

Mapping Carbon Monoxide Using GPS Tracked Sensors

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Abstract In this paper we discuss a pilot study where we have mapped urban air pollution using mobile carbon monoxide (CO) sensors. Our objective is to use inexpensive Global Positioning System (GPS) receivers to track the sensors and explore CO variations at a fine geographic scale. The critical issue in data processing is the treatment of the imprecise logs from the GPS. By using knowledge about the route and the geometry of the buildings, we are able to increase the position accuracy significantly, while at the same time showing that certain events, such as CO profiles while crossing roads, can be detected with a high degree of accuracy. Comparisons between data from our own mobile sensors and a fixed sensor site show good agreement in the vicinity of the fixed sensor, while at the same time identifying significant CO peaks within 100 m of this location. Using the mobile sensors to collect data along two of the main roads in the area, we are able to show CO variations along an urban canyon for parallel and perpendicular wind directions. Finally, a number of significant sources of CO were discovered during the course of the study, which suggest possible locations for fixed sensor sites in the future. We conclude by discussing the results in the context of the push towards large

sensor networks and mobile communications. The potential for ad hoc mobile sensor networks may be very large.

Keywords Air pollution measurements · Carbon monoxide · Global Positioning System (GPS) · Personal exposure · Tracking mobile sensors · Urban pollution

1 Introduction

Many urban environments are now monitored for carbon monoxide (CO) and other pollutants because of health and quality of life issues associated with high exposure to such pollutants. Most CO monitoring is done from fixed sensors that provide continuous data feeds. However, whilst fixed sensors can tell us about temporal variation and the range of values that might be experienced, such as the difference between a kerb-side and green-field monitor, because of their geographic scarcity they do not allow us to explore variation at a scale that would allow us to see effects of particular sources, dispersal by wind or accumulation in calm areas (see Section 2 for a review of urban CO monitoring).

In this paper we describe a pilot study where we have investigated CO pollution in a city environment using a small set of tracked mobile CO sensors. The motivating concept is that small mobile sensors could be carried by the general public going about their everyday business. Mobile devices are dropping rapidly in price but increasing in capability. By its nature, data collected by non-experts in an ad hoc manner will be less reliable and only give intermittent

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temporal coverage, but we expect that by aggregating many unreliable and intermittent logs files we will be able to produce a dense geographic map of variation in CO. By using tracked CO sensors we trade temporal coverage for spatial coverage. These “pollution trails” can be aggregated over time to generate maps of pollution or they can be compared with other trails that go through the same space so that temporal or transient variation can be explored. These maps and comparisons might allow us to do new types of study of CO that look at personal exposure whilst moving through a city, small-scale variation due to street canyon effects and sources and dispersal of CO at a much more detailed scale or with much less preparation and infrastructure than previously achieved.

In this paper we start by discussing further background and related work, and give an outline of the scope of the trials we have undertaken in Section 3. In Section 4 we then discuss the quality of the data that is collected. A key question is the treatment of the unreliable GPS position reports. The quality of GPS position reports varies because the satellite constellation used changes over time, but more significant is the urban-canyon effect that causes the amount of the sky that is visible to change significantly as the user moves.

In the following three sections we outline three different types of analysis that we can do with the data. In Section 5 we do a comparison between the mobile sensor and a fixed sensor demonstrating that the two types of sensor give similar readings. In Section 6 we detail how we have built profiles along a couple of busy road sections. This is the main contribution in this paper because it suggests that we are able to produce interesting profile data that gives the readings that might be expected given the prevailing weather and traffic conditions. In Section 7 we then outline some more novel observations, such as CO profiles whilst crossing roads and unexpected discovery of high CO levels. Finally we conclude with a discussion of the potential for this work and the field of mobile sensors.

2 Related Work

2.1 CO in urban environments

Independent studies of urban carbon monoxide have shown large variations caused by street layout, meteo-

rology and traffic flow. Croxford, Penn, and Hillier (1995) found peak CO concentrations in London, UK, exceeding 10 ppm for short periods with nearby sensors reporting much lower values. There are several related works that aim to increase understanding of pollution variation. These include the dense sensor network of the Discovery Net e-Science project (Ghanem, Guo, Hassard, Osmond, & Richards, 2004), and the combined sensing and air flow modeling approach of DAPPLE (2005).

Complex numerical models exist to predict urban air quality, but these are dependent on suitable input data. The application of meteorological data to pollution monitoring was the subject of COST (2004) (European Co-operation in Science and Technology) action 715 and is still an ongoing area of research. Boddy, Smalley, Dixon, Tate, and Tomlin (2005), in a fixed sensor study around York, UK, use anemometers placed on opposite sides of the street to obtain accurate wind information, while DAPPLE used a number of anemometers placed along the street at different heights. The study in York is of particular interest as the fixed CO sensors used were Learian Streetboxes, which are very similar to the portable Learian sensors used in this experiment. These studies both use meteorological information generated on site, but synoptic data on this scale will not generally be available in a large-area study.

Personal exposure monitoring seeks to measure the concentrations of pollutants that people are exposed to in their daily lives. Although tracking experiments using vehicles have been very successful, as demonstrated by Weijers, Khlystov, Kos, and Erisman (2004) in Northern Holland, tracking of people is only just emerging as a feasible proposition. The authors of this paper have successfully conducted a preliminary test in the Marylebone Road area of London, UK, using sensors carried by pedestrians and cyclists to verify that expected CO features could be detected (Milton & Steed, 2005). In this paper we describe a wider scale experiment where we have been able to compare data from mobile sensors with an existing fixed location sensor. We then demonstrate that significant variations in CO level can be detected along roads. The analysis follows the accepted fixed sensor practice used by Manning, Nicholson, Middleton, and Rafferty (1998) and Boddy et al. (2005) of plotting data by wind direction, along the street axis and perpendicular to it.

2.2 GPS tracking

The Global Positioning System (GPS) is currently the most widely used positioning system. According to GARMIN (2004), 2,300,000 units were shipped that year making 10,000,000 in total. Other estimates suggest that over 100,000 GPS receivers are shipped each month, either for use in mobile phones, PDAs or in standalone units.

With so many different manufacturers producing receivers, there are a number of different options available with varying levels of accuracy and cost. We have chosen consumer-level hardware because it is important for further work that sensor packages can be fabricated cheaply. With a clear view of the sky, a consumer GPS receiver that might retail for less than \$150 has an accuracy of between 10 and 15 m, although with the right satellite geometry this can be within 5 m some of the time. Even at the consumer level there are a number of GPS enhancements that can improve the accuracy considerably. Many commercial GPS receivers output range and phase information when used in binary mode, which opens up the possibility of post processing the data to remove certain sources of error. The National GPS Network (see Appendix) provides many of the resources in the UK for post processing and contains other useful information about GPS systems. Space Based Augmentation Systems (SBAS) can also remove some sources of error and provide accuracies of 3 m in real-time for receivers that support the feature. This includes the Wide Area Augmentation System (WAAS) that operates in the US, while the European Geostationary Navigation Overlay Service (EGNOS) covers Europe. The problem with these systems is that they require a geostationary satellite to be visible, and in an urban environment in Northern Europe, this is frequently not possible as the satellite is not high enough in the southern sky. This problem can be alleviated using a system called SISNeT that transmits the EGNOS correction data via an Internet link. However because we log data continuously over long periods, we would need an Internet that was cheap (thus excluding GPRS) and reliable and pervasive (thus excluding Wavelan). To improve accuracy this means that we will have to retrospectively correct the data logs using knowledge of building footprints and carrier behavior (see Section 4.2).

3 Trial Logistics

3.1 Equipment

The equipment used for the data collection consists of an HP Jornada PDA running our own data logging software, a Garmin 15L GPS receiver with external aerial and an ICOM CO sensor manufactured by Learian Environmental. The ICOM CO devices use an electrochemical CO sensor and are accurate to 0.1 ppm. References to further information on these devices are in the Appendix. All the equipment is housed in a rucksack with the sensor open to the air in a mesh pocket on the right hand side. The GPS and PDA are housed in the centre of the rucksack, with the GPS aerial fixed to the top. Other than switching everything on and starting the data logging software, no further interaction is necessary until it needs to be switched off.

The CO level and GPS position are stored once every second and written to log files on the PDA. Once the logging software is stopped, these files are uploaded to a server for analysis.

