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Effects of Stability Episodes on Air Pollutant Levels Along Roadways

Roderick D. Moe State Department of Highways and Public Transportation, Austin, Texas
Jerry A. Bullin Chemical Engineering Dept., Texas A & M University, College Station, Texas
John C. Polasek Chemical Engineering Department, Texas A & M University, College Station, Texas

Roderick D. Moe, M.S. in Meteorology, Staff Services Officer (Meteorologist), State Department of Highways and Public Transportation, D-8, 11th and Brazos, Austin, Texas 78701

Dr. Jerry A. Bullin, Ph. D. in Chemical Engineering, Assistant Professor in Chemical Engineering, Chemical Engineering Department, Texas A & M University, College Station, Texas 77843

John C. Polasek, graduate student, Chemical Engineering Department, Texas A & M University, College Station, Texas 77843

Introduction

#4 [High carbon monoxide levels along urban roadways are usually associated with episodes of high atmospheric stability caused by strong, deep thermal inversions formed by nighttime cooling, a relatively cool seabreeze, or cold air drainage from steep terrain. Strong thermal inversions are a relative rarity in most Texas cities because of the urban heat island effect and turbulence generated by urban obstructions. Examination of an extensive Texas data base shows a few cases of high carbon monoxide levels which do not appear to be related to strong thermal inversions and are poorly predicted by existing line source dispersion models. These cases were investigated to learn whether or not some other factors were causing high stability episodes and in the hope that greater insight into the complex mechanism of pollutant dispersion along roadways could be gained. This paper covers the results of the study to date.]

Measurements

Dr. Jerry Bullin and John Polasek have been measuring traffic, meteorology, and air pollutants at six sites in four Texas cities for the past four years. The measurement phase is now complete and data are being reduced and analyzed in more detail. An interim report has been published.[1]

Traffic data were acquired using police radars aimed downward at a 45 degree angle. The number of vehicles, speed of each vehicle and vehicle type were acquired. Horizontal anemometers were sampled every 15 seconds, vertical anemometers every 2-5 seconds, psychrometers and thermometers every 60 seconds, and CO every 30 seconds. Meteorological measurements were made from 5-100 feet in elevation from a tower 63 feet from the edge shoulder. CO was measured at 10 locations, two upwind and eight downwind at four levels on the tall tower and two levels (5 and 26 feet) on the shorter towers (See Figure 1).

These data are from a site on North Loop 610 one mile west of I-45 in Houston, Texas, about 5 miles from city center. The site is at grade with very little traffic on the access roads. The land use is light density residential and the average canopy height is estimated at 15 feet. Obstructions are one story houses, small trees, a small church and some billboards. Most of the area not built up is covered with mowed grass.

All data were collected in a trailer equipped with a NOVA II Data General minicomputer with 64 A/D channels and 24 K of core. Data are reduced in a large computer and output as 5, 15 and 60 minute averages. Raw data is also available.

Results

The reduced data were examined for high CO levels. Two cases were chosen which had apparently high CO levels without strong temperature inversions or low wind speeds. The only unusual feature in these data was an apparent negative wind shear, i.e., the wind speed decreased with increasing height instead of increasing as it usually does.

In Figure 2 the five minute average values for CO were plotted for five of the ten sampling stations. The stationscoded L were at 5 feet elevation and those coded H were at 26 feet, except for 4L which was at 52 feet elevation. The dashed line shows the CAL-2 dispersion model prediction. The TRAPS model predicted about 0.5 ppm. The CO levels measured from 1610 to 1615 are 5.5 times larger than those predicted by CAL-2.

Examination of the traffic data showed a large decrease in westbound traffic speed between 1600 and 16~~30~~10 and a sharp increase in volume between 1615 and 1620 (Figure 3). The comments code verified serious congestion in the westbound lanes during this period.

In figure 4 the wind speed is plotted for three levels: 1.5m, 10m and 20m (actual heights were 5, 26, and 52 feet). The solid area is a zone of negative wind shear where the 1.5 meter wind speed is stronger than the wind speed at 10 or 20 meters. Note that this occurred at the same time as the maximum CO levels. Of course the five minute average data obscures the real variation in the data so the raw data were examined next.

In figure 5 the CO concentrations are plotted every 30 seconds for this same time period. The highest peaks were at 1613, 1614, and 1615½ - 1616 for 1L, 2L, and 3L, all at 5 feet elevation. Peaks for 1H occur when valleys occur for other locations. This may indicate wavering of a bent-over plume. The peak raw value at 1L is an order of magnitude greater than predicted by the model.

The most interesting graph of this series is figure 6 which shows wind speeds every fifteen seconds with windspeeds plotted for the three levels and negative wind shear areas solid. A significant reduction in all wind speeds occurred between 1611 and 1616, the approximate period when three major peaks of CO occurred in the raw data. The greatest negative wind shear as measured by area is the one at 1614 where the maximum CO peak occurred at 1L and 2L. There seems to be a strong correlation between maximum negative wind shear, maximum wind speed at all three levels, and maximum CO concentration. It also appears that a sharp reduction in wind speed is concident with reduced CO concentrations at 1613½, 1614¼, and 1615. Surges in wind speed occur at intervals of ½ to 1½ minutes. The negative wind shear ends abruptly just prior to 1615 followed by a sharp increase in wind speed at all levels.

This event occurred in the afternoon with high scattered to broken clouds at 25,000 feet, a temperature of 79°F, and no sign of a temperature inversion. The morning mixing height was 300m and the mean wind speed through the mixing layer was 105°/2.4 m/s as recorded by the Environmental Meteorological Support Unit nearby. The wind speed aloft was relatively low when measured in the morning. The mixing height was about average for the month of May.

In addition, a sharp increase in downwind movement of air (-5.2 mph) was measured at the vertical anemometers mounted on the tower at 16:14:30. This occurred at about the same time as the wind shear became positive.

Another case occurred between 0750 and 0810 on May 6. The five minute average CO concentration at 1L (close to the roadway) was 13.0 ppm at 8:00 AM which gradually decreased to 9 ppm at 0810. Negative wind shear was shown at 0755 and 0800 in the five minute averages. A very slight inversion was evident between the 10 and 30 meter heights at 0800. The Pasquill - Gifford Stability class was estimated to be "D" (neutral stability). The temperature was 72°F and relative humidity 90%. Sky conditions varied from clear and 3 miles visibility in fog and smoke to 1500 feet overcast. The EMSU recorded a morning mixing height of 490 meters and a mean wind in the mixing layer of 175°/8.8 m/s.

