University of Nottingham

Transport Research Group
Department of Civil Engineering

MONITORING AND PREDICTION OF AIR POLLUTION FROM TRAFFIC IN THE URBAN ENVIRONMENT

by

Shirley Anne Reynolds BSc MSc

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For Alistair, my husband.

"Whilst these [Chiminies] are belching it forth their sooty jaws, the City of London *resembles the face rather of* Mount Ætna, *the* Court of Vulcan, Stromboli, *or the Suburbs of* Hell, *than an Assembly of Rational Creatures .... For when in all other places the* Aer *is most Serene and Pure, it is here Ecclipsed with such a Cloud of Sulphure, as the Sun itself, which gives day to all the World besides, is hardly able to penetrate and impart it here; and the weary traveller, at many Miles distance, sooner smells, than sees the City to which he repairs."*

John Evelyn - "FUMIFUGUM: Or the Inconvenience of the Aer and Smoake of London Dissipated"

First published in 1661 and reprinted by the National Society for Clean Air, 1961.

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I have also enjoyed the support of friends and family. So thank you very much to Mum, Dad, Chris, Mick, Liz, Fiona, Jason, Janice, John, Helen and Bob.

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Abstract

Traffic-related air pollution is now a major concern. The Rio Earth Summit and the Government's commitment to Agenda 21 has led to Local Authorities taking responsibility to manage the growing number of vehicles and to reduce the impact of traffic on the environment. There is an urgent need to effectively monitor urban air quality at reasonable cost and to develop long and short term air pollution prediction models.

The aim of the research described was to investigate relationships between traffic characteristics and kerbside air pollution concentrations. Initially, the only pollution monitoring equipment available was basic and required constant supervision. The traffic data was made available from the demand-responsive traffic signal control systems in Leicestershire and Nottinghamshire. However, it was found that the surveys were too short to produce statistically significant results, and no useful conclusions could be drawn.

Subsequently, an automatic, remote kerbside monitoring system was developed specifically for this research. The data collected was analysed using multiple regression techniques in an attempt to obtain an empirical relationship which could be used to predict roadside pollution concentrations from traffic and meteorological data. However, the residual series were found to be autocorrelated, which meant that the statistical tests were invalid. It was then found to be possible to fit an accurate model to the data using time series analysis, but that it could not predict levels even in the short-term.

Finally, a semi-empirical model was developed by estimating the proportion of vehicles passing a point in each operating mode (cruising, accelerating, decelerating and idling) and using real data to derive the coefficients. Unfortunately, it was again not possible to define a reliable predictive relationship. However, suggestions have been made about how this research could be progressed to achieve its aim.

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1. Introduction

1.1 History

Air pollution is a problem that has existed in cities for several centuries, mainly due to the use of fossil fuels for heating and cooking. The problem worsened with the industrial revolution as communities developed which centred around factories that used coal powered steam engines to drive machinery. At that time, the main pollutants were sulphur dioxide and black smoke. In the early nineteenth century complaints about the smell of the smoke, the reduction in visibility and the blackening of buildings, motivated the local and national authorities to introduce abatement measures. Different ways of reducing smoke from steam engines were sought, and the use of anthracitic coals as a domestic smokeless fuel was encouraged. The first legislative curbs on smoke emissions occurred in the mid nineteenth century. However, by the end of the century there had been no real decrease in smoke emission and, in many peoples' view, the problem had worsened. Brimblecombe (1987) suggested that, in London, this was mainly due to a climate change - fogs had become more frequent and thicker. He also described how, in 1905, Des Voeux proposed the word "smog" to describe the mixture of smoke and fog which was common in London. Then, during the first half of the twentieth century the substantial increase in the number of motor cars meant that exhaust emissions contributed significantly to the already polluted atmosphere.

The "Great Smog" in London happened during the first week of December, 1952. On Thursday, 4th December a slow-moving anticyclone came to a stop over London and the city became very foggy. The next day the fog was very thick and by the afternoon people were noticing a choking smell in the air, with skin and clothing becoming quite dirty. Hospitals and doctors reported twice the usual number of patients with respiratory problems (Brimblecombe, 1987). Visibility decreased to nearly zero during Saturday, 6th December, people continued to suffer and the number of deaths was above average. Transport systems ground to a halt and the emergency services could not respond to calls. By Tuesday, 9th December, the episode was over. Figure 1.1 shows a photograph taken during the smog, and Figure 1.2 shows the number of deaths which correlate strongly with the pollutant concentrations recorded at the time (Brimblecombe, 1987).

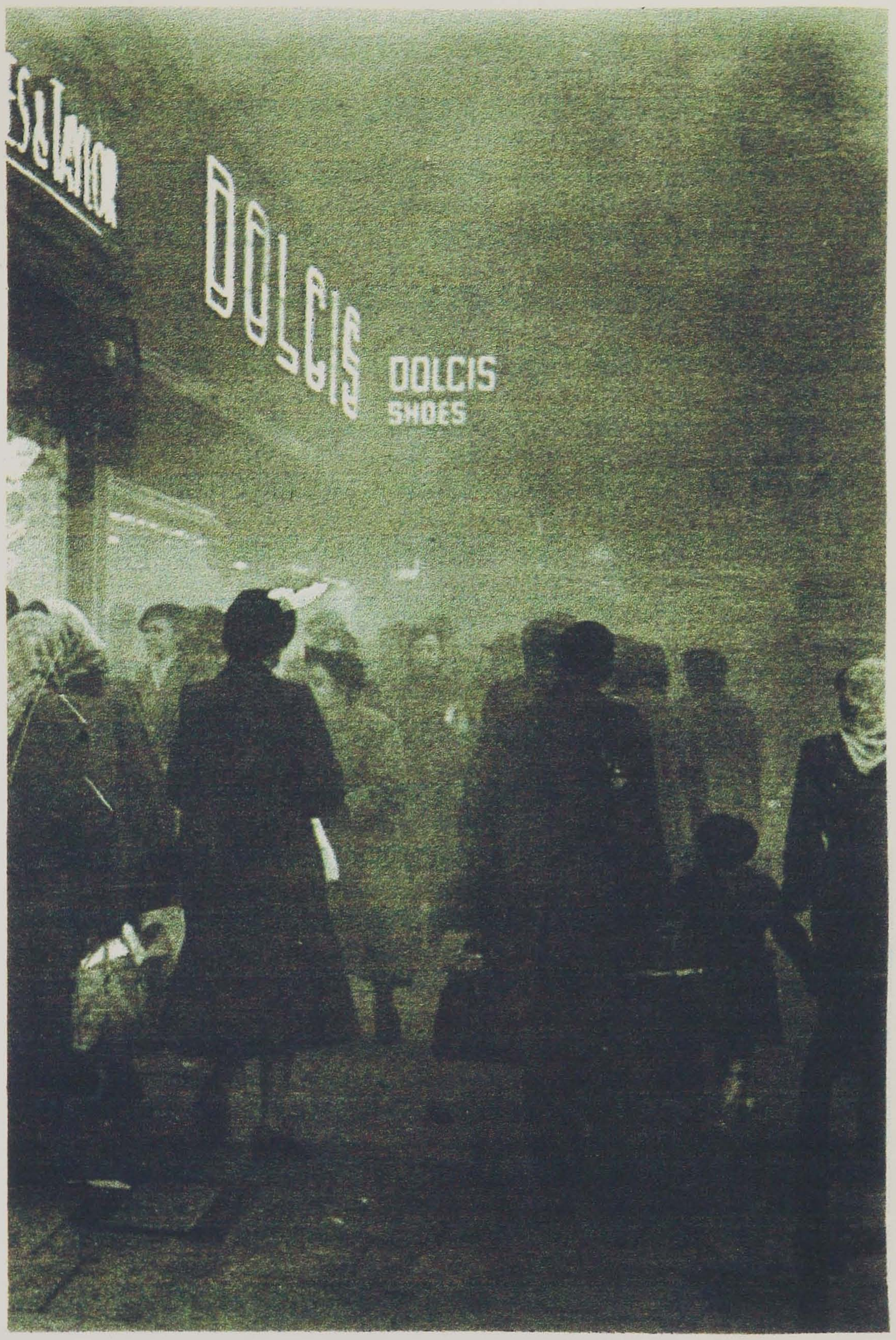

Figure 1.1: Photograph taken during the "Great Smog" of December 1952
(Brimblecombe, 1987)

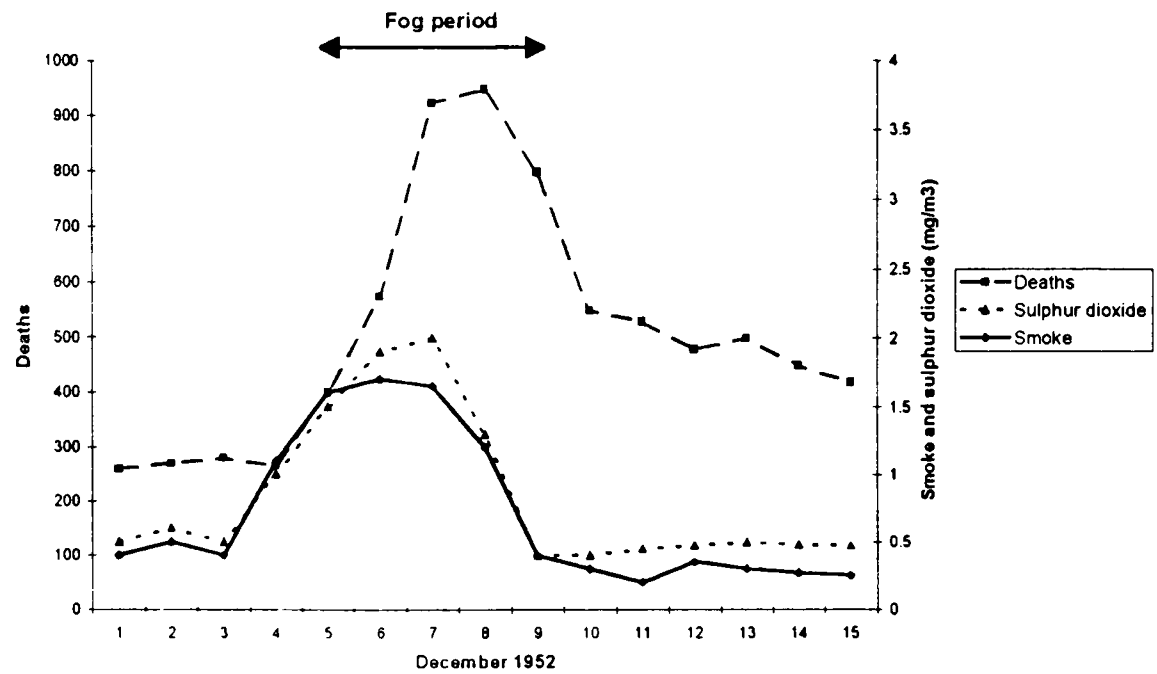

Figure 1.2: Number of deaths and pollution concentration (after Brimblecombe, 1987)

The grave public concern about the death toll during the "Great Smog" motivated the government to enact the Clean Air Act (1956), whereby both domestic and industrial sources of pollution were to be more stringently controlled. This Act led to the creation of smokeless zones (smoke control areas), where the domestic user must use a smokeless fuel or electricity and new industrial furnaces were to be smokeless "so far as practicable".

1.2 Early research

During the 1960s and 1970s researchers at the Road Research Laboratory realised that road traffic was a major source of pollution and began to investigate ways of predicting emissions. This led to the development of the computer model PREDCO (Hickman and Colwill, 1982), which predicted carbon monoxide emissions from free-flowing traffic at the street level. This program is still used today by the Department of Transport and others, to assess, at the design stage, the impact on the environment of, mainly, new road schemes.

During the late 1980s a study by Bell (1990a) used the TRANSYT (TRAffic Network StudY Tool) (Robertson, 1969) program to investigate how traffic signal control policy could be used to reduce air pollution. TRANSYT was used to establish the cruise speeds for vehicles travelling in an urban area for both a radial network and a grid network. Vehicle emissions data from a German study of exhaust emissions from vehicles at seven different engine running speeds (RILSA, 1980) were used to predict the levels of emission of nitrogen dioxide, sulphur dioxide, hydrocarbons, carbon monoxide and lead. Bell developed an objective function for TRANSYT which minimised total emissions, but acknowledged that the assumption that x units of one pollutant can be balanced by $-x$ units of another was not necessarily correct. Medical research was needed to inform traffic engineers which pollutant was more harmful to health. The conclusion of this study was that if air pollution in a network were to be reduced, overall flow levels must be decreased and congestion avoided. Subsequently traffic assignment was employed by Bell (1990a) to reduce the levels of traffic flow on specific links to remove congestion and to redistribute the traffic around the network. Lear and Bell (1988) showed that total link emissions could be reduced by around 3% in an under-saturated network by co-ordinating the timings of signals. Bell and Lear (1990) later found that if critical junctions were oversaturated then air emissions could increase by as much as 40% in some networks studied. However, Bell acknowledged the limitation of this work in the absence of "on-street" data with which to calibrate the model and validate the predictions, so only relative changes in emission levels could be stated. In 1988 attempts were made to persuade various companies to develop a kerbside pollution monitoring system integrated with the SCOOT (Split, Cycle and Offset Optimisation Technique) demand-responsive traffic signal control system (Hunt *et al*, 1981), but at that time there was no perceived market for kerbside monitoring systems.

1.3 Public awareness and Government response

However, over the last few years public awareness of the detrimental effects of atmospheric pollution has increased through media campaigns by environmental pressure groups such as the Friends of the Earth, the World Wide Fund for Nature, the National Asthma Campaign and Greenpeace. This led to growing pressure on the government and the research community to find ways of reducing or eliminating emissions from vehicles. In 1990 the government produced a White Paper on Britain's environmental strategy called "This Common Inheritance" (HMSO, 1990). This covered a whole range of topics which included air pollution. The White Paper recommended that air pollution monitoring should be extended and improved and that an expert panel should be set up to advise the government on air quality standards.

In fact, several expert panels were set up. The three most relevant are (i) QUARG - the Quality of Urban Air Review Group; (ii) EPAQS - the Expert Panel on Air Quality Standards; and (iii) AGMAAPE - the Advisory Group on the Medical Aspects of Air Pollution Episodes. The Quality of Urban Air Review Group has, to date, published two reports - firstly "Urban Air Quality in the United Kingdom" (QUARG, 1993a), and secondly "Diesel Vehicle Emissions and Urban Air Quality" (QUARG, 1993b). The Advisory Group on the Medical Aspects of Air Pollution Episodes has published reports on the health effects of ozone, sulphur dioxide, particulates, acid aerosols and oxides of nitrogen (HMSO, 1992, 1995).

1.4 Department of the Environment Monitoring Network

As a direct result of the White Paper, the Department of the Environment set up the Enhanced Urban Network (EUN) (now known as the Automatic Urban Monitoring Network, AUN). Initially, air pollution monitoring stations were commissioned in twelve cities across the United Kingdom - Belfast, Birmingham, Cardiff, Edinburgh, London (Bloomsbury), Newcastle, Bristol, Leeds, Liverpool, Leicester, Kingston-upon-Hull and Southampton. These are due to be extended by a further thirteen by the end of 1996, including one in Nottingham. The stations are located in sites which give "urban background" levels for the following pollutants - nitrogen dioxide, sulphur dioxide, carbon monoxide, ozone and particulate matter (QUARG, 1993a). The aim of these stations is to represent the "conditions that significant numbers of people will be exposed to for significant periods of time" (QUARG, 1993a).

1.5 Kerbside Pollution Monitoring

In 1991 the Science and Engineering Research Council (SERC) funded a study of kerbside levels of carbon monoxide, to develop an understanding of how the levels vary over time. Siemens Plessey Controls Ltd supported this work by making available, free of charge, a portable carbon monoxide monitoring system. This marked the beginning of the research described in this thesis. Relationships with traffic characteristics (flow, delay, stops and congestion) and climatic conditions were investigated. The traffic characteristics data was obtained from the SCOOT demand-responsive traffic signal control system installed in Leicester. It was anticipated that the data could be used to calibrate and validate pollution models similar to Bell's earlier predictive model (Bell, 1990a). Over the period October 1991 to September 1992, on-street surveys were carried out with portable carbon monoxide monitoring systems which needed constant supervision. The method and results are described in this thesis. During these surveys it was realised that not enough data was being generated to derive statistically sound relationships (Bell and Reynolds, 1992). However, there was no commercially available equipment for continuous roadside pollution monitoring which was vandal-proof and weather-proof. Efforts were then devoted to securing research funds to develop such a continuous remote monitoring capability.

Several air pollution monitoring equipment manufacturers were approached to develop such equipment. Initially there was no interest in pursuing the development of this kind of equipment. However, during late 1992, Siemens Plessey Controls Ltd[1] began to have enquiries from local authorities who were interested in monitoring kerbside air pollution concentrations and traffic flow simultaneously, due to the increased Government and public awareness of the health effects of traffic-related air pollution.

1.6 ITEMMS - Integration of Traffic and Environmental Monitoring and Management Systems

Shortly afterwards, a collaborative research project was funded by the SERC-LINK programme. The project was titled "Integration of Traffic and Environmental Monitoring and Management Systems (ITEMMS)" and the partners were the University of Nottingham Transport Research Group (UNTRG), Siemens Environmental Systems Ltd, Siemens Traffic Controls Ltd, Leicestershire County Council, Nottinghamshire County Council, the Department of Transport and the County Surveyors' Society. The project aimed to develop a low-cost kerbside pollution monitoring system which could be used as a "stand-alone" unit, or fully integrated with an existing traffic signal control infrastructure. The research which supported the development of the monitoring units, the data collection methodology, the statistical analysis procedures and the results are described in this thesis.

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[1]Siemens Plessey Controls Ltd subsequently split into two separate companies - Siemens Environmental Systems Ltd (SESL) and Siemens Traffic Controls Ltd (STCL).

The development of these kerbside air pollution monitoring systems has been fundamental to the research reported in this thesis. The ITEMMS units have provided the raw air pollution data to investigate the suitability of two statistical techniques to predict pollutant concentrations from traffic characteristics data, namely multiple regression and time series analysis. Multiple regression techniques have also been used in the formulation of a semi-empirical model.

1.7 Structure of thesis

Chapters 2 and 3 provide a review of literature in those fields relevant to this research. Chapter 2 considers the three main pollutants considered in this research, *ie* carbon monoxide, sulphur dioxide and oxides of nitrogen. The effects on health of the three pollutants are described and the national and international standards and legislation are reviewed. The literature review in Chapter 3 covers techniques for measuring and predicting the pollutant concentrations, pollutant dispersal and the use of traffic signal control systems to reduce emissions.

Chapter 4 contains background information relevant to the research and the detailed objectives of the research are defined. The study areas in Leicester and Nottingham are described. The mechanism for collecting the traffic characteristics data from the SCOOT system is also presented. In Chapter 4, the details of the surveys carried out to develop the research methodology for the collection of the air pollution concentration data are outlined. This work was carried out in two phases. Firstly, a preliminary survey was performed in Nottingham to establish the basic methodology. Secondly, surveys were carried out in Leicester using the portable equipment and the traffic characteristics data was collected simultaneously. Statistical analysis methods to correlate pollutant concentrations and traffic characteristics were then explored.

In Chapter 5 the equipment developed through the ITEMMS project and the surveys carried out are described. The data from this set of surveys in Leicester used the prototype transportable equipment. This provided large volumes of data over longer periods of time, which allowed the development of the automatic statistical analysis methods. Finally, the surveys in Leicester and Nottingham using the remote permanent monitoring equipment are described.

Chapter 6 details the statistical techniques used to analyse the data collected from the prototype transportable and permanent equipment, and the applicability of the various methods are discussed. Chapter 7 describes the formulation of a semi-empirical model to predict air pollution from the traffic characteristics data. Finally, Chapter 8 contains a summary and discussion of the research carried out, and suggestions are made for future work.

2. Air Pollution From Traffic

2.1 Introduction

This chapter contains a state of art review of papers and reports concerning traffic-related air pollutants. In the first section an overview is presented of the pollutants emitted by vehicles. The characteristics and the health effects of the three pollutants monitored in this research, *ie* carbon monoxide, sulphur dioxide and nitrogen dioxide, are then described.

In response to the 1992 Rio Earth Summit, the British Government has become particularly concerned about traffic-related air pollution and its possible health effects. There have been several national and international reports which have influenced the Government to introduce specific policies and standards. These are reviewed in Section 2.4 and Section 2.5.

2.2 Background

There are many pollutants emitted by vehicles. Figure 2.1 indicates the origin of these pollutants (represented by the black arrows). The five main pollutants are (HMSO, 1994c):-

- Carbon monoxide (CO)
- Nitrogen oxides (NO_x)
- Volatile organic compounds (VOCs)
- Particulate matter (PM)
- Sulphur dioxide (SO_2).

Table 2.1 (HMSO, 1994c) demonstrates that, in 1994, transport-related emissions totalled 8967 kilotonnes and that over 96% of this was due to road transport.

Table 2.1: United Kingdom emissions by mode (kilotonnes) (HMSO, 1994c)

	Road	Rail	Air	Shipping
Carbon monoxide	6029	12	11	19
Nitrogen dioxide	1398	32	14	130
Volatile Organic Compounds	949	8	4	14
Sulphur dioxide	62	3	3	60

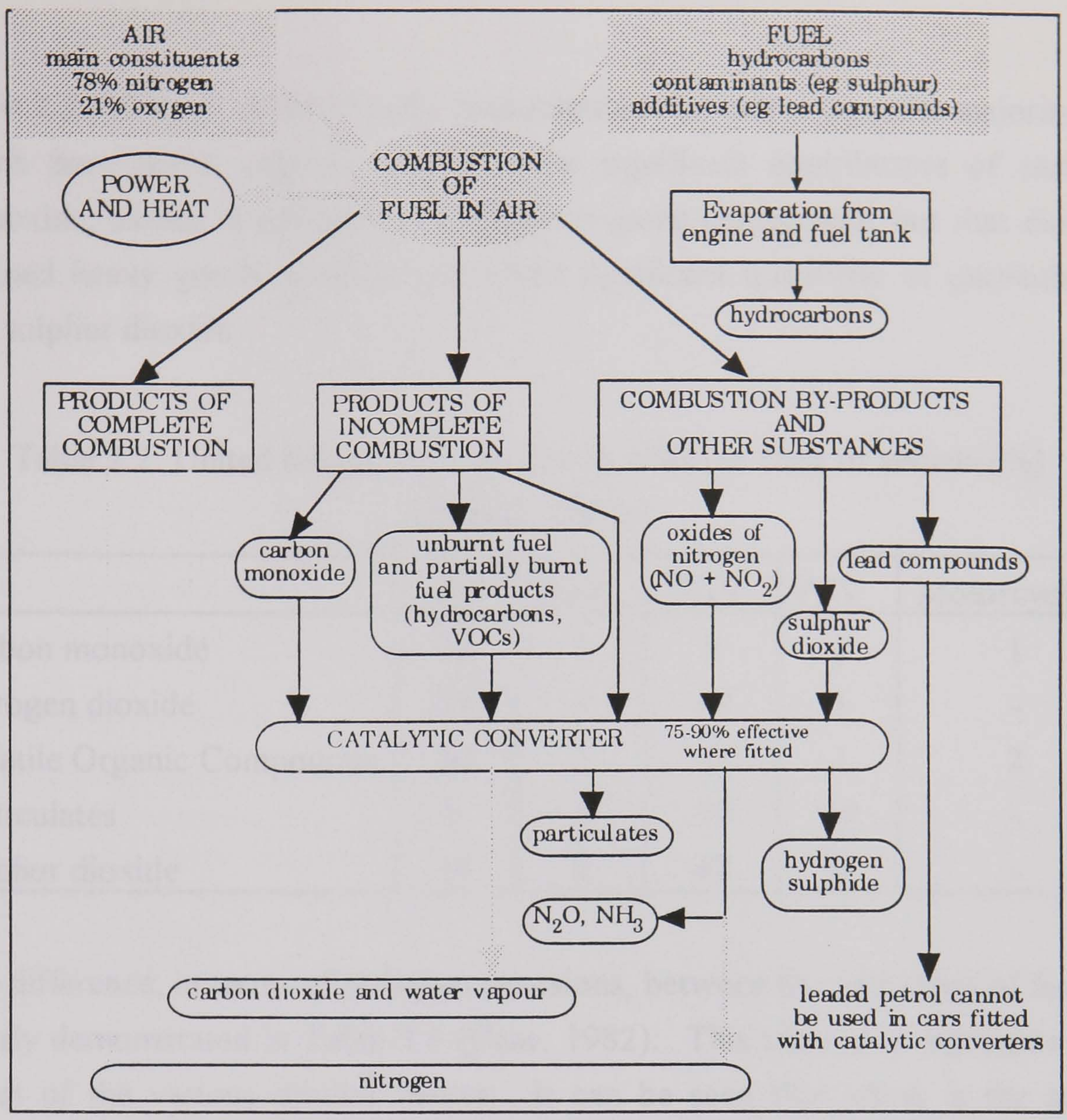

Figure 2.1: Pollutants emitted by petroleum-powered vehicles (HMSO, 1994c)

Figure 2.2 (HMSO, 1994c) shows that, of the road transport-related emissions, 68% was carbon monoxide, 17% was oxides of nitrogen and only 1% was sulphur dioxide.

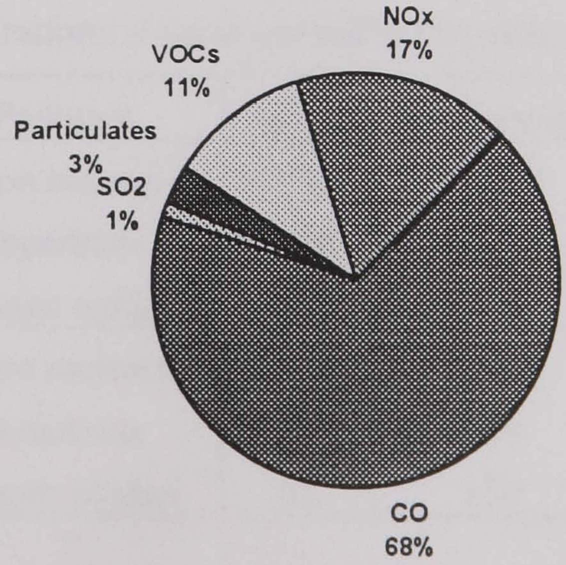

Figure 2.2: Percentage total emissions from transport in the UK in 1992 (HMSO, 1994c)

Table 2.2 (HMSO, 1994c) clearly demonstrates that motor cars, the majority of which have petrol engines, are the most significant contributors of carbon monoxide, oxides of nitrogen and volatile organic compounds, but that diesel-engined heavy goods vehicles contribute significant quantities of particulates and sulphur dioxide.

Table 2.2: United Kingdom emissions by different class of vehicle (%) (HMSO, 1994c)

	Cars	LGV	HGV	PSV	Motorcycles
Carbon monoxide	88	7	3	1	1
Nitrogen dioxide	72	7	19	3	-
Volatile Organic Compounds	84	7	6	1	2
Particulates	6	7	77	10	-
Sulphur dioxide	37	9	47	6	-

The difference, in terms of pollutant emissions, between the two types of fuel is clearly demonstrated in Table 2.3 (Case, 1982). This table also highlights the effect of the various driving modes. It can be seen that idling is the most polluting mode for emissions of carbon monoxide and hydrocarbons, but that idling is one of the least polluting modes for emissions of nitrogen oxides. It is clear from this table that it will not be possible to minimise levels of all air pollutants just by keeping traffic flowing smoothly (Bell *et al*, 1996a).

Table 2.3: Composition of exhaust gases for petrol and diesel engines (concentrations in parts per million by volume) (Case, 1982)

	Pollutant	Idling	Accelerating	Cruising	Deceleration
Petrol Engines	Carbon monoxide	69 000	29 000	27 000	39 000
	Hydrocarbons	5 300	1 600	1 000	10 000
	Nitrogen oxides	30	1 020	650	20
Diesel Engines	Carbon monoxide	Trace	1 000	Trace	Trace
	Hydrocarbons	400	200	100	300
	Nitrogen oxides	60	350	240	30

In 1993 it was estimated that only six percent of cars in the UK had diesel engines (QUARG, 1993b). However, it was forecast that if trends continued then this proportion could increase to around twenty per cent by 2003. When compared with standard petrol-engined cars, diesel cars have lower emissions of all pollutants, except particulates and oxides of nitrogen. However, fitting a three-way catalytic converter (TWC) improves emissions to a level comparable with diesel engines, as demonstrated in Table 2.4.

Table 2.4: Urban emissions of regulated pollutants from current technology cars (QUARG, 1993b)

Vehicle type	Average on-road emissions (g/km)			
	CO	Total HC	NO_x	PM
Standard (petrol without catalyst)	27.0	2.8	1.7	-
Petrol with catalyst	2.0	0.2	0.4	-
Diesel	0.9	0.3	0.8	0.4

Notes:

- Based on the results of on-road tests conducted with 'as received' cars with hot engines.
- The diesel car sample consisted of two with indirect injection diesel (IDI) engines and one with a direct injection (DI) engine. Emissions from the IDI engines were significantly lower than from the DI engine, with average on-road emissions of 0.6 g/km nitrogen oxides and 0.2 g/km particulate matter. Most diesel cars have IDI engines.
- Of the TWC cars, two had an engine capacity of 2.0 litres and one a capacity of 1.4 litres. The two indirect diesel engines had a capacity of 1.8 and 1.7 litres, and the direct injection diesel had a capacity of 2.0 litres.
- '-' means that the particulate matter was not measured.

2.3 Characteristics of the three main pollutants

The research described in this thesis concentrates three of the primary traffic-related pollutants - carbon monoxide, sulphur dioxide and nitrogen dioxide. In this section the characteristics of each pollutant and their effects on human health are described. It is primarily the health effects which has led to the public's increased awareness of traffic-related pollutants and the Government's response to these concerns. The acknowledgement of the problem has meant that the need for research into the links between pollution and traffic, and methods of reducing it, has become even more pressing.

2.3.1 Carbon monoxide

Carbon monoxide (CO) is a colourless, odourless gas. Its main source is the incomplete combustion of carbon-based fuels. It contributes to global warming as it is a constituent of photochemical smog. Carbon monoxide is oxidised to carbon dioxide over a relatively short period (Howard, 1990). The natural background level of carbon monoxide is between 0.01 and 0.23 micrograms per cubic metre ($\mu g/m^3$) (approximately 0.009 to 0.20 parts per million (ppm)). Table 2.5 shows that transport is the only sector in the United Kingdom to have increased its emissions of carbon monoxide between 1978 and 1988 (Howard, 1990).

Table 2.5: Sources of carbon monoxide in the UK 1978-1988 (thousand tonnes) (Howard, 1990)

Source	1978	1983	1988	Change 1978-1988 (%)
Domestic	600	464	388	-35.3
Power Stations	55	46	47	-14.6
Refineries	2	2	2	0.0
Other Industry	370	329	338	-8.7
Transport	3919	3895	4689	19.7
Other	45	43	44	-2.2
Total	4991	4779	5508	10.4

Howard (1990) stated that carbon monoxide interferes with the absorption of oxygen by the red blood cells. Oxygen enters the blood stream by reacting with haemoglobin to form oxyhaemoglobin. Carbon monoxide is absorbed 200 times more readily than the oxygen to form carboxyhaemoglobin. In confined areas only 0.3% by volume of carbon monoxide is necessary to cause death within 30 minutes. Howard also presented evidence which demonstrated that loss of worker productivity and general discomfort can be attributed to carbon monoxide emissions by traffic in the urban environment.

Watkins (1991) demonstrated the effect of carbon monoxide on health. Table 2.6 and Table 2.7 relate carbon monoxide concentrations, levels of carboxyhaemoglobin, and the effects on humans. For those people who are exposed to vehicle exhaust fumes all day, carboxyhaemoglobin levels have been found of up to 8% for smokers, and 4% for non-smokers. Both these levels are sufficiently small to fall within the "no signs or symptoms" category in Table 2.7.

Table 2.6: Carboxyhaemoglobin (COHb) content of blood (percentage of full absorption) for different concentrations of carbon monoxide in the atmosphere (Watkins, 1991)

Concentration of CO in the atmosphere (ppm)	Equilibrium of COHb in the blood (%)	COHb in the blood after 30 min exposure (%)		COHb in blood after 60 min exposure (%)	
		Rest	Heavy work	Rest	Heavy work
30	4.8	0.27	0.99	0.54	1.98
50	8.0	0.45	1.65	0.90	3.30
125	20	1.12	4.12	2.24	8.24
250	40	2.25	8.24	4.50	16.48

Table 2.7: Signs and symptoms at various concentrations of carboxyhaemoglobin for the average man (Watkins, 1991)

% COHb	Signs and symptoms
0-10	No signs or symptoms
10-20	Tightness across the forehead, possible slight headache, dilation of the cutaneous blood vessel
20-30	Headache and throbbing in the temples
30-40	Severe headache, weakness, dizziness, dimness of vision, nausea, vomiting and collapse
40-50	Same as above, greater possibility of collapse, syncope and increased pulse and respiratory rates
50-60	Syncope, increased pulse rate, coma, intermittent convulsions, and Cheyne-Stokes respiration
60-70	Coma, intermittent convulsions, depressed heart action and respiratory rate, and possible death
70-80	Weak pulse, slow respiration, respiratory failure and death within a few hours
80-90	Death in less than an hour
90+	Death within a few minutes

2.3.2 Sulphur dioxide

Sulphur dioxide (SO_2) is also a colourless gas. It is readily soluble in water, including airborne water droplets, forming sulphuric acid and hence acid rain. The natural background level is around 5 $\mu g/m^3$ (CEC, 1991). Sulphur dioxide is mainly produced by burning fossil fuels, especially coal (which contributes approximately 50% of annual global emissions). Table 2.8 shows the sources of sulphur dioxide in the United Kingdom in 1989 from the review commissioned by the Department of Health in 1992 and carried out by the Advisory Group on the Medical Aspects of Air Pollution Episodes (HMSO, 1992).

Table 2.8: Emissions of sulphur dioxide (kilotonnes) in the United Kingdom in 1989 (HMSO, 1992)

User	SO_2		***Fuel***	SO_2	
	kt	*%*		*kt*	*%*
Power stations	2644	71	Coal	2832	77
Other industry	595	16	Smokeless fuel	42	1
Domestic	135	4	Fuel oil	660	18
Commercial	88	2	Gas oil	58	1.5
Road transport	60	2	Petrol	22	0.5
Other	177	5	DERV	38	1
			Other	47	1
Total	3699	100	**Total**	3699	100

The health effects of sulphur dioxide were highlighted during the London smogs of the 1950's. Fog and sulphur dioxide from coal fires and vehicles combined in adverse weather conditions to cause an atmosphere which lead to the deaths of many people from respiratory disorders (Brimblecombe, 1987). Since then there have been a number of studies of the relationships between air pollution and respiratory diseases.

A study was carried out in Barcelona, Spain between 1985 and 1986 by Sunyer *et al* (1991) to assess the relationship between daily hospital emergency admissions for chronic obstructive pulmonary disease and sulphur dioxide, black smoke, carbon monoxide, nitrogen dioxide and ozone. Data was collected from four major hospitals covering 90% of emergencies in the city. Air pollution data were collected from a network of 17 manual samplers and two automatic stations. Daily meteorological information was also collected. They found a weak, but statistically significant, association between emergency room admissions and levels of sulphur dioxide, black smoke and carbon monoxide.

The Department of Health's Advisory Group on the Medical Aspects of Air Pollution Episodes (HMSO, 1992) conducted a review of literature concerning the health effects of exposure to sulphur dioxide. They concluded that, during episodes of high concentrations of sulphur dioxide in the UK, those with no respiratory disease will not be affected, but asthmatic patients who are more sensitive will be affected. These patients may suffer from tightness of the chest, coughing and wheezing. They recommended that when hourly average concentrations of sulphur dioxide are in the range 125 parts per billion (ppb) to 400 ppb advice should be given to asthmatics to spend less time outdoors and to consult their doctors if they suffer problems with their breathing. If hourly averages exceed, or are expected to exceed, 400 ppb, then a warning should be issued to asthmatics. People who do not suffer from any respiratory diseases may find conditions unpleasant, but will not suffer any health effects.

The Advisory Group have categorised the likely effects on asthmatics with the different Department of the Environment air quality bands. They are as follows:-

i. Very good air quality (< 60 ppb sulphur dioxide)

Experiments have shown no effects in asthmatics of sulphur dioxide levels of this order. No detrimental effect on health would be expected.

ii. Good air quality (60 - 125 ppb sulphur dioxide)

The Advisory Group reported only one study which has shown effects of sulphur dioxide at 100 ppb concentration, on exercising asthmatics[1]. However, it was felt that generally concentrations of less than 125 ppb are not likely to be detrimental to health.

iii. Poor air quality (125 - 400 ppb sulphur dioxide)

Many studies have shown changes in indices of lung function in asthmatics taking exercise exposed to concentrations of sulphur dioxide at this level. Non-asthmatics are not affected. In the asthmatics, the symptoms include tightness of the chest and coughing. These symptoms will respond well to treatment with a β_2-agonist inhaler. The presence of other allergens may increase the severity of the effects of the sulphur dioxide.

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[1] Sheppard, D., Saisho, A., Nadel, J.A., Boushey, H.A. (1981); Exercise increased sulfur dioxide-induced bronchoconstriction in asthmatic subjects; Am Rev Respir Dis, 123, 486-491

iv. Very poor air quality (> 400 ppb sulphur dioxide)

At concentrations above 400 ppb many asthmatics will have symptoms such as tightness of the chest, coughing and some breathlessness, and clinically significant changes in indices of lung function. The asthmatics may need to limit exposure and consult their doctors.

2.3.3 Nitrogen oxides

The term nitrogen oxides (NO_x) is used to describe the two gases nitrogen dioxide (NO_2) and nitric oxide (NO). These two are considered together because nitric oxide oxidises rapidly to form nitrogen dioxide. Nitrogen dioxide is therefore referred to as a "secondary pollutant". The nitric oxide is oxidised by ozone or the hydroperoxy radical (HO_2) according to these reactions (HMSO, 1994c):

$$NO + O_3 \rightarrow NO_2 + O_2$$

$$NO + HO_2 \rightarrow NO_2 + OH$$

Globally, natural emissions of nitrogen oxide by bacterial and volcanic action, and by lightning, are far larger than man-made emissions from power stations and transport (CEC, 1991). Nitrogen dioxide, which is a reddish-brown gas, is also produced inside buildings. The major sources are tobacco smoke and the use of gas fired appliances and oil stoves. These sources are major confounding factors when investigating the relationship between transport-related nitrogen dioxide levels and the effects on health. Figure 2.3 shows the main sources of nitrogen dioxide in the United Kingdom (based on QUARG, 1993a). According to Eggleston *et al* (1992), transport contributes approximately 80% of nitrogen oxides emissions in the Greater London area.

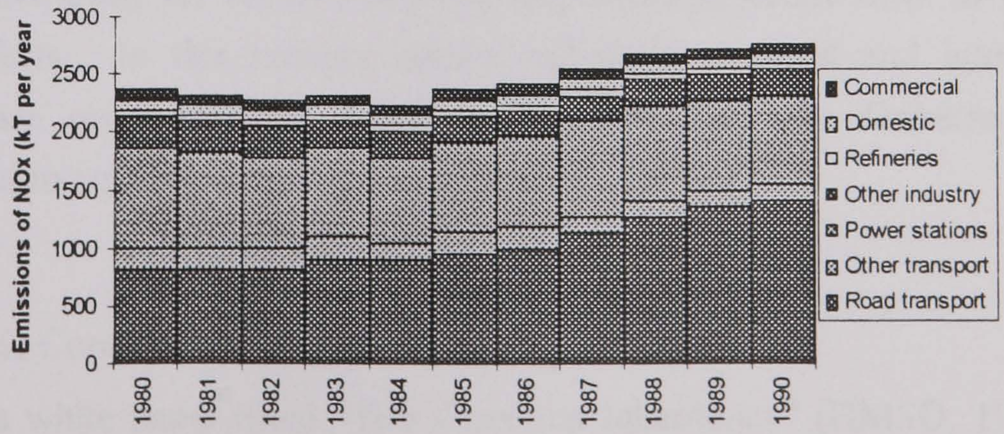

Figure 2.3: Sources of nitrogen dioxide in the United Kingdom (QUARG, 1993a)

Nitrogen dioxide is also associated with another secondary pollutant - ozone (O_3). Ozone is produced by the following reactions:-

$$NO_2 + h\nu \rightarrow NO + O$$

$$O + O_2 (+ M) \rightarrow O_3 (+M)$$

where $h\nu$ is energy from sunlight and M is a molecule of oxygen, nitrogen or some other naturally occurring gas. The equations given above for the formation of nitrogen dioxide show that, when ozone is present, nitric oxide will react with it to form nitrogen dioxide. Hence levels of nitrogen dioxide and ozone will tend to be inversely related (QUARG, 1993a).

When nitrogen dioxide is inspired it passes through the trachea and bronchi into the moist alveoli of the lungs where it forms nitrous acid (HNO_2) and nitric acid (HNO_3). These are irritants to the lungs and corrosive to the mucous lining (Waldbott, 1973). Studies have shown that the odour of nitrogen dioxide can be detected by humans at 1 to 3 ppm. A ten minute exposure to 5 ppm produces a temporary increase in airway resistance. The respiratory mucous membranes are irritated by levels of 13 ppm or more, and exposure for 30 to 60 minutes of levels between 100 to 150 ppm can be fatal. Recently, there has been much concern about links with nitrogen dioxide levels and the increasing prevalence of asthma in the population, especially in children. However, no causal link has been proved, although it is acknowledged that exposure to nitrogen dioxide will exacerbate the symptoms (HMSO, 1994c).

2.4 Government's actions

The last six years have seen a marked increase in the Government's interest about the effects of air pollution on our environment and human health. Many panels have been set up to make recommendations about how to minimise these effects. In this section, several influential national and international reports are reviewed, and clearly demonstrate how the Government has responded to concerns about the environment.

2.4.1 This Common Inheritance

In 1990 a white paper titled "This Common Inheritance" (HMSO, 1990) was published by the government discussing the state of Britain's environment. Air pollution was just one aspect discussed along with subjects such as the greenhouse effect, water pollution, nuclear power, genetically modified organisms and the heritage of our towns. The Government outlined various undertakings to improve controls over outdoor air emissions. Their first plan was to establish an expert advisory panel to develop air quality standards on which to base actions. Secondly, to develop the concept of 'critical loads' for various pollutants so that effective action can be targeted to the areas of greatest need, *ie* find the levels of pollutants that an area can tolerate. Thirdly, to extend and improve the nation-wide air pollution monitoring network and to make information as widely available as possible. Fourthly, to ensure that industry adopts whatever cleaner, cost-effective technologies become available in the future. Furthermore, they proposed to press the European Commission for tighter standards for emissions from vehicles.

The Government also undertook to make people more aware of the environmental consequences of their use of transport. They hoped to achieve this through a public information campaign about fuel economy and efficient driving, and through taxation.

By 1996 considerable progress had been made in all these areas. Firstly, the Expert Panel on Air Quality Standards (EPAQS) was set up and has published reports on six different pollutants (see Section 2.4.4). Secondly, local authorities are now required by law to assess sources of pollutants in their areas (especially industrial) and ensure that standards are met. Thirdly, a national network of air pollution monitoring stations known as the Automatic Urban Network (AUN) has been set up by the Department of the Environment in, currently, 20 cities across the United Kingdom and data is available on CEEFAX, Teletext, a telephone information line and the World Wide Web[1]. Air quality predictions are now routinely presented along with the weather forecast. Finally, standards for emissions have become tighter and the MOT test for vehicles now includes exhaust emission testing.

2.4.2 The Rio Earth Summit and Agenda 21

At the UN Conference on Environment and Development (The Earth Summit) held in Rio de Janeiro in 1992, the 150 nations represented produced four main agreements (HMSO, 1994a).

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[1]The URL for this WWW page is
http://www.aeat.co.uk/products/centres/netcen/airqual/bulletins/welcome.html

i. Agenda 21 - a comprehensive programme of action needed throughout the world to achieve a more sustainable pattern of development for the next century. The principles of Agenda 21 have been adopted by the United Kingdom government and local authorities have been required to draft their own "Local Agenda 21".

ii. The Climate Change Convention - an agreement establishing a framework for action to reduce the risks of global warming by limiting the emission of so-called "greenhouse gases."

iii. The Biodiversity Convention - for the protection of species and habitats.

iv. The Statement of Principles for forests.

2.4.3 Quality of Urban Air Review Group (QUARG)

During 1993 the Quality of Urban Air Review Group published two reports at the request of the Department of the Environment. The first, published in January, was titled "Urban Air Quality in the United Kingdom" (QUARG, 1993a). The second, published in December, was called "Diesel Vehicle Emissions and Urban Air Quality" (QUARG, 1993b). The brief given to the Group was to prepare a state of art review of the urban air quality in the United Kingdom and give recommendations about the impact of measures such as the increased use of catalytic converters.

The first report reviewed the current knowledge about various pollutants, including their monitoring. These were nitrogen compounds, sulphur compounds, carbon monoxide, particulate matter, oxidants, metals and organic compounds. The Group recognised the importance of the Automatic Urban Network of monitoring stations, but encouraged the Government to extend this to at least 24 cities across the United Kingdom. They also recommended that there be central co-ordination of the monitoring being carried out by different local authorities and other organisations. The Group realised that the Automatic Urban Network serves a purpose for assessing the general exposure of the public to air pollution, but that substantially more monitoring should be carried out at other locations especially at the kerbside and inside vehicles.

Finally, they highlighted several areas of research to give a better understanding of the nature of urban air emissions and potential ways of reducing levels. These were:

- atmospheric chemistry and dispersion modelling;
- emission inventories;
- vehicle emissions and alternative fuels;
- influence of the weather;
- airborne fine dust;
- traffic management; and
- public information and perception.

The second report (QUARG, 1993b) reviewed specifically the issues related to diesel vehicle emissions. They were especially concerned about larger emissions of nitrogen oxides, particulate matter and black smoke, compared with the emissions from petrol engined vehicles. The group warned that if the market penetration of diesels continues to increase, then the potential improvements in levels of nitrogen oxides and particulate matter from improvements to petrol and petrol engines, could be eliminated.

