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Inspection and Maintenance Evaluation using Historical U.S. Remote Sensing Measurements

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5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Gary A. Bishop
Department of Chemistry and Biochemistry
University of Denver
Denver, CO 80208

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Prepared for:

Coordinating Research Council, Inc.
5755 North Point Parkway, Suite 265
Alpharetta GA 30022

Executive Summary

National Ambient Air Quality Standards (NAAQS) were established as part of the Clean Air Act Amendments of 1970 (CAAA) to protect the public health and environment. This law required the United States Environmental Protection Agency (EPA) to set outdoor limits for many common air pollutants and establish a monitoring network in metropolitan areas to demonstrate compliance. The Clean Air Act (CAA) further required states with areas that exceeded the NAAQS to submit an acceptable State Implementation Plan (SIP) to the EPA detailing the steps that would be taken to bring the area into compliance. Since internal combustion engines used in transportation are a common source for many of the pollutants regulated by the NAAQS, many subsequent regulations and control programs focused on reducing these emissions.

Inspection and maintenance programs (I/M) were conceived by state regulators as a way to locally maintain new car emission standards after the vehicle warranty period had expired. Under the 1977 CAAA the U.S. EPA published guidelines that established criteria and performance standards for these programs and began requiring them in SIPs. The initial program concepts were straight forward; establish some type of emissions inspection with limits based on the age and type of the vehicle and require each vehicle registered in the area to meet these limits on a prescribed periodic basis. Repairs are suggested for vehicles that don't meet the program limits, usually with an upper dollar limit on those repairs, until the vehicle can pass a subsequent test. Failure to comply with the program requirements most often results in the owner being unable to renew the vehicle's registration.

The effectiveness of the programs in meeting their overall emissions reductions targets established in each states SIP has been the subject of many studies (National Research Council, 2001). In part because the programs are not inexpensive to the public in either direct costs for the test fees or in time required to meet the requirements. Many of the program evaluations compare the emissions performance of a fleet known to have complied with program requirements against a local or nearby fleet that is outside the jurisdiction of the program. Any differences found between the mean emissions of the two fleets are then ascribed to be a benefit of the I/M program under study. In contrast, state government and EPA evaluations of the I/M program benefits are generally predicted through the use of an approved EPA computer model. Both approaches have significant short-comings in effectively evaluating the program benefits.

The fundamental mechanism of all I/M programs is to increase the successful repair rate of malfunctioning vehicles in the program's area. Since malfunctioning vehicles may emit more pollution, successfully targeted vehicle repair should speed up the reduction of ambient emission levels or help to maintain them. This means that vehicle fleets in I/M areas should have in-use emission characteristics that are demonstrably different than those in areas that do not have such programs. This report bases its evaluation of the effectiveness of I/M programs by looking for these emission differences. We will do this by comparing and contrasting emission reduction trends, vehicle emission deterioration rates and quantifying any differences in the two fleet's emission distributions.

All of these types of evaluations require long continuous emissions measurement records and measurements from thousands of vehicles in each cities fleet to define their emission characteristics. Vehicle emission remote sensing devices offer a non-intrusive way to collect a large number of vehicle tailpipe emission measurements (typically 3,000 to 6,000 measurements per day) in a short period of time without the vehicles and the owners knowing they are being tested. The ability to collect a large number of emission measurements in each city benefits the statistical comparisons and is a major strength of having a large number of measurements. However, measurement sites generally limit the observed vehicle operating conditions to a fully warmed up state and engine loads to those observed in Federal Test Procedure testing. In addition, information on the vehicles measured is limited to non-personal manufacturers' information that can be obtained through local motor vehicle registration databases.

In 1997, the Coordinating Research Council (CRC) contracted with the University of Denver to begin a long-term (10 year) roadside vehicle emission measurement campaign using on-road remote sensing devices at a site in the northwest suburbs of Chicago, IL. Subsequent campaigns were added at locations in Denver, CO (1999), Riverside, CA (1999 – 2001 only), West Los Angeles, CA (1999, eventually replaced the Riverside site) and Phoenix, AZ (1998) that produced thirty data sets and more than three quarters of a million measurements through 2007. This program was extended starting in 2013 at all of the sites but the Phoenix, AZ site where the ramp was eliminated by new construction. All of these sites were located in areas where vehicle owners were subject to a local I/M program as part of the region's air quality improvement plans.

In addition to the CRC supported measurements, the University of Denver has made vehicle emission measurements in additional cities with and without an I/M program. In 2003 we began collecting emission measurements at a site in Tulsa, OK, an area that has never had an I/M program, and to date have collected a total of five data sets at this site. To date the University of Denver has collected 88 emission measurement data sets with 18 of these having been collected in 12 different cities that did not have an I/M program at the time of the measurements. A full description of all of these sites, the measurement campaigns and the database files collected are publically available and can be found online at www.feat.biochem.du.edu. These data sets provide the emission measurements that will be used in making the comparisons between I/M and non-I/M areas.

