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2001

## How to Evaluate an On-Road Remote Sensor

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## **ON-ROAD EVALUATION OF A REMOTE SENSOR:**

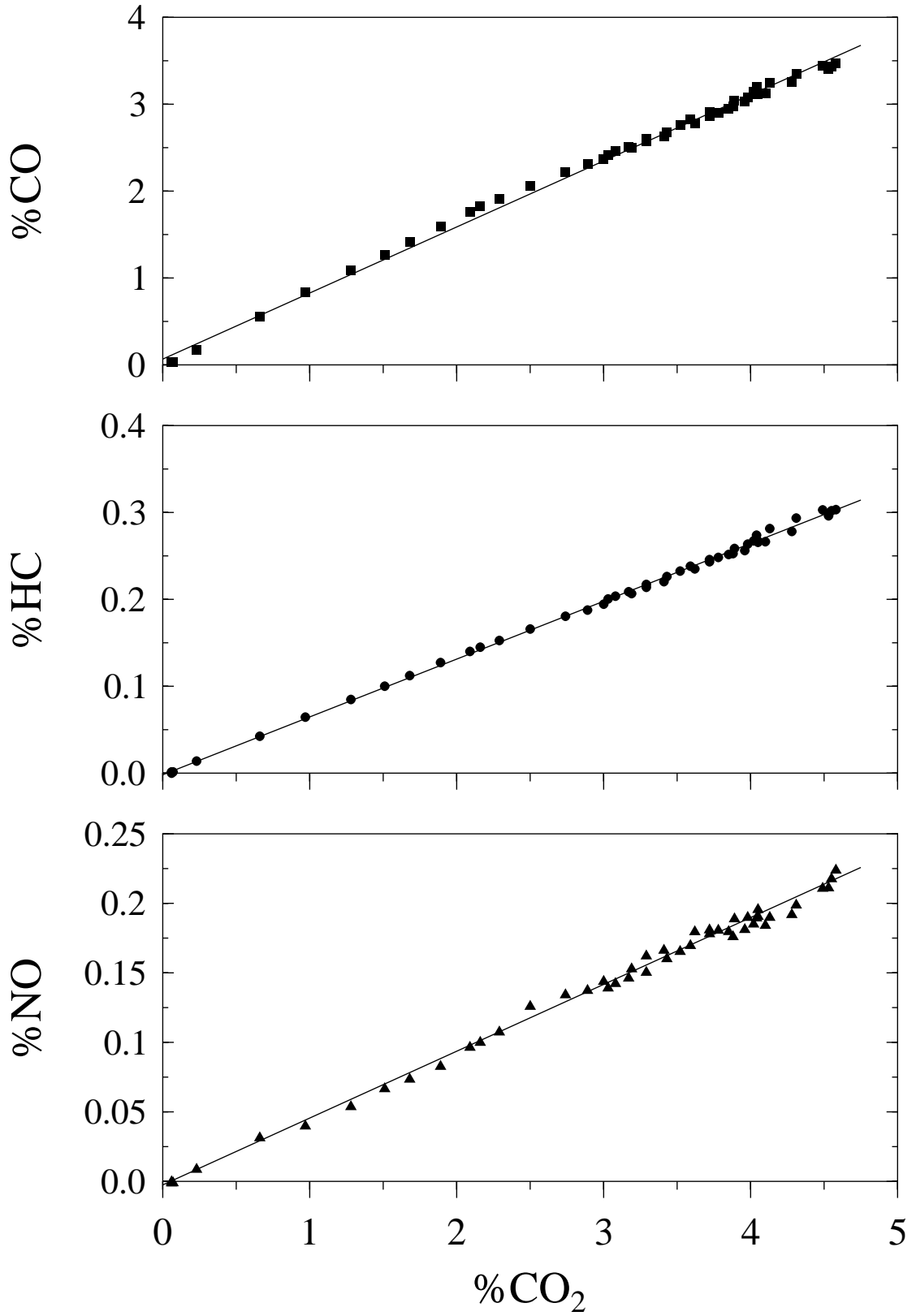
All on-road remote sensors of which we are aware carry out at least a measurement of the CO/CO<sub>2</sub> ratio in the exhaust of a passing vehicle. It is possible for an interested party to carry out a quantitative evaluation of the precision of this measurement. This evaluation can be done without going to the expense and complexity of an on-road audit using a vehicle of known emissions (wet gas audit), or a vehicle designed to puff surrogate compressed gas mixtures of known ratios (dry gas audit).

