qualify as newly tested because they were subject to emissions testing 14 years prior to enhanced I/M program implementation. Furthermore, there is no mechanism for extracting from TECH5 the incremental effectiveness of enhanced testing on a fleet previously subject to basic I/M testing. Consequently, nine-county vehicles offer the emissions data most comparable to the TECH5 factors.

DATA OVERVIEW

The remote sensing data used by this evaluation were collected at 39 Atlanta I/M program area sites and 8 nonprogram area sites in Augusta and Macon.[19] Measurements in the I/M program were conducted from January to December 1998, and nonprogram area measurements were collected during 9 days in March, October, and December. Temperature at the nonprogram area sites averaged 58° Fahrenheit, in comparison with 64° Fahrenheit at the nine-county I/M program sites (see National Climatic Data Center at http://lwf.ncdc.noaa.gov/oa/ncdc.html).[20]

CAFE collected 15,790 measurements from 14,741 nine-county vehicles with a 1997 or 1998 inspection. Fifty-eight percent of these vehicles (n = 8,508) received 1997 inspections, whereas 42% (n = 6,233) received 1998 inspections. In the nonprogram areas, 12,017 measurements were collected from 10,640 vehicles registered in the counties comprising Augusta and Macon. In both program and nonprogram areas, we randomly selected one CO measurement from unique vehicles with multiple readings.

This evaluation of the Atlanta enhanced I/M program relies on measurements of CO rather than HC or NOx data. The primary reason for focusing on CO rather than HC is that the former pollutant has a smaller signal-to-noise ratio (see Figure 1). CO's lower variance is due to its presence in higher concentrations in the atmosphere than HC, making it easier to measure by RSD and less susceptible to weather and driving conditions. NOx data were not collected during the time frame of the study and thus were not available for analysis.

VALIDITY OF FLEET COMPARISONS

Our ability to infer I/M effectiveness from the emission differences in Atlanta and Augusta-Macon vehicles hinges on the comparability of the three fleets. The inspected Atlanta and uninspected Augusta-Macon vehicle fleets have similar model year distributions, although the inspected Atlanta fleet is slightly newer than the uninspected Augusta-Macon fleet (see Figure 2). A second issue for the validity of our analysis is whether the Augusta and Macon fleets are similar enough to be combined into one uninspected fleet. The average CO emissions by model year and vehicle type do not differ significantly between the two fleets, as revealed by an error bar graph comparison (see Figure 3).

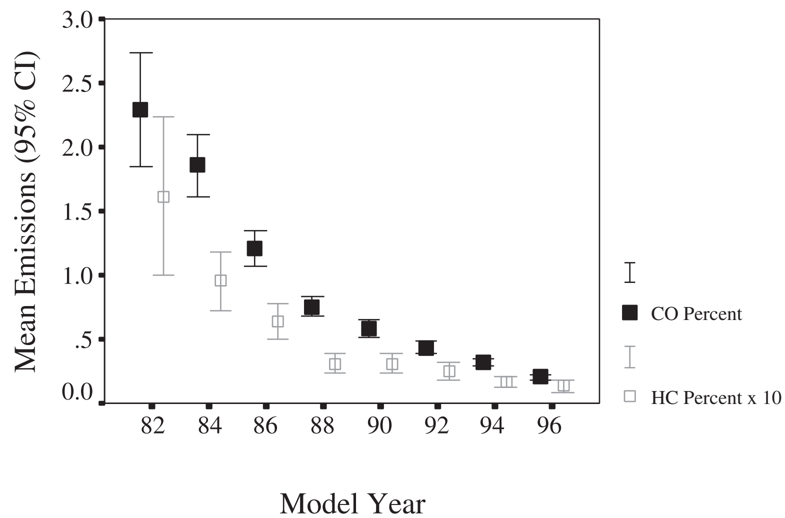

Figure 1: On-Road Carbon Monoxide (CO) and Hydrocarbons (HC), by Model Year
SOURCE: Continuous Atlanta Fleet Evaluation (1998).
NOTE: HC has been rescaled to enable comparison with CO; CI = confidence interval.

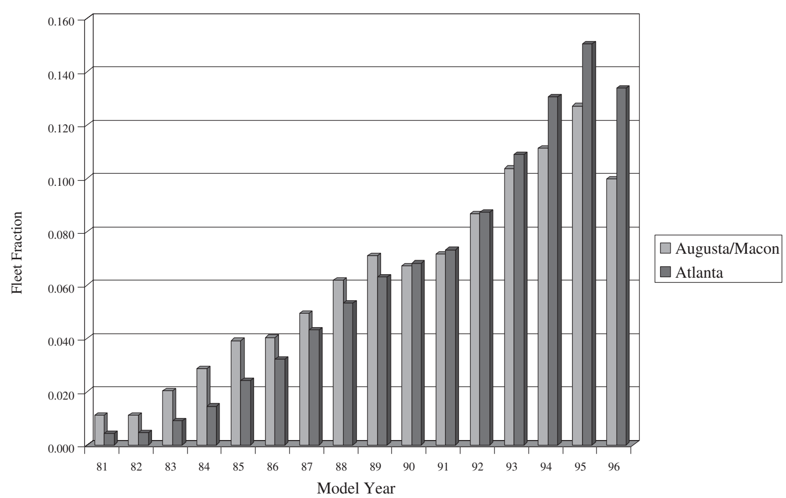

Figure 2: On-Road Model Year Comparison: Inspection/Maintenance (I/M) (Atlanta) Versus Non-I/M (Augusta-Macon) Vehicle Fleets
SOURCE: Remote sensing from Continuous Atlanta Fleet Evaluation (1998).