Figure E1 plots the historical fuel specific mean emissions for CO (top), HC (middle) and NO (bottom) against measurement year for the four long-term measurement sites: Chicago, Denver, Tulsa and West Los Angeles. The uncertainties plotted are standard error of the mean determined using the daily mean emissions for each site's campaign. Table E1 compiles the overall percent emission reductions for the mean (shown in Figure E1) and 99th percentiles for CO, HC and NO for these same locations. The Chicago, Denver and West Los Angeles sites, which have longer

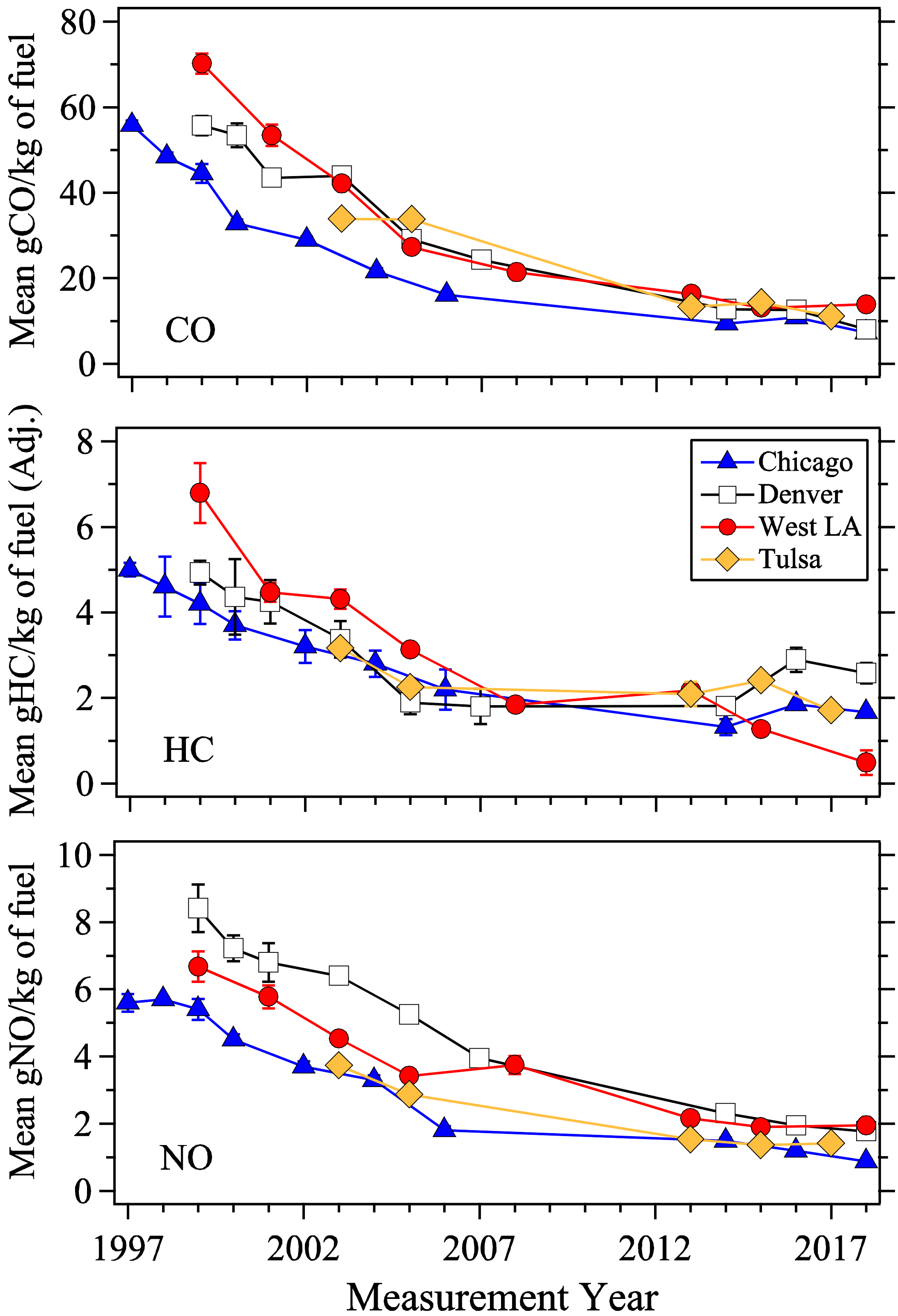

Figure E1. Mean fuel specific emissions by measurement year for Chicago, Denver, Tulsa and West Los Angeles sites. Uncertainties are standard errors of the mean determined using the daily measurements.

Table E1. Overall percent reductions in fleet mean and 99th percentiles for CO, HC and NO emissions by location.

Location	First and Last Measurement Year and Number of Data Sets	%△CO Mean / 99th	%△HC Mean / 99th	%△NO Mean / 99th
Chicago, IL	1997 / 2018 / 10	86% / 75%	66% / 56%	84% / 48%
Denver, CO	1999 / 2018 / 9	86% / 70%	49% / 48%	79% / 36%
Tulsa, OK	2003 / 2017 / 5	67% / 66%	47% / 27%	62% / 16%
West LA, CA	1999 / 2018 / 8	84% / 73%	79% / 66%	78% / 40%

time trends than Tulsa, show larger emission reductions. However, overall we have observed significant emission reductions in both metrics at all four locations.

