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DURING WORST CASE METEOROLOGY ARE BUOYANCY EFFECTS IMPORTANT?

By

T.P. Kear[1],
Anthony Held[2],
Daniel P.Y. Chang[2], and
John J. Carroll[3]

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1) Institute of Transportation Studies, University of California, Davis (UCD)
2) Department of Civil and Environmental Engineering, UCD
3) Department of Land, Air, and Water Resources, UCD

Abstract

Observations of carbon monoxide (CO) adjacent to high density CO emission sources often fail to exhibit the intensity of CO concentrations predicted by current models used for conformity determination. Meteorological conditions associated with CO episodes are commonly very light wind or calm, stable conditions. Buoyancy of the emissions has been hypothesized as one possible reason for the discrepancy under those meteorological conditions. A preliminary experiment to determine the height to which CO would rise was conducted adjacent to Interstate 80 near Sacramento during February 1996. Sampling lines were carried by two tethered balloons, on either side of Interstate 80, and a 20 meter tall meteorological tower placed above the median strip on an unused overpass. The balloon sampling heights, the sampling locations and tower configuration are shown in the first three figures, respectively. Simultaneous five-minute average "bag" samples and a few continuous analyzer measurements were made. Corresponding traffic volumes during the measurements are shown in the fourth figure. The results of the experiment suggest that CO is carried to levels as high as 20 to 30 meters above the roadway, possibly greater, under strongly stable, near calm, near parallel wind situations. Two examples of CO concentration profiles are shown in the fifth and sixth figure. A model such as CAL3QHC or CALINE4 would not fully account for the extent of the vertical dispersion or the buoyant rise of the plume. Plans for further numerical modeling and experimental studies of the phenomenon are also be presented.

Introduction

For environmental analysis, the dispersion of air pollution from roadways (and the resulting pollutant concentrations) are estimated using computer models. These models treat the roadway as a series of short links. Gaussian dispersion algorithms are used to estimate the concentrations of non-reactive pollutants near the roadway, e.g., carbon monoxide. The specific places for which concentration estimates are modeled are termed "receptors."

Modeled concentrations are estimated from functions of the local meteorological conditions, vehicle activity, roadway geometry, and emission rates. Inaccuracies in the estimated concentrations result from, among other things, users over-generalizing the input data, and the limitations of the gaussian solution to the atmospheric dispersion equation. However, the models are calibrated and tested using field data. This imperial basis to the model makes up for the limitations of the gaussian solution, as long as the assumptions implicit to the imperial calibration are not violated. When the meteorological conditions, roadway geometry, traffic activity, and emissions have been correctly represented, and are reasonably close to the calibration conditions, accurate concentrations will be predicted at the receptors.

It is commonly felt that there is poor agreement between roadway dispersion models (e.g., CALINE3, CALINE4, CAL3QHC) and observed maximum concentrations under "worst case" conditions. One basis for this feeling is that while modeled exceedances of the NAAQS are common, real no longer occur in most of the country. Worst case conditions are characterized by peak traffic flow, cold temperatures, low wind speeds, and stable atmospheric conditions -- such as a ground level inversion. Unfortunately, none of the data sets used to calibrate / test the available models contain an adequate representation of such conditions. The tendency of these models to over predict has come under increased scrutiny since conformity tied highway funding to protecting the national ambient air quality standards (NAAQS).

It is hypothesized that the current models do not properly account for heat emissions under the stable atmospheric conditions assumed for "worst case meteorology." Current model formulations keep the centerline of the plume, which is where the highest concentrations are found, at ground level. But, when high traffic volumes and stable atmospheric conditions coincide, the plume may develop enough buoyancy for the centerline to rise above ground level. This buoyant plume phenomenon would explain some of the tendency for model over-prediction. Emissions would be mixed into a larger volume than that predicted by existing models, and peak concentrations would occur above the height where ambient monitors sample.