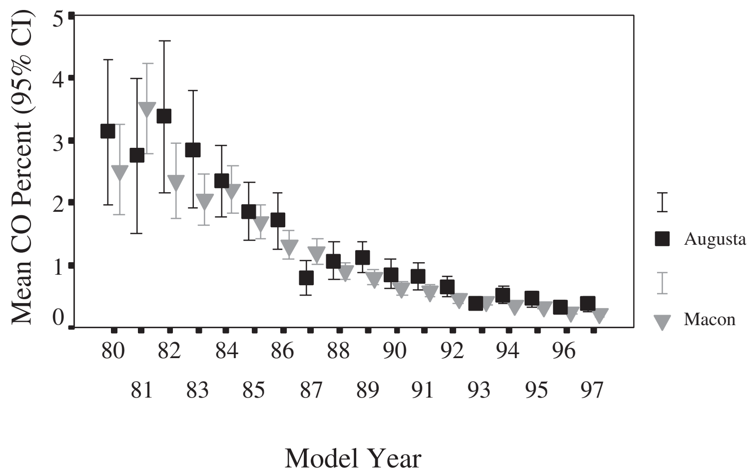

Figure 3: On-Road Carbon Monoxide (CO) Emissions, by Model Year, Augusta Versus Macon Vehicles
SOURCE: Continuous Atlanta Fleet Evaluation (1998).
NOTE: CI = confidence interval.

Another comparison pits Augusta vehicles against untested even-model-year vehicles registered in the nine counties in 1997. During this 1st year of biennial enhanced I/M testing, during which time only odd-model-year vehicles were required for inspection, the emissions of the nine counties not covered under the previous testing program should resemble the emissions of the untested Augusta vehicle fleet.[21] Figure 4 reveals statistically indistinguishable CO emissions between the two fleets.

Our analysis also relies on the representativeness of the on-road Atlanta fleet. A model year comparison of vehicles present in the 1998 I/M records with those measured on-road by 1998 CAFE yields similar distributions (see Figure 5). Although the on-road fleet is generally newer than the inspection roster, this is an expected result given that newer vehicles tend to be driven more frequently, for more miles per year, than do older vehicles and thus are more likely to be measured on-road. However, a comparison of the CO emissions test results of vehicles measured on-road by CAFE 1998 and those without 1998 CAFE measurements reveals statistically similar emissions profiles (see Figure 6). Thus, we conclude that the on-road Atlanta fleet represents the inspected Atlanta fleet, in both emissions and model year distribution.

A final assessment of fleet comparability involves examining the composition of the inspected Atlanta and uninspected Augusta-Macon fleets according to their probability of I/M failure. We used a software that decodes

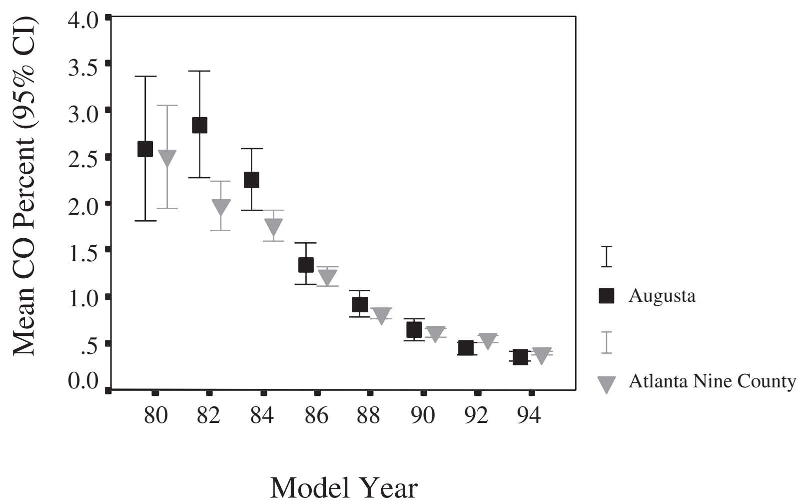

Figure 4: On-Road Carbon Monoxide (CO) Emissions, by Model Year, Augusta Versus Atlanta Nine-County Vehicles
SOURCE: Continuous Atlanta Fleet Evaluation (1997).
NOTE: CI = confidence interval.

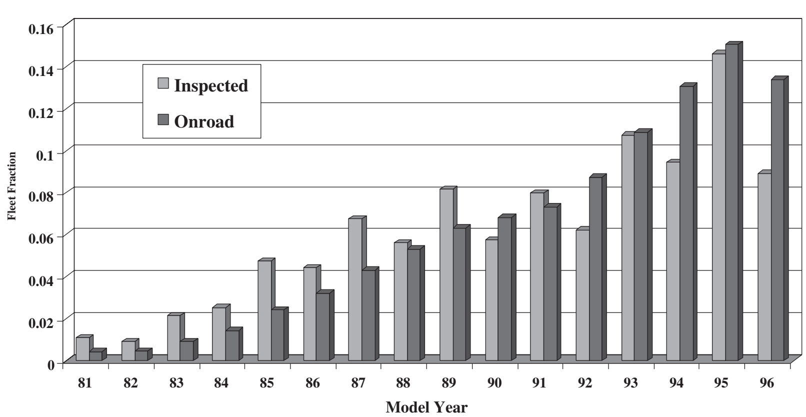

Figure 5: Model Year Comparison: 1998 On-Road Atlanta Vehicle Fleet Versus 1997-1998 Atlanta Inspected Fleet
SOURCE: On-road vehicles were measured by the Continuous Atlanta Fleet Evaluation (1998). Inspected vehicles data are present in the 1997 and 1998 Atlanta enhanced inspection/maintenance records (Inspection/Maintenance Records 1998).