Using a first order rate equation we calculated year over year percent reductions for the non-diesel fleets (the focus of most I/M programs) in these four areas since ~2003 to match the Tulsa measurement's time span. To improve the regression statistics we included additional data sets in the analysis that were available from the LA Basin (Van Nuys 2010 and two Lynwood 2018 sites) and at the Denver 6th Avenue site (Summer 2005). Figure E2 shows the observed reductions with the calculated 95% confidence intervals. The shorter time period increases the uncertainty in the emission reduction estimates but, despite this, the CO and NO estimates are all significant at the 95% confidence interval. For HC emissions only the Chicago and Los Angeles Basin reductions are significant. Since 2003 the emissions changes for these three species on a year over year basis again are statistically similar between all of the sites despite differences in fleet ages, fraction of car vs truck representation in the measured fleet and any driving mode differences.

We acquired the MOVES2014a input files from the Colorado Department of Public Health and Environment that were used in the 2017 audit of Colorado's seven county Denver Metro area (Adams, Arapahoe, Boulder, Broomfield, Denver, Douglas and Jefferson) I/M program to compare model predicted emission differences with those in the 2017/2018 Denver CO and 2017 Tulsa OK measurements. The MOVES2014a model was run for the seven county Denver CO region with and without the I/M program to generate the fleet average emissions for these two scenarios. We restricted the model output to only include gasoline passenger cars and light-duty trucks (light-duty diesel vehicles are administered under a separate program in Colorado that only requires a tailpipe opacity test) and an urban restricted access highway driving mode which best describes the Denver, CO and Tulsa, OK remote sensing sampling sites.

The model predicts significantly higher emissions (1.5 to 3.5x's) for both the I/M and non-I/M fleets than observed on-road. For the direct comparison the model predicts an I/M benefit in the Denver Metro of 17.9% for CO, 33% for HC and 21.9% for NO_x (a 22.4% reduction for NO). In the on-road fleet comparison the measurements generally agree for CO with lower emissions in Denver (20%) but Tulsa (non-I/M) has lower HC (32%) and NO (15%) emissions. The comparison is complicated by the fact that in the Denver Metro I/M program vehicles from the

