Preliminary Studies Using Remote Sensing to Evaluate I/M Effectiveness

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INTRODUCTION

Many cities in the United States are in violation of the air quality standards established by the Environmental Protection Agency (EPA). Carbon monoxide (CO) levels become elevated primarily due to direct emission of the gas, and ground-level ozone, a major component of urban smog, is produced by the photochemical reaction of nitrogen oxides (NO_x) and hydrocarbons (HC). As of 1998, on-road vehicles were estimated to be the single largest source for the major atmospheric pollutants, contributing 60% of the CO, 44% of the HC, and 31% of the NO_x to the national emission inventory.[1]

For a description of the internal combustion engine and causes of pollutants in the exhaust see Heywood[2]. Properly operating modern vehicles with three-way catalysts are capable of partially (or completely) converting engine-out CO, HC and NO emissions to CO_2, H_2O and N_2.

Control measures to decrease mobile source emissions in non-attainment areas include inspection and maintenance (I/M) programs, oxygenated fuel mandates, and transportation control measures, but the effectiveness of these measures remains questionable. Many areas remain in non-attainment, and with the new 8 hour ozone standards introduced by the EPA in 1997, many locations still violating the standard may have great difficulty reaching attainment.[3]

The remote sensor used in this study was developed at the University of Denver for measuring the pollutants in motor vehicle exhaust, and has previously been described in the literature.[4,5] The instrument consists of a non-dispersive infrared (IR) component for detecting carbon monoxide, carbon dioxide (CO_2), and hydrocarbons, and a dispersive ultraviolet (UV) spectrometer for measuring nitric oxide. The source and detector units are positioned on opposite sides of the road in a bi-static arrangement. Colinear beams of IR and UV light are passed across the roadway into the IR detection unit, and are then focused onto a dichroic beam splitter, which serves to separate the beams into their IR and UV components. The IR light is then passed onto a spinning polygon mirror, which spreads the light across the four infrared detectors: CO, CO_2, HC and reference.

The UV light is reflected off the surface of the beam splitter and is focused into the end of a quartz fiber-optic cable, which transmits the light to an UV spectrometer. The UV unit is then capable of quantifying nitric oxide by measuring an absorbance band at 226.5 nm in the UV spectrum and comparing it to a calibration spectrum in the same region.

The exhaust plume path length and density of the observed plume are highly variable from vehicle to vehicle, and are dependent upon, among other things, the height of the vehicle's exhaust pipe, wind, and turbulence behind the vehicle. For these reasons, the remote sensor only measures directly ratios of CO, HC or NO to CO_2. The ratios of CO, HC, or NO to CO_2, termed Q, Q' and Q'' respectively, are constant for a given exhaust plume, and on their own are useful parameters for describing a hydrocarbon combustion system. This study reports measured emissions as %CO, %HC and %NO in the exhaust gas, corrected for water and excess oxygen not used in combustion. The %HC measurement is a factor of two smaller than an equivalent measurement by an FID instrument.[6] Thus, in order to calculate mass emissions as described below, the %HC values must first be multiplied by 2.0, assuming that the fuel used is regular gasoline. These percent emissions can be directly converted into mass emissions by the equations shown below.

$$\text{gm CO/gallon} = 5506 \bullet \%CO/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$
$$\text{gm HC/gallon} = 8644 \bullet \%HC/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$
$$\text{gm NO/gallon} = 5900 \bullet \%NO/(15 + 0.285 \bullet \%CO + 2.87 \bullet \%HC)$$

These equations indicate that the relationship between concentrations of emissions to mass of emissions is quite linear, especially for CO and NO and at low concentrations for HC. Thus, the percent difference in emissions calculated from the concentrations of pollutants reported here is equivalent to a difference calculated from masses.

Another useful conversion is from percent emissions to g pollutant per kg of fuel. This conversion is achieved directly by first converting the pollutant ratio readings to the moles of pollutant per mole of carbon in the exhaust from the following equation:

$$\frac{\text{moles pollutant}}{\text{moles C}} = \frac{\text{pollutant}}{CO + CO_2 + 3HC} = \frac{(\text{pollutant}/CO_2)}{(CO/CO_2) + 1 + 3(HC/CO_2)} = \frac{(Q, 2Q', Q'')}{Q + 1 + 6Q'}$$

Next, moles of pollutant are converted to grams by multiplying by molecular weight (e.g. 44 g/mole for HC since propane is measured), and the moles of carbon in the exhaust are converted to kilograms by multiplying (the denominator) by 0.014 kg of fuel per mole of carbon in fuel, assuming gasoline is stoichiometrically CH_2. Again, the HC/CO_2 ratio must use two times the reported HC (as above) because the equation depends upon carbon mass balance and the NDIR HC reading is about half a total carbon FID reading.[6]

Quality assurance calibrations are performed twice daily in the field unless observed voltage readings or meteorological changes are judged to warrant more frequent calibrations. A puff of gas containing certified amounts of CO, CO_2, propane and NO is released into the instrument's path, and the measured ratios from the instrument are then compared to those certified by the cylinder manufacturer (Praxair). These calibrations account for day-to-day variations in instrument sensitivity and variations in ambient CO_2 levels caused by local sources, atmospheric pressure and instrument path length. Since propane is used to calibrate the instrument, all hydrocarbon measurements reported by the remote sensor are as propane equivalents.

Studies sponsored by the California Air Resources Board and General Motors Research Laboratories have shown that the remote sensor is capable of CO measurements that are correct to within ±5% of the values reported by an on-board gas analyzer, and within ±15% for HC.[7,8] The NO channel used in this study has been extensively tested by the University of Denver, but we are still awaiting the opportunity to participate in an extensive blind study and instrument intercomparison to have it independently validated. Tests involving a late-model low-emitting vehicle indicate a detection limit (3σ) of 25 ppm for NO, with an error measurement of ±5% of the reading at higher concentrations. Appendix A gives a list of criteria for valid or invalid data.

The remote sensor is accompanied by a video system to record a freeze-frame image of the license plate of each vehicle measured. The emissions information for the vehicle, as well as a time and date stamp, is also recorded on the video image. The images are stored on videotape, so that license plate information may be incorporated into the emissions database during post-processing. A device to measure the speed and acceleration of vehicles driving past the remote sensor was also used in this study. The system consists of a pair of infrared emitters and detectors (Banner Industries) which generate a pair of infrared beams passing across the road, 6 feet apart and approximately 2 feet above the surface. Vehicle speed is calculated from the time that passes between the front of the vehicle blocking the first and the second beam. To measure vehicle acceleration, a second speed is determined from the time that passes between the rear of the vehicle unblocking the first and the second beam. From these two speeds, and the time difference between the two speed measurements, acceleration is calculated, and reported in mph/s. Appendix B defines the database format used for the data set.