In Figure 7 the CO concentrations for four of the CO analyzers are plotted at 30 second intervals for the 30 minute period. Note the peak value of 23.4 ppm at 0752½ and another of 18.6 ppm at 0754. Many of the peaks and valleys correlate well. Some are out of phase. The high tower at station 2 (2H) reads consistently higher than the high tower at station 1 (1H). This probably indicates dispersion via a bent-over plume as described by David P. Chock.[2]

In Figure 8 the negative wind shear areas are again colored solid. Negative wind shear dominates for the first 10 minutes and gradually decreases over the next 10. Once again a striking correlation is shown between wind speed peaks where negative shear exists and carbon monoxide peaks. The same can be said for the valleys, although there is not a one to one correlation in all cases. Since the CO values are only taken every 30 seconds, some of the sharp peaks may have occurred at times other than those recorded and instrument sensitivity may also be a factor in inhibiting an accurate pattern.

The cessation of negative shear is marked by a sharp increase in positive shear, especially at the upper levels. Between 0800 and 0805 the amplitude of wind speed in the positive wind shear areas grows progressively larger.

In Figure 9 the integrated wind shear values have been plotted for each minute of the second case. The dashed line shows a smoothed representation from a three-minute running average of these integrated values. Note the buildup of negative wind shear to 0755 in the running average followed by a steady decrease to 0810. This correlates well with the average CO data as a general trend.

One of the most striking features of the data base was a large downward vertical velocity at very nearly the same instant as the shear changed from negative to positive. This happened at all levels except at the surface (5 feet elevation) for the last two shear changes at 0809 and 0810. The arithmetic mean of these vertical movements is 1.33 mph and the standard deviation 0.48 mph. This vertical movement is an order of magnitude greater than the mean movement and usually occurred a few seconds earlier at the lower levels. The greatest vertical movement on the average occurred at the 20 meter height (56 feet), although in some cases it occurred at 40 meters or 10 meters.

Discussion

In normal turbulent flow near the ground negative wind shear is a rarity. Winds usually get stronger aloft because frictional effects slow the lower winds. In all of the hundreds of hours of data acquired during this study at six sites, only a few cases of negative wind shear have been found. Pollution levels measured in these rare cases were much higher than the model predicted. In these two cases the peak values measured exceeded the modeled concentrations by an order of magnitude. Wind speeds were not low, 8-10 mph in the first case and 4 mph in the second. This does not qualify as a stagnant episode in the usually accepted sense; i.e., low wind speed and a strong stability as measured by Pasquill - Gifford criteria. The first case had "B" stability and the second "D".

A non-dimensional number usually used to define stability as a ratio of thermal stability to wind shear is the Richardson number.

$$Ri = \frac{\frac{g}{\theta}\frac{\partial\bar{\theta}}{\partial z}}{\left(\frac{\partial\bar{u}}{\partial z}\right)^2} \qquad (1)$$

This expression has little value in exploring variations in the amount and sign of wind shear since the wind shear term is squared.

The Monin - Obukhov mixing length theory holds more promise. Myrup and Ranzieri in a recent work[3] recommended the use of the following approximations for stable surface conditions:

For the diffusivity of momentum

$$km = K = \frac{k\,U_*Z}{\Phi\left(\frac{Z}{L}\right)} \qquad (2)$$

$$\Phi\left(\frac{Z}{L}\right) = 1. + 4.7\,\frac{Z}{L} \qquad (3)$$

$$U_* = \frac{KU_{ZW}}{\left[\ln\frac{Z_W}{Z_0} + 4.7\,(Z_W - Z_0)\right]} \qquad (4)$$

This is useful for calculating vertical diffusivity, but does not handle the cyclic variation of wind speed and shear.

To recapitulate, high wind speed and large negative shear correlates well with high pollution concentration. Low wind speed and high negative shear correlates well with a decrease in pollution level. A sudden shift from negative to positive shear results in sudden downward velocity at a tower 63 feet from the roadway. The peaks are separated by 30 second to two minute intervals and the same can be said for the positive shear episodes. In the second case the negative wind shear gradually disappears.

Everything points to some type of stable wave motion, possibly some kind of gravity wave. The wind speed variation is cyclic. Even the absence of negative shear is cyclic. The high energy situation (maximum wind speed) is the most stable situation as shown by the relatively high pollutant levels. The low energy situation shows low level of pollution. Wind speeds at all levels fluctuate cyclically at the same time. A small temporary slow moving perturbation in the wind field like a gravity wave appears to be the most reasonable description of what is happening during the unusual stability episodes.

In the second case an apparently stable gravity wave occurs for the first 10 minutes monitored followed by a gradual destabilization of the wave in cyclical spurts with a gradual reduction of the total amount of negative wind shear per unit of time and an increase in amplitude of the waves. This is characteristic of shear waves or unstable gravity waves.

A discontinuity in wind shear or potential temperature may be a factor contributing to the formation of shearing - gravitational waves. There does seem to be a significant gradient of water vaper content between 5 and 82 feet of elevation in case 2. The phase velocity of a shearing gravity wave can be expressed by the equation:

$$c = \frac{\rho U + \rho' U'}{\rho + \rho'} \pm \sqrt{\frac{gL(\rho - \rho')}{2\pi(\rho + \rho')} - \frac{\rho\rho'(U - U')^2}{(\rho + \rho')^2}} \qquad (5)$$

The first term is a convective term with density and velocity discontinuities expressed in the dynamic term. The density discontinuities have a stabilizing and the velocity discontinuities have a destabilizing effect on the perturbations.

If the discontinuity is due to water vapor content with moist air above, the density discontinuity would be stabilizing. The complex form of the equation is unstable.

Gravity waves are perturbations found in many atmospheric or water phenomena. They have been documented by radars, acoustic sounders, and satellite photographs in association with fronts, thunderstorms, atmospheric tides, deep ocean waves, mixing height, multiple stabilized layering, jet streams, and ocean currents.

Further research is needed to show how they are formed, how they can be predicted, and how long they are likely to last. They appear to be relatively rare along a highway, but these phenomena do have a significant effect in elevating pollutant levels. A more sensitive and complete monitoring network is needed.

To speculate on the nature of the sudden downward movement at the tower when the shear becomes positive, it may be because the air above the highway rises in buoyant turbulent flow. Or it could lapse into the disorganized turbulent eddies normally found. The downward motion at the tower may either be the trigger which causes the switch to positive shear or the reaction of the air along the roadway to replace air buoyed upward. It has been shown by CHOCK, DABBERDT,[4] and others that a significant amount of heat is produced by vehicles moving along a roadway and this can have a profound effect on pollutant levels, especially at low wind speeds.

Other possible explanations of this phenomena might be vortex shedding due to aerodynamic flow around structures or some irregular diabatic heat source. In the first case traffic was congested in the westbound lanes during that episode. This could result in stabilization of the air above the freeway and buoyant pluming from heat generated by the idling vehicles. It may be true that vehicular movement is an important factor in dispersing pollutants along the roadway. It has been found that pollutant levels can vary with the direction of movement of traffic where the winds are parallel to the roadway as recorded by Chock.