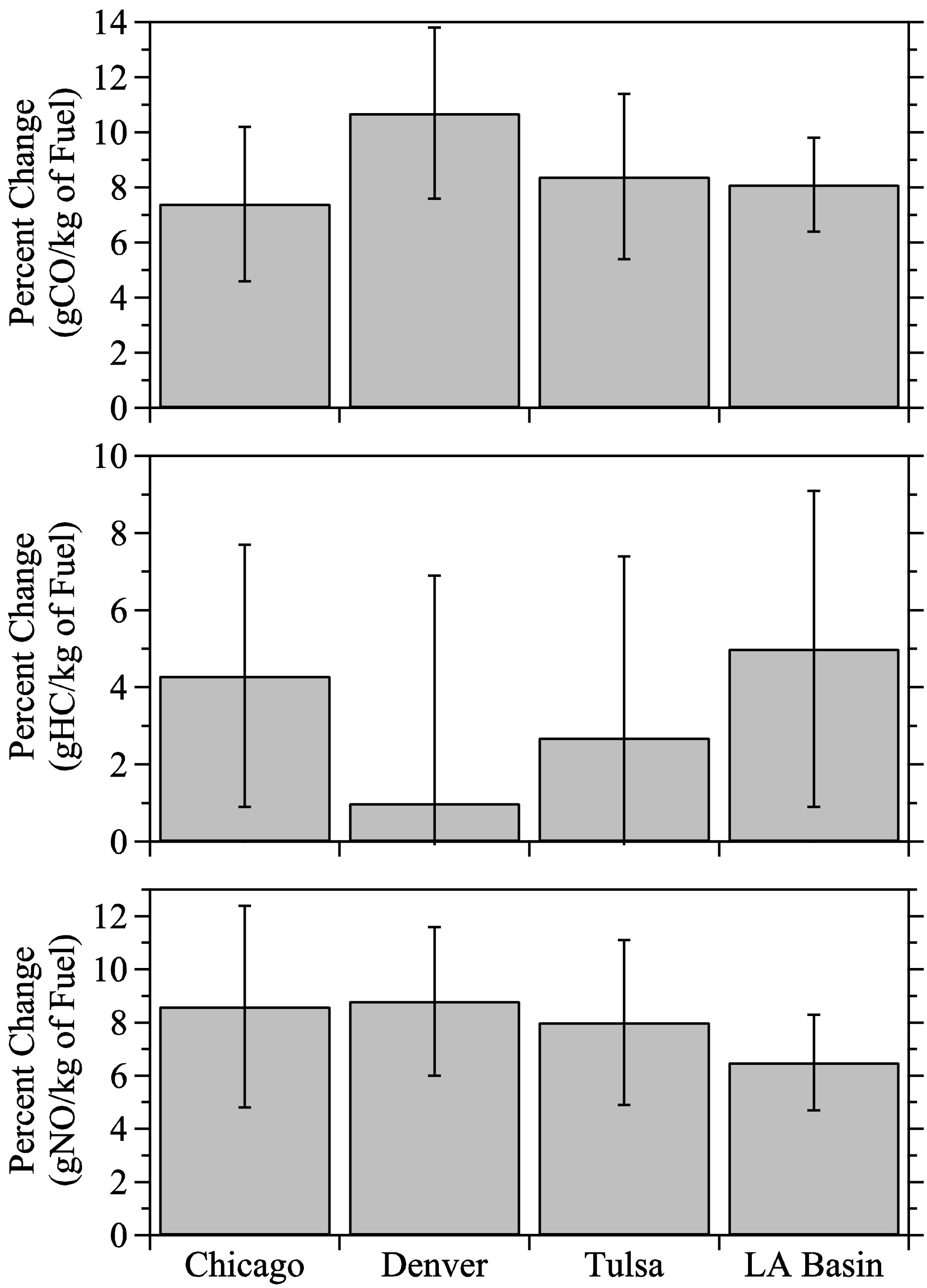

Figure E2. Year over year percent changes in fleet emission for CO (top), HC (middle) and NO (bottom) with 95% confidence interval estimates for the non-diesel fleet using only measurements collected since ~2003 to match the Tulsa measurements.

first seven model years are exempted. This results in the MOVES2014a model ascribing the same emissions to these vehicles in the I/M and non-I/M fleets. In the on-road comparison there are significant percentage differences in the CO and NO emissions within the first seven model years that account for a majority of the fleet emission differences found. This indicates that factors other than the Denver Metro I/M program are responsible for these observed differences. Higher HC emissions are observed on-road in Denver due to a higher proportion of decelerations that are now observed at this location after the ramp was reconstructed in 2014.

After the first seven model years MOVES2014a predicts emissions that increase at a faster rate for the non-I/M fleet increasing the differences found with the I/M fleet. Figure E3 illustrates this for the comparison of the molar ratios of CO for the non-diesel non-I/M fleet versus the I/M fleet (on-road measurements upper panel, model comparison lower panel). Age is accounted for by plotting the means of each model year (2017 - 1987) and the Denver means have been calculated using the Tulsa car/truck ratio for each model year to normalize these differences between the two locations. The on-road emissions data comparison between Tulsa (non-I/M) and Denver (I/M) does not show the increasing emissions difference with age predicted by the model. As previously mentioned, differences occur in the first seven model years as well as in the older model years, however, the differences that do occur show a consistency across all model years with a quantile-quantile plot comparison resulting in a straight, not curved correlation.

One possible explanation for the increasing emission differences found in the model predictions is that the emission deterioration rates in the model are equal for the first seven model years and then increase at a faster rate for the non-I/M vehicles. Using measurements collected across many years, and assuming that emissions deterioration can be modeled as a linear process, we calculated emission deterioration rates for all of the possible model years in the non-diesel fleets in our four major cities. The deterioration rate is the slope of a line fit to each model year's mean emissions versus age using each calendar year's data. Figure E4 is a plot of emission deterioration rates in g/kg of fuel/year for CO (top), HC (middle) and NO (bottom) versus model year comparing the West Los Angeles (I/M) with the Tulsa (non-I/M) fleets. The uncertainties plotted are the standard error of the slope of the least squares fit. This comparison should maximize any emission deterioration differences between fleets. Not only does the Los Angeles area have what is considered to be the premier I/M program in the world but also has vehicles that are manufactured to California certification standards. In general the older model year vehicles in Los Angeles and Tulsa have deterioration rates that are similar; however, the newest model years for CO show the most disagreement (2010 & newer model years exempted from I/M program) and the largest uncertainties having the fewest number (only 3) of data sets. However, in general, this comparison indicates that the deterioration rates in the on-road fleets are not significantly different as we presume are predicted by the MOVES2014a model.

The Pitchford and Johnson (Environ. Sci. Technol., 1993) model of fleet emissions predicts that if the malfunction and repair rate constants are equal, then the emissions distribution will not change over time. If the malfunction rate is larger, then the total emissions will increase over