Remote Sensing Devices (RSD) are able to obtain independent I/M program evaluation information, since actual on-road emissions can be monitored. On-road remote sensing has previously been used to assess I/M program effectiveness through separate measurements inside and outside of I/M areas[9,10] and through simultaneous measurements of vehicles that have undergone I/M testing and those that have not inside an I/M program area (step method).[11,12] The method of separate measurements has the drawback that many factors can remain uncontrolled and must be calibrated. For example, load on vehicle, instrument calibration, fleet make-up, atmospheric variables, and socioeconomics are not easily controlled. The step method takes advantage of a unique opportunity during the imposition of an I/M program to measure a fleet of vehicles which controls for these factors. This control group can then be used as an effective comparison to a fleet of I/M tested vehicles. In the absence of such a transition period in the I/M program, we propose an alternate method of I/M evaluation using remote sensing which controls for many of the factors also controlled in the step method.

The alternate method is related to the step method in that both vehicles that have undergone I/M testing and those that have not are measured together. Differing from the step method, however, one set of measured vehicles is registered within an I/M area and the other set is registered outside. The vehicles are measured at a site containing a significant fraction of each fleet. In this manner, many site-specific variables such load, instrument calibration, and atmospheric conditions are controlled. Here we report on preliminary studies using this method at two sites in Western Colorado which do not undergo any I/M program but which contain transient vehicles registered in I/M areas.

RESULTS and DISCUSSION

Overall data characteristics

Two sets of measurements were made for this preliminary study. The first campaign involved one day (4/4/01) of measurement on I-70 just west of Glenwood Springs, Colorado. A scheduled lane closure was utilized to obtain the required single lane of traffic (See Figure 1). The average speed of the traffic was quite high here with a slight average deceleration (see Table 1), and road incline of 0.3 degrees. Measurements from 10:50 am to 15:20 pm yielded 621 vehicles whose plates were read and matched and contained valid CO and CO_2 readings. Unfortunately, the lane closure was suspended the following day and further measurements at the site could not be obtained.

The second set of measurements was conducted further west off of I-70 just outside Grand Junction, Colorado. Five days of field work between April 25th and 29th, 2001 on the off-ramp from Business 70 eastbound which becomes a slightly uphill on-ramp to I-70 eastbound (See Figure 2) resulted in 5222 valid CO and CO_2 measurements with matched DMV records. Average speed was 49.2 mph with an average acceleration of 0.24 mph/s. The incline of the road was 1.7 degrees.

Table 1 shows the overall fleet emission averages at the two sites. The sites have differing fleet and load characteristics. Thus, the average emissions differ. This example illustrates the difficulty in obtaining accurate comparisons of measurements made at differing locations and, hence, the need for a one-site method for I/M evaluation.

Table 1. Fleet emissions summary.

	Glenwood Springs	Grand Junction
Mean CO (%)	0.35	0.57
Mean HC (ppm)	198	212
Mean NO (ppm)	708	652
Mean Model Year	1995.22	1993.62
Mean Speed (mph)	63.5	49.2
Mean Acceleration (mph/s)	-1.1	0.24
Mean Specific Power (kW/t)	-0.5	17.3

Figure 3 illustrates the model year distribution and average CO by model year at the two sites. What is apparent from the plot is the nose in the average CO data of older model years, especially in the Glenwood data. This noise is due to the small number of measurements in each model year bin. Since vehicle emissions are γ-distributed, the presence of high emitters in a small data set can raise the mean significantly. If one were to use averages of bins containing at least 100 measurements only, a much more smooth trend could be seen. Model years 1986 and newer in Grand Junction meet this cutoff, while only MY 2000 does in Glenwood because of the overall small number of measurements there. Due to this limited number of samples in the Glenwood database, those measurements will not be included in the analysis below.

Model year profiles of all three pollutants are shown in Figure 4. CO is unconventionally reported in ppm*10 so that the plot uses the full scale of the graph. These plots indicate the expected trends in emissions as a function of model year. NO increases linearly with increasing model year, while CO and HC show the onset of significant deterioration after model years are several years old.

<u>Evaluation of RSD</u>

In order to compare program effectiveness calculated from RSD data to that calculated from I/M data themselves, it must first be shown that the two measurement techniques correlate well. This has been shown previously with Denver RSD and I/M data from 1996, 1997 and 1999,[12] and also with data from Phoenix and Chicago.[13] The Denver 2000 data correlations are given here in Figure 5. The correlations are excellent (R^2>0.9) when both measurements are converted to grams of pollutant per kg of fuel. The percent values from RSD are converted to g/kg using the method given above. The IM240 g/mile values are converted to g/kg by multiplying by the calculated mile/gallon (from the IM240 database) and dividing by the density of gasoline. These excellent correlations validate RSD as a comparable I/M evaluation tool even if each RSD site has a limited range of driving modes.

Another step in validating RSD as an evaluation method is an analysis of its ability to distinguish emission differences between two groups of vehicles. This study was accomplished by obtaining two separate groups of vehicles from the Grand Junction data set. One group was those vehicles marked as "PAS", or passenger vehicles, in the DMV database and the other was those marked "LTK" – light truck. An analysis of the model year distribution of the measurements and the average percent CO is presented in Figure 6. Even though some of the model years contain relatively few measurements, it can be seen that the LTK group is higher emitting for all model years except two. These two model yeas are among the ones with very few samples so one expects noise. Even with this limited number of measurements a PAS/LTK difference of 33 ± 10% is observed, where the reported error is the standard error of the fleet mean and obtained by treating each of the five days of measurement as independent measurements. This difference is seen to be significantly different from zero at better than the 1% level by a paired *t*-test. Thus, RSD can easily distinguish a difference of 30% even if one of the groups only contains 1200 samples. The ability to distinguish even small differences is expected.

Program benefit analysis

The actual I/M benefit analysis was accomplished by dividing the Grand Junction data set into other sets of vehicles. The first separation was into three groups. The first group had flags in the DMV dataset that showed the vehicles had undergone Enhanced I/M; the second set consisted of those vehicles that had Basic I/M flags; finally, the third set had no I/M flag in the DMV records. Table 2 shows the averages and number of samples for the three groups of only "PAS" vehicles. The Basic I/M group was not further analyzed because of the small sample number and older average model year.