Conclusions

On rare occasions relatively high CO levels occur along roadways in association with negative wind speed shear. The negative wind shear surges to sharp wind speed peaks at fairly regular intervals of one-half to two minute intervals. Pollutant concentrations are highest when wind speeds are highest. The occurrence of positive shear is accompanied by a sudden increase in downward wind velocity up to 100 feet in height and 60 feet away from the roadway. The wave motion observed is consistent with gravity waves which are apparently short lived in the usually turbulent flow along roadways. Further research with more elaborate instrumentation is recommended.

Acknowledgements

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Disclaimer

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2. D. P. Chock, "A simple line-source model for dispersion near roadways", Research Publication GMR-2407, Research Laboratories, General Motors Corporation, Warren, Mich. (May 29, 1977).

3. L. O. Myrup and A. J. Ranzieri, "A consistent scheme for estimating diffusivities to be used in air quality models", Interim Report 1, FHWA-CA-TL-7169-76-32, Department of Transportation, Federal Highway Administration, (June 1976).

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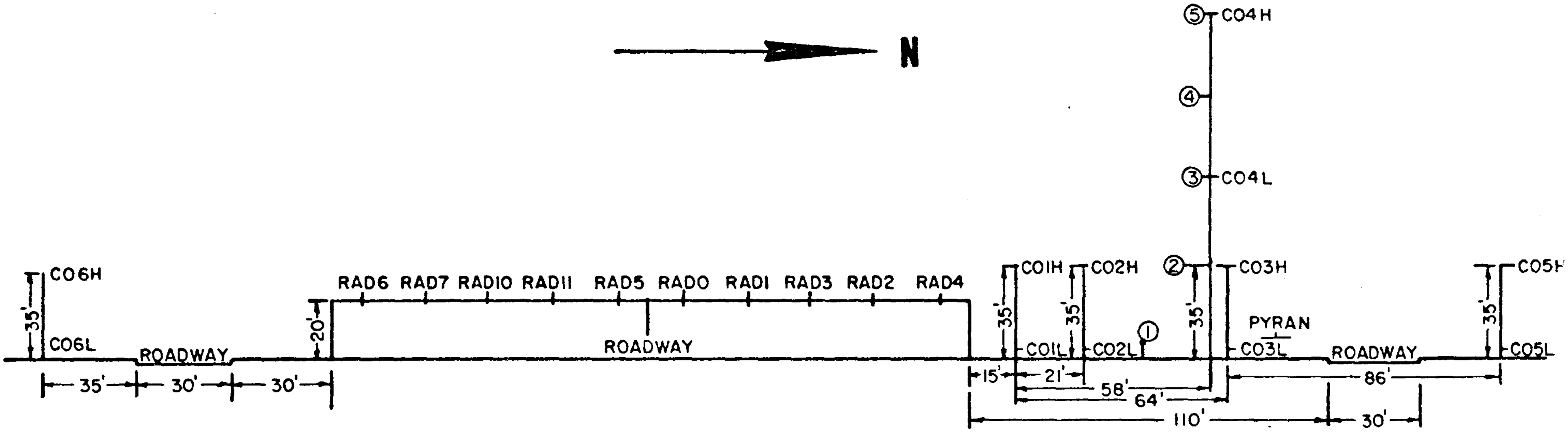
CAPTIONS

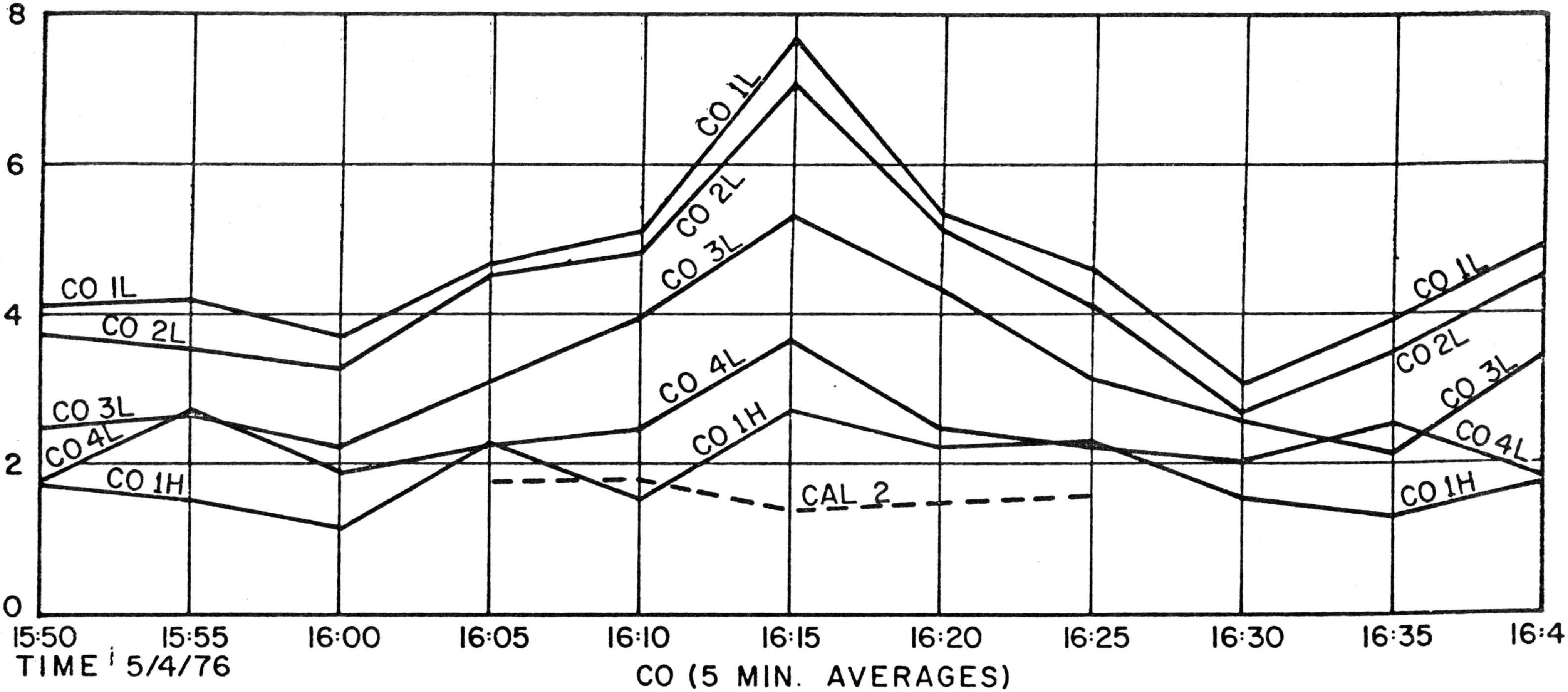
FIGURE 1	This is a cross-section through the freeway showing instrument locations at a 10 lane site in Houston, Texas.
FIGURE 2	CO concentration peaks sharply at 1615 in these five minute averaged data. CAL-2 predictions for the 1L location are dashed.
FIGURE 3	Westbound traffic was congested between 1600 and 1630 as shown by the decrease in speed.
FIGURE 4	The only area of negative wind speed shear shown in the five minute averages is the solid zone centered at 1615.
FIGURE 5	Sharp peaks of CO occurred at 1613, 1614, and 1615½-1616. Peaks for 1H are out of phase with other points.
FIGURE 6	Wind shear has been plotted every 15 seconds for three levels. Zones of negative shear are shaded. Note the correlation of peaks and values of CO with wind speeds in Figure 5.
FIGURE 7	Not all CO peaks for four sampler stations for case 2 are in phase with wind speed peaks, but many are.
FIGURE 8	For case 2 the waves of wind speed and negative wind shear are stable until 0800 and then gradually destabilize as negative wind shear diminishes.
FIGURE 9	An integrated amount of negative wind shear has been plotted for each minute and then a three point moving average constructed to show the decrease in negative wind shear.
FIGURE 10	Vertical velocity increases sharply at each level when negative wind shear changes to positive.



