Environmental Science & Technology

Article

pubs.acs.org/est

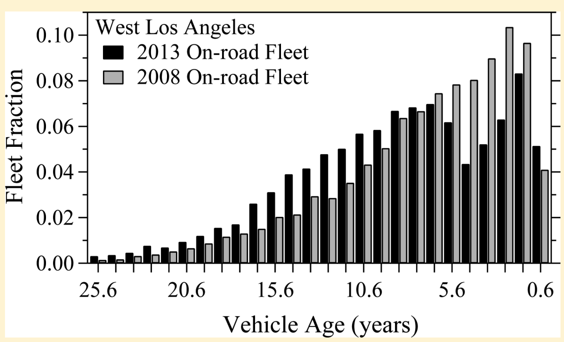
The Recession of 2008 and Its Impact on Light-Duty Vehicle Emissions in Three Western United States Cities

Gary A. Bishop* and Donald H. Stedman

Department of Chemistry and Biochemistry, University of Denver, Denver, Colorado 80208, United States

Supporting Information

ABSTRACT: The global economic recession of 2008–2010 severely depressed light-duty vehicle sales in the United States. On-road fleets observed with a remote vehicle exhaust sensor in 2013 at three historical sampling locations in Denver, Los Angeles, and Tulsa showed large reductions in the fleet fractions of 2009 model year vehicles of 40%, 38%, and 35%, respectively, when compared to prerecession 2007 levels with the light-duty truck category suffering the largest percentage declines. The fleet fraction for these ~5 year old vehicles is normally reserved for vehicles more than twice their age. This resulted in a significant increase in the on-road freeway fleet age, which had been relatively stable. The fleet average age increased by two years in Denver and Los Angeles but only by one year in Tulsa, likely due to its faster economic recovery. Using fleet fractions from previous data sets, we estimated age-adjusted mean emissions increases for the 2013 fleet to be 17–29% higher for carbon monoxide, 9–14% higher for hydrocarbons, 27–30% higher for nitric oxide, and 7–16% higher for ammonia emissions than if historical fleet turnover rates had prevailed.



INTRODUCTION

Light-duty vehicle emissions continue to be considered a significant source of carbon monoxide (CO), hydrocarbons (HC), oxides of nitrogen (NO_x), and particulate matter in United States cities.[1] However, many decades of regulations and vehicle improvements have produced dramatic reductions in light-duty fleet emissions and improved ambient air quality despite continued increases in the number of vehicles and miles driven.[2−5] These improvements have been driven by a continual turnover of the vehicle fleet to not only lower emitting new vehicles but to vehicles that maintain their low emission rates for increasingly longer periods of time.[6,7]

United States fleet turnover rates are a product of many economic and personal choice factors. For the last two decades, Americans have been keeping their vehicles longer as vehicle prices and reliability have increased, despite expensive federal and state government programs that place bounties on older vehicles commonly called "Cash for Clunkers".[8] This has led to a slow and steady increase in the average age of the registered United States fleet from approximately 8.5 years old in 1995 to just over 11 years old in 2012.[9]

The global economic recession, which began in 2008 and continued through 2010, contributed to the continuation of this trend as new vehicle sales in the United States were severely impacted. Nationwide light-duty vehicles sales for 2009 models were 21% less than in 2008 and 35% less than 2007 prerecession levels, which were the fewest new vehicles sold in the United States since the early 1980s.[10,11] New vehicle sales, or lack thereof, have a cascading effect on the overall vehicle fleet with delayed purchasing decisions impacting the number of vehicle retirements, which in turn changes not only the age of the on-road fleet but can also alter its emissions profile. Using recently collected on-road emission measurements from three western United States cities, we can highlight some of the changes that have occurred in the on-road fleet's age distribution and estimate the implications on the fleet's emissions.

EXPERIMENTAL SECTION

The three sites sampled in this study are listed in Table 1 along with a summary of their locations, sampling specifics, mean driving modes observed, and the dates of the last measurements collected at the same location.[7] Data were collected at the West Los Angeles (WLA) site over 8 days between April 27 and May 4, 2013, at the Tulsa site for 5 days between September 30 and October 4, 2013 and for 3 days in Denver (December 12 and 13, 2013, and January 3, 2014). The sites in Denver and Tulsa are curved uphill interchange ramps connecting major freeways, while the WLA location is a traffic light-controlled on-ramp to eastbound I-10 from a major arterial road (La Brea Ave.). All of the valid and matched records from each site were used in this analysis and were not filtered for fuel use or weight classifications unless indicated. The data sets described in this paper, along with previous data sets that we have collected, are

Received: September 3, 2014
Revised: October 30, 2014
Accepted: November 19, 2014
Published: November 26, 2014

Table 1. Summary of Sampling Locations, Measurement Statistics, Driving Mode, and Prior Sampling Dates

city sample dates	location/roadway grade	vehicle records attempts/plates/matched	mean model year	mean speed (mph)/ acceleration (mph/sec)	prior sampling date/ mean MY
West Los Angeles 4/27−5/4/2013	SB La Brea Ave. to EB I-10/2.0°	33,807/27,808/27,247	2004.7	21.9 −0.2	March 2008 2001.2
Tulsa 9/30−10/4/2013	WB US64 to SB US169/2.7°	29,268/21,988/21,115	2006.3	24.3 −0.01	September 2005 1999.3
Denver 12/12−13/2013, 1/3/2014	NB I-25 to WB 6th Ave./4.6°	25,881/19,883/19,242	2005.2	22.9 0.01	February 2007 2000

available for download from our Web site at www.feat.biochem.du.edu.