Table 2. Summary of Grand Junction data divided by DMV records' emission type flag. Values in parenthesis are number of measurements.

	Enhanced	**Basic**	**None**
CO (%)	0.56 (185)	0.61 (54)	0.52 (3305)
HC (ppm)	250 (185)	210 (53)	230 (3300)
NO (ppm)	490 (185)	580 (54)	560 (3295)
Model Year	1993.8	1993.2	1993.7

The data for the two groups are plotted in Figure 7. It can be seen that the model year profiles are not very distinct between the two groups and are rather noisy. A *t*-test for paired means determined the averages of the two groups to not be significantly different for CO and HC. The NO *t*-test showed the lower average of the non-I/M fleet (which would be a disbenefit for I/M) to be only significant at the 10% level. Thus, this difference was not further analyzed.

Another method of dividing the whole fleet into those that have undergone I/M and those that have not is to designate by where they are registered. The DMV records include the legal zip code for each vehicle. Thus, a group of vehicles that have undergone I/M was constructed of all passenger vehicles (PAS designation) with registered zip codes between 80000 and 80400 (the Denver metropolitan area). The non-I/M group consisted of vehicles registered in zip codes above 81000 (outside any I/M area). Furthermore, since the newest four model years do not undergo I/M even if residing within an I/M program area, only model years 1997 or older and 1990 and newer were used. The average emissions and number of samples are given in Table 3. It is apparent that average CO is effectively the same for the two groups; average HC seems higher for the I/M group, while average NO is somewhat higher for the non-I/M group. The average model years do differ somewhat.

Table 3. Summary of Grand Junction data divided by zip code of legal residence. Values in parenthesis are number of measurements.

	I/M	Non-I/M
CO (%)	0.34 (122)	0.33 (1587)
HC (ppm)	250 (122)	210 (1585)
NO (ppm)	450 (122)	560 (1580)
Model Year	1994.4	1993.8

Again, the differences in averages were tested using the *t*-test with each day's average as a separate sample. The differences in averages of model year, CO and HC were not significant. But in the case of NO, with this designation also the difference was significant at the 10% level.

The third and final method of dividing the vehicles into I/M and non-I/M fleets involved matching VINs of the measured vehicles with IM240 records from the state of Colorado. Again, only records with "PAS" designations for "Lic_type" were used. Vehicles which showed up in the IM240 databases from 1998, 1999 or 2000 or which had "Enhanced" emission flags in the I/M records were designated as I/M vehicles. Vehicles with no I/M records as far back as 1995 and with no I/M flag in the DMV records were designated as non-I/M vehicles. Those vehicles which matched IM240 databases from 1995, 1996 or 1997 and which were not in the 1998, 1999 or 2000 databases or marked as having enhanced I/M in DMV records were discarded. The averages are presented in Table 4. The model year profiles are in Figure 8. One can see that the I/M fleet data is still rather noisy due to the small sample size in each model year group.

Table 4. Summary of Grand Junction data divided by records in IM240 database of past three years. Values in parenthesis are number of measurements.

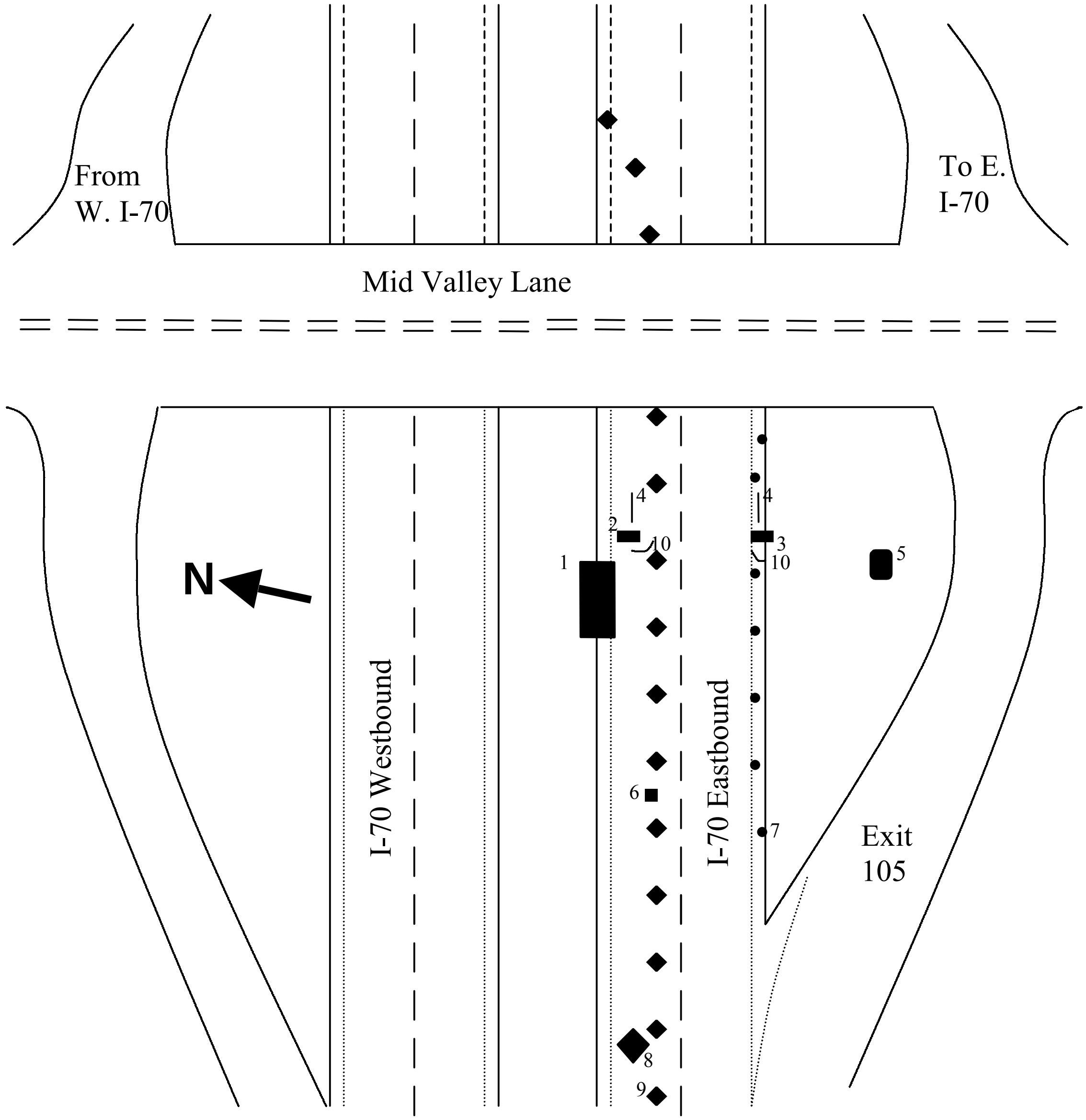
	I/M	Non-I/M
CO (%)	0.47 (369)	0.52 (3029)
HC (ppm)	250 (368)	220 (3024)
NO (ppm)	520 (369)	550 (3020)
Model Year	1993.9	1993.7

Tests for significance were again conducted. None of the differences in the means were found to be significant down to the 10% level.

