EFFECTS OF STREET GRID CONFIGURATION ON KERBSIDE CONCENTRATIONS OF VEHICULAR EMISSIONS

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0 Abstract

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Up to now little has been understood about the way that airborne pollution is distributed spatially at head height and kerbside in the urban street grid. This paper reports on research in which a new monitor has been developed and validated, and then used to sample a small urban neighbourhood at finer temporal and spatial resolutions than has been achieved previously. These data show that pollution concentrations at head height vary radically within metres of each other. A method is developed for using the shape of the frequency distribution of pollutant concentrations to 'fingerprint' monitoring sites in terms of their pollution exposure at both average levels and at the extremes and to compare the effects of climatic, seasonal and diurnal changes on pollution concentrations, as well as to help isolate effects of traffic management and other interventions on local ambient pollution concentrations. 'Space syntax' methods of analysis of street grid configuration which have been shown to predict vehicular flows on the basis of representations of the geometry and topology of the street grid alone, were found to predict both average and extreme (total percentile) CO concentrations (r2=.78, p=.0002) at street segment resolution in the urban grid.

1 Introduction

This paper reports on a recently completed project 'Effects of street grid configuration on pedestrian exposure to vehicular pollution: civilising urban traffic' funded by the UK's Engineering and Physical Science Research Council (EPSRC GR/J50613). The project was stimulated by previous research (GR/H48422) which had found that both pedestrian and vehicular traffic flows in the fine scale structure of the urban areas depended on the spatial configuration of the street grid itself (r2~.81) irrespective of land use, major attractors or traffic control systems (Penn et al 1994, 1997). It was known that the primary source of many urban air pollutants of health concern is vehicular traffic (QUARG, 1993), and it was known that dispersion of these pollutants from the car exhaust by wind in urban areas depended greatly on the configuration of surrounding buildings (Oke, 1987; Berkowicz & Hertel, 1994). Since the pedestrian consumer, the vehicular producer and wind dispersion all related to the spatial configuration of the built complex, we hypothesised that spatial variations in pollutant concentrations at head height might also be found that would lead to differential exposure of the pedestrian population as they moved through the city. If we could understand how the configuration of the grid gave rise to the distribution of pollutant concentrations, it was hoped that ultimately one could begin to use the design of urban space and the management of traffic flows through the network to reduce pedestrian exposure. This was seen to be a pressing concern in the light of public worries about both amenity and health in city centres (RCEP, 1994).

There are only a small number of studies that have gathered fine spatial resolution data on pollution concentrations at head height in urban areas, and the lack of data was noted by the QUARG (1993) review of research needs. Amongst the few studies in which data have been collected at fine resolution are those by Laxen & Noordally (1987). Their studies of NO2 distribution were first carried out during 1985. In the first study 34 sites all within an area of 50 x 100m were monitored using passive diffusion tubes. A second survey used 58 diffusion tubes in a slightly larger area, and a third used 36 sites over the same area as the first study. Fairly uniform results were obtained over 50m stretches of road. Concentrations were higher closer to and upstream of traffic lights. NO2 concentrations were highest along the centreline of the road and decreased rapidly away from this, they were close to local background within 15m of the centreline. The concentrations decreased with height approaching local background towards the top of the canyon (18.4m), although a variation of a few metres in height was found to make little difference to measured concentrations. These findings give useful indications on patterns of concentration distribution based on measurements of long term average concentrations. However, since the measurement period over which diffusion tubes are exposed is typically much longer than the periods of variation in wind or traffic flows, these studies tell us little about the way that variables such as wind speed and direction, or variations in traffic flows and congestion affect longer term average pollution concentrations in different locations.