The measurement of exhaust CO/CO<sub>2</sub> ratio is obtained by estimating the slope of a graph of CO versus CO<sub>2</sub> (or properly delta CO versus delta CO<sub>2</sub>). Evaluation is carried out by observing the quality of the individual data points which are used to derive this slope. Several on-road remote sensors operate for 0.5 seconds at 100z, thus obtaining 50 data points for this correlation. Several on-road remote sensors use a puff of gas of known CO/CO<sub>2</sub> ratio as a field calibration. For these sensors, the system operator can display the CO/CO<sub>2</sub> graph from a calibration, whether the calibration was considered valid or not.

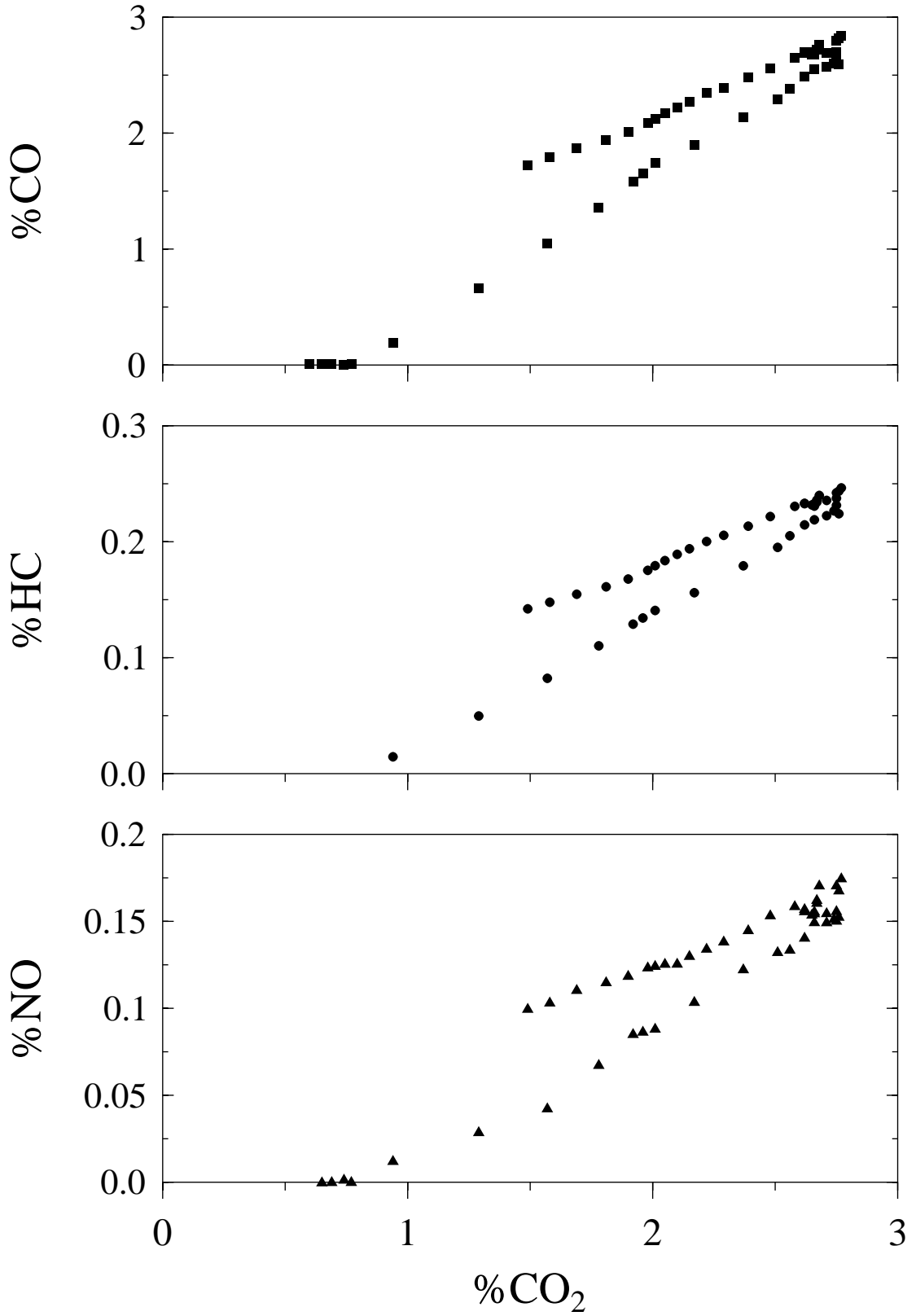
## **EVALUATION OF A CALIBRATION PUFF:**

Figure 1 shows a valid CO/CO<sub>2</sub>, HC/CO<sub>2</sub> and NO/CO<sub>2</sub> on-road calibration puff (FEAT 3002, Sept. 27, 2001, Casa Grande, AZ). When evaluating a remote sensor, the first parameter to note is the quality of the data and the fit. In the case shown, all 50 points are almost touching the straight line and  $r^2 = 0.99$ . The next parameter to note is the extent of the data spread on the CO, HC, NO and CO<sub>2</sub> axes. Different instruments use different units. These graphs show the gas concentrations %CO, %HC (propane), %NO and CO<sub>2</sub> in an 8cm cell. These units are chosen to correspond approximately to what would be measured were one to directly probe a tailpipe. The units however do not matter, but the spread of both gases in a plot such as Figure 1 is important to note.