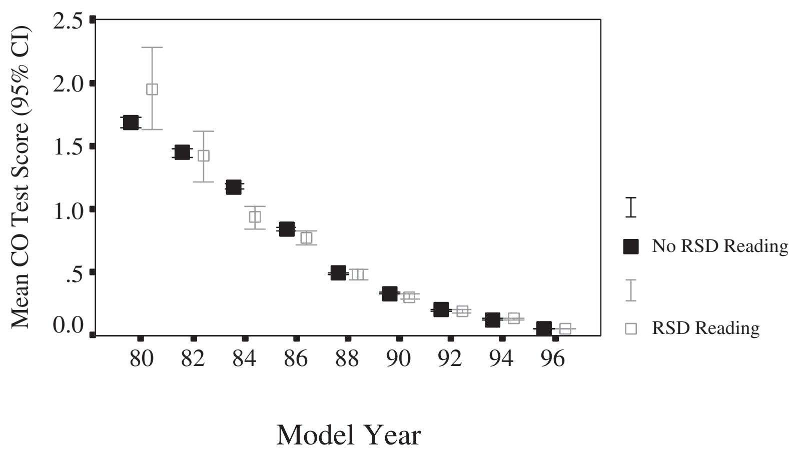

Figure 6: Inspection/Maintenance (I/M) Test Scores for Carbon Monoxide (CO): Vehicles With and Without On-Road Remote Sensing Devices (RSD) Reading

SOURCE: Inspection/Maintenance Records (1998) and Continuous Atlanta Fleet Evaluation (1998).
NOTE: CI = confidence interval.

vehicle identification numbers to determine various vehicle characteristics and then "looks up" various I/M failure rates for particular make, model, and model year vehicles in another table.[22] Comparing failure rates for CO, it appears that the Augusta-Macon fleet comprises vehicles averaging a failure rate of 2.79%, compared with the 1.94% average failure rate for Atlanta nine-county vehicles (see Table 1). A *t* test for independent samples confirms its statistical significance ($p = .00$). Although the absolute difference in failure rates is small, the comparison nonetheless raises the possibility that slight differences in fleet composition not captured in this analysis—for example, vehicle quality, domestic versus foreign manufacturer—could somewhat bias our results in favor of the nine-county Atlanta fleet.

ESTIMATING I/M EFFECTIVENESS OVER TIME

The availability of Atlanta on-road emissions data back to 1994 allows us to examine over time the emission differences in inspected and uninspected vehicles, with particular interest in how these differences vary with I/M program changes. Our temporal analysis involves regressing on-road CO data over different years as a linear function of vehicle age, vehicle type (car vs.

TABLE 1: IM240 Test Failure Probabilities for Carbon Monoxide

	Nine-County Atlanta		*Augusta-Macon*
N	20,376		9,354
M	1.94		2.79
SD	4.47		5.84
SE (M)	0.03		0.06
F		474.83	
P		.00	
T		–13.79	
Df		29,728	
P(t)		.00	

truck), and I/M county registration (within or outside of an I/M program county).[23] Vehicle age is measured by subtracting the model year from the calendar year, so that a 1998 vehicle measured in 1998 has a vehicle age of 0. A dummy variable delineates light-duty cars (0) versus trucks (1). I/M county registration is also measured using a dummy variable, with 0 marking vehicles registered in I/M counties with an inspection record for that year and 1 marking non–I/M county vehicles without an inspection record. Non-I/M counties differ depending on the calendar year being modeled. From 1994 to 1996, the nine counties of the Atlanta ozone nonattainment area that were not included in the four-county basic I/M program area represent non-I/M counties. For 1997—when those nine counties joined the enhanced I/M testing area—we use Richmond and Columbia County vehicles to represent the untested Augusta, Georgia, vehicle fleet. For 1998, the uninspected fleet includes Richmond, Columbia, and Bibb Counties to capture Augusta and Macon, Georgia, vehicles.

Five ordinary least squares (OLS) regression models are generated,[24] one for each calendar year from 1994 to 1998. Table 2 presents the results, with several trends worthy of discussion. First, the emissions differences between I/M and non-I/M vehicles over time form a parabola, with a 15% difference in 1994 and 1998, slightly lower differences of 10% and 11% in 1995 and 1997, respectively, and the lowest difference (5%) in 1996 (see Figure 7). For all years except 1, each additional year of vehicle age increases CO emissions by 10%. The exception to this pattern is found in 1996 data, when emissions increase with vehicle age by 7% per year. The emissions difference between cars and trucks is 14% in 1994 and 16% in 1995, dropping to 4% in 1996 and gradually increasing to 8% and 10% in 1997 and 1998. The explanatory power of the models also varies, ranging from 4% in 1996 to 11% in 1998.[25]

TABLE 2: Modeling On-Road Carbon Monoxide Using Vehicle Age, Vehicle Type, and Inspection/Maintenance (I/M) Registration

		SE (B)	SE (B)´	t(B)´	p(t)	*95% CI*´	F	*Prob* > F	R^2	*Root* MSE	n
1994											
Age	.10	.0019	.0023	42.47	.00	.09 -.10	897	.00	.07	1.12	37,557
I/M	.15	.0141	.0149	9.77	.00	.12 -.17					
Vehicle Type	.14	.0137	.0139	10.00	.00	.11 -.17					
Constant	.04	.0123	.0109	4.07	.00	.02 -.07					
1995											
Age	.11	.0017	.0022	48.12	.00	.10 -.11	780	.00	.07	1.17	49,372
I/M	.08	.0110	.0112	7.15	.00	.06 -.10					
Type	.16	.0114	.0118	13.60	.00	.14 -.18					
Constant	.10	.0103	.0096	10.71	.00	.08 -.12					
1996											
Age	.07	.0013	.0016	46.76	.00	.07 -.08	1045	.00	.04	0.98	69,494
I/M	.04	.0084	.0089	4.22	.00	.02 -.05					
Type	.04	.0082	.0082	4.73	.00	.02 -.06					
Constant	.21	.0071	.0065	33.00	.00	.20 -.23					
1997											
Age	.106	.0014	.0020	52.25	.00	.10 -.11	2071	.00	.11	1.20	52,948
I/M	.104	.0151	.0194	5.35	.00	.07 -.14					
Type	.083	.0116	.0118	7.03	.00	.06 -.11					
Constant	.195	.0084	.0078	24.95	.00	.18 -.21					

(continued)

TABLE 2 Continued

		SE (B)	SE (B)´	t(B)´	p(t)	*95% CI*´	F	*Prob* > F	R^2	*Root* MSE	n
1998											
Age	.10	.0010	.0016	66.31	.00	.10 -.11	1474	.00	.11	1.13	82,929
I/M	.15	.0128	.0165	8.91	.00	.11 -.18					
Type	.10	.0085	.0086	11.97	.00	.09 -.12					
Constant	.10	.0068	.0065	15.43	.00	.09 -.11					

NOTE: β = ordinary least sqares (OLS) regression coefficient; *SE (B)* = standard error of OLS regression coefficient; *SE (B)*´ = heteroskedasticity–robust standard error of OLS regression coefficient; *t(B)*´ = heteroskedasticity–robust regression coefficient; *p(t)* = area of distribution outside of *t* statistic; 95% CI´ = 95% confidence interval based on heteroskedasticity–robust standard error; *F* = *F* statistic; Prob > *F* = area of distribution outside of *F* statistic; R^2 = explanatory power of model; root *MSE* = root mean square error.