Although a lot is known about the behaviour of vehicular traffic in the primary route structure of urban areas, and a range of methods exist for modelling the likely effects of traffic management and network changes on traffic flows and congestion, there is a relative lack of understanding of the behaviour of traffic in the fine scale structure of urban neighbourhoods. Recently 'space syntax' methods developed for modelling pedestrian flows in urban networks have been validated for vehicular traffic in this fine scale structure (Penn et al 1994, 1997). Space syntax models are based on a representation of the geometry of the urban open space network itself, called the 'axial map', which subdivides open space into the fewest and longest lines of sight and access, which pass through all circulation routes open to the traffic mode in question. The axial map is then transformed into a discrete graph in which each line of sight is represented by a node and each intersection of lines forms a relation between the respective nodes. This graph differs from the network representation used in conventional traffic models in that it effectively represents the space of the street as a node and the road intersection as a link and the resulting graphs are highly non-planar. A range of graph theoretic measures can then be calculated and used to represent the pattern properties of the network. Space syntax models are simple or multiple regression models based on these measures of the route network, along with other attributes of streets, such as development density or street width, that can be shown to affect the traffic flow parameter of interest. In a recent large scale study of six London areas involving traffic flow counts at over 400 locations, two spatial factors were found to account for over 80% of the variance in traffic flows from location to location. These were a measure of the mean depth in the graph from a node (radius 3 integration) and the effective street width open to traffic. The regression model based on these two variables gave an $r2 > .81$, $p<.0001$. Penn et al (1997) suggest that the street width and integration components represent the supply and demand sides of an equilibrium that distributes traffic flows in the network. No matter how much a street is widened, if it is in a spatially isolated part of the network its traffic flows will not increase substantially, equally, if a spatially integrated street is of restricted width, flows will not be able to increase much above capacity. Space syntax methods are significant in the context of the present study in that they give a simple and well validated proxy both for vehicular and pedestrian traffic flows, not only on primary routes, but also in the finest scale structure of the network. They also provide a means of measuring the two dimensional (plan) configuration of the space pattern between buildings, and this may prove useful in consideration of wind dispersion of pollutants.

A certain amount is known about wind movement and dispersion in complex built up areas. In particular work by Oke (1987) and Berkowicz and Hertel (1994), has found that boundary layer air flows in urban areas give rise to characteristic wind behaviours within street canyons, which, although complex are regular, depend on the configuration of space between buildings and are essentially predictable. However, existing pollution modelling approaches based on assumptions of Gaussian plume dispersion or interpolation between monitoring sites, which may hold for open sites or background measurements, cannot be validated for urban street level predictions without fine spatial and temporal resolution data, which at present are lacking.

Data of this resolution has not been gathered to date for a number of practical reasons. Since accurate monitoring equipment is expensive, most effort has been concentrated on gathering background pollution data, and where more than one kerbside site is available these have been dispersed rather than clustered. Other techniques such as the UK's national NO2 survey have also tended to distribute sites as widely as possible in order to gain a good picture of overall distributions for geographic areas rather than to look in detail at differences from street to street within a neighbourhood. Where detailed kerbside data have been gathered (eg. Hickman & Lunn, 1981) often only a single site has been monitored at a time with high temporal resolution in order to investigate variations of pollution concentration with traffic flow and speed. The assumption behind most studies, models and policy formulations has been either that pollution concentrations vary smoothly or that variations on the micro scale would be so masked by 'noise' that they were not worth collecting. A recent study by Bell's group at NUTRG backs up the last contention (Bell, 1996). By developing a pollution monitor for use in association with traffic light control systems in the Instrumented City at Leicester, Bell is investigating whether traffic light timing and sequencing can be used to minimise ambient pollution concentrations. However, their equipment is relatively expensive, and constrained by power supply and data communications to be located at traffic light control boxes, and so necessarily to measure main route locations at junctions which are spatially complex, where traffic flows are high and where queuing, stopping and starting may have significant effects on the data. Little in the way of consistent spatial variation has been reported from this work, and the relationships reported between dynamic traffic flows and monitored kerbside pollution concentrations suggest that the data are subject to a great deal of noise and that new methods of handling these data need to be developed.

2 Objectives

The study we proposed therefore aimed to gather fine scale data concentrated within a small urban neighbourhood, so that a number of scales of route and different configurations of space could be monitored at the same time in order to see whether or not we could identify regular variations in pollution concentration from location to location. If we could identify regular spatial variations then we proposed to move on to investigate whether modelling techniques based on a representation of the detailed configuration of space in an urban area could be used to predict those variations, and whether we could identify ways of estimating pollution exposure of the pedestrian population. The modelling techniques we proposed to employ are called 'space syntax' models. These have proven to be useful predictors of both pedestrian and vehicular flow rates at this fine scale of spatial resolution. Since they describe the physical configuration of the street grid, and this appears to be the single intervening variable between vehicular flows - and so pollution emission, wind dispersion and pedestrian flows - and so potential consumption, it was hoped that they might prove to be a useful new modelling technique for this application. Finally we wanted to develop the modelling and monitoring protocols needed to evaluate traffic management and calming measures at both design and implementation stages for their effects on pedestrian exposure to pollutants.