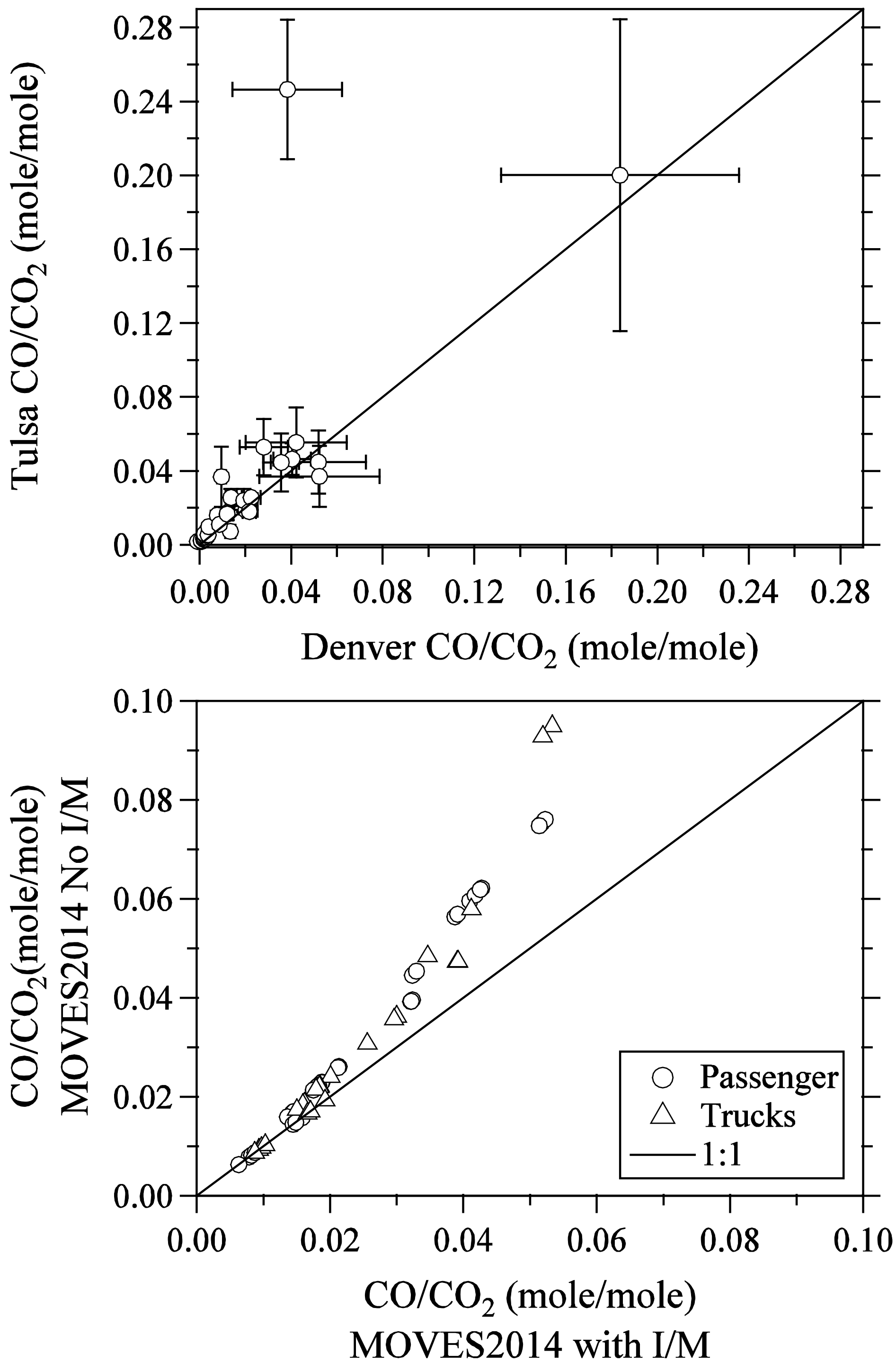

Figure E3. 2017 Tulsa non-diesel mean CO molar ratios, grouped by model year (2017 – 1987), versus 2017 Denver data forced to match the Tulsa car/truck distribution (top panel). MOVES2014a gasoline mean CO molar ratios for the Denver Metro area with I/M, grouped by model year (2017 – 1987), for passenger vehicles (O) and trucks (Δ) against the same fleet without I/M. Uncertainties in the top panel are standard error of the mean calculated from the daily measurements. The diagonal lines are 1:1 lines drawn for comparison.