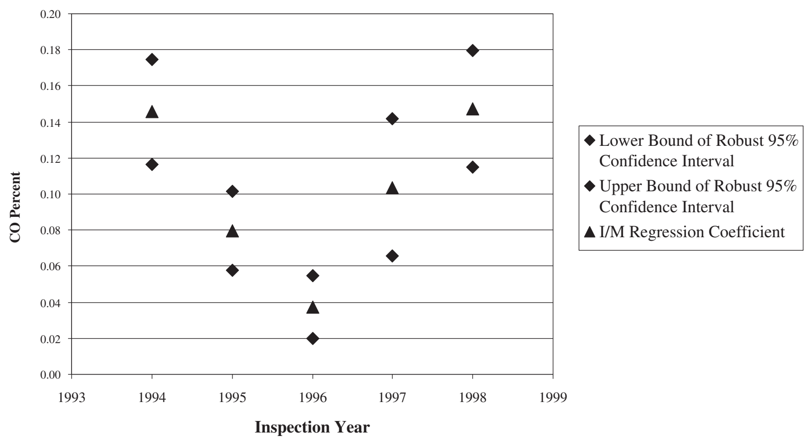

Figure 7: Difference in On-Road Carbon Monoxide (CO) Between Inspected and Uninspected Vehicles

Multiple linear regression makes two key assumptions that undergird the validity of its estimates. First, error terms are assumed to be identically distributed over levels of the independent variables. Second, error terms are assumed to be uncorrelated with each other spatially or temporally. Violation of these assumptions, known respectively as heteroskedasticity and autocorrelation, can inflate standard errors and interfere with the ability to measure the precision of the estimates. Although statistical tests indicate no autocorrelation, they do indicate heteroskedasticity.[26] To address heteroskedasticity, we estimate the standard errors of the regression coefficients using White's robust regression technique (1980). This approach estimates a standard error for regression coefficients that is valid regardless of the presence or functional form of heteroskedasticity. As Table 2 indicates, there is little difference in the original OLS regression standard errors and those estimated by White's heteroskedasticity robust regression technique. Thus, no data patterns are altered by the use of this alternative estimation technique.

Emissions differences in inspected and uninspected vehicles display a curious pattern over time. The decrease in emissions differences in inspected four-county vehicles and uninspected nine-county vehicles from 1994 to 1996 coincides with the last 3 years of Atlanta's basic I/M program. The latter year also marks the transition in responsibility for I/M program administration from the Georgia Department of Public Safety to the Georgia Department of Natural Resources. This timing raises the possibility that the transition resulted in a relaxation in enforcement by the outgoing agency, which produced an increase in the inspected vehicle fleet's emissions.

Initially, it appears that emissions differences between inspected and uninspected vehicles are similar for basic and enhanced I/M testing (see Figure 7). However, this is likely due to changes in how we operationalize inspected vehicles. The inspected fleet from 1994 to 1996 composed four-county vehicles subject to a mature basic I/M program, one that had been in operation for 12-plus years. This compares with the inspected fleet in 1997 and 1998, which adds in nine-county vehicles never before subject to I/M testing. Accordingly, the 15% difference in inspected and uninspected vehicles in 1994 can be interpreted as an estimate of cumulative effectiveness, whereas the same difference in 1998 may be viewed as the initial effectiveness of enhanced I/M programming on a partially untested fleet. Putting the 1998 regression coefficient into policy context, 15% of the gross emissions inventory for light-duty cars and trucks during that period (1,882 tons CO per day) was 282 tons of CO per day (Jon Morton of the Georgia Department of Natural Resources, personal conversation with author, 5 December 2001). This figure is significant in that it represents half of the emission reduction credit claimed by the state of Georgia for all mobile source emission reduction programs, including an antitampering program and technician training to maximize repair effectiveness.

REFERENCE METHOD RESULTS

The results of the reference method for evaluating the effectiveness of the Atlanta enhanced I/M program are laid out in Tables 3 and 4. But first, let us review the methodology for generating the estimates. We calculate the emissions difference in inspected and uninspected cars and trucks by model year and then weight those differences to that model year's annual average mileage and fleet fraction. The exercise is undertaken separately for predicted emissions factors and on-road emissions data. The weighted emissions differences in each category are then summed over all model years. The weighted value based on on-road emissions data becomes the numerator, whereas the weight value based on predicted emission factors becomes the denominator. Dividing the numerator by the denominator yields the percentage of expected emissions differences actually achieved in inspected and uninspected vehicles. The results of this exercise indicate that the Atlanta enhanced I/M program captures 87% of the emission reductions predicted by EPA for cars and 75% of the emission reductions predicted by EPA for trucks.