Consider Figure 8. The peaks in CO and HC in the I/M fleet seen in MY 1989, 1992 and 1998 correspond to dips in the NO by MY for the same MY, showing that even the apparent “noise” in the data is caused by a few higher emitting cars which, when observed, were apparently operating with an overly rich stoichiometry (high CO and HC and low NO)

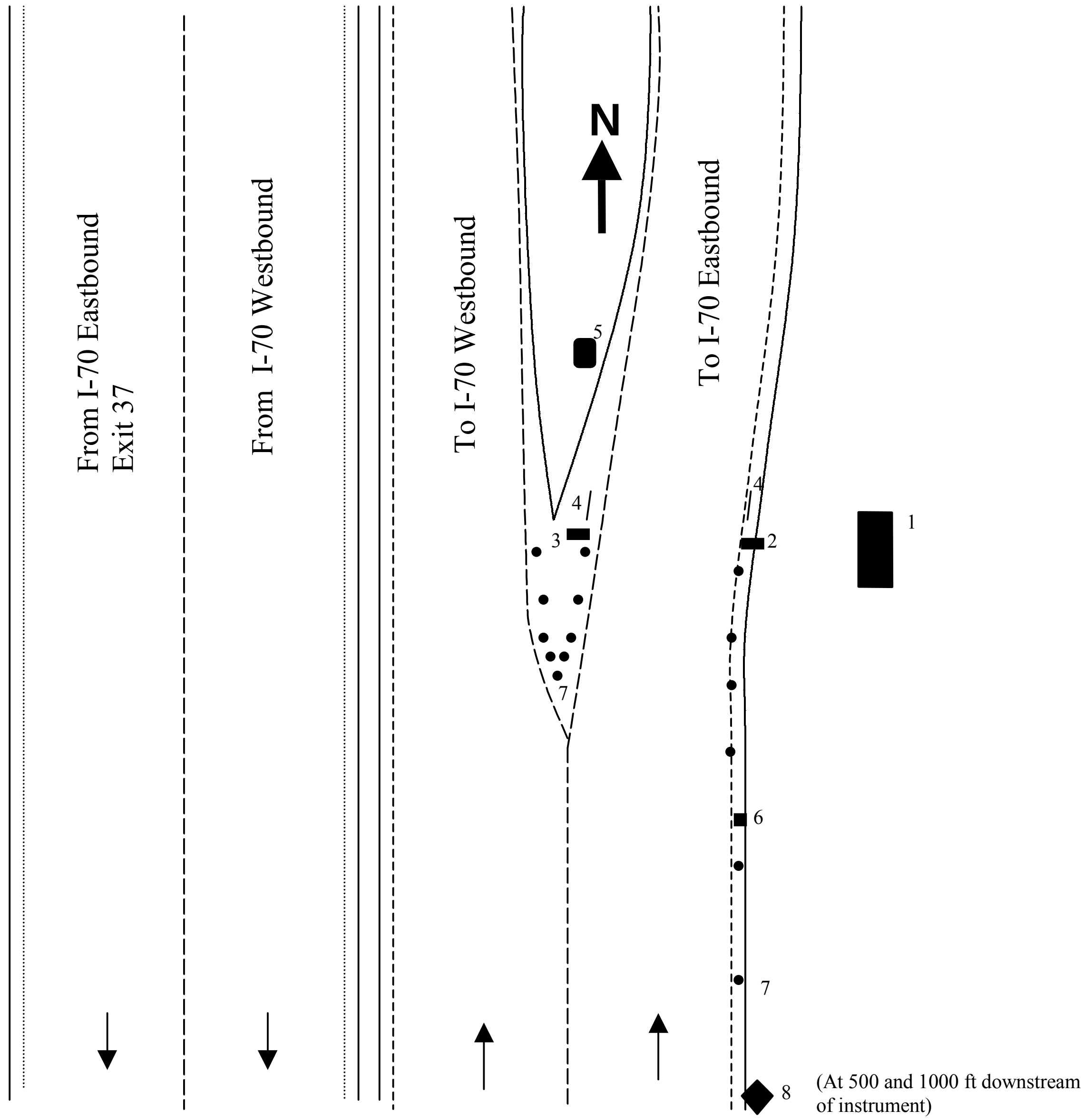
CONCLUSIONS

Several analyses were conducted in a preliminary study with a small sample size, to estimate I/M effectiveness. All analysis attempts indicate, to first order, no significant benefit beyond about 10% due to the program in the Denver area, relative to vehicles also registered in Colorado but not participating in the program. It was shown that RSD would have been capable of detecting differences of 10% in averages of two fleets of vehicles had the data set contained 1200 samples in the smaller group. When dividing the Grand Junction measurements into I/M and non-I/M vehicles, however, none of the three methods yielded more than 400 samples in the I/M group. This limited sample size is most likely the cause of the insignificant differences. Further measurements at a site with a higher ratio of I/M vehicles or just high traffic volume, would greatly improve the sample size. Then, differences even smaller than 10% could be observed with quantifiable statistical significance.



1. Winnebago
2. Detector
3. Light Source
4. Speed/Accel. Sensors
5. Generator
6. Video Camera
7. Road Cones
8. "Shoulder Work Ahead" Sign
9. Lane closure barrels
10. Wind shields

Figure 1. Diagram of first measurement site at New Castle, CO. Shown are locations of instruments and traffic control devices. Not to scale.



1. Winnebago
2. Detector
3. Light Source
4. Speed/Accel. Sensors
5. Generator
6. Video Camera
7. Road Cones
8. "Shoulder Closed Ahead" Sign

Figure 2. Diagram of second measurement site at Clifton, CO. Shown are locations of instruments and traffic control devices. Not to scale.