3 Methodology

The research strategy was simple. A neighbourhood in central London was selected in which to monitor kerbside pollution concentrations at head height, measures of prevailing meteorological conditions as well as observations of vehicular and pedestrian traffic flows. The aim was to develop a detailed data set at the individual street or street segment scale for the neighbourhood, and then to subject this to statistical analysis to investigate the interdependencies between the various variables. It was then proposed to use an existing 'space syntax' computer model of central London to quantify the spatial pattern properties of the monitoring locations, and to incorporate these measures in the statistical analysis, so as to investigate whether measures of the configuration of the street grid itself would perform as a proxy for locational variations in pollution concentration.

A study area was chosen in Bloomsbury which was characterised by a street grid of 'canyon' streets, with buildings of fairly uniform height (between 5-7 floors), and with some 'London squares' planted with mature trees. The road network had major traffic arteries, minor through routes and back streets and showed a wide variation in vehicular flow rates. There was also considerable variation in pedestrian movement rates in the area.

Carbon monoxide (CO) was selected as an indicator of pollution since it is relatively stable, easily measured and comes mainly from vehicular emissions. An investigation was carried out of the use of CO as a proxy for a wide range of other pollutants of more direct health concern, including particulates (PM10) and benzene, by compiling existing national monitoring point data from the Russell Square site, and bringing it together with meteorological data from the closest Met Office station. This confirmed previous studies that had found that CO can be used as a good proxy for a wider range of pollutants including NOx, hydrocarbons and PM10.

It was originally envisaged that fine scale pollution data would be gathered using solid substrate adsorption tubes and a Brüel and Kjaer photo-acoustic gas analyser.

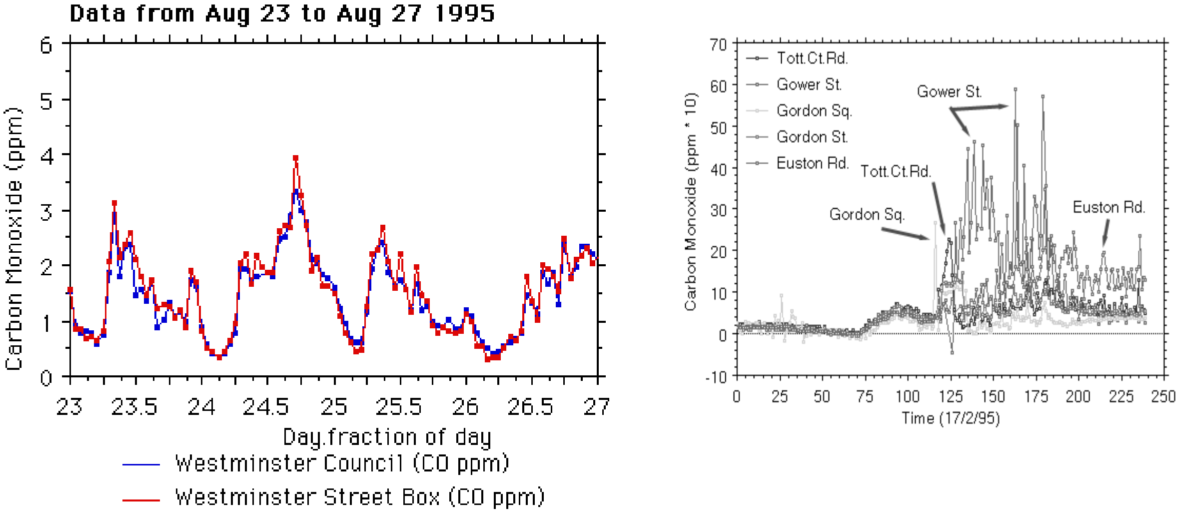
Experiments were set up to test the accuracy achievable using these techniques. During this phase of the project it became clear that the proposed adsorption tube methodology was problematic. Although equipment was cheap, lab analysis time was expensive and while the tubes and analyser could be used to measure high concentrations such as those found in vulnerable work environments to give 8 hour data, at the low concentrations we expected to find in urban back streets it was clear that the level of accuracy achievable would not be adequate for the needs of the study. In order to acquire the data needed to fulfil the main objectives of the research a new monitoring methodology had to be designed, developed and validated. The main requirements for the monitoring methodology which were defined during the early stage work were as follows:

1) that it should be cheap enough to allow simultaneous monitoring at a number of sites;
2) that it should have fine enough temporal resolution to allow data to be acquired in terms of extremes as well as averages over time;
3) that it should be able to log all variables continuously so that the overall survey programme could be carried out on a compressed time scale;
4) that it should be able to be sited independent of power supply or other wiring constraints, according to the needs of the monitoring programme;
5) that it should be able to monitor key meteorological variables at the monitoring site (wind speed, light, humidity, and temperature) at the same time as pollutant concentration.

4 The StreetBox

The monitoring method we developed was based on the use of a carbon monoxide electro-chemical fuel cell (City Technology Ltd.) a relatively cheap and extremely accurate sensor with a detection limit of less than 0.1ppm and an accuracy of ±5%. Laboratory tests verified the manufacturer's accuracy claims using standard gases, and identified the temperature and humidity sensitivity of the sensor. An algorithm for temperature correction was developed based on these laboratory data. Variations from sensor to sensor and drifts over time were investigated through long term experimental set ups (6 months+). The sensor was established to be highly accurate and robust in all respects, and showed virtually no signs of long term drift. The 'StreetBox' monitor itself was developed to include the CO sensor as well as sensors for temperature (within and outside the box), relative humidity and incident light (to detect direct sun, daylight or night). In addition, a novel solid state wind speed sensor was developed based on ionisation using a small ß source, and validated against conventional mechanical anemometers in the wind tunnel and outdoors. This provides qualitative (windy, breezy, calm) measures of local wind speed at the monitor. All sensors were mounted in a box about the size of an orange juice carton together with a small data logging computer. This is user programmable to log all the sensors at any time interval from 3 seconds upwards. A program and simple user interface was written for downloading data on site into a Psion Organiser. With sampling at 6 minute intervals the data logger can hold up to 6 weeks' data between downloading (which takes about 2 minutes). A battery power supply with top up solar cell was developed and the whole set up tested under laboratory conditions in the environmental chamber and out on the street. Two prototype designs were subject to failure for various reasons including water penetration, inadequate power supply and internal overheating under direct sun. The final design corrected these faults and was tested against both Westminster and Islington Councils NDIR national urban network monitoring points. An extremely close match (r2=.89) was found (hourly averages over a period of 3 weeks, see Figure 1). Twenty-four StreetBox monitor units were built. Boxes have run continuously without failure for over 6 months at a stretch without need for maintenance and, although there have been some failures due to flat batteries and water penetration, the reliability record of the final design is very good. The unit cost of a StreetBox is in the region of £1,200.

A six minute sampling period was selected and data were collected at 24 monitoring sites in 12 streets within the Bloomsbury study area. Paired sites were located as nearly as possible on opposite sides of each street strapped to lamp posts at 1.8-2m high. In addition StreetBoxes were located at roof top level (above the 10th floor) alongside the Bartlett weather station at Torrington Place and within 1m of the sampling point at the Westminster City Council urban network station at Baker Street. Whilst these data were being gathered observations of pedestrian and vehicular flows were gathered at each site as well as at other locations in the area. For practical reasons traffic flow data were not gathered continuously, sample observations were made at each monitoring site throughout the day on weekdays using an observation protocol that has proven to give highly reliable average flow rates. Rooftop wind speed and direction were logged continuously at the Torrington Place station. All of these data were brought together in a statistical database for analysis.