INSTRUMENT LOCATIONS

LOOP 610 HOUSTON

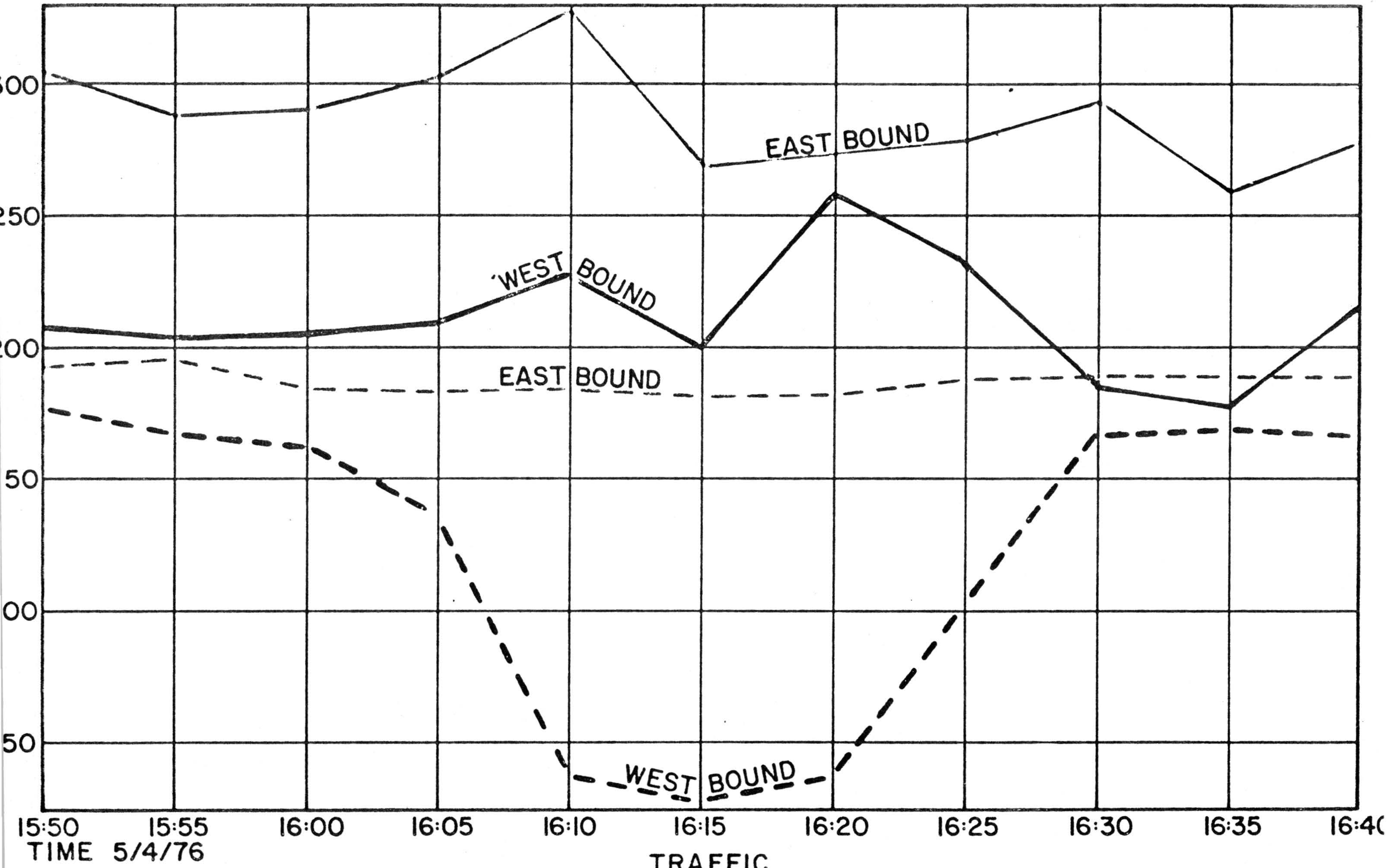
FIGURE 1



INSTRUMENT LOCATION

LOOP 610 HOUSTON

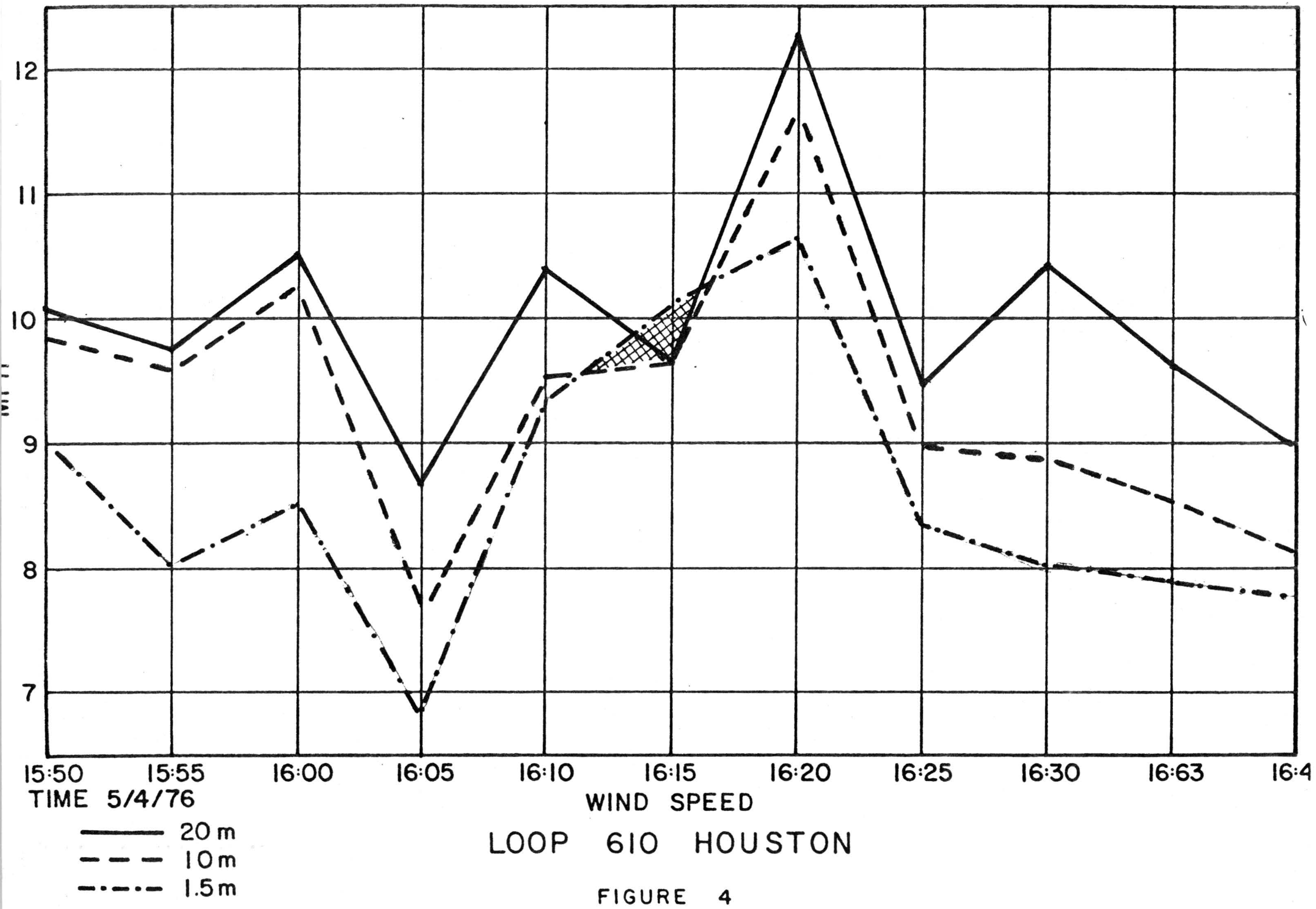
FIGURE 2