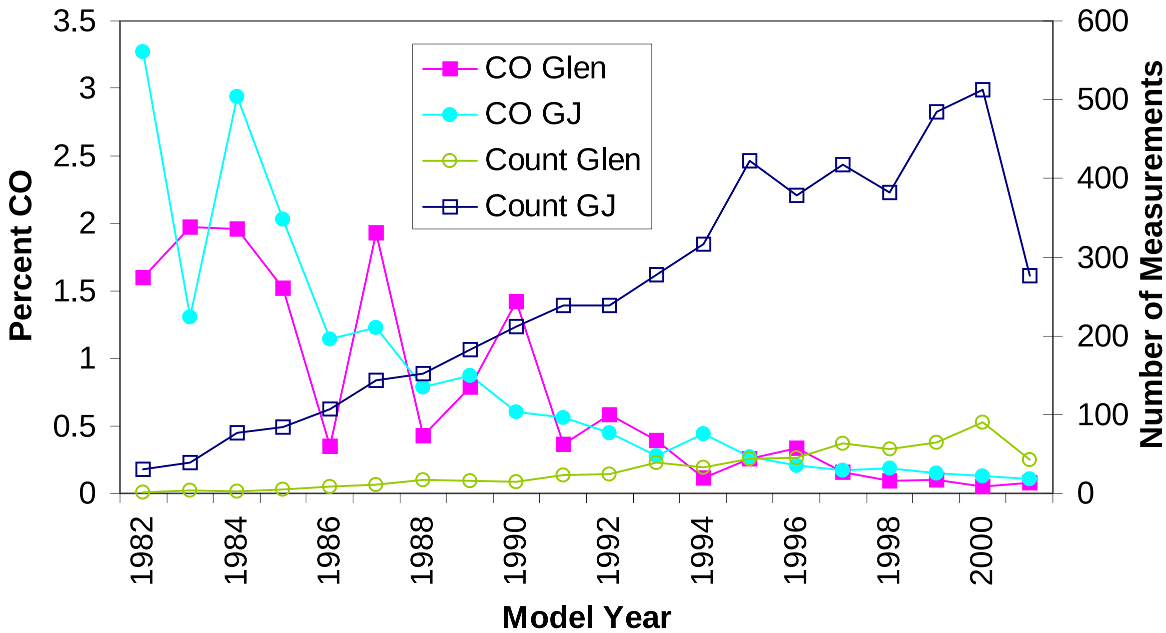


Figure 3. Average CO and number of measurements as a function of vehicle model year at Grand Junction and Glenwood Springs sites.

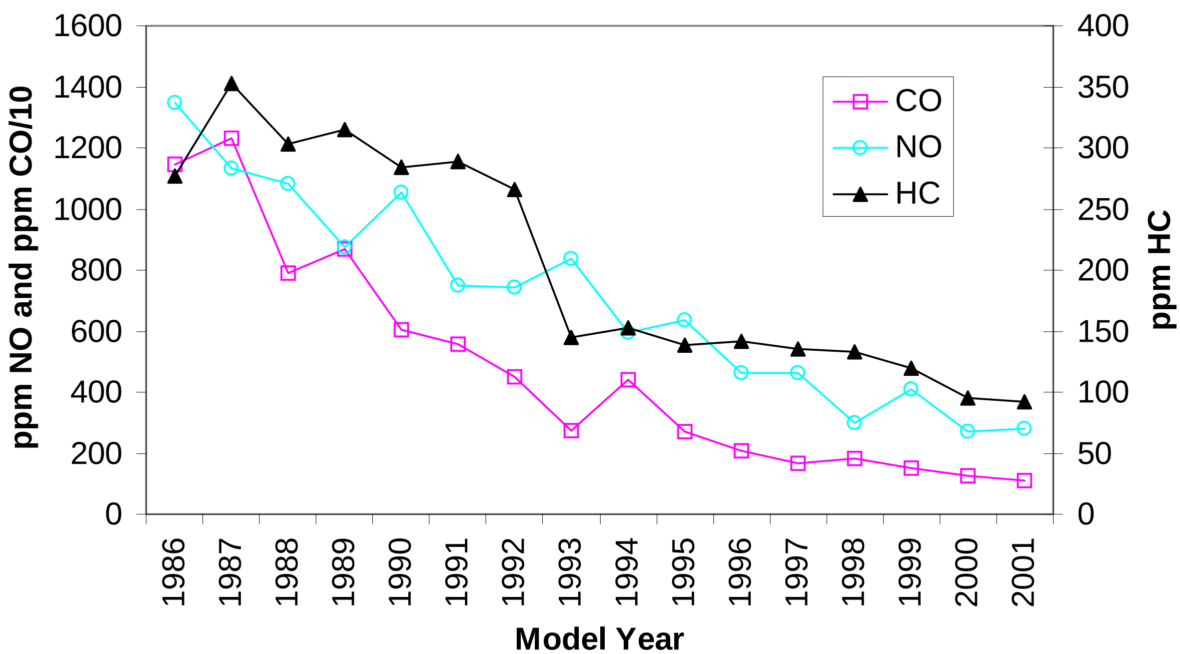


Figure 4. Model year profiles of all three pollutants at Grand Junction site. CO is reported in ppm*10 to best fit the plot.