TABLE 3: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Cars

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1981	.45	.32	.004	11,009	1,202	854
1982	.36	.32	.005	10,660	979	883
1983	.16	.32	.010	11,091	852	1,772
1984	.52	.38	.016	11,397	4,544	3,298
1985	.14	.34	.027	11,398	1,897	4,725
1986	.33	.37	.034	11,797	5,506	6,261
1987	.12	.34	.047	12,162	2,621	7,270
1988	.37	.36	.058	12,942	9,678	9,446
1989	.19	.32	.067	12,947	5,467	8,981
1990	.33	.35	.076	13,448	10,083	10,636
1991	.17	.24	.079	13,821	4,902	7,226
1992	.39	.28	.091	14,174	12,263	8,616
1993	–.02	.17	.105	15,162	–655	5,712
1994	.26	.21	.123	15,408	8,578	6,800
1995	.09	.09	.143	16,223	2,927	2,897
1996	.30	.13	.116	15,238	5,128	2,192
	$\bar{x}$ = .26	$\bar{x}$ = .28			Σ 75,973	Σ 87,569

NOTE: Inspection/Maintenance effectiveness = 0.87; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

Delving into the data composing these results, Figures 8 and 9 compare the emissions differences in inspected nine-county Atlanta and uninspected Augusta-Macon vehicles measured on-road by RSD versus those predicted by TECH5. For both cars and light-duty trucks, the TECH5-predicted differences form an oscillating pattern that corresponds with the 1998 biennial testing schedule: The ratios are higher for even model years (which were last tested in 1998) and lower for odd model years (which were last tested in 1997). The on-road emission differences mimic this pattern, although with steeper oscillations. In comparing on-road with modeled emission differences for cars, a distinguishing pattern emerges. The on-road emission differences fall short of the predicted emission differences mostly in the off-cycle odd model years, whereas on-road emission differences meet or exceed predicted emission differences for even model years.[27] This pattern suggests that postinspection emissions deteriorate more rapidly than anticipated by the

TABLE 4: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Trucks

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1981	.32	.32	.004	11,287	686	699
1982	–.06	.32	.004	10,882	–95	544
1983	.36	.32	.007	11,755	1,216	1,109
1984	.34	.38	.011	11,803	1,868	2,092
1985	.18	.34	.018	11,574	1,530	2,910
1986	.36	.37	.029	12,724	5,190	5,399
1987	.21	.34	.035	12,483	3,407	5,487
1988	.39	.36	.042	13,645	7,836	7,320
1989	.19	.32	.055	13,879	4,743	8,031
1990	.06	.35	.052	13,891	1,307	7,556
1991	.13	.24	.062	14,911	3,194	6,100
1992	.06	.28	.079	15,391	1,633	8,180
1993	–.17	.17	.117	16,364	–6,818	6,922
1994	.35	.21	.147	16,352	14,935	8,861
1995	.22	.09	.167	17,863	9,416	3,905
1996	.31	.13	.172	17,192	9,457	3,848
	$\bar{x}$ = .20	$\bar{x}$ = .28			Σ 59,506	Σ 78,963

NOTE: Inspection/Maintenance effectiveness = 0.75; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

TECH5 model. Similar patterns are seen for trucks, except there are fewer instances of on-road emissions differences' being higher or near to the predicted differences for even model years.

DISCUSSION

Interpreting emissions differences in the Atlanta and Augusta-Macon fleets as effectiveness of the enhanced I/M program effectiveness assumes that we have controlled for all differences in these fleets. This assumption is challenged by the possibility that the Augusta-Macon fleet comprises higher mileage or poorer quality vehicles than the Atlanta nine-county fleet. One source of evidence for mileage differences, the U.S. Department of Transportation data on daily vehicle miles traveled (VMT), suggests that vehicles in Atlanta travel 34 miles per day per capita versus 22 miles for vehicles in

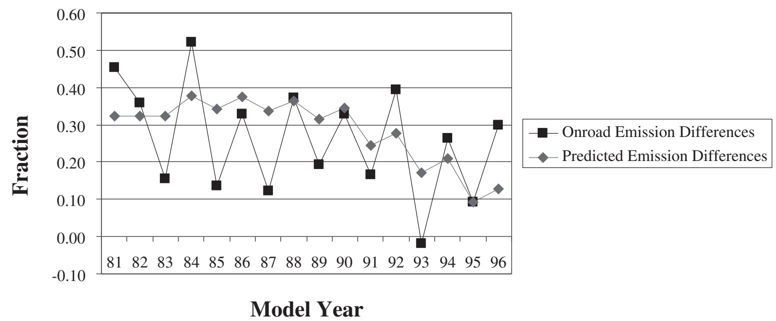

Figure 8: Carbon Monoxide (CO) Differences in Inspected and Uninspected Cars

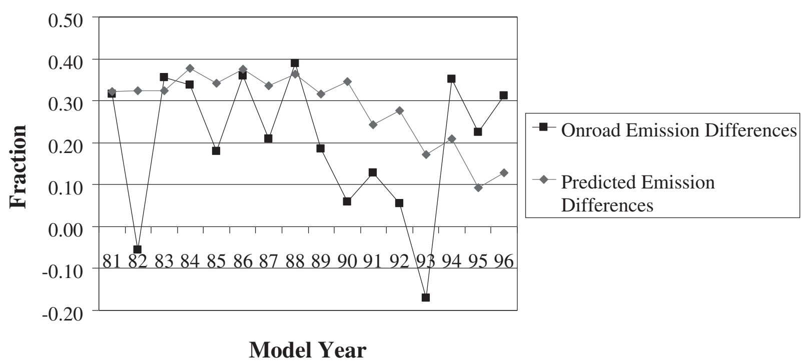

Figure 9: Carbon Monoxide (CO) Differences in Inspected and Uninspected Trucks

Augusta. This information would seem to weaken any hypothesized mileage difference, at least between Augusta and Atlanta. However, because Georgia Department of Transportation estimates are based on observed freeway traffic flows that capture out-of-state as well as local vehicles, it is difficult to extrapolate these VMT estimates to the local vehicle fleet.

Differences in fleet quality—in terms of make and model, maintenance, and foreign versus domestic manufacture—potentially confound the emissions differences in the Atlanta and Augusta-Macon fleets. That vehicles represented in the Augusta-Macon fleet had a slightly higher I/M failure probability lends credence to this possibility. However, similarities in the 1997 emission profiles of on-road Augusta and untested Atlanta nine-county vehicles question the impact of this difference on emissions. And whereas Macon data were not available for the 1997 emissions comparison with untested nine-county vehicles, Augusta and Macon vehicles have statistically similar 1998 emissions, thus making a significantly poorer quality Macon fleet unlikely.