Approach

Preliminary results from numerical wind field modeling support the theory that there may be sufficient thermal emissions from a congested roadway to generate a buoyant plume. Under highly stable conditions, the initial mixing of hot exhaust gasses is not necessarily sufficient to prevent the plume centerline from lofting as it begins to move away from the road. A three part study was designed to investigate the hypothesis:

1. Determine if phenomenon exists by conducting preliminary field measurements.
2. Perform computational model simulations to predict conditions when the phenomenon would impact ground level concentrations.
3. Verify the modeling results by conducting additional field studies.

The preliminary field measurements were designed as to see if the phenomena could be observed -- and if the remainder of the study is worth pursuing. That study, scheduled for late February and early March 1996, was so successful that it was decided there was no need to return to the field after the first day of sampling. That preliminary work was not detailed enough to provide robust scientific data, but does strongly suggest that the plume centerline was not at ground level.

The computational modeling is being carried out using a three dimensional wind field model that numerically solves the Navier-Stocks Equations. The computational model is too extensive incorporate into common dispersion models. It is hoped that numerical modeling can be used predict plume behavior under a wide variety of conditions. If the computational model results are verifiable, then the model could be used to derive plume rise algorithms and new dispersion coefficients for use in models such as CALINE and CAL3QHC. The third phase of the study, an attempt to verify the results from the computational model, will be carried out in fall, 1996. A tethersonde will be used to collect atmospheric profiles up to 500 meters aloft, CO samples will be collected both upwind and downwind so that contribution from the highway is discernible. Once the field data and atmospheric profiles have been collected, the second stage may need to be revisited to better account for the boundary conditions when running the computational model. The second and third stages of the study may prove to be an iterative process.

The goal of the study will be to fine tune the specification of the computational model such that it can be used to develop rough plume rise algorithms and new dispersion coefficients for use in dispersion models.

The remainder of this paper is dedicated to the preliminary field experiment. The first two sections detail the conditions and scope of that field study, and presents some of the concentration data collected. The last two sections summarize the implications of this work and highlight some of the important questions that were raised.

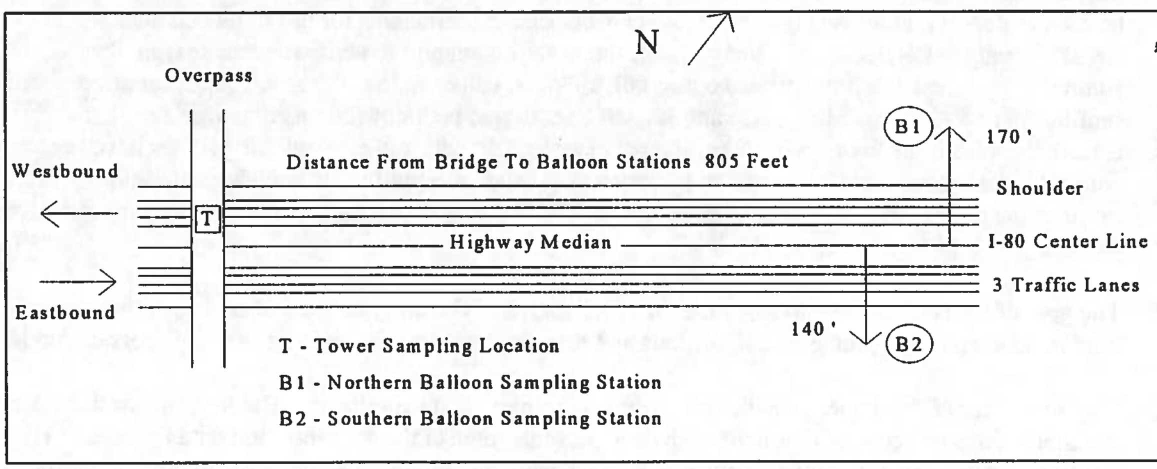
Preliminary Experiment

A preliminary field study was undertaken to determine if the buoyant plume phenomena existed. The study design was simple. Surround the highway with carbon monoxide (CO) samplers up to 100 feet above the highway -- so that no mater where the plume went, it could be detected. Sampling was conducted on a clear, frosty February morning that had nearly ideal conditions to generate a buoyant plume. The major characteristics of the study are bulleted out below:

- Limited scope to two balloons carrying CO sample lines and a meteorological (Met.) tower on an overpass, also carrying sample lines.
- Met conditions favorable with light winds of 1.0 to 2.5+ M/s aloft, likely less than 1.0 M/s at ground most of the time.
- Moderate traffic of roughly 5000 to 7500 vehicles per hour.