A University of Denver developed remote vehicle exhaust sensor, named Fuel Efficiency Automobile Test (FEAT), was used to collect all of the data sets listed in Table 1. The instrument consists of a source and detector unit aligned across a single lane roadway and consists of a nondispersive infrared (NDIR) component for detecting CO, carbon dioxide (CO_2), HC, and twin dispersive ultraviolet spectrometers capable of measuring nitric oxide (NO), sulfur dioxide (SO_2), ammonia (NH_3), and nitrogen dioxide (NO_2) at 100 Hz and has been fully described in the literature.[12−14] Since the reduction of sulfur from gasoline and diesel fuel in the United States to very low levels, SO_2 emissions have become an exercise in measuring zero, and while they were collected as a part of this study, they were not calibrated for and will not be reported. FEAT measures vehicle exhaust gases as a ratio to exhaust CO_2 because the path length of the plume is unknown, and the ratios are constant for a given exhaust plume. Each species'-measured ratio is compared and scaled by its certified gas cylinder ratios measured at each location. For this analysis, the ratios have been converted into fuel specific emissions of grams of pollutant per kg of fuel by carbon balance using a carbon mass fraction of 0.86 and doubling the HC/CO_2 ratio to account for the poor quantification of certain hydrocarbon species by NDIR absorption.[12,15]

A freeze-frame video image of the license plate of each vehicle is recorded along with the emission measurements. The license plate information was used to obtain nonpersonal vehicle information including make, model year, and vehicle identification number (VIN) from the state registration records for California, Colorado, and Oklahoma. The VIN information was further decoded for vehicle type (passenger or truck) and fuel type for the Oklahoma records. In addition to emission measurements, a pair of parallel infrared beams (Banner Industries) 6 feet apart and approximately 2 feet above the roadway is used to measure the speed and acceleration of the vehicles. Measurements were only collected during daylight hours with dry roadway conditions.

Ratio calibrations were performed in the field at each of the three sites using three certified gas mixtures (Air Liquide, Longmont, CO): (1) containing 6% CO, 0.6% propane, 6% CO_2, and 0.3% NO, balance nitrogen, (2) 0.05% NO_2 and 15% CO_2, and (3) 0.1% NH_3 and 0.6% propane. The field calibrations are used to scale the measurements for any day-to-day variations in instrument sensitivity and, most importantly, variations in ambient CO_2 levels caused by atmospheric pressure, temperature, and ambient pollution differences.

RESULTS AND DISCUSSION

All three sites listed in Table 1 have been part of long-term sampling campaigns to measure and track on-road light-duty vehicle emissions in the United States. The WLA site has five previous emission databases starting in 1999. The Denver site has the longest record with 12 previous databases starting in 1995. The Tulsa location has two databases collected in 2003 and 2005.

Figure 1 plots the fleet fractions by model year for each site listed in Table 1. Each model year grouping has been subdivided between diesel and gasoline fuel types and between passenger vehicles (blue diagonal hatching) and trucks (which include vans and SUVs, green horizontal hatching) as defined by the vehicle's VIN showing the site differences in the passenger and truck populations. The diesel passenger and truck classifications have been combined (solid black bars) because of their small numbers. Only the Denver measurements were collected at a late enough date to enable the 2013 model year fractions to be fully populated. The economic downturn that started in 2008 can be easily seen in the lack of 2009 and newer model year vehicles. At the WLA site, the

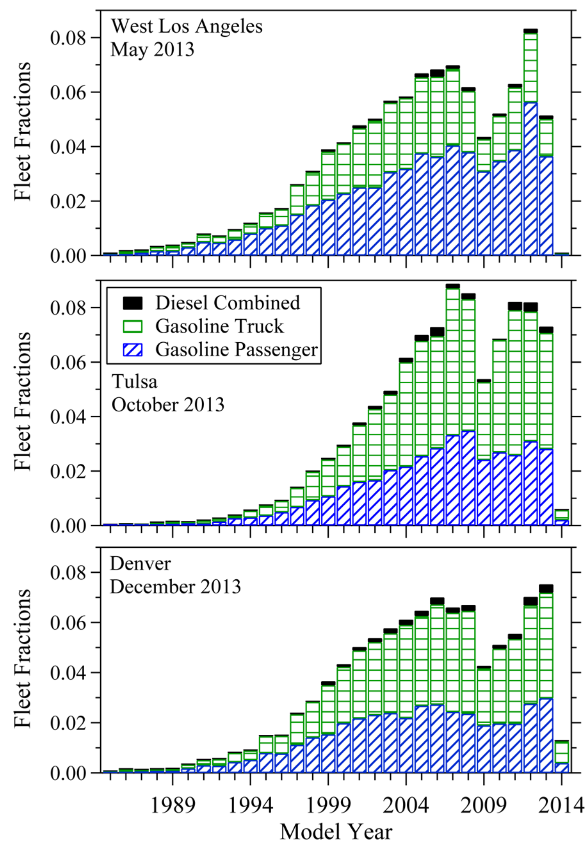


Figure 1. On-road fleet fractions versus model year for the three data sets collected in each city. Each model year is subdivided by fuel and vehicle type as defined by the vehicle identification number.

overall 2009 models were 38% fewer than 2007 models, which is similar to that reported for measurements in August of 2010 in Van Nuys, California, about 15 miles northwest of the WLA site.[16] However, this value is smaller than the reported 45% drop in statewide California new 2009 vehicle registrations when compared with 2007 registrations.[10] We have previously reported that the WLA fleet appears to have more resistance to economic factors as its fleet fractions for new vehicles showed no measurable reductions during the 2001 economic downturn when compared with sites in San Jose and Fresno, California.[17]

At the Tulsa and Denver sites, 2009 model year population fractions are 35% and 40% lower than the prerecession 2007 model year. The 2009 population fractions observed in 2013 are at levels more consistent with vehicles more than twice their age. Both the gasoline and diesel truck segments suffered the largest contractions, with the 2009 gasoline truck segment dropping 58%, 47%, and 42% for WLA, Tulsa, and Denver, respectively, compared with 2007 model year levels. Reductions in the percentage of diesel-fueled vehicles were comparable. Each site has noticeable differences in the shapes of the age fraction plots, with Tulsa exhibiting an enhanced number of 2007 and 2008 models and a faster recovery to near prerecession levels by the 2011 models, driven by the rebound in the number of trucks. The WLA site recovery in 2012 is driven by an increase in the fraction of passenger vehicles.