2.4.4 Transport Select Committee

During 1994 the Transport Select Committee of the House of Commons produced a report on "Transport-Related Air Pollution in London" (HMSO, 1994a,b). Dr Margaret Bell of UNTRG and Ian Bywaters of Siemens Environmental Systems Ltd were invited to inform the committee about the roadside pollution monitors developed for the research described in this thesis (Bell, 1994). Other representatives from various government agencies, doctors, pressure groups, the petroleum and vehicle manufacturing industries and motoring organisations also gave evidence. Their report considered several aspects:

- the nature of traffic in London;
- principal sources of atmospheric pollution;
- alternative fuel technologies and vehicle technology to reduce pollution;
- the specification and monitoring of air quality standards;
- the relationship between pollution and health (asthma and cancer); and
- government policy initiatives.

They concluded that although much had been achieved recently in the field of vehicle and alternative fuel technologies more needs to be done to reduce the levels of emissions. Legislation is required to set realistic targets for improvements in air quality, leaving industry to determine the best ways to achieve these, although some public money will need to be made available where there is no commercial incentive. They realised that the problem of traffic-related air pollution is not confined within geographical boundaries, with London's pollution being carried by the wind into neighbouring counties.

2.4.5 Royal Commission on Environmental Pollution

The Eighteenth Report of the Royal Commission on Environmental Pollution was titled "Transport and the Environment" (HMSO, 1994c). The focus of the report was the impact of transport (air as well as land) on the environment in its widest sense, with special emphasis on the need for sustainability. The report used the World Health Organisation's definition of sustainability "*Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*"

The report comprised four sections. Firstly, there was an analysis and assessment of the environmental problems created by transport. In the second section various approaches to the future of transport were discussed. These were - managing congestion, economic aspects, technology and land use planning. Under the heading of "managing congestion" the following issues were considered:-

- letting congestion find its own level;
- predict and provide;
- greening the way we live;
- collective action;
- selling road space; and
- relying on technology.

The third section examined present transport policies in the light of the need for sustainability, and the fourth section contained the Commission's conclusions and recommendations.

The report concluded that sustainable transport must have the following clear objectives:-

i. "To ensure that an effective transport policy at all levels of government is integrated with land use policy and gives priority to minimising the need for transport and increasing the proportion of trips made by environmentally less damaging modes.

ii. To achieve standards of air quality that will prevent damage to human health and the environment.

iii. To improve the quality of life, particularly in towns and cities, by reducing the dominance of cars and lorries and providing alternative means of access.

iv. To increase the proportions of personal travel and freight transport by environmentally less damaging modes and to make the best use of existing infrastructure.

v. To halt any loss of land to transport infrastructure in areas of conservation, cultural, scenic or amenity value unless the use of the land for that purpose has been shown to be the best practicable environmental option.

vi. To reduce carbon monoxide emissions from transport.

vii. To reduce substantially the demands which transport infrastructure and the vehicle industry place on non-renewable materials.

viii. To reduce noise nuisance from transport."

In the specific case of air quality, the Commission proposed two specific targets. The first was "to achieve full compliance by 2005 with World Health Organisation health-based air quality guidelines for transport-related pollutants." Secondly, "to establish in appropriate areas by 2005 local air quality standards based on the critical levels required to protect sensitive ecosystems."

2.4.6 Expert Panel on Air Quality Standards (EPAQS)

The Government decided that nine air pollutants should be investigated initially, so that standards can be set according to the pollutants' hazard to human health (HMSO, 1995). The pollutants were:-

- ozone
- benzene
- 1,3 butadiene
- sulphur dioxide
- carbon monoxide
- oxides of nitrogen
- particulate matter
- polycyclic aromatic hydrocarbons (PAHs)
- lead.

Currently, reports have been published on six of the nine (the remaining three are oxides of nitrogen, lead and polycyclic aromatic hydrocarbons). To date, the Government has accepted and implemented the standards proposed for benzene, 1,3-butadiene, carbon monoxide and particulate matter.

2.4.7 Air Quality - Meeting the Challenge

The "Air Quality - Meeting the Challenge" report (HMSO, 1995) was published after a series of consultations within the different Government departments with an interest in urban air quality. Policies were proposed which are needed to improve air quality to the extent that the air is so clean that there is no risk to human health or the environment. These policies fall into three main categories: (i) a framework of national air quality standards and targets; (ii) local air management; and (iii) effective control of emissions, particularly from vehicles. These policies are all backed up by a commitment to monitoring and public information.

The air quality standards and targets are based on the advice given to the Government by EPAQS (see Section 2.4.4), directives from the European Union and advice from the World Health Organisation. Specific standards will be discussed in Section 2.5.

The 1995 Environment Act made local air quality management a legal requirement which set in place the duty of local authorities to review air quality in their area and to identify where standards may be exceeded. These areas are known as Air Quality Management Areas, and an action plan must be devised to show how standards will be met. The highway authorities will have an important role to play in this process, by developing "environmentally friendly" transport policies and planning measures. The Bill also gives local authorities the powers to issue prohibition notices to vehicles with high emissions, including financial penalties. Local authorities are also expected to provide meaningful information to the public about air quality in their area.

The policies for controlling vehicle emissions are based on five main themes:-

i. "new standards for technology, emissions and fuels;

ii. planning policies and local transport strategies aimed at reducing the need to travel and encouraging use of less polluting modes of transport;

iii. new environmental responsibilities in partnership with public service and other fleet operators;

iv. tighter enforcement of emissions regulations, targeting those vehicles doing most damage to the environment; and

v. voluntary action and guidance."

2.5 Standards

In the European Community there have been a number of directives concerning exhaust emission limits and air quality standards over the last 25 years. Similarly, limits have been set by the United Kingdom, the United States, the World Health Organisation and many other countries and organisations. Murley (1991) details the standards which have been set around the world.

2.5.1 Concentration units and conversion factors

Concentrations of air pollutants can be expressed in two ways. Firstly, as the mass of pollutant in a given volume of air (*eg* micrograms per cubic metre, $\mu g/m^3$), or as the ratio of the volume of the pollutant to the volume of air in which the pollutant is contained (*eg* parts per million or billion (ppm or ppb)) (HMSO, 1992). There is no common agreement on the use of one concentration unit, therefore it is often necessary to convert between the two.

The relationship between the two sets of units is as follows:-

$$\mu g / m^3 = ppb \times \frac{molecular\ weight}{molecular\ volume}$$

where $molecular\ volume = 22.41 \times \frac{T}{273} \times \frac{1013}{P} litres$ where T is the ambient temperature in kelvin (K) and P is the atmospheric pressure in millibars (mbar) (HMSO, 1992). Table 2.9 gives the conversion factors for the most common gaseous pollutants, at 0°C and 20°C with 1013 mbar pressure.

Table 2.9: Conversion factors (HMSO, 1992)

Pollutant	Molecular weight	ppb to μg/m^3		μg/m^3 to ppb	
		0°C	20°C	0°C	20°C
Sulphur dioxide	64	2.86	2.66	0.35	0.38
Nitrogen dioxide	46	2.05	1.91	0.49	0.52
Nitric oxide	30	1.34	1.25	0.75	0.80
Ozone	48	2.14	2.00	0.47	0.50
Carbon monoxide*	28	1.25	1.16	0.80	0.86

* for carbon monoxide the factors also apply to the more commonly used conversions of ppm and mg/m^3.

2.5.2 Carbon monoxide

Table 2.10 shows the carbon monoxide limits which have been set by the European Community since 1970 (Watkins, 1991). These are the limits for light duty vehicles and are based upon the United Nations Regulation Economic Commission for Europe (ECE) 15 standard. The emission standard for diesel lorries and buses is 11.2 to 12.8 g/kWh, and is given in Directive 88/77/EEC.

In the United Kingdom the emission standards for all new cars registered from 1/1/93 is 2.72 g/km for type approval (*ie* manufacturers' vehicles submitted for certification), and 3.16 g/km for all production vehicles.

Table 2.10: Vehicle exhaust emission control history (Watkins, 1991)

Year	Directive	Carbon monoxide standard (g/test)
1970[a]	70/220/EEC	100-220
1974[a]	74/290/EEC	80-176
1977[a]	77/102/EEC	80-176
1978[a]	78/665/EEC	65-143
1983[a]	83/351/EEC	70-132
1988[b]	88/76/EEC	25-45
	88/436/EEC	
1989[c]	89/458/EEC	19
1990[d]	proposal	2.72[e]

Notes:
a Standards based on vehicle weight: urban driving cycle
b Standards based on engine capacity: urban driving cycle
c For all cars with engines <1.41cc only: urban driving cycle
d For all classes of car: combined urban and extra-urban driving cycle
e Standards expressed in g/km

The MOT test standards are:-

- For vehicles first used on or after 1 August 1983, a maximum of 4.5% carbon monoxide in the exhaust gas.
- For vehicles first used between 1 August 1975 and 31 July 1993, a maximum of 6% carbon monoxide in the exhaust gas.

In 1994, the Expert Panel on Air Quality Standards set standards for carbon monoxide based on the reversible nature of this pollutant's effect on humans (EPAQS, 1994). They stated that the standard should be set such that the concentration of carboxyhaemoglobin in the blood should not exceed 2.5%, which provides a safety margin for even those people who are most at risk, *ie* people with heart problems. The standards they set were 10 ppm maximum based on an 8 hour rolling average, 25 ppm over one hour, 50 ppm over 30 minutes and 87 ppm over 15 minutes.

Murley (1991) states that in the United States the National Ambient Air Quality Standards for carbon monoxide are 9 ppm (10 mg/m^3) (8 hour average), and 35 ppm (40 mg/m^3) (1 hour average). These standards are not to be exceeded more than once per year. The World Health Organisation standards for carbon monoxide are 26 ppm (30 mg/m^3) (1 hour average) and 9 ppm (10 mg/m^3) (8 hour average).

2.5.3 Sulphur dioxide

Two European Community Directives have been adopted on sulphur dioxide levels. Council Directive 80/779/EEC gave air quality limit values and guide values for sulphur dioxide (and suspended particulates). This was amended by 89/427/EEC.

These limits are also in force in the United Kingdom (Murley, 1991). The one year (median of daily values) limits are 120 $\mu g/m^3$ if black smoke levels are less than 40 $\mu g/m^3$, and 80 $\mu g/m^3$ if black smoke levels are more than 40 $\mu g/m^3$. The winter (median of daily values) limits are 180 $\mu g/m^3$ if black smoke levels are less than 60 $\mu g/m^3$, otherwise 130 $\mu g/m^3$. The yearly peak limits (98th percentile of daily values) are 350 $\mu g/m^3$ if black smoke levels are less than 150 $\mu g/m^3$, otherwise 250 $\mu g/m^3$. The 24 hour guide values are 100 to 150 $\mu g/m^3$, and the one year mean guide values are 40 to 60 $\mu g/m^3$.

In the United States, the standards are 0.03 ppm (80 $\mu g/m^3$) annual (arithmetic) mean and 0.14 ppm (365 $\mu g/m^3$) 24 hour average. These standards are not to be exceeded more than once per year. The WHO standards are 150 $\mu g/m^3$ (1 hour average), 125 $\mu g/m^3$ (24 hour average) and 50 $\mu g/m^3$ (1 year average).

2.5.4 Nitrogen oxides

The vehicle exhaust emission directive 88/78/EEC also contains limits for nitrogen dioxide. These are 6 grams per test for vehicles with engines which have a capacity of less than 1400 cm^3, and 3.5 grams per test for those with a greater capacity. Diesel lorries and buses limits are 14.4 g/kWh for type approval vehicles and 15.8 g/kWh for production vehicles (Directive 88/77/EEC) (Murley, 1991).

The European and United Kingdom air quality standards are a limit value of 200 $\mu g/m^3$ (105 ppb) (one year period, based on 98th percentile of 1 hour means), and guide values of 50 $\mu g/m^3$ (26 ppb) (one year period, based on 50th percentile of 1 hour means) and 135 $\mu g/m^3$ (71 ppb) (one year period, based on 98th percentile of 1 hour means). The relevant directive is 85/203/EEC.

The United States standard is 0.053 ppm (100 $\mu g/m^3$) annual (arithmetic) mean. The World Health Organisation standards are 400 $\mu g/m^3$ (1 hour average) and 150 $\mu g/m^3$ (24 hour average).

2.6 Summary

In this chapter the source and nature of traffic-related pollutants have been introduced. The research described in this thesis focuses on the pollutants carbon monoxide, sulphur dioxide and nitrogen dioxide, and therefore these have been described in greater detail.

It has been shown that these pollutants are all harmful to health in excessive concentrations. In particular, traffic-related air pollutants have been linked with an exacerbation of the symptoms experienced by sufferers of respiratory illnesses. However, no causal link has been proved (Bell *et al*, 1996b).

Recent Government publications have increasingly focused on the specific problem of transport-related air pollution. There has also been an increase in the amount of action taken by the Government. These include the setting up of the Automatic Urban Network of monitoring stations, the adoption of tighter emission standards, and a legal requirement for local authorities to ensure good air quality.

3. Traffic-related air pollution monitoring and prediction

3.1 Introduction

In this chapter previous research into the monitoring and prediction of traffic-related air pollutants is reviewed. Different methods of monitoring are discussed and the results of surveys are presented. This includes details of the national network of pollution monitoring stations set up by the Department of the Environment.

Next, the different approaches which have been taken to model and predict traffic-related air pollutants are discussed. Models produced by other researchers are described. Methods for reducing traffic-related air pollution are discussed. The main methods are technological measures and, more importantly, the use of traffic management strategies.

The final section in this chapter highlights the key areas of research and policy presented in this chapter and the previous chapter forming the basis for the research described in this thesis.

3.2 Traffic-related air pollution monitoring

3.2.1 Carbon monoxide

Carbon monoxide is usually measured with instruments which utilise the principle of non-dispersive infra-red gas correlation, or using portable battery operated electrochemical analysers. The infra-red analysers detect the characteristic energy of absorption of the carbon monoxide molecule (Davies, 1991). Portable systems incorporate a pump to draw in the air sample which causes an electro-chemical reaction. The current generated by the sensor is proportional to the carbon monoxide concentration (Watkins, 1991).

Koushki (1988, 1989, 1991) spent three years studying carbon monoxide emissions in Riyadh, Saudi Arabia. The concentrations of vehicle-generated carbon monoxide at six major arterial roadways were measured and used to validate models of the impact of transport systems on air quality. Carbon monoxide was measured at each site during at least six peak hour periods, spread over different working days of the week and months of the year. The concentrations were measured at one minute intervals at two locations during the peak hour period. One measurement was made close to the traffic lanes (at a height of 1.5m above ground) and the other was made at the far edge of the footpath at a height of 0.5m. The exposure to carbon monoxide for the pedestrian stood at the kerbside and sat by the facade could then be estimated. Carbon monoxide concentrations were also monitored continuously at each arterial location for between 10 and 15 days. Measurements were made at a height of three metres. Typical kerbside levels of carbon monoxide were between 9 and 26 ppm.

Claggett *et al* (1981) measured carbon monoxide levels, traffic characteristics and meteorological conditions at an urban intersection in America over a six week period. Carbon monoxide detectors were placed at the head of the queue and halfway along the block. Classified vehicle and turning movement counts on each of the arterials at the intersection were made simultaneously. A wind vane, placed at a height of 10m, to the east of the intersection, was used to establish air speeds. Background levels were measured at a distance of 150m from the road. The results are given in Table 3.1.

Table 3.1: Summary of results from Claggett *et al* (1981)

	Queue zone	Midblock
Maximum carbon monoxide concentration including background	43.7 ppm	24.0 ppm
Mean carbon monoxide concentration including background	12.8 ppm	3.3 ppm
Mean wind speed	7.5 mph	7.5 mph
Mean traffic volume	2239 vph	2239 vph
Mean vehicle speed range	0 - 28 mph	39 mph
Temperature mean	54°F	
Temperature range	30 - 78°F	
Average background	1.2 ppm	
Maximum background	9.0 ppm	

Three major studies were carried out by the Transport Road Research Laboratory[1] (TRRL) during the 1970's to measure exhaust emissions. These are reported in Colwill (1973), Hickman (1976) and Hickman *et al* (1976). Table 3.2 is based on Watkin's (1991) summary of these TRRL studies.

[1] The TRRL is now known as the Transport Research Laboratory (TRL).

Table 3.2: Carbon monoxide levels measured at sites in England (ppm) (Watkins, 1991)

	Average	Minimum Hourly Average	Maximum Hourly Average	Traffic Flow (vehicles/h)
Reading Dec 1971				
Residential	2	0	6	670
Main Road	6	2	10	1200
London North Circular Rd				
May-June 1973	4	0	18	3500
Weekdays[1]	6	0	7	5300
Coventry Nov-Dec 1973				
Residential	10	0	35	1200
Shopping	3	0	27	830
Mixed	2	0	8	830

[1]Average overnight level

The first study (Colwill, 1973) took place in Reading, Berkshire, in the summer and winter of 1971. One monitoring site was at the side of a main road with a high flow, and the second was in an urban area, but remote from traffic, to give a background level. Colwill found that the concentration at the kerbside varied continuously throughout the day. Concentrations exceeded ten parts per million for seven per cent of the time, and the peak value recorded during all the surveys was 77 ppm. The background level was found to be 1 ppm during the summer, and between 3 and 4 ppm during the winter.

Surveys carried out in West London during 1973 are reported in Hickman (1976). Three sites were chosen along a very low flow road which intersects with the busy A4 (Cromwell Road). These sites were at a distance of 20m, 30m and 50m respectively from the junction. Readings were also taken at an installation on the kerbside of Cromwell Road which belonged to the Warren Spring Laboratory. It was found that the level of pollutants decreased as the distance increased from the main road (30% of kerbside level at 50m). It was also concluded that wind speed, but not wind direction, was a significant factor.

Hickman *et al* (1976) described monitoring carried out in Coventry during 1973. Four sites were chosen comprising of residential, industrial and commercial areas. Again, carbon monoxide levels were found to vary greatly during the day. Hourly average values were found to correlate well with traffic flow and other pollutants (hydrocarbons, nitric oxide and ethylene). Wind speed was also found to have a considerable effect on concentration.

3.2.2 Sulphur dioxide and nitrogen dioxide

Traditionally, sulphur dioxide and nitrogen dioxide concentrations have been measured using diffusion tubes. Diffusion tubes are usually made of acrylic and contain a stainless steel mesh coated with a catalyst called triethanolamine. The tubes are fixed in position for, usually, a fortnight and then sent to a central laboratory for analysis. The amount of nitrogen dioxide absorbed is determined by colorimetrically measuring the amount of nitrite and converting this amount using the diffusion coefficient of nitrogen dioxide in air (Hewitt, 1991). A non-exposed blank tube from each batch is used to provide a reference zero. The advantage of these tubes is that they are very cheap, and can give an indication of long-term trends.

Studies relating to the monitoring of nitrogen dioxide and sulphur dioxide are difficult to find in comparison with carbon monoxide. One study reported measured nitrogen dioxide concentrations at 49 sites in Lancaster using diffusion tubes during 1989, and the results were related to the traffic flow on nearby roads (Hewitt, 1991).

The results of the study carried out in Lancaster are shown in Table 3.3. The original paper gave the nitrogen dioxide measurements in $\mu g/m^3$ only, but these have been converted to parts per billion using the factor given in Section 2.5. Hewitt's main conclusion was that small differences in the location of the sampler can lead to large differences in annual mean concentrations, and this can be crucial in assessing whether standards have been exceeded or not. It is obvious therefore, that monitoring should have been carried out at similar locations, *ie* all at the kerbside or all at the facade.

Table 3.3: Summary of fortnightly nitrogen dioxide concentrations measured at 49 sites in five locations in Lancaster (22 January 1989 - 21 January 1990) (Hewitt, 1991)

Location type	No of sites	Units	Annual mean ± sd	2-week min	2-week max	Mean daily traffic flow (vehicles)
City centre one-way main road	12	$\mu g/m^3$	63±24	12	222	<30 000
		ppb	33±12	6	115	
City centre road	6	$\mu g/m^3$	58±17	5	107	~9 000
		ppb	30±9	3	56	
City centre pedestrian precinct	6	$\mu g/m^3$	45±17	5	111	<100
		ppb	23±9	3	58	
Suburban main road	11	$\mu g/m^3$	38±16	10	96	10 500
		ppb	20±8	5	50	
Suburban residential street	14	$\mu g/m^3$	30±13	7	67	<800
		ppb	16±7	4	35	

Bower *et al* (1991) deployed nitrogen dioxide diffusion tubes at the 363 existing smoke and sulphur dioxide monitoring stations across the United Kingdom and monitored all three pollutants from July to December 1986. They found that the highest average nitrogen dioxide concentrations were measured in London, especially at sites close to busy roads. Concentrations were found to be moderately higher in winter than in summer. When they compared the concentrations of nitrogen dioxide with the concentrations of black smoke and sulphur dioxide they found that nitrogen dioxide and sulphur dioxide were not highly correlated. However, the results were influenced by those sites in non-smoke controlled areas. When these sites were discounted there was a substantially higher correlation which they attributed to the fact that traffic not only emits nitrogen dioxide, but also sulphur dioxide.

3.2.3 The Fuel Efficiency Automobile Test (FEAT) system

The FEAT system was developed by Dr Steadman of University of Colorado, Denver (Revitt, 1995). It measures the carbon monoxide and hydrocarbon levels in the exhaust emissions of individual vehicles using an open-path spectroscopic apparatus. An infrared beam is directed through each vehicle's exhaust to a receptor. The monitor is linked to a video camera and the levels are superimposed on the picture of the vehicle. The make and model of each vehicle can then be determined, and those vehicles with high emissions could then be followed up by the Driver and Vehicle Licensing Authority.

Researchers at Middlesex University have used this equipment to carry out a number of surveys (Revitt, 1995). They found that 12% of vehicles contributed up to 50% of the total fleet emissions. These vehicles were termed "gross polluters." They also showed that carbon monoxide emissions increase with the age of the vehicles, and stated that if these vehicles were regularly serviced or removed from service, then there is a potential to cut carbon monoxide emissions by up to 40%.

3.2.4 The Department of the Environment's urban monitoring network

As stated in the previous chapter, by 1994 the Department of the Environment had set up "urban background" pollution monitoring stations in twelve cities across the United Kingdom. This was then known as the Enhanced Urban Network. The cities were Belfast, Birmingham, Cardiff, Edinburgh, London (Bloomsbury), Newcastle, Bristol, Leeds, Liverpool, Leicester, Kingston-upon-Hull and Southampton (QUARG, 1993a). In 1995 the Enhanced Urban Network was amalgamated with the Statutory Urban Monitoring network of nitrogen dioxide, sulphur dioxide and smoke monitors, to form the Automatic Urban Monitoring Network (AUN).

The stations in the Automatic Urban Monitoring Network contain high precision equipment to monitor various traffic-related pollutants. A further 13 monitoring stations are expected to be in operation by the end of 1996, giving a comprehensive national network of urban monitoring (AEA, 1995). The pollutants being monitored are (QUARG, 1993a):-

- nitrogen dioxide and nitric oxide - using chemiluminescence (precision of ±3 ppb and ±2 ppb respectively)

  This method is based on the luminescence from an activated molecular nitrogen dioxide species produced by the reaction between nitric oxide and ozone in an evacuated chamber: $NO + O_3 \rightarrow NO_2^* + O_2$. As the activated species reverts to a lower energy state, it emits broad-band radiation. Since one nitric oxide molecule is required to form one nitrogen dioxide molecule, the intensity of the chemiluminescence reaction is directly proportional to the nitric oxide concentration.

- sulphur dioxide - using ultraviolet fluorescence (precision of ±1 ppb)

  Sulphur dioxide exhibits a strong ultraviolet absorption spectrum between 200 and 240 nm, and this results in the emission of fluorescence photons at higher wavelengths. The amount of fluorescence emitted is directly proportional to the sulphur dioxide concentration.

- carbon monoxide - using infra-red absorption (precision of ±0.5 ppm)

  Carbon monoxide absorbs infrared radiation at a specific wavelength, so therefore the presence and amount of carbon monoxide can be determined by measuring the amount of this absorption.

- ozone - using ultraviolet absorption (precision of ±2 ppb)

  Ozone absorbs ultraviolet radiation at a specific wavelength and therefore the amount of ozone can be determined by measuring this absorption.

- particulate matter - using a tapered element oscillating microbalance (TEOM) (precision of ±1 $\mu g/m^3$)

  Particulate matter less than 10 microns in diameter is known as PM_{10}. A piezo-electric tapered element is induced to vibrate at its natural frequency. The air stream is drawn through a heated inlet onto a Teflon-coated glass fibre filter. As the mass on the filter increases, the natural frequency of oscillation decreases. This change is detected by the microprocessor which outputs the total mass accumulation on the filter.

The following is the comprehensive list of the criteria for the location of the sites in city centres, taken from the operator's manual (Department of the Environment, 1992):-

i. "The site should be located where a significant number of people spend their time.

ii. It should be in as open a setting as possible in relation to surrounding buildings.

iii. Immediately above should be open to the sky with no overhanging trees or buildings.

iv. The sample intake should be no higher than 10m above local ground level and ideally less than 5m.

v. There should be no major sources of pollution within 50m *eg* a large multi-storey car park.

vi. There should be no medium sized sources within 20m *eg* petrol stations, ventilation outlets to catering establishments *etc*.

vii. Cars/vans/lorries should not be expected to stop with their engines idling within 5m of the sample inlet.

viii. The site should not be within

- 30 m of a very busy road (>30 000 vehicles/day)
- 20m of a busy road (10 000 - 30 000 vehicles/day)
- 10m of any other road (<10 000 vehicles/day).

ix. The surrounding area, within say 100m, should not be expected to undergo major redevelopment, so as to avoid disruption and to allow long-term trends to be followed."

It can be seen from this list that the objective of these monitoring stations is not to measure at the kerbside, but in an "urban background" site. In some cities these criteria have been very difficult to satisfy and has led to locations being chosen which are not ideal. For example, in Leicester, the station is located between two tower blocks which means that it is not very open.

These stations are also extremely expensive. They cost over £90 000 to equip and install, and at least £12 000 per year to operate (Elsom, 1994). The Government will only fund one station for each city with a population exceeding 200 000. Therefore, those smaller cities who want to carry out monitoring, or those larger cities who do not feel that one station is enough, must find the costs from elsewhere in their budgets.

3.3 Modelling of traffic-related air pollutant concentrations

Most of the empirically derived relationships between air pollution and traffic characteristics were developed in the 1970's, *eg* Watkins (1972) and Colwill and Hickman (1981). However, since that time traffic flows have increased, especially in urban areas, and congestion is now a major problem. Since these models considered traffic driving in mainly free-flow conditions, they are now largely out of date and new models relating to congested environments are needed.

In general air pollution is modelled in two stages. Firstly, models are used to predict the amount of pollution emitted into the atmosphere by the vehicles. Secondly, dispersion relationships are used to model air pollution concentrations at different points in the atmosphere. This approach was used by Chiquetto and Mackett (1994) to assess the effect of various transport policies on future air pollution levels in Chester.

Matzoros and Van Vliet (1992a) state that there are three main approaches to dispersion modelling. The first is known as the "eulerian" approach whereby the continuity equations of mathematical physics are used to describe the processes which govern the relationship between emissions and concentrations. The second, "lagragian" approach describes the motion of particles of pollutants using a probability distribution. The final approach uses statistical techniques to infer relationships between emissions and concentrations from observations, an approach that is currently the least well developed (Hassounah and Miller, 1994).

The second approach is the one most usually adopted, and the probability distribution used is the normal, Gaussian, distribution. The Gaussian model assumes a point source emitting at a uniform rate at the origin of the co-ordinate system. The model equation is

$$C(x,y,z) = \frac{E}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \exp\left[-\frac{1}{2}\left(\frac{z}{\sigma_z}\right)^2\right]$$

where C denotes the pollutant concentration at a receptor point with co-ordinates x, y, z (g/m^3)

E denotes the emission rate (g/s)

u denotes the wind speed (m/s). Wind direction is taken to be parallel to the x-axis

σ_y, σ_z denote the standard deviations of the plume concentration distributions (in metres) at the downwind distance x.

The most notable example of this type of model is the PREDCO model (Hickman and Colwill, 1982), which is recommended by the Department of Transport. This model is mainly applicable to free flow highway environments and not urban areas. PREDCO considers roads as linear sets of point sources, where characteristics of each section of road can be specified. Wind speed and wind direction are also input as it is generally true that "the higher the wind speed, the lower the pollutant levels" (Watkins, 1991).

Hickman and Colwill (1982) gave a simple flow chart, as shown in Figure 3.1, to represent the model. This model assumes that the emissions from petrol and diesel engined vehicles are the same. It uses the following formula involving vehicle speed to obtain the source emission rate Q

$$Q = 1.031TS^{-0.795} \times 10^{-4} \text{ g/ms}$$

where T = total traffic flow (vehicles/h)

S = mean traffic speed (km/h).

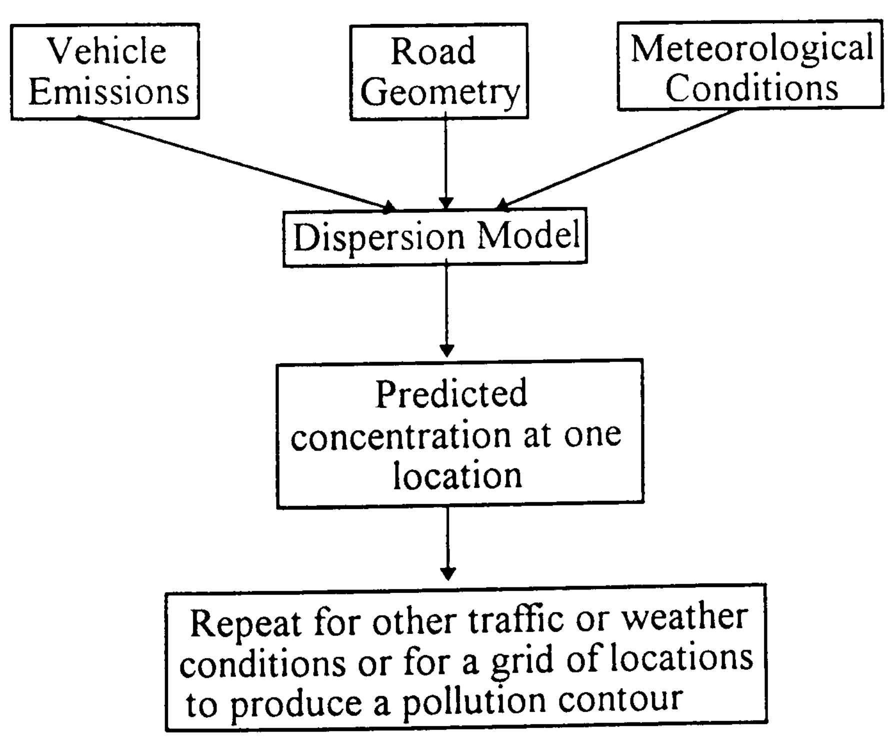

Figure 3.1: Simple flow chart for PREDCO (Hickman and Colwill, 1982)

The Graphical Screening method of Waterfield and Hickman (1982) is based on output from PREDCO. The purpose of this method is to estimate the annual maximum eight-hour concentration of carbon monoxide due to vehicle emissions. Four graphs were developed from outputs of PREDCO. Two graphs give the concentration of carbon monoxide as a function of the horizontal distance between the road and the gas detector (one is used for straight roads, and the other for roundabouts). The third graph gives a correction factor for vehicle speed. The fourth graph converts the hourly average concentration into the maximum eight-hour annual concentration.

Johnson *et al* (1973) developed a Gaussian-type empirical model to calculate carbon monoxide levels as a function of climatic conditions and traffic distribution. The model was evaluated using data collected in San Jose, California, over a period of two months. The model was refined by incorporating a street canyon model to allow for the aerodynamic effects of buildings. The inputs to the model included emission rates, street canyon depth, street width, wind speed at roof level and the diagonal distance between the receptor and the nearest traffic lane.

Richardson (1982) and Linkaritakis (1983, 1988) stated that empirical models based on multiple regression statistical methods have the potential to produce robust models to describe pollution along street canyons. Crompton and Gilbert (1970) adopted multiple regression techniques to analyse data on environmental factors such as noise, vibration and carbon monoxide. The results obtained by Claggett *et al* (1981) for an urban intersection were examined using linear regression techniques and the results were compared with the Gaussian model HIWAY (Zimmerman and Thompson, 1975). Poor correlations between the measured and the predicted values were found. This is not surprising as Gaussian models are more relevant to free flow traffic conditions, and therefore it is inappropriate to apply these to urban conditions.

Elsom (1994) states that few local authorities use any form of air quality prediction model. The most notable exception is Sheffield City Council who use the INDIC AirViro Air Quality Management System. This system is also connected to the automatic pollution and meteorological monitoring stations around the city and will automatically dial-up and collect data. The data from these stations and the data from an emissions inventory are input into a suite of air quality prediction models. The output from these models is displayed on a digitised topographical map. Sheffield was the first city in the UK to install this system, but it is now being used in London, Birmingham and Bristol.

Leicestershire and Kent County Councils will soon be installing the system as part of the EU:Fourth Framework project called EFFECT (Environmental Forecasting For the Effective Control of Traffic).

The Department of the Environment recommends the use of the ADMS Urban Air Quality Management System developed by CERC in association with the Meteorological Office (Curruthers and Edmonds, 1995). A geographical information system (GIS) is used to enter data about sources of pollution and local topography in an area. Meteorological data is also entered into the model which uses sophisticated atmospheric boundary layer and dispersion prediction equations to calculate the pollution concentrations. These concentrations can be displayed graphically on the GIS map, or presented numerically in tables. The main difference between ADMS and AirViro is that the latter can be used to interface directly with the pollution and meteorological data from automatic monitoring sites. However, the boundary layer and dispersion equations are believed to be more sophisticated in ADMS.

3.3.1 Matzoros and Van Vliet's model

Matzoros and Van Vliet (1992a,b) developed a model known as UROPOL (Urban ROad POLlution). It consisted of traffic assignment, queuing, emission and dispersion models. The structure of the complete model is given in Figure 3.2.

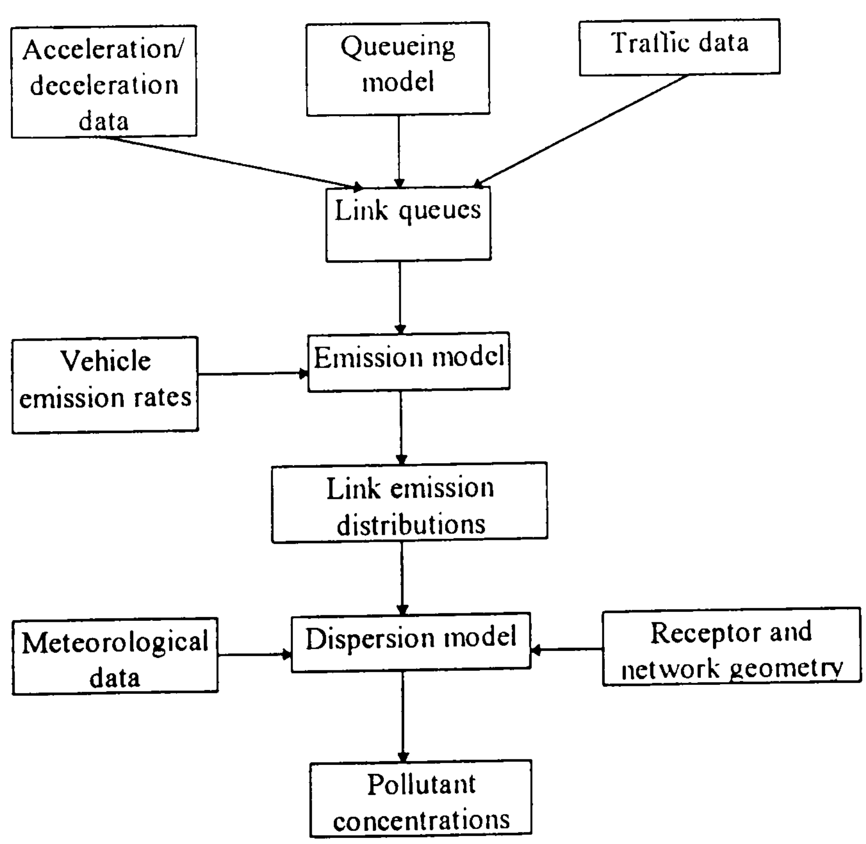

Figure 3.2: Structure and information flow diagram of Matzoros and Van Vliet's model (Matzoros and Van Vliet, 1992a)

The assignment model SATURN (Van Vliet, 1982) provided the network flows. These flows were input into queuing models for signalised, priority and roundabout intersections as appropriate. The queuing model output the number of vehicles in the four driving modes - cruising, decelerating, queuing (idling) and acceleration, over time. The queuing model was based on the "shock wave" theory of traffic flow, as shown in Figure 3.3.

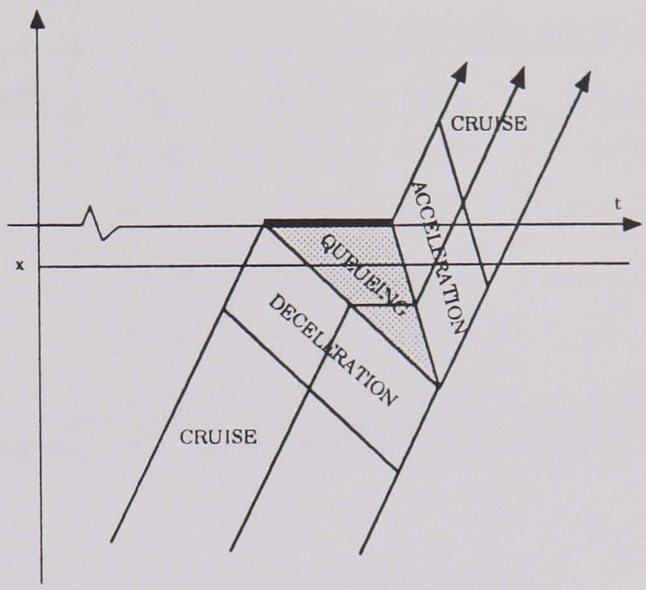

Figure 3.3: The four vehicle operating modes at a signalised junction with approximated acceleration and deceleration trajectories (Matzoros and Van Vliet, 1992a)

The emission rate at any point x was calculated as:-

for the queuing mode:

$$ER_q(x) = \frac{T_q(x)E_q}{TL}$$

for the cruise/decelerating/accelerating modes:

$$ER_m(x) = \frac{T_m(x)F_m E_m}{TV_m}, m \neq q$$

where $ER_m(x)$ denotes the emission rate (g/m/s) of operating mode m at a point x

E_m denotes the car emission rate (g/s) of mode m

$T_m(x)$ denotes the total time (s) spent by a vehicle in mode m

L denotes the length of the queue (m)

F_m denotes the flow (veh/s) of vehicles in mode m

V_m denotes the average speed (m/s) of vehicles in mode m

T denotes the modelling period (s).

Then $ER(x) = \sum_m ER_m(x)$.

Emission rates for each mode were applied to obtain the link emission distribution. The vehicle emission rates and the acceleration and deceleration rates are given in Table 3.4. The link emissions were then dispersed spatially using a dispersion model to obtain the concentrations at the point of interest.

Table 3.4: Queuing and emissions model data (Matzoros and Van Vliet, 1992a)

	Vehicle emission rate (g/min)				
Operating mode	CO	HC	NO_x	Lead	Rate (m/s^2)
Cruise	5.08	0.95	1.71	0.0060	
Decelerating	8.34	2.45	1.22	0.0038	1.1
Idle	3.00	0.50	0.03	0.0015	
Accelerating	10.00	1.34	2.05	0.0127	2.8
Creeping*	5.00	1.05	1.48	0.0048	

* Applies to priority junctions only. Lead figures derived from fuel consumption data. Lead content 0.15 g/l.

Furthermore, Matzoros and Van Vliet stated that,

- "For the cruise mode V_m is equal to arrival speed (V).
- The average speed for acceleration and deceleration modes is taken as $V_m = V/2$.
- For the deceleration and cruise behind the stopline, F_m is assumed equal to arrival flow, $F_m = F$.
- Cars departing from the queue accelerate and, subsequently, cruise are assumed to flow at saturation, $F_m = S$."

As a result of this work, Matzoros and Van Vliet made the following statements based on the main characteristics of traffic pollution:-

i. "Emissions during acceleration and deceleration are generally higher than those at steady speed cruising and, thus, interrupted traffic flow is more polluting than uninterrupted flow.
ii. Traffic emissions are higher near junctions with the maximum occurring in the queuing area of each link.
iii. As a result of this, pollutant emissions exhibit a high spatial variability, with peaks near junctions and troughs at mid-block positions.
iv. Gaussian dispersion modelling can be applied (with care) to inert traffic pollutants.

v. The movement of vehicles affects the dispersion of their exhaust gases, creating a rapid initial dispersion.

vi. Street canyons restrict and distort normal gas dispersion."

3.3.2 Statistical analysis of air pollution data

Sunyer *et al* (1991) investigated the relationship between air pollution and emergency room admissions for chronic obstructive pulmonary disease (see Section 2.3.2) by first building a set of multiple linear regression models which adjusted the air pollution effects to allow for the three sets of confounding factors - meteorology, season and day of week. They also considered one- and two-day lagged variables for the air pollution and meteorological data. The different air pollutants were considered separately because of their collinearity.

The control variables for the model were selected in two stages. Firstly, indicators of all three confounding factors were included *a priori*. Secondly, a set of indicators was selected on the basis of statistical criteria - indicators which were significantly associated with emergency room admissions ($p < 0.05$) were retained, and then their interactions with air pollution variables were tested. If the indicators were then significantly related with the effect ($p < 0.05$) they were retained.

The Durbin-Watson test was used to test the hypothesis of random distribution of the regression residuals. However, autocorrelation was suspected as both the air pollution and emergency room admissions were time series observations with a temporal structure. This meant that the multiple regression models were not valid.

3.3.3 Pollution dispersal

The main factors which influence dispersion are meteorology, topography, distance from the source, traffic movement and the time between the release of the pollutant and its measurement (André *et al*, 1991, Ayland *et al*, 1991). The meteorology factor is concerned with the strength and direction of the wind, ambient temperature and the humidity. The wind profile at a particular location is difficult to define or model, and turbulence has a significant effect on pollutant dispersal. Koushki (1989) concluded that wind direction and velocity may significantly contribute to fluctuations in carbon monoxide levels. This result was supported by Davies (1991) who stated that "when monitoring and predicting environmental parameters such as carbon monoxide levels, it is necessary to sample wind speed and direction, temperature and humidity".

The topography of the area surrounding a site has considerable effect on pollutant dispersal. It is more difficult for pollutants to disperse from within a street canyon than from a road in the countryside. Much research is being carried out investigating pollutant dispersion using wind tunnel tests and numerical modelling (Baker, 1993; Pearce, 1995).

Hickman (1976) showed that as the distance between the source and the gas detector increases then the levels recorded decrease. This occurs for both horizontal and vertical changes (Green *et al*, 1979). In general, leeward concentrations are higher than the corresponding windward ones (Green *et al*, 1979).

Traffic movement contributes to the mixing of air and induces areas of turbulence. In calm periods this mixing is very noticeable (*eg* gusts can be felt by pedestrians as heavy goods vehicles pass), whilst in periods of higher winds it only adds to the ambient conditions (André *et al*, 1991, Ayland *et al*, 1991).

3.4 Reducing traffic-related air pollution

In Section 2.4, the steps taken by the Government to deal with air pollution were outlined. In the short term, the development of local air quality management strategies should give local authorities the power to carry out random spot checks to deal with gross polluters, and to impose short term restrictions on traffic during episodes of poor air quality (Elsom, 1994). However, this can only be achieved by understanding the effect that various traffic management strategies have on air pollution (Koushki, 1989). Therefore, long term solutions should address land-use planning issues in order to reduce the need to travel, and technological means of reducing emissions at source should be further explored. Furthermore, if these measures are combined with a public education program promoting the use of alternative modes of transport, then it should be possible to further reduce emissions[1].

[1] The recently funded EU:Fourth Framework EMMA (Integrated Environmental Monitoring, Forecasting and Warning Systems in Metropolitan Areas) project seeks to implement and assess a program of public information initiatives to encourage the public to travel in a more "environmentally-friendly" mode. The consortium partners include Leicestershire County Council and UNTRG.

3.4.1 Technological methods of reducing pollution emissions

In general there are two ways of reducing pollution at source: preventative and curative. In preventative measures alterations to the design of the engine are made or alternative sources of energy are employed, eg electricity, compressed natural gas and bio-diesel (Haseley, 1996).

In the past, curative methods have included thermal after-burning and manifold air injection, however these have been largely superseded by the use of catalytic converters. Catalytic converters work to reduce emissions of carbon monoxide, hydrocarbons and nitrous oxides by enhancing the oxidation and reduction processes which take place in the exhaust gases. Cars fitted with catalytic converters must run on unleaded petrol, as the lead in petrol poisons the catalyst. Watkins (1991) gave a table (presented here as Table 3.5) of the effects of various exhaust emission control technologies on fuel consumption. The changes are given relative to the base case of a conventional engine with a carburettor and mechanical ignition.

Table 3.5: The effects of various exhaust emission control technologies on the fuel consumption of petrol engined cars (Watkins, 1991)

Engine/vehicle modifications	Change in fuel consumption from base %
Electronic ignition system	-3 to -6
Full engine management	-3 to -10
Air injection	+7 to 0
Air injection + EGR (Exhaust Gas Recirculation)	+19 to 0
Electronic ignition + EGR	+2 to -4
Lean burn (carburettor)	-4 to -20
Lean burn (fuel injection)	-15 to -22
Lean burn (carburettor) + EGR	-3 to -13
Air injection + oxidation catalyst	0
Air injection + EGR + oxidation catalyst	+27 to 0
Lean burn (carburettor) + oxidation catalyst	-13
Controlled 3-way catalyst	+16 to -5

3.4.2 Traffic management techniques to reduce pollution levels

Traffic management measures would aim to reduce pollution levels by reducing demand, keeping traffic moving and avoiding congestion (Bell, 1990a). Koushki (1989) states that this could be achieved by re-routing heavy goods vehicles; prohibiting trucks from certain streets and/or stating a specific time period for their operation; optimising traffic signal timings to achieve co-ordination to minimise frequent starts and stops; implementing one- or two-way operation to reduce the interruptions caused by left-turning traffic (in Saudi Arabia, whereas in the United Kingdom this would apply to right-turning vehicles); or by prohibiting on-street parking to minimise flow interruptions.

