Micro-scale Pollution Modelling Using a Wind Tunnel

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Introduction

The major source of air pollution in modern cities comes from motor vehicles. There is increasing recognition of this problem in policies controlling roading and urban planning authorities, that in turn requires accurate data and modelling capabilities. Road traffic pollution is generally confined to busy urban roads and intersections. Modelling is best undertaken as a two-tier approach. The first tier is the use of simplified analytical models at the local network level, which can identify problem areas within the network, but these models don't address the movement of pollutants through an urban built environment.

The second tier is the micro-scale modelling where the 'hot spots' can be examined in some detail. Accurate numerical modelling at the micro-scale level is difficult in the irregular spaces of built urban areas, making wind tunnel modelling of the air quality an attractive alternative [1, 2, 3, 4]. Although physical modelling of the full meteorological condition is difficult, for pollution effects at the urban micro-scale, it is wind effects that are usually dominant and these wind effects are adequately addressed in the wind tunnel.

This paper describes the development of a low cost technique, which can be used in conjunction with an existing wind tunnel model of a city to examine pollution effects. A real urban area was tested when developing this modelling technique, which was centred on the intersection of Vivian and Victoria Streets in Wellington City, New Zealand. This area was selected as recent monitoring undertaken at this site and other sites around the city had highlighted some unexpected results. Pollution levels at this intersection, in a low-rise area, were consistently around the upper guideline limit. In comparison, pollution levels at a second site (Jervois Quay) at the fringe of the high rise city centre were significantly lower, even though vehicle flows at this second site are about two times greater. This highlights that localised building effects, the influence of pollution from nearby roads, and localised anomalies at the monitoring point are significantly influencing pollution at the monitoring point.

Wind Tunnel Test Method

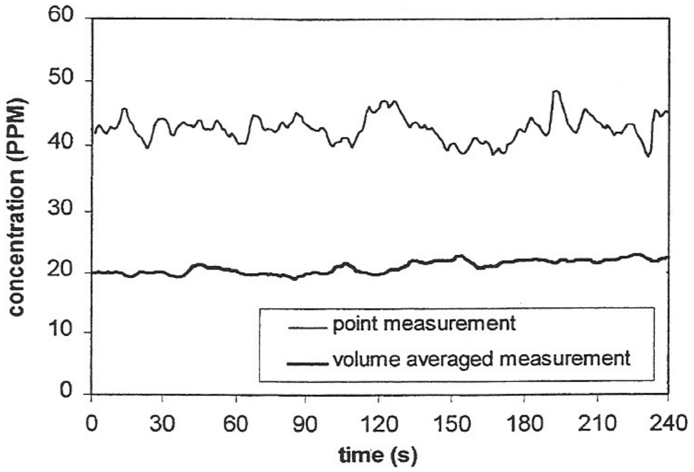
The Opus Central Laboratories boundary layer wind tunnel was used in this study. The wind tunnel test section measures 2.7 m wide by 1.2 m high by 5 m long and incorporates a blockage tolerant slatted roof. A 1:250 scale, neutrally buoyant (no heating or cooling), boundary layer simulation of urban terrain roughness (z_o = 0.2 m) was produced using conventional fence and block roughness elements. The wind tunnel flow speed used for the tests was 2.5 m/s at a scale height of 10 m. An area of Wellington city measuring 600 m square, centred on the intersection of Vivian and Victoria Streets, was modelled at a scale of 1:250.

The basic concept of the pollution modelling system was that tracer gas was continuously distributed, via source tubes, over the whole of the city model. Simultaneously, a tracer gas detector was used to measure the fluctuating concentration at each measurement point sequentially.

The tracer gas selected was 10% carbon monoxide (CO) in nitrogen. This was released into the tunnel at a total flow rate of 1.5 L/min via 16 tubes, each of 1.5 mm internal diameter. The CO supply rate was set so that CO measurements lay within the measuring range of the instrument. The gas collected at the measurement locations was pumped to an 'INTERSCAN 1000 Series' carbon monoxide analyser via a flexible single tube of 5 mm internal diameter. The analyser measured CO concentrations in the range 0-100 parts per million (ppm) with a sensitivity of 0.1 ppm. Fluctuations in the CO concentration at frequencies up to about 0.2 Hz could be measured. The analyser is factory calibrated and the instrument gain was set using a standard gas of CO in nitrogen at 81 ppm ± 2 ppm.