The WLA site shows the earliest recession impacts of the three sites with noticeable reductions in the fraction of 2008 models. This dovetails with the U.S. Bureau of Labor Statistics annual metropolitan unemployment rates, where California showed earlier increases and higher overall recession impacts while the Tulsa area had the lowest unemployment rate during the 3 year period (i.e., 2009/2011 Tulsa 7.1%/6.6%, Denver 8.3%/8.6%, and LA 10.9%/11.4%) and recovered faster.[18] Both the WLA and Denver fleets took until the 2012 models to reach 2007 levels, with the WLA site registering a significant enhancement in the fraction of 2012 models. This combination of effects results in Tulsa having 5% more 2009 and newer models than the other two sites.

The lack of three to five year old vehicles has led to increases in the age of these on-road fleets. Taking advantage of the historical measurement records at each site, we can estimate the magnitude of the fleet age increases. Figure 2 is a plot of fleet age, computed assuming that new model years begin in September, versus measurement year for all of our Denver and LA basin databases. Denver and the LA basin have two of the longest historical records of on-road measurements, both beginning in 1989, including 12 data sets from the I-25/6th Ave. Denver site (filled circles) and 6 data sets from the La Brea Ave./I-10 WLA location (filled triangles) used for the 2013 measurements. The solid line has been drawn at 7 years to highlight the fact that both weekday fleets' observed age at our freeway sites over the past 25 years have been remarkably stable and have not experienced the age increases reported for the national registered fleet.[9] The two right most points show age increases for Denver and WLA that are slightly more than 2 years older than their previous measurements. The 9 year old fleet observed in 2011 is the previously mentioned data set collected in Van Nuys, California.[16] We can check our age calculation for the WLA site by using the five previous data sets to perform a simple linear regression of mean model year versus measurement year (Figure S1, Supporting Information). This eliminates age conversion assumptions and predicts that in 2013 the on-road mean model year, with fleet turnover rates of the previous 15 years, would have been 2006.7 or two years newer than observed (2004.7), which is consistent with the age difference estimate from Figure 2. The Tulsa site has the shortest historical record, the largest gap in the data record (8 years), and the youngest fleet of the three measurement sites. In estimating the Tulsa age increase, we have assumed that fleet age stability is similar to that observed in Denver and WLA, simply by comparing the 2013 measurements with the 2005 data set. This comparison results in an estimated age increase for the 2013 Tulsa fleet of slightly more than 1 year (~6.7 to 7.8 years) older than the 2005 fleet.

Again using our historical statistics from each site, we can estimate where the age changes have occurred in the fleet by comparing the current vehicle age distribution with each site's previous age distribution. Figure 3 is a bar chart of fleet fraction versus age (estimated assuming new vehicle model years start in September) for the 2013 (black bars) and 2008 (gray bars) on-road measurements collected at the WLA location. Because of the five year gap between data sets, the 0.6 year old vehicles represent 2013 and 2008 model year vehicles, respectively. The

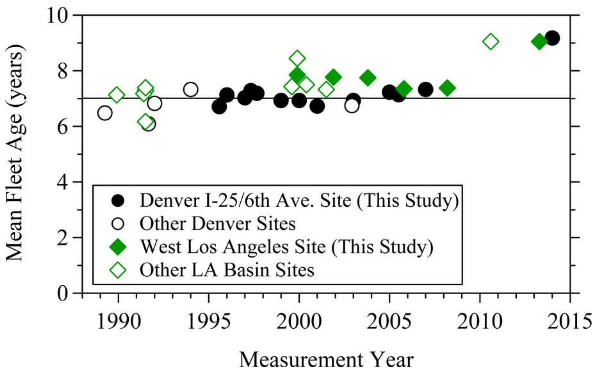


Figure 2. Historical mean fleet age in years versus the measurement year for light-duty vehicle emission data sets collected in Denver, Colorado, and Los Angeles, California. The filled symbols represent data collected at the I- 25 and 6th Ave. site in Denver and the West LA site in Los Angeles used for the 2013 measurements in this study. The open symbols denote data sets collected at other Denver and Los Angeles basin sites. The solid line is simply drawn at a fleet age of 7 years. The fleet age was calculated assuming new vehicle model years begin in September.

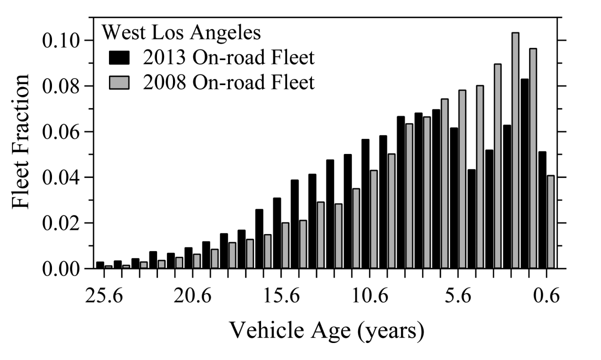


Figure 3. Comparison of on-road fleet fractions versus vehicle age in years for the last two data sets collected at the West Los Angles site. Black bars are the current data set collected in April/May of 2013, and gray bars were collected in March of 2008. Vehicle age was calculated assuming that new vehicle model years begin in September, and as a result, the newest vehicles (0.6 yrs old) represent model years 2013 and 2008, respectively.