Maclennan (1994) described the environmental impact of five traffic management strategies - priority routes, traffic restrictions, traffic calming, pedestrianisation and the installation of urban traffic control. Priority routes (also known as 'red routes') have been introduced on major roads in London to improve traffic flow, especially for buses. This has been achieved by restrictions on stopping, loading and unloading, on-street parking and the introduction of more bus lanes. A 12.5 km stretch from Highgate to Stepney was monitored by the Transport Research Laboratory in a 'before' and 'after' study. They found reductions in the three pollutants measured (nitrogen oxides, carbon monoxide and volatile organic compounds) which they attributed to the reduction in traffic delays and the amount of stopping and starting.

Traffic restrictions were implemented in the City of London to reduce traffic in the central area and to divert it onto other routes around the City. The Transport Research Laboratory again carried out the evaluation and found that inside the cordon the levels of the pollutants monitored (nitrogen oxides, carbon monoxide, hydrocarbons and particulates) all decreased by approximately 15%. This was, however, associated by a small increase of approximately 2% outside the cordon. They concluded that if traffic was diverted onto roads with lower pedestrian activity, then there may be a reduced impact on human health.

A study of traffic calming measures carried out in Germany showed lower emissions at 30 km/h than at 50 km/h because of the adoption of calmer driving styles. However, aggressive driving in lower gears would increase emissions. Pedestrianisation of areas reduces local pollution concentrations in the pedestrian area itself, however it is also likely to lead to an overall increase in emissions because journeys are longer. Therefore, the benefit in these schemes depends on the layout of the network, traffic patterns and how easily emissions are dispersed.

3.4.3 Use of urban traffic control to reduce emissions

In the United Kingdom there are several ways in which traffic signals are controlled. These fall into two distinct categories - isolated control and co-ordinated control. In the case of isolated control, the signals at a junction are programmed with a set of signal timings which take no account of what is happening elsewhere in the network. In contrast, the co-ordinated control system means that the timings of several sets of signals in an area of a network can be calculated to allow vehicles to progress through the area with a minimum of delay. The first co-ordinated signal control program implemented widely in the United Kingdom was TRANSYT (TRAffic Network StudY Tool) (Robertson, 1969). Using this program a set of fixed signal timings were derived and then implemented on-street. However, the benefits from implementing these signal plans were found to decrease over time as traffic levels changed and alterations were made to networks (Withill, 1993). Bell (1986) estimated that the plans degrade, or *age*, by approximately 3% per year.

As a result of the deficiencies in fixed-time control, a new signal control method was developed which could adapt and be *demand-responsive*. This is known as SCOOT (Split, Cycle and Offset Optimisation Technique) (Hunt *et al*, 1981), and it is used by many local authorities across the United Kingdom and the world. The term *cycle* refers to the amount of time taken for a complete sequence of signals to the traffic on an approach to a junction, *ie* from the start of the red, through red and amber, green, amber and back to red. The *split* is the proportion of the cycle time for which the signal is green on any one approach. The *offset* is the difference between the start of the cycle at one junction and the start of the cycle at the next upstream junction.

Development of the SCOOT demand responsive urban traffic control system was begun in 1973 by the Transport and Road Research Laboratory, in collaboration with Ferranti, GEC and Plessey. The initial research was implemented in Glasgow where full-scale trials commenced in 1979. A SCOOT system was installed in Coventry in 1980 (Hunt *et al*, 1982). Hunt *et* *al* (1982) carried out surveys using the floating car technique in these two cities to establish the benefits of SCOOT compared to fixed time co-ordination using TRANSYT. In Glasgow they found a six per cent reduction in journey time averaged over the day. This was equivalent to a 12 per cent reduction in delay at signalised junctions. In Coventry an average of 5.5 per cent reduction in journey time was measured, equivalent to a 27 per cent saving in delay. They also found that at night SCOOT causes fewer stops than fixed-time control. However, when flows were very low, they felt that vehicle activated control was the better system.

The objectives for SCOOT were to:-

i. "Reduce vehicle delay, stops and congestion below the levels achieved by the best fixed-time system;

ii. Remove the need for updating fixed-time plans; and

iii. Provide information for traffic management purposes." (Hunt *et al*, 1982)

In an area controlled by SCOOT, data is collected by inductive loops in the road approximately 10 to 15 metres downstream of the stop line. Every quarter second the loop detects whether it is occupied or not and outputs a 1 or 0 accordingly. This stream of 1's and 0's is transmitted to a central computer which stores the data as link profile units. The process by which this measure of occupancy is converted to link profile units is a commercial secret. The link profile unit is then divided by 17 to give the modelled flow (in vehicles per hour) across the stop line. This conversion factor of 17 does not change in the SCOOT model, but research carried out by UNTRG has shown that the true conversion factor can vary from as little as 9 to as much as 33, depending on the type of link (*ie* one lane or two) and the time of day (Bell *et al*, 1994). Figure 3.4 shows the flow of information between the detector loops, the SCOOT model computer and the traffic signal (after Hunt *et al*, 1981).

The link profile units are stored in SCOOT as cyclic flow profiles. These are histograms of flow (in link profile units) against time for each cycle, and were developed by Robertson (1974). SCOOT uses these cyclic flow profiles to predict delay, queues and stops. The predicted delay and stops values are then used to calculate a 'performance index', which evaluates the effectiveness of the signal timing strategy to control the traffic flow in the network, and therefore SCOOT seeks to minimise the performance index (Bell *et al*, 1996b).

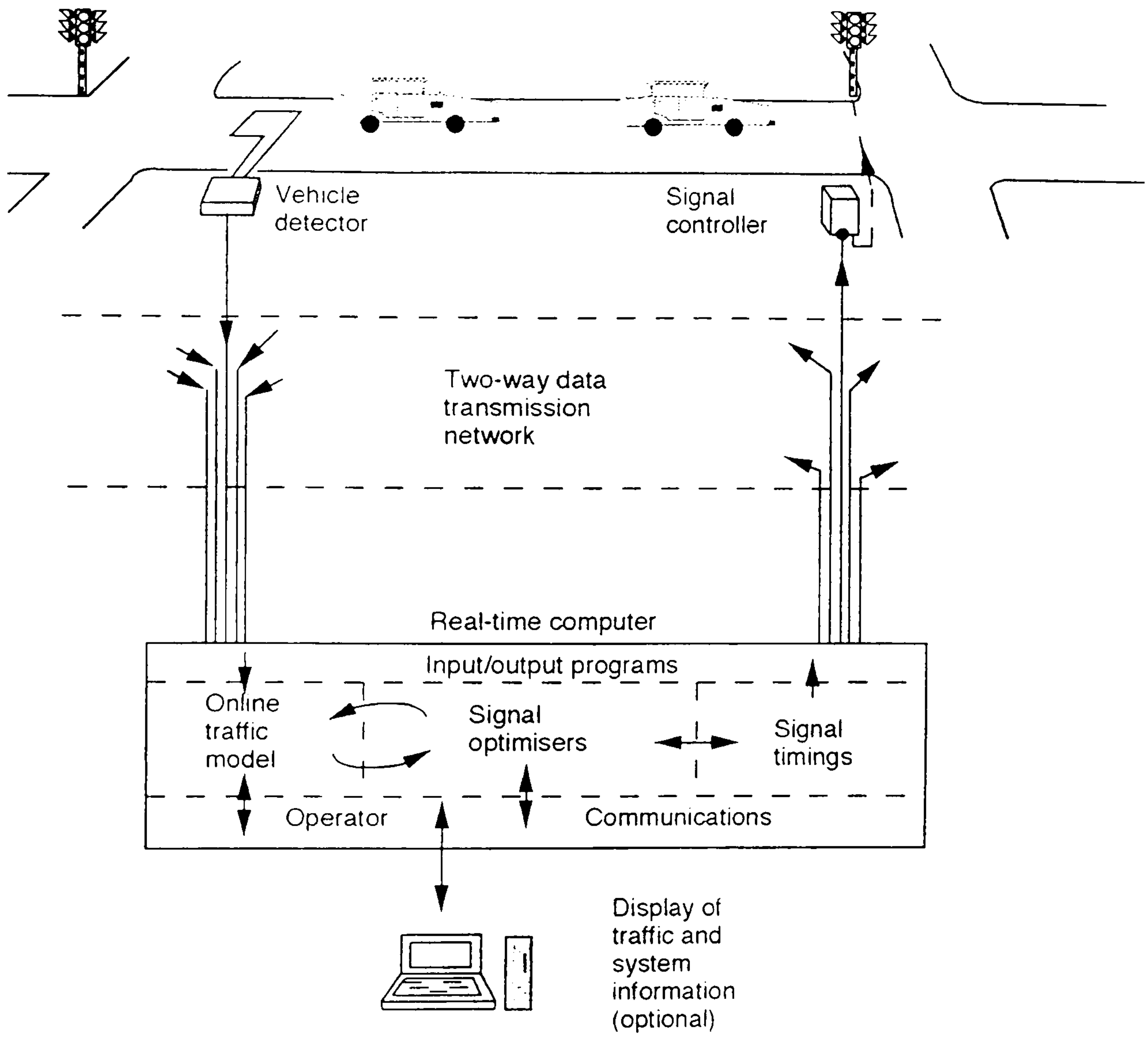

Figure 3.4: The flow of information in the SCOOT traffic control system (after Hunt *et al*, 1981)

The SCOOT model optimises the splits, cycles and offsets for the traffic signals. The split optimiser determines whether the changes in phase should occur earlier, as scheduled or later. Information from the cyclic flow profile determines whether a change in the offset will improve traffic progression immediately upstream or downstream of the junction. Finally, the cycle-time optimiser varies the cycle time for each sub-area, and can chose to double-cycle selected junctions if this improves the performance of the network.

When the SCOOT urban traffic control system was installed in Toronto, Canada, emissions were estimated in three districts. It was found that carbon monoxide emissions reduced by 5% on average (Maclennan, 1994). Work being carried out by Winter (1995) at the University of Nottingham is attempting to quantify these benefits through direct measurement, rather than using predictive relationships to estimate emissions.

Robertson *et al* (1996) carried out a detailed study of the effects of co-ordinated and isolated signal control on journey times and exhaust emissions along the A12 in London. Firstly, six junctions along a six kilometre stretch were operated independently and journey times were measured. After six days a set of fixed time plans were prepared using the TRANSYT program (Robertson, 1969) to co-ordinate the junctions and the study was repeated.

Robertson *et al* (1996) then estimated the exhaust emissions using the MODEM model[1]. They found that carbon monoxide and hydrocarbon emissions were highly correlated with journey times, unlike nitrogen oxides and carbon dioxide. Furthermore, they found that co-ordinating the signals did not necessarily decrease the level of emissions especially at the most heavily-loaded junctions in the morning and evening peak periods.

3.5 Summary and discussion

This chapter and the previous chapter presented a state of art review of research and papers in the field of traffic-related air pollution monitoring, modelling and reduction. Concern about the need for sustainability and the health effects of these pollutants has led to a growing interest in the role of traffic management techniques in reducing emissions.

However, first the exact nature of the relationship between traffic characteristics and air pollution needs to be fully understood. Traditionally, kerbside pollution monitoring surveys were carried out for short periods of time and the simultaneous collection of traffic data was limited. The pollution monitoring equipment used in these surveys was either high precision, expensive systems, or low precision, inexpensive diffusion tubes. The main disadvantages of these were that it was not possible to leave the precision equipment unattended for long periods of time, and the diffusion tubes could only give total pollutant levels aggregated over long periods of typically one or two weeks. Therefore, before substantial progress in research can be made,

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[1] Jourmard, R. J., Hickman, J., Remerlin, J. and Hassel, D. (1992). "Modelling of emissions and consumption in urban areas." Final report. Deliverable No 12 of DRIVE project V1053 - INRETS Report LEN9213. Bron, France.

there is an urgent need for a monitoring system that is inexpensive, can be left unattended and will record levels at regular intervals for 24 hours a day. This has become increasingly important since local authorities have a legal obligation to monitor the air quality in urban areas.

Historically, models for the prediction of air pollution levels from traffic have made simplifying assumptions concerning the nature of the traffic flow and the shape of the pollutant dispersion plume. Also, the most widely used model in the United Kingdom for the prediction of carbon monoxide levels (PREDCO) assumes the traffic is free-flowing, an assumption which is clearly not valid in our present day cities. Statistical techniques for producing empirical models are the least well developed. Potentially, these are the most accurate because they are based on real data. However, these are rarely used due to the lack of suitable data with which to create the models. Large quantities of simultaneously monitored pollution and traffic data are generally not available.

Another issue raised by recent Government publications is the importance of accurate and meaningful air pollution information. This information should take the form of pollution concentration measurements made in real-time to check whether standards have been exceeded, and to make short-term (*eg* day ahead) forecasts. The Government requires local authorities to take action to warn the public about poor air quality and to implement special traffic management strategies to reduce emissions. Such demand management strategies include gating, metering, road pricing, promoting the use of alternative modes or vehicle bans to reduce emissions.

The research described in this thesis therefore seeks to address each of these areas. In the next chapter the mechanism for collecting data from the SCOOT demand-responsive traffic signal control system and the search for a suitable pollution monitoring system will be presented. The design, methodology and implementation of a preliminary set of monitoring surveys will be described. The statistical analysis of the air pollutant concentrations, traffic characteristics and meteorological conditions data will be outlined. The recommendations from these surveys form the basis of subsequent survey and analysis work described in later chapters of this thesis.

4. Monitoring air pollution and traffic in Nottingham and Leicester

4.1 Introduction

The state of art review presented in Chapter 2 and Chapter 3 showed that, to date, long-term traffic-induced air pollution monitoring has been carried out at background sites using either inexpensive diffusion tubes (approximately £30) or expensive precision systems (approximately £130 000). Alternatively, short-term surveys have been carried out at the kerbside using equipment which required constant supervision.

Diffusion tubes are useful for identifying long-term trends in air pollution. Each tube, when sent to a laboratory for analysis, will reveal how much nitrogen dioxide, for example, has been absorbed in the previous two weeks. Diffusion tubes can be placed at the kerbside (attached to a lighting column, for example) or in rural or urban background sites.

The expensive precision pollution monitoring systems, such as those forming the Department of the Environment's Automatic Urban Monitoring Network, require a site which is approximately six metres by three metres. The site will preferably have a mains supply (although some systems can be run from batteries which only supply power for about eight hours) and a telephone connection to allow remote access to the data. These systems are usually permanently sited in a background location according to the standard criteria described in Section 3.2.4.

As previously stated, many kerbside monitoring studies have been short-term because the equipment could not be left unattended. The surveys which lasted for longer periods of time (a few weeks or more) generally used equipment which was not able to give real-time information (diffusion tubes were used, or data had to be downloaded before analysis could take place). Hence one of the aims of this research was to develop a low-cost kerbside pollution monitoring system which could be left in place for long periods of time (indefinitely if required) without fear of vandalism. Furthermore, this system should be capable of remotely giving real-time information about pollution concentrations.

An important step in the development process was to identify suitable kerbside locations for the monitoring systems which would provide useful data. Two other important factors were the choice of sensors with a suitable sensitivity, and an adequate data sampling rate to obtain meaningful air pollution data.

Once data has been collected it needs to be processed and stored in a suitable form for statistical analysis to investigate its nature, trends and relationships. There are a vast number of statistical techniques available, so an objective of this research was to identify appropriate techniques for the analysis of air pollution data, including the meaningful tabulation of vast quantities of information. This issue needed to be addressed because local authorities will want to provide information to the public in a clear and concise format.

The main goal of this research was to formulate a model which used SCOOT traffic characteristics data to predict pollutant concentrations. Historically, pollution concentration prediction has taken one of two forms - either the development of a model from the first principles of dispersion, meteorology and site characteristics or, less commonly, the use of existing data and statistical techniques, such as linear multiple regression, to develop an empirical model.

The state of art review in Chapter 3 demonstrated that to date no work has been carried out to use the real-time traffic data available from the SCOOT model to predict pollutant concentrations. Such a model could then be used in many different ways. For example, on-line to provide a real-time assessment of air quality without actually needing to monitor pollution concentrations, as part of signal control software to optimise for air quality rather than delay or stops, or off-line to assess the environmental impact of new urban roads at the design stage (in the same way as PREDCO predicts carbon monoxide levels for roads with free-flowing traffic), and so on.

This chapter describes the first stages of the research which was carried out to achieve these objectives and aims. The infrastructure which made this research possible, the study areas in Leicester and Nottingham, and the mechanism by which SCOOT traffic data was collected will be described. The preliminary surveys carried out will be discussed.

4.2 Leicester study area

Leicester is a typical medium-sized city in the East Midlands. The road network in and around the city centre comprises of a series of connected radial and ring roads. In 1988 a SCOOT system was installed in Leicestershire, and there are now eleven SCOOT regions - eight in Leicester and one in each of the satellite towns of Loughborough, Hinckley and Melton Mowbray (Bennett, 1992). Figure 4.1 shows the road network in Leicester and its SCOOT regions.

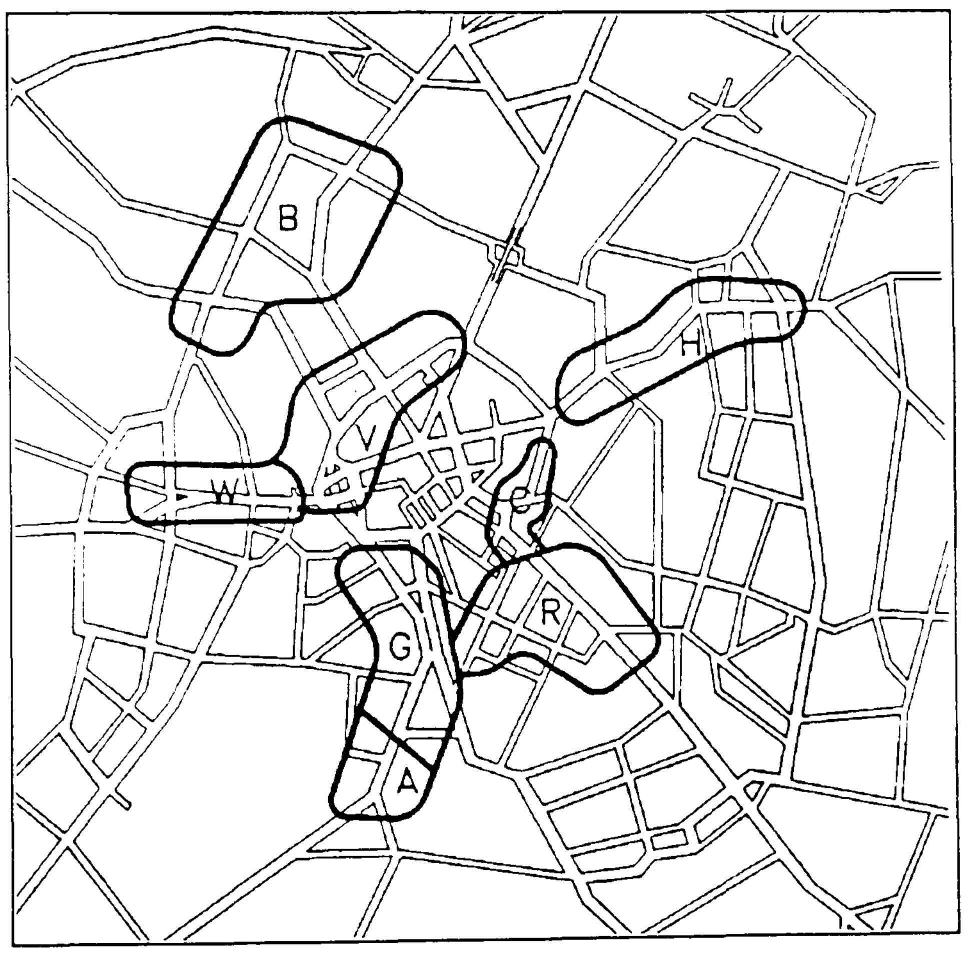

Figure 4.1: Leicester SCOOT regions (Bennett, 1992)

The area of Leicester shown in Figure 4.1 is approximately five kilometres square. The eight SCOOT regions have a total of 167 links with 62 SCOOT controlled junctions and pelican crossings. During the last few years research at UNTRG has concentrated on Region R. This is because its road layout allows traffic to take alternative routes whilst travelling into, across and out of the region. Figure 4.2 shows the layout of the SCOOT loops in Region R.

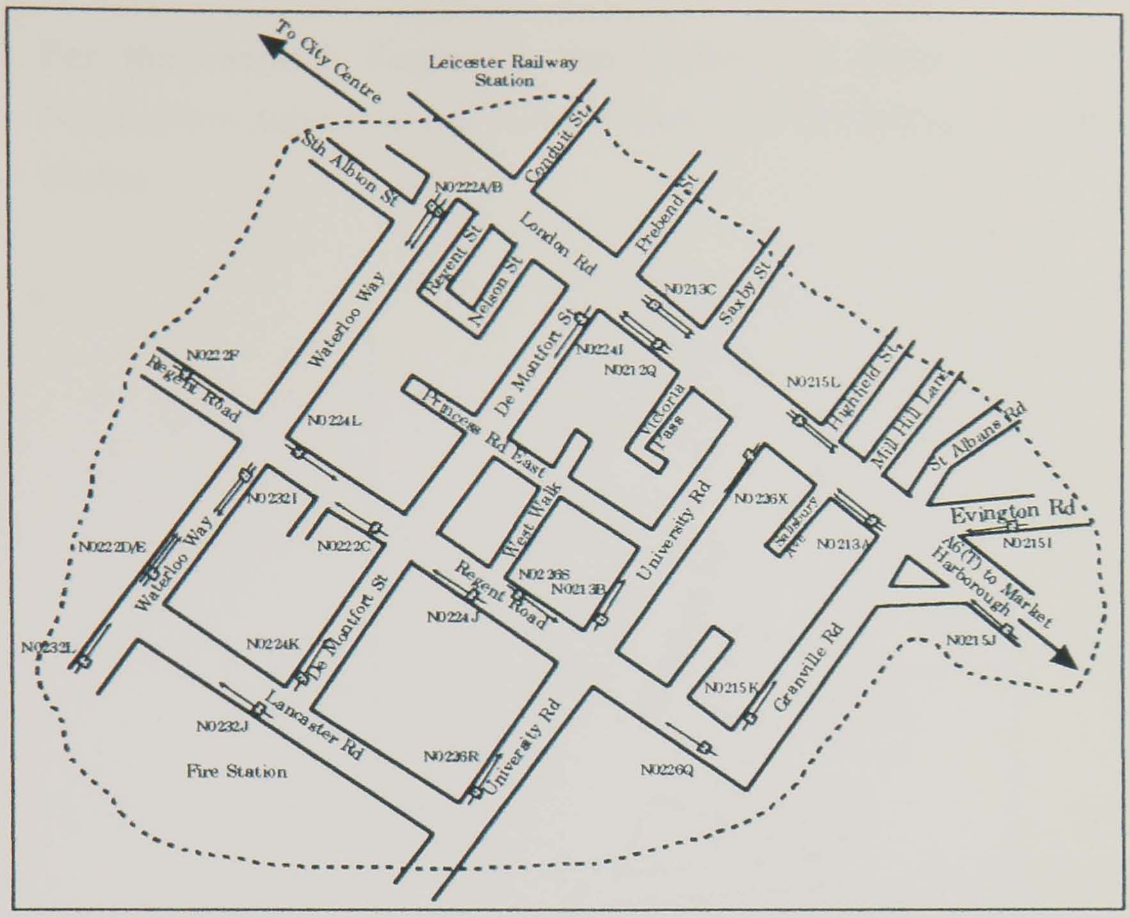

Figure 4.2: Region R and its SCOOT loops

4.3 Nottingham Study Area

In November 1994 Nottinghamshire County Council began to install a SCOOT system in Nottingham. There are currently eight SCOOT regions, with a ninth to be installed in the near future (Figure 4.3). This figure clearly demonstrates the different characteristics of the Nottingham and Leicester SCOOT regions.

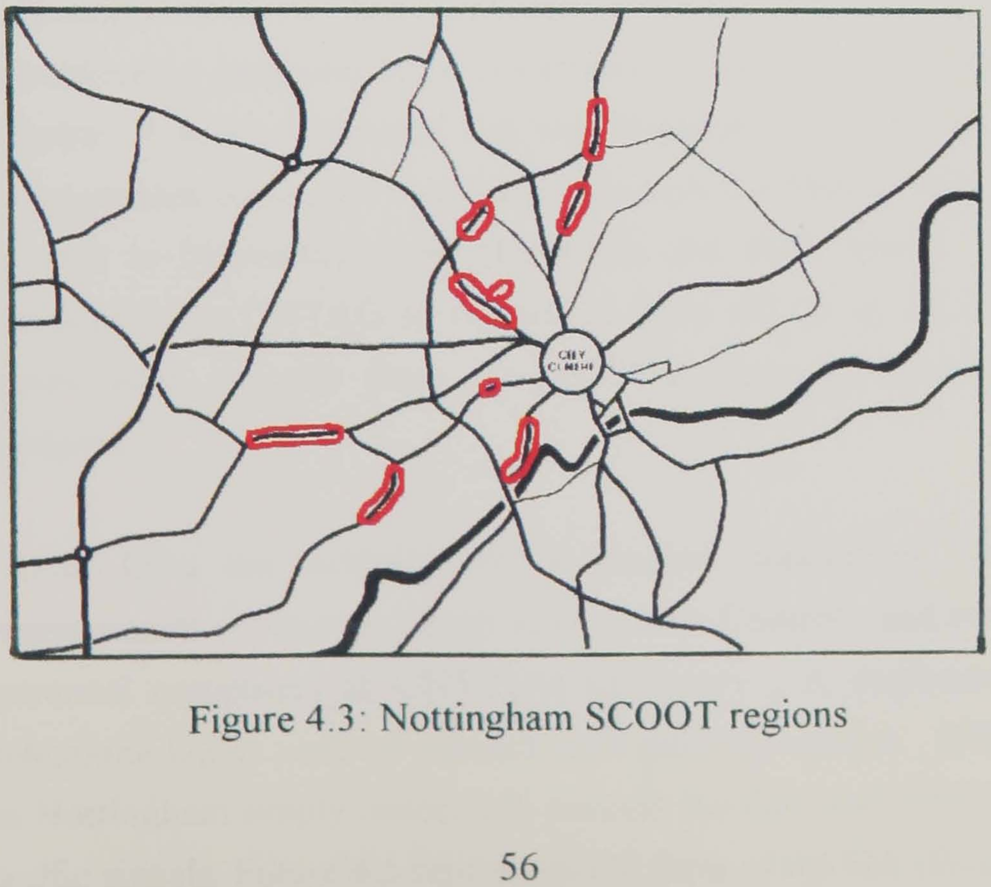

Figure 4.3: Nottingham SCOOT regions

For this research Region S was studied, as shown in Figure 4.4. The Nottingham sub-areas are radial routes with little scope for alternative route choice.

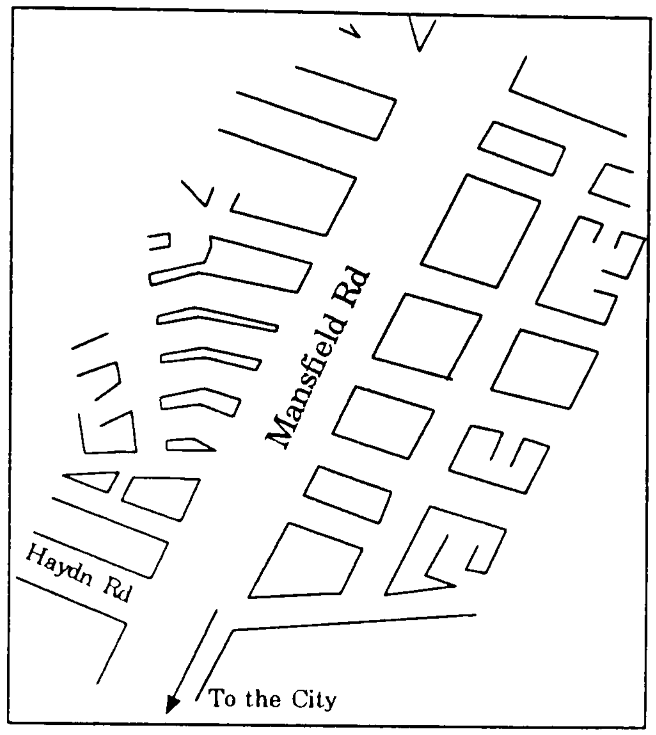

Figure 4.4: Region S

4.4 SCOOT data collection

In 1989 the Science and Engineering Research Council (SERC) funded the research project "A study of traffic route patterns in a city with demand responsive traffic signal control" (Bell, 1990b; Martin, 1992) which financed a telecommunications link between UNTRG's laboratory and the traffic management computer at Leicestershire County Council's Area Traffic Control Centre. A second, identical link with Nottinghamshire County Council's traffic management computer was funded through the SERC:LINK funded ITEMMS project in November 1994 (Reynolds and Bell, 1995). These links enable researchers at UNTRG to collect 12 hour (07:30 to 19:30) continuous data seven days a week from the SCOOT demand-responsive traffic control systems.

These links are achieved by a modem connection between the traffic management computer at each Area Traffic Control, and two IBM compatible personal computers at UNTRG's laboratory. A dedicated British Telecom telephone line is used to connect each pair of modems. UNTRG's computers in Nottingham simply collect and process the data and are unable to control the traffic signals. Figure 4.5 represents the form of the link (Evans, 1991).

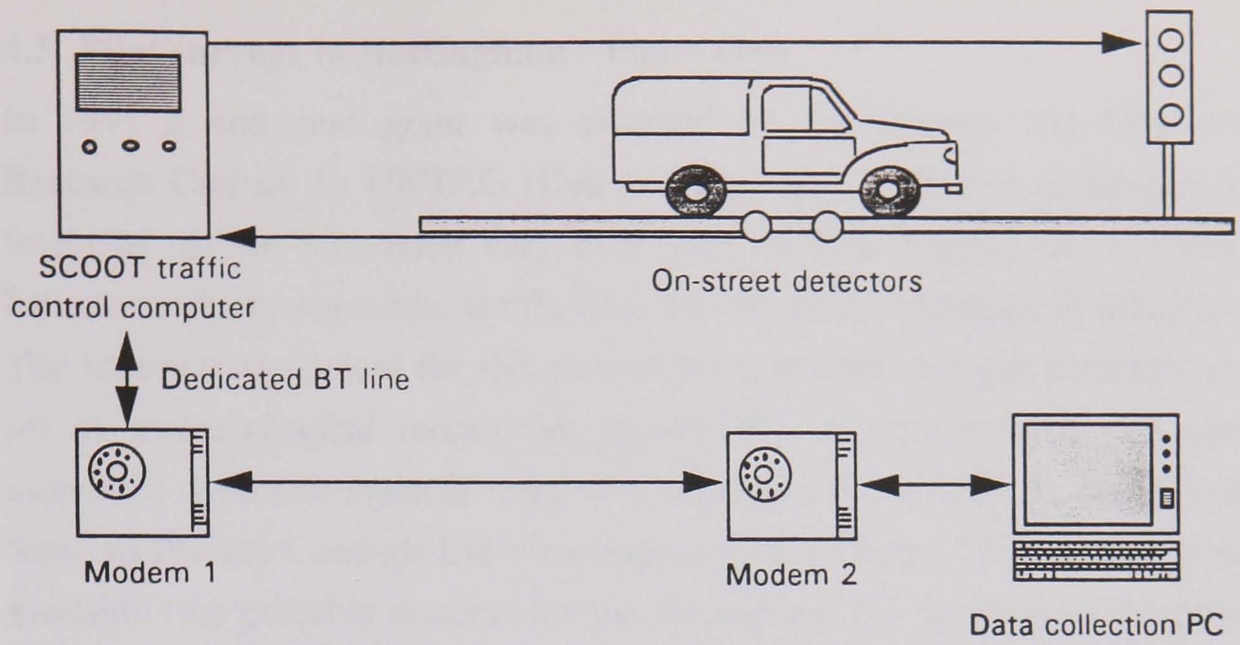

Figure 4.5: The SCOOT data collection link (Evans, 1991)

The SCOOT model outputs information in the form of messages. The M02 message is of particular importance to the research described here. The format of the M02 message is as follows:-

day *time* M02 *LINK* *CYC* *STP* *DLY*10* *FLO* *RAW* *CONG* *FLT*

where

day	is the day of the week
time	is the time that the M02 message was output by the traffic control computer
LINK	is the unique link identifier which starts with "N" and then a four or five digit identifier for the junction (node) followed by a letter for the particular link (*eg* N13221R)
CYC	is the cycle time for the junction (s)
STP	is the number of vehicles which are predicted to stop at the stopline, in vehicles per hour (veh/h)
*DLY*10*	is the delay experienced by the vehicles on a link in (1/10)veh.h/h
FLO	is the flow of vehicles across the stopline in veh/h
RAW	is a measure of congestion in intervals[1]/h
CONG	is an alternative measure of congestion in intervals/h
FLT	is a fault indicator.

[1] One interval is four seconds long.

4.5 Pilot surveys in Nottingham - Phase One

In 1991 a one year grant was awarded by the Science and Engineering Research Council to UNTRG (Bell and Reynolds, 1993) to investigate how levels of carbon monoxide vary over time, and to explore the relationship between carbon monoxide, traffic flow and climatic conditions in urban areas. The required equipment for this project were at least two gas detectors and a set of meteorological monitoring equipment. It was realised that carbon monoxide detection systems were very expensive (£10k to £15k each), and so Siemens Plessey Controls Ltd were approached for help. They agreed to make available two portable systems for use throughout the duration of the project, and to provide technical assistance where necessary. These gas detectors were made by Biosystems of California, USA. The trade-names of these systems was "Cannonball" and are referred to as such here. The climate equipment was bought from Eltek Ltd, and consisted of an anemometer, a wind vane and a temperature/humidity probe. All of the equipment was mounted on a bar attached to a camera tripod, as shown in Figure 4.6. Although this equipment could not be left unattended, it did at least allow data to be collected so that the research could commence.

The aims of this first phase of surveys were to gain familiarisation with the equipment, to develop a methodology for the next phase of surveys in Leicester and to develop the data processing and analysis techniques.

Firstly, the literature was examined to establish how other researchers have carried out air pollution surveys (see Section 3.2). Most notably, Koushki (1989, 1989, 1991) had recorded carbon monoxide levels at a height of 1.5m above the road surface, and it was decided to use this height for the survey work in this project, as it corresponds roughly with head-height. However, it was not clear exactly where the gas detector should be placed in relation to the stop-line at a junction. Therefore a preliminary study was undertaken to investigate the effect of different locations.

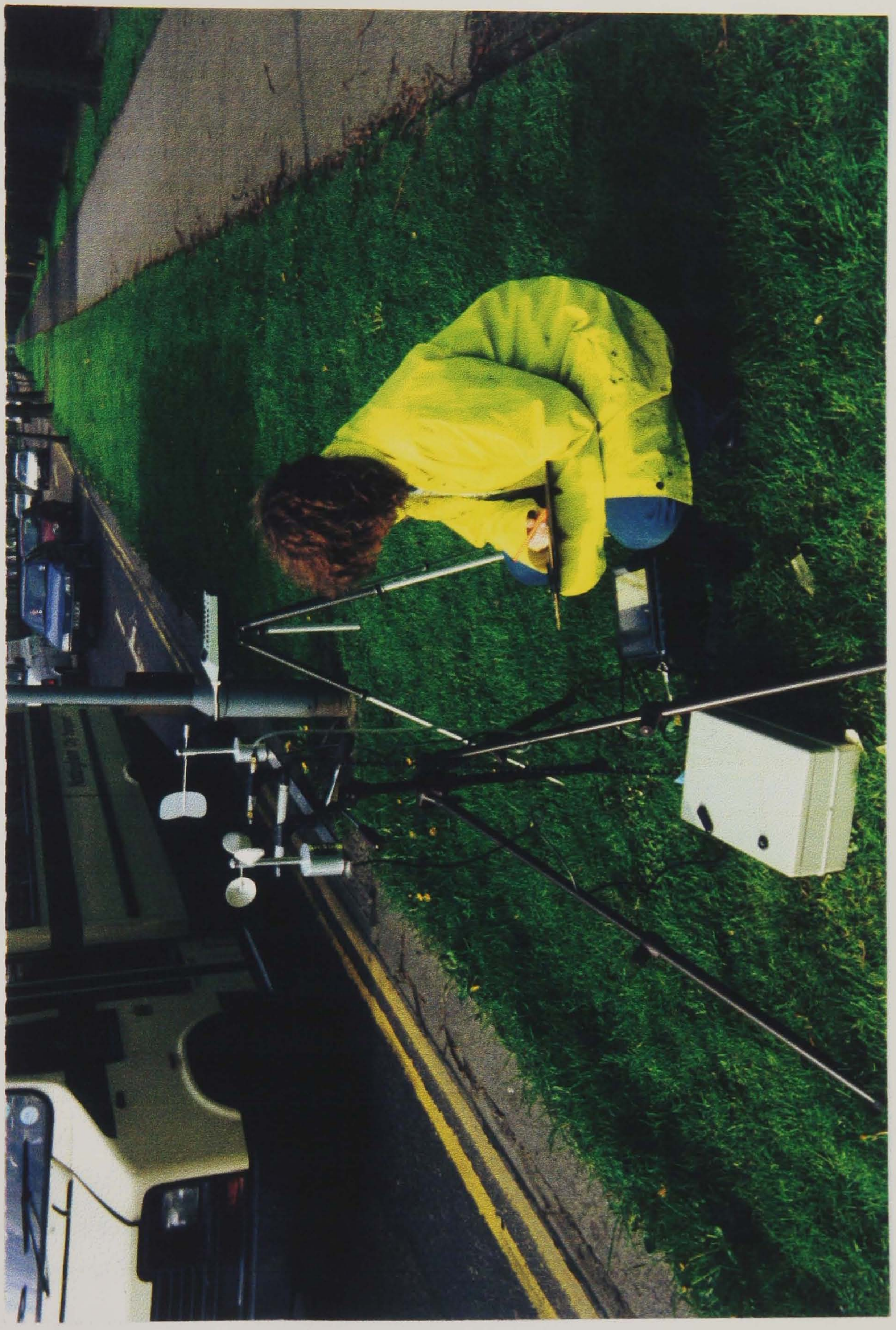

Figure 4.6: Pollution and climate monitoring equipment.

4.5.1 Methodology

This survey took place on a main road just outside the University of Nottingham Campus using two gas detectors (referred to as "Cannonball" One and "Cannonball" Two). Figure 4.7 shows the layout of the road, and the inset shows the various positions used.

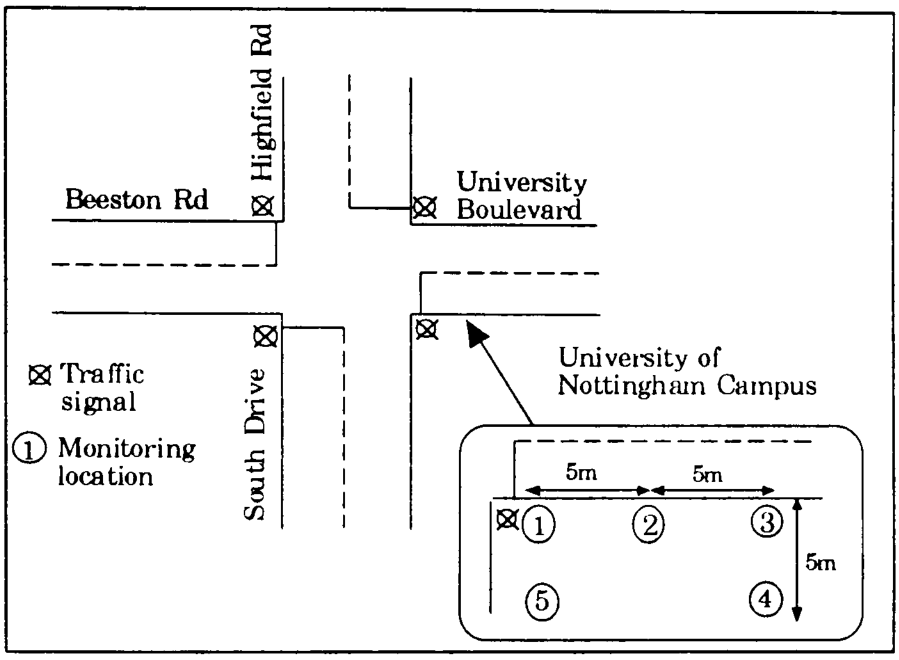

Figure 4.7: Nottingham survey layout

Cannonball One was placed two metres down from the stopline, and 1.5m from the edge of the road, at position 1 (the control site). Cannonball Two was placed next to Cannonball One for 15 minutes and then moved to position two for 15 minutes, position three for 15 minutes, position four for 10 minutes and position five for 10 minutes.

4.5.2 Statistical analysis technique

The statistical technique chosen to investigate the difference between the carbon monoxide levels measured at the control site and the other four sites was bivariate correlation analysis. When two variables are plotted against each other as a scatterplot (see Figure 4.8), it possible to fit a "best straight line" and the strength of the relationship (*ie* the correlation) between the variables can be calculated using ordinary least squares estimation.

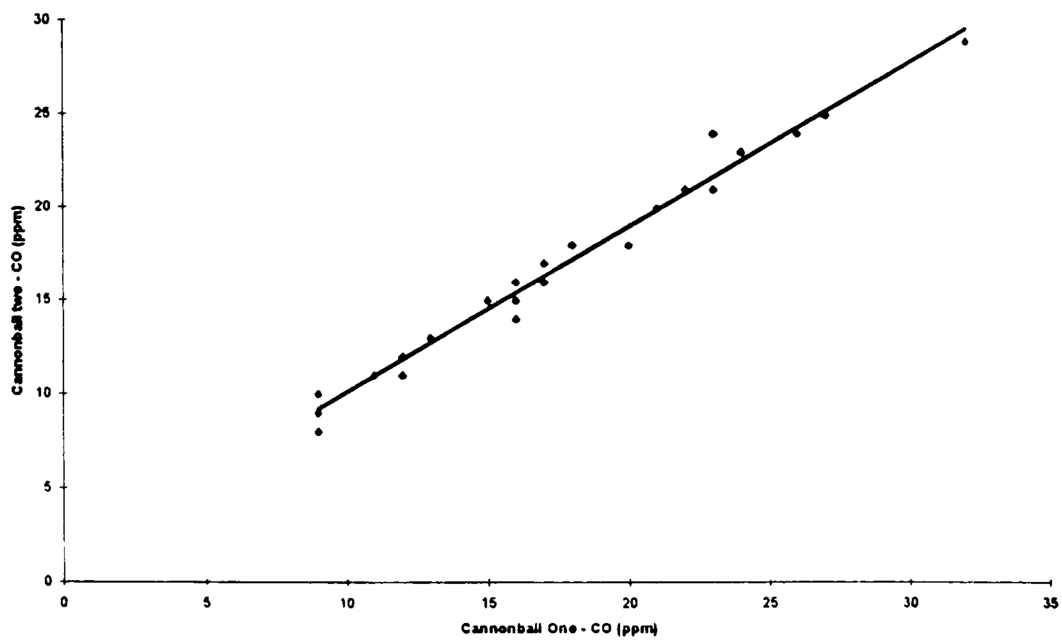

Figure 4.8: Scatterplot of carbon monoxide (ppm) levels measured using Cannonball One and Cannonball Two at position 1

4.5.2.1 Ordinary least squares estimation

The equation of the fitted, best straight line is written as

$$y_i = c + b_1 x_{1,i} + \varepsilon_i \qquad i = 1,\ldots,n$$

where b_1 represents the average change in y per unit change in x. The constant, c, represents the effect on y of all independent variables which are excluded from the equation, and ε_i is the disturbance (residual) term.

Norušis (1993) showed that, using a minimized least squares criterion, it is possible to estimate the values of b_1 and c:-

$$\hat{b}_1 = \frac{\sum_{i=1}^{n}(x_{1,i} - \bar{x}_1)(y_i - \bar{y})}{\sum_{i=1}^{n}(x_{1,i} - \bar{x}_1)^2}$$

$$\hat{c} = \bar{y} - \hat{b}_1 \bar{x}_1$$

where $\bar{y} = \frac{1}{n}\sum_{i=1}^{n} y_i$ and $\bar{x}_1 = \frac{1}{n}\sum_{i=1}^{n} x_{1,i}$.

The standard error of the slope, b_1, is calculated as

$$\sigma_{b_1} = \frac{\sigma}{\sqrt{(n-1)s_x^2}}$$

and the standard error of the intercept, c, is calculated as

$$\sigma_c = \sigma\sqrt{\frac{1}{n} + \frac{\bar{x}^2}{(n-1)s_x^2}}.$$

However, since the population variance of the errors, σ^2, is not known, it is estimated using the equation

$$S^2 = \frac{\sum_{i=1}^{n}(y_i - c - b_1 x_i)^2}{n-2}.$$

The positive square root of S^2 is called the *standard error of the estimate* (Norušis, 1993).

4.5.2.2 Measuring the strength of the relationship

When a best straight line is fitted to a dataset it is important to measure the strength of the relationship between the observed and the calculated values. It is determined by calculating the correlation coefficient, R^2, which is derived as follows:

It can be shown (*eg* in Draper and Smith, 1981) that

$$\sum(y_i - \bar{y})^2 = \sum(\hat{y}_i - \bar{y})^2 + \sum(y_i - \hat{y}_i)^2$$

ie $\quad \text{TSS} = \text{ESS} + \text{RSS}$

where TSS is the total sum of squares, *ie* the total variation of the y values about their own mean, ESS is the explained (or regression) sum of squares, and RSS is the residual (or unexplained) sum of squares. The correlation coefficient, R^2, is a measure of the fraction of the total sum of squares that is explained by the x's,

$$R^2 = \frac{\text{ESS}}{\text{TSS}} = 1 - \frac{\text{RSS}}{\text{TSS}} = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \qquad 0 \le R^2 \le 1.$$

An R^2 value of 0 represents no correlation between the variables, and an R^2 value of 1 represents a perfect correlation between the variables.

4.5.3 Results

Figure 4.9 shows the levels of carbon monoxide measured by each detector during the survey. It can be seen that the carbon monoxide levels measured by the two meters were almost identical for the first 15 minutes, and were very similar for the next 15 minutes. The next step was to examine the correlation coefficient between the readings at the control site and the other monitoring sites.