CO concentrations were sampled at each location for 240 seconds with a 60-180 second settling period prior to recording. This procedure was found to give sufficient repeatability in the measurements for the development phase of the technique. Figure 1 shows a typical 4 minute recording of point and volume averaged measurements.

Figure 1. Typical sample of volume averaged and point measurement of CO.



Development of a Line Source

Initially the system was tested with the tracer gas distributed from 16 point sources. The test system was shown to work satisfactorily, but it was apparent that, in order to simulate the emission of vehicle exhaust gasses, a method for distributing the tracer gas more evenly along the streets was required. Heidorn et al [5] and Meroney [6] describe details of line source systems, which are built into the city model below street level, the method of Meroney [6] being particularly complex in order to achieve a uniform distribution of the tracer gas. We wanted to develop a line source using a length of thin tubing, which would be simple to construct and install.

Trial and error using different tubes and holes diameters showed that a copper tube, of 4.5 mm outside diameter (O.D.), 3.0 mm internal diameter (I.D.) was a suitable material that is easily drilled (with clean holes) and flexible enough to be bent to fit onto a city model. Each copper tube was 550mm long, being connected to a source tube at one end, and blocked at the end. Each copper tube has 11 small holes along its length at 50 mm intervals, increasing in size from 0.5 mm diameter near the input end to 2.5 mm diameter near the closed end. With this line source design we achieved a flow rate from each hole that was constant to within ± 15% and these tubes were used in all subsequent tests.

Most of the 16 copper tubes were simply laid out in a regular distribution on top of the model streets. An additional method of diffusing the source tracer gas was used for those tubes positioned within 500 mm of the city intersection where the study was to be centred. The roadways, excluding the footpaths, were recessed to a depth of 15 mm, and the copper tubes positioned in the centre of the recess. Stiff cloth was then used for the road surface, to allow the tracer gas to diffuse through. Vertical baffles were placed in the recessed areas at 100 mm intervals to prevent airflow along the streets under the road surface. The purpose of the porous cloth was to distribute the tracer gas more evenly over the street area, as large variations in CO concentration were measured close to the exposed line source tubes that depended on the relative positions of the sampling tube and the CO plume emitted from the holes in the source tube. A further advantage of the set-up was that it improved the flow simulation close to the ground by removing the artificial obstruction of the source tube.

Measurement Tubes

For point measurements, a flexible tube of 7 mm O.D. and 5 mm I.D. was used to extract the gas sample from the model. This was usually positioned close to the ground, with the opening pointing approximately upwind, and therefore measuring over an area approximately equivalent to heights from 0.3 to 1.7 m at full scale. Figures 2 and 3 show point CO concentration measurements of the horizontal and vertical CO distribution above the model.

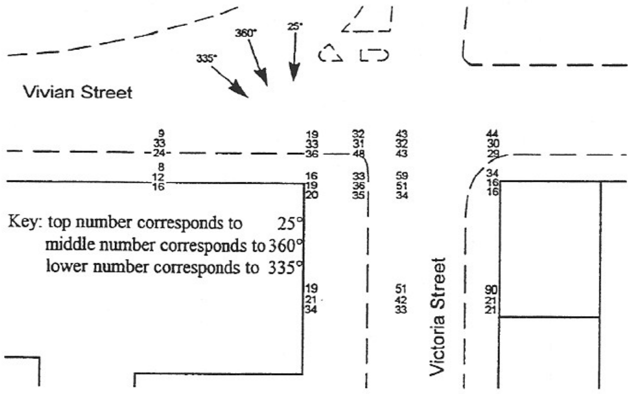


Figure 2. Relative point CO concentrations measured at the Vivian Street and Victoria Street intersection for the wind directions, 25°, 360° and 335°.