TRAFFIC

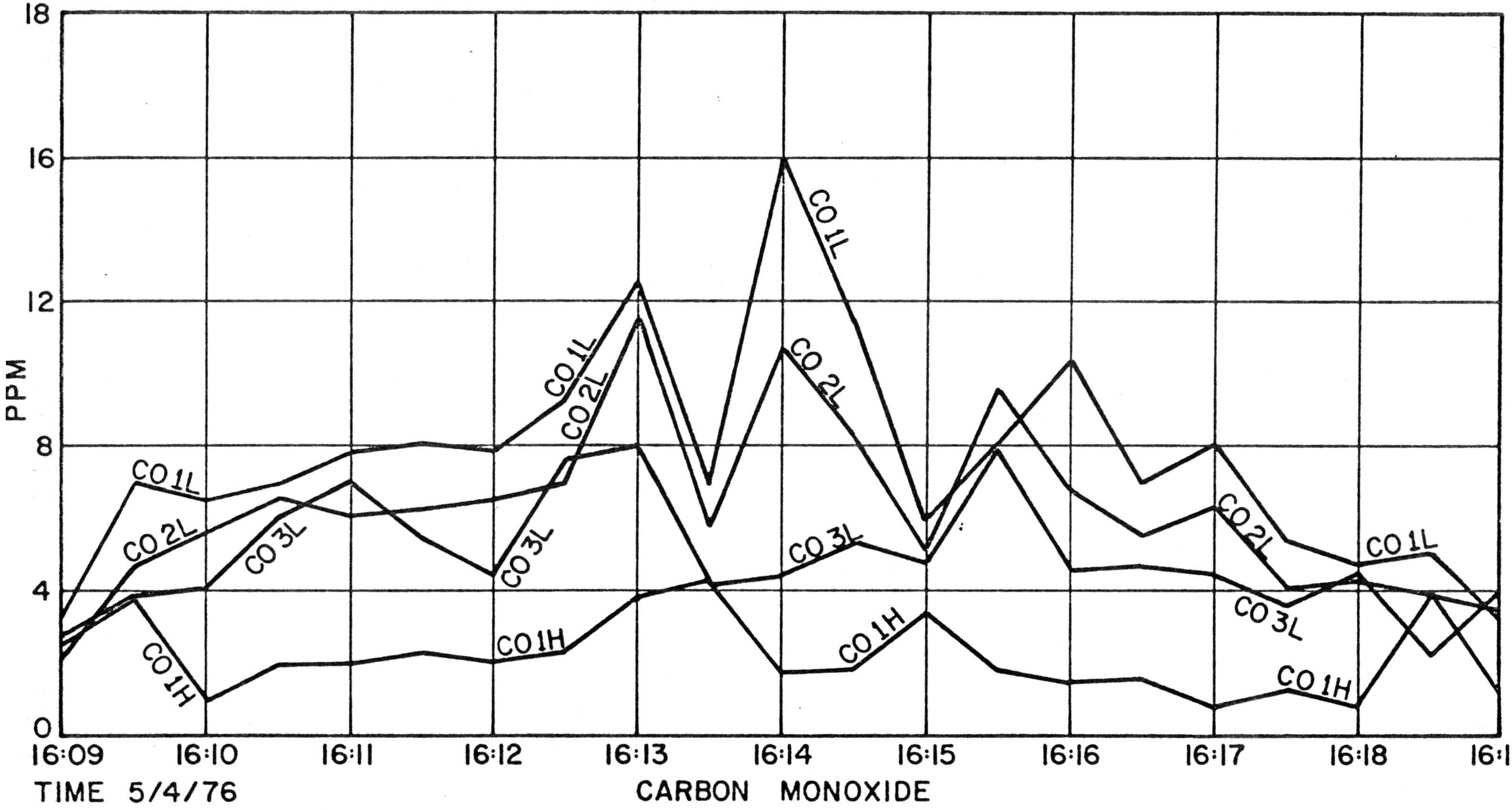
LOOP 610 HOUSTON

FIGURE 3



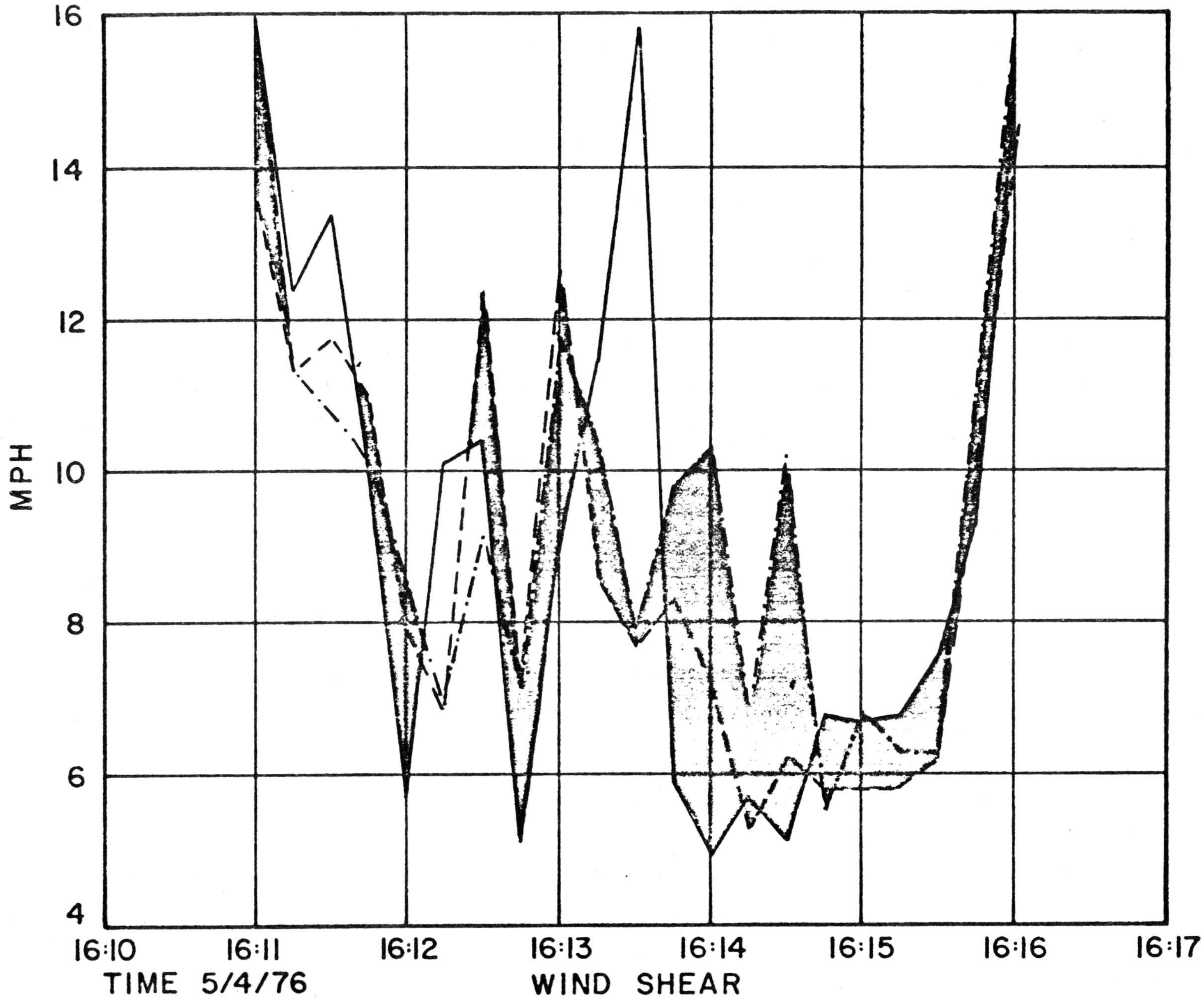
LOOP 610 HOUSTON

FIGURE 4



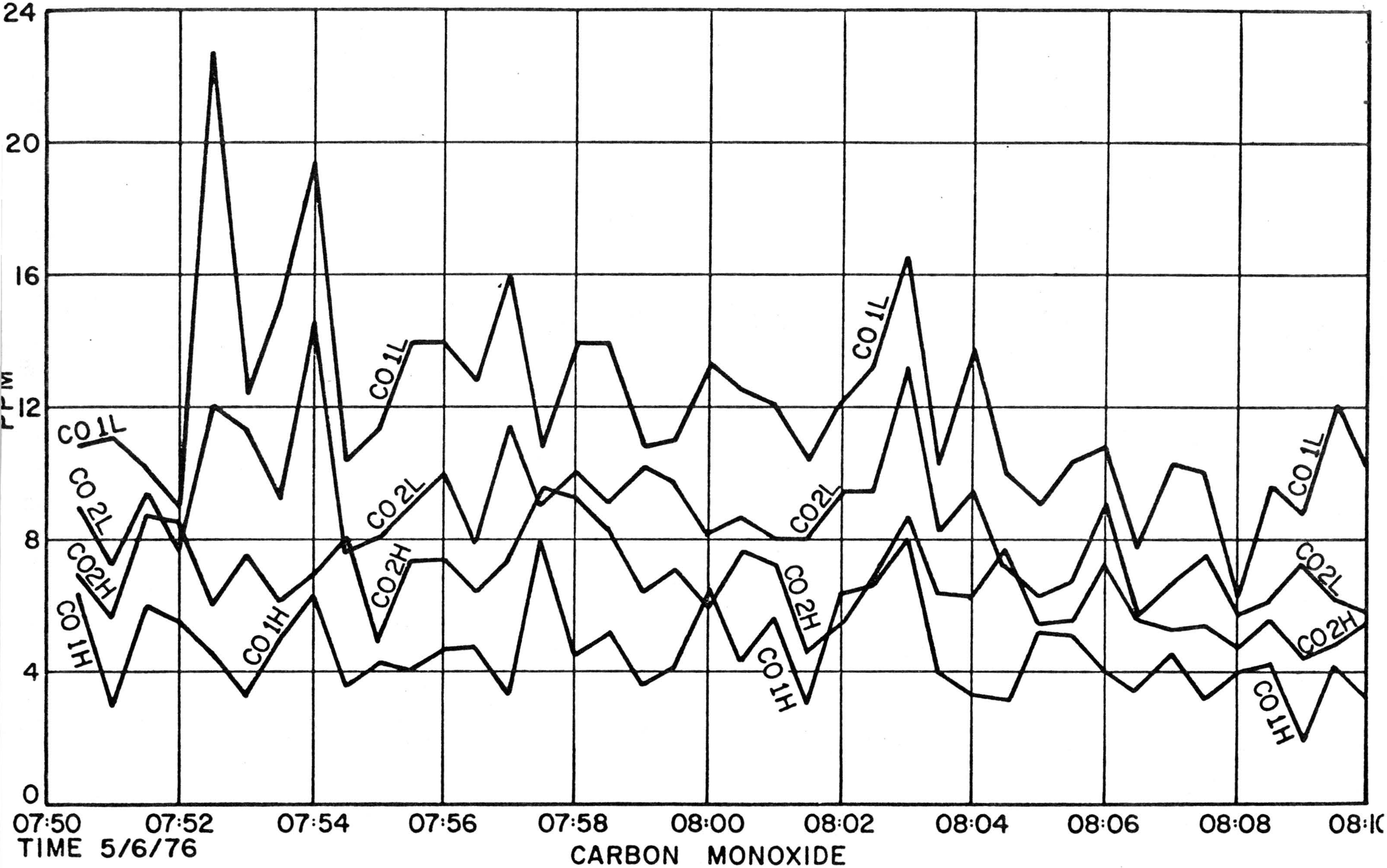