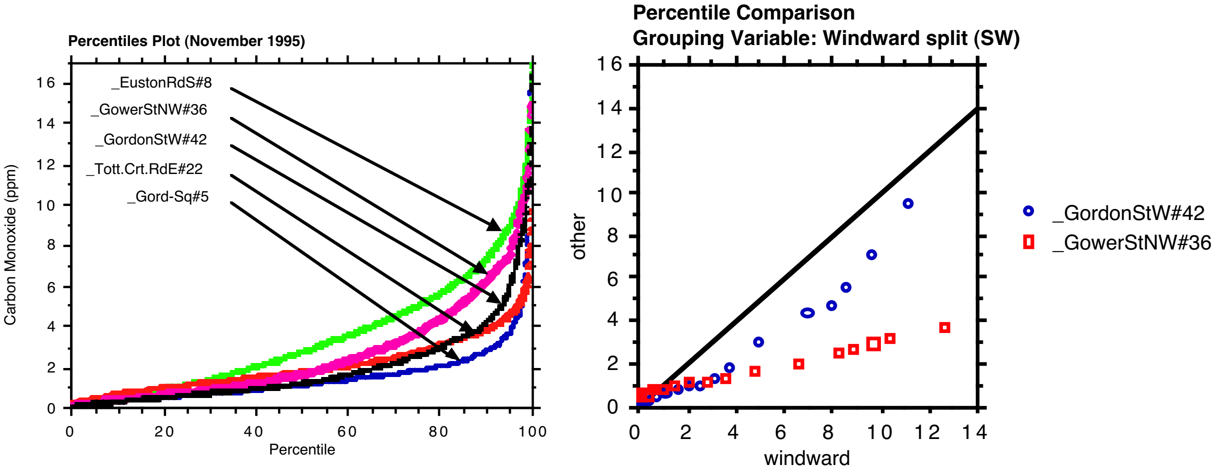


Figures 1-2.

5 The data and analysis

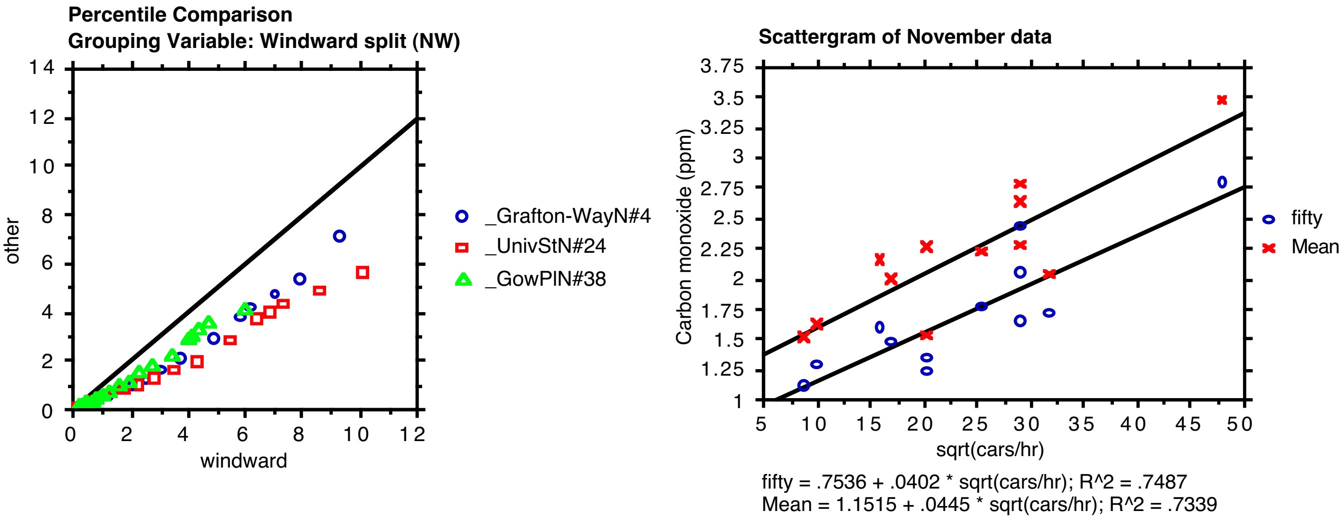
The body of data discussed in this paper was gathered over a one month period in October-November 1995. Figure 2 shows a plot of CO concentration through time at the beginning of the monitoring period. Initially all traces are superimposed as all monitoring boxes were co-located in the laboratory. Then, as they were each mounted in their respective street locations the traces diverge. The first point to be noted is that it is possible to distinguish between the CO concentration plots from monitoring locations within metres of each other. The Euston Road trace is consistently higher than other traces, with that on Gower Place only some 20 metres distant being consistently lower.