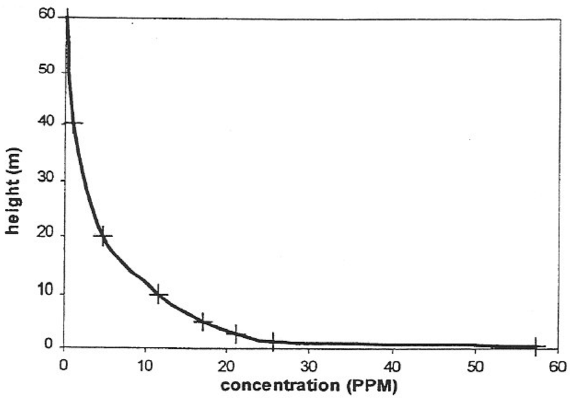


Figure 3. Variation in area averaged CO concentration with height above ground, at the intersection of Vivian and Victoria Street

Large gradients of CO concentration are evident above and across the intersection, which may result in unusual or unrepresentative values where only one or two measurements are taken within an area. To allow average CO concentration measurements to be made efficiently over these areas, an array of thin vertical tubes was developed that drew gas from a volume of air above the model. This approach also had the benefit of reducing the uncertainty associated with the location and height of the sampling tube used for the point measurements. The volume-averaging array consisted of 27 thin metal tubes, joined together in bundles of 3 (each tube set at a different height), with the 9 bundles arranged into a 3 x 3 grid, forming a 40 mm x 40 mm square. The metal tubes were 1.6 mm internal diameter and were 300 mm, 295 mm or 285 mm long depending on the sampling height. The 27 tubes were manifolded at the top, from which the 5 mm diameter point measurement tube was used to collect the combined gas for sampling. The tubes were mounted vertically, 5 mm above the model so that the gas was collected from a horizontal square, 40 mm x 40 mm (equivalent to 10 m x 10 m at full scale), at heights of 5mm, 10 mm and 20 mm (1.25m, 2.5m and 5m at full scale).

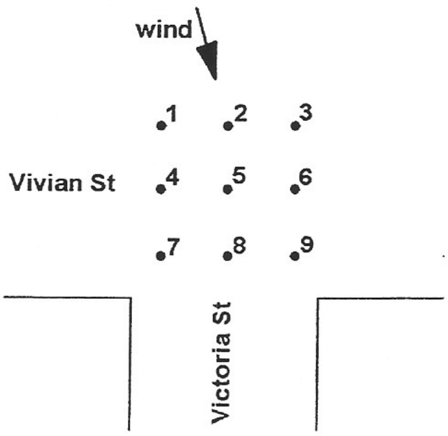


Figure 4(a). Location of point measurements used to compare the point and volume averaged CO concentrations.

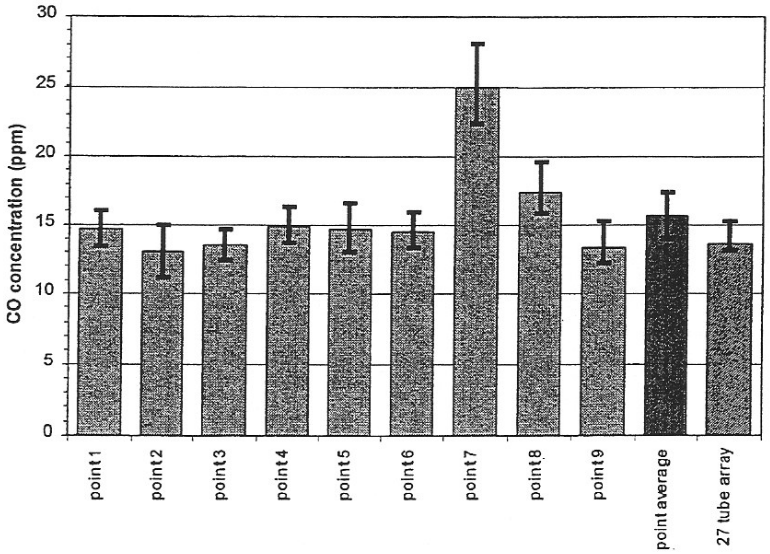


Figure 4(b). Comparison of point concentrations and volume averaged concentration measured at the same model location.

The effect of the volume averaging array on the CO concentration at ground level was measured by comparing the concentrations found from point measurements, with and without the averaging array positioned above the measurement area. The results of these tests are graphed in Figures 4 and 5, and show that the array has some effect on the CO concentrations at ground level. However the volume averaging array is a useful tool.

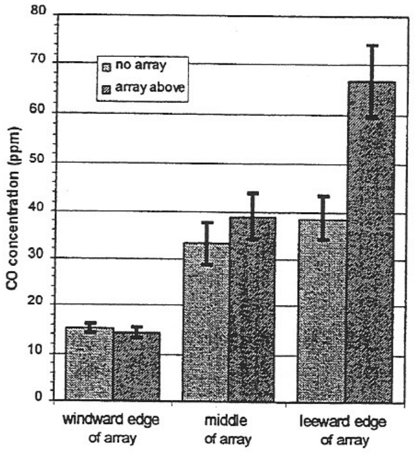


Figure 5. Point concentration measurements, with and without the volume averaging array positioned above (point measurement was taken downwind of CO source).