Figure 2 shows a CO/CO<sub>2</sub>, HC/CO<sub>2</sub> and NO/CO<sub>2</sub> on-road calibration puff (FEAT 3002, August 29, 2001, Phoenix AZ). This was not a valid calibration. In this case, the calibration gas appears to be mixed with exhaust from a vehicle which had recently passed through the optical beam. It is not important that occasional invalid calibrations look bad. It is important that the instrument is able to obtain valid calibrations, which look like Figure 1, AND are carried out with a data spread comparable to a typical automobile at the same site. This parameter also must be determined at the roadside in order to evaluate the instrument. Another noise evaluation which one should ask any instrument to be able to perform is a calibration but without any added calibration gas. The graphical evaluation is uninteresting, namely a cluster of points at the origin. However, the spread of these points along each of the axes is a direct measure of the noise which the instrument will see from all passing vehicles. Again, the spread should be compared to the spread expected from a typical motor vehicle in a realistic roadway situation using the same remote sensing unit.



**Figure 1.** Half-second puff calibration plots for CO, HC and NO. The straight lines are linear least squares regressions of the data.



**Figure 2.** Half-second calibration gas puff for CO, HC and NO which has been contaminated with exhaust from a passing vehicle.

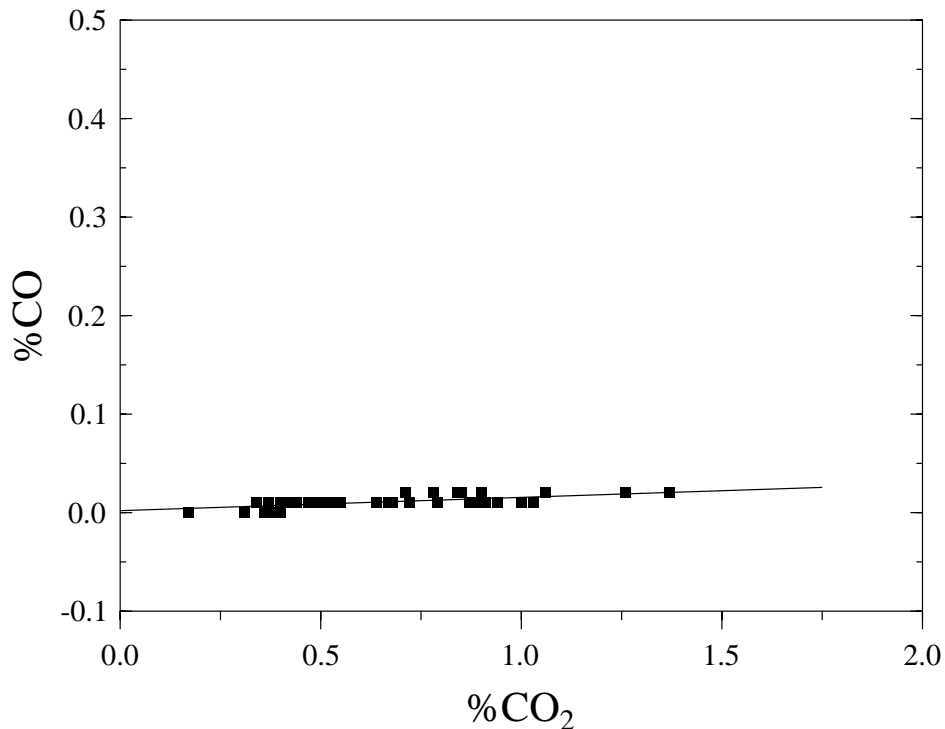
## EVALUATION OF INDIVIDUAL MOTOR VEHICLE EMISSIONS:

At the roadside, when the instrument is operating and calibrated, call up and observe CO/CO<sub>2</sub> ratio graphs from about three randomly chosen vehicles. The skewed distribution of emissions implies that these are all likely to be low emitting cars with very small CO/CO<sub>2</sub> slopes. The parameter to observe on these graphs is the range (spread) of the CO<sub>2</sub> data. If the CO axis is auto scaling, the noise may look very bad but actually be very good. Note the CO<sub>2</sub> spread. It should be comparable to the calibration, or at least not less than about 10x smaller.