The second point to note is that the data are very noisy. The problem is that kerbside pollution concentrations vary enormously from moment to moment as the wind gusts and as traffic passes. This results in a signal to noise ratio so low that direct time series comparison from location to location, or between pollution concentration and instantaneous traffic flows (Bell, 1996) is virtually pointless. In order to overcome this and since we were interested in 'systematic' spatial variations (those that exhibit regularity over time) rather than temporal variations per se, we developed the use of frequency percentile plots to characterise a particular location and, in effect, to give it a 'fingerprint' that reflected not just the average concentrations, but the extreme peaks and troughs and all concentrations in between. Given a large number of sampling 'moments' most factors other than spatial location are randomised. Where there is a consistent bias (say an effect on the local CO concentration resulting from a particular direction of prevailing wind) the bias is, in effect, a characteristic outcome for that spatial location, the local configuration of buildings and the overall sampling period. Frequency plots of this sort appear to be a particularly valuable tool for investigating the differences between locations as these are experienced through time. Figure 3 shows the percentile plots for a series of streets monitored in the study. It can be seen that different streets show characteristically different frequency distributions of CO concentration. Euston Road, as might be expected, lies above the others throughout the percentile range. The more interesting profiles are those for Gordon Street and Tottenham Court Road, which cross each other at about the 80%ile position. In other words, for 80% of the time Tottenham Court Road, which is a major 3-4 lane one way northbound traffic route in this part of town, shows consistently higher CO concentrations than Gordon Street, which is a parallel, though much less important route, of one lane width in each direction. However, for the top 20% of measurements Gordon Street is more polluted than Tottenham Court Road. This may be because it provides the main access route to Euston Station for taxis from London's West End, and is prone to severe congestion during the afternoon peak period due to preferential traffic light timings for the Euston Road. We believe that the higher CO concentrations at the upper extreme reflect a build-up of congested station traffic, much of it diesel burning, and certainly concur with experience of perceived pollution.



Figures 3 and 4

This example suggests that the percentile plot may prove to be a useful analytic tool for characterising locational variations in kerbside pollution. However, we believe that much needs to be done to develop ways of measuring and comparing the precise shape of the percentile curve, and to study the specific factors present at a given location that give rise to the shape of its percentile plot. One method for investigating the way that specific factors are involved in creating the CO concentration profile at a monitoring site was developed. By splitting the sample of measurements by one of the factors, say, rooftop wind direction, and then investigating the effect of different wind directions in constructing the shape of the percentile plot of pollution concentrations at that location, it is possible to determine the contribution of wind direction to the CO concentration at a particular location. For instance, by splitting the measurement set for a particular site into two sets, those in which the monitoring site was on the windward facing side of the street canyon, and those for all other directions, and then plotting a scattergram of CO concentration at a series of percentile points throughout the range for the two measurement sets against each other, Figure 4 shows the effects of a SW rooftop wind direction on CO concentration at street level on monitors on the west of Gordon St. and Gower St. The difference is consistent throughout the percentile range showing that the CO concentrations on the down-wind face to be between one half and one third of those when the wind comes from the other directions. This result is reproduced for a range of 'street canyon' sites (Figure 5) and is consistent with research on urban air movement (Oke, 1987; Berkowicz & Hertel, 1994) which suggests that wind flows across street canyons result in a vortex flow bringing 'clean' rooftop air down the windward facing building facade onto monitors on that side, back across the street, carrying vehicular emissions onto monitoring sites on the leeward facing side of the street. CFD modelling of the area confirmed this hypothesis (Ni Riain et al, 1996). This finding has important implications for siting of kerbside monitors in street canyons, suggesting that monitors should be paired on opposite sides of the canyon if representative measures for a street are to be obtained under any given wind conditions (Croxford & Penn, 1997).



Figures 5-6.

The 'splitting' method provides a flexible means of studying the main criteria which construct the pollution fingerprint for a particular location, allowing investigations to be made under congested or free flowing traffic conditions, under windy or calm conditions or before and after some type of traffic management implementation. We believe that by careful investigation it should be possible to 'unpack' the various contributory variables and their effects on the pollution characteristics of a particular site. If any generalisations can be drawn from comparisons between sites then we believe that these could be useful for urban designers and planners.