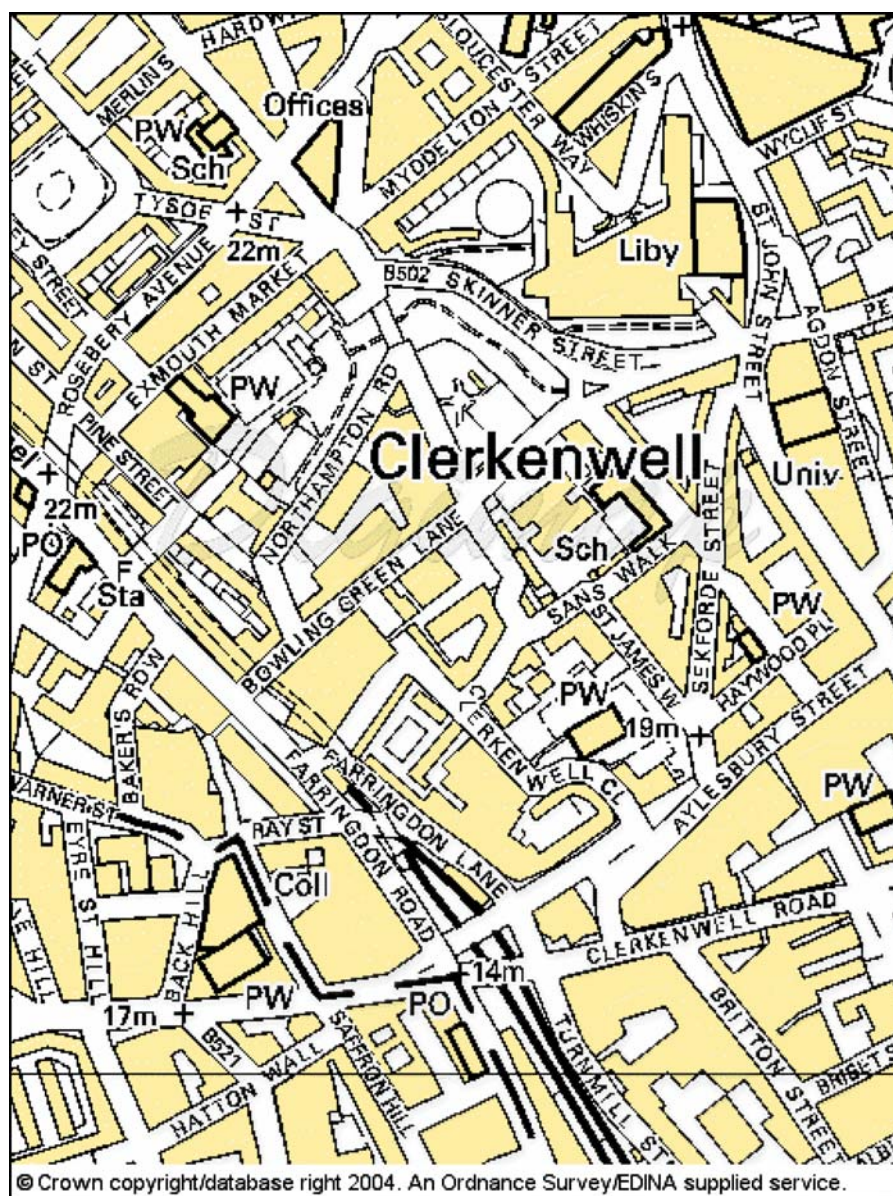
3.2 Server and tools support

The CO and GPS data are stored in a Postgres database and uploaded or viewed using web-based services. This allows data to be analysed in the field where a wireless Internet connection is available. More complex analysis tools requiring direct access to the database have also been developed and these have been used to produce the composite charts in Section 6. Various forms of 3D visualisation have also been used during the data analysis process.

3.3 Geographic area and time-scale

As discussed in Section 2.1 our previous experiments have concentrated on a single road, or route around a small area. In the current study, the emphasis is on proving the potential of more ad hoc data collection over longer periods of time. Thus, the area is much larger (1×1.5 km, see Figures 1) and the period of data collection is 2.5 months (November 2004–February 2005). This particular area of London was chosen because it was also being studied by the VivaCity2020 project (<http://www.bartlett.ucl.ac.uk/research/space/vivacity-overview.htm>). That project placed four fixed pollution sensors in the local

Figure 1 The Clerkenwell area with Exmouth Market, Farringdon road and Clerkenwell road shown.



environment and conducted other related studies around the area in that period.

As mentioned in Section 1, the concept motivating these trials is that the data would be collected by a passive data collector who visited an area occasionally whilst going about their everyday business. However, at this stage there were only a few devices available, so it was necessary to concentrate the effort on a few smaller areas to collect enough data for analysis. The data collectors were instructed to walk on the kerb-side whenever possible to further reduce ambiguity in the data set. In the area chosen, we hypothesized that most pollution and

variation in pollution would be found on Clerkenwell Road and Farringdon Road because they have the highest amount of traffic. We also explored Exmouth Market, which is a pedestrianised area, bordering Farringdon Road. Other roads around the area were covered in less detail as the data collectors explored the area.

4 Initial Data Processing

In total, data was sampled for 94 separate paths between 17 November 2004 and 4 February 2005

(Figure 2). This resulted in a total of 328,601 data points, of which 183,830 had valid GPS positions (Figure 3). The first author of this paper collected all of the data presented, apart from two days in November when a second person was available.

Three or more GPS satellites could be seen, and thus a GPS fix received, for 55.9% of the time. This is slightly higher than the 42% in our previous experiments on Marylebone road, see Milton and Steed (2005), and is comparable to figures achieved with a consumer GPS unit in a study of GPS availability in London carried out by Ochieng et al. (2003).

4.1 GPS accuracy

The GARMIN GPS receivers used for the trial report an estimate of the horizontal position error in metres, in addition to the usual horizontal dilution of precision (HDOP), or standard deviation of position errors. Using the horizontal error, the percentage of the time that the GPS error was within certain limits can be calculated. Figure 4 shows the cumulative probability of obtaining a GPS fix with an accuracy better than the radius in metres indicated on the X axis. Using this data, it can be seen that the GPS positions are within 15 m 64% of the time, or better than 45 m 95% of the time. The accuracy of the GPS

devices used for this experiment should be within 15 m 95% of the time, but in an urban environment this is significantly reduced due to a limited view of the sky forcing the GPS to use non-optimal satellites for the position fix.

Occasionally, multipath reflections from buildings can cause a much larger error than this estimate based on satellite geometry would suggest. In this situation, the reflected signal from the satellite will be attenuated and show a longer path to the receiver than the direct line of sight, displacing the location fix by many metres.

One final piece of information reported by the GPS is the track angle. This is a compass heading reported by the GPS giving the direction of travel. The angle reported is not particularly accurate, but is good enough to highlight 90° changes in direction when crossing roads. A track angle can also be calculated manually from successive GPS points, but the track angles reported by the GPS will also work while the receiver is stationary.

4.2 GPS correction

The GPS accuracy discussed in the previous section indicates that, on its own, GPS is not sufficient to position a user on a particular side of the street. No

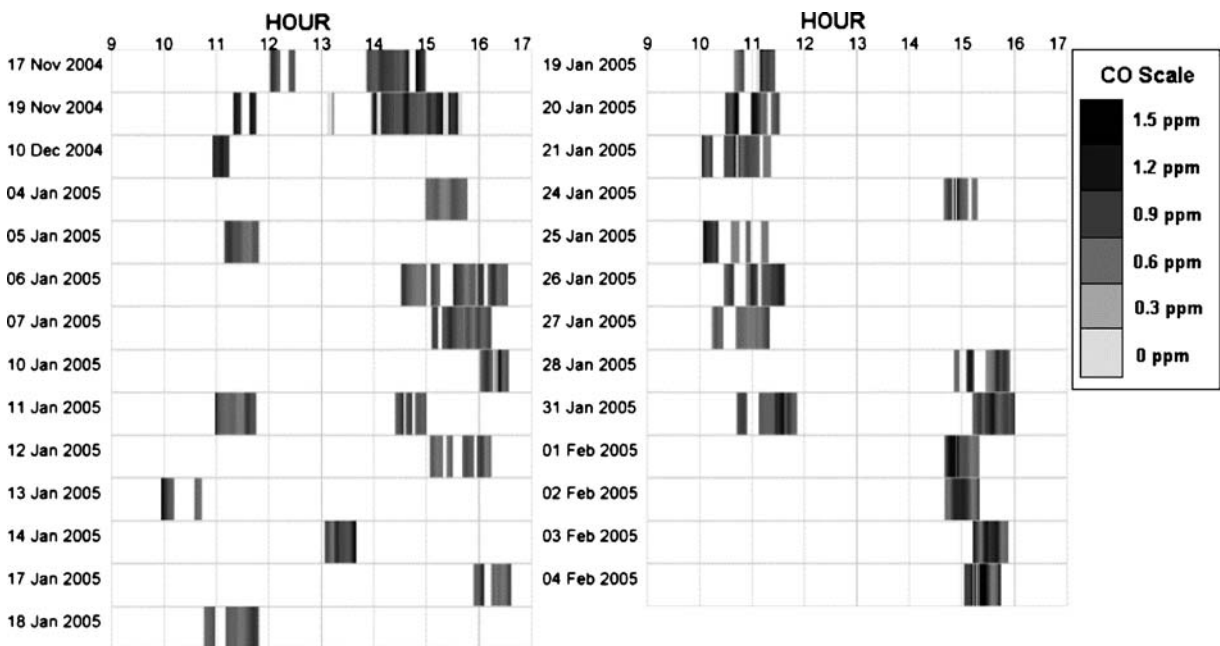


Figure 2 All data collected in the Clerkenwell area between 17 November 2004 and 4 February 2005.