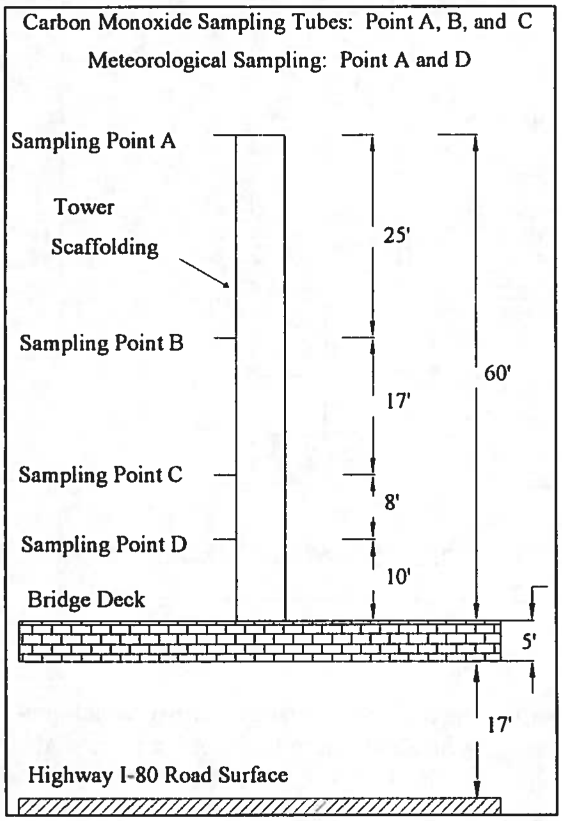
The study was conducted on February 26, 1996, at a site along Interstate 80, near the Arco Arena in Sacramento, during the morning commute hour. The land surrounding the observed highway section was unplanned agricultural fields -- flat with few vertical obstructions. The site included an unused overpass that allowed the positioning of sampling equipment directly above I-80. Three sampling stations were located on the site. Figure 1. Location of Sampling Stations, shows where equipment was located. A Met. tower was positioned on the unused overpass above I-80 and two balloon stations were located approximately 805 feet from the tower location along the edge of the roadway.

Figure 1. Location of Sampling Stations



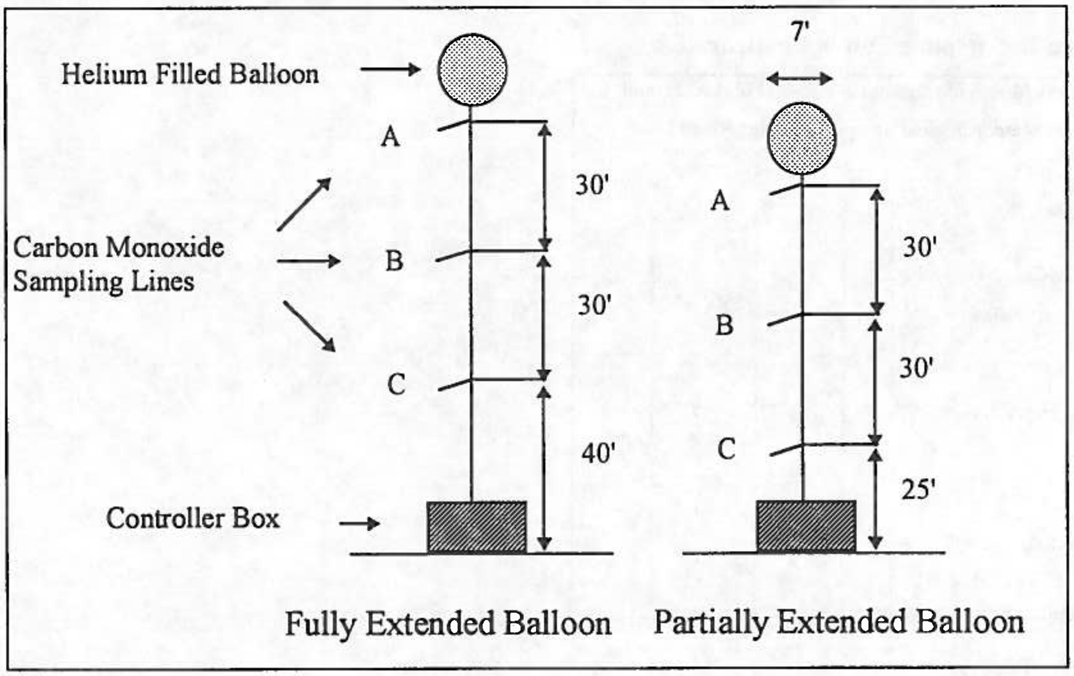
The Met. tower carried three CO sampling lines and two meteorological stations (Met. stations). The Met. stations measured temperature, relative humidity (RH), and triaxial wind speed. The triaxial wind speed, which implicitly includes wind direction, temperature, and RH sensors were all sampled at one hertz, the data were recorded on data logger located at the tower base. The CO sampling lines were composed of plastic tubing and extended from the tower base to the sampling point elevation. Figure 2. Met. Tower Configuration, shows the elevations where CO and Met. Data were collected.