In order to overcome the vortex differences in concentration due to prevailing wind direction, measures from streetboxes on the opposite sides of each street were averaged. The resulting percentile plots could be held to be characteristic for the given street. Various concentration measures (mean, 50%ile, 75%ile etc.) were then included in a statistical file for each of the monitored streets, together with observed traffic flow figures for each street.

The statistical relationships between observed vehicular flows, configurational variables and pollution concentrations characterised in terms of percentile concentrations at various percentile ranges were investigated using simple and multiple regression. Figure 6 shows the correlation between mean and 50%ile values for CO concentration, and the square root of the hourly vehicular flow rate in the 12 sampled street locations. The correlations at r2=.73 and .75 respectively (p=.0002) suggest that vehicular flow rate alone is a major factor in determining the ambient CO concentration at head height. Figure 7 shows the same correlation but substituting the configurational variable incorporating radius 3 integration and street width which had been shown to best predict vehicular flows in the previous London study areas. The best correlation at r2=.78 (p=.0002) is with total percentiles. These findings are strong and significant, given the relatively small sample size (n=12), and suggest the possibility of the development of a novel modelling method to allow prediction of likely resulting pollution concentrations on the basis of the configuration of the urban space network. If these results are reproduced in larger scale studies, this could provide a cheap and effective modelling method for assessing different urban plans and traffic management implementations with respect to local kerbside pollution impacts.

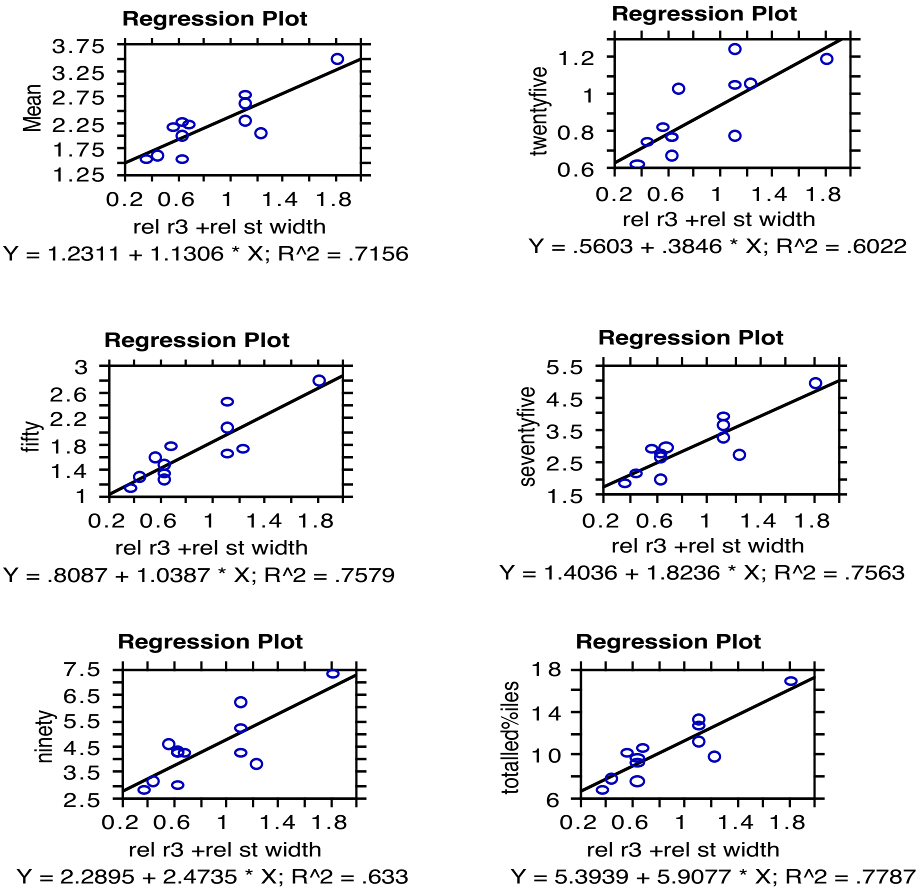


Figure 7

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