Figure 3 The complete set of data collected. This is a plot of mean CO values on a 10 m grid.

matter what tracking technology is used, there will always be some ambiguity. Street side is very important for the scenarios we envisage, since CO levels can differ greatly due to traffic flow, building layout, wind speed and direction. Using a single sensor for the pilot study, differences between sides of

a street will be hard to measure unless we can guarantee that conditions do not change in the time it takes to cross the road.

Figure 5 shows an extract from a section of a log along Clerkenwell Road. The section investigated (between labels A and D) contains three bus stops and

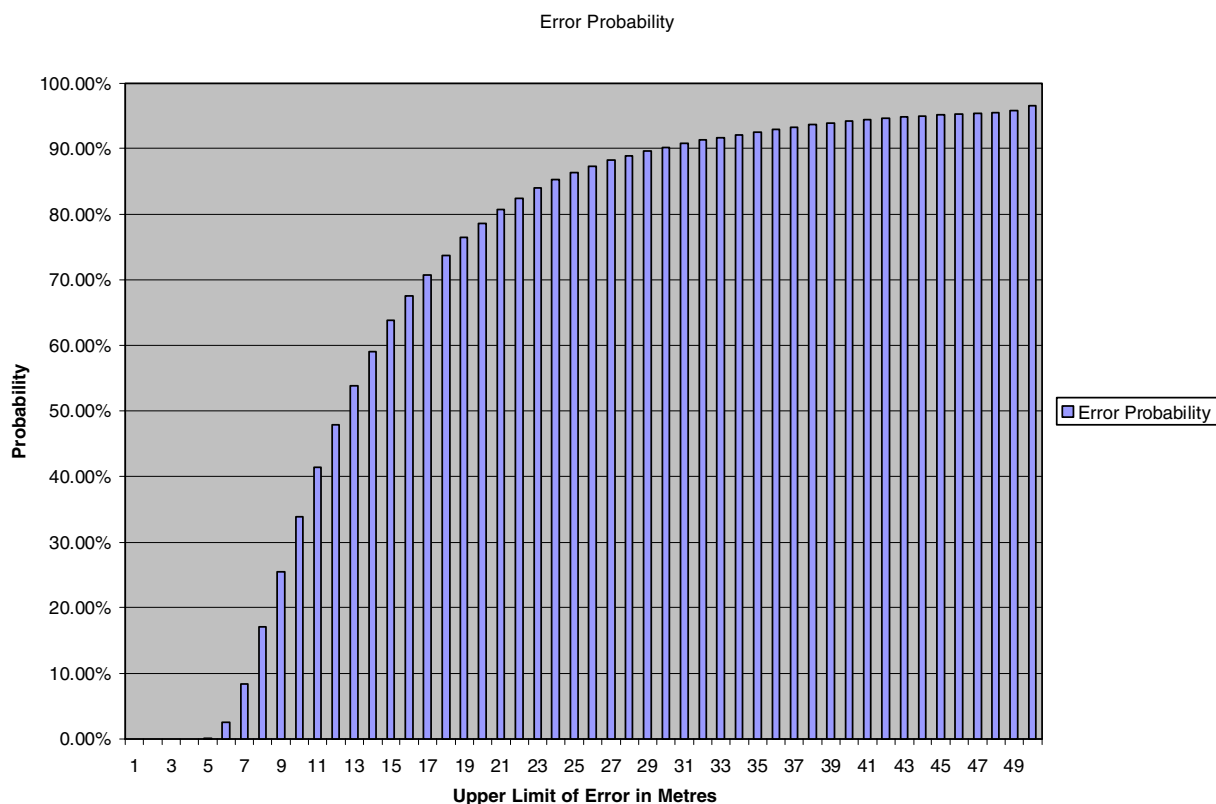


Figure 4 The cumulative error of GPS accuracy from all log files. This data can only be plotted for times when a 2D or 3D position fix was possible.

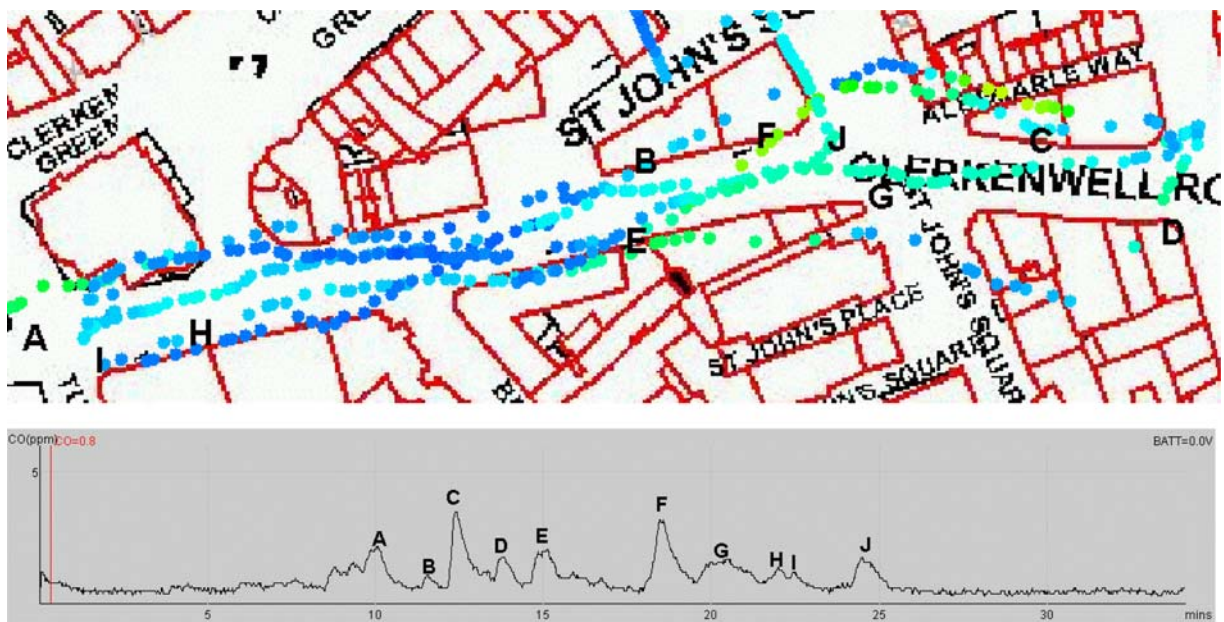


Figure 5 Plots of the raw GPS and CO traces along Clerkenwell Road on 4 February 2005 at 15:05, sampled west to east on the north side, east to west on the south side and then repeated to give

two traces for each side of the road. North is upwards. Labels A–J are discussed in the main text.

a petrol station. It is a short stretch of road approximately 15 m wide from building to building. The sensor travels from west to east on the north side, east to west on the south side and then repeats the route, giving two traces for each side of the road. It is not immediately apparent which side is which from the figure.

Given we know the expected behavior of the carrier, we can note some characteristics of these behaviors in the GPS log. Direction of travel is an obvious one, and this would allow us to segregate north and south in this particular example given we know the route. A further observation is that points where the road was crossed can be identified from where the carrier of the GPS waits by the side of a road before crossing, or from the track angle. This opens up the possibility of automatically extracting crossing profiles from the collected data to investigate how CO varies across the width of the road.

When analyzing the data in more detail, it is apparent that there are distinct CO peaks sampled along the road where the levels are rising or falling between successive samples. Points B and E and also F, G and J in Figure 5 show examples of this. The GPS device reports the standard deviation of the

position errors calculated from the satellite geometry at each sample point, and it is known that the sensor was always carried along the pavement by the kerb, so, by correcting the raw GPS positions to the closest kerb-side point, the positions can be corrected to within a reasonable degree of error.

In order to perform the correction, the Ordnance Survey data for the area is used to find the closest pavement edge to the reported GPS position. If no edge is found within a 20 m radius, then the GPS point is not moved. Side road crossings are detected from the change in track angle and points in the road can be interpolated from the raw data and previous modified point. Figure 6 shows the results of applying this algorithm.

In general though, correcting to the nearest kerb point can only be applied in conjunction with a threshold less than half the road width. If the corrected data in Figure 6 is animated it is apparent that a significant percentage of points have been placed on the wrong side of the road as the position reported by GPS has crossed the road centre line. This example has been deliberately chosen as a test case as the correct side of the road can be worked out from the direction of walking: left to right on the north side



Figure 6 Clerkenwell Road 4 February 2005 at 15:05, GPS corrected to the pavement with detection of road crossings based on a change in track angle. This does not use any additional route knowledge.

and right to left on the south side. In this case, to expose the CO peaks on opposite sides of the road, the only available option is to use route knowledge.