LOOP 610 HOUSTON

FIGURE 5



LOOP 610 HOUSTON

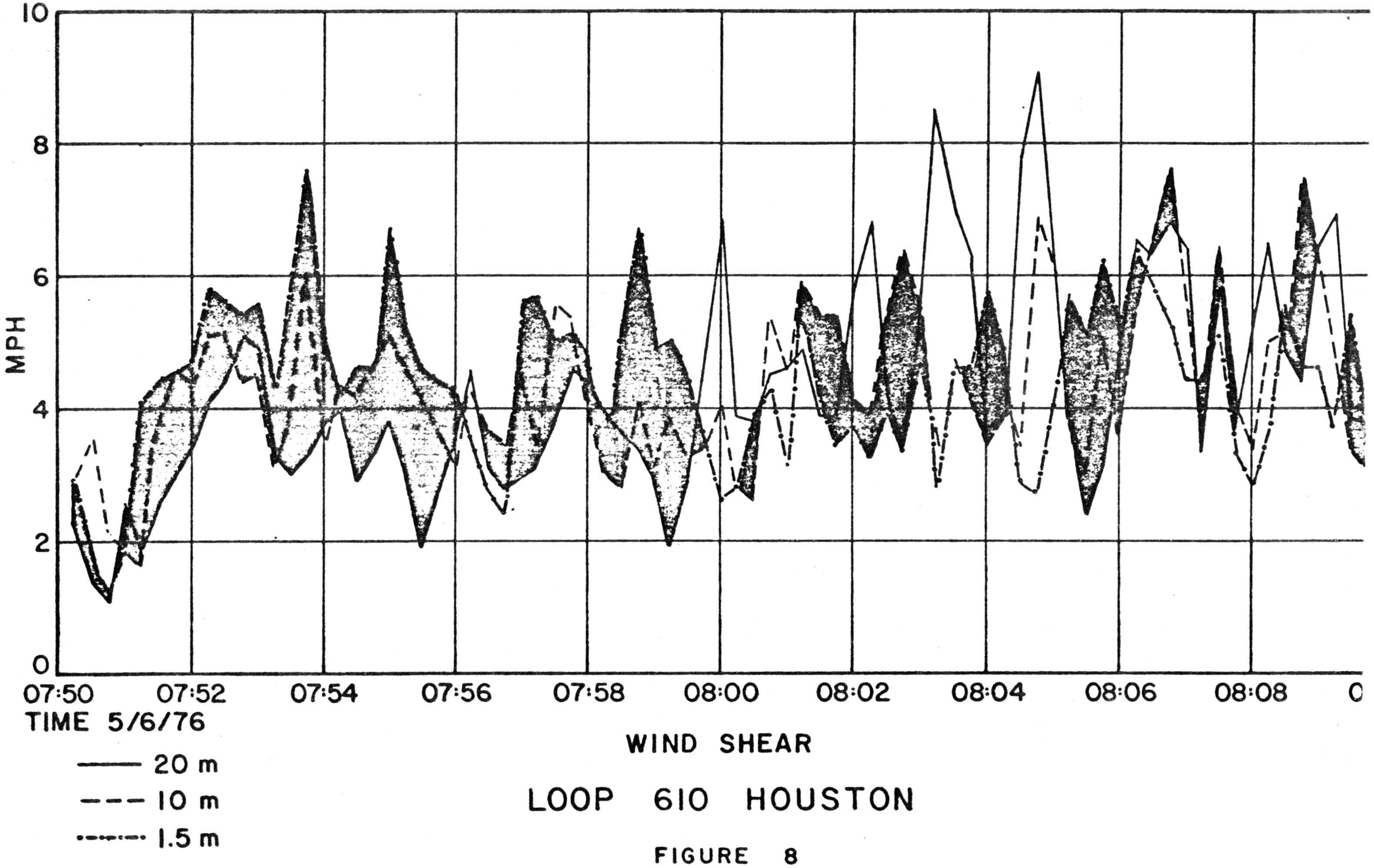
FIGURE 6



CARBON MONOXIDE

LOOP 610 HOUSTON

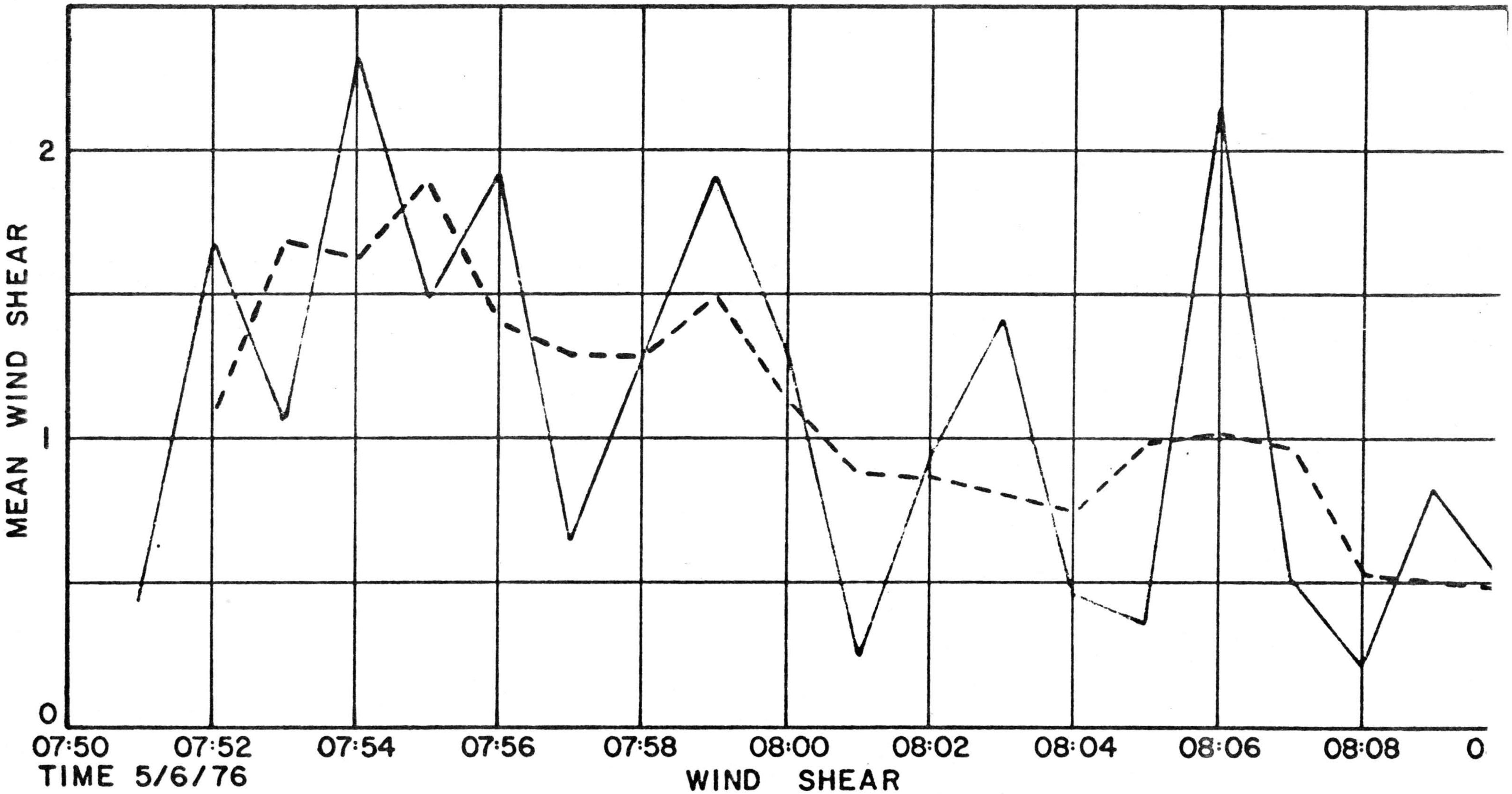