Figure 3 shows typical data from a passing vehicle. The CO<sub>2</sub> readings are from about 0.3% to 1.3%, for a total spread of 1% CO<sub>2</sub> in 8cm. The spread for the calibration shown in Figure 1 is about 4.5% and in Figure 2 about 2.2%. In both cases the calibrations are at a comparable, although larger spread than the on-road data. Now it is necessary to evaluate the CO/CO<sub>2</sub> graph on a vehicle with higher than zero CO/CO<sub>2</sub> ratio. If the raw data are stored and can be recalled and graphed from each vehicle, then wait for a vehicle with CO/CO<sub>2</sub> > 0.25 (about 3.5% CO on the video screen). Now observe this CO/CO<sub>2</sub> graph. The CO<sub>2</sub> spread should be comparable to the three low CO emitters observed earlier. The CO spread should be comparable to the CO spread on the calibration puff, or at least not less than about 10x smaller. If these criteria are met and this graph looks “good”, for instance,  $r^2 > 0.9$ , then you have an instrument likely to provide precise (and accurate if the calibration gas supplier is trustworthy) data.

Figure 4 shows on-road CO/CO<sub>2</sub> data from a cold-start vehicle measured at the University of Denver. A similar evaluation analysis can be carried out for HC and NO; however, if the CO/CO<sub>2</sub> data do not pass muster, then HC/CO<sub>2</sub> and NO/CO<sub>2</sub> are much less useful because the readings are missing a major component of the carbon balance. Note also that HC emissions are smaller and harder to measure than CO, so more (relative) noise is to be expected. If the data you see at roadside are of similar or better quality then you are observing a good instrument. If they are not up to this quality, then you should think twice about accepting the data until the operator/vendor can convince you that the instrument is functioning properly.

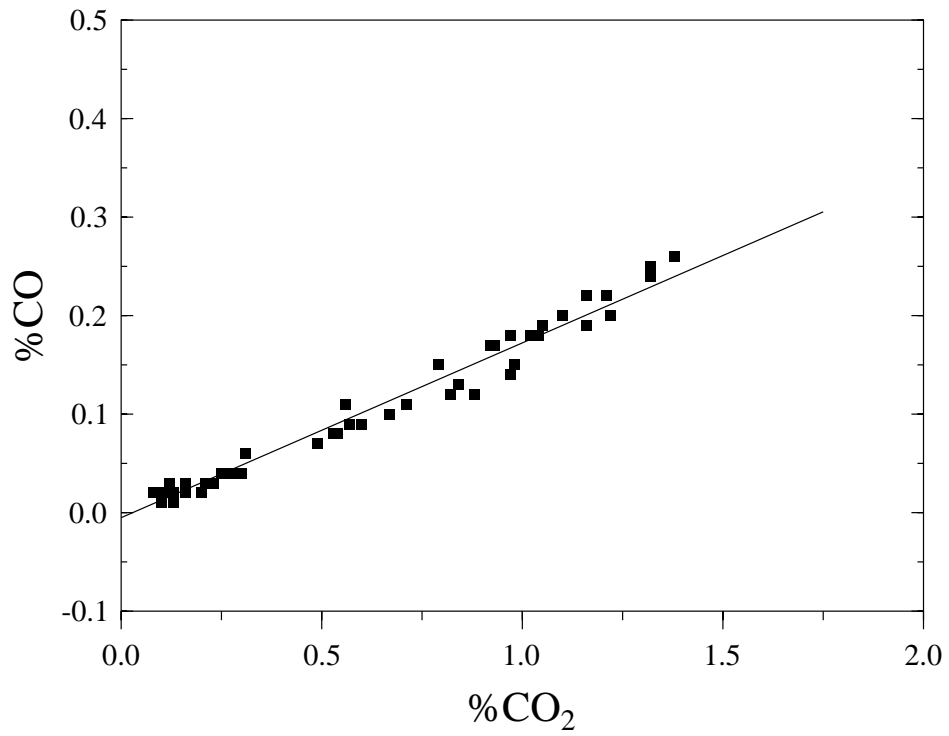
While observing roadside operations make a note of the valid reading rate from normal sedans and from SUV's and pickups. In a perfect world all vehicles with ground level exhaust should be measured. In reality some are not, but this should be observed to be a random process or a systematic one caused by driving mode (noticeable decelerations) not one caused by vehicle type or body height.



**Figure 3.** In-use data for a low CO emitting vehicle.

**EVALUATION USING EXHALED BREATH:**

A non-smoking human exhales CO<sub>2</sub> and negligible amounts of CO, HC and NO. The remote sensor should be able to read human breath as a passing car, as long as it is accompanied by a blocked and unblocked optical beam. Fifteen readings of breath with our instrument in the laboratory yielded a mean CO reading of 0.07% with a standard deviation of 0.04%. HC read a mean of 39 ppm propane with S.D. of 50 and NO a mean of -3ppm with a S.D. of 18ppm.



**Figure 4.** In-use data from a cold-start vehicle with elevated levels of CO.