In summary, the raw GPS data from a current consumer GPS shows errors less than 15 m for 65% of the time. Thus, automatically placing a point in the correct position on the pavement, or even just placing it building side or kerb-side, is unrealistic. However, by using additional map knowledge and knowledge about carrier behavior, these errors can be reduced in a semi-automatic editing process. This allows various types of analysis on the CO data to be performed. We discuss the general problem of semi-automatic log file correction in another paper by Milton and Steed (2005).

5 Comparison with Fixed Sensors

5.1 CO values in the vicinity of a fixed sensor

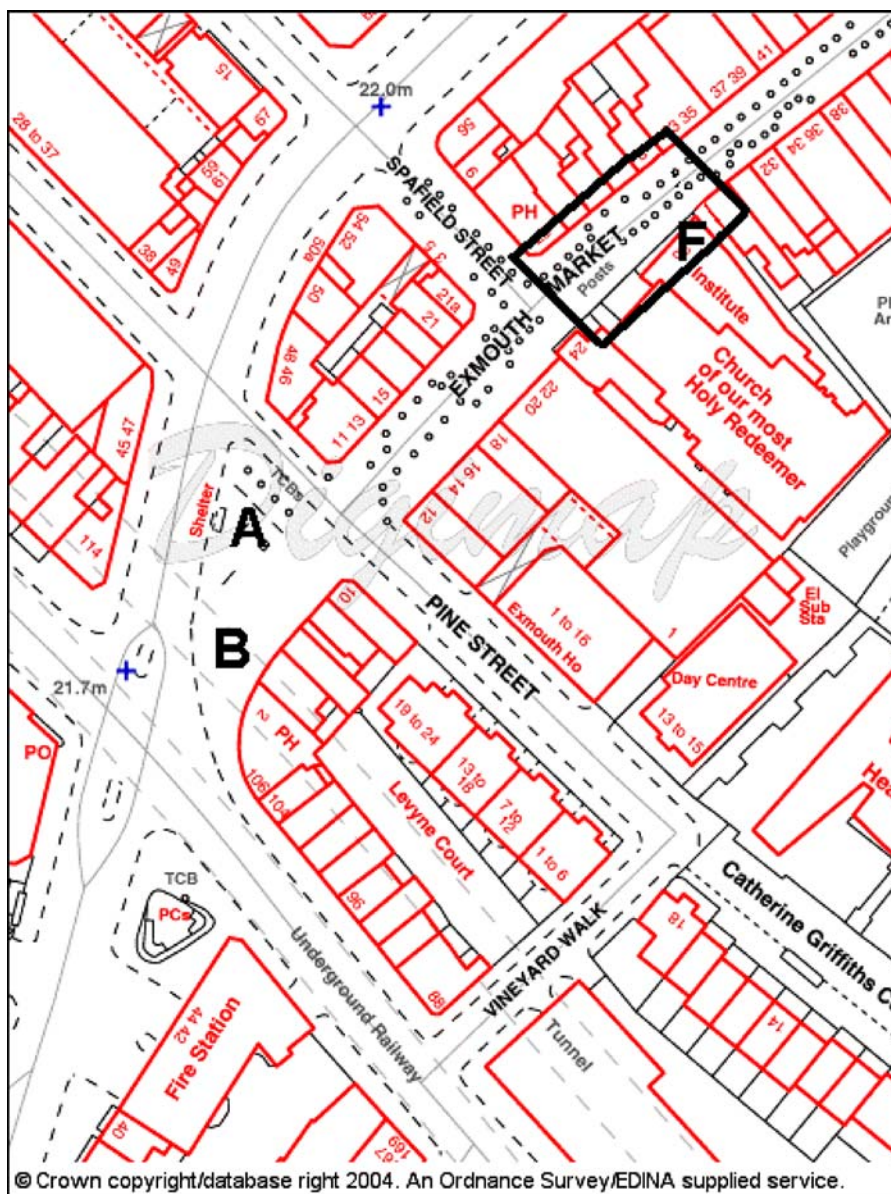
During the period the mobile sensors were being used in Clerkenwell, there was also a fixed location CO sensor in the area as part of the VivaCity2020 project (<http://www.bartlett.ucl.ac.uk/research/space/vivacity-overview.htm>). This fixed sensor, sited in Exmouth Market, outputs a 15 min mean, four times an hour. A comparison was made by taking the average of all mobile sensor data collected in a rectangle 43 by 22 m immediately in front of the fixed sensor. This area was chosen to cover most of the street in front of the sensor and allow for small GPS errors. There were 26

separate comparisons possible during January and February, but one unavoidable problem with the results was that the mean CO levels throughout the period were very low. The mobile sensors are accurate to 0.1 ppm, while the fixed sensor mean for the whole period is 0.3 ppm. Despite this, and other sources of error, there is a good correlation between the fixed and mobile sensors. The overall RMS error of the difference between the fixed and mobile sensors is 0.17 ppm, while the 95% confidence level is 0.06 ppm. This gives a 95% probability that the fixed and mobile difference will be ± 0.06 ppm from the mean, very close to the accuracy level of the sensors.

The Exmouth Market sensor is mounted 3 m above the ground in a pedestrianised area, so the background CO level should dominate the readings with few traffic effects. The data produced by the fixed and mobile sensors are not directly compatible, leading to a number of sources of error. Situations where the CO level is slowly rising or falling throughout the 15 min period will cause the mobile sensor's short period mean to be too high or low. In this particular experiment, this did not cause much of problem due to the generally low values, so no attempt to correct for it has been made.

The secondary aim of comparing fixed and mobile sensor data was to identify how CO levels varied around the location of the sensor. Data for 20 January and 1 February are particularly good examples of where the mobile sensor sampled large CO peaks (2.8 and 5.0 ppm, respectively) at a major junction about

Figure 7 Exmouth Market with the fixed sensor position labelled 'F' and the catchment area outlined in black. Two nearby CO peaks are labelled 'A' and 'B'. The Distance between 'A' and 'F' is approximately 80 m.



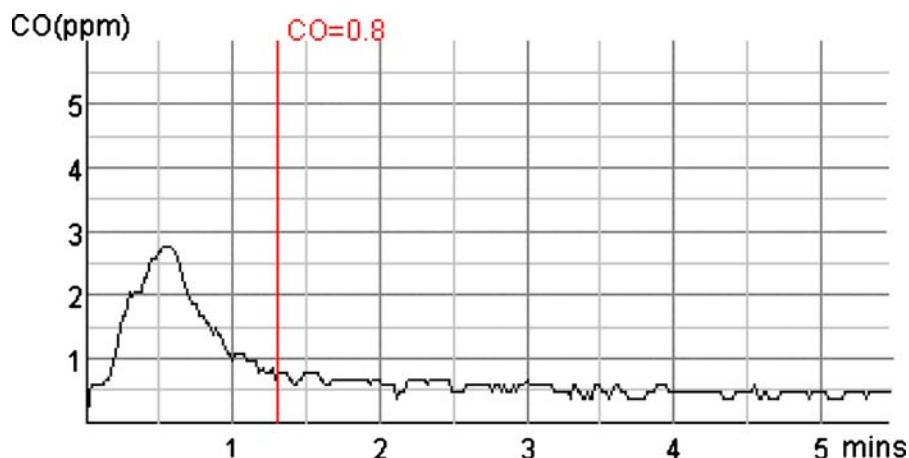
80 m from the fixed sensor (Figure 7). On both occasions the minimum recorded mobile sensor reading is closer to the fixed value than the mean, due to the reduction in CO as the fixed sensor is approached.

The vertical CO lines on the graphs in Figures 8 and 9 indicate the location of the fixed sensor. Figure 8 shows a gradual drop in CO from an area where food was being cooked on portable gas cookers near the junction to the fixed sensor location. Figure 9,

shows a trace starting at point 'A,' walking towards the sensor at 'F,' then turning round and walking back past 'A' and on to point 'B,' where the 5.0 ppm peak is recorded. Looking at the first part of Figure 9, from 0 to 2 min (walking from 'A' to 'F'), a gradual drop in CO levels from 0.8 to 0.4 ppm is seen walking away from the junction to the fixed sensor location.

In general, the CO trend from the fixed sensor shows how the background levels are varying with time, while the variance of the mobile samples around

Figure 8 CO Peak 'A', 20 January 2005. The vertical CO line marks the position of the fixed sensor.



the area show how they vary with distance. These two facts can be used to improve the comparison between the fixed and mobile sensors.

Given the limitations inherent in comparing the fixed and mobile data, together with the low CO levels during the winter, the result of 0.007 ppm mean difference between the fixed and mobile data, ± 0.06 ppm with 95% confidence is surprisingly good and is within the accuracy of the sensors.