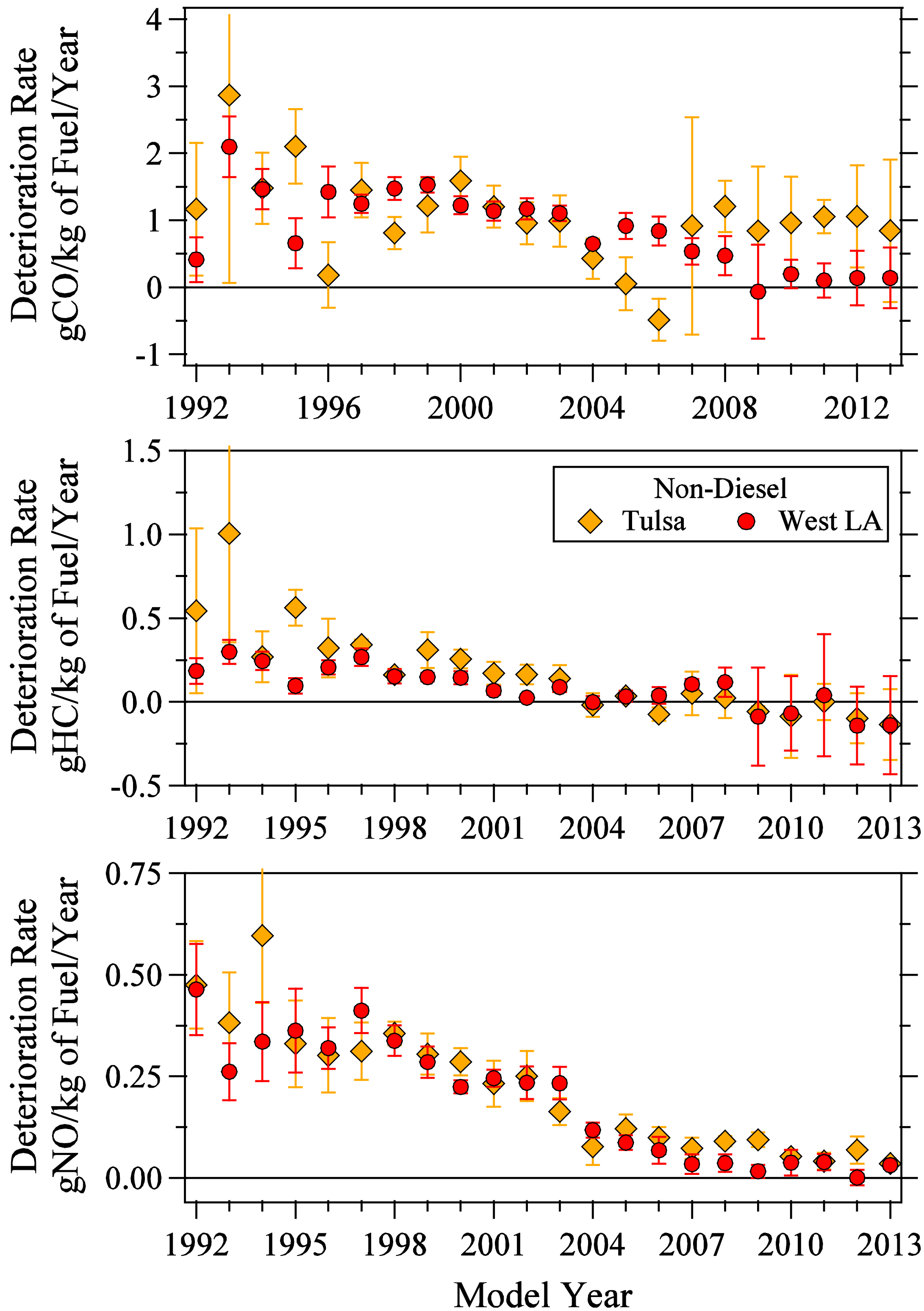

Figure E4. On-road fuel specific emissions deterioration rates (grams/kg of Fuel/Year) vs. model year for non-diesel Tulsa (◆) and West Los Angeles (●) fleets. The uncertainty bars plotted are the standard error of the slope for the least squares fit.

time and if the repair rate is larger, then the emissions will decrease. We have firmly established that U.S. fleet emissions have decreased significantly over the last twenty years which means that the repair rate is larger than the malfunction rate and that fleet emission distributions should also have changed. Figure E5 is a cumulative probability plot with an x-axis that has been transformed for a normal distribution. If the data were normally distributed they would plot as a diagonal straight line. Plotted are the fuel specific CO emissions distributions for the 2005 and 2017/2018 Denver and Tulsa measurements. The larger open symbols are the mean emissions for each cities distribution.