Another issue for the validity of our evaluation is the extent to which we underestimate Atlanta enhanced I/M program effectiveness by using vehicles inspected in 1997 and 1998. Obviously, most vehicles inspected in 1997 have a longer time lag between their last inspection and the first remote sensing reading than 1998-inspected vehicles. To illustrate, 133 days (slightly more than 4 months) is the average time lag between 1998-inspected vehicles and their first remote sensing measurement. By comparison, 466 days (about 16 months) typically distance a 1997-inspected vehicle and its first 1998 remote sensing measurement.

To distinguish vehicles with current-year versus prior-year testing, Tables 5, 6, 7, and 8 evaluate even- and odd-model-year vehicles separately. The emissions difference between Atlanta inspected and Augusta-Macon uninspected even-year cars is 118% of the same difference predicted by TECH5, whereas the inspected-uninspected emissions difference in even-year trucks is 96% of that predicted. By contrast, both odd-model-year cars and odd-model-year trucks display 49% of the TECH5 inspected-uninspected emissions difference. Considering the 70%-30% split between cars and trucks in the inspected fleet, as well as the average time lag between emissions inspection and RSD measurement for even- and odd-model-year vehicles, it appears that differences in Atlanta inspected and Macon-Augusta uninspected vehicles are 111% at 4 months (combining the car-truck emission differences for even-model-year vehicles) and 49% at 16 months (combining the car-truck emission differences for odd-model-year vehicles). Inspected-uninspected emissions differences that fluctuate between inspection cycles may be due to deterioration, repair experience (as repair technicians become adept at diagnosing and treating emission failures), and testing competency (as inspectors improve at identifying emission failures for repair).

Two additional factors potentially confound the comparisons between the Atlanta and Augusta-Macon fleets. The first factor is the presence of an annual Reid Vapor Pressure fuels program in the Atlanta 13-county non-attainment area between 1 June and 15 September. Although the program intends to reduce HC emissions, it has the potential to lower CO emissions and thus confound comparisons of summer data between the I/M and non-I/M fleets. Suppressing measurements of the 9-county inspected Atlanta fleet during this time period (10% of the data, $n = 1,358$) and reapplying the

TABLE 5: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Even-Year Cars

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1982	.36	.32	.005	10,660	979	883
1984	.52	.38	.016	11,397	4,544	3,298
1986	.33	.37	.034	11,797	5,506	6,261
1988	.37	.36	.058	12,942	9,678	9,446
1990	.33	.35	.076	13,448	10,083	10,636
1992	.39	.28	.091	14,174	12,263	8,616
1994	.26	.21	.123	15,408	8,578	6,800
1996	.30	.13	.116	15,238	5,128	2,192
	$\bar{x}$ = .36	$\bar{x}$ = .30			Σ 56,759	Σ 48,131

NOTE: Inspection/Maintenance effectiveness = 1.18; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

TABLE 6: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Even-Year Trucks

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1982	–.06	.32	.004	10,882	–95	544
1984	.34	.38	.011	11,803	1,868	2,092
1986	.36	.37	.029	12,724	5,190	5,399
1988	.39	.36	.042	13,645	7,836	7,320
1990	.06	.35	.052	13,891	1,307	7,556
1992	.06	.28	.079	15,391	1,633	8,180
1994	.35	.21	.147	16,352	14,935	8,861
1996	.31	.13	.172	17,192	9,457	3,848
	$\bar{x}$ = .23	$\bar{x}$ = .30			Σ 42,132	Σ 43,800

NOTE: Inspection/Maintenance effectiveness = 0.96; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

reference method actually slightly increase effectiveness, by 1% for cars and 3% for trucks. Thus, the presence of the Reid Vapor Pressure program during the I/M evaluation period is not suspected of confounding the study results.

TABLE 7: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Odd-Year Cars

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1981	.45	.32	.004	11,009	1,202	854
1983	.16	.32	.010	11,091	852	1,771
1985	.14	.34	.027	11,398	1,897	4,725
1987	.12	.34	.047	12,162	2,621	7,270
1989	.19	.32	.067	12,947	5,467	8,981
1991	.17	.24	.079	13,821	4,902	7,226
1993	–.02	.17	.105	15,162	–655	5,712
1995	.09	.09	.143	16,223	2,927	2,897
	$\bar{x}$ = .16	$\bar{x}$ = .27			Σ 19,214	Σ 39,438

NOTE: Inspection/Maintenance effectiveness = 0.49; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

TABLE 8: Calculating Atlanta Enhanced Inspection/Maintenance Effectiveness for Odd-Year Trucks

Model Year	*$(ON_{ij} – OM_{ij})$ / ON_{ij}*	*$(PN_{ij} – PM_{ij})$ / PN_{ij}*	*C_{ij}*	*VMT_{ij}*	*NUM*	*DEN*
1981	.32	.32	.004	11,287	686	699
1983	.36	.32	.007	11,755	1,216	1,109
1985	.18	.34	.018	11,574	1,530	2,910
1987	.21	.34	.035	12,483	3,407	5,487
1989	.19	.32	.055	13,879	4,743	8,031
1991	.13	.24	.062	14,911	3,194	6,100
1993	–.17	.17	.117	16,364	–6,818	6,922
1995	.22	.09	.167	17,863	9,416	3,905
	$\bar{x}$ = .18	$\bar{x}$ = .27			Σ 17,374	Σ 35,163

NOTE: Inspection/Maintenance effectiveness = 0.49; ON_{ij} = emissions observed from noninspected vehicles; OM_{ij} = emissions observed from inspected vehicles; PN_{ij} = TECH5-predicted emissions from noninspected vehicles; PM_{ij} = TECH5-predicted emissions from inspected vehicles; C_{ij} = 1998 on-road fleet fraction by vehicle type; VMT_{ij} = mean vehicle miles traveled; NUM = $[(ON_{ij} – OM_{ij}) / ON_{ij}] \times PN_{ij} \times C_{ij} \times VMT_{ij}$; DEN = $(PN_{ij} – PM_{ij}) \times C_{ij} \times VMT_{ij}$.