5.2 CO levels at fixed times of the day

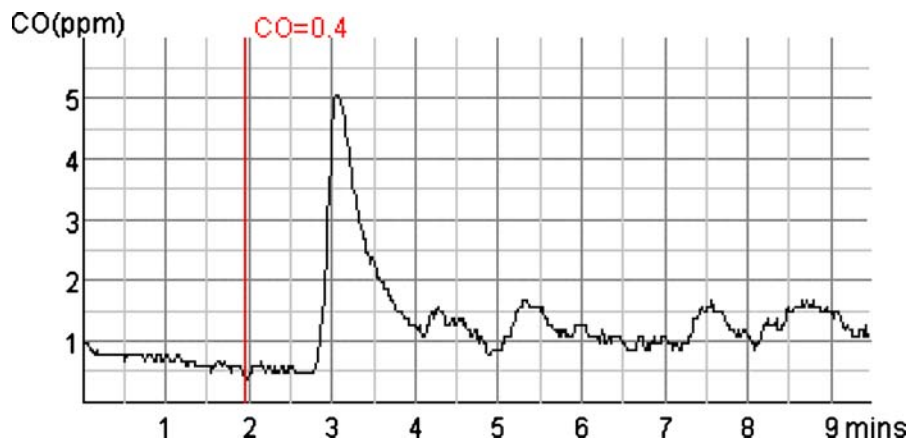
Given that there is a good match between mobile readings and static readings, the next logical step is to plot how the CO levels vary throughout the day. However, here we hit a problem of data density. Because the device is moving, there is good spatial coverage of the area, but very little data for specific locations e.g., within 20 m of a fixed sensor. Both

daily running means and scatter graph plots were attempted using the mobile data by selecting points around the Exmouth Market fixed sensor. In this case, the mobile data shows an unrepresentative picture when compared to the fixed sensor of the VivaCity2020 project (<http://www.bartlett.ucl.ac.uk/research/space/vivacity-overview.htm>), due to the poor temporal coverage of the mobile sensor. For this type of data to be plotted using mobile sensors, much more data is required to give a uniform spread of samples throughout each day of the sampling period.

6 Composite Profiles Along Roads

In the following results, both automatic GPS correction and manual correction based on knowledge of the route have been combined to identify features at a finer scale than is possible with the raw GPS data.

Figure 9 CO Peak 'B', 1 February 2005. The vertical CO line marks the position of the fixed sensor.



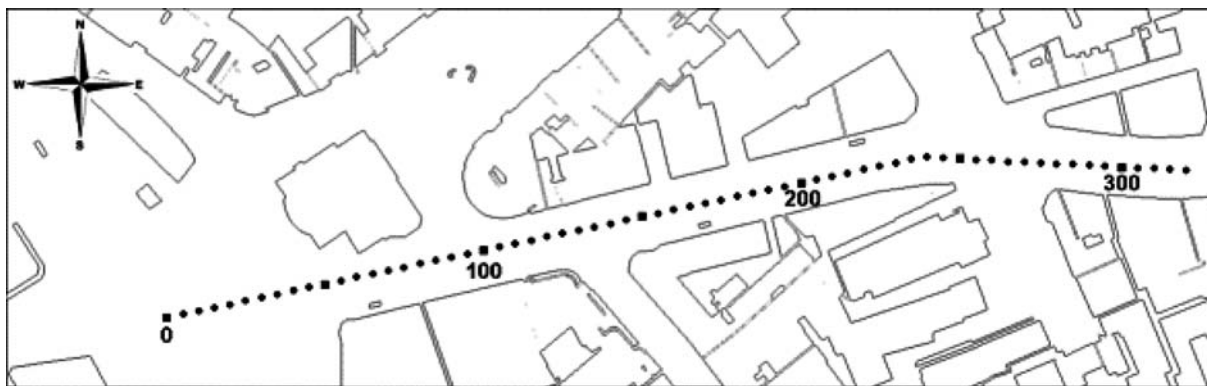


Figure 10 Clerkenwell Road showing the distances in metres corresponding to the following Figures 11 and 12.

Profiles along the length of roads have been plotted to show the variation in CO levels. This data could be used to decide the best locations for fixed sensors, or to calculate how critical the positioning of a fixed sensor is. The method of plotting is to average all the values within a radius that spans the road, so a GPS correction algorithm that places samples on the correct side of the road is not necessary in this context. The general CO trend along a road can be calculated from the raw data to an acceptable level of accuracy, while simple linear interpolation of missing GPS points can increase the accuracy further. More complex correction schemes are not necessary as long as the data is bounded by the confines of the road.

6.1 Clerkenwell road

Using wind data for the closest synoptic station and time, composite profiles of days with similar wind directions can be produced. Clerkenwell Road runs along bearing 255°, 15° rotated from west to east (Figure 10). With a 25° window either side, the two parallel and two perpendicular wind groupings are shown in Table I.

Table I Clerkenwell Road CO data grouped by time and wind direction relative to the road

Along road	Number of days	Mean wind speed (ms^{-1})	Bearing
West to east	9	5.78	230 to 280
East to west	1	5.0	050 to 100
Perpendicular			
North to south	5	3.4	320 to 010
South to north	0		140 to 190

Figure 11 shows similarly shaped CO traces for both parallel and perpendicular winds, except for the peak of 1.8 ppm at the west end of the road on the perpendicular wind profile. The only other difference is that the parallel trace is shifted approximately 45 m west. It is interesting to see that the variance around the 1.8 ppm peak at 30 m is significantly higher than anywhere else along the road, while there are also large areas of very low variance. Up to 30 m, the GPS accuracy is at its highest, so the high variance is unlikely to be the result of badly placed GPS samples as has been seen in previous studies. A more likely explanation is that queues of traffic often build up in this heavily congested area, with three bus stops in close proximity to the junction. In addition to this, the area is very exposed, with no buildings close by, and a bridge crossing over a railway cutting at the 15 m point. The high variance on both traces is caused by the fact that high CO peaks were sampled here when queues of traffic formed, but being very exposed, any slight wind quickly transported CO away from the site. This resulted in both high and low peaks being sampled in the area and the high variance shown in Figure 11.

Figure 12, shows the ‘Horizontal Dilution of Precision’ (HDOP) reported by the GPS for the same data as used in Figure 11. The reported HDOP value is the standard deviation of the position errors as calculated by the GPS, based on the satellite geometry used for the position fix. The graph in Figure 12 is plotted by taking the mean of all the HDOP values within the same positions along the road profile as the previous Figure 11, giving an estimate of the GPS accuracy along the road. In order to obtain a rough estimate of the position accuracy in metres, the HDOP

CO Mean and Variance Along Clerkenwell Road

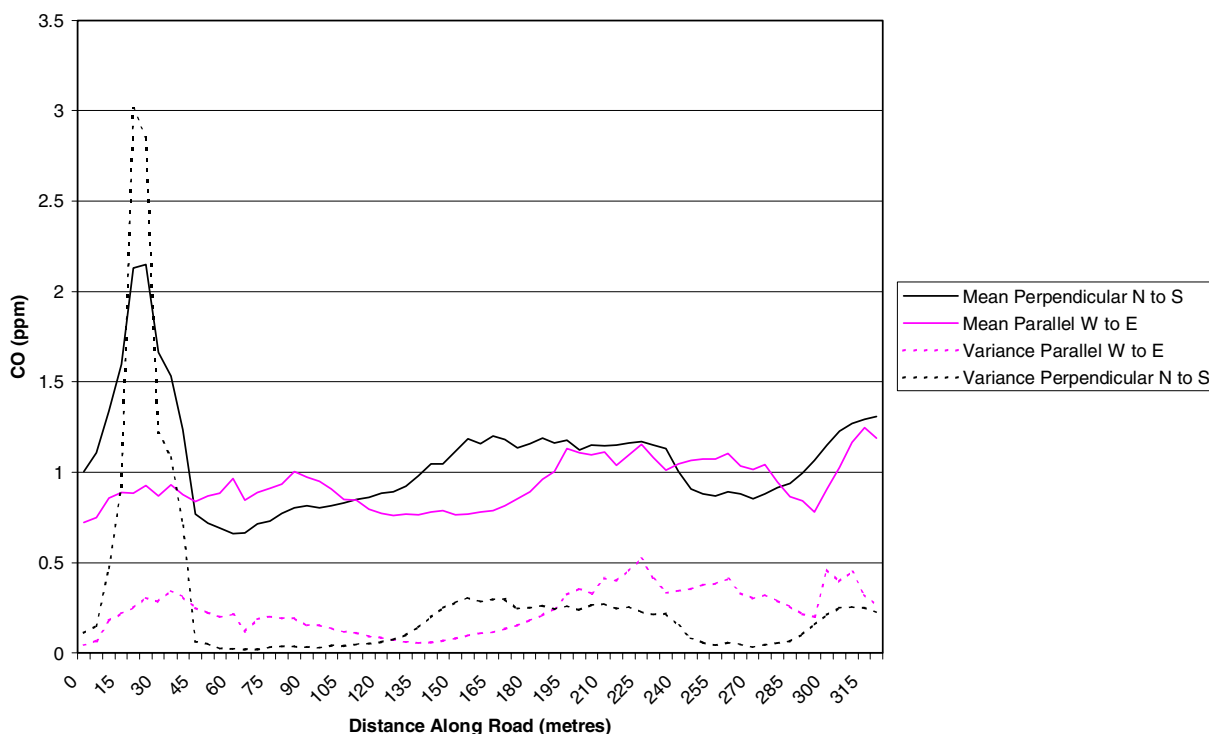


Figure 11 Comparing profiles for W/E (parallel) winds and N/S (perpendicular) winds.

value should be multiplied by the receiver's basic accuracy, in this case 11 m.