2013 fleet shows that the recession caused reductions in approximately six year old and younger vehicles, even for the 1.6 year old vehicles (2012 models) that had appeared to have fully rebounded after the recession (Figure 1). This has resulted in more 9−25 year old vehicles remaining in the fleet at this site than would have been expected had previous fleet turnover rates continued. The changes observed in the WLA fleet age distribution are not only a result of the economic recession's impact on new vehicle sales but also on the public's choices involving retiring older vehicles. Similar changes to the fleet fractions were also observed at the other two sites.

In general, on-road vehicle fleet emission factor increases are correlated with increasing age (Figure 4), and in the United States, those fleet average emissions have been decreasing rapidly over the last two decades.[5,7,19,20] While economic forces may not directly result in an increase in tailpipe emissions, this past recession has resulted in a fleet age increase that has likely slowed the rate of the previous decreases. To estimate the magnitude of the changes, we have used the fleet age fractions from our prior on-road data sets for each of the three measurement sites to adjust their 2013 emission measurements distribution. The age adjustment is accomplished by using the 2013's measured mean emission factors by vehicle age and multiplying them by the sites' previous fleet age fractions and then summing for an age adjusted (modeled) mean emissions factor, essentially combining the data from Figures 3 and 4 for the WLA site for example. Table 2 lists the 2013 measured means of CO, HC, NO, and NH_3 for each site and the calculated emissions penalty resulting from the recession induced fleet age increase. The uncertainties reported are standard error of the means calculated for the 2013 measured data using the daily means for each species at each site, applying the same measured data percentage uncertainty to the modeled means, and for the difference uncertainty, we have summed the uncertainties in quadrature.

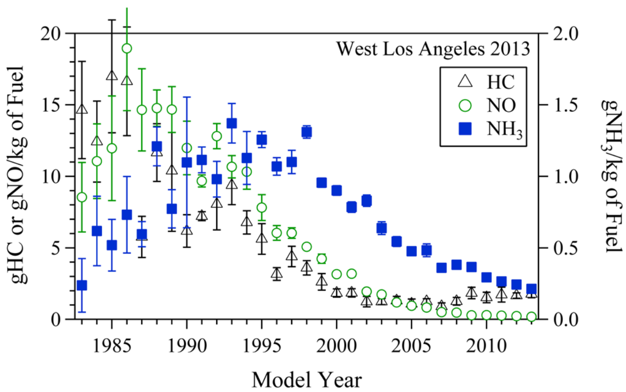


Figure 4. Fuel-specific emission factors for HC, NO (left axis, open symbols), and NH_3 (right axis, filled squares) versus model year for the 2013 West Los Angeles data. The uncertainties plotted are standard errors of the mean determined from the daily means..

It is not surprising that the modeled mean emissions calculated using a younger fleet age are lower for all of the species at all three sites again emphasizing the important link between fleet age and emissions. The youngest observed 2013 fleet, at the Tulsa site, has the lowest measured emissions and the smallest emissions penalties for all species. On a percentage basis, HC emissions have been impacted the least, with the WLA and Tulsa sites having differences that are not distinguishable from zero and therefore not statistically significant, while NO emissions appear to have suffered the most. On-road light-duty HC emissions have the lowest deterioration rates of all the species, with the newest 14 model years having mean emissions that are statistically the same (Figure 4), making HC emissions less sensitive to the increased fleet age.

We can distribute the g/kg of fuel emissions differences from Table 2 for the WLA site across the 2013 model years to show which model year's emissions were affected the most by the recession slowed fleet turnover. Figure 5 graphs the 2013 measured minus modeled emission differences in grams per kilogram of fuel by model year for CO and NH_3 for the WLA site where the sum total of the bars is equal to the g/kg of fuel difference calculated in Table 2. The 1983 model year bar includes all of the 1983 and older models. The HC and NO model year distributions look very similar to CO, and the plots for the WLA site are also representative of the other two sites. A positive value indicates emissions that likely would have been eliminated if the rate of fleet turnover had not been slowed by the recession and assumes that the age distribution of the 2013 fleet would be the same as was measured in 2008. The negative

Table 2. Three City Emission Comparison of Calculated Emissions Penalty Resulting from Measured, Recession Induced, and Fleet Age Increase, with Associated Standard Errors of the Mean Estimates[a]

location	West Los Angeles	Tulsa	Denver
modeled age distribution year	2008	2005	2007
2013 measured mean CO	16.4 ± 0.6	13.4 ± 0.4	12.6 ± 0.9
modeled mean CO	12.5 ± 0.5	11.1 ± 0.3	9.0 ± 0.6
measured − modeled CO (Δ%)	3.9 ± 0.8 (24%)	2.3 ± 0.5 (17%)	3.6 ± 1.1 (29%)
2013 measured mean HC[c]	2.2 ± 0.2	2.1 ± 0.3	1.8 ± 0.1
modeled mean HC[c]	1.9 ± 0.2	1.9 ± 0.3	1.6 ± 0.1
measured − modeled HC[c] (Δ%)	0.3 ± 0.3 (14%)	0.2 ± 0.4 (9%)	0.2 ± 0.1 (11%)
2013 measured mean NO[d]	2.2 ± 0.1	1.5 ± 0.04	2.7 ± 0.1
modeled mean NO[d]	1.6 ± 0.1	1.1 ± 0.03	1.9 ± 0.1
measured − modeled NO[d] (Δ%)	0.6 ± 0.1 (27%)	0.4 ± 0.1 (27%)	0.8 ± 0.1 (30%)
2013 measured mean NH_3	0.58 ± 0.02	0.43 ± 0.01	0.44 ± 0.02
modeled mean NH_3	0.50 ± 0.02	0.40 ± 0.01	0.37 ± 0.02
measured − modeled NH_3 (Δ%)	0.08 ± 0.03 (14%)	0.03 ± 0.01 (7%)	0.07 ± 0.03 (16%)