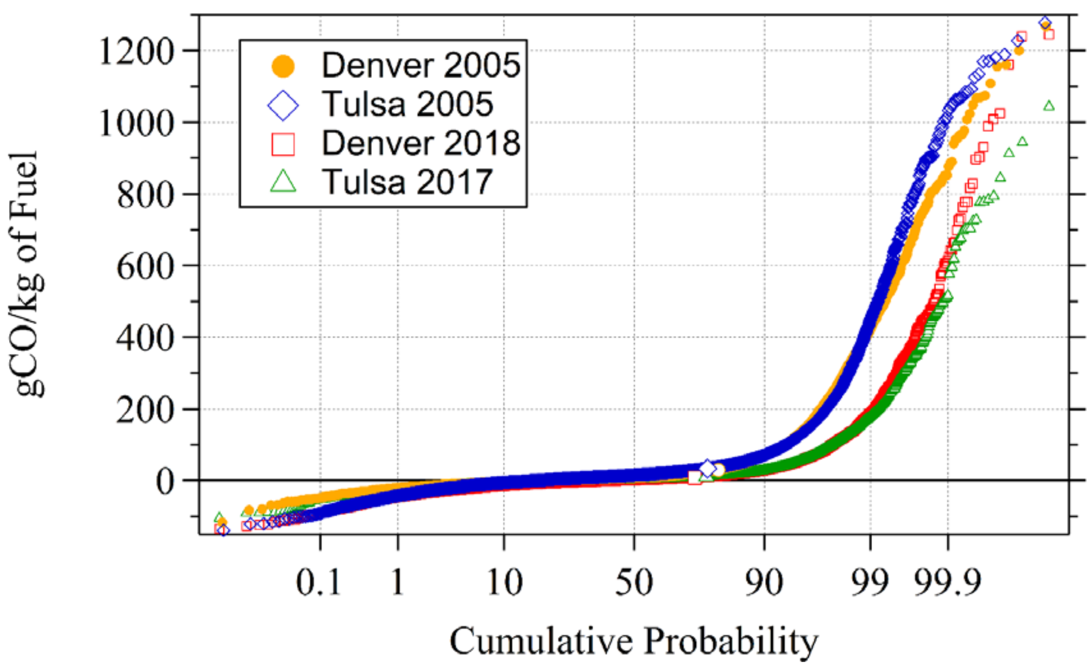

Figure E5. Cumulative probability plot of fuel specific CO emissions for the 2005 and 2017/2018 Denver and Tulsa data sets. The x-axis has been transformed to a normal distribution. If the data sets were normally distributed they would plot as a diagonal straight line. Open symbols are the mean emissions for each distribution.

These plots give the probability of finding a gCO/kg of fuel emissions reading that is less than or equal to a value on the y-axis. The changes observed between the emission distributions collected in 2005 and 2017/2018 confirms that the repair rates in these two fleets is larger than the malfunction rate as the emission distributions have changed significantly since 2005. In addition, these plots show that a majority of vehicles have zero or near zero emissions and a small minority of the vehicles, those at the top of the distribution in Figure E5, are responsible for a disproportionate share of the total emissions. I/M programs by design should reduce the frequency and the magnitude of the emissions of these vehicles by increasing their successful repair rate when compared to a similar fleet without a program. These plots show no significant differences between the I/M fleet in Denver and the non-I/M fleet in Tulsa especially in the upper portions of the distributions where the emissions matter the most.

To date we have collected 18 vehicle emissions data sets in 12 different cities including Tulsa, that did not have an I/M program in place when the measurements were collected (see Appendix A). To show that Tulsa is not a unique case one can compare the shapes of the upper portion of I/M and non-I/M city emissions distributions by calculating the fraction of the total vehicle emissions contributed by the vehicles above the 99th percentile. This involves rank ordering the data for each species and then calculating the fraction of the emissions contributed by the 99th percentile (top 1%) and following the changes in this fraction over time for the I/M and non-I/M fleets. This evaluation consists of 70 data sets from I/M areas and 18 data sets from non-I/M areas. Figure ES6 is a plot of the top 1% emissions fraction for CO (top), HC (middle) and NO (bottom) for I/M fleets (●) and non-I/M fleets (Δ) versus measurement year. The solid lines are the least squares best fit lines to each data set and the dashed lines are the 95% confidence intervals for those fits. As the emissions distribution has become skewed, the top 1% of the measurements at each location account for an increasing share of the total. For example, the percent of CO emissions, the species collected the longest, emitted by the top 1% has grown from ~5% of the total in 1989 to greater than 35% of the total in 2018. In general the trends are the same for the I/M and the non-I/M fleets as the 95% confidence intervals overlap for each of the species plotted. The similar changes over time in the fraction of emissions by the top 1% of the measurements in Tulsa and other I/M and non-I/M locations indicates that the tops of the emissions distribution are not significantly different.

It should be expected that when an I/M program successfully reduces fleet emissions, those reductions will result in a change in the shape of the emissions distribution. By collecting emission measurements from a large number of vehicles at a given site over a long period of time we can: (a) establish the emissions distribution of a fleet and (b) determine the extent of any changes that occur over time in those distributions. Using the emissions data collected in our four major cities, Chicago, Denver, Tulsa and Los Angeles, we have shown that:

1. Emission reductions for CO, HC and NO have occurred at similar levels and rates in each of these cities.

2. The current EPA computer model (MOVES2014a) over predicts the levels of CO and NO emissions for both I/M and non-I/M areas for the urban restricted driving mode.

3. Higher emission deterioration rates for the non-I/M fleet, which the EPA computer model appears to assume, are not observed in the on-road fleets.

4. The shape of the emissions distribution, especially at the top where the highest emitters are found, shows no meaningful differences between I/M and non-I/M cities. The result is that the emissions level and frequency of occurrence of high emitters is similar in I/M and non-I/M cities.