From Figure 12, it can be seen that the GPS accuracy in Figure 11 varied between 19 and 49.5 m along the length of the road. The most noticeable feature of Figure 12 is the similarity in the shape of the two curves. This is an important result as it shows that there was no bias in the CO data of Figure 11 caused by differences in GPS accuracy. Given that each is a plot of data from different days and so no data is shared between the two curves, it suggests that building layout along the road is affecting the satellites visible to the GPS. HDOP is a function of the position of the satellites. You would not normally expect to change so quickly in such a small area, unless the view of the sky is occluded and the GPS is forced to use non-optimal satellites for the fix. This is supported by the fact that the two lowest points of the graph are at 0 and 255 m. From 0 to 45 m there are no surrounding buildings as can be seen from Figure 10. At 255 m there is a large gap in the buildings at St John's Square on both sides of the road. The HDOP graph matches the position of this gap between the

buildings exactly and is the same width at 45 m. This sudden widening of the road causes an interesting CO gradient, while the junctions at either end also produce CO peaks where traffic is idling. This means that we may be fortunate in that where we expect interesting pollution events, we might expect to get better GPS availability and accuracy.

Taking the GPS accuracy into account, it is possible that the CO peaks on the two traces in Figure 11 should line up as they are approximately 45 m out of phase but show the same trough, peak, trough, peak pattern from 110 m onwards. It is also possible that this 45 m offset could be caused by the difference in wind direction, but additional information is needed to prove this. The high CO variance and mean from 0 to 45 m when the wind is northerly is probably due to the wind blowing straight down Farringdon Road and across the very open junction with Clerkenwell Road. Traffic build-up here is common due to the road layout and this area was particularly congested during the whole of the collection period. Areas where the CO variance is high need to be treated with particular care, as

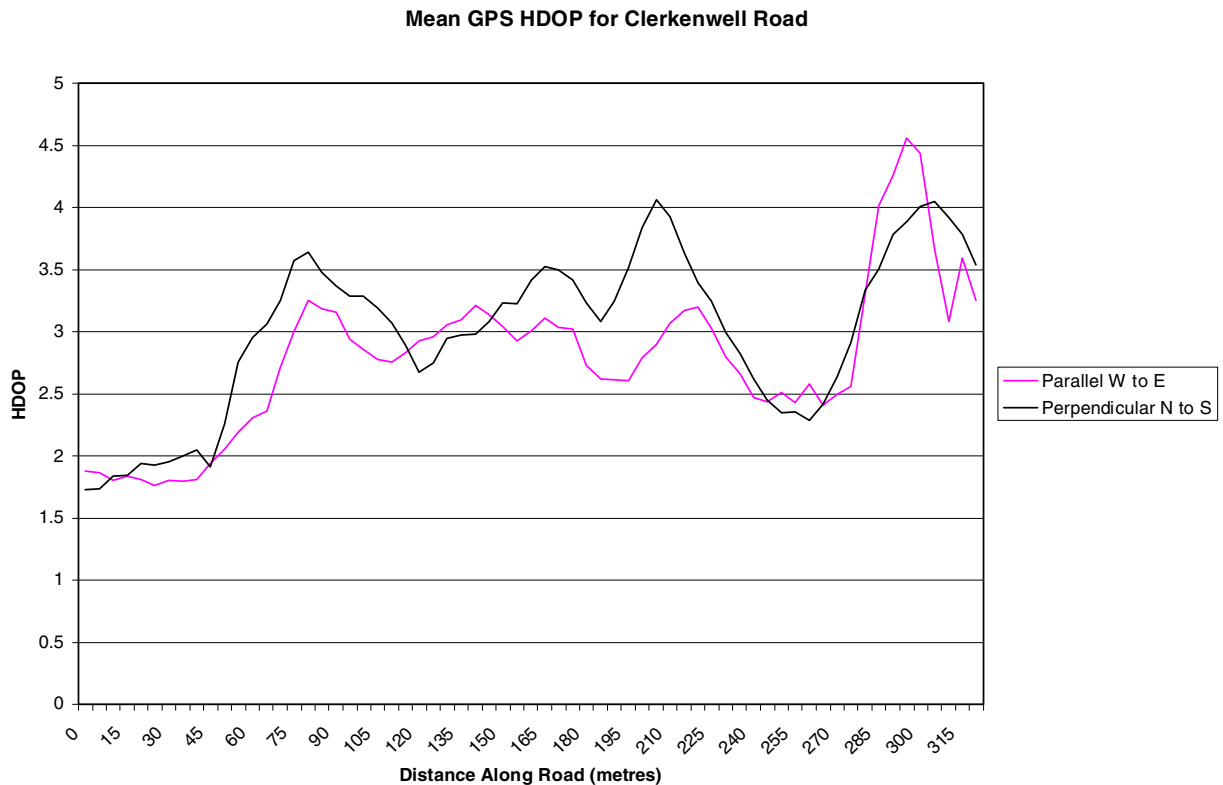


Figure 12 Horizontal Dilution of Precision (standard deviation of position errors) reported by the GPS receiver for the position data used in Figure 11.

previous studies have shown that high CO variance and areas of low GPS accuracy are often linked. In this case, the GPS HDOP value is only 2.0, so the high CO variance is almost certainly a real CO characteristic rather than an effect of badly positioned

samples. One other feature worth noting in Figure 11 is the final trough on both traces at the 260 m (northerly wind) and 300 m (easterly wind) positions. This corresponds to the point where the road opens out on both sides into St. John's Square. When the wind is

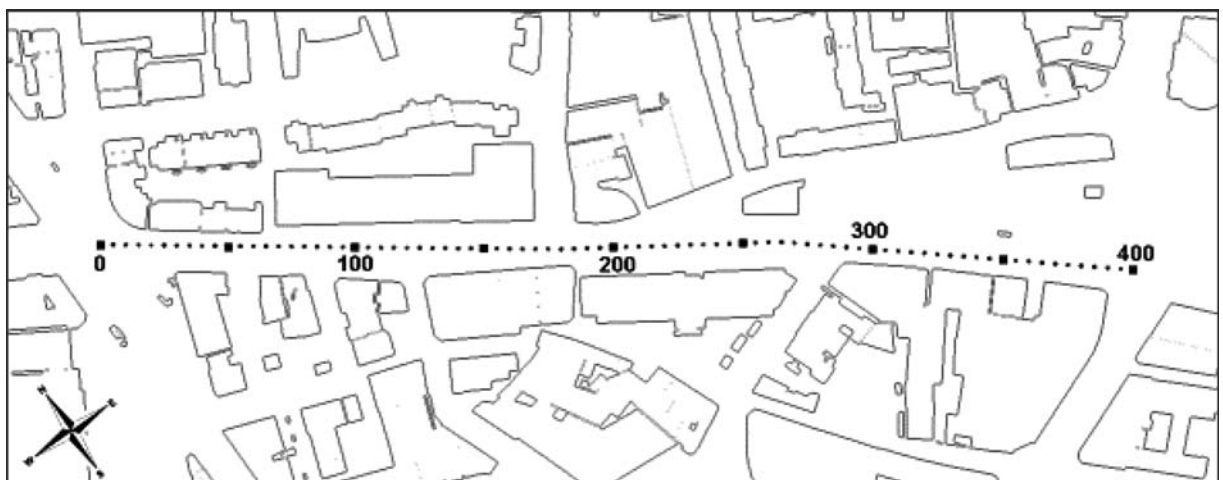


Figure 13 Farringdon Road showing the distances in metres corresponding to the following Figures 14 and 15. The large squares are 50 m apart, while the small squares are 5 m apart.

Table II Farringdon Road CO data grouped by time and wind direction relative to the road

Along road	Number of days	Mean wind speed (ms^{-1})	Bearing
Northwest to southeast	7	5.57	280 to 330
Southeast to northwest	0		100 to 150
Perpendicular			
Northeast to southwest	7	4.43	010 to 060
Southwest to northeast	6	5.17	190 to 240

blowing along the road from the east, this trough is very narrow, but when the wind is from the north there is a drop in CO the same width as the gap in the buildings. This is also matched by extremely low variance. On many occasions during data collection, CO gradients around this corner were measured.