[a]All table entries are in g/kg of fuel[b]. [b]All g/kg calculations have assumed a carbon mass fraction of 0.86. [c]HC grams are expressed using a NDIR correction factor of 2. [d]Grams of NO.

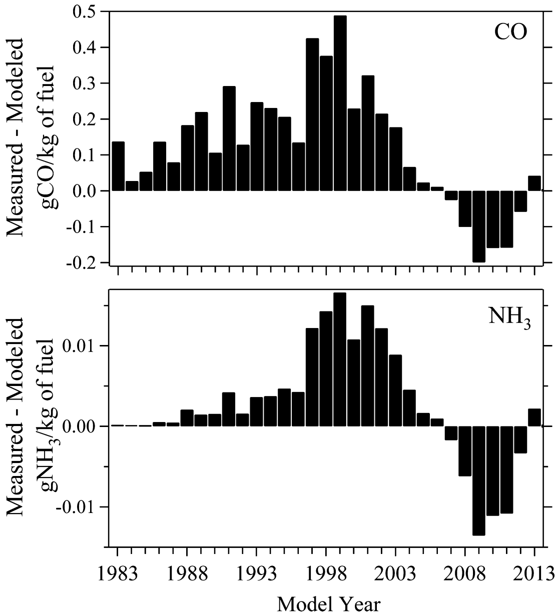


Figure 5. Measured minus modeled g/kg of fuel emission differences from Table 2 (3.9 g/kg of fuel for CO and 0.08 g/kg of fuel for NH_3) distributed by model year for the 2013 West Los Angeles data set. Positive values indicate 2013 emissions that would not be present if the rate of fleet turnover had not been slowed by the recession, and the 2013 fleet's age distribution was as measured in 2008. Negative values are model years where emissions are lacking due to fewer vehicles.

values represent model years where emissions are lacking due to fewer vehicles. Not surprisingly, the fleet fraction differences shown in Figure 3 for the WLA site are mirrored in this plot with emission deficits for the 6 year old and newer vehicles and excess emissions starting around 8–9 year old vehicles (2004 models) peaking around 15 year old vehicles (1998 to 1999 models) and then tailing off.

The NH_3 differences plot shares a similar shape with CO over the first 15 model years with both species peaking at the same model year (1999), but the NH_3 measured minus modeled emission differences recede faster than CO. For the first 15 model years, the magnitude of the measured minus modeled emission differences are dictated by the fleet fractions that are larger than the emission factors. As vehicle age increases, the attrition and retirement rates increase, leading to a significant drop in vehicle numbers, and it is the emission factors that become more important in determining the extent of the differences. NH_3 emissions from light-duty gasoline vehicles depend on the reducing capability of three-way catalytic converters. As a vehicle ages, it reaches a point (~15 to 18 years old currently) where NH_3 emission factors decrease as the catalysis die (Figure 4), eliminating the measured minus modeled differences shown in Figure 5 at a faster rate than for CO, HC, and NO.[16]

The two most prominent on-road vehicle emission models used in the United States are the state of California's EMFAC (newest version is EMFAC2011) and the Environmental Protection Agency MOVES model (newest version is MOVES2014).[21,22] We ran EMFAC2011 (2013 release) and MOVES2014 (October 2014 release) and compared their predicted vehicle miles traveled (VMT) fractions with our on-road fleet fractions for the WLA (EMFAC and South Coast Air Basin) and Denver (MOVES and national defaults) sites prior and current data sets (Figure 6 and Figure S2, Supporting Information). Both of the previous data sets (2008 WLA, 2006 Denver) age distributions are very similar to the model predicted age distributions. For the 2013 data sets, both models capture the large drop in 2009 model year vehicles, but the EMFAC model quickly returns to near prerecession levels the very next model year. The MOVES model better follows the slow economic recovery for the 2010 and 2011 models but likely overstates the 2012 and 2013 fractions. Neither model predicts any increases in the number of the older model year vehicles seen at the WLA and Denver sites. The modeled fleet age increases are only 0.6 years for the EMFAC model and a better 1.5 years for the MOVES model; however, both underestimate the observed fleet age increases. Because fleet emission estimates depend upon the model's ability to accurately predict the modeled fleet's age, both models will also likely underestimate the 2013 fleet emissions using the default vehicle VMT data.