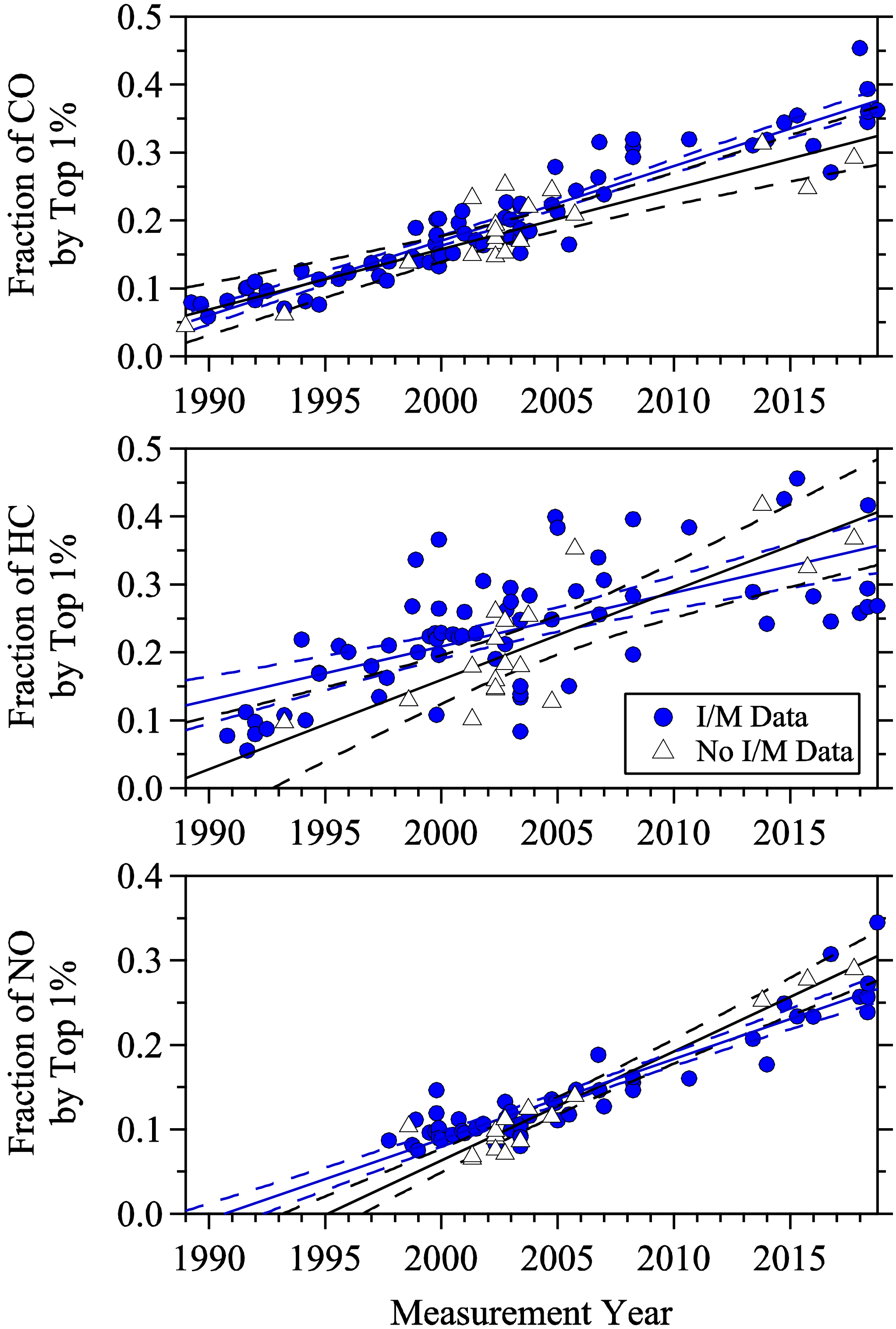

Figure E6. Fleet fraction of the 99[th] percentile emissions for CO (top), HC (middle) and NO (bottom) for all U.S. data sets collected in an I/M area (●) and all U.S. data sets collected in areas that do not have an I/M program (Δ) versus measurement year. Solid lines are least squares best fit lines and the dashed lines are 95% confidence intervals.

5. The lack of any significant differences between the shapes of the CO, HC and NO emission distributions implies that there is also no difference in the high emitter repair rates, as defined in the Pitchford and Johnson (Environ. Sci. Technol., 1993) fleet emissions model, for malfunctioning vehicles in these four cities.

Recent random roadside inspection data from California supports the finding of a lack of a significant difference between I/M and non-I/M cities emission distributions. Random roadside inspection data from 2018 found significant recidivism rates (35% roadside failure rate) among 2000 - 2006 model year vehicles that initially failed and then passed a Smog Check test within a year of that test (Bureau of Automotive Repair, 2019). In addition 17% of these same model years, that initially passed their test, were also found to fail during the roadside inspections. The combination led to a higher overall failure rate than was found on the day these vehicles were tested by the Smog Check program. This information supports the findings of similarly shaped emission distributions observed in the remote sensing data and a similar frequency of high emitters in Los Angeles and other I/M program areas that have not been reduced by the programs.

Acknowledgements

This work would not have been possible without the vision of Don Stedman who conceived of the FEAT remote sensing system and recognized that long term data collection projects are invaluable. In addition I would like to acknowledge the many graduate and post-graduate students that contributed to the collection of these emissions databases and Ms. Annette Bishop who has transcribed the majority of the license plates. I would like to acknowledge the Colorado Department of Health and Environment for making available the MOVES input files used in the model comparisons. Also that I have benefited from helpful statistical discussions with Dr. Cathy Durso and Dr. Eric Gilleland. Comments from the various reviewers of this report were also appreciated.