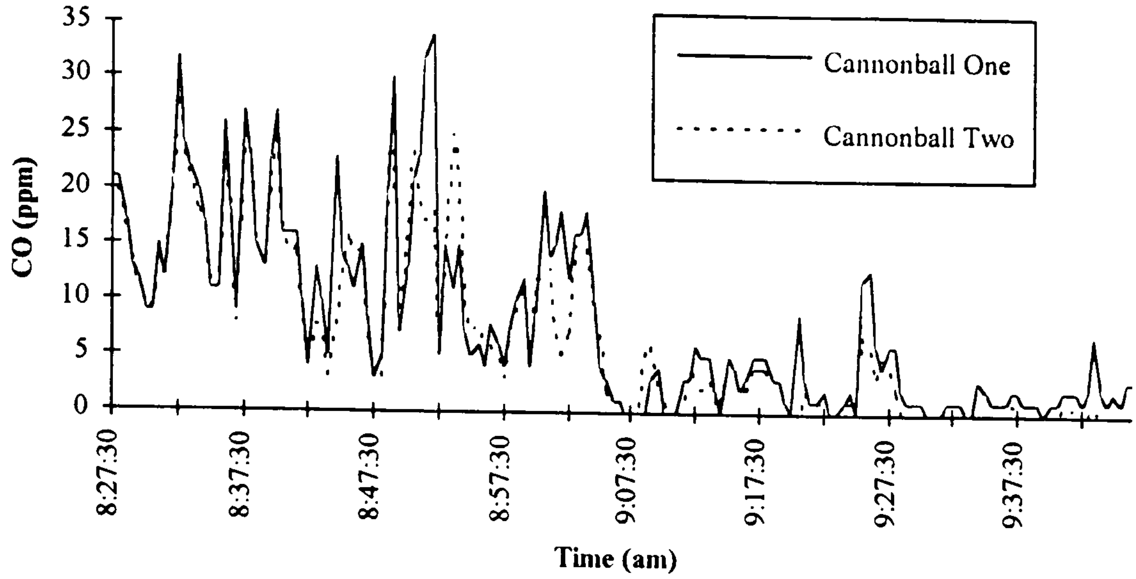

Figure 4.9: Results from the Nottingham survey

Table 4.1 gives the correlation coefficient (R^2) between the readings from the two monitors at each position. This table confirms that the carbon monoxide levels measured by the two monitors at the control site were almost identical, and therefore it was possible to be confident in the measurements from the other sites. The correlation between the control site and site 2 was surprisingly low, despite the apparent similarity in the graph in Figure 4.9. The high correlations between the measurements at the control site and at sites 3 and 5 suggested that kerbside pollution monitoring could be carried out up to 10 metres upstream of the stopline, and up to 5 metres from the kerbline.

Table 4.1: Correlation between readings for Cannonballs One and Two

Cannonball Two location	Duration (minutes)	Correlation between readings
1 (Control site)	15	0.99
2	15	0.56
3	15	0.75
4	10	0.66
5	10	0.83

Figure 4.10 shows the scatterplot for the levels measured at each position. It can be seen that there are several outlying values which correspond to the measurements made at site 2. These explain why the correlation coefficient was relatively low.

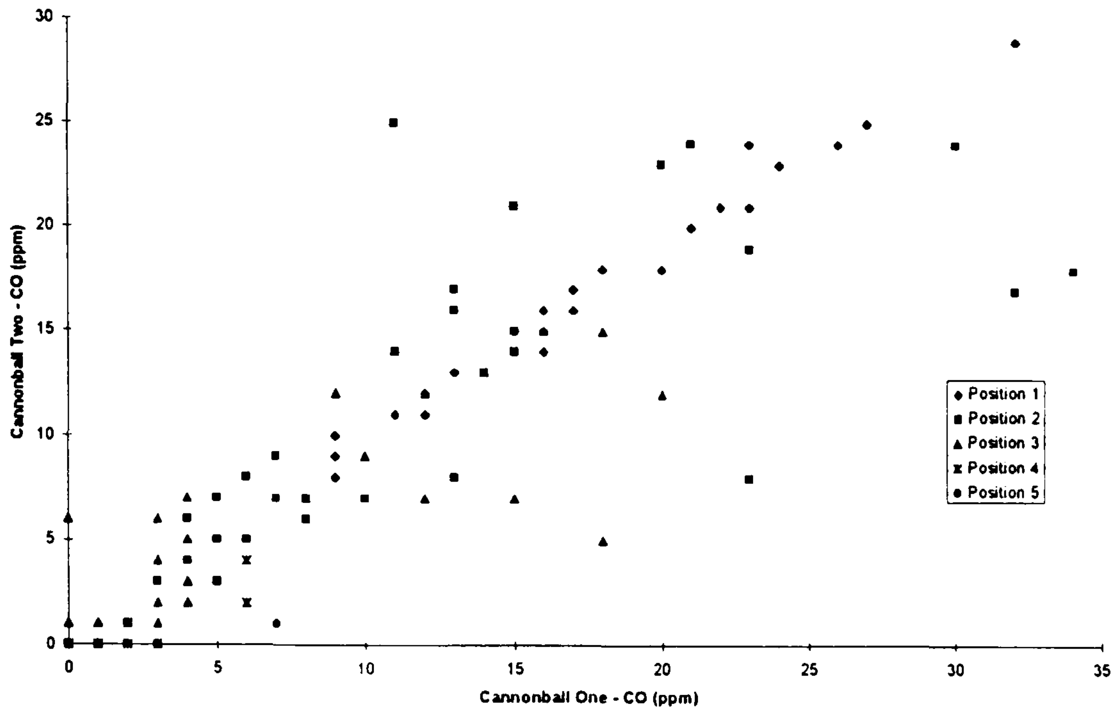

Figure 4.10: Scatterplot of carbon monoxide levels at each position

4.5.3.1 Difference of means test

The carbon monoxide levels measured at each of the positions were compared with the levels measured at the control site using the difference of means test (t-test). This examines whether two samples of size N_1 and N_2, with means $\bar{x}_1$ and $\bar{x}_2$, and standard deviations S_1 and S_2 come from the same population. It is calculated using the following formula (Kanji, 1994):

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\sigma\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}}$$

where $$\sigma = \sqrt{\frac{N_1 S_1^2 + N_2 S_2^2}{N_1 + N_2}}.$$

The degrees of freedom of this test is calculated as $\nu = N_1 + N_2 - 2$. Once the t-value has been calculated, tables of critical values (such as Neave, 1989) are consulted to determine whether there is a statistically significant difference between the means of the samples. There is a difference if the calculated t-value is greater than the critical value.

In the case of the data collected during this survey, there was no statistically significant difference between the means of the levels monitored at the control site and at positions 2 and 3 at the 95% confidence level.

4.5.4 Conclusions

Two conclusions were drawn from this pilot study. Firstly, that the correlation between emissions measured at the control site and the other sites was fairly high. Secondly, at the flow levels and climatic conditions prevailing during the survey, the levels of emissions remained statistically similar at the sites along the kerbside. This meant that the sensor could be placed up to 10 metres from the stopline, but it must be close to the kerbside. It was decided that a standard monitoring location should be used for the next phase of surveys in Leicester so that results from different links could be directly compared if necessary. The position chosen was five metres upstream of the stopline, which is approximately one vehicle length, one metre from the kerbside and one and half metres high, which corresponds to head height.

4.6 Surveys in Leicester - Phase Two

4.6.1 Introduction

The second phase of surveys using the portable carbon monoxide and meteorological monitoring system were carried out in Region R of the Leicester SCOOT network. This region has 25 SCOOT loops controlling six signalised junctions. The programme of surveys is given in Table 4.2. A total of fifty three hours of monitoring was carried out. No survey was longer than six hours.

Table 4.2: Survey programme

Date	SCOOT loop	Junction	Time
29/4/92	N0215J	London Rd/Granville Rd	7.42-9.12
15/5/92	N0215J	London Rd/Granville Rd	7.31-11.56
27/5/92	N0232I	Waterloo Way/Lancaster Rd	7.33-10.53
16/6/92	N0226X	University Rd/Regent Rd	7.35-12.00
17/6/92	N0226X	University Rd/Regent Rd	12.05-17.55
13/8/92	N0224J	Regent Rd/DeMontfort St	12.06-14.01
18/8/92	N0224J	Regent Rd/DeMontfort St	12.09-17.59
20/8/92	N0224J	Regent Rd/DeMontfort St	8.04-12.14
3/9/92	N0213A	London Rd/University Rd(inbound)	7.56-10.46
10/9/92	N0213C	London Rd/University Rd(outbound)	12.22-17.57
14/9/92	N0224I	DeMontfort St/Regent Rd	12.16-17.41
16/9/92	N0215I	Evington Rd/London Rd	8.14-11.59
21/9/92	N0222F	Regent Rd/Waterloo Way	9.14-12.54

4.6.2 Methodology

The equipment used on each survey was a gas detector (Cannonball), a wind vane, an anemometer, a temperature/humidity probe and two hand tallies for counting and classifying the vehicles. The equipment was set up five metres from the stop line and one metre from the kerb to a height of 1.5 metres to be consistent with the work carried out in Nottingham (see Section 4.5) (Reynolds and Bell, 1992). The two surveyors sat by the equipment and counted the passing vehicles, using a three vehicle type classification, which were recorded every five minutes for the duration of the survey. On single carriageway links flows in both directions were recorded (designated as nearside and offside flows) whereas, on dual carriageways, only the flow on the surveyors' side of the road was recorded (designated as total flows). It was felt that traffic on the opposite side of the road would contribute more to the pollution levels on single carriageway roads than on dual carriageway roads because of the distance over which the pollutants will disperse. The classification of the traffic was noted to give an indication of the proportions of diesel-engined vehicles compared with petrol-engined vehicles.

The variables recorded during the survey period were the concentration of carbon monoxide in parts per million (ppm), the temperature (°C), the relative humidity (%), the wind speed (m/s), the wind direction (degrees clockwise from a line perpendicular to the road), number of cars, number of buses and number of heavy goods vehicles (HGVs). The carbon monoxide values recorded were five minute averages based on one second samples, and the instantaneous values of the meteorological variables were recorded every five minutes. The values of FLOW, DELAY, STOPS, CONGESTION and RAW from the SCOOT M02 message for the particular link were collected by the method described in Section 4.4. Data for each SCOOT link was transmitted every five minutes. Some SCOOT data was not available due to technical problems with the communications link between Leicestershire County Council's traffic management computer and UNTRG's laboratory.

4.6.2.1 Descriptive statistics

Table 4.3 summarises all the data collected throughout the programme of 12 surveys. This table gives the mean, standard deviation, standard error, minimum, maximum and number of five minute intervals for which the data was collected. The tables in Appendix 1 contain the full set of results for each survey. It was calculated that only 4% of the vehicles counted were buses or HGVs, which was assumed to be representative of the proportion of diesel engined vehicles travelling in Region R.

Table 4.3: Summary of data collected

Variable	Mean	Standard Deviation	Standard Error	Min	Max	N
Carbon Monoxide (ppm)	17.753	22.706	0.894	0	188	645
Temperature (°C)	19.291	4.096	0.161	9.2	28.8	645
Wind Speed (m/s)	1.044	0.564	0.022	0.1	3.5	645
Wind Direction (°)	224.658	75.706	2.981	1.44	355.7	645
Relative Humidity (%)	52.032	17.274	0.68	16	88.5	645
Cars (total)	67.309	35.87	1.92	10	161	349
HGVs (total)	1.903	2.011	0.108	0	11	349
Buses (total)	1.63	1.803	0.097	0	8	349
Cars (nearside)	29.945	10.224	0.621	0	57	271
HGVs (nearside)	0.336	0.634	0.038	0	3	271
Buses (nearside)	0.48	0.682	0.041	0	3	271
Cars (offside)	29.339	13.269	0.806	5	76	271
HGVs (offside)	0.443	0.658	0.04	0	3	271
Buses (offside)	0.498	0.704	0.043	0	3	271
STOPS (veh/hr)	279.256	245.072	11.221	18	1610	477
DELAY (1/10(veh.hr/hr))	15.128	25.378	1.162	0	306	477
FLOW (veh/hr)	365.147	285.151	13.056	22	1674	477
CONGESTION (intervals/hr)	0.604	5.411	0.248	0	72	477
RAW (intervals/hr)	3.119	10.776	0.506	0	96	454

The data collected during the 12 air pollution surveys carried out in Leicester show that levels of carbon monoxide can vary greatly from one five minute interval to the next. The graph given in Figure 4.11 is a typical example. In general, it was found from the analysis of the data that there was no systematic increase or decrease in the carbon monoxide levels throughout the period of each survey. However, this may simply be due to the fact that the surveys were relatively short, and the variations in carbon monoxide levels were quite large.

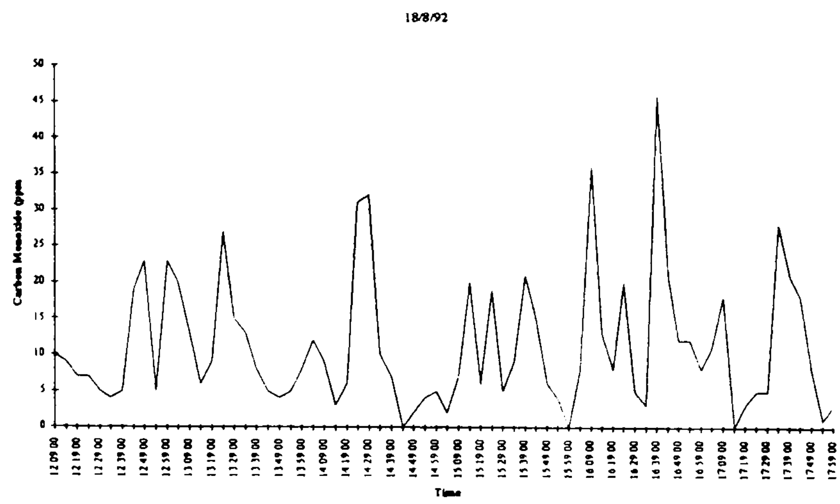

Figure 4.11: Variation in carbon monoxide levels

4.6.2.2 Bivariate scatterplots

As described earlier, the first stage in identifying relationships between variables is to produce bivariate scatterplots of the variables. These are given in Figure 4.12 to Figure 4.14, the units of the variables are those given in Table 4.3. Figure 4.12 is a matrix scatterplot of the measured carbon monoxide levels against all of the meteorological variables. To interpret the scatterplots in each cell of the matrix it is necessary to note which row and which column the cell is in. The abbreviated variable names are given on the leading diagonal of the matrix. The row identifies the variable on the *y*-axis and the column identifies the variable on the *x*-axis. It is unfortunate that no scale is given, but the matrix scatterplot is designed to draw attention to any relationships which should be investigated further. Figure 4.12 shows that there is no linear relationship between carbon monoxide levels and any of the meteorological variables, but that temperature and relative humidity are linearly related.

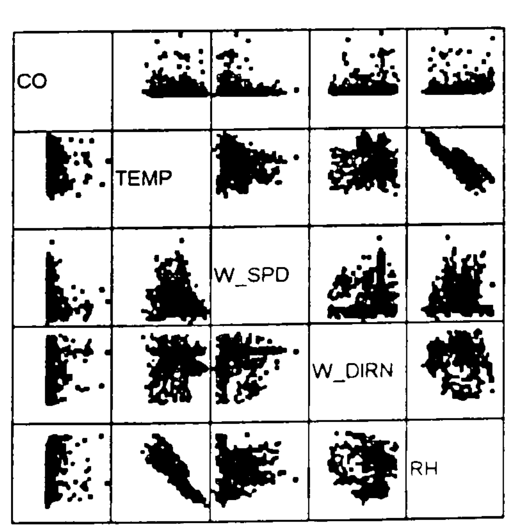

Figure 4.12: Matrix scatterplot of carbon monoxide levels and meteorological variables

Figure 4.13 is a matrix scatterplot of carbon monoxide levels and the various SCOOT parameters from the M02 message. Again, there are no obvious linear relationships except between STOPS and FLOW. Figure 4.14 shows scatterplots of carbon monoxide levels against the number of cars, in each five minute interval, counted during the surveys. It is interesting to note that 90% of carbon monoxide levels are below 37 ppm and that the high levels do not necessarily correspond to high numbers of cars. In fact, the maximum carbon monoxide level of 188 parts per million, recorded in the survey on the 17th June 1992, was entirely due to *one* car stopped at the set of traffic lights. This implies that a few poorly maintained vehicles in the fleet with high emission levels can give rise to higher kerbside concentrations of carbon monoxide than a high flow of well maintained vehicles.

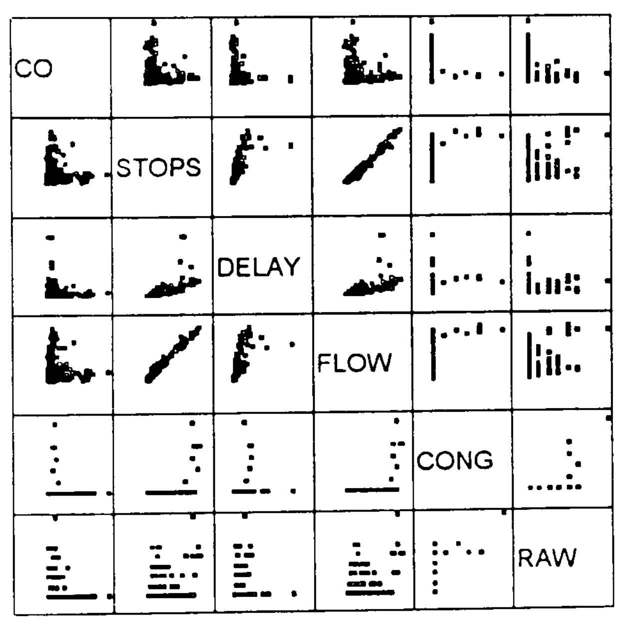

Figure 4.13: Matrix scatterplot of carbon monoxide levels and SCOOT parameters

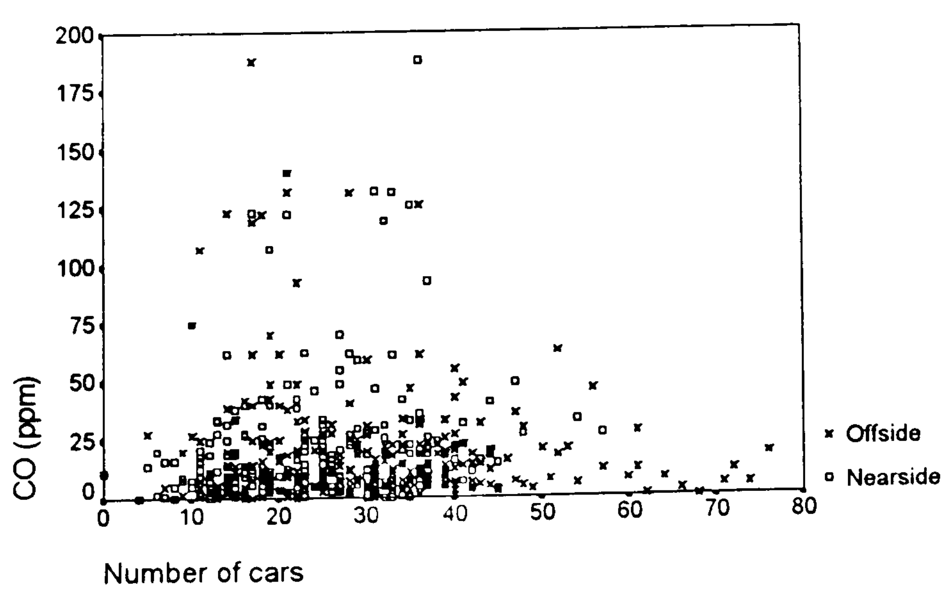

Figure 4.14: Scatterplot of carbon monoxide levels against number of cars

Tables A1 to A18 in Appendix 1 show that the correlation (r = $\sqrt{R^2}$) between each of the measured parameters (temperature, wind speed and direction, relative humidity, number of cars, buses and heavy goods vehicles, STOPS, DELAY, FLOW, CONGESTION and RAW) and carbon monoxide were not statistically significant. This indicates that there was not one parameter which alone can be used as an predictor of carbon monoxide levels, which is confirmed by the scatterplots shown in Figure 4.12 to Figure 4.14.

4.6.2.3 Multiple regression

The theory of bivariate regression extends to multiple regression. The multiple linear regression equation can be most readily expressed in terms of matrix notation. The equation for a regression with k - 1 independent variables, and n observations is

$$Y = X\hat{B} + \hat{a}$$

where $Y = \begin{bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_n \end{bmatrix}$; $X = \begin{bmatrix} 1 & X_{1,1} & \cdots & X_{k-1,1} \\ 1 & X_{1,2} & \cdots & X_{k-1,2} \\ \vdots & \vdots & & \vdots \\ 1 & X_{1,n} & \cdots & X_{k-1,n} \end{bmatrix}$; $\hat{B} = \begin{bmatrix} \hat{b}_1 \\ \hat{b}_2 \\ \vdots \\ \hat{b}_n \end{bmatrix}$ and $\hat{a} = \begin{bmatrix} \hat{a}_1 \\ \hat{a}_2 \\ \vdots \\ \hat{a}_n \end{bmatrix}$.

Then, $\hat{B} = (X'X)^{-1} X'Y$.

The SPSS for Windows package (Norušis, 1993) calculates the components of the matrix $\hat{B}$, and calculates the residuals, $\hat{a}$, by subtraction. In addition, the correlation coefficient, R^2, and the t-values for each coefficient are calculated.

It is important to assess whether the coefficients of the variables in the regression equation are statistically significantly different from zero. This is achieved using the t-test. The t-value is calculated by dividing the coefficient by its standard error, and comparing the result with the tabulated critical value at the chosen level of significance (*eg* Neave, 1989).

It is also important to test the significance of the whole group of coefficients. This is achieved by an F-test, which is calculated within the "regression" procedure. The F-test has the joint null hypothesis $H_0 : b_1 = b_2 = \ldots = b_{k-1} = 0$.

If H_0 is true (and if the model includes a constant) then the F-value has an F-distribution with k -1 and n - k degrees of freedom, where

$$F = \frac{\mathrm{ESS}/(k - 1)}{\mathrm{RSS}/(n - k)}.$$

In the case where there is only one independent variable, *ie* bivariate correlation, then $F = t^2$.

Using the multiple regression technique a relationship of the form $\hat{y} = c + b_1 x_1 + b_2 x_2 + \ldots + b_n x_n$ was fitted to the data for each of the surveys. In this equation $\hat{y}$ is the predicted level of carbon monoxide, x_n are each of the different variables and b_n is the coefficient calculated using the multiple regression. Table B1 in Appendix 1 gives the multiple regression results derived from the data for each survey. The first column gives the date of the survey. The second gives the multiple regression coefficient R^2, where 1.0 implies a perfect fit of the data. In columns three to twenty-one the coefficients of the variables in the regression equation are given. One of the regression equations for the survey of the 3rd September 1992 is given as an example here.

Carbon Monoxide = 6.77(Temperature) - 4.70(Wind speed) + 0.05(Wind direction) + 2.28(Relative Humidity) - 0.20(Cars) + 1.85(HGVs) - 2.93(Buses) - 0.01(STOPS) + 0.05(FLOW) - 0.03(DELAY) - 0.09(CONGESTION) - 0.14(RAW) - 247.5

$R^2 = 0.45$

However, when the t-test was carried out on each coefficient it was found that very few of the coefficients were statistically significantly different to zero. This may be due to the variables used in the multiple regression not adequately explaining the carbon monoxide levels, the limited amount of data used to construct the equation, or the presence of *collinearity* between one or more variables.

One of the underlying assumptions of multiple linear regression is that there is no exact linear relationship between the independent variables, *ie* there is no collinearity. Belsley *et al* (1980) define collinearity as "k variates are collinear if the vectors that represent them lie in a subspace of dimension less than k, that is, if one of the vectors is a linear combination of the others". However, whilst exact collinearity is rare, variables may have a high degree of collinearity. This can be assessed in a number of ways. The most straightforward is by calculating the correlation coefficient r or R^2 for pairs of variables. However, this does not take into account the fact that a variable may be a linear combination of two or more variables, and yet not correlated with any one variable alone. Montgomery and Peck (1992) stated that multicollinearity has four primary sources:

1. The data collection method employed;
2. Constraints on the model or in the population;
3. Model specification; or
4. An overdefined model.

The effect of the collinearity is to produce estimates of the regression coefficients, the $\hat{b}_j$, which are too large in absolute value.

The scatterplot matrices in Figure 4.12 and Figure 4.13 highlighted that temperature and relative humidity, and FLOW and STOPS may be pairwise linearly related, and therefore may affect the accuracy of the regression equations derived. Montgomery and Peck (1992) also gave several methods for dealing with collinearity:

1. Collection of additional data;
2. Model respecification; or
3. Use of estimation methods other than least squares.

In the case of the research described in this thesis, there was no advantage to be gained by collecting more data, as it would be of the same format as before. This meant that either the model could be re-specified using a combination function, or by eliminating variables, or that an alternative estimation technique could be tried, such as time series analysis.

However, before dealing with any potential collinearity problem it was decided to further investigate the frequency distributions of the carbon monoxide data.

4.6.3 Distributions

When the frequency distributions of the carbon monoxide levels for five minute intervals for each survey were plotted, they seemed to fall into two distinct categories. The first category was characterised by a distribution which had a long tail due to one or more extreme values. This means that the data has a large standard deviation and a large standard error (given by $\sigma/\sqrt{n}$). Figure 4.15 shows a typical distribution of this form. This data is from those surveys carried out on the morning of the 16th June 1992 and continued on the afternoon of the 17th June. The other surveys which displayed this characteristic were from the 20th August, the 3rd, 16th and 21st September 1992. These will be collectively referred to as "set A".

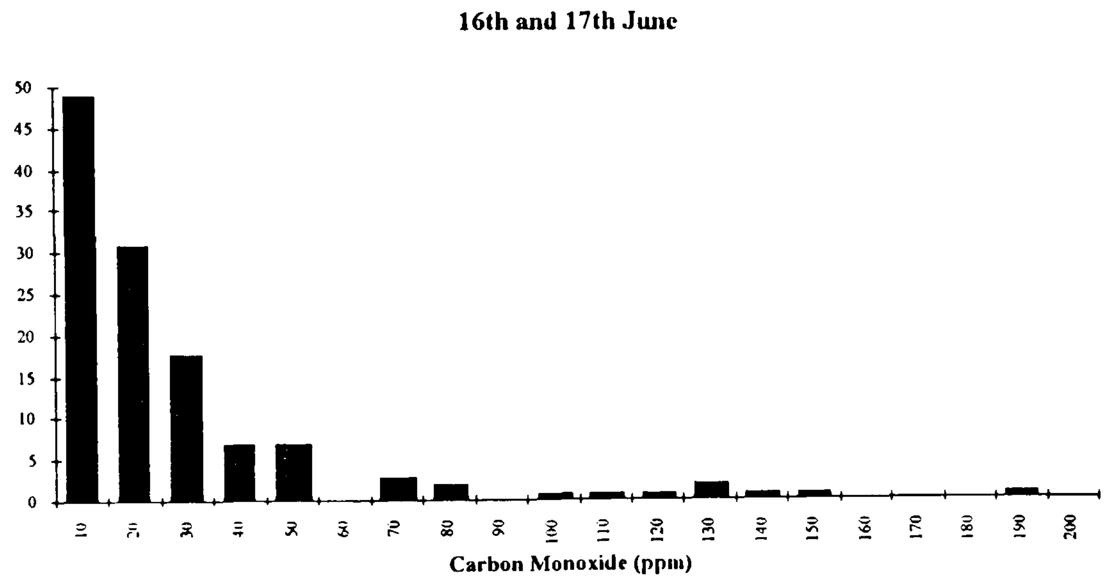

Figure 4.15: Typical "set A" frequency distribution

The second category was characterised by smaller standard deviations and standard errors. A typical example is given in Figure 4.16. These surveys, which will be referred to as "set B", are those of 29th April, 15th and 29th May, 13th and 18th August, 10th and 14th September 1992.

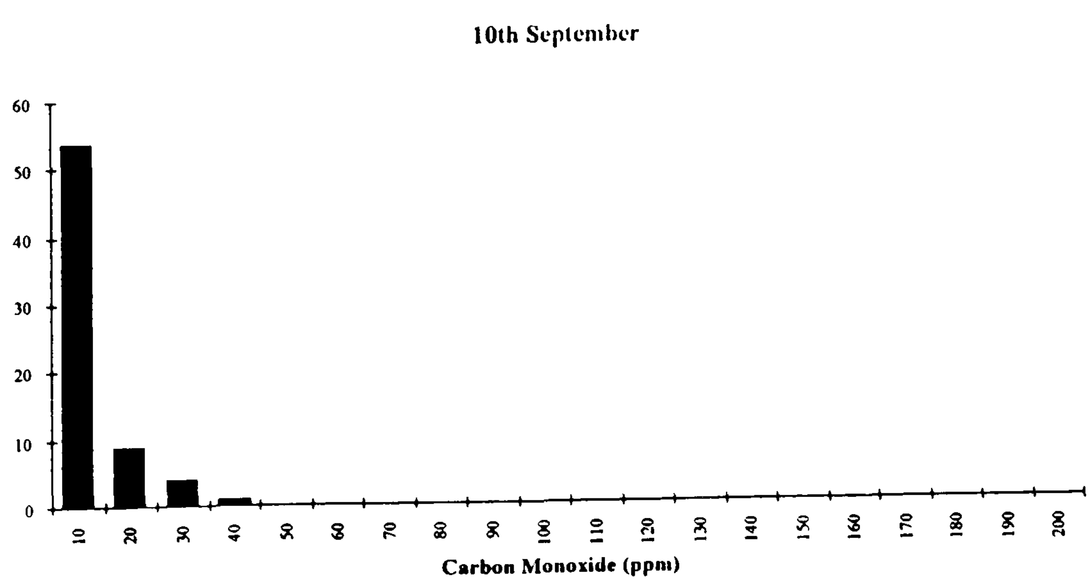

Figure 4.16: Typical "set B" frequency distribution

These two sets were analysed separately using multiple regression. When the data for set A were combined the variables included in the regression equations were carbon monoxide (independent variable), and the dependent variables temperature, wind speed, wind direction, relative humidity, cars, buses, HGVs, STOPS, DELAY, FLOW and RAW. The resulting regression equation had a R^2 of 0.075 (n = 266). For set B the corresponding equation had a R^2 of 0.132 (n = 160).

Figure 4.17 and Figure 4.18 show scatterplots of STOPS and FLOW for the set A and set B data respectively. There is obviously a very strong linear relationship between these two variables. This is confirmed by correlation coefficients (r) of 0.981 and 0.904 respectively for each set. As a result, the regression equations were computed using the combination function $\frac{\text{STOPS}}{\text{FLOW}}$. This function is intuitively reasonable, as it represents the proportion of vehicles which have to stop at the stopline. In the case of the set A data, the R^2 value for the new regression model increases slightly to 0.080, and for the set B data it increases marginally to 0.150.

The regression equations were then computed without the SCOOT data. The R^2 for set A was 0.040 (n = 302) and for set B was 0.054 (n = 301). A third run of the equation including $\frac{\text{STOPS}}{\text{FLOW}}$, DELAY and RAW, but excluding the manual traffic count data gave an R^2 for set A of 0.023 (n = 266) and R^2 of 0.082 (n = 160) for set B. This shows that there is no benefit to be gained by categorising data according to its distribution as these two sets of data are not behaving differently, and are therefore not independent. This analysis also highlights the importance of checking for the presence of collinearity in the data.

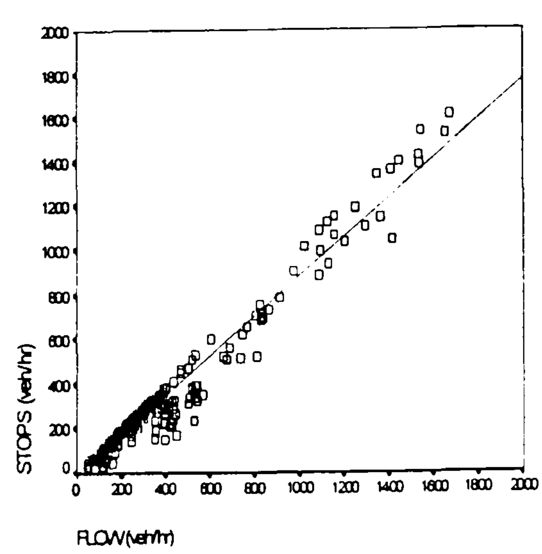

Figure 4.17: Scatterplot of STOPS and FLOW for set A data

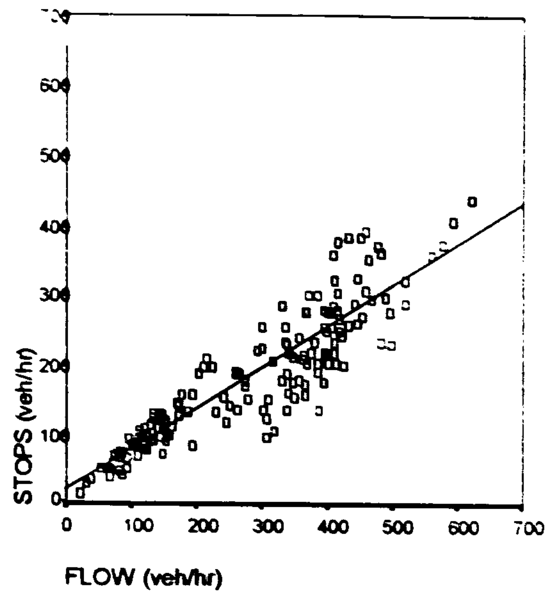

Figure 4.18: Scatterplot of STOPS and FLOW for set B data

4.6.4 Conclusions

Despite a large number of surveys with exhaustive data collection and analysis there was no evidence to suggest that the distribution of carbon monoxide levels described different populations. In addition there was no evidence to suggest that trends existed in the relationships between carbon monoxide levels and the parameters considered.

Although considerable effort and resources were expended in carrying out these surveys, it was felt that they were far too short to produce statistically significant results from which to draw useful conclusions. Therefore the most important result of this second phase of the research was demonstrating that it was essential to carry out continuous monitoring of pollutant levels and climatic conditions, simultaneously with traffic characteristics throughout the day and over long periods of time *eg* weeks.

5. ITEMMS - Integration of Traffic and Environmental Monitoring and Management Systems

5.1 Introduction

The main conclusion of the kerbside monitoring carried out using the portable equipment in Leicester was that the surveys were too short to yield statistically significant results. This was because it was not humanly possible to gather more than about six hours data per survey. It therefore became essential to try and find some remote monitoring equipment which could fulfil the following criteria:-

- inexpensive;
- monitor carbon monoxide, sulphur dioxide and nitrogen dioxide at least;
- be able to be left unattended for long periods of time at the kerbside; and
- be vandalproof and weatherproof.

At this time (1993) no equipment was available commercially which fulfilled all of these criteria. Therefore, Siemens Plessey Controls Ltd was approached again to assist. As a consequence, a LINK project was funded by SERC (now the Engineering and Physical Sciences Research Council, EPSRC), the Department of Transport, Siemens Plessey Controls Ltd[1], Leicestershire County Council, Nottinghamshire County Council and the County Surveyors' Society to develop a system which fulfilled these requirements. This system could then be used to gather the necessary data to further our understanding of the relationships between air pollution and traffic. This project was known as "Integration of Traffic and Environmental Monitoring and Management Systems (ITEMMS)."

The specific objectives of this research were to

1. carry out a literature review (given previously in Chapters 2 and 3) and to investigate the needs of potential users of traffic-related air pollution data;
2. commission the development of transportable, "stand-alone" air pollution monitoring units which fulfil the criteria listed above (known as "transportable prototype units");

---

[1]Shortly after the beginning of this project Siemens Plessey Controls Ltd split into two separate companies - Siemens Environmental Systems Ltd and Siemens Traffic Controls Ltd.

3. install these transportable prototype units at various locations in Leicester and carry out monitoring for several months at each site.
4. establish a methodology for data collection and analysis, building upon the lessons learnt during the preliminary surveys (described in Chapter 4);
5. research statistical analysis techniques to develop empirical relationships between air pollution and traffic characteristics;
6. commission the development of a pollution monitoring unit which is fully integrated with the SCOOT traffic control infrastructure (known as "ITEMMS units");
7. install these ITEMMS units at various locations in Leicester and Nottingham;
8. develop the software to allow capture of the pollution data along with the SCOOT data.

The design and building of the monitoring units was carried out by Siemens Environmental Systems Ltd (with advice on specification from the author). The computer software was developed by Dr Ray Evans of UNTRG. The remaining tasks were undertaken by the author. For completeness, descriptions of the software are included in this thesis. The remaining sections of this chapter will deal with each objective in turn.

5.2 User requirements

Throughout the course of the ITEMMS project discussions took place with many different groups of people in order to ascertain the usefulness of roadside pollution monitoring equipment. At these meetings the system was described, initially as a product under development and later when it was fully operational. An overwhelmingly positive response to the availability of an inexpensive, transportable pollution monitoring system was received, and the product was very much in demand. The ability to predict traffic-related air pollution was seen to greatly enhance the decision making of traffic engineers, environmental health officers, doctors (especially in understanding its relationship with respiratory diseases) and university researchers.

As a result of these discussions, a format for summary data tables was defined. It was obvious that these tables needed to be consistent with those produced by the Department of the Environment and give hourly average, median, minimum, maximum, standard deviation and 98th percentile values.

5.3 Specification of the transportable prototype units

Siemens Environmental Systems Ltd constructed four prototype transportable units. The first one was delivered in December 1993. They used "off-the-shelf" electrochemical cells for carbon monoxide, sulphur dioxide and nitrogen dioxide. Electrochemical cells were chosen because they are relatively low cost and have fast response times. These cells each contain a chemical which reacts with the target gas to produce a small electric current (in the same way as a battery), which is amplified and converted into the gas concentration level using software in a datalogger. The accuracy of the cells was stated by the manufacturers to be ±5%, which was thought to be sufficient for kerbside pollution monitoring.

An existing design of traffic signal control cabinet was used to house the monitoring system. This was so that the unit would be almost identical to the existing street furniture and therefore had Department of Transport approval. Also, it would not draw the attention of the public. The cabinet pedestals were modified by Siemens Environmental Systems Ltd to provide a semi-permanent mounting at the kerbside. This was achieved by fitting a flat plate to the base of the pedestal. The units were fixed to the footpath using rawlbolts in holes drilled around the plate.

Inside the cabinet there was a mounting for the cells, a datalogger and a 12V battery. The battery also powered a small pump which drew the air through a filter and across a manifold behind the cells. The air inlet of the system was located where the fault warning light would have been if the cabinet had been used for traffic signal control. The battery lasted for about twelve days and the datalogger had sufficient memory to store the one minute average values (based on one second sampling) for 24 hours a day for this period. The data stored in the logger had to be downloaded using a portable computer and the battery changed at the same time. Figure 5.1 is a picture of a transportable prototype unit installed on-street in Leicester, and Figure 5.2 shows the inside of the cabinet.

Figure 5.1: Transportable prototype unit on-street in Leicester

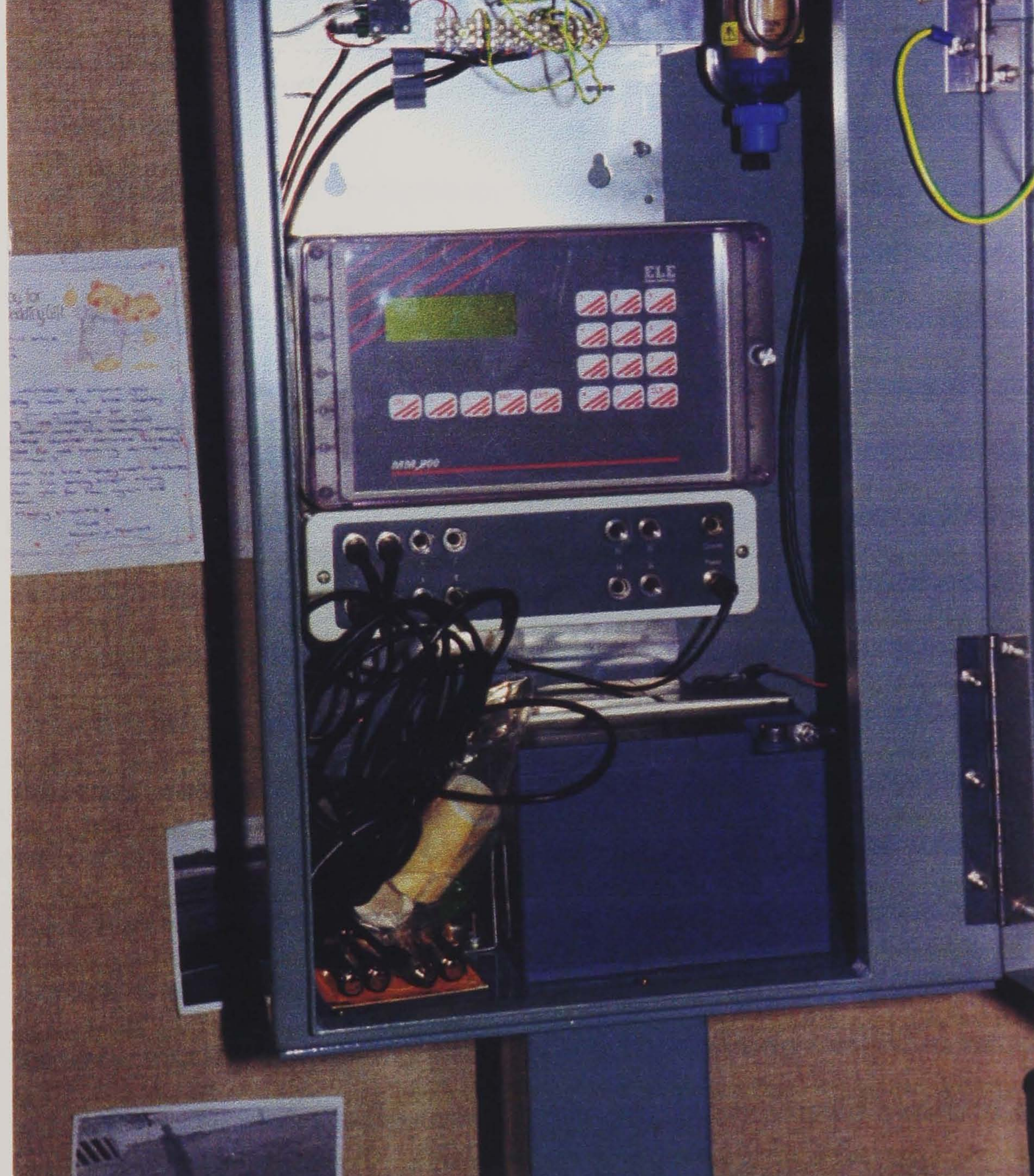

Figure 5.2: Interior of an transportable prototype unit

One of the aims of the ITEMMS project had been to identify a hydrocarbons sensor which could be used in this system. However, Siemens Environmental Systems Ltd had not been able to identify a suitable technology. For the future, Siemens Environmental Systems Ltd have proposed the inclusion of a system for monitoring PM_{10}, *ie* particulate matter less than 10 μm in diameter. PM_{10}, and indeed $PM_{2.5}$, is now a major cause for concern because of its possible effects on asthmatics. A suitable monitoring system, known as GRIM, has been identified which uses laser technology rather than the tapered element oscillating microbalance (TEOM) system used in the Department of the Environment Automatic Urban Network monitoring stations (see Section 3.2.4). However, the GRIM system does not currently have US EPA (Environmental Protection Agency) standard approval for use outdoors.

One of the original four transportable prototype units had a climate monitoring station connected to it. This station comprised of an anemometer, a wind vane, a combined temperature and relative humidity sensor and a barometric pressure sensor. These were attached to a separate pole. There is no doubt that this station would have been vandalised if it had been left on-street, so a location was found which was (a) inaccessible to the public; and (b) would allow "urban background" levels of air pollution to be measured. This background measurement was important to show the contribution of the traffic to the pollution in the urban environment. The site chosen was on top of one of the old city gates in Leicester. This building (known as "The Magazine") is approximately 1.5 miles north-west of Region R (see Figure 5.3). The combined air pollution and climate monitoring station was put on the roof, which is three storeys above ground level, during October 1994. Figure 5.4 shows the transportable prototype unit and the meteorological monitoring system.

5.4 Specification of the ITEMMS units

In addition to producing the transportable prototype units, Siemens Traffic Control Ltd designed an interface card to enable environmental sensors to be connected to the outstation transmission units (OTUs) and interfaced with the urban traffic control infrastructure. Siemens Traffic Control Ltd also developed outstation-embedded software to enable environmental data to be captured and formatted. These monitoring units are referred to here as

"ITEMMS units". From the exterior they look identical to the transportable prototype units, but the internal layout is completely different (see Figure 5.5).