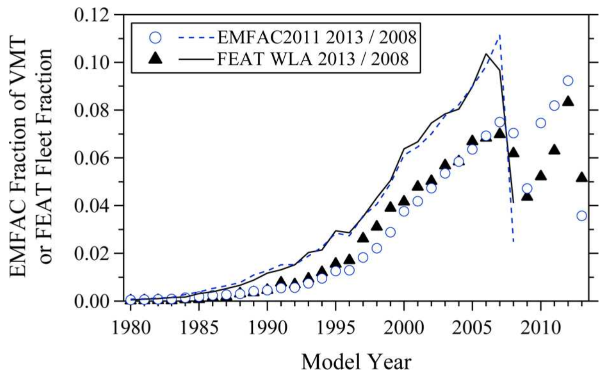


Figure 6. EMFAC2011 estimated fraction of VMT versus vehicle model year for calendar years 2013 (open circles) and 2008 (dashed line) compared with the fleet fractions calculated from the WLA FEAT data sets collected in the spring of 2013 (filled triangles) and the spring of 2008 (solid line). EMFAC2011 VMT data were generated using the South Coast Air Basin region, vehicle categories of LDA/LDT1/LDT2/LHD1/LHD2/MDV, aggregated speeds, and all fuels. Fraction of VMT was calculated using the sum of all 30 model years' VMT as the normalizing factor and daily VMT values converted into full year values for all but the 2013 and 2008 model years, which were converted to their fractional year value. FEAT fleet fractions were normalized by the total number of records. EMFAC estimates the mean model year for calendar year 2008 of 2000.7 (~7.3 years old) and for calendar year 2013 of 2005.1 (~7.9 years old).

Keep in mind that we are reporting differences in the fuel specific emissions changes, and site air quality impacts are a combination of our measured emission factors and the amount of fuel consumed. The recession also resulted in reductions in fuel sales in most states through less driving and the reductions in light-duty trucks. Statewide gasoline sales in California slowed by more than 8% between 2007 and 2012. In Colorado, a 1.3% reduction was recorded during the same period, while gallons sold actually increased each year during the recession in Oklahoma.[23−25] Thus, while Oklahoma showed the smallest increase in fleet modeled emission factors when combined with increased fuel sales, assuming of course that our site followed statewide trends, it is possible that the Tulsa site experienced a larger increase in total emissions than the measured emission differences in g/kg of fuel suggest.

■ ASSOCIATED CONTENT

Supporting Information

Figures S1 and S2 referenced in the text. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: (303) 871-2584; e-mail: gbishop@du.edu.

Notes

The authors declare the following competing financial interest(s): The authors acknowledge receipt of patent royalty payments from Envirotest, an operating subsidiary of Opus Inspection, which licenses the remote sensing technology developed at the University of Denver.

■ ACKNOWLEDGMENTS

This paper is a result of work supported by the California Environmental Protection Agency Air Resources Board (12-303), Coordinating Research Council (E-106), and University of Denver. Results and conclusions presented here are solely the responsibility of the authors and may not represent the views of the sponsors. The authors would like to gratefully acknowledge the assistance of Ian Stedman (equipment repair), Annette Bishop (license plate transcription), and Jim Sidebottom (license plate matching).

■ REFERENCES

(1) National Emissions Inventory Air Pollutant Emissions Trends Data. U.S. Environmental Protection Agency. http://www.epa.gov/ttn/chief/trends/ (accessed November 2014).

(2) Seinfeld, J. H. Air pollution: A half century of progress. *AlChE J.* **2004**, *50* (6), 1096−1108 DOI: 10.1002/aic.10102.

(3) Pollack, I. B.; Ryerson, T. B.; Trainer, M.; Neuman, J. A.; Roberts, J. M.; Parrish, D. D. Trends in ozone, its precursors, and related secondary oxidation products in Los Angeles, California: A synthesis of measurements from 1960 to 2010. *J. Geo. Res.: Atm.* **2013**, *118*, 1−19 DOI: 10.1002/jgrd.50472.

(4) Dallmann, T. R.; Harley, R. A. Evaluation of mobile source emission trends in the United States. *J. Geo. Res.* **2010**, *115*, D14305−D14312 DOI: 10.1029/2010JD013862.

(5) McDonald, B. C.; Gentner, D. R.; Goldstein, A. H.; Harley, R. A. Long-term trends in motor vehicle emissions in U.S. urban areas. *Environ. Sci. Technol.* **2013**, *47* (17), 10022−10031 DOI: 10.1021/es401034z.

(6) Pokharel, S. S.; Bishop, G. A.; Stedman, D. H. Emissions reductions as a result of automobile improvement. *Environ. Sci. Technol.* **2003**, *37*, 5097−5101 DOI: 10.1021/es026340x.

(7) Bishop, G. A.; Stedman, D. H. A decade of on-road emissions measurements. *Environ. Sci. Technol.* **2008**, *42* (5), 1651−1656 DOI: 10.1021/es702413b.

(8) Gayer, T.; Parker, E. *Cash for Clunkers: An Evaluation of the Car Allowance Rebate System*; Economic Studies, Brookings Institution: Wshington, DC, 2013.

(9) Izzo, P. Number of the Week: Aging Fleet Could Boost Car Sales, *Wall Street Journal*, February 16, 2013.

(10) NADA Data: Annual Financial Profile of America's Franchised New-Car Delaerships. National Automobile Dealers Association. http://www.nada.org/NR/rdonlyres/DF6547D8-C037-4D2E-BD77-A730EBC830EB/0/NADA_Data_2014_05282014.pdf (accessed August 2014).

(11) Rechtin, M. Average Age of U.S. Car, Light Truck on Road Hits Record 11.4 Years, Polk Says. Automotive News. . http://www.autonews.com/article/20130806/RETAIL/130809922/average-age-of-u-s-car-light-truck-on-road-hits-record-11-4-years (accessed August 2014).

(12) Burgard, D. A.; Bishop, G. A.; Stadtmuller, R. S.; Dalton, T. R.; Stedman, D. H. Spectroscopy applied to on-road mobile source emissions. *Appl. Spectrosc.* **2006**, *60*, 135A−148A DOI: 10.1366/000370206777412185.