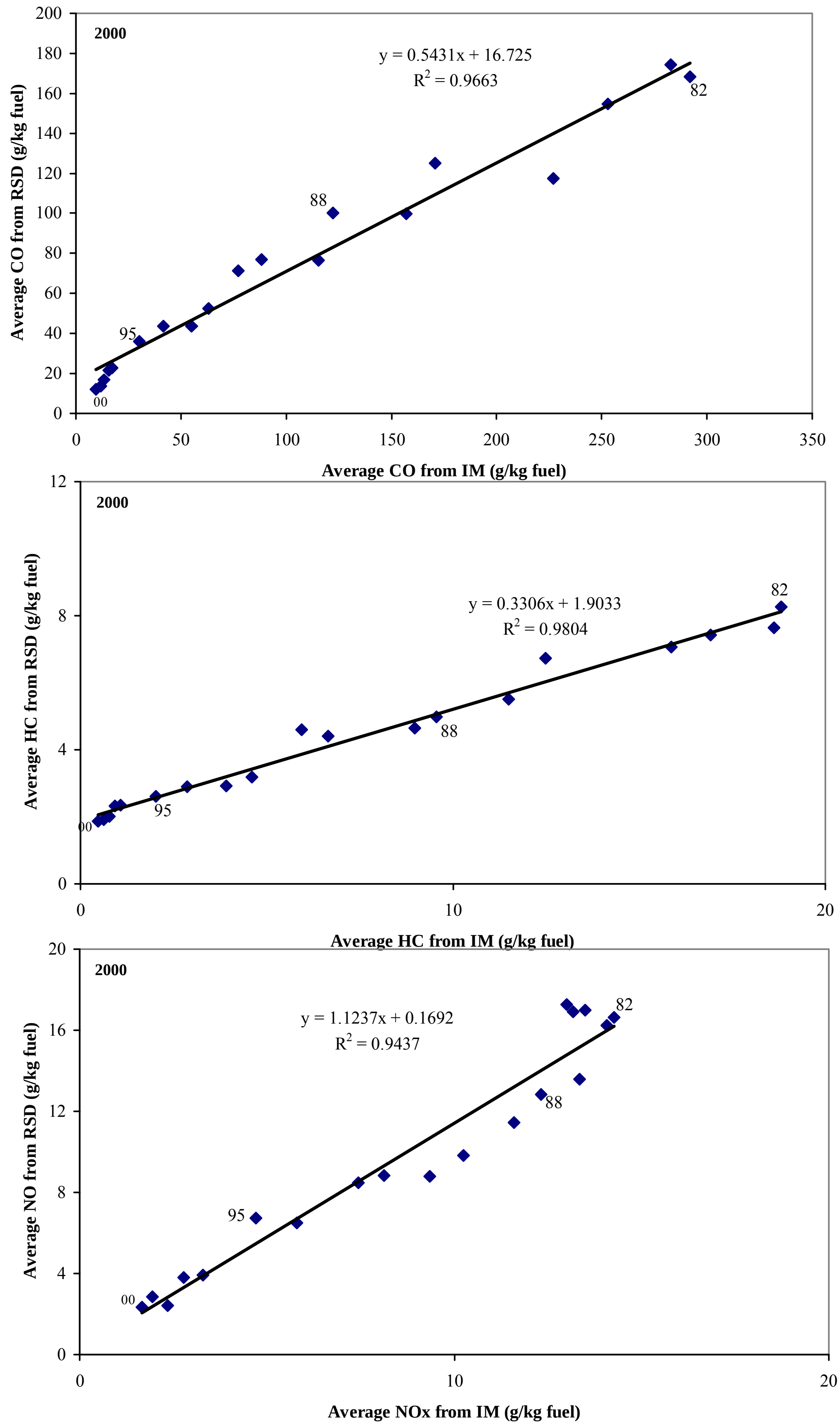


Figure 5. RSD vs. IM240 correlations for three pollutants by model year. Denver, January 2000 RSD data and Colorado 2000 IM240 data.

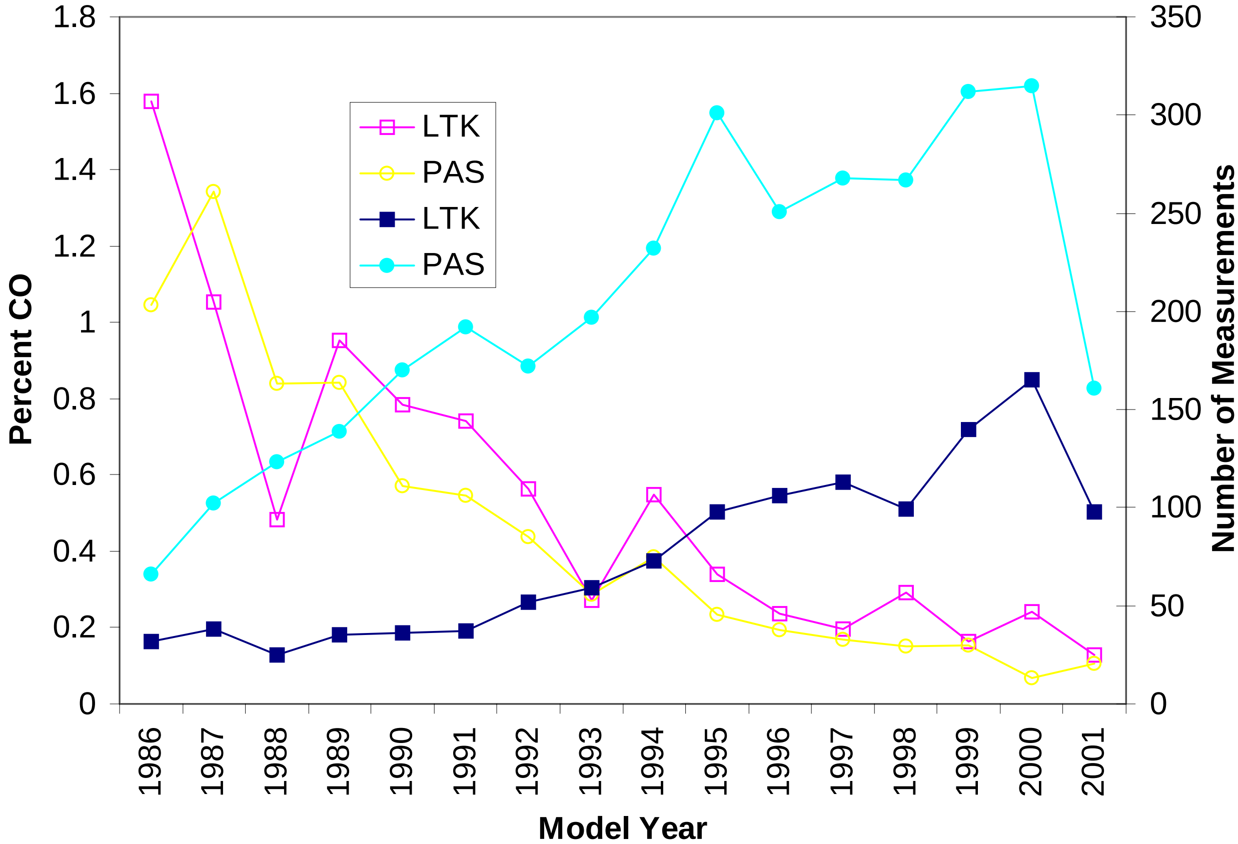


Figure 6. Grand Junction data divided by DMV vehicle type (LTK=light truck, PAS=passenger vehicle). Filled markers are measurement distribution counts while open markers represent average percent CO.