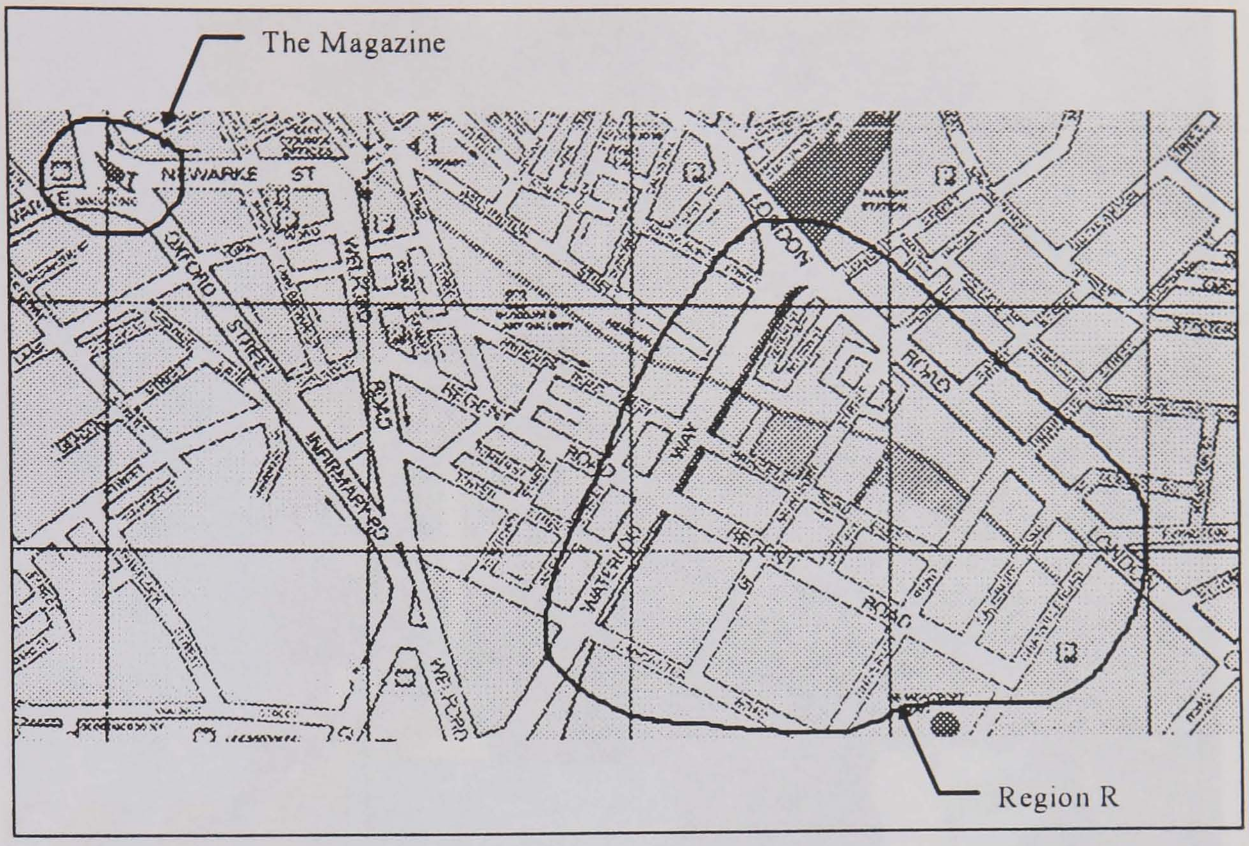

Figure 5.3: Map showing relative positions of Region R and The Magazine

At an early stage of the project it was decided to develop the software for a VAX computer to be consistent with the latest SCOOT systems. As Leicestershire's SCOOT system was installed in 1988 it was operated on a PDP-11 computer, linked to Telecommand 8 outstation transmission units (OTUs). Therefore a Telecommand 12 OTU and a VAX computer were purchased (using an award from the County Surveyors' Society) to be located at Leicestershire County Council's Area Traffic Control centre. The software on the VAX captures the air pollution data, and then passes the data, along with SCOOT data, to UNTRG's laboratory. Due to the incompatibility between the PDP-11 and the VAX, three possible set-ups, shown in Figure 5.6, were proposed to achieve this. Eventually, it was decided to implement Option 2.

Figure 5.4: Transportable research unit and meteorological monitoring unit on the roof of the Magazine

Figure 5.5: Interior of an ITEMMS unit

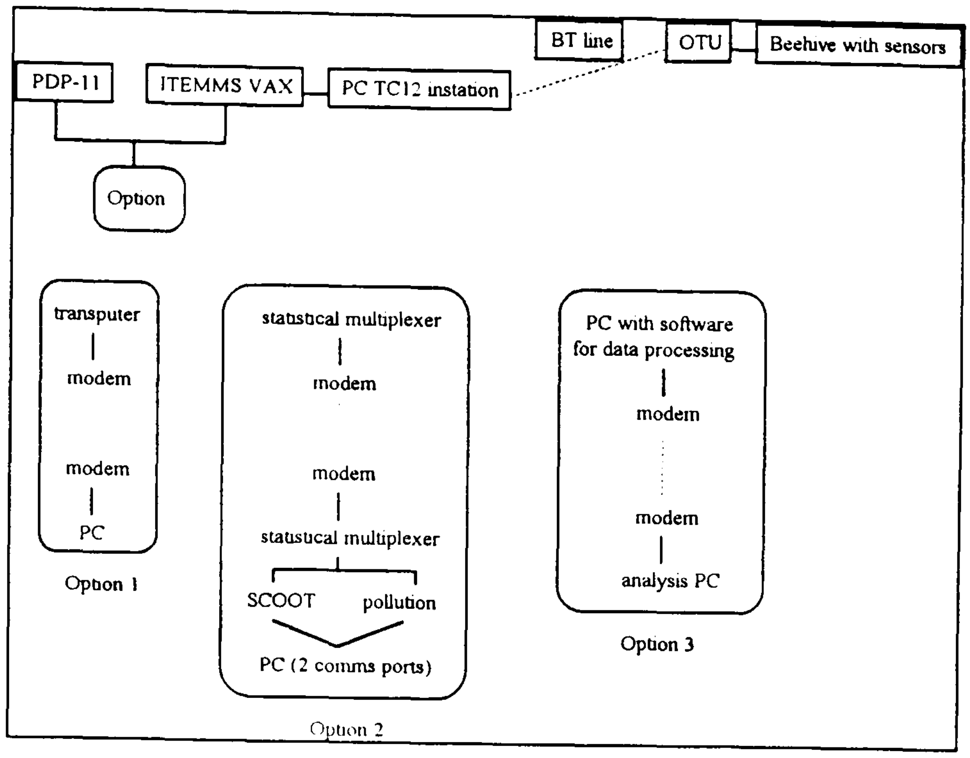

Figure 5.6: Options for transmitting pollution and SCOOT data from Leicester to UNTRG.

Three ITEMMS units are currently in operation[1]. One is located in Leicester on Waterloo Way (see Figure 5.7), and two are sited in Nottingham. The Nottingham units are located on Bentinck Road (in Region AR) and Mansfield Road (see Figure 5.8).

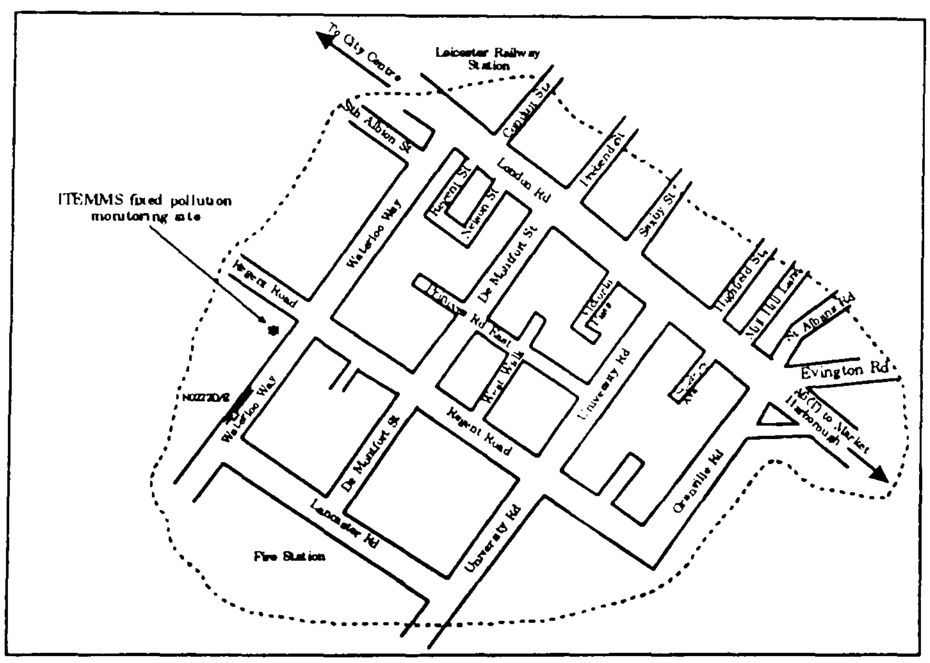

Figure 5.7: Location of ITEMMS unit in Leicester

[1]ITEMMS units are now commercially available from Siemens and, to date, units have been purchased by several local authorities to assist in their environmental monitoring work. The units developed for this research were prototypes, but were paid for by Leicestershire and Nottinghamshire County Councils, for which the author is grateful. The technical data sheet for the unit, now known as RPM (Roadside Pollution Monitor) is included as Appendix 2.

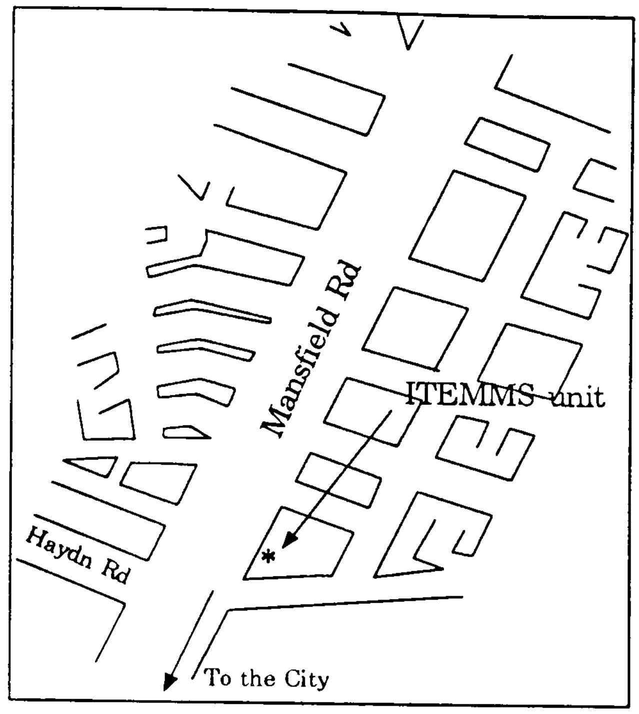

Figure 5.8: Location of ITEMMS unit in Region S, Nottingham

5.5 A01 message

The data from the ITEMMS units was logged automatically by the same method as the M02 message. The specific SCOOT-type message was the A01 message. Like the M02 message, it contained information about the date, time, location and the raw data. The format of the message was:-

<Day> <Time> <Message type> <Location number> <Location> <Sensor type> <Data> <Fault>

for example

```
TU 14:50:00 A01 W13221 Mansfld Rd NO2  TYPE: 1   DATA: 174   SUSPECT 0
TU 14:50:00 A01 W13222 Mansfld Rd SO2  TYPE: 2   DATA: 182   SUSPECT 0
TU 14:50:00 A01 W13223 Mansfld Rd CO   TYPE: 3   DATA: 192   SUSPECT 0
TU 14:50:00 A01 W13224 Mansfld Rd Tmp  TYPE: 4   DATA: 542   SUSPECT 0
```

The data then had to be converted into a parts per million value (or centigrade, in the case of temperature) using the formulae given in Table 5.1. This was done during the processing of the logged data from the traffic management computer using software specially written by Dr Evans of UNTRG (Evans, 1995).

Table 5.1: Sensor data conversion formulae

Type	Sensor	Formula	Units
1	Nitrogen dioxide	0.03231(DATA - 160) - 1	ppm
2	Sulphur dioxide	0.03231(DATA - 160) - 1	ppm
3	Carbon monoxide	0.18615(DATA - 160) - 1	ppm
4	Temperature	0.11538(DATA - 160) - 15	°C

5.6 Roadside air pollution monitoring in Leicester

Roadside monitoring of air pollution using the transportable prototype units commenced in Leicester in December 1993. Figure 5.9 shows the sites at which monitoring took place with dates indicating the periods of sampling. The sites were chosen to represent a variety of road layouts and traffic flow rates. Several of the locations were dictated by the needs of other research projects which required actual kerbside carbon monoxide concentrations (Namdeo, 1995; Pearce, 1995).

Once the units were secured to the footpath they were left for several months. Every ten to fourteen days it was necessary to visit the site, change the battery and to download the information from the datalogger. Vandalism was not a problem because the public are familiar with signal control street furniture and do not suspect that an air inlet substitutes the fault warning bulb.

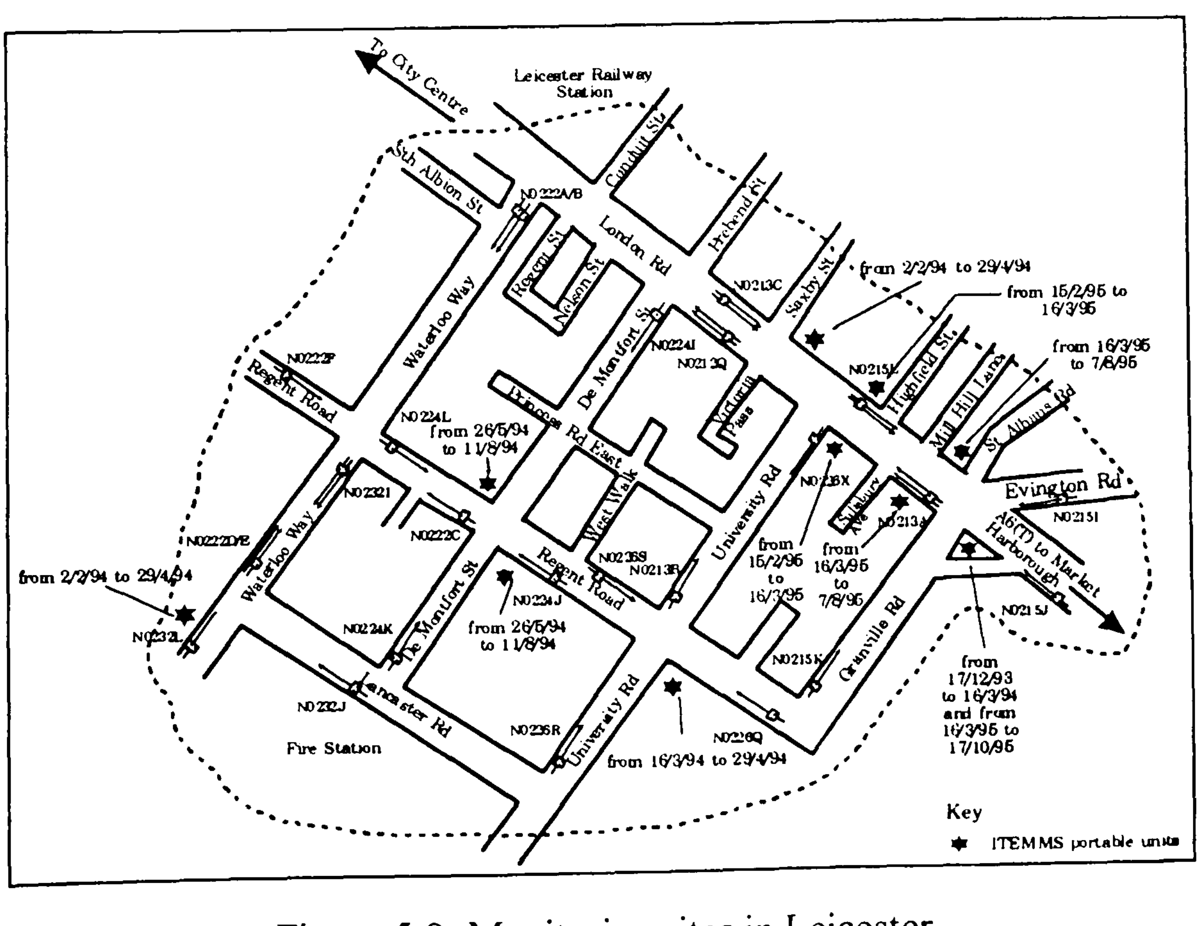

Figure 5.9: Monitoring sites in Leicester

The units were placed at a distance of approximately five metres upstream of the stopline, and one metre from the kerb. This position was defined by the earlier research carried out in Nottingham (see Section 4.5), and from other monitoring exercises (Bell and Reynolds, 1992). The data sampling rate was set at one second, and one minute averages were stored in the datalogger. This made detailed analysis of the raw data possible. It was also possible to aggregate the data to any required level using the TABULATE software developed by Dr Evans.

5.6.1 Calibration of the electrochemical cells

Throughout the project, discussions were held with Siemens Environmental Systems Ltd to ensure the reliability of the data. The cell manufacturers (City Technology) had stated that the accuracy of the cells was ±5%. Siemens Environmental Systems Ltd had calibrated the units before delivery using laboratory facilities which provided known mixtures of nitrogen dioxide and sulphur dioxide in the range 0.1 ppm to 0.3 ppm, and carbon monoxide in the range 0.5 ppm to 1.5 ppm. Siemens Environmental Systems Ltd confirmed these values using laboratory standard measuring instruments. These calibrations were performed with pure gases and therefore cross-sensitivity was not a problem.

5.6.2 Electrochemical sensor cross sensitivity

Further research carried out by Siemens Environmental Systems Ltd and City Technology showed that the nitrogen dioxide and sulphur dioxide cells in the original transportable prototype units never worked properly. This was due to several factors. Firstly, there were strong cross-sensitivity problems. These occur when the chemical in the cell reacts with a gas other than the target gas. Table 5.2 shows the percentage cross-sensitivity for each cell when exposed to a certain gas. It can be seen that the carbon monoxide cell was the least affected, and therefore the research described in this thesis concentrated on the carbon monoxide data.

Table 5.2: Cell cross-sensitivities

		Cell		
		Nitrogen dioxide	Sulphur dioxide	Carbon monoxide
Gas	Nitrogen dioxide	100%	0%	0%
	Sulphur dioxide	-120%	100%	1%
	Carbon monoxide	-60%	65%	100%

The second problem encountered was that the air flow rate across the cells was found to be approximately half of its optimum level (0.8 litres per minute instead of 1.6 litres per minute). This meant that the cell was not receiving a sufficiently large air sample to achieve an accurate analysis. Another serious limitation was the inability of these cells to compensate for the effect of temperature. Laboratory investigations carried out by the cell manufacturers have now demonstrated that rapid changes of temperature affects the stability of the cells. Siemens Environmental Systems Ltd have subsequently developed an algorithm to correct for temperature effects as a component of the data processing. In addition, it was found necessary to include a chemical scrubber to perform a daily zero check. Both of these modifications have been incorporated into later versions of the system.

Hence, of the three cells in the units, only the carbon monoxide sensor has provided reliable data. However, the "shelf-life" of these sensors was only 18 months, therefore the data collected since May 1995 has to be used with caution. It is believed that whilst the data is no longer accurate in absolute terms, it is still useful in quantifying the percentage changes in concentrations and has value in measuring the changes in levels that may occur following, for example, the implementation of traffic management schemes.

Notwithstanding the potential inaccuracy of absolute level of carbon monoxide, valuable awareness has been gained into the nature of the relationship between carbon monoxide levels and traffic data. The data collected over the course of the project has also allowed the processing and analysis techniques, described later, to be developed.

5.7 Preliminary data processing

The raw data from the transportable prototype units was in a format recognisable only by the datalogger software (ELE's DIALOG program). These data files were translated inside DIALOG into tab-delimited ASCII text format for input into the spreadsheet and statistical analysis packages. The naming convention adopted for the files was

<link number><collection date>.<file type>

eg 224J2906.txt. Files were stored in separate directories according to the link number, and separate sub-directories according to the year, *ie* 1993, 1994, *etc.* A log book was also kept with records of the periods to which each file referred.

For the days on which downloading took place, the data were split between two separate files, *ie* the end of one file and the beginning of the next. This was accommodated by extracting the data for that day from the two files (using the EXTRACT program (Evans, 1995), or in a spreadsheet) and then joined together in a separate file.

For the data from the transportable prototype units, the next stage in the processing was to combine the air pollution data and the SCOOT data appropriate to the day and the link. This was achieved using the MSPD (Merge SCOOT and Pollution Data) computer program written by Dr Evans. This program took the pollution data file and the SCOOT M02 file as inputs, specified in a initial file called "mspd.ini" (see Figure 5.10). The contents of the M02 file were examined to determine the start and end times of the SCOOT data collection period (usually 07:30 to 19:30). The air pollution data from outside these times were disregarded. The air pollution data was aggregated over five minute periods to correspond exactly to the times 07:30, 07:35, *etc.* The program formed a weighted average to accommodate the fact that the air pollution data was rarely logged exactly on the minute. This was achieved by examining the seconds part of the time at which the data was logged, *eg* if datalogging commenced at 11:20:45, the seconds part is 45. This was then converted to a fraction of a minute, *ie* 45/60 = 0.75. The pollution data was then split in the ratio 0.75:0.25 between the preceding and the following minute. For example, at 11:49:45 the carbon monoxide level was 6 ppm. Then 4.5 ppm would be attributed to time 11:49, and 1.5 ppm to 11:50.

SCOOTFILE 261094.m02
POLLFILE 213A2910.txt
OUTFILE 261094.msp
DATE 26-Oct-94
LINK N0213A
SLINK 2
STIME 1
SDELAY 4
SFLOW 5
SSTOPS 3
SCONG 6
SRAW 7

Figure 5.10: Merge SCOOT and Pollution Data initial file

In addition to calculating the average air pollution level, the minimum and maximum one minute levels in the five-minute period were also stored. The final merged file (which was given the extension ".msp") had the following fields:-

Time; STOPS; DELAY; FLOW; RAW; CONGESTION; LEN; AV_NO_2; MIN_NO_2; MAX_NO_2; AV_CO; MIN_CO; MAX_CO; AV_SO_2; MIN_SO_2; MAX_SO_2.

LEN was a checking variable which showed the number of logged times in a five minute period, *eg* 08:07:40, 08:08:40, 08:09:40, 08:10:40, 08:11:40, 08:12:40 are the six times in a five minute period 08:07:40 to 08:12:40.

After these two stages of data processing there were two data files available for analysis for each day's data for each link. The first was the (raw) air pollution file of TIME, NO_2, CO and SO_2, containing the one-minute samples (1440 maximum). The second was the merged SCOOT and pollution data file with usually 144 five-minute aggregated data values.

5.8 Preliminary data analysis

In sharp contrast to the early work described in Section 4.6, the supply of data was plentiful. For a ten to fourteen day period a raw pollution file took approximately 1 Mbyte of disc storage, and a merged SCOOT and pollution data file took approximately 18 Kbytes. It soon became obvious that preliminary data analysis using descriptive statistical techniques would have to be automated as far as possible. Hence, an SPSS for Windows macro was written called "12hrsum.sps". The listing of the "12hrsum.sps" macro can be found in Appendix 3.

The "12hrsum.sps" macro took the merged SCOOT and pollution data file and produced eight tables, four line graphs, a correlation matrix and six scatterplots. The first table calculated the overall mean, standard deviation, minimum, maximum, median, 95th percentile and the number of cases, for the five-minute average, minimum and maximum pollution levels (see Table 5.3). The second table calculated the same statistics for the SCOOT data (see Table 5.4).

Table 5.3: Summary statistics from "12hrsum.sps" macro

	Mean	Std Deviation	Minimum	Maximum	Median	98Percent	Valid N
average NO2 (ppm)	-.008	.099	-.223	.083	.038	.082	197
minimum NO2 (ppm)	-.011	.100	-.229	.082	.034	.080	197
maximum NO2 (ppm)	-.005	.097	-.220	.085	.042	.083	197
average CO (ppm)	3.607	3.608	.491	21.287	2.370	15.808	197
minimum CO (ppm)	2.420	2.406	.322	15.263	1.567	10.539	197
maximum CO (ppm)	5.373	5.537	.578	29.545	3.471	26.176	197
average SO2 (ppm)	.013	.066	-.097	.177	.002	.142	197
minimum SO2 (ppm)	-.001	.061	-.101	.132	-.012	.126	197
maximum SO2 (ppm)	.036	.085	-.094	.475	.019	.220	197

Table 5.4: Summary statistics from "12hrsum.sps" macro

	Mean	Maximum	Minimum	Median	98Percent	Valid N
STOPS (veh/hr)	622	1736	59	580	1685	197
DELAY (1/10 veh.h/h)	48	401	5	37	270	197
FLOW (veh/hr)	772	1736	96	768	1685	197
CONGESTION	21	528	0	0	384	197
RAW	2	132	0	0	12	197

The five-minute data was then further aggregated to give one-hour average data. Tables three to eight contain the mean, standard deviation, minimum, maximum, median and number of cases for the one-hour averages of nitrogen dioxide, carbon monoxide, sulphur dioxide, STOPS, DELAY and FLOW (Table 5.5 and Table 5.6 are examples of these tables).

Table 5.5: Hourly summary statistics

10/02/94	average CO (ppm)						
	Mean	Std Deviation	Minimum	Maximum	Median	98Percent	Valid N
HOUR							
07:30 - 08:25	10.746	4.589	4.842	21.287	9.648	21.287	12
08:30 - 09:25	12.980	2.539	10.337	18.124	12.143	18.124	12
09:30 - 10:25	5.387	1.017	3.844	7.720	5.261	7.720	12
10:30 - 11:25	4.336	.841	3.181	5.445	4.431	5.445	12
11:30 - 12:25	3.756	.612	2.870	5.002	3.663	5.002	12
12:30 - 13:25	3.040	1.251	1.742	4.779	2.600	4.779	12
13:30 - 14:25	1.739	.324	1.224	2.208	1.745	2.208	12
14:30 - 15:25	1.371	.303	1.043	1.999	1.240	1.999	12
15:30 - 16:25	1.882	.481	1.143	2.825	1.872	2.825	12
16:30 - 17:25	3.096	.506	2.277	4.014	2.980	4.014	12
17:30 - 18:25	3.133	.633	2.377	4.773	3.003	4.773	12
18:30 - 19:25	2.423	.477	1.614	3.301	2.360	3.301	12

Table 5.6: Hourly summary statistics

10/02/94	FLOW (veh/hr)						
	Mean	Std Deviation	Minimum	Maximum	Median	98Percent	Valid N
HOUR							
07:30 - 08:25	1339	[illegible]	864	1736	1426	1736	12
08:30 - 09:25	1516	181	1166	1728	1561	1728	12
09:30 - 10:25	945	110	768	1118	926	1118	12
10:30 - 11:25	849	149	660	1135	817	1135	12
11:30 - 12:25	789	105	649	960	805	960	12
12:30 - 13:25	902	168	655	1194	889	1194	12
13:30 - 14:25	915	118	756	1146	905	1146	12
14:30 - 15:25	754	121	536	909	783	909	12
15:30 - 16:25	857	202	587	1160	867	1160	12
16:30 - 17:25	710	112	559	897	702	897	12
17:30 - 18:25	681	80	516	801	686	801	12
18:30 - 19:25	812	143	632	1129	779	1129	12

Line graphs of the nitrogen dioxide, carbon monoxide (see Figure 5.11) and sulphur dioxide data, and the SCOOT data STOPS, DELAY and FLOW (see Figure 5.12) over time were then produced.

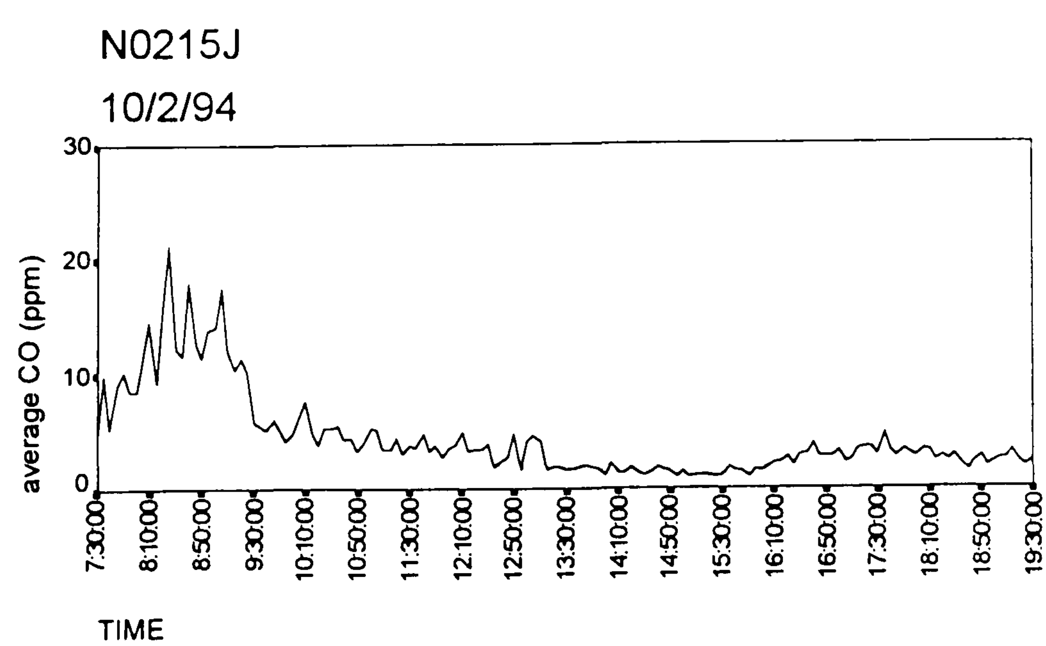

Figure 5.11: Average carbon monoxide level over time

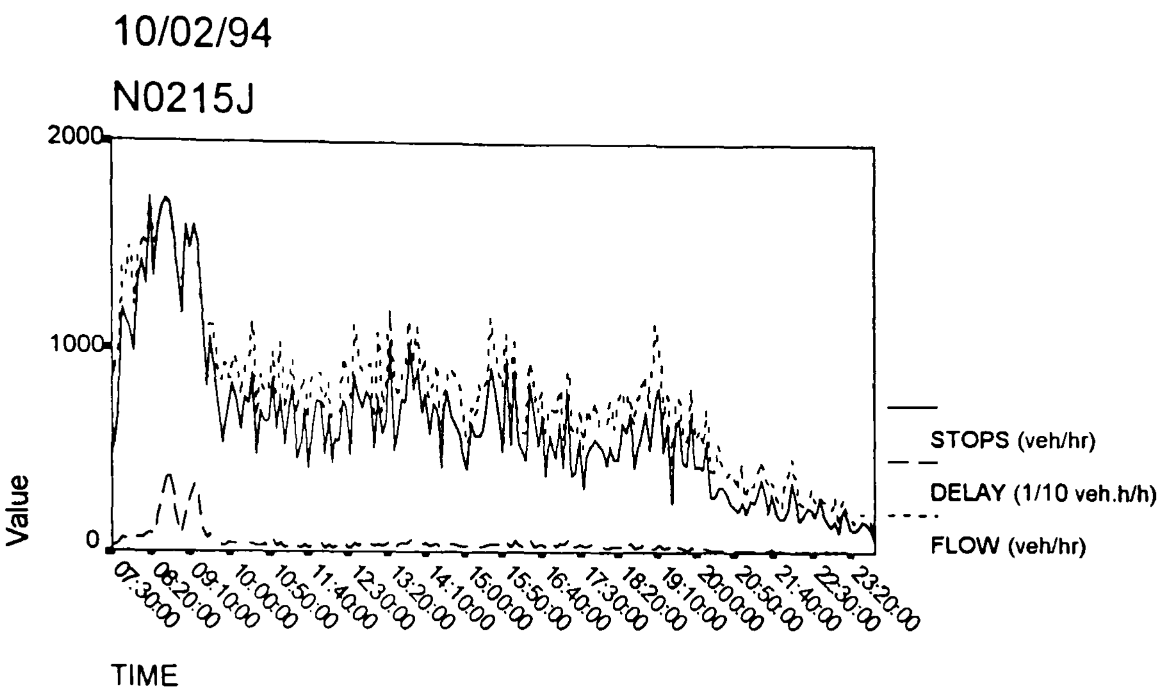

Figure 5.12: Line graph of SCOOT parameters

A matrix of the pairwise correlations (r) of nitrogen dioxide, carbon monoxide, sulphur dioxide, STOPS, DELAY and FLOW, with the significance levels, was then produced (see Table 5.7). Finally, scatterplots of the pollutants against the SCOOT parameters were produced (see Figure 5.13 and Figure 5.14).

Table 5.7: Correlation matrix

	AV_NO2	AV_CO	AV_SO2	STOPS	DELAY	FLOW
AV_NO2	1.0000	-.0409	-.8442	-.2499	-.0744	-.2969
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .	P= .568	P= .000	P= .000	P= .299	P= .000
AV_CO	-.0409	1.0000	.4204	.8112	.7199	.7800
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .568	P= .	P= .000	P= .000	P= .000	P= .000
AV_SO2	-.8442	.4204	1.0000	.5936	.3599	.6333
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .000	P= .000	P= .	P= .000	P= .000	P= .000
STOPS	-.2499	.8112	.5936	1.0000	.8100	.9749
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .000	P= .000	P= .000	P= .	P= .000	P= .000
DELAY	-.0744	.7199	.3599	.8100	1.0000	.7331
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .299	P= .000	P= .000	P= .000	P= .	P= .000
FLOW	-.2969	.7800	.6333	.9749	.7331	1.0000
	(197)	(197)	(197)	(197)	(197)	(197)
	P= .000	P= .000	P= .000	P= .000	P= .000	P= .

(Coefficient / (Cases) / 2-tailed Significance)   " . " is printed if a coefficient cannot be computed

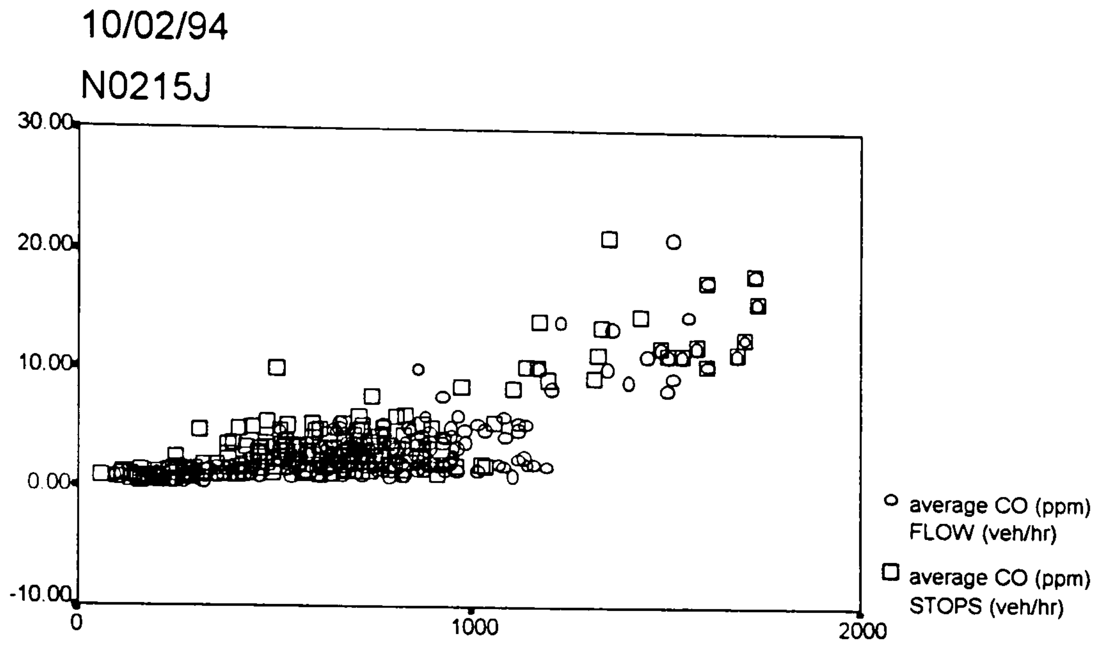

Figure 5.13: Scatterplot of carbon monoxide against STOPS and FLOW

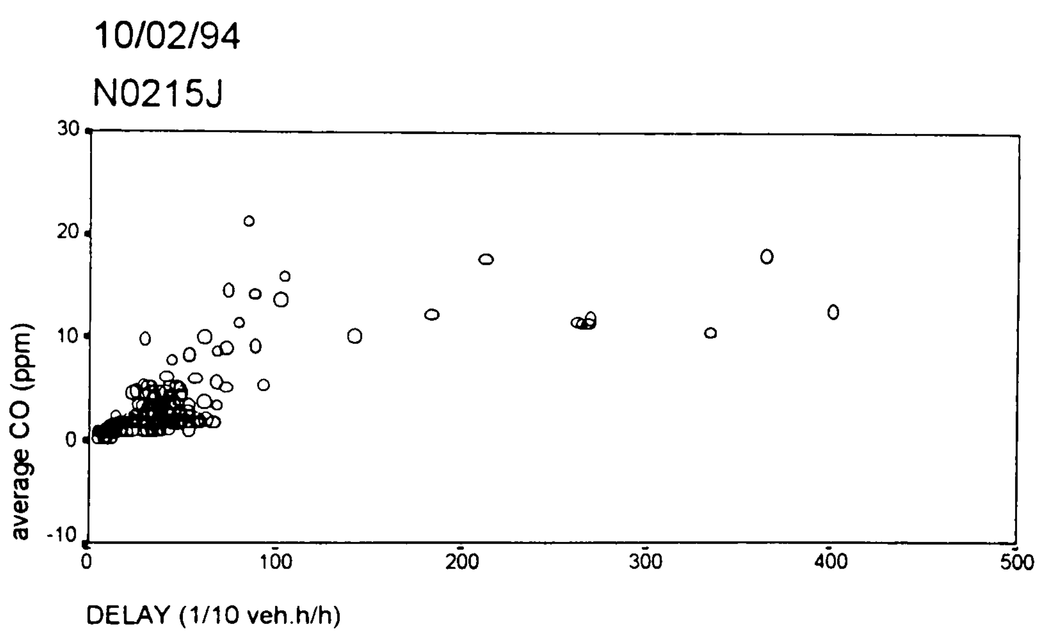

Figure 5.14: Scatterplot of carbon monoxide against DELAY

Nine sheets of paper would be used if all of these tables and graphs were printed for just one day's data. Therefore, they were stored electronically and throughout this thesis only examples of data will be used to illustrate analysis techniques.

5.9 Summary and discussion

In this chapter the development of a kerbside pollution monitoring system has been described. The aim of this system was to address the deficiencies highlighted in the research described in the previous chapter. However, the development of the transportable research units and the ITEMMS units has not been problem-free. It was found that only the carbon monoxide concentration measurements were reliable for the first 18 months after the delivery of the units. These units have, however, provided this research with a wealth of carbon monoxide concentrations data to be compared with the traffic characteristics data available from the SCOOT demand-responsive traffic signal control system.

The research carried out in the first project had defined the methodology for monitoring collecting and storing of the air pollution and SCOOT data. It was then necessary to develop data-processing strategies for the routine storage and processing of the data. A macro and a computer program were written to facilitate these tasks. The specification for these was partly based on the perceived needs of the end user of such data - university researchers, traffic engineers, environmental health officers, doctors, *etc*.

In the next chapter the statistical analysis of the data will be described. The objective is to identify the underlying characteristics and trends of the kerbside air pollution concentrations and the traffic characteristics data. The overall aim of this analysis is to produce an empirical relationship between the kerbside pollution levels and traffic characteristics.

6. Statistical analysis of air pollution and traffic data

6.1 Introduction

It is necessary to understand the characteristics of the kerbside pollution concentrations and the traffic characteristics data, in particular their underlying distribution, as a first step towards developing an empirical relationship to predict pollutant concentrations from SCOOT parameters. Progress can then be made to identify a statistical analysis technique which is appropriate to the data being studied and the form of the expected relationship. This chapter describes the investigations carried out using data mainly collected from the transportable prototype units. The statistical techniques considered are described in depth and their appropriateness for deriving empirical relationships are assessed.

6.2 Descriptive statistics

The first objective of the analysis was to get an appreciation of the relative orders of magnitude and spread of the variables being monitored. Appendix 4 contains the average five minute values of the variables contained in MSPD files (see Section 5.7), for link N0215J, for the entire monitoring period (52 days in the period 17th December 1993 to 16th March 1993).

6.2.1 Overall summary

Table 6.1 contains the summary statistics for the SCOOT and pollution data for link N0215J after processing using MSPD. The minimum pollution levels had negative values because the electrochemical cells (particularly the nitrogen dioxide and sulphur dioxide cells) suffered from two problems - temperature sensitivity and cross-sensitivity (as discussed in Section 5.6).

The analysis of the raw, one-minute, pollution data was not as straightforward as would be expected. Over the course of one month the number of data points collected was 40 300, which is too large to analyse in an EXCEL spreadsheet. Statistical analysis was therefore carried out using SPSS for Windows (Norušis, 1993). The results of the summary statistic analysis for the one-minute data pollution data from link N0213A is given in Table 6.2. It is interesting to note in both Table 6.1 and Table 6.2 that the values of nitrogen dioxide and sulphur dioxide have a small range, but that there is a much larger range of carbon monoxide values.

Table 6.1: Summary statistics for link N0215J 17th December 1993 to 16th March 1994 (processed using MSPD to give five minute averages)

	Average	St Dev	Min	Max	Range	Count
STOPS (veh/hr)	597.49	322.82	0	2064	2064	8385
DELAY (1/10(veh.hr/hr))	40.62	41.32	0	741	741	8385
FLOW (veh/hr)	758.45	340.61	0	2095	2095	8385
Carbon monoxide (ppm)	1.94	1.96	-0.38	21.29	21.66	8385
Nitrogen dioxide (ppm)	0.0021	0.050	-0.335	0.193	0.528	8385
Sulphur dioxide (ppm)	-0.060	0.062	-0.241	0.194	0.435	8385

Table 6.2: Summary statistics for link N0213A 16th February 1995 to 15th March 1995 (one-minute averages)

	Nitrogen dioxide (ppm)	Carbon monoxide (ppm)	Sulphur dioxide (ppm)
Average	0.08	1.50	0.11
Standard error	0.00	0.02	0.00
Standard deviation	0.08	3.33	0.35
Minimum	-0.856	-1.765	-0.288
Maximum	0.423	42.143	2.900
N	40300	40299	40283

6.2.2 Variations in pollution and traffic levels over a day

The next stage in understanding the nature of the data was to explore how the levels of the different variables changed over the course of the twelve hour SCOOT and pollution data collection period. Figure 6.1 to Figure 6.3 show the values of carbon monoxide, STOPS, DELAY and FLOW for link N0215J, averaged over the period 17th December 1993 to 16th March 1994, for every five minutes between 7.30 am and 7.30 pm (using the data given in Appendix 4). The SCOOT data in Figure 6.2 and Figure 6.3 demonstrates the pronounced morning peak period along this very busy inbound arterial link. This is matched by a peak in carbon monoxide levels in the morning peak suggesting a link with higher traffic flow, stops and delay. In Figure 6.1 it is also interesting to note a peak in carbon monoxide values corresponding with the evening peak period. This is most likely due to the high flow on the opposite side of the road. Unfortunately this outbound link on London Road is not a SCOOT link, so the relationship could not be investigated further. Another interesting feature in Figure 6.2 is the midday peak in traffic which is matched by only a very slight increase in carbon monoxide levels.

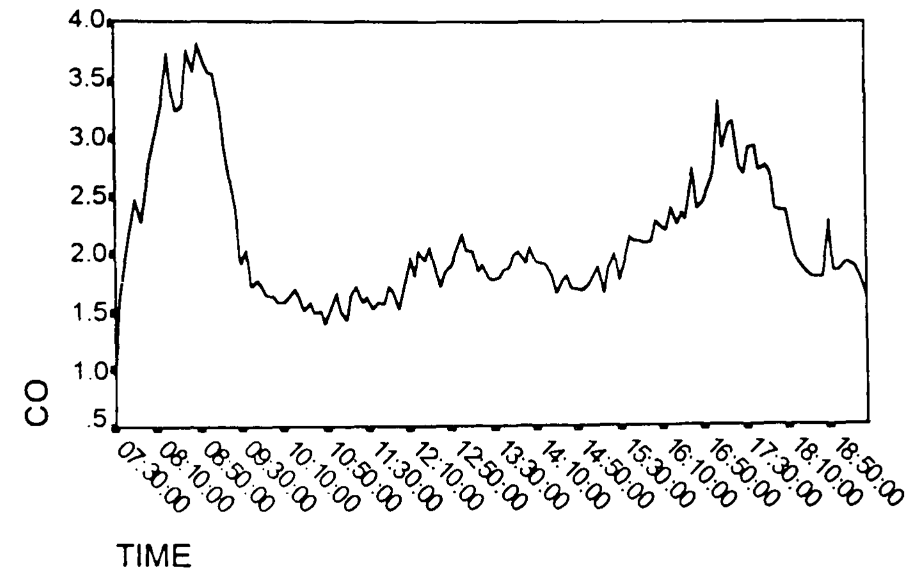

Figure 6.1: Average of carbon monoxide concentrations (ppm) on link N0215J, 17th December 1993 to 16th March 1994

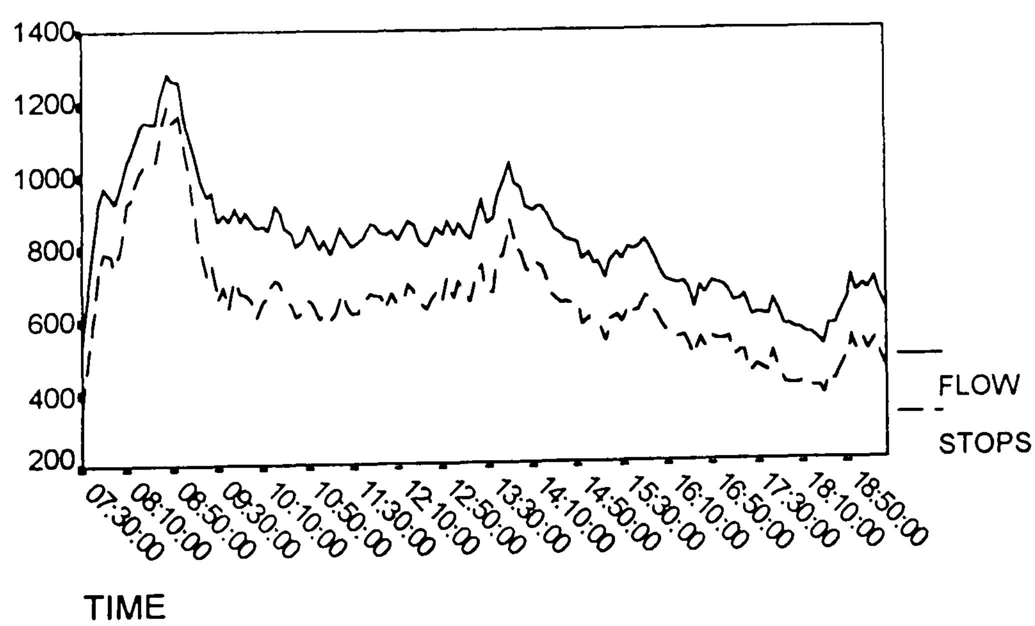

Figure 6.2: Average of FLOW (veh/hr) and STOPS (veh/hr) on link N0215J, 17th December 1993 to 16th March 1994

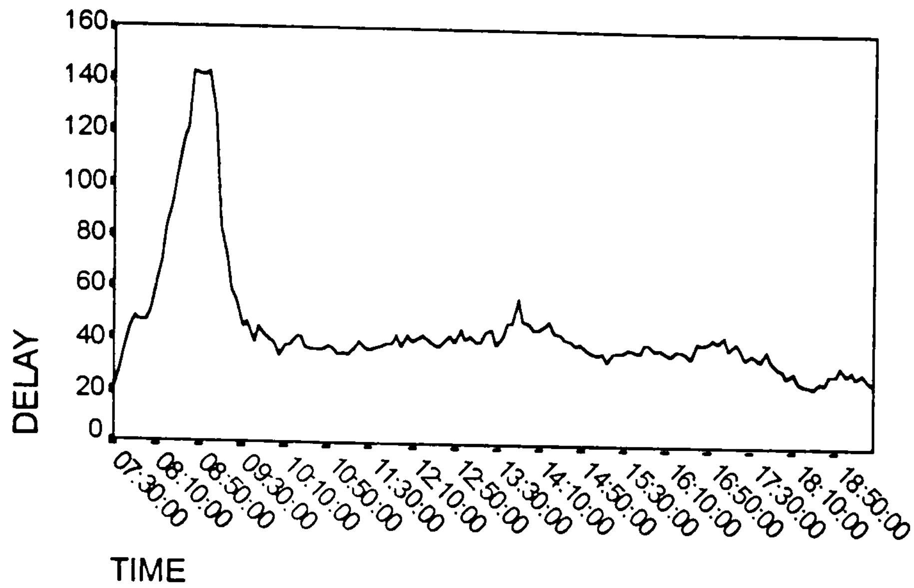

Figure 6.3: Average of DELAY (1/10(veh.hr/hr)) on Link N0215J, 17th December 1993 to 16th March 1994

6.2.3 Urban background air pollution levels

The background air pollution and meteorological monitoring station installed on the top of The Magazine in the centre of Leicester (see Section 5.3) became fully operational on the 11th April 1995. However, some gaps occur in the data, usually due to battery failure earlier than expected.