(13) Popp, P. J.; Bishop, G. A.; Stedman, D. H. Development of a high-speed ultraviolet spectrometer for remote sensing of mobile source nitric oxide emissions. *J. Air Waste Manage. Assoc.* **1999**, *49*, 1463−1468 DOI: 10.1080/10473289.1999.10463978.

(14) Burgard, D. A.; Dalton, T. R.; Bishop, G. A.; Starkey, J. R.; Stedman, D. H. Nitrogen dioxide, sulfur dioxide, and ammonia detector for remote sensing of vehicle emissions. *Rev. Sci. Instrum.* **2006**, *77* (014101), 1−4 DOI: 10.1063/1.2162432.

(15) Singer, B. C.; Harley, R. A.; Littlejohn, D.; Ho, J.; Vo, T. Scaling of infrared remote sensor hydrocarbon measurements for motor vehicle emission inventory calculations. *Environ. Sci. Technol.* **1998**, *32*, 3241−3248 DOI: 10.1021/Es980392y.

(16) Bishop, G. A.; Schuchmann, B. G.; Stedman, D. H.; Lawson, D. R. Multispecies remote sensing measurements of vehicle emissions on Sherman Way in Van Nuys, California. *J. Air Waste Manage. Assoc.* **2012**, *62* (10), 1127−1133 DOI: 10.1080/10962247.2012.699015.

(17) Bishop, G. A.; Peddle, A. M.; Stedman, D. H.; Zhan, T. On-road emission measurements of reactive nitrogen compounds from three California cities. *Environ. Sci. Technol.* **2010**, *44*, 3616−3620 DOI: 10.1021/Es903722p.

(18) Unemployment Rates for Metropolitan Areas. U.S. Bureau of Labor Statistics. http://www.bls.gov/lau/ (accessed September, 2014).

(19) McDonald, B. C.; Dallmann, T. R.; Martin, E. W.; Harley, R. A. Long-term trends in nitrogen oxide emissions from motor vehicles at national, state, and air basin scales. *J. Geo. Res.: Atm.* **2012**, *117* (D18), 1−11 DOI: 10.1029/2012jd018304.

(20) Parrish, D. D.; Trainer, M.; Hereid, D.; Williams, E. J.; Olszyna, K. J.; Harley, R. A.; Meagher, J. F.; Fehsenfeld, F. C. Decadal change in carbon monoxide to nitrogen oxide ratio in U.S. vehicular emissions. *J. Geo. Res.* **2002**, *107* (D12), ACH5−1−ACH5−9 DOI: 10.1029/2001jc000720.

(21) EMFAC Emissions Database. Air Resources Board, California Environmental Protection Agency. http://www.arb.ca.gov/emfac/ (accessed October, 2014).

(22) Modeling and Inventories; MOVES (Motor Vehicle Emission Simulator). U.S. Environmental Protection Agency. http://www.epa.gov/otaq/models/moves/ (accessed October, 2014).

(23) Fuel Taxes Statistics & Reports. California State Board of Equalization. http://www.boe.ca.gov/sptaxprog/spftrpts.htm (accessed January 2013).

(24) Motor Fuel Taxes. Colorado Department of Revenue. http://www.colorado.gov/cs/Satellite?c=Page&cid=1213954144067&pagename=Revenue-Main%2FXRMLayout (accessed August 2014).

(25) Annual Reports, Oklahoma Tax Commission. http://www.tax.ok.gov/annrpts.html (accessed August 2014).

<u>SupportingInformationFor:</u>

The Recession of 2008 and Its Impact on Light-Duty Vehicle Emissions in Three Western United States Cities

Gary A. Bishop* and Donald H. Stedman

Department of Chemistry and Biochemistry MSC 9020, University of Denver, Denver CO 80208

*Corresponding author email: gbishop@du.edu; phone: (303) 871-2584

Summary of Supporting Information:

3 Pages (excluding cover): S-1 – S-3

Figures

S1. Mean model year versus measurement year for all of the West Los Angeles data sets.

S2. MOVES2014 fraction of vehicle miles traveled and FEAT fleet fractions versus vehicle model year for calendar years 2013 and 2006.