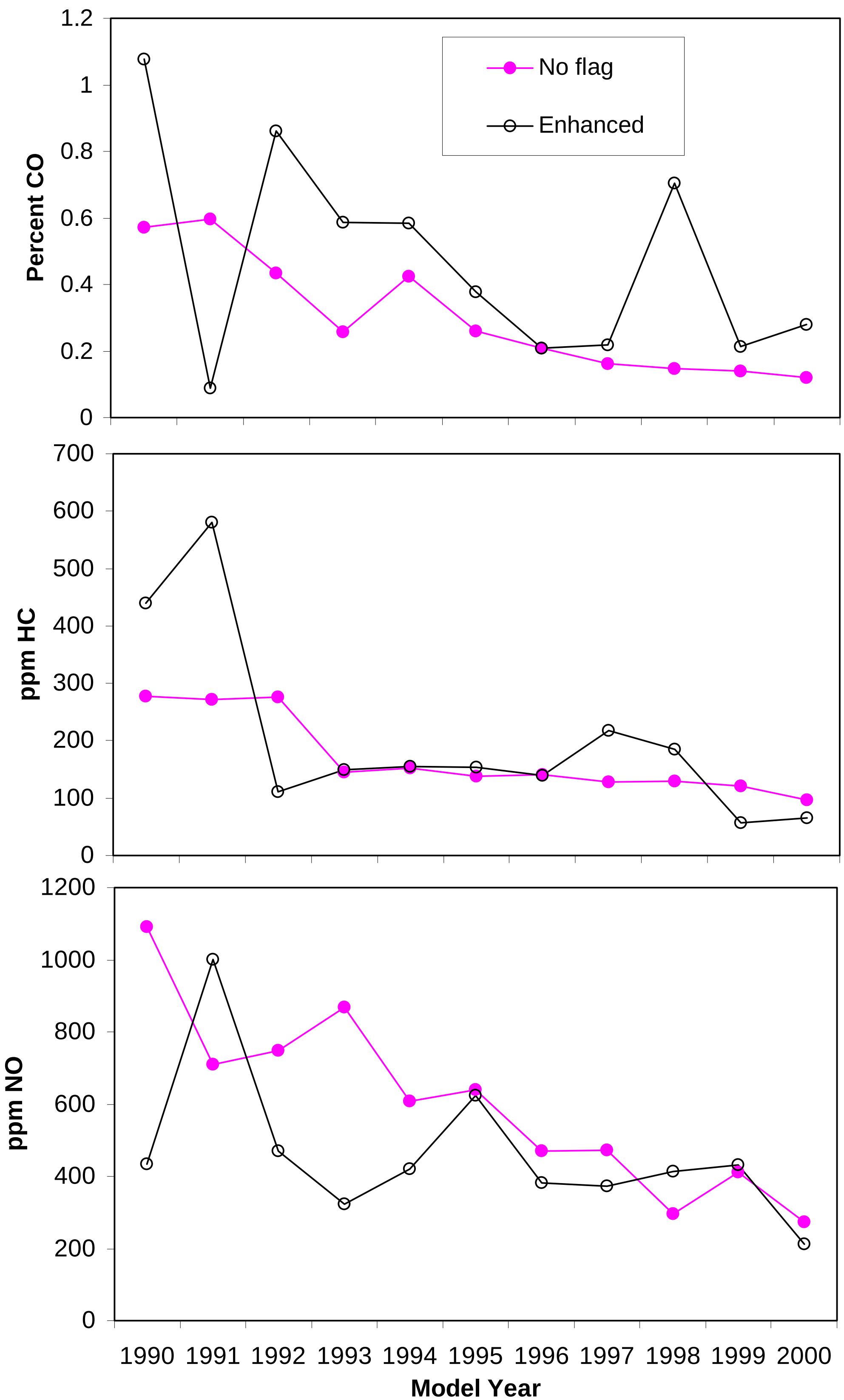


Figure 7. Average emissions as a function of model year of vehicles with Enhanced I/M flags in DMV records and those with no I/M records.