6.2 Farringdon road

Farringdon Road runs along bearing 305, approximately northwest to southeast (Figure 13). Allowing a

25° window either side, the two parallel and two perpendicular wind groupings are shown in Table II.

Figure 14 shows a strong similarity between the parallel profile and the perpendicular profile in the SW to NE direction with a small shift of less than 30 m. In this case, a second perpendicular profile in the opposite direction (NE to SW) has been plotted, which does not follow the same trend as the other two. This profile has a distinct peak with a width of 45 m at the north end of the road (20 to 65 m), finishing just before the car park. As the adjacent Rosebury Avenue joins Farringdon Road from the northeast, this might explain the peak for this wind direction. Towards the 400 m end, where the junction with Clerkenwell Road is, the two perpendicular profiles become very similar while the parallel profile finishes with a much higher mean level. This is interesting as it corresponds to the 2.2 ppm peak on the Clerkenwell Road North to South profile in Figure 11 earlier. With the wind in similar directions on both roads, there are significant peaks around the same junction.

CO Mean and Variance Along Farringdon Road

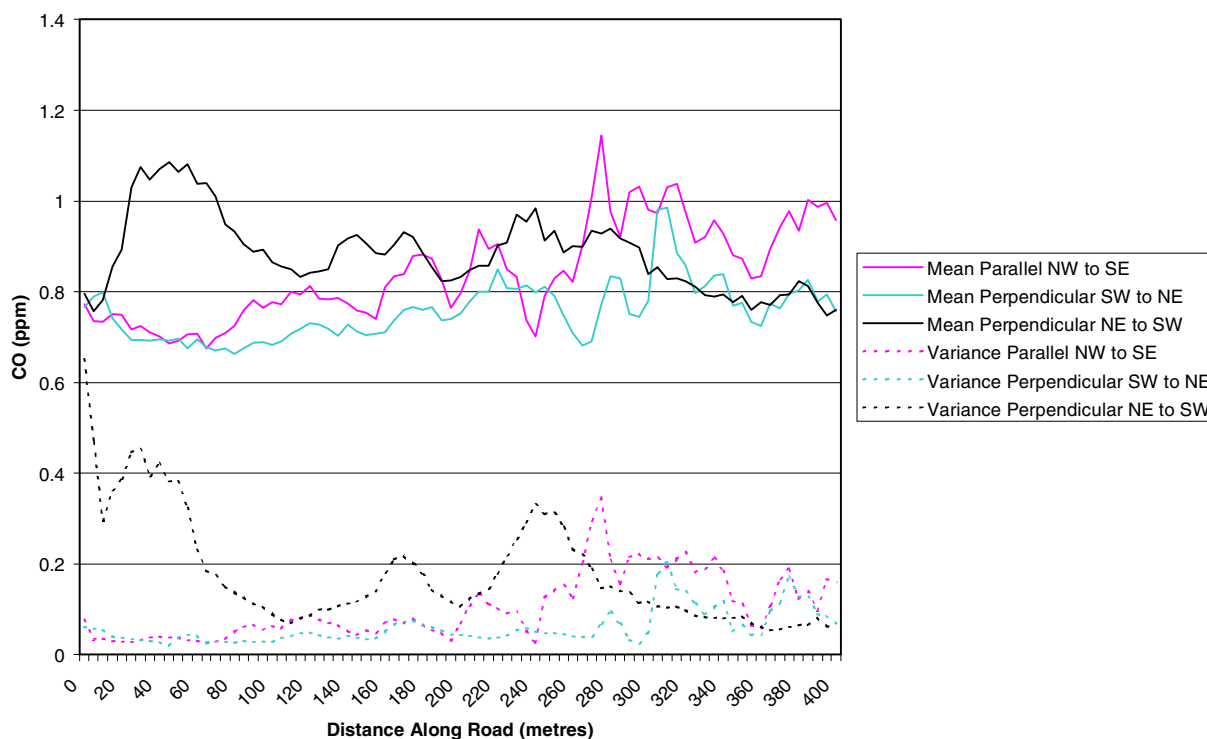


Figure 14 Comparing CO profiles for NW/SE (parallel) winds, SW/NE (perpendicular) winds and NE/SW (perpendicular) winds along Farringdon Road.

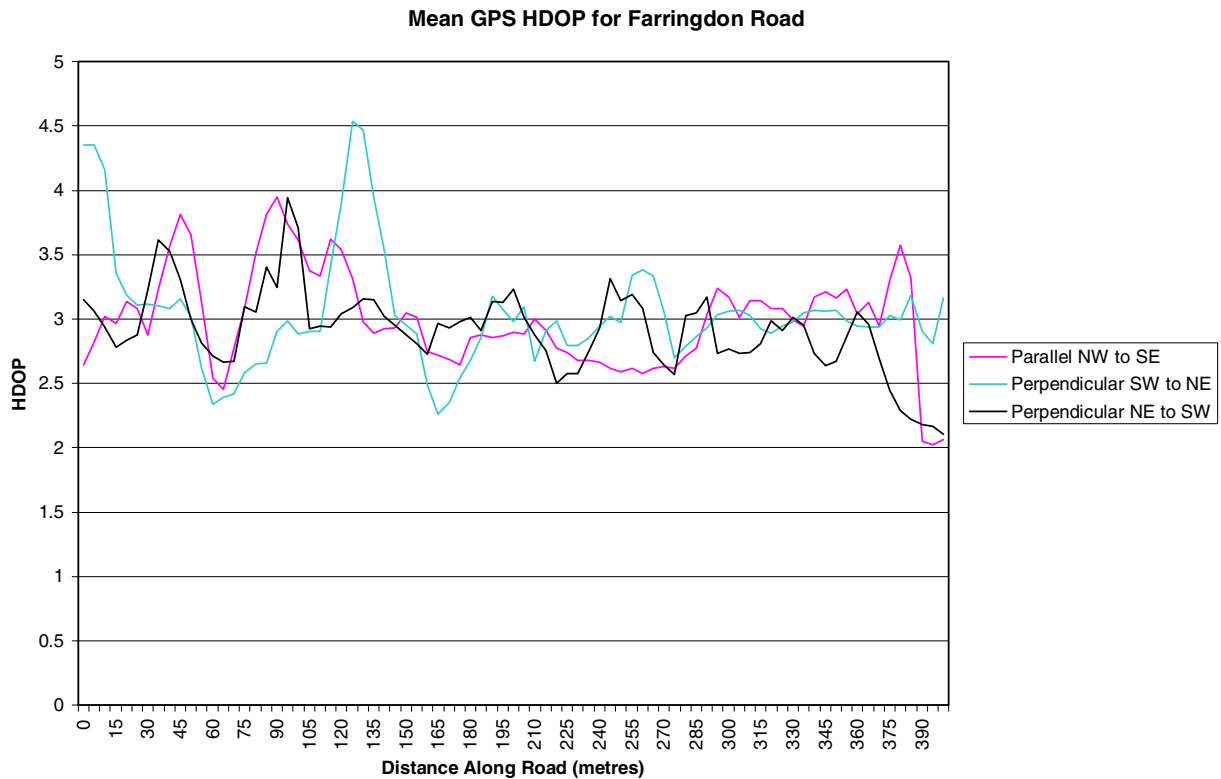


Figure 15 Horizontal Dilution of Precision (standard deviation of position errors) reported by the GPS receiver for the position data used in Figure 14.

The GPS accuracy plotted in Figure 15 shows the error to be around 30 m for most of the length of the road. There is generally good similarity between the GPS data used for the three profiles in Figure 14, so it is unlikely that any consistent bias has been introduced into the CO data by the GPS. Looking at the CO data in Figure 14 together with the GPS accuracy of Figure 15, a few points do look as though they

might have been displaced along the road. In particular, 240 m on the NW to SE trace and 275 m on the SW to NE trace look similar and happen to coincide with significant differences in GPS accuracy between these two data sets in Figure 15. The two peaks on the same trace at the 0 and 130 m positions also suggest that the position might be displaced in the three plotted profiles at these locations.

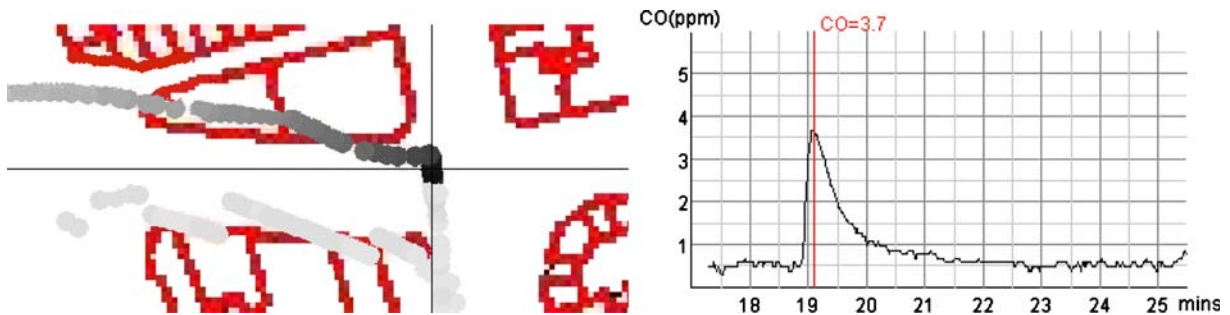


Figure 16 GPS Trace and CO profile crossing Clerkenwell Road on 31 January 2005, 11:33. The cross shows the position of the maximum peak while crossing the north carriageway. The colour

of the trace is a *greyscale* that represents the CO level with *black* as 5.0 ppm and *white* as 0 ppm. The higher CO levels on the north side where traffic is queuing can be clearly seen.