Figure 2. Sampling Tower Configuration



The balloons (seven foot diameter helium advertising balloons) carried three CO sampling lines to a maximum height of 100 feet. The balloons were connected to a controller box that varied the balloon elevation. Each balloon station was equipped with a wind vane to make visual observations of the wind direction. Figure 3. Balloon Station Configuration, is a schematic of how the balloons were configured.

Figure 3. Balloon Station Configuration



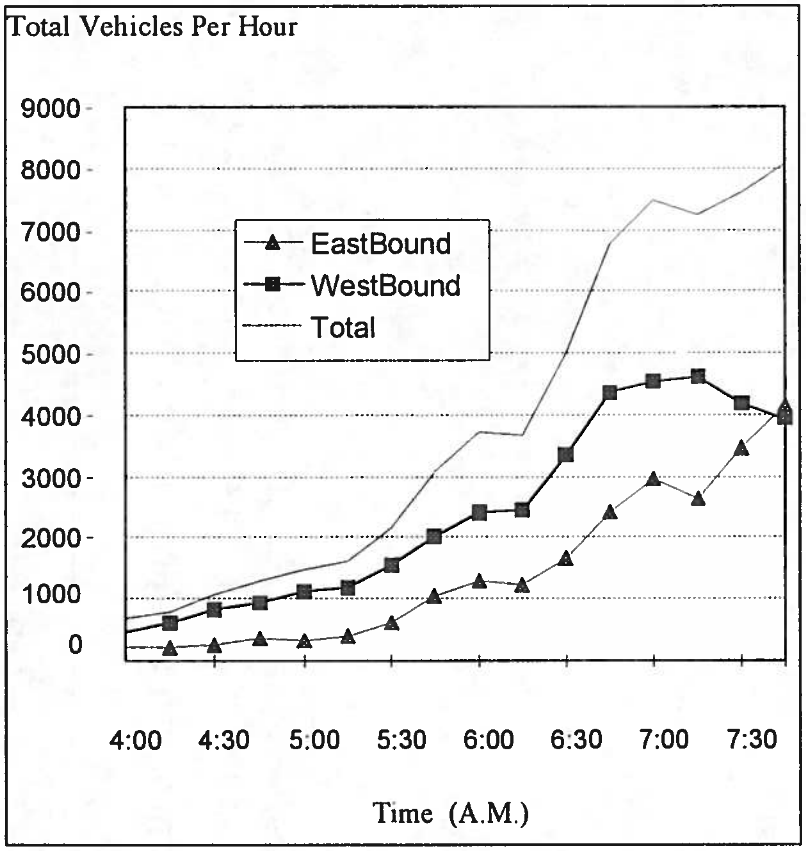
Ground level CO sampling was performed intermittently at the two balloon stations with a Dasibi non-dispersive infrared CO sampler. Six sets of five minute grab samples were collected at the tower and balloon stations. Samples were collected at 6:00, 6:20, 6:45, 6:55, 7:15, and 7:30 a.m. The five minute samples were obtained by connecting the CO sampling lines to small pumps that filled individual tedlar bags. The subsequent analysis of the tedlar bags was performed within six hours, at the University of California at Davis, using the same Dasibi CO analyzers.