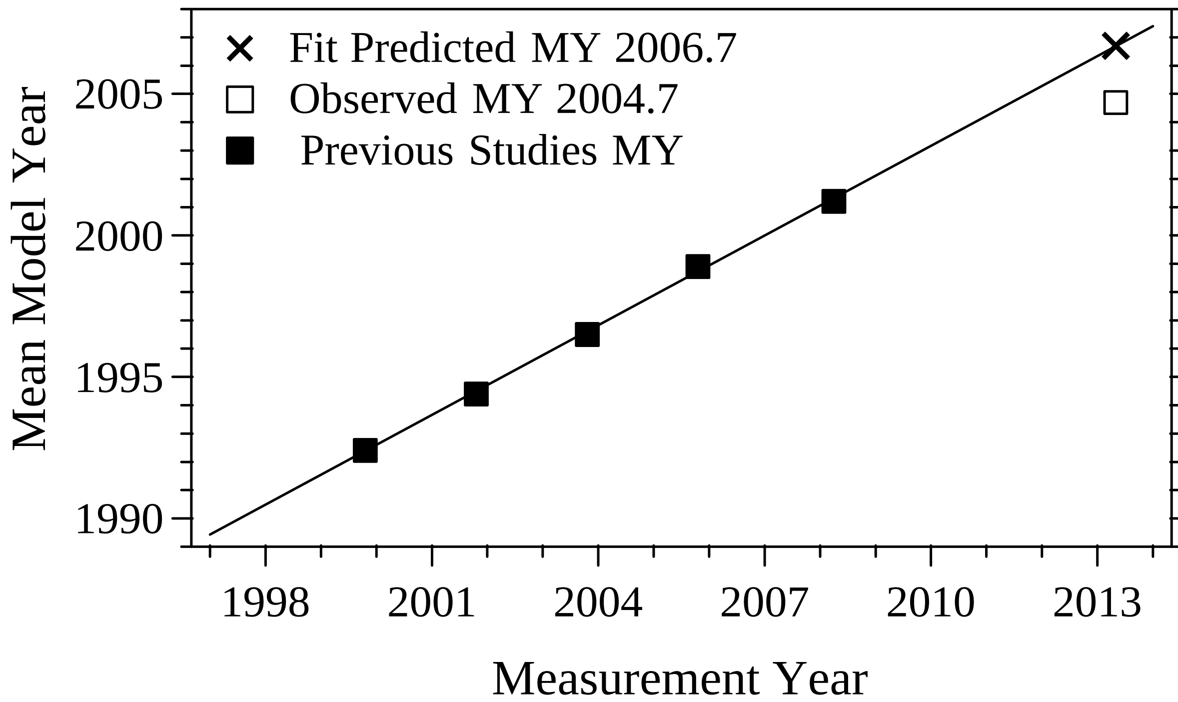


Figure S1. Mean model year versus measurement year for the six on-road emission data sets collected at the West Los Angeles site. Filled squares are for the five previous data sets and the open square marks the 2013 data sets mean model year of 2004.7. The solid line is a linear least squares fit to the five previous data sets and the X is its predicted mean model year of 2006.7. This is two model years newer than likely would have been observed if the fleet turnover rate at the West LA site had continued as in the previous fifteen years.

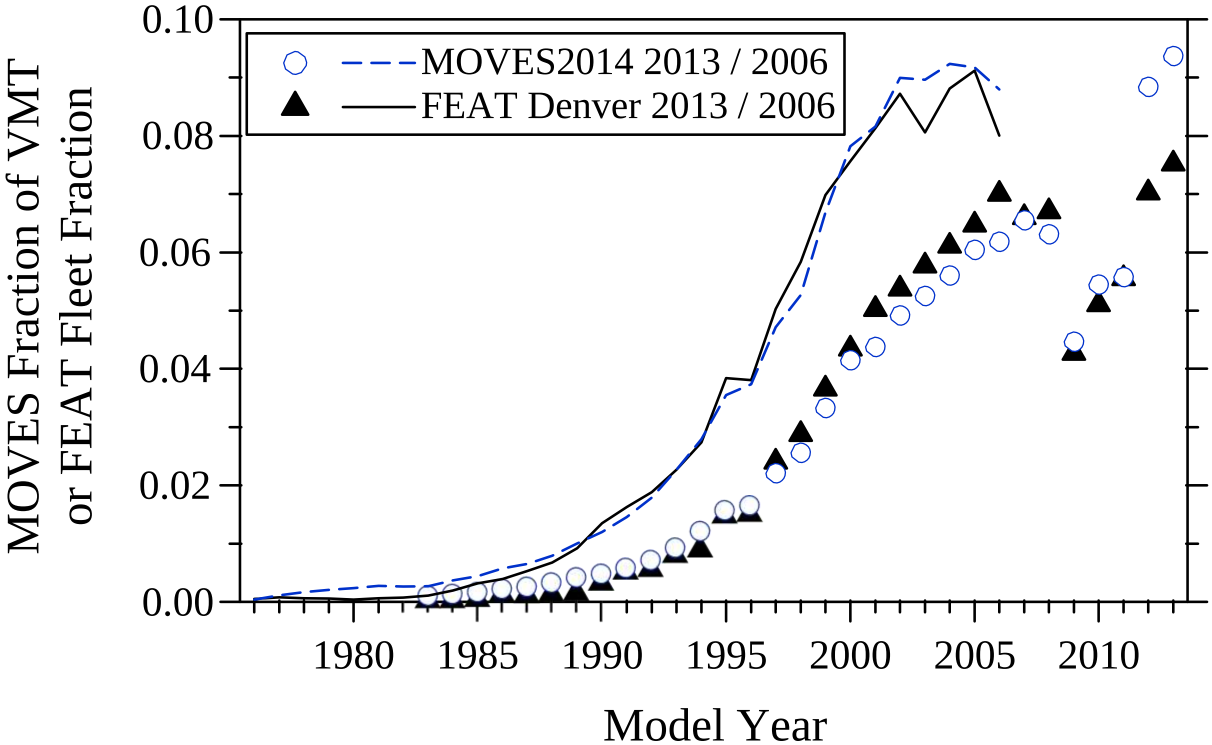


Figure S2. MOVES2014 (1) estimated fraction of vehicle miles traveled (VMT) versus vehicle model year for calendar years 2013 (open circles) and 2006 (dashed line) compared with the fleet fractions calculated from the Denver FEAT data sets collected in December 2013 (filled triangles) and February 2007 (solid line). MOVES2014 VMT data were generated using the on-road national defaults, vehicle categories of passenger cars, passenger trucks and light commercial trucks, all fuels except electric and urban restricted access road type. Fraction of VMT was calculated using the sum of all 30 model years VMT as the normalizing factor. FEAT fleet fractions were calculated using the sum total of all of the records as the normalizing factor. MOVES estimates the mean model year for calendar year 2006 of 1999.7 (~6.3 years old) and for calendar year 2013 of 2005.2 (~7.8 years old).

References

1. MOVES (Motor Vehicle Emission Simulator), United States Environmental Protection Agency, http://www.epa.gov/otaq/models/moves/ (accessed October 2014).