By contrast, the second factor presents a more serious confounding risk in the use of the reference method. Three Smog Dog (the registered trademark for the remote sensing instruments used in the study, originally manufactured

TABLE 9: Emission Differences in Atlanta and Augusta-Macon Fleets, by Remote Sensing Devices Instrumentation

Smog Dog Number	n_{atl}	n_{augmac}	$\overline{co}_{augmac} - \overline{co}_{atl}$
1	7,728	1,671	.18
2	10,214	5,445	.16
3	NA	2,651	NA

NOTE: NA = not applicable.

by Hughes Santa Barbara) instruments were used to measure the non-I/M fleet, and two were used to measure the I/M fleet (see Table 9). Although not enough data are available to generate effectiveness estimates per Smog Dog, isolating the two instruments used commonly in both cities indicates statistically significant differences of 18% and 16%, respectively ($p = .00$). It should be noted that these averages are lower than the 24% emissions difference between the I/M and non-I/M fleet calculated in Tables 3 and 4. The difference in these averages indicates that the third Smog Dog may be introducing an upward bias in the Augusta-Macon measurements, thereby artificially inflating I/M effectiveness estimates. Determining the instrumentation issues of each Smog Dog is beyond the scope of this analysis, but evaluators considering remote sensing data for I/M evaluation should consider carefully the effects of multiple instrumentation in the quasi-experimental design.

CONCLUSIONS

The reference method for evaluating vehicle I/M programs yields several advantages over other methods using on-road remote sensing data. Unlike the step method, the reference method's usefulness is not limited to the 1st years of an I/M program. In fact, the reference method could be repeated over time to measure incremental effectiveness as more of the fleet is tested, inspectors become adept at identifying noncompliant vehicles, repair technicians gain experience at repairing emission control failures, and (more pessimistically) motorists learn better how to co-opt the test. And although the reference method's sample size requirement is significant—driven by the need to account for program and nonprogram fleet differences—it is not nearly as formidable as that of the comprehensive method. The latter approach involves large-scale data collection to ensure that vehicles are measured before and after inspection.

The reference method is not without its limitations, however. Selecting a comparable nonprogram fleet is a challenging task, to say the least. Although differences in fleet age and car-truck composition are relatively easy to account for between I/M and non-I/M fleets, discrepancies in maintenance trends, socioeconomic conditions, and vehicle quality are difficult to discern. Furthermore, differences in remote sensing instruments may confound results if equipment usage is applied unevenly in the quasi-experiment. Until additional studies of non-I/M fleets shed light on the role of these influences on fleet emissions, equating fleet differences with I/M effectiveness will be a tentative proposition.

As for the Atlanta enhanced I/M program, the reference method suggests that the program is reducing on-road emissions but not meeting EPA model predictions. Critics of EPA emission models, who complain about weak assumptions and outdated supporting information, will contest its use as a benchmark for program effectiveness (see Harrington, McConnell, and Cannon 1998). Setting aside model predictions for the moment, we depart with an estimate that the Atlanta enhanced I/M program reduced CO emissions by 26% for cars and 20% for trucks on average for the first 2 years of the program. These figures are expected to change over time due to increased inspection and repair competency, the 1999 implementation of a more advanced testing technology for older vehicles, the transition to annual testing in 2001, and annual adjustments in the waiver limit to more than $600 for difficult-to-repair vehicles. Future research efforts will include replicating the reference method at these different points in time to estimate the impact of these program changes on on-road fleet emissions.

NOTES

1. Enhanced inspection/maintenance (I/M) programs are required in areas of the United States in serious, severe, or extreme nonattainment of federal ozone standards (see note 3 for explanation of how nonattainment is determined). Moderate nonattainment areas are required to implement the less rigorous basic I/M programs. Marginal nonattainment areas have no I/M requirement.

2. Infrared technology is used to measure carbon monoxide (CO) and volatile organic compounds. Ultraviolet technology is used to measure nitrogen oxides.

3. The federal ozone standard is 0.12 parts per million averaged on an hourly basis. Ozone is one of the eight National Ambient Air Quality Standards set by the Environmental Protection Agency (EPA) to protect public health. (The remainder are CO, nitrogen dioxide, sulfur dioxide, ozone, particulate matter-10, particular matter-2.5, and lead.) There are five levels of nonattainment for these pollutants, ranging from marginal to extreme, which are determined by the number of times air monitoring stations in an area detect pollutant levels above federal standards during a specific time period.

4. The model year vehicles subject to testing vary across I/M programs.

5. New Jersey implemented the first I/M program in 1974, requiring annual idle testing of 1968 and newer light-duty vehicles at a state-operated testing facility.

6. Although the Clean Air Act (CAA) Amendments legislation emphasized annual testing, most enhanced I/M programs conduct biennial inspections to defray higher inspection fees that result from more costly advanced testing technologies.

7. 1992 Georgia Air Quality Act, Article 2: Motor Vehicle Emissions Inspection and Maintenance Act (Official Code of Georgia § 12-9-40 *et seq*.).

8. October 1996 was chosen as the soonest possible start-up date after the previous basic I/M program, which operated during a January to April vehicle registration season. Vehicle registration is now conducted year-round in Georgia, as is enhanced emissions testing.

9. Three significant changes have recently been made to the Atlanta enhanced I/M program. The waiver limit increased in January 2000 to $608, which represents $450 plus the consumer price index and fulfills EPA requirements. In 2001, testing frequency changed from biennial to annual; the requirement to inspect back to 1975 model years was replaced with the requirement to inspect the latest 25 model years; and the exemption of the newest 2 model years was changed to exempt the newest 3 model years.