The Met. conditions were constant with those thought to favor the buoyant plume phenomena. A small temperature inversion was recorded by the Met. Tower above the highway -- roughly one degree centigrade over the 50 feet separating the temperature sensors. It is believed that the inversion was stronger over the surrounding agricultural land. Ground fog and frost formed during the experiment -- providing additional evidence of a ground level inversion and stable atmosphere. Winds at the 82 foot level were generally between 1.0 and 2.5 M/s. At the 32 foot level, they were lower, with a slightly different direction. It is unclear if the directional difference was due to wind motion around the bridge deck or if was so stable that an Ekman Spiral was detectable. There was almost no discernible wind at ground level. Despite the strongly stable atmosphere, there was significant vertical mixing taking place over the highway. The vertical component of the wind occasionally reached magnitudes of over 1.0 M/s, well above the cosine error attributable to triaxial anemometers. There also appeared to be a strong correlation between low wind speed and updrafts.

Traffic during the study was between roughly 5000 and 7500 vehicles per hour, with the heaviest flow on the westbound lanes of the highway (toward downtown Sacramento). When sampling began at roughly

6:15 AM, the traffic was at free flow in both directions. By 7:00 AM, the westbound traffic was congested, and slowed to roughly 40 MPH. The study was aided by heavier than average traffic -- caused by incidents on alternate routs that diverted traffic to the study site. The study itself caused additional congestion as motorist slowed to watch the balloons.

Figure 4. Traffic Volume During the CO Study



CO concentrations measured during the study are shown on the following pages in figures 5 and 6. Note that the concentrations at 25 and 40 feet above the ground are consistently higher than those at near the ground level (samplers were set up at roughly 5 feet).

Figure 5. CO Concentrations at 6:55 A.M.

(Traffic volume approximately 7250 VPH, wind perpendicular to highway)