Table 6.3 gives a statistical summary of the data collected at The Magazine from 11th April 1995 to 21st August 1995. Pollution concentrations were sampled every second and averaged in the minute prior to logging every ten minutes. The negative minimum values were due to the cross-sensitivity problems described in Section 5.6. Acknowledging the lack of calibration of the absolute level, this data does give an indication of the range of levels measured. For example, the range of carbon monoxide levels is only about 10 ppm, demonstrating that the "urban background" levels of carbon monoxide do not vary greatly. This is in sharp contrast to the kerbside levels described in Section 6.2.1 above.

Table 6.3: Summary statistics for pollutants measured at the Magazine

Pollutant (ppm)	Mean	Std Dev	Minimum	Maximum	N
Carbon monoxide	0.20	0.68	-4.91	5.71	13054
Sulphur dioxide	0.04	0.14	-0.82	0.89	13054
Nitrogen dioxide	0.11	0.15	-0.82	1.08	13054

The carbon monoxide values in Table 6.3 were compared with those in Table 6.1 to confirm that the means were statistically significantly different, *ie* that the average level measured at the kerbside is significantly different to the average level at the "background". The *t*-test for two population means was used (Kanji, 1994), which gives an approximate value if the populations are normally distributed or if the sample sizes are sufficiently large. The null hypothesis was that the two population means were equal ($\mu_1 = \mu_2$). The *t*-statistic is calculated using the formula

$$t = \frac{\bar{x}_1 - \bar{x}_2}{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^{\frac{1}{2}}}$$

where $\bar{x}_k$ is the mean of sample k, s_k^2 is the variance of sample k and n_k is the number in sample k. The degrees of freedom are calculated using the following formula (Kanji, 1994)

$$\mathrm{v} = \left(\frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{s_1^4}{n_1^2(n_1+1)} + \frac{s_2^4}{n_2^2(n_2+1)}} \right) - 2$$

In this case, the t value was calculated as 73.8, and the degrees of freedom were 48584, which was so large that the critical value of t was taken to be the value at infinity, *ie* 1.96, at the 95% confidence level (Neave, 1989). As the calculated value was considerably larger than 1.96, the null hypothesis was rejected, *ie* the mean of the kerbside levels was statistically significantly different to the mean of the background levels.

6.3 Distributions

The next step in understanding the data was to plot a histogram of processed data for each of the monitored variables, so that the underlying probability distribution could be identified. Figure 6.4 and Figure 6.5 show typical histograms with normal distribution curves superimposed (these are calculated by SPSS for Windows). The carbon monoxide data could conform to several possible probability distributions. The normal, the gamma and the lognormal distributions were considered to be the most likely.

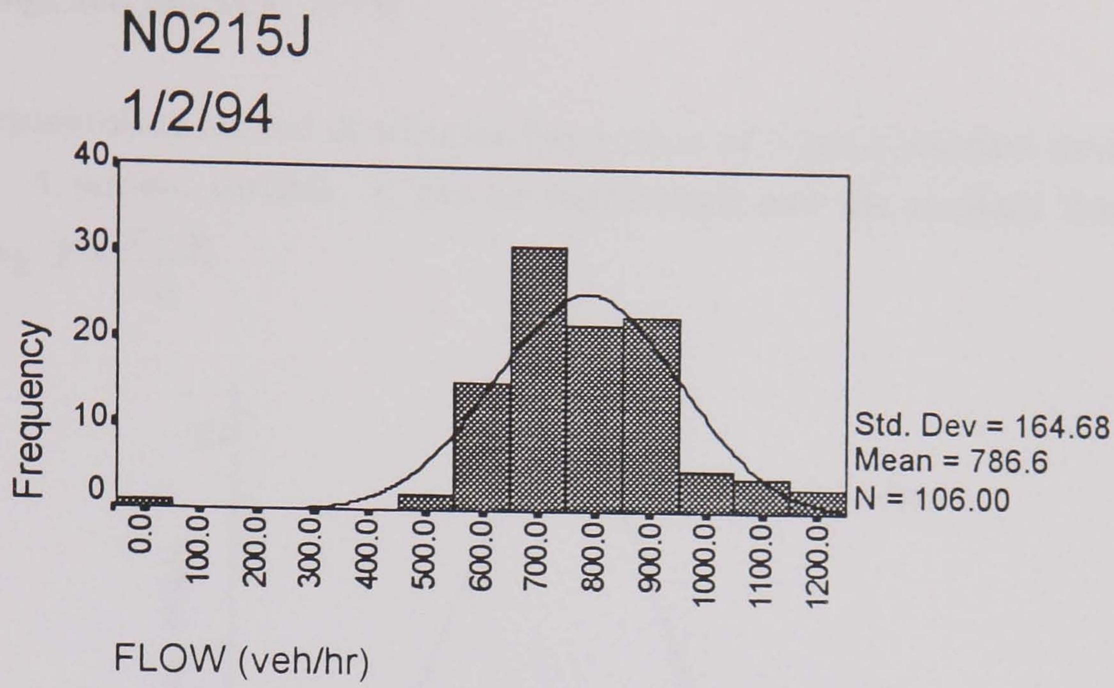

Figure 6.4: Typical FLOW distribution

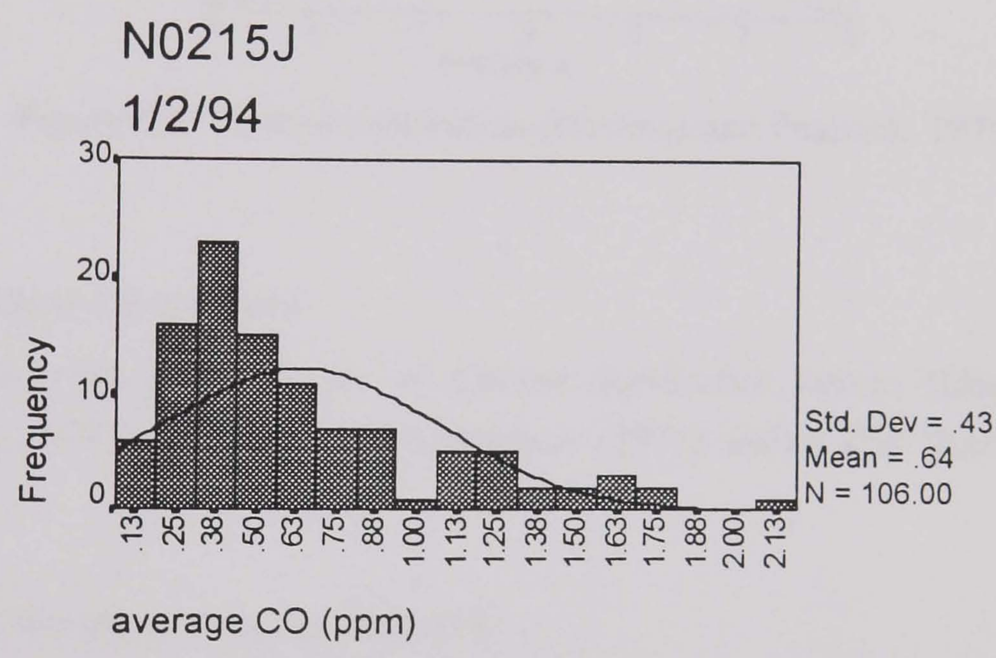

Figure 6.5: Typical carbon monoxide distribution

6.3.1 Normal distribution

The normal distribution is one of the most important examples of a continuous probability distribution. It is also referred to as the "Gaussian distribution". Many statistical tests assume that the data, and the errors, are normally distributed. Figure 6.6 shows the typical "bell-shaped" curve of the normal distribution. The equation of the curve is

$$y = \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

where μ is the population mean, and σ is the population standard deviation (Hastings and Peacock, 1975).

The standardised normal distribution has a mean of 0 and a standard deviation of 1. A normal variable, x, can be transformed into the standard form by defining $Z = \frac{x - \mu}{\sigma}$.

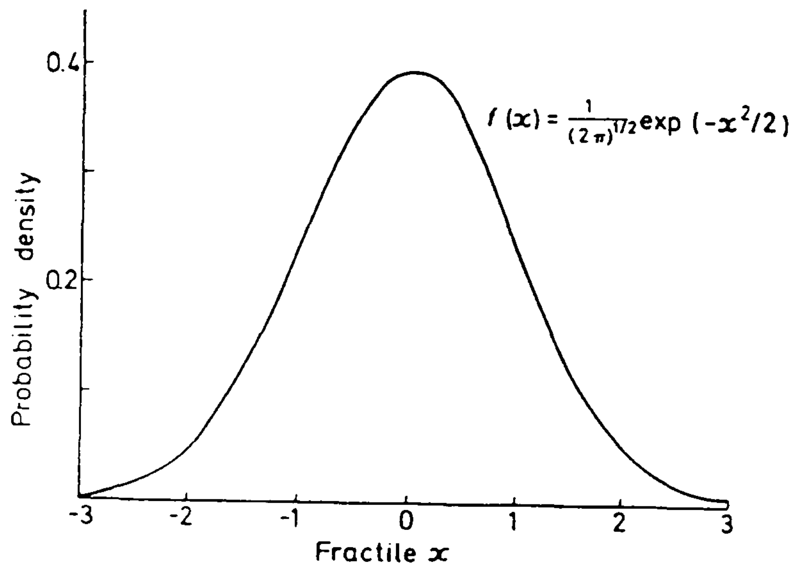

Figure 6.6: Normal distribution (Hastings and Peacock, 1975)

6.3.2 Gamma distribution

Figure 6.7 shows the family of gamma distribution curves (Hastings and Peacock, 1975). Green and Margerison (1978) define this distribution as follows:

> x has the gamma distribution if
>
> $$f(x) = a^c x^{c-1} \frac{e^{-ax}}{\Gamma(c)} \qquad x \geq 0; a, c > 0$$
>
> where c is the number of degrees of freedom, and
>
> $$\frac{\Gamma(c+1)}{\Gamma(c)} = c, \quad \frac{\Gamma(c+2)}{\Gamma(c)} = (c+1)c$$
>
> If c is an integer, then $\Gamma(c) = (c-1)!$
>
> Also, $\mu = \frac{c}{a}$, $\sigma^2 = \frac{c}{a^2}$ and $\Gamma(n) = \int_0^\infty x^{n-1} e^{-x} dx \qquad n > 0$.

This distribution is difficult to calculate and use in the SPSS for Windows package. Calculations were carried out by hand to fit a gamma distribution to some data collected during the early work described in Section 4.6.3. This work was unable to prove statistically that the carbon monoxide data conformed to the gamma distribution.

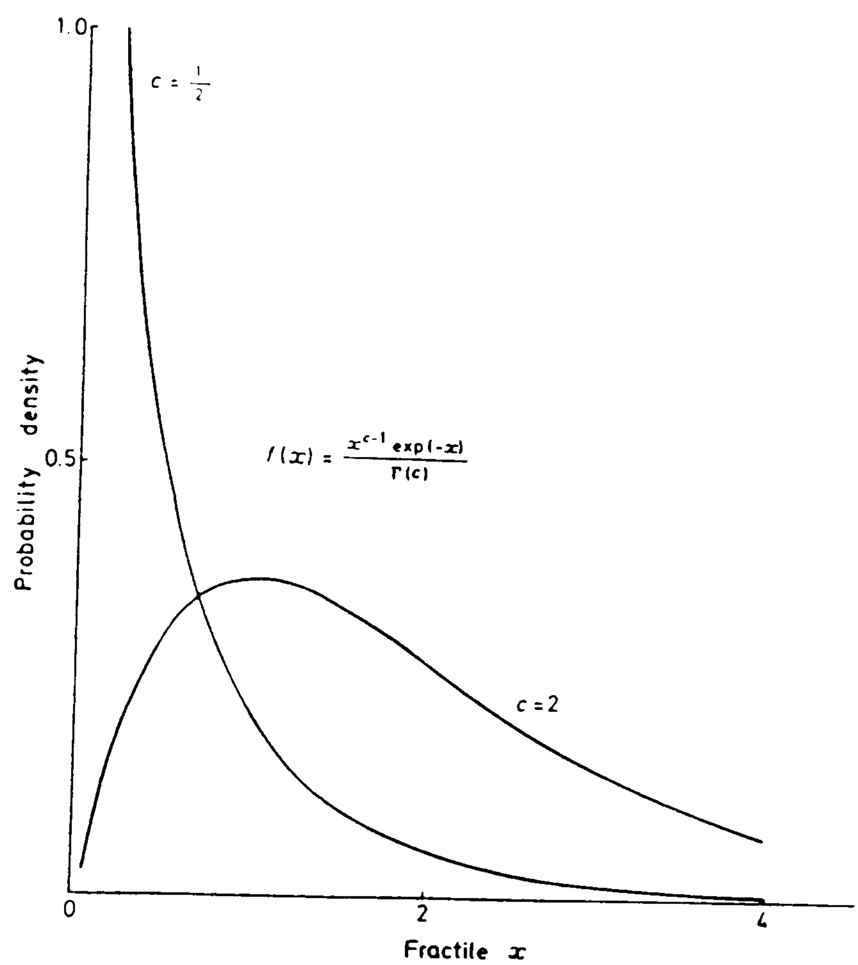

Figure 6.7: Gamma distribution (Hastings and Peacock, 1975)

6.3.3 Lognormal distribution

Ott (1990) reported that many investigators have found that distributions of pollutant concentrations appear to conform to a lognormal distribution, as shown in Figure 6.8 (Hastings and Peacock, 1975). Ott justified this finding by describing a computer simulation of a dilution process to generate data, which had a right-handed skewed distribution. Once plotted on logarithmic-probability paper, a straight line, with a slight downward curvature at the higher concentrations was observed. Ott argued that successive random dilution process occur widely in the environment, which explains why pollutant concentrations often tend to be lognormally distributed.

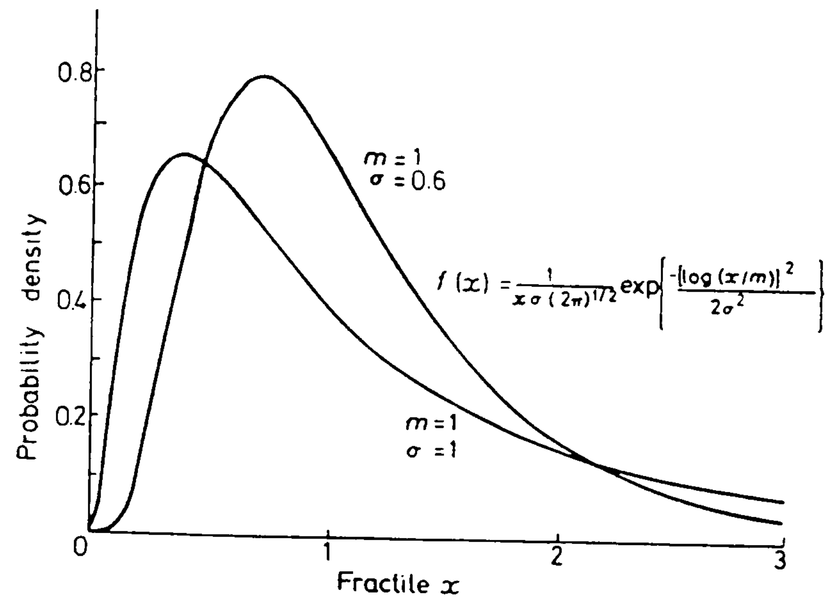

Figure 6.8: Lognormal distribution (Hastings and Peacock, 1975)

Kahn (1973) gave a heuristic justification for the use of the lognormal distribution, as a rigorous proof would be extremely difficult due to the complexity of the emission-transport-receptor process:

Kahn stated that air pollution concentration measured at regular time intervals constitutes a positive, discrete random process, $X_0, X_1, \ldots, X_n$ where X_0 is the concentration at an arbitrary starting point, and X_n is the value of the nth observation. Kahn then assumes that the change in pollutant concentration from one observation to the next can be expressed as

$$X_j - X_{j-1} = p_j X_{j-1} \qquad j = 1, \ldots, n$$

which is the model for the "law of proportionate effect" (Aitchison and Brown, 1957).

Kahn states that this can be rewritten as

$$\frac{X_j - X_{j-1}}{X_{j-1}} = p_j \qquad j = 1, \ldots, n$$

Then
$$\sum_{j=1}^{n} \frac{X_j - X_{j-1}}{X_{j-1}} = \sum_{j=1}^{n} p_j$$

Assuming the change at each point in time is small then

$$\sum_{j=1}^{n} \frac{X_j - X_{j-1}}{X_{j-1}} \approx \int_{X_0}^{X_n} \frac{dx}{x} = \log X_n - \log X_0$$

Therefore $\log X_n \approx \log X_0 + p_1 + p_2 + .. + p_n$

Kahn then concluded that central limit theory states that log X_n is asymptotically normally distributed regardless of the distribution of the p_j and therefore X_n is asymptotically lognormally distributed.

6.3.4 Statistical tests using graphical methods

Figure 6.4 and Figure 6.5 showed typical distributions for FLOW and carbon monoxide data. These were produced by the "12hrsum.sps" macro described in Section 5.8. In this section various statistical tests to explore the character of the distribution will be described.

The "Q-Q plot" is a graphical method to produce a normal probability plot. This procedure plots the observed against expected values based on the rank of the observed value and the number of cases in the sample. The SPSS for Windows package uses Blom's transformation[1] to calculate the expected normal distribution:-

$$\frac{(r - (3/8))}{(n + (1/4))}$$

where n is the number of observations, and r is the rank, ranging from 1 to n.

Figure 6.9 and Figure 6.10 are normal Q-Q plots of the data for the distributions shown in Figure 6.4 and Figure 6.5. If the data conforms to a normal distribution, then the normal Q-Q plot should be a straight line (as indicated by the dotted line here). These plots reinforce the suggestion that the FLOW data is approximately normally distributed, but that this is not the case for the carbon monoxide data.

[1]Blom, G. (1958); Statistical estimates and transformed beta variable; John Wiley and Sons, New York.

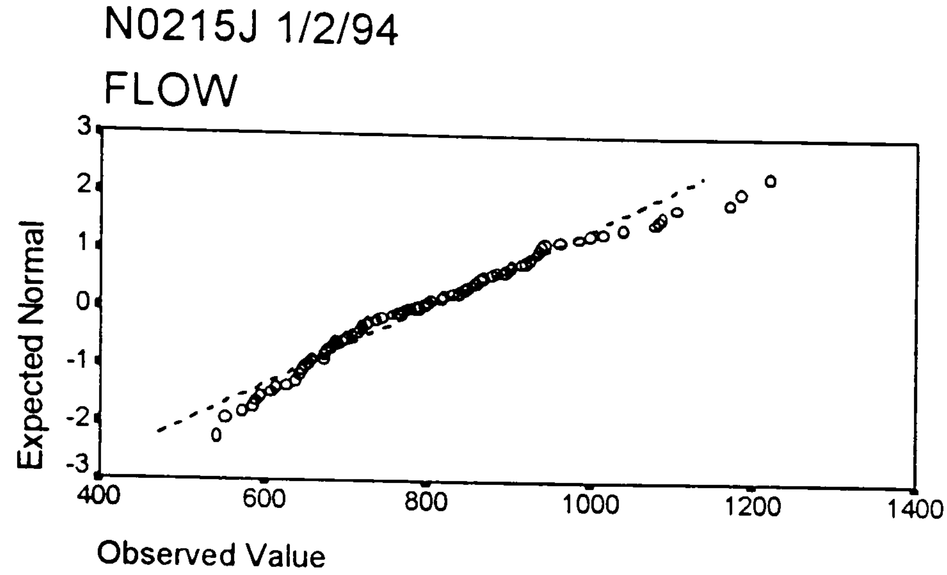

Figure 6.9: Normal Q-Q plot of FLOW (veh/hr)

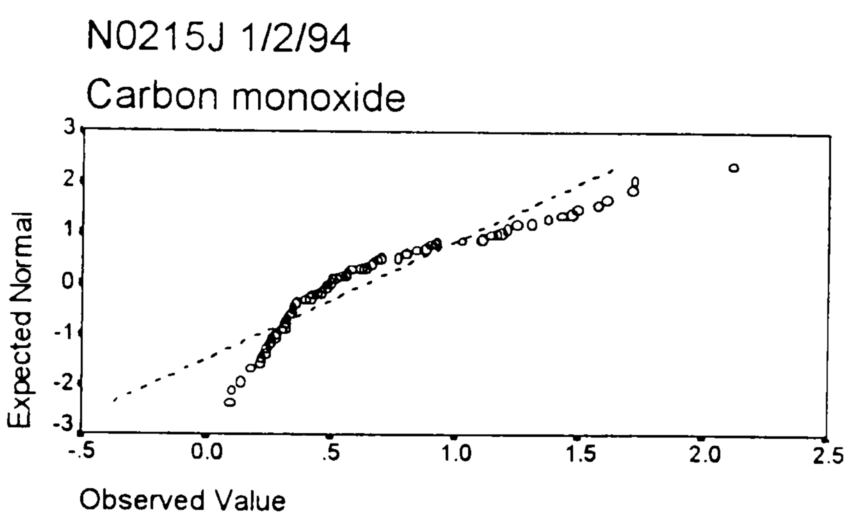

Figure 6.10: Normal Q-Q plot of carbon monoxide (ppm)

6.3.5 χ^2 and Kolmogorov-Smirnov tests

Once the candidate distributions have been identified "by eye" a rigorous statistical test can be used. Two possible tests are discussed here. The first is the χ^2 (chi-squared) test, and the second is the Kolmogorov-Smirnov test, both of which are non-parametric tests based on measuring the discrepancy between observed and expected values.

To use the χ^2 test on the data it was first necessary to produce a frequency table of the data and calculate the mean and standard deviation. These are then used in the formula for the normal distribution (see Section 6.3.1) to produce the expected distribution for the values given in the frequency table. This procedure was carried out by hand. Once the expected distribution had been produced, the χ^2 test statistic could be calculated

$$\chi^2 = \sum_{j=1}^{k} \frac{(O_j - E_j)^2}{E_j}$$

where O_j is the observed value, and E_j is the expected value. The degrees of freedom, ν, was calculated as k-1-m, where k is the number of values and m is the number of population parameters which had to be computed to produce the expected distribution (two in this case - the mean and standard deviation). Tables of the χ^2 distribution were then used to obtain the critical value of χ^2 to determine whether or not the data conformed to the fitted normal distribution (Neave, 1989). If the calculated χ^2 value is less than the critical χ^2 value, then there is no statistically significant difference between the distribution of the observed data and the fitted normal distribution at the chosen significance level (usually 5%).

This method was, however, extremely time consuming, due to the continuous nature of the distribution and the need to first aggregate the data into frequency tables. The Kolmogorov-Smirnov test, however, is suitable for use with continuous distributions, and is easily calculated in SPSS for Windows.

The null and alternative hypotheses for the two-sided Kolmogorov-Smirnov test are as follows (Daniel, 1978):-

$$H_0\text{: } F(x) = F_0(x) \text{ for all values of } x$$
$$H_1\text{: } F(x) \neq F_0(x) \text{ for at least one value of } x$$

where $F(x)$ is the cumulative (population) distribution from which the observed (sample) distribution, $S(x)$, is drawn, and $F_0(x)$ is the hypothesised (test) distribution. Then, the test statistic is

$$D = \sup_x |S(x) - F_0(x)|$$

where "$\sup_x$" denotes the suprenum over all x. Tables of critical D values, D_{crit}, can be found in many statistics textbooks (*eg* Neave, 1989). If the calculated value of D is less than the tabulated value, then the null hypothesis is accepted at the chosen significance level.

The Kolmogorov-Smirnov test was used to compare the distributions of data for each air pollutant and SCOOT variable for each day in February 1994 with the normal distribution. In addition, the natural logarithm (ln) of the carbon monoxide data was calculated and its distribution examined. The significance level chosen was 5%. For samples sizes greater than 100 Daniel's approximation was used to calculate D_{crit} ($D_{crit} \approx 1.36/\sqrt{n}$) (Daniel, 1978). Table 6.4 summarises the results of these tests.

Table 6.4: Distributions of variables tested using Kolmogorov-Smirnov statistic

Variable	Number of days when the sample distribution was normal (max = 28)
FLOW (veh/hr)	20
STOPS (veh/hr)	20
DELAY (1/10(veh.hr/hr))	13
Carbon monoxide (ppm)	14
ln (carbon monoxide)	20
Nitrogen dioxide (ppm)	7
Sulphur dioxide (ppm)	16

It was found that on nine days the carbon monoxide data were not statistically significantly different to either the normal or the lognormal distribution at the 95% confidence level. However, five of these were closer to lognormal than normal. In addition, one had a very small sample size (10, instead of the usual 144), which meant that the critical value of D was comparatively large.

It is interesting to note that out of the eight weekend days in February 1994, on five of these days the carbon monoxide data were normally distributed, and on one it was lognormally distributed. On two days it conformed to neither. It is proposed that this is due to the fact that there is little congestion at the weekend which, during the weekdays, gives rise to the high carbon monoxide values found in the long tail of its distribution (which is characteristic of the lognormal distribution).

This analysis confirmed that the distribution of FLOW data shown in Figure 6.4 was not statistically significantly different from a normal distribution, and that the carbon monoxide data shown in Figure 6.5 was not statistically significantly different from a lognormal distribution.

The datasets analysed above all contained five minute averages for the 12 hour period 07:30 to 19:30. Therefore, one dataset of raw, one-minute values was also analysed to validate the conclusions about the distributions. Figure 6.11 shows the distribution of carbon monoxide levels from link N0213A for the period 16th February 1995 to 15th March 1995. A visual inspection of the graph suggests that the data conforms to a lognormal distribution. However, using the Kolmogorov-Smirnov test, it is not possible to prove this statistically. This is possibly due to the fact that the sample was very large (23 721 valid cases where the natural logarithm can be calculated) and the Kolmogorov-Smirnov test is designed for much smaller sample sizes.

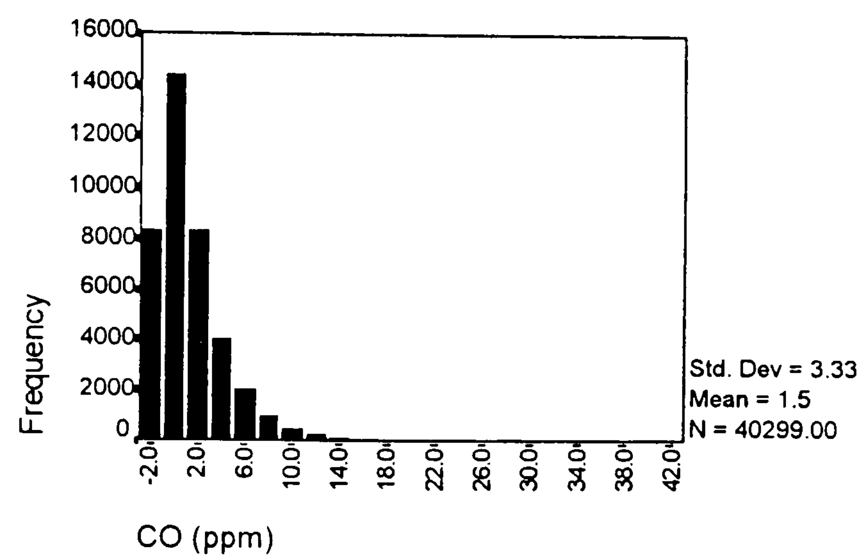

Figure 6.11: Distribution of carbon monoxide levels on link N0213A

Figure 6.12 shows the distribution of the carbon monoxide levels monitored at the Magazine. The histogram has a normal curve superimposed. A Kolmogorov-Smirnov test confirms that the distribution did not statistically significantly conform to the normal distribution. The distribution displays a high frequency of carbon monoxide levels around the mid range, and it is this mode which is responsible for the lack of normality. It is suggested that this reflects the 'average' background level which was prevailing for most of the day. The spread was due to the low overnight values and the high peak traffic periods. It is important to note that the shape of the distribution of carbon monoxide levels at this "urban background" location was very different to the distribution of levels at the kerbside. Therefore, it may be assumed that the long tail in the distribution of roadside levels was almost entirely due to the traffic.

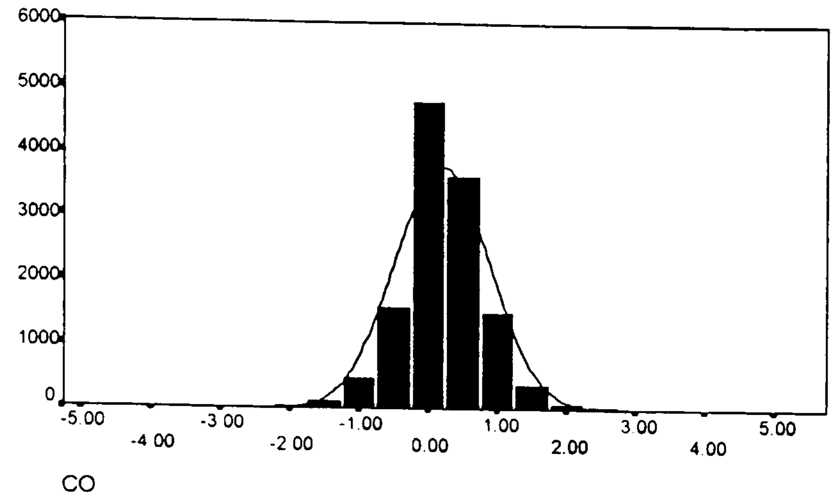

Figure 6.12: Distribution of carbon monoxide levels at the Magazine

6.4 Multiple regression

6.4.1 Bivariate regression

In Section 4.5.2 it was stated that, when two variables are plotted against each other as a scatterplot, as shown in Figure 6.13, it is possible to fit a "best straight line" and to calculate the strength of the relationship using regression techniques. This technique was used with the data from the prototype transportable units and an example using one day's data is given here.

For the data shown in Figure 6.13 the equation of the best-fit line is

$$\underset{}{CO = \underset{(0.000253)}{-0.000477}\,(FLOW) + \underset{(0.2029)}{1.0147}}$$

The standard errors of the coefficients are shown in brackets. From Figure 6.13 it is obvious that this line is a poor fit of the data and the coefficient of correlation (R^2) was calculated to be 0.182. This demonstrates that there are other factors which need to be taken into consideration as there is no direct and straightforward relationship between carbon monoxide and FLOW. This confirms the results of the work described in Section 4.6, although at that time the low correlation was attributed to a lack of data.

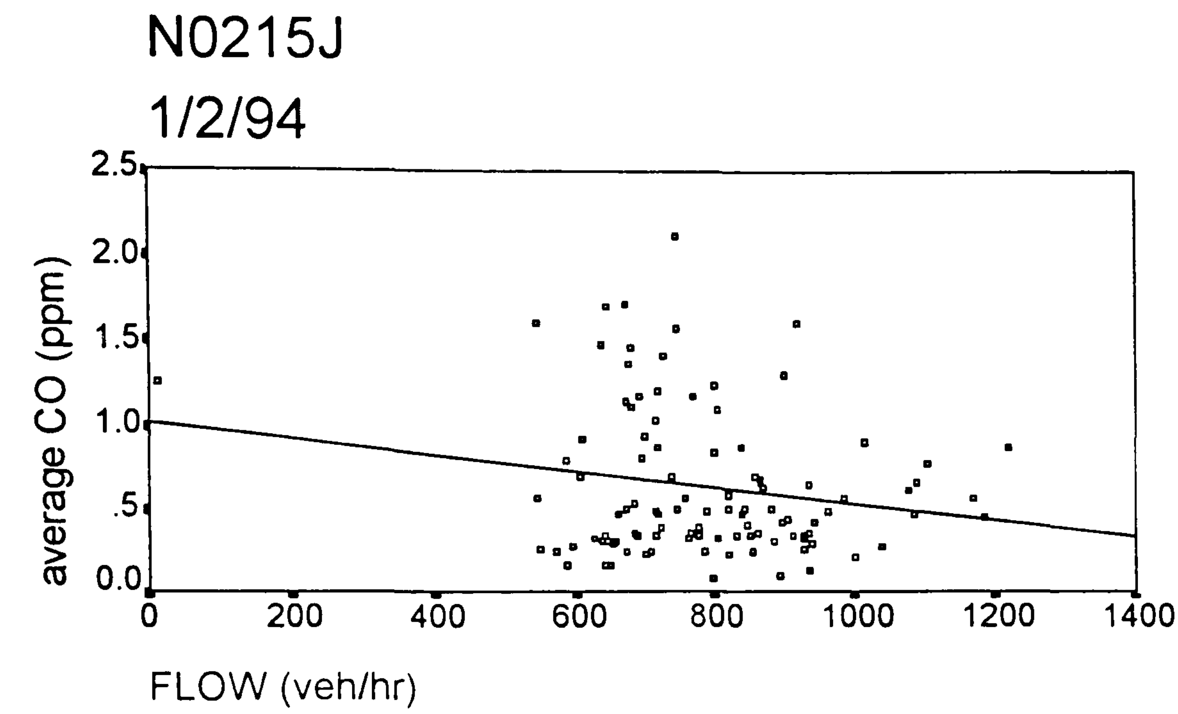

Figure 6.13: Scatterplot of carbon monoxide against FLOW

In the equation above, the absolute value of the estimate of b was 0.0005, and its standard error was 0.0003. Dividing the estimate of b by its standard error gives the t value, which was calculated as 1.885, *ie* $\hat{b}$ falls 1.885 standard deviations from zero. The critical value of t, at the 95% significance level, is 1.976. As 1.885 is less than 1.976 the hypothesis that $\hat{b}$ is statistically significantly different from zero cannot be accepted.

6.4.2 Investigation of differences in carbon monoxide levels throughout the week

Data was collected on link N0213A for the period of one month between 16th February 1995 and 15th March 1995, with only two days missing. The raw pollution data (in four separate files) was sorted by time and then averaged to give a minute-by-minute average of data over the month. Figure 6.14 shows the variation of carbon monoxide over time of day for weekdays (*ie* Monday to Friday) during this month. Figure 6.15 shows the variation of carbon monoxide levels over time of day for the four weekends. The influence of the morning and afternoon traffic peak periods is obvious in Figure 6.14.

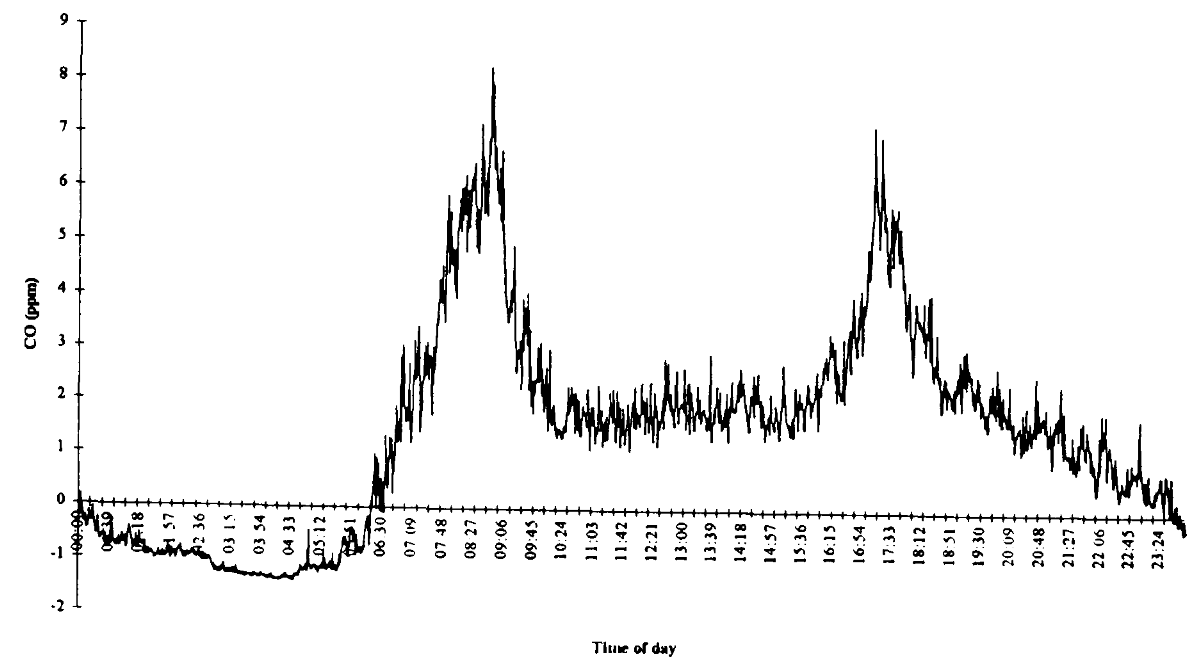

Figure 6.14: Diurnal average for Monday to Friday, link N0213A, 16th February 1995 and 15th March 1995

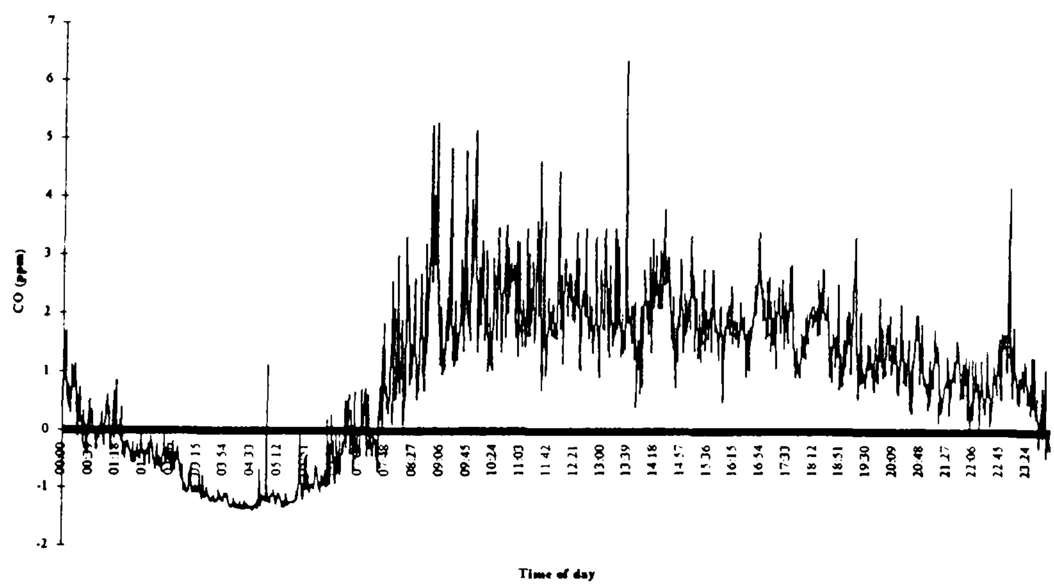

Figure 6.15: Diurnal average for the weekends, link N0213A, 16th February 1995 and 15th March 1995

Figure 6.16 is a scatterplot which shows the five minute averages of carbon monoxide levels for the five days of the working week, compared to the levels for the seven day week. The slope of the regression line is 1.209, which is statistically significantly different to 1.0, at the 95% confidence level (tested using a *t*-test). This graph shows that, on average, carbon monoxide levels are 20% higher when averaged over the working week than when averaged over the whole week. This implies that it may be necessary to produce two different sets of empirical relationships - one for the working week and one for the weekend.

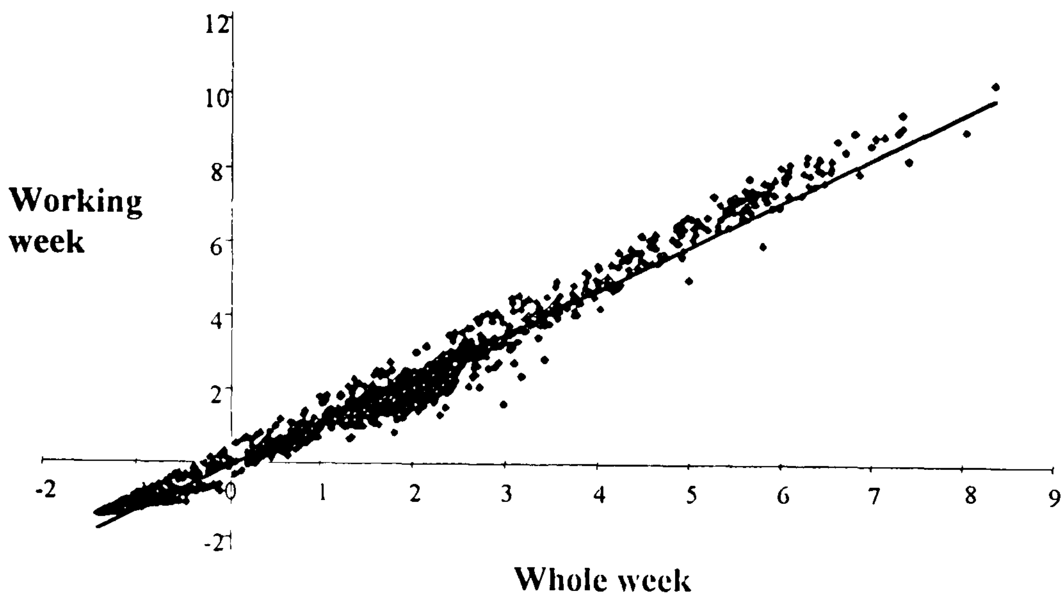

Figure 6.16: Comparison between carbon monoxide (ppm) data collected during the working week and the whole week

6.4.3 Investigation of an empirical relationship between carbon monoxide levels and SCOOT parameters

The data for link N0215J on 1st February 1994 was analysed using multiple linear regression to investigate the suitability of this statistical technique to derive the empirical relationship between carbon monoxide levels and traffic characteristics. It was decided to have three independent variables - STOPS, DELAY and FLOW, and the dependent variable was AV_CO (*ie* the carbon monoxide levels averaged over five minutes). These independent variables were chosen because they give the number of vehicles crossing the stopline in a period (FLOW), the number of vehicles which have to stop on the link (STOPS) and the amount of time for which vehicles are delayed on average (DELAY). Section 6.4.1 demonstrated that carbon monoxide levels were not simply dependent on FLOW. Therefore, by using the three variables available from the SCOOT M02 message - FLOW, STOPS and DELAY, the nature of the traffic in urban areas can be taken into account, *ie* vehicles constantly cruising, accelerating, decelerating and idling between signal controlled junctions.

The SPSS for Windows REGRESSION procedure was used to calculate the regression equation and perform the associated statistical tests. Figure 6.17 shows the output from the procedure.

Multiple R	.53865
R Square	.29014
Adjusted R Square	.26926
Standard Error	.36874

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	3	5.66853	1.88951
Residual	102	13.86878	.13597

F = 13.89667 Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
DELAY	.030067	.005119	.802803	5.874	.0000
FLOW	-.001107	5.3089E-04	-.422623	-2.085	.0395
STOPS	-9.33091E-04	5.9914E-04	-.363021	-1.557	.1225
(Constant)	.889269	.189230		4.699	.0000

Figure 6.17: Results of multiple linear regression equation estimation

In the top left section the values of r $(=\sqrt{R^2})$ and R^2 are given and the standard error of the estimate. (The adjusted R^2 is an alternative measure of the fit of the regression equation to the data (Norušis, 1993)). The value of R^2 was low, indicating that the predicted equation could not explain much of the scatter in the data, although it is considerably better than the R^2 of 0.033 when FLOW alone was the independent variable (see Section 6.4.1). The top right section contains the results of the analysis of variance calculations to find the estimated sum of squares (ESS) and the residual sum of squares (RSS).

In this case, the ESS was 5.66853, with 3 degrees of freedom ($k - 1 = 4 - 1 = 3$). The RSS was 13.86878, with 102 degrees of freedom ($n - k = 106 - 4 = 102$). Hence $F = \dfrac{5.66853/3}{13.86878/102} = 13.89667$. From tabulated values of the F distribution (*eg* Neave, 1989) the critical value of F at the 95% confidence level is approximately 2.70. This value is less than the calculated F-value, so the joint null hypothesis that the coefficients of X are all zero is rejected, which is confirmed by the value of `Signif F` being 0.0000.

The bottom section of the output in Figure 6.17 gives the details of the parameters of the regression equation. The equation has three independent variables and a constant. The column labelled "B" gives the estimated coefficients, *ie* the matrix $\hat{B}$, and the next column contains the standard error of each coefficient. The "Beta" value is the standardised regression coefficient.

This is calculated by multiplying the regression coefficient by the ratio of the standard deviation of the independent variable to the standard deviation of the dependent variable.

In the next column the *t*-value is calculated. The critical value of *t* is 1.984 at the 95% significance level (Neave, 1989). The *t*-value for the coefficient of DELAY was 5.874 which is larger than 1.984, therefore it was statistically significantly different from zero. The *t*-value for the coefficient of STOPS was 1.557, which is smaller than 1.984, therefore it was not statistically significantly different from zero. The *t*-value for the coefficient of FLOW was very close to 1.984, but was slightly larger. The *t*-value for the constant term was 4.699, and was therefore statistically significantly different from zero.