10. Changes have been made to the program since the first 2 years of operation, which are the focus of this analysis. For example, the program began to require vehicles more than 6 years of age to undergo the more rigorous acceleration simulation mode (ASM) testing in October 1998. The primary difference between ASM and two-speed idle testing is the approximation of real-world driving conditions, that is, placing the engine under load. In ASM testing, while the emissions inspector depresses the accelerator to achieve 25 miles per hour, the vehicle's drive wheels are placed on a treadmill-like dynamometer that applies a 25% load on the vehicle engine. The latter approach is more representative of actual driving conditions than is an idle test.

11. The Federal Test Procedure is an elaborate testing protocol established in the early 1970s to certify manufacturer compliance with the 1970 CAA-mandated new vehicle emission standards.

12. Regression to the mean occurs when two imperfectly correlated measures are compared for a nonrandom sample. The nonrandom sample is typically drawn from high or low scorers on either measure. Regression to the mean refers to when the sample mean moves toward the population mean in the absence of intervention. In the context of I/M evaluation, this means that certain vehicles failing their initial I/M test will score more closely to the mean of the population on the retest, that is, register passing emissions without repair. Regression to the mean can also occur in vehicles that pass their initial inspection but would fail a subsequent retest.

13. The evidence of such bias is mixed. One recent study that used remote sensing to measure the vehicle emissions of refusals and participants alike found no significant difference between the two groups (Wenzel, Gumerman, et al. 2000, III-8), whereas an earlier similar study found that refusal vehicles had 2.5 times the emissions of volunteer vehicles (Stedman et al. 1994).

14. One challenge to I/M evaluations that employ data from adjacent geographic areas is the possibility that one form of I/M program avoidance—reregistration out of the I/M area to the control non-I/M area—can overestimate I/M benefit. This can happen in two ways. The exodus of I/M failures or probable I/M failures cleans up the I/M area's emissions, and the influx of I/M failures or probable I/M failures into the adjacent non-I/M area creates an artificially dirty emissions baseline there. The paper summarized here assessed the nine-county fleet's prior testing history, finding that less than 3% of the nine-county vehicles had received emissions tests within a 3-year window of their remote sensing measurement.

15. Augusta is located 136 miles east of Atlanta, whereas Macon is 76 miles south of Atlanta.

16. Vehicle identification numbers are 17-digit alphanumeric strings that uniquely identify every vehicle manufactured. When decoded, they provide additional characteristics of vehicles.

The vehicle identification number–decoded data of particular relevance to this research are vehicle type (car, truck, multipurpose vehicle, van) and model year.

17. Savannah, Athens, and Rome were also considered as potential control areas. Athens and Rome feature lower median household incomes and population densities than do Macon and Augusta. Savannah was ruled out based on its travel distance from Atlanta—226 miles and 4 hours—which rendered the cost of remote sensing research in this locale prohibitive.

18. All states except for California use EPA's MOBILE models to estimate emission factors with and without an I/M program. (California uses its own EMFAC model to estimate mobile source emissions.) The base emission rates computed by TECH5 are adjusted by MOBILE5b to account for the fraction of vehicles receiving an I/M waiver and the percentage of vehicles complying with I/M requirements. MOBILE-adjusted emission factors are then applied to travel demand models to obtain estimates of aggregate fleet emissions. Fleet emission estimates inform the emission inventories that test compliance with federal regulations in state implementation plans.

MOBILE5b (1996) is the third version of the MOBILE5 model released by EPA.

19. I/M program area measurements span 13 counties that compose the metropolitan Atlanta ozone nonattainment area: Cherokee, Clayton, Cobb, Coweta, DeKalb, Douglas, Fayette, Fulton, Gwinnett, Henry, Forsyth, Paulding, and Rockdale. Non-I/M program measurements include Bibb, Richmond, and Columbia counties.

20. Given that cooler temperatures can increase CO readings by reducing engine-operating temperature, there exists the possibility that temperature is driving some of the emissions differences between the inspected and uninspected fleets. The results of the semilogarithmic regression model dispute this assertion, however. Even when temperature differences are considered, Augusta and Macon vehicles have 16% higher emissions than Atlanta vehicles do. Furthermore, temperature exerts a negligible, albeit statistically significant, positive influence on CO emissions in the presence of vehicle type and age and inspection status.

21. The Continuous Atlanta Fleet Evaluation conducted remote sensing only in Augusta during 1997; thus, we have no Macon measurements to include in this analysis.

22. The software used is manufactured by Eastern Research Group. The I/M failure rates provided are based on California and Arizona I/M data. Although several types of I/M failure rates are provided, we chose that associated with the IM240 test procedure: the technology that most closely parallels the Federal Test Procedure.

23. Statistical analysis is not formally justified for these data, which are from a convenience sample. Nonetheless, the usual confidence intervals and tests are provided for those readers who find them useful.

24. A linear functional form is chosen to mirror the pattern seen in graphical displays of mean emissions plotted against model year. This choice is consistent with the assumption made by the mobile emissions models of the U.S. EPA and the state of California, which linearly relate mileage to emissions. We use vehicle age as a surrogate for mileage data, which were not available for uninspected vehicles.

25. These R^2 statistics indicate a lack of fit that is most likely attributable to tremendous variability in vehicle emissions. Emissions can vary across vehicles by several orders of magnitude due to factors such as emission control technology, age, mileage, model, maintenance, and socioeconomic status of vehicle owners (Wenzel, Singer, and Slott 2000). Individual vehicle emissions can also vary depending on the reliability of emission control systems, engine and catalyst temperature, ambient temperature and humidity, and fuel quality. The majority of these factors are unobserved in studies of vehicle emissions, producing one explanation for low explanatory power of regression models.

26. We conducted a Modified Levine (ML) test on the residuals of an ordinary least squares model of on-road CO using model year and vehicle type as explanatory variables. ML was chosen because it does not require normally distributed residuals and, in fact, is robust against serious departures from normality (Neter et al. 1996, 112). Focusing on the relationship between the residuals and model year, we determined that the probability of identical residual distributions between older and younger vehicles of is 0 (t(ML) = –2101).

27. The on-road emissions ratio for 1981 cars runs contrary to expectations, with higher inspected than uninspected vehicle emissions. This is most likely due to small sample size for this model year (n = 110).

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