Modelling Considerations

Large variation in the CO concentration was measured with changes in the wind direction as can be seen in Figures 2 and 6. To account for this variability in tests, 3 directions are typically measured and the concentrations averaged for comparison with field measurements.

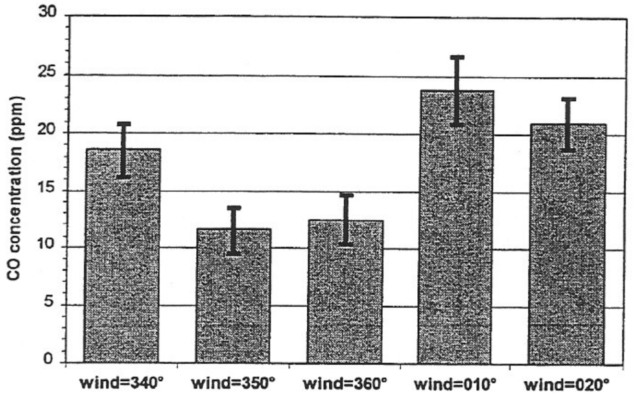


Figure 6. Variation of volume averaging CO concentration with wind direction.

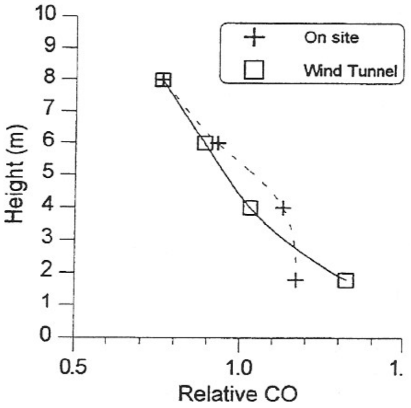


Figure 7. Vertical profiles of field and wind tunnel measurements of relative CO concentrations.

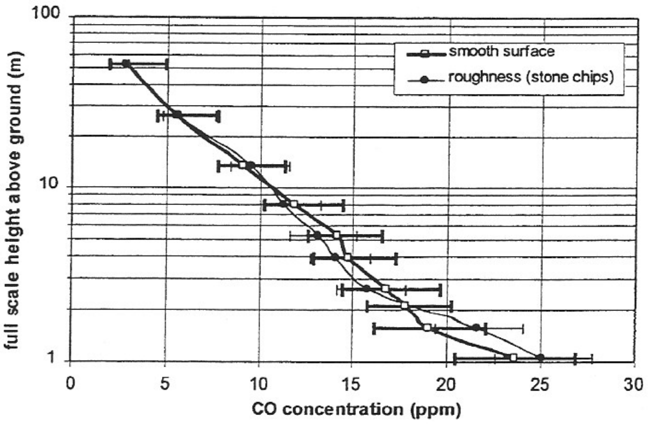


Figure 8. Vertical profiles of CO concentration measured in the wind tunnel, with and without additional roughness (6 mm high stones evenly spread over the model surface).

Comparison of the vertical profiles of CO concentration profiles field measurements and wind tunnel measurements showed a flattening of the field profile near the ground, that was not observed in the wind tunnel data (see Figure 7). This is likely to be due to the additional mechanical mixing of moving vehicles, exhaust fumes, and also the increased mixing due to buoyancy of the exhaust gasses that is not simulated in the wind tunnel. Additional roughness was placed on the wind tunnel model surface (stone chips approximately 6 mm high = 1.5m full scale) to simulate additional mixing. The resulting profiles, plotted in Figure 8, do not show a significant change from the existing model surface. As the extra roughness has the undesirable effect of increasing the CO gradient near the ground, and is an additional complication to the modelling process, it has not been used in subsequent modelling.

Conclusions

A simple technique has been developed to measure the micro-scale movement of pollution through urban areas. Wind tunnel and field measurements comparisons have to date been limited to a number of point positions around an urban intersection. Future work is planned to collect full scale pollution measurements throughout a city block to check modelling assumptions and allow calibration of the CO concentrations measured in the wind tunnel to full scale.

Acknowledgements

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