The regression equation was then recalculated without the STOPS variable. The resulting equation was

$$\begin{array}{c} AV\_CO = 0.0261\ (DELAY) - 0.0018\ (FLOW) + 0.9991 \\ \qquad\qquad (0.0045) \qquad\qquad (0.0003) \qquad\qquad (0.1768) \end{array}$$

The standard errors of the coefficients are given in brackets. All three coefficients were statistically significantly different from zero, and the joint null hypothesis could also be rejected. The R^2 value was 0.273, which was only slightly less than when STOPS was included in the equation (0.290). Hence, in this case, not including STOPS did not affect the results very much, and in fact led to a more parsimonious equation. Figure 6.18 shows the predicted values plotted against the actual values. There is a large degree of scatter which is reflected by the low R^2 value.

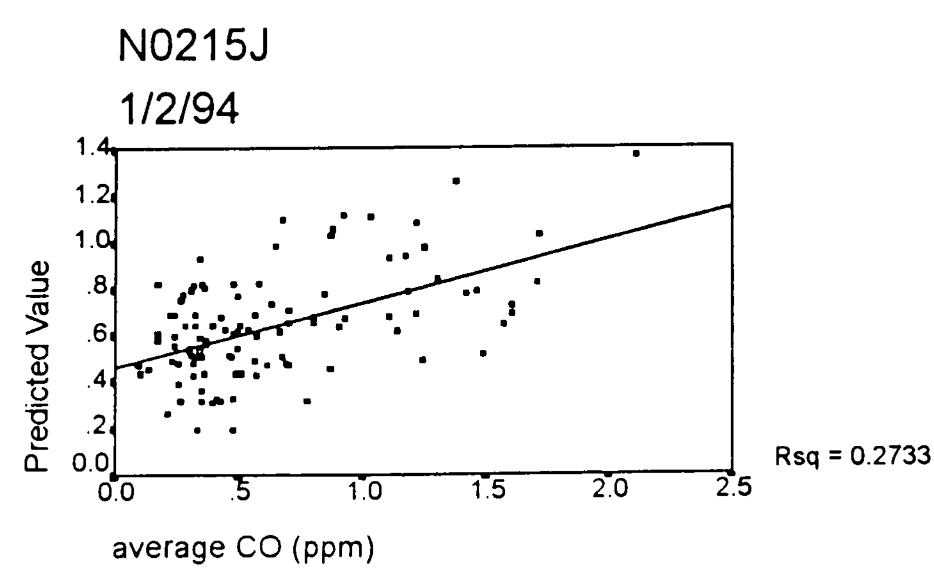

Figure 6.18: Predicted carbon monoxide value against actual carbon monoxide value

6.4.4 Collinearity

It was stated in Section 4.6.2 that one of the underlying assumptions of multiple linear regression is that there is no exact linear relationship between the independent variables. The *variance inflation factor* can be used to assess the factor by which the variance of an estimated regression coefficient is increased due to near linear dependencies among the regressors (Montgomery and Peck, 1992). SPSS for Windows will calculate the tolerance and the variance inflation factor which assesses the degree of collinearity and multicollinearity.

The variance inflation factor (VIF) is calculated as

$$\mathrm{VIF} = \frac{1}{1 - R_i^2}$$

where R_i^2 is the regression coefficient, R^2, of the independent variable X_i regressed on all of the other independent variables (Belsley *et al*, 1980). The tolerance is the inverse of this factor (Norušis, 1993). A high VIF, *ie* greater than 5 to 10, (or low tolerance) gives a strong indication of the presence of collinearity.

Table 6.5 shows the pairwise correlation coefficients (r) for each of the independent variables in the original model. The variance inflation factors for each variable are shown in Table 6.6. These show that all three SCOOT variables are significantly correlated with each other.

Table 6.5: Pairwise correlation coefficients (r) for the independent variables

Correlations

		STOPS	DELAY	FLOW
Pearson Correlation	STOPS	1.000	.793**	.912**
	DELAY	.793**	1.000	.711**
	FLOW	.912**	.711**	1.000
Sig. (2-tailed)	STOPS	.	.000	.000
	DELAY	.000	.	.000
	FLOW	.000	.000	.
N	STOPS	105	105	105
	DELAY	105	105	105
	FLOW	105	105	105

**. Correlation is significant at the 0.01 level (2-tailed).

Table 6.6: Variance inflation factors for the independent variables

Variable	VIF
STOPS	7.903
DELAY	2.698
FLOW	5.944

In fact, it has already been shown that it was necessary to reformulate the model by removing the STOPS variable because the estimate of its regression coefficient was not statistically significantly different to zero. The variance inflation factor of FLOW and DELAY in this new model were each 2.02. This is an example of eliminating collinearity by removing variables. Otherwise, it may have been necessary to try a combination function such as $\frac{\text{STOPS}}{\text{FLOW}}$ instead of considering these as two separate variables.

6.4.5 Homoskedastic and heteroskedastic disturbances

One further assumption of multiple linear regression is that the residuals are homoskedastic. The residual is the difference between the observed value and the value predicted using the equation fitted to the data. Homoskedastic means that the variance of the residual series, σ_a^2, is constant. If the variance is not constant, *ie* the residuals are heteroskedastic, then the least-squares estimator of the coefficients is no longer accurate (Pankratz, 1991). In this case, it is necessary to transform the original series by taking the natural logarithm, the square root or some other power transformation, in order to stabilise the variance.

6.4.6 Normally distributed residuals

As well as being homoskedastic the residuals should be normally distributed with mean 0 and variance σ^2. Montgomery and Peck (1992) stated that small departures from normality will not affect the model to any great extent, but gross non-normality is more of a problem since the *t*- and *F*- statistics depend on the assumption of normality.

If the residuals are found not to be normally distributed, then it is most probable that the dependent variable is also not normally distributed, and *vice versa* (Montgomery and Peck, 1992). This is an important point in the context of the research described in this thesis, as it was shown in Section 6.3.5 that the carbon monoxide levels measured at the kerbside were often lognormally distributed.

Figure 6.19 shows the normal probability plot of the residual series from the multiple regression model fitted in Section 6.4.3. A one-sample Kolmogorov-Smirnov test gave a D value of 0.09151. The tabulated critical value is 0.1340. This indicates that the residual series was normally distributed at the 95% confidence level.

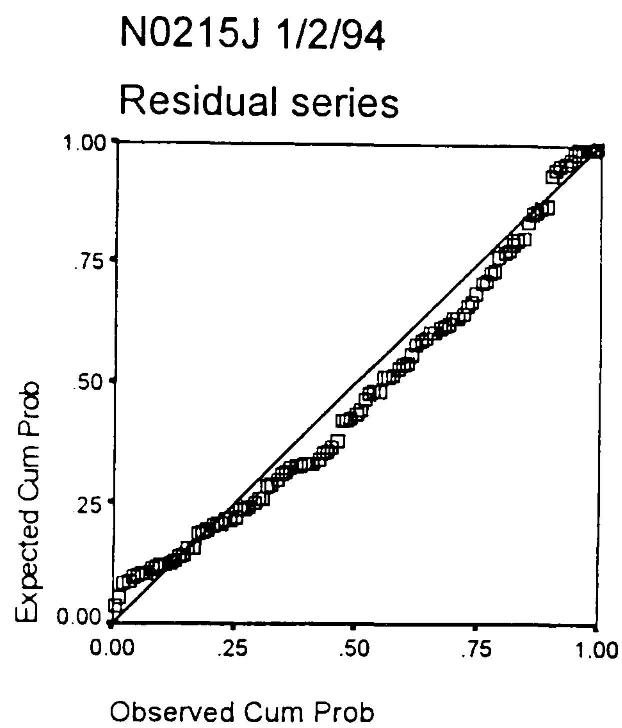

Figure 6.19: Normal probability plot of the residual series

Figure 6.5 indicated that the carbon monoxide data for this day was not normally distributed. A Kolmogorov-Smirnov test gave a D value of 0.17195, which confirms this result. Figure 6.20 is a lognormal probability plot of the data, which shows that the data is lognormally distributed. It is important to note that, in this case, the residuals were normally distributed although the carbon monoxide data was not.

These results appear to contradict the general statement made by Montgomery and Peck (1992) about the relationship between the normality of residuals and the normality of the dependent variable. These results therefore highlight that it is important to check the normality conditions at all stages of multiple regression analysis for each data set analysed.

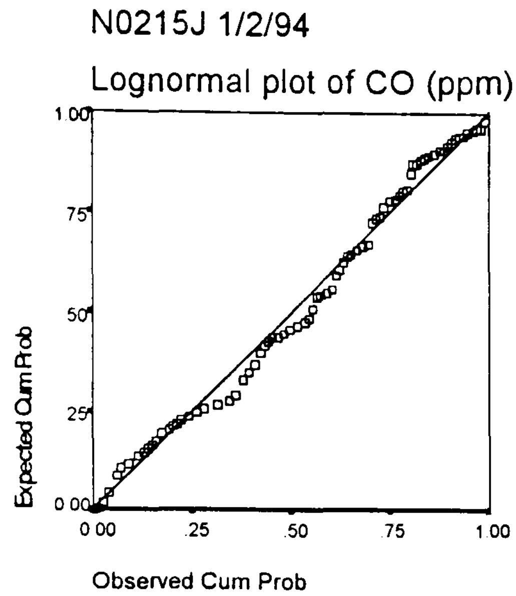

Figure 6.20: Lognormal probability plot of the carbon monoxide data

Alternatively, a different modelling approach could be used. Generalised Linear Modelling is a technique which can be used to analyse data with normal or non-normal error distributions (Francis *et al*, 1994). A computer program known as GLIM (Generalised Linear Interactive Modelling) can be used to produce this type of model (Francis *et al*, 1994). Generalised linear models have three parts:-

1. The *random component*: this is a description of the underlying probability distribution of the dependent variable, which may be from any member of the exponential family. For example, $\underline{Y}$ has an independent normal distribution with constant variance σ^2 and $E(Y) = \mu$, where $\mu = x\beta$.

2. The *systematic component*: this is generally a linear combination of the explanatory variables. Hence, the covariates $x_1, x_2, \ldots, x_p$ produce a *linear predictor* η given by

$$\eta = \sum_{j=1}^{p} \beta_j x_j .$$

3. The *link function*: this exists between the random and systematic components, such that $\eta_i = g(\mu_i)$, and $g(.)$ is the link function.

It must be noted that generalised linear modelling assumes that the observations are independent and uncorrelated. This is an important condition, since it was shown in Section 6.4.3 that STOPS and FLOW are often highly collinear.

Using generalised linear modelling with normally distributed data sets will, however, give the same results as multiple linear regression, therefore it was decided to proceed with the regression analysis, albeit with caution.

6.4.7 Durbin-Watson test for serial autocorrelation

Another important check on the accuracy of a regression analysis is whether or not the residual series is autocorrelated. If autocorrelation is present then the *t*- and *F*-tests are not valid. If a series is autocorrelated then there is a relationship between observations in the series which may be due to an incorrect specification of the form of the relationship between the variables (Johnston, 1972). The Durbin-Watson statistic is used to test for autocorrelation. Johnston (1972) defines the Durbin-Watson d statistic as

$$d = \frac{\sum_{t=2}^{n}(a_t - a_{t-1})^2}{\sum_{t=1}^{n} a_t^2}$$

where a_t is the series being tested. The null hypothesis is that there is no autocorrelation. Critical upper (d_U) and lower (d_L) values are tabulated, for example in Neave (1989). If $d \le d_L$ then the null hypothesis is rejected. If $d \ge d_U$ then the null hypothesis is accepted. If $d_L < d < d_U$ then the test is inconclusive.

In the case of the regression equation fitted here the Durbin-Watson statistic was calculated, by SPSS for Windows, as 1.13. The tabulated value of d_L was approximately 1.634 at the 5% level of statistical significance (sample size was 106, and there were two explanatory variables) and the critical value of d_U was 1.715. Hence, d was less than d_L, and the null hypothesis of no autocorrelation was rejected and therefore the results of the *t*- and *F*-tests were invalid. The multiple regression procedure was then repeated for data from several other days and, in each case, the residual series was found to be autocorrelated.

Montgomery and Peck (1992) stated that autocorrelation is a common problem when analysing time series data, such as that collected during the course of this research. One method for dealing with time series data is to include lagged values of the dependent variable as regressors, *eg*

$$y_t = \beta_0 + \beta_1 y_{t-1} + \beta_2 x_t + \varepsilon_t .$$

However, in this case the Durbin-Watson test is no longer valid.

Montgomery and Peck (1992) described the Cochrane-Orcutt method for eliminating autocorrelation. In this method the dependent variable is transformed so that

$$y_t' = y_t - \rho y_{t-1}$$

where $y_t = \beta_0 + \beta_1 x_t + \varepsilon_t$.

Then,

$$y_t' = \beta_0 + \beta_1 x_t + \varepsilon_t - \rho(\beta_0 + \beta_1 x_{t-1} + \varepsilon_{t-1})$$
$$y_t' = \beta_0(1-\rho) + \beta_1(x_t - \rho x_{t-1}) + \varepsilon_t - \rho\varepsilon_{t-1}$$
$$y_t' = \beta_0' + \beta_1' x_t' + a_t$$

where $\beta_0' = \beta_0(1-\rho)$, $\beta_1' = \beta_1$, $x_t' = x_t - \rho x_{t-1}$ and $a_t = \varepsilon_t - \rho\varepsilon_{t-1}$.

The value of ρ can be estimated by calculating the residuals e_t from a least squares regression of y_t on x_t and then regressing e_t on e_{t-1}, *ie*

$$\hat{\rho} = \frac{\sum_{t=2}^{n} e_t e_{t-1}}{\sum_{t=1}^{n} e_t^2}.$$

Once the value of ρ has been estimated, the transformed dependent and independent variables can be calculated. The method of least squares is then applied to the transformed data. The Durbin-Watson test can then be used to assess whether autocorrelation is present in the residuals from the re-parameterised model. If no autocorrelation is indicated, then no further analysis is needed. However, if autocorrelation is still indicated, then another iteration is necessary.

In the case of the model for carbon monoxide using FLOW and DELAY as the independent variables, as described above, the estimate of ρ was calculated to be 0.417. The dependent and independent variables were then transformed using the equations shown above, and the least squares regression procedure was repeated. The resulting equation was

$$\underset{}{\mathrm{AVCO}_t'} = \underset{(0.093)}{0.5129} - \underset{(0.0003)}{0.0009}(\mathrm{FLOW}_t') + \underset{(0.004)}{0.0121}(\mathrm{DELAY}_t')$$

The standard errors are given in brackets below the coefficients. All of the coefficients were statistically significantly different from zero and the variance inflation factor for both independent variables was 2.284. The R^2 value was calculated to be 0.099. Most importantly, the Durbin-Watson statistic was calculated to be 1.825, which is greater than the upper critical value, d_U, of 1.72. This means that the residuals were not autocorrelated.

6.4.8 Discussion

Many researchers have applied multiple linear regression techniques to statistically analyse data and therefore it was a logical choice to analyse the kerbside pollution and SCOOT data. The data analysed in this section was representative of the data collected from the prototype transportable units and therefore the results are also representative. The multiple regression analysis appeared to produce a consistent, unbiased equation until the residual series was analysed and found to be autocorrelated. This result meant that both the t- and the F-tests were invalid. The Cochrane-Orcutt method for eliminating autocorrelation was investigated to overcome this. The only disadvantage with this method was that the resulting model was no longer expressed in terms of the original parameters. Therefore it was decided to investigate an alternative analysis technique - Time Series Analysis.

6.5 Time Series Analysis

The phrase "time series analysis" refers to statistical techniques for investigating the relationships between variables which change over time. All the variables considered in this research are suitable for analysis using these techniques.

Possibly the most well known technique is the one developed by Box and Jenkins (1976) - the AutoRegressive Integrated Moving Average (ARIMA) technique. The simple ARIMA model states how the values in a time series are related to past values of that time series. The model can then be used to forecast future values. The technique was developed for use in the manufacturing industry, to enable engineers to forecast if a process was going out of control, *ie* outside tolerance limits.

Box and Jenkins proposed a three phase modelling strategy for developing ARIMA models to describe time series. Each phase is equally relevant to all levels of model development:

1. model identification;

2. model estimation; and
3. model checking.

Figure 6.21 is a diagrammatic representation of this process.

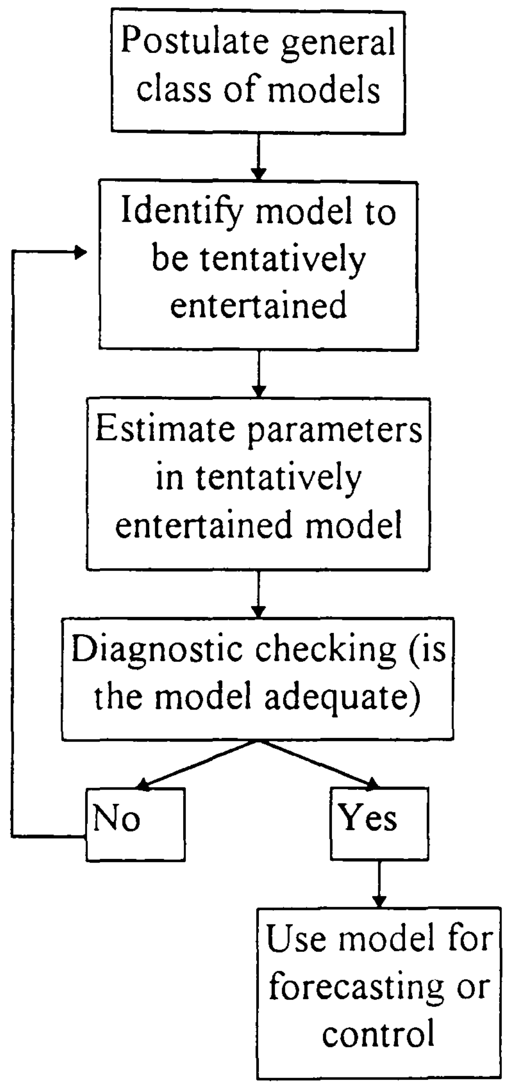

Figure 6.21: Stages in the iterative approach to model building (Box and Jenkins, 1976)

The general form of a (non-seasonal) ARIMA model of order p, d, q is

$$\phi(B)\nabla^d z_t = C + \theta(B)a_t$$

where z_t = observation at time t

B = backward shift operator, $B^j z_t = z_{t-j}$

∇^d = $(1-B)^d$, the d-order differencing operator

$\phi(B)$ = $(1-\phi_1 B - \phi_2 B^2 - \ldots - \phi_p B^p)$, the p-order auto-regressive operator

$\theta(B) = \left(1-\theta_1 B-\theta_2 B^2-\ldots-\theta_q B^q\right)$, the q-order moving average operator

C = constant

a_t = random shock term.

An *autoregressive* process is one in which each value is a linear function of the preceding value or values. In a *moving average* process, each value is determined by the average of the current disturbance (random shock) and one or more disturbances up to order q. ARIMA models can be either pure autoregressive processes, or pure moving average processes or mixed autoregressive and moving average processes. The random shock term is assumed to have a zero mean, and to be normally distributed white noise (Pankratz, 1991).

The ARIMA technique was used to study the five minute average carbon monoxide levels (from the MSPD program, see Section 5.7). The analysis of the data for link N0215J in Leicester, on 26th February 1994, is described here as an example. The objective was to identify and fit a suitable ARIMA model using the Box and Jenkins strategy so that the suitability of this technique for deriving an empirical relationship could then be assessed. Firstly, a sequence chart was plotted, shown in Figure 6.22, where the mean of the series is shown by the horizontal line through 5.50 ppm.

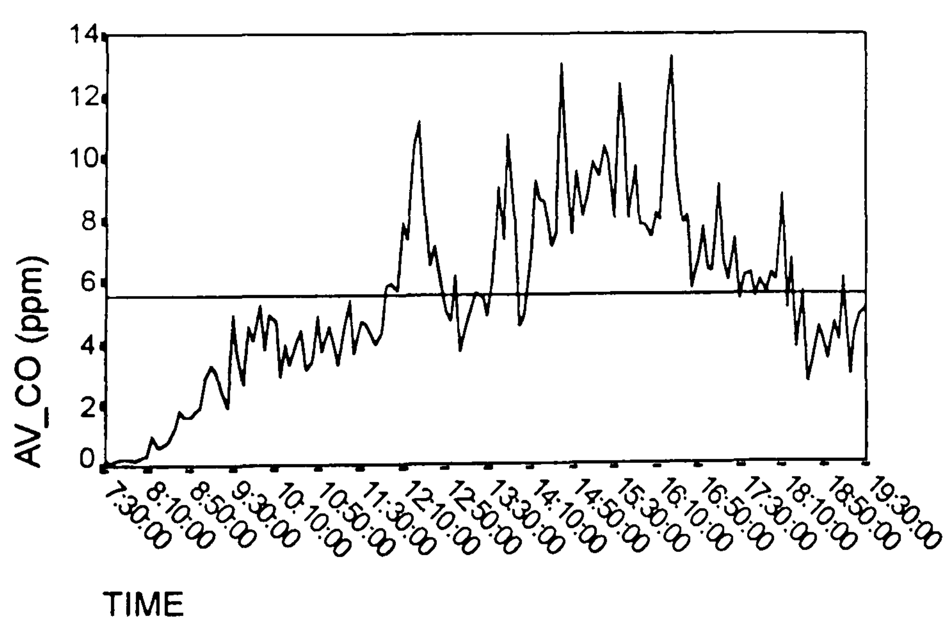

Figure 6.22: Sequence chart of the carbon monoxide data from link N0215J on 26th February 1994

6.5.1 Stationarity conditions

Before identifying a general class of models to be examined, it is necessary to ensure that the series is stationary. Pankratz (1991) defines a stationary series as one "whose mean, variance and autocorrelation function are constant through time". From Figure 6.22 it is obvious that the series has neither constant variance nor constant mean.

To stabilise the variance a natural logarithm transformation was chosen. This is one of a family of Box-Cox power transformations,

$$z_t' = \frac{z_t^\lambda - 1}{\lambda}$$

where $\lambda = 0$, to give the transformed series $z_t' = \ln(z_t)$. Figure 6.23 shows the result of applying this transformation. Pankratz (1991) states that this kind of transformation should bring the series closer to normality. This is intuitively reasonable in this case, as it was shown in Section 6.3.5 that carbon monoxide levels generally conform to a lognormal, rather than a normal, distribution. However, it can be seen from Figure 6.23 that the mean of the series still was not constant. This was rectified by taking the first-order differences of the series (*ie* integrating),

$$w_t = z_t' - z_{t-1}'$$

Figure 6.24 shows the resulting transformed series, which is stationary.

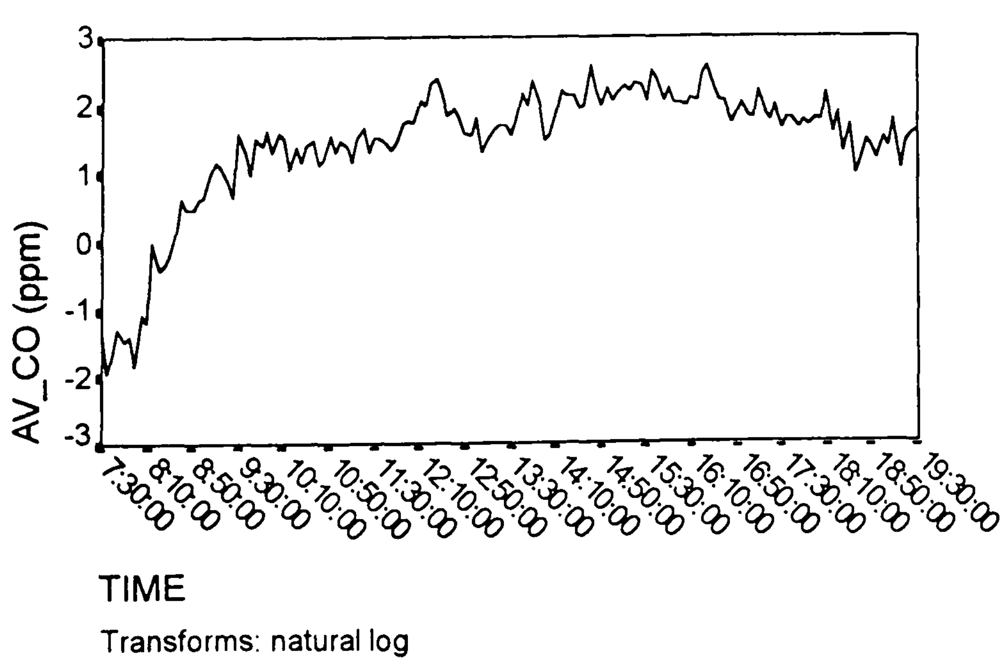

Figure 6.23: Series transformed by taking the natural logarithm

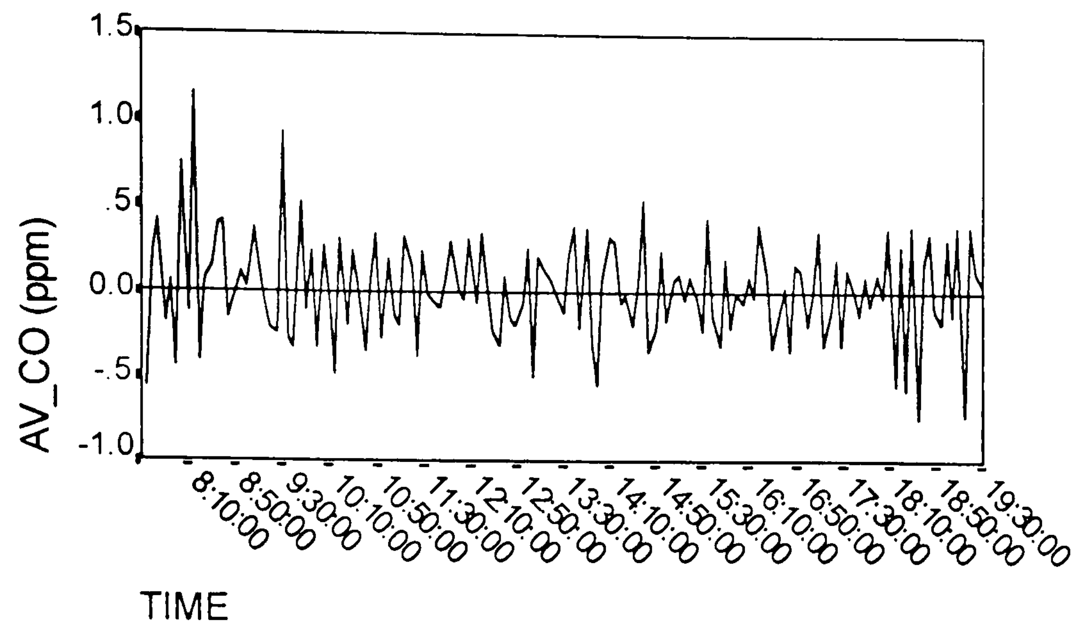

Figure 6.24: Transformed series

6.5.2 Autocorrelation

The stationarity of the mean of the series is usually confirmed by checking the autocorrelation function. As discussed in Section 6.4.7, autocorrelation occurs when there is a relationship between observations. The autocorrelation function (acf) measures the direction and strength of the relationship between observations in a time series, when the observations are separated by k time periods (*ie* a lag of k periods). The sample autocorrelation function, r_k is calculated as

$$r_k = \frac{\sum_{t=1}^{n-k}(w_t - \overline{w})(w_{t+k} - \overline{w})}{\sum_{t=1}^{n}(w_t - \overline{w})}$$

where $\overline{w}$ is the mean of the time series (Pankratz, 1991).

The standard error is given by

$$s(r_k) = \sqrt{\frac{\left(1 + 2\sum_{j=1}^{k-1} r_j^2\right)}{n}}.$$

In addition to the sample autocorrelation function it is also important to derive the partial autocorrelation function (pacf). The sample partial autocorrelation function is described as follows (Pankratz, 1991):-

Consider the set of K regression equations:

$$
\begin{aligned}
z_t &= C_1 + \phi_{11} z_{t-1} + e_{1,t} \\
z_t &= C_2 + \phi_{21} z_{t-1} + \phi_{22} z_{t-2} + e_{2,t} \\
&\vdots \\
z_t &= C_K + \phi_{K1} z_{t-1} + \phi_{K2} z_{t-2} + \ldots + \phi_{KK} z_{t-k} + e_{K,t}
\end{aligned}
$$

The partial autocorrelation coefficient at lag $k = 1, 2, \ldots, K$ is the last coefficient (ϕ_{kk}) in each equation. The standard error is calculated as $s(\phi_{kk}) = \frac{1}{\sqrt{n}}$.

The sample autocorrelation function and the partial autocorrelation function are usually displayed graphically as a function of the lag. The type of ARIMA model to be fitted can then be identified by comparing the sample autocorrelation function and partial autocorrelation function graphs with standard, reference graphs found in all textbooks on ARIMA analysis. The main characteristics of stationary autoregressive processes of order p are:-

1. The (theoretical) autocorrelation function decays, either exponentially or with a damped sine wave pattern, or with both of these patterns;

2. The (theoretical) partial autocorrelation function has spikes through to lag p, and then all zeros.

The main characteristics of stationary moving average processes of order q are:-

1. The (theoretical) autocorrelation function has spikes through to lag q, then all zeros;

2. The (theoretical) partial autocorrelation function decays.

The (theoretical) autocorrelation function and partial autocorrelation function for mixed autoregressive and moving average processes both decay.

6.5.3 Model identification

Figure 6.25 shows the sample autocorrelation function for the untransformed data series shown in Figure 6.22. In a stationary series, the sample autocorrelation function will decay quickly towards zero, *ie* to within two standard errors of zero, by lag 5 or 6. However here the sample autocorrelation function decays very slowly, which is a characteristic of nonstationary series.

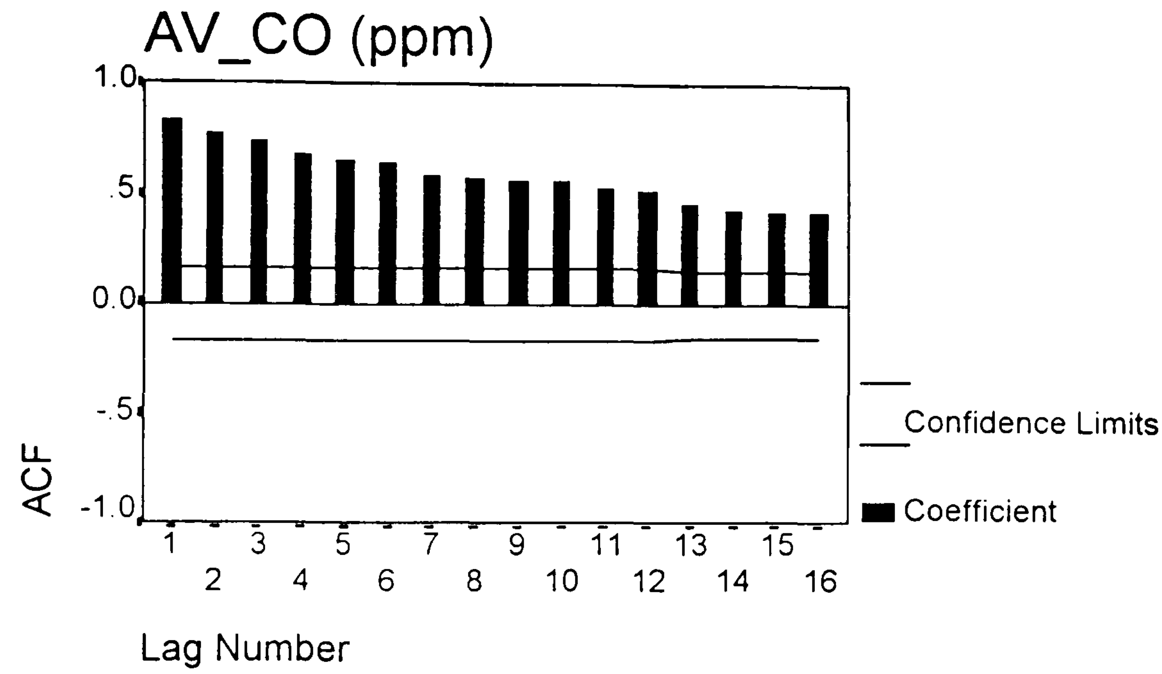

Figure 6.25: Sample autocorrelation function for the untransformed series

The next step was to apply the logarithmic and differencing transformations discussed in Section 6.5.1 and then the sample autocorrelation function and the sample partial autocorrelation function were calculated. These are shown in Figure 6.26 and Figure 6.27.

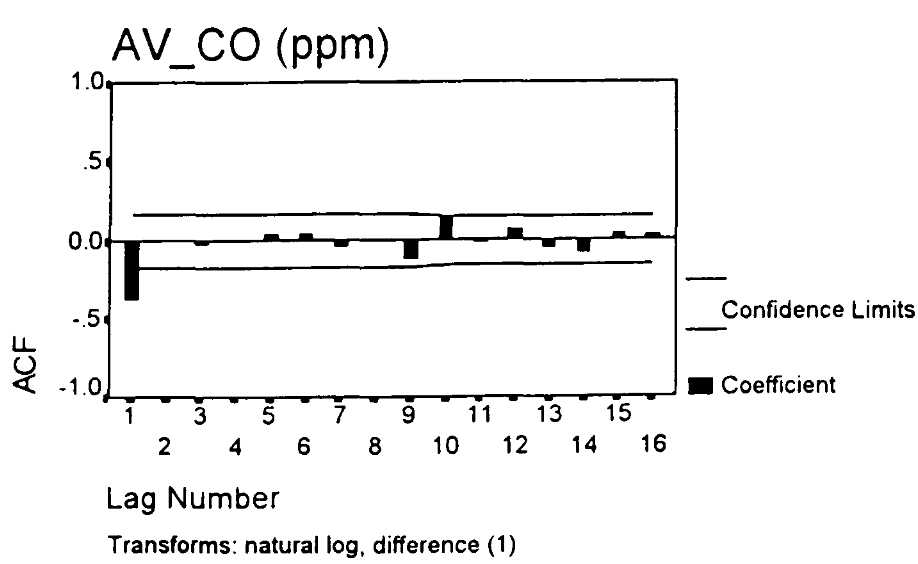

Figure 6.26: Sample autocorrelation function for the transformed series

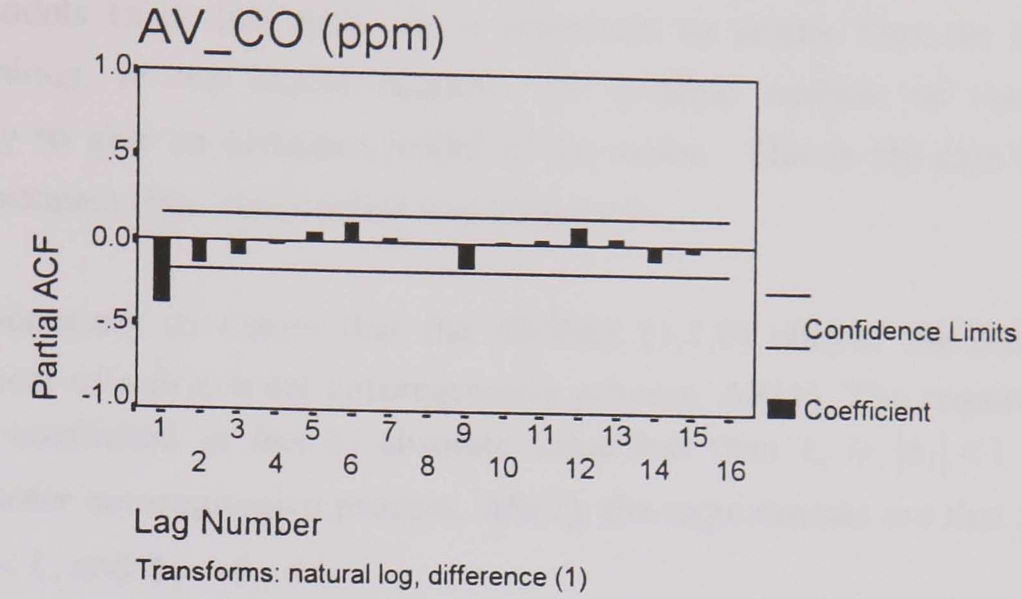

Figure 6.27: Sample partial autocorrelation function for the transformed series

Comparison with the reference graphs in Pankratz (1991) suggested that the model may be an ARIMA (1,1,0), an ARIMA (0,1,1) or an ARIMA (1,1,1). These models are postulated because both the autocorrelation function and the partial autocorrelation function have just one peak at lag 1, and then decay to inside the two standard error confidence limits for the other lags.

The ARIMA analysis routine in SPSS for Windows was used for these three possible models. The ARIMA analysis was completed for both possible models with a constant included, and then without a constant. (This is because the constant term represents a deterministic time trend, and the effect of it can accumulate over forecast periods. This can be a problem if the trend fails to continue). The results from this analysis are shown in Table 6.7. The shaded cells show where the *t* value is less than 2.0 (standard errors), which indicates that the term in the ARIMA equation is not significantly different to zero.

Table 6.7: Results of ARIMA analysis

Model	AR term	*t* value	MA term	*t* value	Constant	*t* value
1,1,0	-0.3889	-5.039			0.0219	1.305
0,1,1			0.4270	5.602	0.0218	1.649
1,1,1	-0.0962	-0.501	0.3558	1.971	0.0219	1.611
1,1,0	-0.3805	-4.929				
0,1,1			0.4052	5.274		
1,1,1	-0.1179	-0.590	0.3154	1.648		

Table 6.7 shows that the ARIMA (1,1,0) and ARIMA (0,1,1) are the most likely models to fit this data. It is important to ensure that the model is parsimonious, *ie* the model contains the smallest number of coefficients necessary to give an adequate model of the series. This is the case for both models because they only contain one term each.

It was necessary to ensure that the ARIMA (1,1,0) obeyed the stationarity requirement of a first-order autoregressive process, AR(1). The requirement is that the coefficient ϕ_1 has an absolute value less than 1, *ie* $|\phi_1| < 1$. For a second order autoregressive process, AR(2), the requirements are that $|\phi_2| < 1$, $\phi_2 + \phi_1 < 1$, and $\phi_2 - \phi_1 < 1$.

Similarly, it was necessary to ensure that the ARIMA (0,1,1) obeyed the requirement that a moving average process must be invertible. A moving average process has an equivalent autoregressive form, but this form is not parsimonious. Pankratz (1991) states that the invertibility condition "ensures that the absolute values of the implied weights on past *z*'s in this equivalent autoregressive form become smaller as the lag length on the past *z*'s increases". The necessary condition for invertibility for a first-order moving average process, MA(1), is that $|\theta_1| < 1$. For a second order moving average process, MA(2), the requirements are that $|\theta_2| < 1$, $\theta_2 + \theta_1 < 1$, and $\theta_2 - \theta_1 < 1$. It can be seen in Table 6.7 that all six proposed models conform to stationarity and invertibility conditions.

6.5.4 Diagnostics

Next, it is important to ensure that the residuals do not display any significant autocorrelation. This is done by plotting the sample autocorrelation function for the residual series (Figure 6.28 and Figure 6.29). All the coefficients lie within the two standard error confidence limits, therefore there is no significant autocorrelation and the models are acceptable.

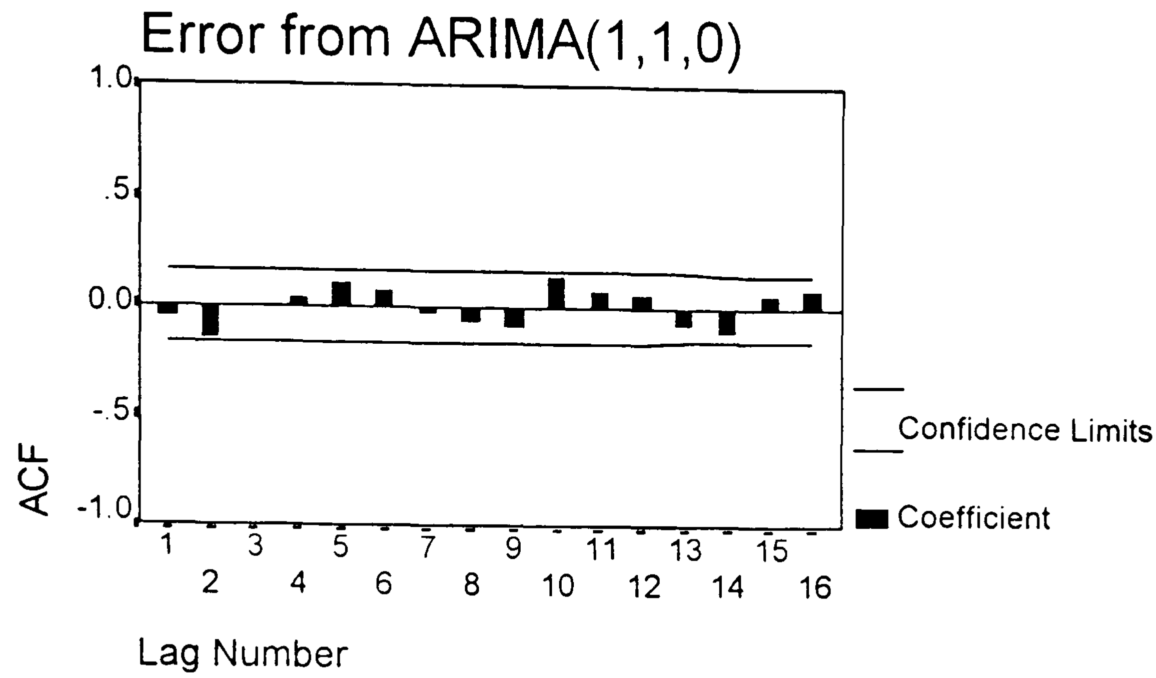

Figure 6.28: Residual autocorrelation function from the ARIMA (1,1,0) model

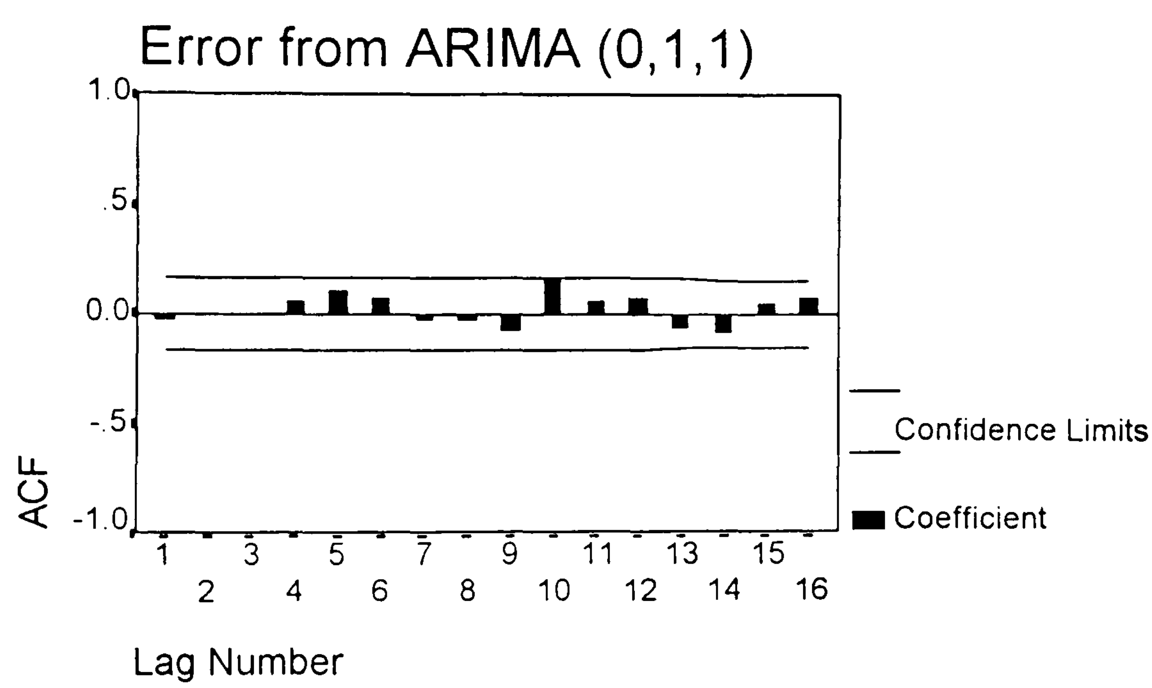

Figure 6.29: Residual autocorrelation function from the ARIMA (0,1,1) model

The presence of autocorrelation can be further tested using the Box-Ljung statistic (Norušis, 1993). This tests the (null) hypothesis, H_0, that $\rho_1(a) = \rho_2(a) = \ldots = \rho_K(a) = 0$, where ρ is the population autocorrelation coefficient. If H_0 is true then the Box-Ljung statistic, Q^*, is approximately χ^2 distributed with $K - m$ degrees of freedom, where m is the number of coefficients estimated in the model. The Box-Ljung statistic is calculated using the following formula:

$$Q^* = n(n+2)\sum_{k=1}^{K}(n-k)^{-1} r_k^2(\hat{a}).$$

The SPSS for Windows autocorrelation procedure calculates this automatically, along with its significance level. In the case of the two ARIMA models proposed here, the Box-Ljung test showed that there is no statistically significant autocorrelation pattern in either residual series.

In addition, the residuals should be normally distributed. A Kolmogorov-Smirnov test (see Section 6.3.5) was used to test the null hypothesis that the residual series were normally distributed. The critical values of the Kolmogorov-Smirnov test statistic, D_{crit}, is 0.114 for a sample size of 143, and a significance level of $\alpha = 0.05$ (from the approximation for large sample sizes given by Daniel (1978), $D_{crit} \approx 1.36/\sqrt{n}$). In the case of the ARIMA (1,1,0) model, the calculated D value was 0.056, which is less than 0.114, and hence the residuals conformed statistically significantly to a normal distribution at the 95% confidence level. In the case of the ARIMA (0,1,1) model, D was calculated to be 0.078, which is also less than 0.114, and again the residuals conformed statistically significantly to a normal distribution at the 95% confidence level.

6.5.5 Model accuracy

As a result of the analysis described above, there were two proposed models. The first was an ARIMA (1,1,0). The equation for this model is:

$$\underset{(-4.929)}{(1-0.3805B)}(1-B)z_t' = \hat{a}_t$$
$$\hat{\sigma}_a^2 = 0.0781$$

The second is an ARIMA (0,1,1). The equation for this model is:

$$(1-B)z_t' = \underset{(5.274)}{(1-0.4052B)}\hat{a}_t$$
$$\hat{\sigma}_a^2 = 0.0769$$

where $z_t' = \ln(z_t)$, $\hat{\sigma}_a^2$ is the sample variance of the residual series, $\hat{a}_t$, and the standard error of the coefficients are given in the brackets below.