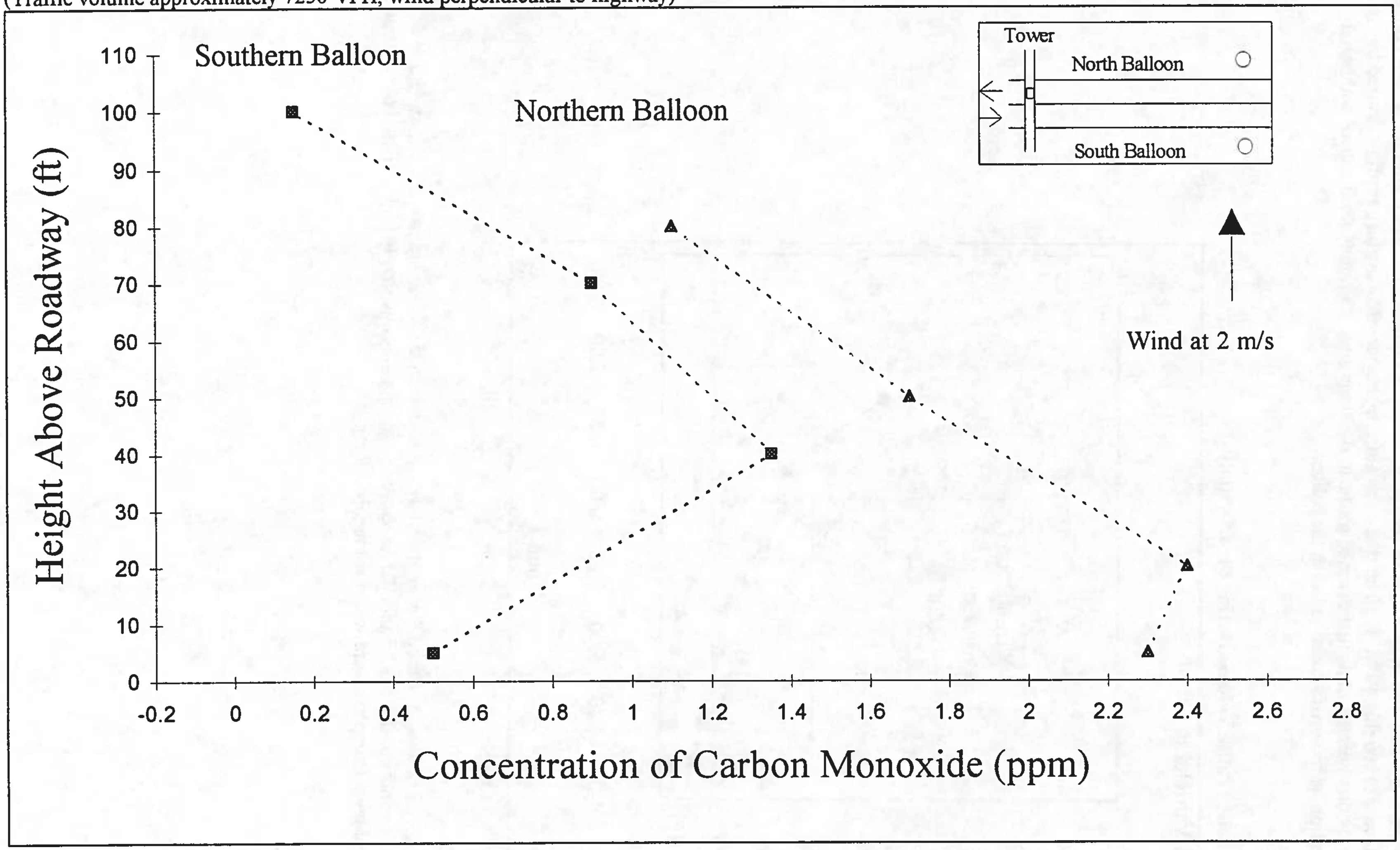
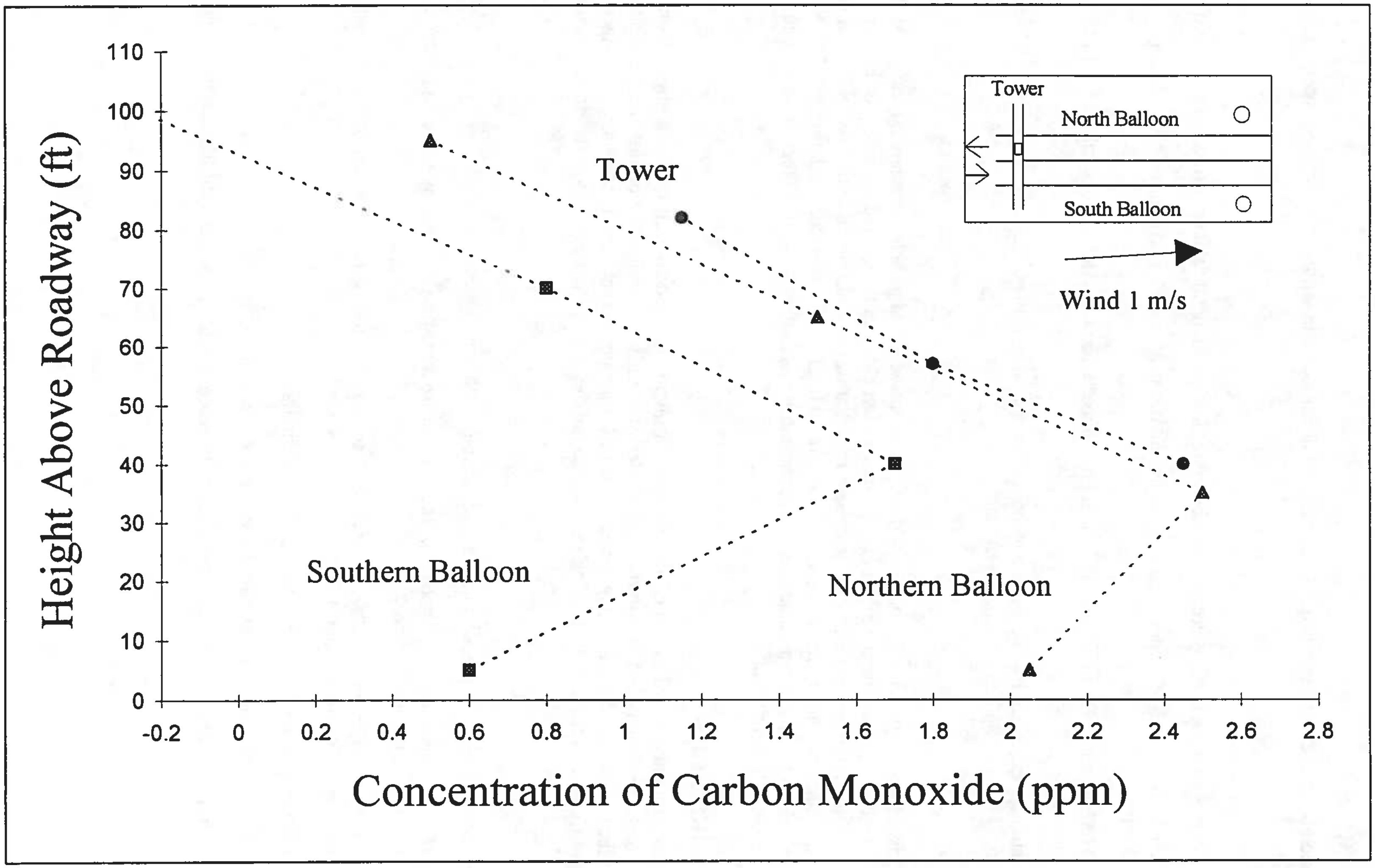