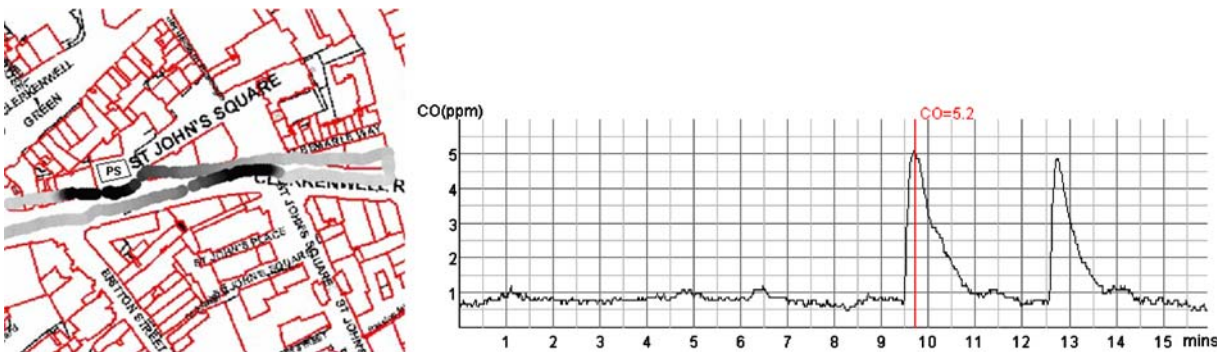


Figure 17 24 January 2005 15:14 showing identical peaks on opposite sides of the road. On the map, the location of the petrol station is marked with 'PS' and the grey trace represents

the CO level. Black is 5.0 ppm with white 0 ppm. The first peak on the graph is outside the petrol station.

6.3 Implications

The link between GPS accuracy, building layout and CO levels has some interesting implications. At junctions where CO tends to build up due to idling traffic, the unobstructed view of the sky often leads to significantly improved GPS accuracy. Even where the GPS at junctions is bad, finding the point where the carrier waits to cross, or where the track angle changes by 90°s can often position the crossing accurately. In dense urban canyons, where buildings often block the GPS signal, CO levels are likely to be higher where traffic is stopped, or when re-circulation occurs. In this case it is probably sufficient to know the correct side of the street and an approximate position.

7 Other Observations

7.1 Profiles across roads

In addition to sampling data along the length of roads, a significant amount of data was collected while crossing from one side of the road to the other. This turns out to be relatively easy to detect manually if the approximate crossing points on a route are known, as it does not rely on the actual reported GPS position. Points of zero velocity while waiting to cross and 90° changes in direction, either from the GPS location track or the reported track angle, are indicative of road crossings. This enables a crossing point to be positioned accurately even when the GPS position is 50 m out.

Figure 18 GPS accuracy around the double CO peak on 24 January 2005. 'PS' marks the petrol station.



Table III Unusually high readings and possible explanations

CO Level	Location	Possible explanation
14.9 ppm	Malet Street	Caused by a motorbike starting up close by. Unfortunately it is not known how long this persisted for, but as this location contains a motorbike parking bay, it might be an interesting location to monitor.
4.5 ppm	Exmouth Market	Occasional high peaks at the end of Exmouth Market possibly caused by food being cooked on gas stoves in the open air and by portable generators.
2.4 ppm	Exmouth Market	Lorries making deliveries in this pedestrianised area show distinct tracks when the CO trace is plotted.
3.4 ppm	Indoors	Inside a coffee shop and inside a house. On both occasions the level outside was less than 1.0 ppm.
2.2 ppm to 0.9 ppm in 30 metres	St. John Square	The CO gradient around St John Square on Clerkenwell road was not unexpected, but is shown particularly well by the tracked sensors.
3.9 ppm	Malet Street	A portable generator on the corner throughout November and December was seen to produce CO peaks at the times when it was running.
2.3 ppm	Guildford Street	Peak observed outside a hospital over a period of months where building work was going on.

Figure 16 shows Clerkenwell Road being crossed at the St. John Street end. In this case, the GPS accurately identifies the south carriageway as 0.5 ppm and the north carriageway as 3.7 ppm. This is probably due to the traffic waiting at the lights on the north side while the traffic on the south side is free-flowing. The same crossing was made 5 min later and is labeled at 25 min in the diagram, but without any noticeable peak.

On numerous occasions, CO peaks were sampled multiple times at the same location, or on opposite sides of the road. Figures 5 and 17 show examples of CO peaks.

Figure 17 shows a peak of 5.2 ppm detected when walking past the petrol station on the north side of Clerkenwell road. Heading towards the junction at the east end, the levels drop. After crossing to the south side and walking west, an almost identical peak is detected 3 min later on the opposite side of the road.

Figure 18 shows the GPS errors for this trace as a radius around the reported point. The initial peak outside the petrol station shows errors of 3 to 5 m, while the second trace on the other side of the road is around 12 m. No accurate wind measurements were made in the street, but the prevailing wind was reported as coming from 020° at 6 ms⁻¹. Unfortunately, each side of the road was only covered once in this instance, limiting the amount of data available for analysis. Looking at previous data collected in this area, peaks of this magnitude are comparatively rare, so to find two in close proximity is significant. However, it is still possible that the two peaks originate from independent

CO sources, perhaps from a car pulling out of the petrol station, queuing at the traffic lights and pulling away again. It is also possible that a single continuous plume of CO was sampled at different points on opposite sides of the road, or alternatively, this could be a single CO peak that has drifted.

Without any additional information, it is impossible to know what caused these two peaks. This set of data is interesting as it suggests that we may be able to track moving peaks using the mobile sensor. Although in this pilot trial we have explored only passive data collection, active collectors might be able to track such peaks.

7.2 Unexpected sources

During the course of the data collection, there were a number of unexpected CO sources discovered. Table III lists some of them with a possible explanation for each.

8 Conclusions

In this paper we investigated the use of GPS tracked sensors to map CO pollution in an urban environment. Specifically, we were interested in whether GPS could be used to place CO samples accurately enough so that expected environmental features could be observed. From the GPS data obtained over three months, it was found that for 95% of the time, the samples could only

be positioned to within 50 m, with GPS only available for around 50% of the time. Some GPS correction schemes and the use of additional knowledge were investigated in an attempt to improve this accuracy, resulting in data at a much higher resolution for selected features. Road crossings in particular are easy to detect, so peaks at junctions can be positioned with 5 m accuracy. Separation and comparison of data on opposite sides of the road is also possible using similar techniques, while differences in the CO profiles along roads due to wind direction can be built up over time.

The mobile sensors were successfully compared with existing fixed sensors, showing how fixed sensor data could be compared with a snapshot of data taken from a mobile sensor. Using the mobile sensors, we were able to take CO readings in areas not normally accessible, for example inside a coffee shop, on the tube or on buses. Some use was made of the equipment's real-time display to locate CO peaks as they were forming and to track them, but the low CO levels during the winter made this almost impossible.

Using a single mobile sensor in an urban area has already provided much useful data that would not have been possible using fixed sensors alone. If the number of sensors can be increased into the hundreds, then high-resolution maps of the changing CO levels in an area of the city can be built. This could provide a valuable resource in the understanding of how pollution dissipates at street level by providing data for selected areas at a finer resolution than the current sensor network.

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The vector data used was supplied by the UK Ordnance Survey.

Appendix

Further information on the GPS device used for the experiment can be found on the GARMIN website at: <http://www.garmin.com/products/gps15h/>.

The CO sensors used for the experiment are manufactured by 'Learian Environmental Systems' and use the 'Citicel A3CO' semiconductor device. Further information can be found on the Learian Website at: <http://www.learian.com/pdfs/icom.pdf>. The datasheet for the A3CO semiconductor sensor can be found at: <http://www.citytech.com/PDF-Datasheets/a3co.pdf>.

The 'National GPS Network' is the main source of GPS information in the UK, enabling the download of differential GPS information from fixed sites for post-processing, as well as containing technical information on the GPS system itself. For a good introduction to the different options available, see: http://www.gps.gov.uk/additionalInfo/whatisGPS_01.asp.

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