FIGURE 7



WIND SHEAR

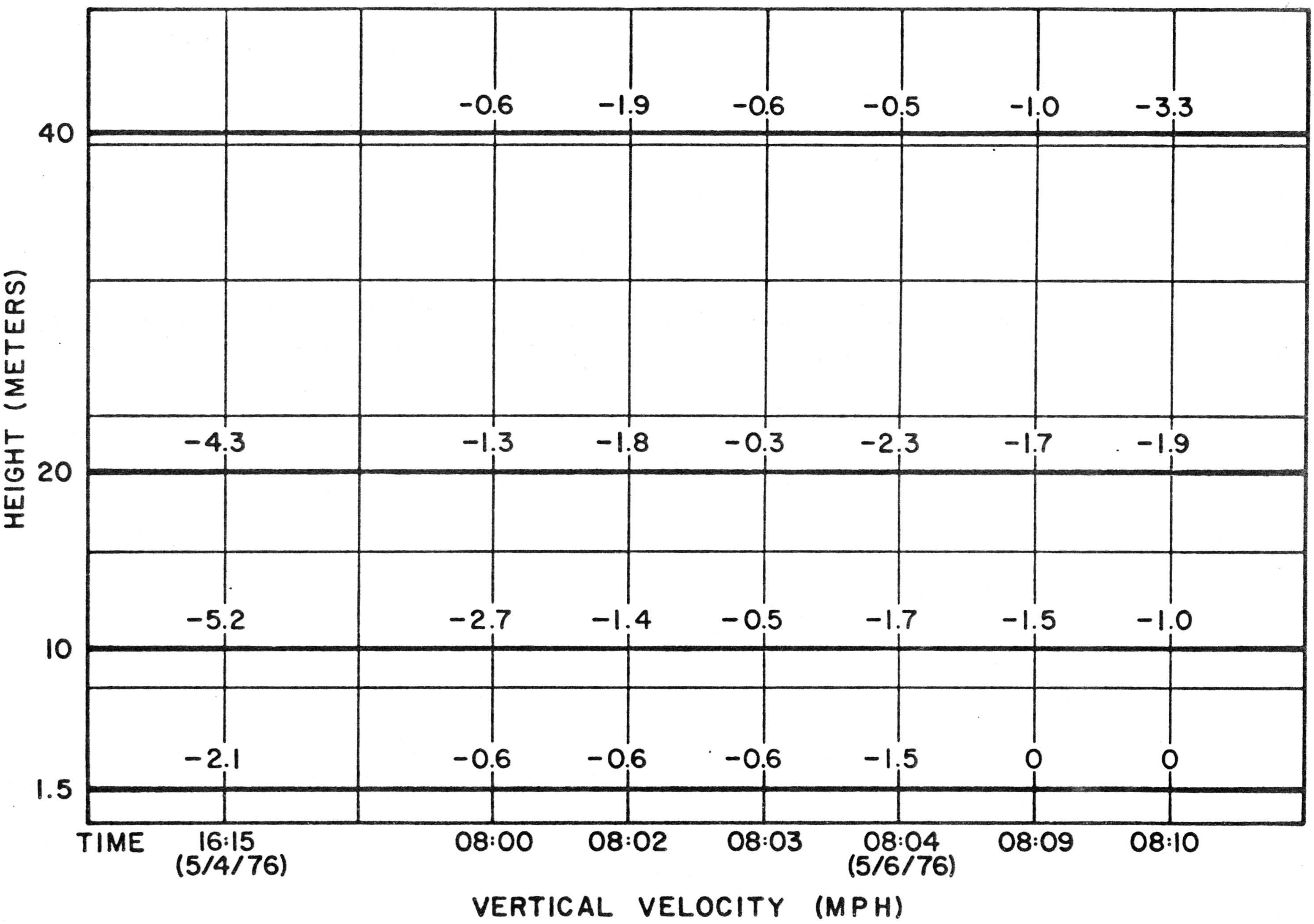
LOOP 610 HOUSTON

FIGURE 8



LOOP 610 HOUSTON

FIGURE 9



HEIGHT (METERS)	16:15 (5/4/76)	08:00	08:02	08:03	08:04 (5/6/76)	08:09	08:10
40		−0.6	−1.9	−0.6	−0.5	−1.0	−3.3
20	−4.3	−1.3	−1.8	−0.3	−2.3	−1.7	−1.9
10	−5.2	−2.7	−1.4	−0.5	−1.7	−1.5	−1.0
1.5	−2.1	−0.6	−0.6	−0.6	−1.5	0	0

FIGURE 10