Figure 6. CO Concentrations at 7:15 A.M.

(Traffic volume approximately 7500 VPH, near parallel wind)



Results

While one field experiment is not a scientifically defensible data set, there are several observations that are worth noting:

- Carbon monoxide (CO) decreases much more slowly with height than existing models would predict.
- Under weak, near parallel wind conditions, there may be a weak maximum aloft -- "lofting" up to about 20 or 30 meters.
- The buoyancy effect appears to be more pronounced when the wind angle is parallel and near parallel to the roadway.
- Higher density on LA freeways may imply that buoyancy is important even at ground level wind speeds above 0.5 M/s (perpendicular to the freeway).

CALINE4 would predict that roughly 95% of the pollution would be below roughly 60 feet. CALINE3 or CAL3QHC would predict the bulk of the pollution even closer to the ground because they lack an improvement in the way the initial vertical mixing is parameterized that was not introduced until CALINE4. All of the models would predict the maximum concentrations at ground level. While this study did not identify the elevation or magnitude of the maximum, it suggests that concentrations as high as 40 to 70 feet above ground can be higher than those at ground level.

Implications

This preliminary study has several implications for microscale modeling. It raises questions about what meteorological conditions lead to the most conservative estimates of ambient pollution concentrations, and suggests that the current set of models may systematically over predict ambient concentrations near congested roadway links. Caution is needed when using some aspects of the models -- consideration should be given to the items listed below.

- Current line source models may not be accurate with wind speeds of 0.5 M/s.
- A better understanding is needed of the heat release rate at which the buoyancy effect becomes important as a function of the wind speed.
- Existing methodology of "worst case" wind angle search may not apply under some conditions even if the wind speed is greater than 1 M/s.
- CO and primary $PM_{2.5}$ are likely to disperse similarly.
- CO and a portion of re-entrained PM_{10} may disperse similarly.
- Similar dispersion algorithms are likely to be recommended with minor differences for deposition velocity.

Unanswered Questions

The two biggest unanswered questions at this point are:

- Are buoyancy effects important to model in an urban setting? (i.e., increased surface roughness and slight stability)
- What is the relation between heat emission rate, stability and wind?

It is hoped that the second and third phases of this project, which will include computational modeling, direct measurements, and possibly re-analysis of new / existing databases will answer these questions.