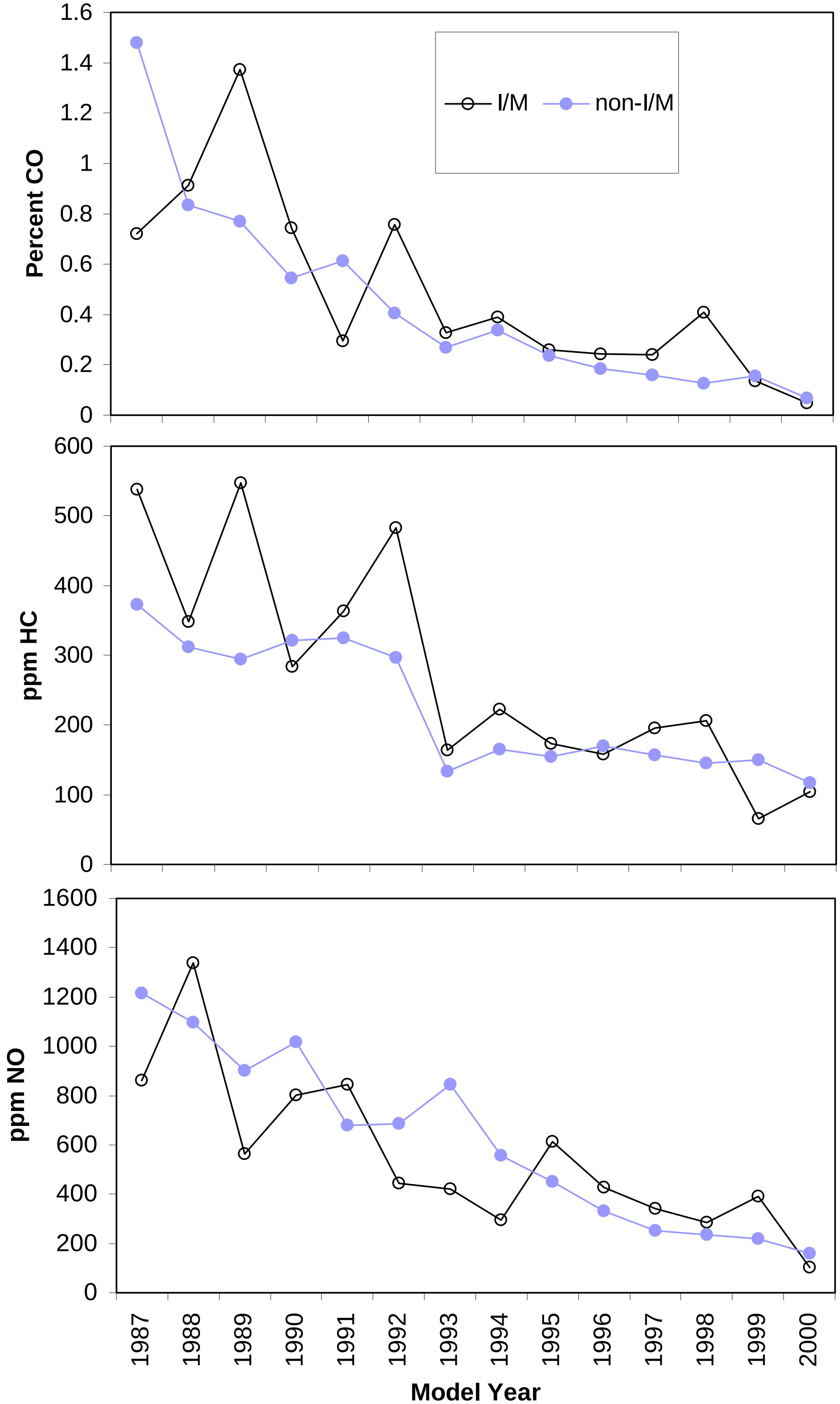


Figure 8. Average emissions as a function of model year of vehicles with IM240 records in 1998, 1999 or 2000 and those with no Colorado IM240 records in the past three years.

APPENDIX A: FEAT criteria to render a reading "invalid" or not measured.

Not measured:

1) vehicle with less than 0.5 seconds clear to the rear. Often caused by elevated pickups and trailers causing a "restart" and renewed attempt to measure exhaust. The restart number appears in the data base.

2) vehicle which drives completely through during the 0.4 seconds "thinking" time (relatively rare).

Invalid :

1) Insufficient plume to rear of vehicle relative to cleanest air observed in front or in the rear; at least five, 10ms averages >0.25% CO_2 in 8 cm path length. Often HD diesel trucks, bicycles.
2) too much error on CO/CO_2 slope, equivalent to ±20% for %CO. >1.0, 0.2%CO for %CO<1.0.
3) reported %CO , <-1% or >21%. All gases invalid in these cases.
4) too much error on HC/CO_2 slope, equivalent to ±20% for HC >2500ppm propane, 500ppm propane for HC <2500ppm.
5) reported HC <-1000ppm propane or >40,000ppm. HC "invalid".
6) too much error on NO/CO_2 slope, equivalent to ±20% for NO>1500ppm, 300ppm for NO<1500ppm.
7) reported NO<-700ppm or >7000ppm. NO "invalid".

Speed/Acceleration valid only if at least two blocks and two unblocks in the time buffer and all blocks occur before all unblocks on each sensor and the number of blocks and unblocks is equal on each sensor and 100mph>speed>5mph and 14mph/s>accel>-13mph/s and there are no restarts, or there is one restart and exactly two blocks and unblocks in the time buffer.

APPENDIX B: Explanation of the GJA_2001.dbf database.

The GJA_00.dbf is a Microsoft Foxpro database file, and can be opened by any version of MS Foxpro, regardless of platform. The following is an explanation of the data fields found in this database:

License	Colorado license plate
Date	Date of measurement, in standard format.
Time	Time of measurement, in standard format.
Percent_co	Carbon monoxide concentration, in percent.
Co_err	Standard error of the carbon monoxide measurement.
Percent_hc	Hydrocarbon concentration (propane equivalents), in percent.
Hc_err	Standard error of the hydrocarbon measurement.
Percent_no	Nitric oxide concentration, in percent.
No_err	Standard error of the nitric oxide measurement
Percent_co2	Carbon dioxide concentration, in percent.
Co2_err	Standard error of the carbon dioxide measurement.
Opacity	Opacity measurement, in percent.
Opac_err	Standard error of the opacity measurement.
Restart	Number of times data collection is interrupted and restarted by a close-following vehicle, or the rear wheels of tractor trailer.
Co_flag	Indicates a valid carbon monoxide measurement by a “V”, invalid by an “X”.
Hc_flag	Indicates a valid hydrocarbon measurement by a “V”, invalid by an “X”.
No_flag	Indicates a valid nitric oxide measurement by a “V”, invalid by an “X”.
Co2_flag	Indicates a valid carbon dioxide measurement by a “V”, invalid by an “X”.
Opac_flag	Indicates a valid opacity measurement by a “V”, invalid by an “X”.
Max_co2	Reports the highest absolute concentration of carbon dioxide measured by the remote sensor; indicates the strength of the observed plume.
Speed_flag	Indicates a valid speed measurement by a “V”, an invalid by an “X”, and slow speed (excluded from the data analysis) by an “S”.
Speed	Measured speed of the vehicle, in mph.
Accel	Measured acceleration of the vehicle, in mph/s.
Ref_factor	Reference detector voltage. Used along with “CO2_factor” to observe calibration shifts.

CO2_factor	CO_2 detector voltage. Used along with “Ref_factor” to observe calibration shifts.
Lic_type	Three letter code designates vehicle type (PAS, LTK, etc.)
County	Number designation of county.
Vin	Vehicle identification number.
Bus_date	Registration renewal date?
Year	Model year of the vehicle.
Make	Manufacturer of the vehicle.
Model	Model name of the vehicle.
Body	Body style of the vehicle.
Series	Series code of vehicle.
Fuel_type	Fuel type: ‘G’ indicates gasoline, ‘D’ indicates diesel.
Legl_city	City the vehicle resides in.
Legal_St	State the vehicle resides in.
Legl_zip5	Zip code the vehicle resides in.
Mail_City	City of owner mailing address.
Mail_St	State of owner mailing address.
Mail_zip5	Zip code of owner mailing address.
Urbn_rl_cd	Urban or rural designation where vehicle resides. ‘R’ is rural and ‘U’ is urban.
Expire_Date	Date that current vehicle registration expires.
Purch_Date	Date vehicle was purchased.
Gvw	Unknown. (Gross vehicle weight?).
Msrp	Manufacturer suggested retail price in US$.
Odometer	Odometer reading during I/M inspection.
Prch_price	Price at which vehicle was purchased in US$ x 100.
Emiss_flag	I/M flag: ‘Y’, ‘N’, ‘X’.
E_Status	I/M status: ‘P’ is pass and ‘E’ is exempt.
E_Prog_Type	I/M type: ‘E’ is enhanced and ‘B’ is basic.
Test_date	I/M test date.
Next_insp	Due date for next inspection.

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