The original data and the two fitted models were then plotted in order to identify which fitted the data better. Figure 6.30 and Figure 6.31 show that both models fit well. Correlation analysis showed that the ARIMA (1,1,0) model fitted the data with an R^2 value of 0.9424, and the ARIMA (0,1,1) model fitted the data with an R^2 value of 0.9458. Hence it was difficult to choose between them.

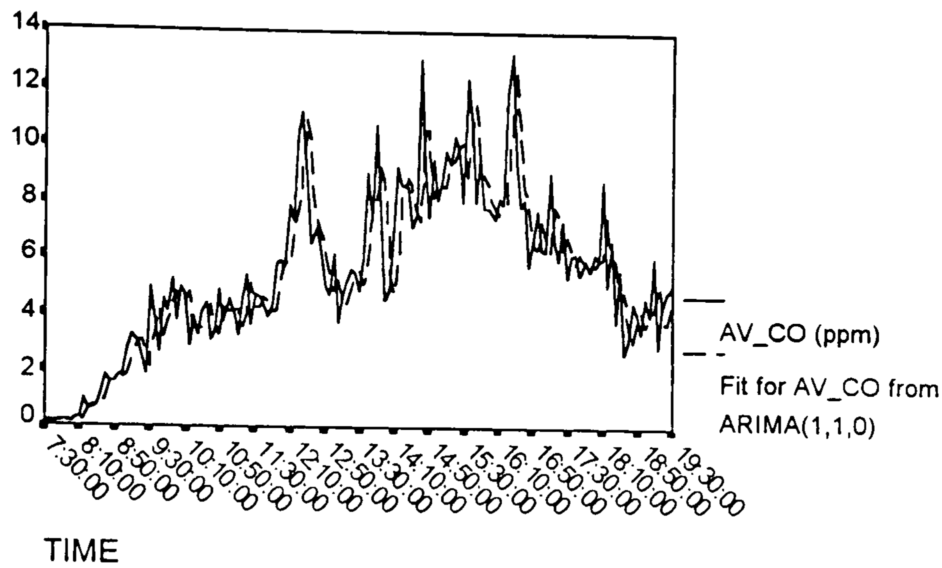

Figure 6.30: Original series and ARIMA (1,1,0) model

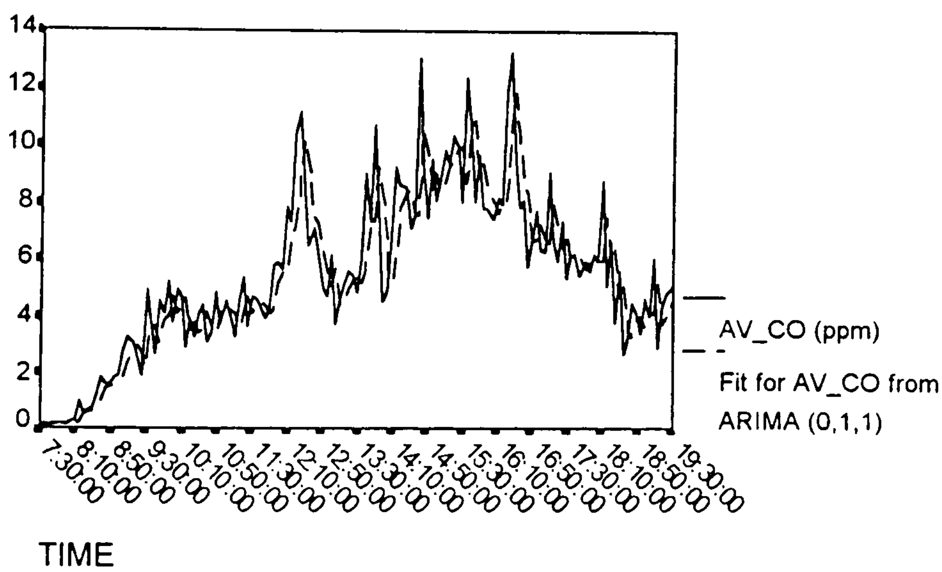

Figure 6.31: Original series and ARIMA (0,1,1) model

The analysis described above has demonstrated how a time series model can be produced for a set of carbon monoxide data collected during this research. The outcome was slightly unsatisfactory as two potential models were identified, not just one. However, the ARIMA models developed only apply to this one day (26/2/94), for this one link (N0215J) and do not take any account of the traffic characteristics. In addition, the model is designed to predict levels for only one or two time periods ahead, based on the previously monitored values. This technique is therefore clearly not appropriate for predicting carbon monoxide levels on links without monitoring units.

6.5.6 Prediction using time series analysis

An ARIMA model was fitted to data from one of the Nottingham ITEMMS units on 8th November 1995. The dependent variable was the carbon monoxide data and the independent variables were STOPS, DELAY and FLOW. After examining the autocorrelation function and the partial autocorrelation function an ARIMA(1,1,1) was fitted to the first 100 cases and then used to predict the carbon monoxide levels for cases 101 to 144. Figure 6.32 shows the original data and the model prediction.

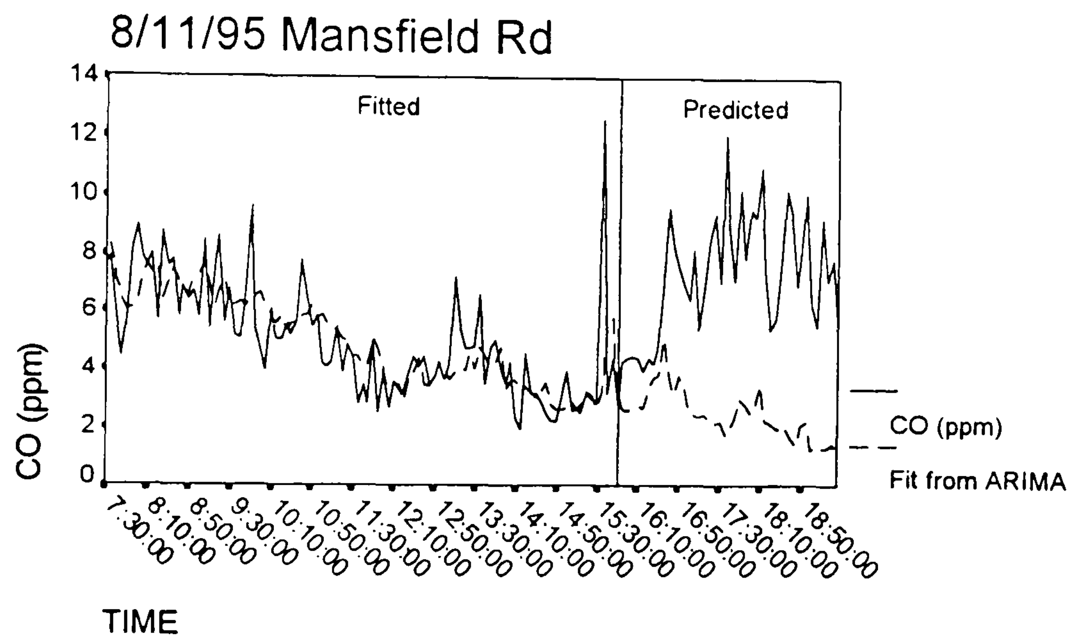

Figure 6.32: ARIMA model for carbon monoxide

Although the prediction does follow the initial trend of the data, it does not predict the sudden increase in carbon monoxide levels which corresponds to the onset of the evening peak period. As discussed in Section 6.2.2, this peak in carbon monoxide levels during the evening period is almost certainly due to the flow on the opposite side of the road. Consequently, the STOPS, DELAY and FLOW data for both sides of the road were then used to produce an ARIMA model and prediction. The graph shown in Figure 6.33 shows the original data series, the fitted and predicted data using the traffic data series from both sides of the road, and the fitted and predicted data series using the traffic data from monitor side of the road alone (as Figure 6.32). This clearly shows that including the traffic data from the opposite side of the road improves the prediction very slightly, but still does not predict the large increase in carbon monoxide levels in the evening peak.

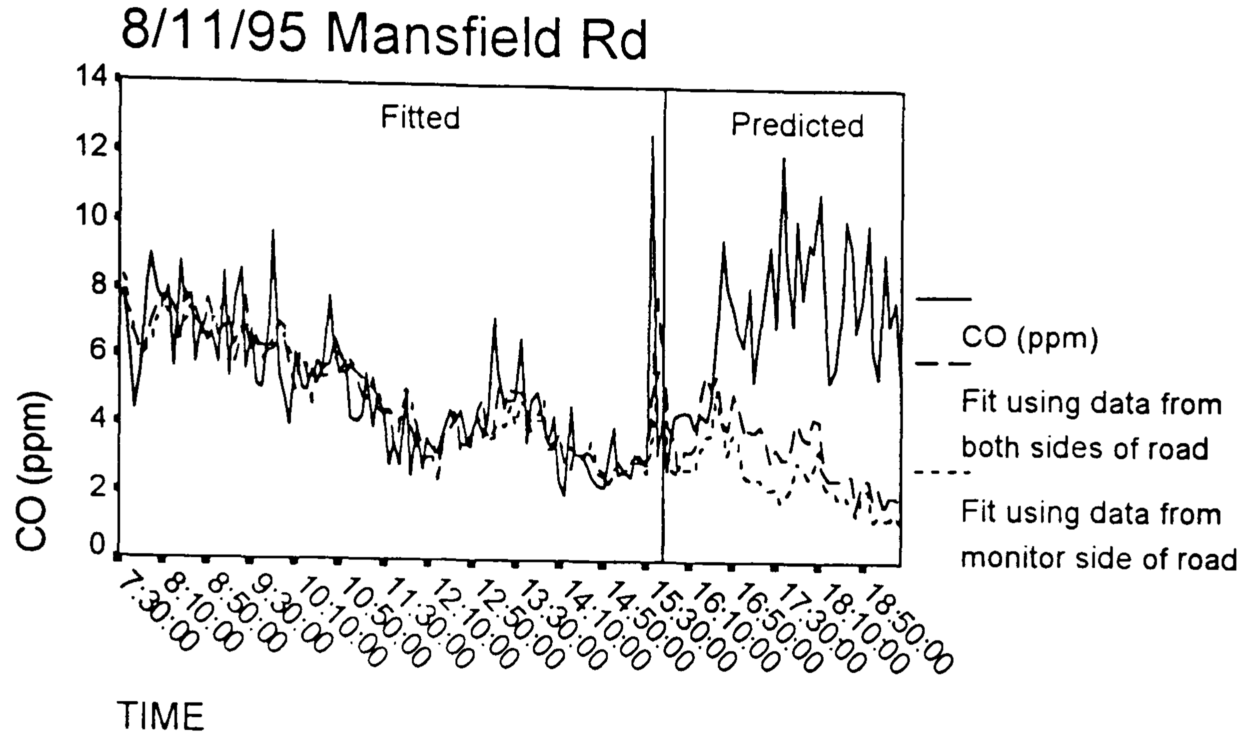

Figure 6.33: ARIMA model for carbon monoxide using traffic data from both sides of the road

6.6 Conclusions about the statistical analysis techniques

The aim of the data analysis and discussion of statistical analysis techniques presented in this chapter was to identify a suitable technique to derive empirical relationships to predict air pollution levels from SCOOT data. This has been achieved to a certain extent.

The examination of the underlying probability distributions of the variables showed that pollutant levels could be assumed to be normally distributed, and are, in fact, more likely to be *log*normal. This finding is very important since many statistical tests rely on the assumption of normality.

Next, two candidate statistical techniques were considered. Firstly, the most obvious, and widely used, multiple linear regression method using STOPS, DELAY and FLOW as independent variables. This technique has been used by many researchers in the field and is easy to use and interpret. However, it became obvious that the underlying assumption of non-autocorrelated residuals was being violated virtually every time it was used. The Cochrane-Orcutt method for eliminating autocorrelation was therefore investigated. However, the resulting model could no longer be expressed in terms of the original parameters.

As a result, the more complicated time series technique was investigated. This technique was specifically developed for the kind of time varying data being collected for this research. It was shown to be possible to fit an ARIMA model to the data with a high degree of statistical confidence for the particular link and day being studied. This means that it should be possible to produce very short-term (no more than one hour) predictions from a model calibrated using several day's data. However, these models did not take into account any variables which affect pollution levels, such as traffic characteristics and meteorological variables. As a direct result, this technique was therefore inappropriate for predicting carbon monoxide levels on links without monitoring units - one of the aims of this research.

It was then decided not to pursue the search for a *empirical* model using statistical techniques any further, but instead a slightly different approach was adopted. This led to the development of a *semi-empirical* model and this is discussed in the next chapter.

7. Formulation of a semi-empirical model to predict carbon monoxide concentrations from SCOOT data

7.1 Introduction

The previous chapter described the investigations carried out to identify a suitable statistical analysis technique for the derivation of empirical relationships between kerbside pollutant levels and SCOOT data. It was found that there were problems with the use of both multiple linear regression and time series analysis. Therefore, it was decided that a linear semi-empirical model should be developed to predict carbon monoxide levels at the kerbside.

Matzoros and Van Vliet (1992 a,b), Bostock (1995) and Namdeo (1995) demonstrated that it was essential for models predicting concentrations of traffic-related pollutants to take into consideration the four main vehicle operating modes - cruising, accelerating, decelerating and idling, as these give rise to differing levels of emissions. Furthermore, the statistical analysis work described in the previous chapter highlighted the importance of including the emissions from vehicles on *both* sides of the road when predicting the kerbside carbon monoxide concentrations. Therefore, it was necessary to take these factors into account in any further model development. In this chapter the previous research is extended to use the information available from SCOOT messages as "proxies" for the operating modes by applying traffic theory and 'engineering judgement' to develop a *semi-empirical* model as follows:-

1. Propose a model based on the definition of SCOOT parameters;

2. Estimate the coefficients of the parameters in the model using actual pollutant levels and SCOOT data as inputs; and

3. Use the model to predict concentrations using only SCOOT data and check with measured values.

7.2 Basic theory of the proposed model

Figure 7.1 is a representation of a section of road between two signal controlled junctions ① and ②, with an ITEMMS monitoring unit approximately five metres upstream of the stopline at junction ① (at the position marked ⚐) and SCOOT loops upstream of the stopline (at the positions marked ▭). In this figure, M_q denotes the traffic flow on the side of the road adjacent to the monitoring unit, and O_q denotes the traffic flow on the opposite side of the road.

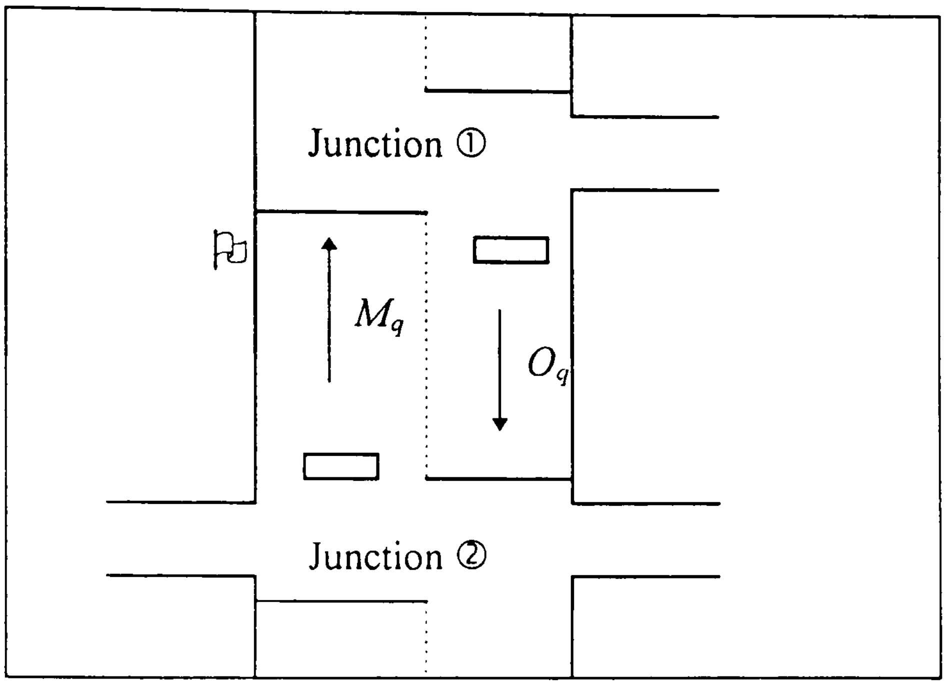

Figure 7.1: Representation of section of road with SCOOT loops and ITEMMS unit

7.2.1 Specification of the model

The data from the SCOOT M02 message was used as the basis for developing the proxies for the vehicle operating modes. It must be remembered that the values in the message are the predictions from the SCOOT model about the traffic arriving at the stopline. The rationale for the proposed model is as follows:

Firstly, consider the flow of vehicles past the monitoring unit on the adjacent link *in each cycle*. Now,

i. the number of vehicles passing the unit is $\frac{\mathbf{FLOW}}{3600} \times \mathbf{cycle}$, where 3600 is the number of seconds in an hour;

ii. the number of vehicles which are idling is assumed to be 1, since one vehicle will idle at the head of the queue, and the monitoring unit is approximately one vehicle length from the stopline;

iii. the number cruising is $\left(\dfrac{\mathbf{FLOW} - \mathbf{STOPS}}{3600}\right) \times \mathbf{cycle}$;

iv. the number decelerating is assumed to be 0, since the vehicle which idles will have decelerated before it reaches the stopline; and

v. the number accelerating is the remaining number of vehicles, *ie*

$$\left(\frac{\mathbf{FLOW}}{3600} \times \mathbf{cycle}\right) - 1 - \left(\left(\frac{\mathbf{FLOW\ -\ STOPS}}{3600}\right) \times \mathbf{cycle}\right)$$
$$= \left(\frac{\mathbf{STOPS}}{3600} \times \mathbf{cycle}\right) - 1.$$

Secondly, consider the flow past the monitoring unit on the opposite link *in each cycle*. In this case the traffic is entering the link is assumed to either be stopped on the SCOOT loop (idling) or cruising. The presence of vehicles stopped on the loop is indicated by a **CONG** value which is greater than 0.

Therefore,

i. the number of vehicles which are idling =
$$\frac{\text{flow in one cycle} \times \text{number of congested intervals in one cycle}}{\text{maximum number of congested intervals in one cycle}}\text{; and}$$

ii. the number cruising = flow in one cycle - the number of vehicles which are idling.

Hence, in *one hour* on the adjacent (monitoring unit) side of the road,

i. the number idling = $\dfrac{3600}{\mathbf{cycle}} = M_{i,t}$;

ii. the number cruising = **FLOW** - **STOPS** $= M_{c,t}$;

iii. the number accelerating = **STOPS** $- \dfrac{3600}{\mathbf{cycle}} = M_{a,t}$;

and, on the opposite side of the road,

iv. the number idling = $\dfrac{\mathbf{FLOW} \times \mathbf{CONG}}{900} = O_{i,t}$, where 900 is the maximum number of congested intervals in an hour; and

v. the number cruising= $\mathbf{FLOW} - \dfrac{\mathbf{FLOW} \times \mathbf{CONG}}{900}$

$$= \frac{\mathbf{FLOW}(900 - \mathbf{CONG})}{900} = O_{c,t}.$$

7.2.2 The form of the model

The model proposed here is a combination of the terms developed above to represent the vehicle operating modes on each side of the road, *ie*

$$\text{predicted pollution levels} = \hat{y}_t = f(M_{i,t}, M_{c,t}, M_{a,t}, O_{i,t}, O_{c,t}).$$

However, this assumes that the pollution at time t is instantaneously created and disappears. Therefore the fact that pollution may take a time to disperse must be taken into account in the proposed model. This is achieved by including the predicted pollution level from previous time intervals in the proposed model.

A simple linear relationship between the variables was assumed. This meant that the coefficients of the parameters in the model could be estimated using the ordinary least squares techniques described in Section 4.6.2.3. Therefore, the proposed model to predict pollution levels *at the monitoring point* was as follows:

$$\hat{y}_t = \beta_0 + \beta_1 M_{i,t} + \beta_2 M_{c,t} + \beta_3 M_{a,t} + \beta_4 O_{i,t} + \beta_5 O_{c,t} + \beta_6 \hat{y}_{t-1} + \beta_7 \hat{y}_{t-2} + \varepsilon_t$$

where

$\hat{y}_t$	=	predicted pollution level at time t (ppm)
$\hat{y}_{t-1}$	=	pollution level predicted in the previous interval, $t - 1$ (ppm)
$\hat{y}_{t-2}$	=	pollution level predicted at time $t - 2$ (ppm)
$M_{i,t}$	=	number of vehicles idling on the monitoring unit side of the road
$M_{c,t}$	=	number of vehicles cruising on the monitoring unit side of the road
$M_{a,t}$	=	number of vehicles accelerating on the monitoring unit side of the road
$O_{i,t}$	=	number of vehicles idling on the opposite side of the road
$O_{c,t}$	=	number of vehicles cruising on the opposite side of the road

β_n = constants

ε_t = error term.

7.2.3 Processing of M02 and A01 data

As discussed previously, M02 messages are output every cycle, and A01 messages are output every minute. Therefore, before the M02 and A01 data can be used in this model they have to be processed into a consistent form. This processing used the REGULISE program written by Dr Evans. This program takes any SCOOT message file and selects the data for any sites specified in a separate file called "site.dat". The program then calculates averages over a specified interval, *eg* five or ten minutes. The format of the SCOOT message file is specified in the "rgl.tmp" file.

The command line is

```
regulise <infile> <outfile> site.dat <start time> <finish time> <interval>
```

for example,

```
regulise 150296.m02 1502reg.m02 site.dat 07:30 19:30 10
```

The "rgl.tmp" file corresponding to M02 messages contains the line

```
any time site d1 d2 d3 d4 d5
```

which shows that the M02 message contains unimportant data in the first field (usually the date), time in the second field, link name in the third field and then five fields of data.

The "site.dat" file contains the link names of the sites of interest, for example

```
N13221R
N13231S
```

The resulting output file contains data at regular time intervals, as shown in Table 7.1.

Table 7.1: REGULISE output

time	link	cycle	stops	delay	flow	cong
07:30:00	N13221R	60.0	195.7	3.8	818.8	0.0
07:35:00	N13221R	60.0	335.5	7.6	918.0	0.0
07:40:00	N13221R	66.3	187.3	4.2	1052.2	0.0
07:45:00	N13221R	79.2	187.8	5.6	1063.8	0.0
07:50:00	N13221R	80.0	145.8	4.0	1086.5	0.0
07:55:00	N13221R	80.0	181.8	6.4	1058.0	0.0
08:00:00	N13221R	80.0	143.6	7.7	1249.0	0.0
08:05:00	N13221R	80.0	119.0	2.9	1116.6	0.0
08:10:00	N13221R	80.0	179.5	8.3	1238.4	24.0
08:15:00	N13221R	80.0	102.0	3.4	989.1	0.0

Once the data has been processed, the separate files can then be combined and analysed in a spreadsheet package. An SPSS macro ("model.sps" - see Appendix 3) was written to automate the calculation of the idling, cruising and accelerating parameters defined above and subsequently to perform the ordinary least squares analysis to estimate the coefficients of the parameters.

7.3 Data analysis

Carbon monoxide data from the ITEMMS unit on Mansfield Road, Nottingham was collected over the period 1st February to 31st March 1996. This was processed using the method described in the previous section to assess the suitability of the proposed model. The following is a detailed description of the analysis of data from 15th February 1996. Figure 7.2 shows the five minute average carbon monoxide levels for the period 7:30 to 19:30, after processing the data from the A01 message using REGULISE.

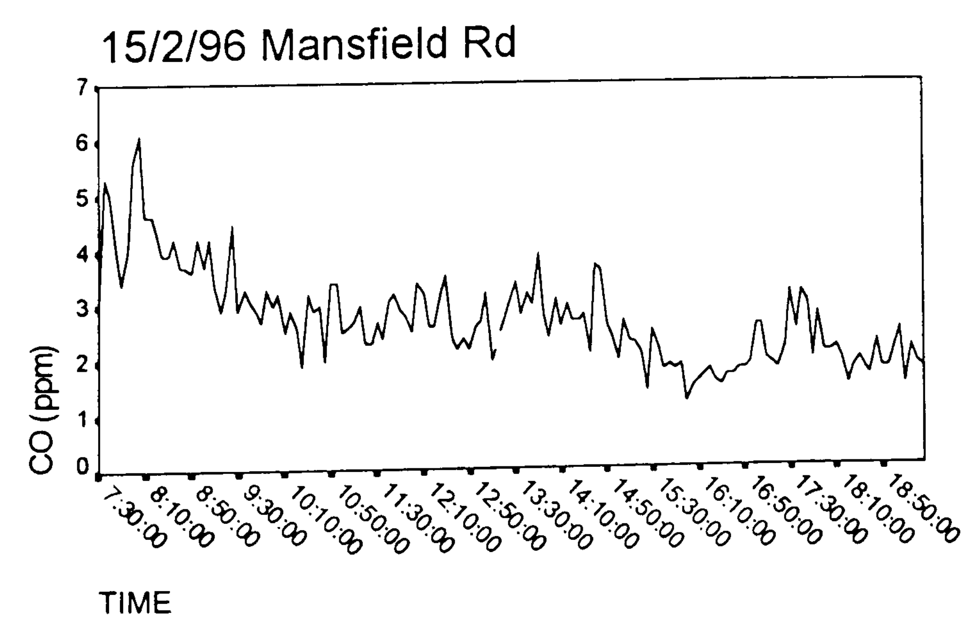

Figure 7.2: Five minute average carbon monoxide levels (after processing with REGULISE)

The SPSS macro, "model.sps" was used to calculate the parameters and to perform the ordinary least squares analysis to estimate the coefficients of the parameters in the model. Table 7.2 shows a listing of the parameters and Figure 7.3 shows an example of the final output from the macro. The variables were labelled according to the link to which they refer, *ie* link N13221R, which is adjacent to the monitoring unit, and link N13231S, which is on the opposite side of Mansfield Road.

Table 7.2: Parameter list

Model parameter	SPSS variable
$M_{i,t}$	IDLE21R
$M_{c,t}$	CRUISE21
$M_{a,t}$	ACC21R
$O_{i,t}$	IDLE31S
$O_{c,t}$	CRUISE31
$\hat{y}_{t-2}$	PRE_1_1
$\hat{y}_{t-1}$	PRE_2_1

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.809	.655	.637	.5225	1.273

ANOVA

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	67.429	7	9.633	35.286	.000
	Residual	35.489	130	.273		
	Total	102.918	137			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	-1.7E-02	.797		-.022	.983		
IDLE21R	-1.4E-03	.011	-.009	-.123	.902	.488	2.049
CRUISE21	2.4E-03	.000	.608	5.819	.000	.243	4.122
ACC21R	2.2E-03	.000	.353	4.837	.000	.498	2.008
IDLE31S	1.2E-04	.001	.013	.225	.822	.775	1.291
CRUISE31	-4.8E-05	.000	-.011	-.131	.896	.359	2.787
PRE_1_1	-.228	.277	-.179	-.824	.412	.056	17.803
PRE_2_1	.693	.260	.565	2.663	.009	.059	16.956

a. Dependent Variable: CO

Figure 7.3: Final output from SPSS for Windows "model.sps" macro

There are several important factors to note in the output shown in Figure 7.3. Firstly, the R^2 value is 0.655, which is encouragingly high, especially since the analysis described in Section 6.3 gave rather lower R^2 values. Secondly, the analysis of variance output shows that the value of the F statistic is such that the joint null hypothesis that the coefficients are all zero can be rejected. However, the t-values indicate that only the coefficients of CRIUSE21, ACC21R and PRE_2_1 were statistically significantly different from zero. Furthermore, the variance inflation factors show that PRE_1_1 and PRE_2_1 were collinear. In fact, the correlation between them was calculated to be 93.5%.

Repeating the analysis with only CRUISE21 and ACC21R reduced the R^2 value by only 0.02, thus indicating that these two variables were the most influential. In this case the data from the opposite side of the road did not explain any of the variation. However, it can be seen in Figure 7.2 that there was an absence of a pronounced evening peak in carbon monoxide levels, which probably explains this result.

It was shown in Section 6.4.6 that, before relying on the result of the ordinary least squares analysis, the residuals should be checked for autocorrelation. The SPSS REGRESSION procedure used in the "model.sps" macro can automatically calculate the Durbin-Watson statistic, which, in this case, was 1.273. The tabulated value (Neave, 1989) for d_L was 1.571 (n = 144, k = 5), therefore the null hypothesis of no autocorrelation was rejected and, consequently, the t- and F-tests were invalid. This was confirmed by the graph of the residual autocorrelation function shown in Figure 7.4, which exhibits a significant spike at lag 1 and one at lag 4 which is very close to the upper 95% confidence limit.

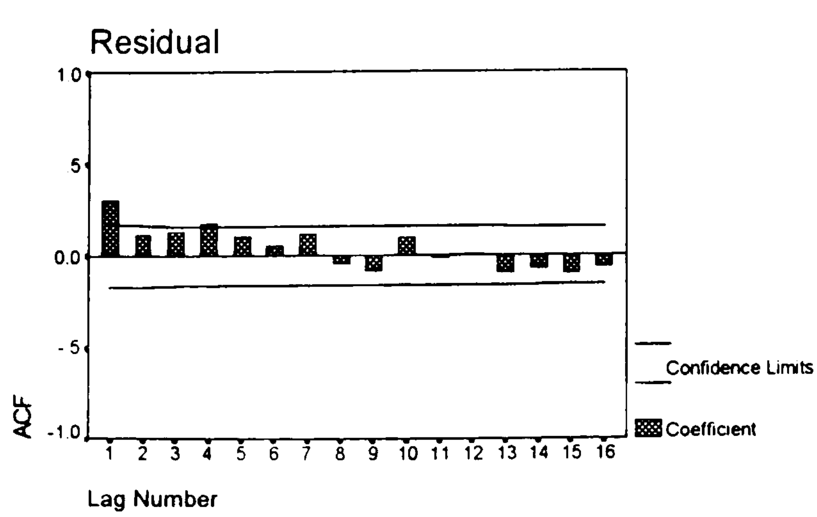

Figure 7.4: Residual autocorrelation function

7.3.1 Further analysis to eliminate autocorrelation

Several alternatives were explored to eliminate the autocorrelation. These included using the natural logarithm of the carbon monoxide values, and using first order differences. However, the most effective solution found was to average the variables over 10 minutes, rather than five minutes.

Figure 7.5 shows the SPSS output from the model once the data had been averaged to 10 minutes. It can be seen that the R^2 improved to 0.748, but PRE_1_1 and PRE_2_1 were again collinear. However, in this case the value of the Durbin-Watson statistic was of greater interest. The value was calculated to be 1.565. The critical value of d_L was 1.487 (n = 73, k = 5) and of d_U was 1.770. The test is inconclusive as the calculated value falls between the critical values at the 5% significance level. However, the graph of the autocorrelation function shown in Figure 7.6 gives a strong indication that there was no autocorrelation. Therefore it is possible to be confident in the calculated t- and F-test values in Figure 7.5, which, again, clearly show that CRUISE21 and ACC21R were the only two significant variables.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.865	.748	.719	.4243	1.565

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	33.126	7	4.732	26.282	.000
Residual	11.164	62	.180		
Total	44.290	69			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Tolerance	VIF
(Constant)	-.751	.996		-.754	.454		
IDLE21R	4.4E-03	.014	.031	.324	.747	.437	2.287
CRUISE21	3.0E-03	.001	.775	5.709	.000	.220	4.538
ACC21R	2.7E-03	.001	.429	4.298	.000	.409	2.446
IDLE31S	5.3E-04	.001	.058	.803	.425	.785	1.274
CRUISE31	3.0E-04	.000	.072	.644	.522	.325	3.077
PRE_1_1	-9.7E-02	.345	-.085	-.281	.780	.044	22.726
PRE_2_1	.514	.349	.456	1.474	.146	.042	23.590

a. Dependent Variable: CO

Figure 7.5: Output from model after averaging over 10 minutes

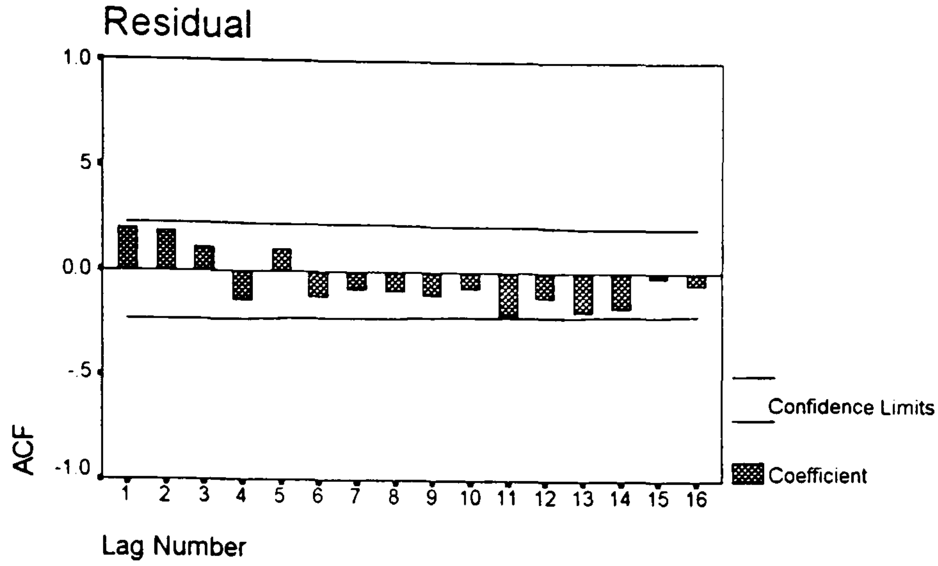

Figure 7.6: Residual autocorrelation function

The coefficients of the variables estimated in Figure 7.5 were then used in the proposed model to calculate the predicted values of carbon monoxide. Figure 7.7 shows the actual and predicted values of carbon monoxide for the dataset analysed here.

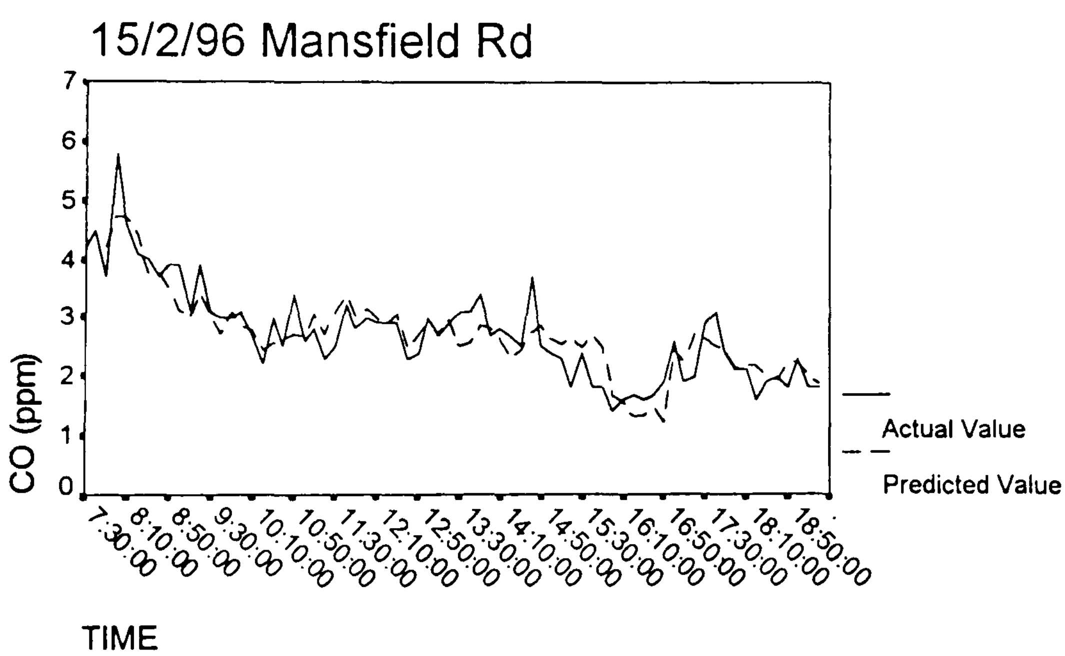

Figure 7.7: Graph of actual and predicted carbon monoxide levels

7.4 Analysis of one month's data

The M02 and A01 data from the ITEMMS unit on Mansfield Road was collected throughout March 1996 so that the performance of the model could be assessed over a longer period. Data for three days were missing (Saturday 23rd March 1996, Sunday 24th March 1996 and Saturday 30th March 1996) and the data from some days were not complete. The M02 and A01 files were processed using the REGULISE program to obtain 10 minute averages (as described in Section 7.2.3 above), and the "model.sps" macro was used to analyse the data. Missing values were excluded from the equations.

7.4.1 Analysis of individual days

The table in Appendix 5 gives the complete results for each day. The date and the day of the week are given, followed by the R^2 value, the F statistic and the significance of the F statistic. Next, the coefficients of the parameters are given, with the significance of the t-value beneath them. The significance of the F- and t-tests should be less than 0.05 if the coefficients are statistically significantly different from zero at the 95% confidence level. The number of valid cases is given, followed by the calculated Durbin-Watson statistic and the critical values of d_L and d_U.

The Durbin-Watson test shows that out of the 28 days analysed with the proposed model, eleven days had autocorrelated residuals, seven days did not, and on the remaining ten days the test was inconclusive. A χ^2 test was used to investigate whether there was any statistically significant difference between the number of days with autocorrelated residuals, *etc*, for the weekend days (Saturday and Sunday) against the rest of the week (Monday to Friday). The results are given in Table 7.3. The test showed that there was no statistically significant difference at the 95% confidence level.

Table 7.3: Number of days with autocorrelated, not autocorrelated or inconclusive residuals

	Autocorrelated	Not autocorrelated	Inconclusive	Total
Mon - Fri	7	6	8	21
Sat - Sun	4	1	2	7
Total	11	7	10	28

On four of the days the F statistic had a significance level greater than 0.05, which implies that the joint null hypothesis that the coefficients of the parameters not statistically significantly different from zero cannot be rejected (these are highlighted in the table in Appendix 5). Three of these four days were weekdays.

When the significance of the t-values for each of the coefficients of the parameters were examined it was found that many were greater than 0.05, *ie* less than 95% confident that the coefficients were statistically significantly different from zero (these are also highlighted in the table in Appendix 5). Table 7.4 shows the number of days when the coefficient was not statistically significantly different from zero, at the 95% confidence limit, for each of the parameters. On eight days the coefficient for PRE_1_1 (*ie* $\hat{y}_{t-2}$) was not calculated because SPSS determined that the correlation matrix was likely to be positive definite, and therefore the parameter had to be excluded. Similarly, on one day coefficients for IDLE21R, CRUISE21 and ACC21R were not calculated because the SCOOT loop N13221R was faulty. Table 7.4 shows that the parameters CRUISE21, ACC21R and CRUISE31 are most likely to have coefficients that are statistically significantly different from zero, which is consistent with the results presented in Section 7.3 above.

Table 7.4: Number of days when each coefficient was not statistically significantly different from zero (maximum n = 31)

	n	Total	%
IDLE21R	24	27	89
CRUISE21	15	26	58
ACC21R	8	27	30
IDLE31S	23	28	82
CRUISE31	17	28	61
PRE_1_1	16	20	80
PRE_2_1	23	28	82
Constant	24	28	86

The R^2 values shown in the table in Appendix 5 vary considerably from day to day. They range from 0.157 to 0.874. There is no obvious pattern to the results - low R^2 values occur at both weekends and during the week, similarly for the high R^2 values.

Notwithstanding the reservations about the autocorrelation the predicted carbon monoxide values were plotted against the measured carbon monoxide values for each day in the month. This provided an overall assessment of the performance of the proposed model. The scatterplot given in Figure 7.8 shows that, overall, the correlation coefficient (R^2) is 0.60. The prediction appear to be better for the lower levels of carbon monoxide compared with the higher values.

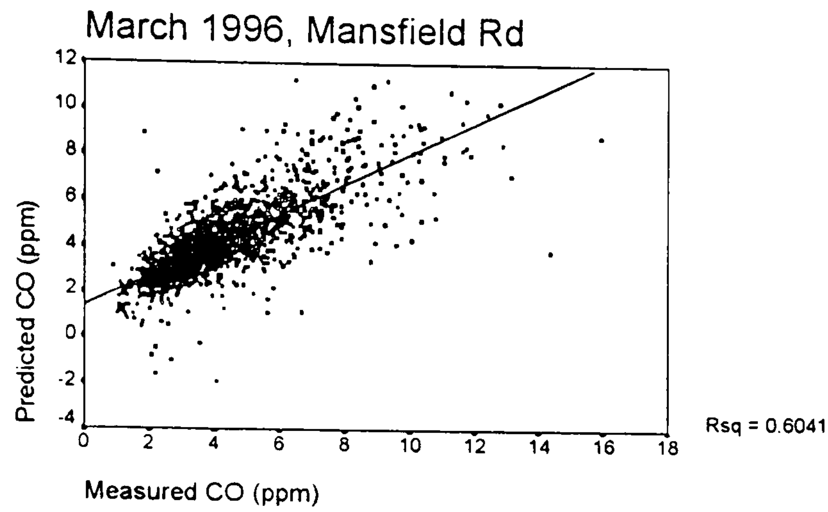

Figure 7.8: Scatterplot of predicted carbon monoxide values against measured values

7.4.2 Analysis of complete month

Next the complete dataset for March was analysed using the proposed model. The terms for the prediction from the previous two time intervals (PRE_1_1 and PRE_2_1) could not be included here because the model would then be using a prediction from 19:20 and 19:30 one evening in its prediction for 07:30 the next morning! Figure 7.9 shows the result of the analysis using the model. As before, the missing values were excluded pairwise.

The R^2 value was calculated to be only 0.12. The value of the F-statistic showed that the joint null hypothesis that the coefficients are not statistically significantly different from zero can be rejected. The t-tests showed, however, that the coefficients of IDLE31S and the constant are not statistically significantly different from zero. The calculated Durbin-Watson statistic was 0.600 and the number of valid cases, n, was 1682, which suggests that there was significant autocorrelation in the residuals. This is confirmed by the graph of the autocorrelation function, shown in Figure 7.10.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.350	.122	.120	1.7757	.600

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	736.753	5	147.351	46.730	.000
Residual	5284.843	1676	3.153		
Total	6021.597	1681			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	-1.257	.765		-1.643	.101		
IDLE21R	4.2E-02	.011	.115	3.776	.000	.560	1.785
CRUISE21	2.1E-03	.000	.201	6.884	.000	.616	1.624
ACC21R	3.7E-03	.000	.287	10.212	.000	.664	1.507
IDLE31S	1.2E-03	.001	.037	1.580	.114	.959	1.043
CRUISE31	2.8E-03	.000	.316	10.695	.000	.599	1.670

a. Dependent Variable: CO

Figure 7.9: Results from model of analysis of data from the whole of March 1996 for the ITEMMS unit in Mansfield Road

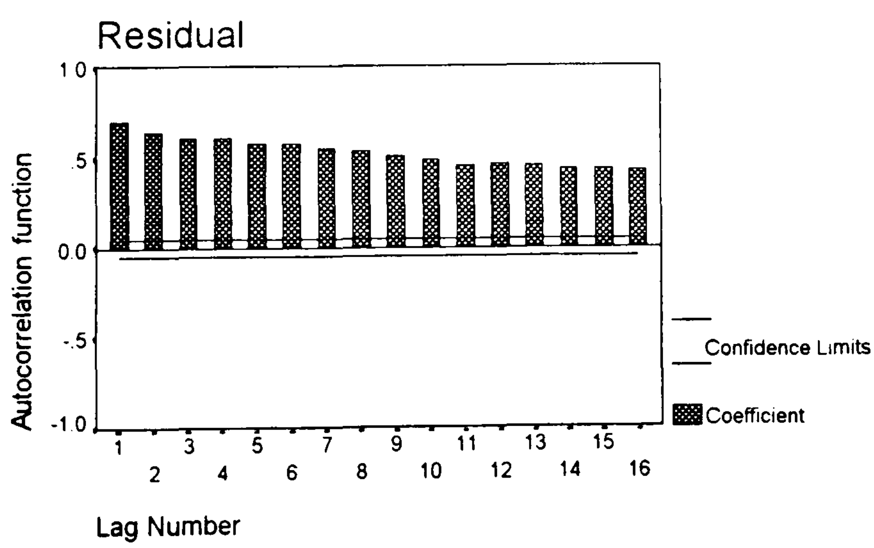

Figure 7.10: Autocorrelation function for the residual series

Figure 7.11 gives the output from the model when only the weekdays, Monday to Friday, were analysed. The R^2 value was lower than the one calculated for the whole of the March 1996 dataset shown in Figure 7.10. The Durbin-

Watson statistic was 0.629 and the valid number of cases was 1339, which again implied that the residuals were significantly autocorrelated.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.306	.094	.090	1.6561	.629

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	377.229	5	75.446	27.507	.000
Residual	3656.103	1333	2.743		
Total	4033.332	1338			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	1.684	.805		2.093	.037		
IDLE21R	-1.9E-02	.012	-.047	-1.557	.120	.761	1.315
CRUISE21	2.4E-03	.000	.250	6.264	.000	.428	2.335
ACC21R	4.1E-03	.000	.339	8.879	.000	.466	2.146
IDLE31S	1.2E-03	.001	.044	1.656	.098	.970	1.031
CRUISE31	2.3E-03	.000	.269	8.118	.000	.621	1.611

a. Dependent Variable: CO

Figure 7.11: Output from model for weekdays (Monday - Friday) only in March 1996

Figure 7.12 shows the output for just the weekends in March 1996. The R^2 was considerably better (0.30), but the Durbin-Watson statistic (0.688) again indicated significantly autocorrelated residuals. Bell *et al* (1996) had suggested that lower R^2 values would be found for the weekend data because there is less congestion and the variation in carbon monoxide levels would be less influenced by traffic variations, but the results presented here do not support this hypothesis. It is likely that the model prediction for the weekend data is better than for the working week because the carbon monoxide and traffic levels do not exhibit the peaks associated with weekdays.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.552	.304	.294	1.9264	.688

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	546.803	5	109.361	29.471	.000
Residual	1250.551	337	3.711		
Total	1797.354	342			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	-1.492	2.257		-.661	.509		
IDLE21R	3.4E-02	.034	.065	1.016	.310	.511	1.956
CRUISE21	3.2E-03	.001	.223	3.464	.001	.498	2.009
ACC21R	4.2E-03	.001	.278	3.967	.000	.421	2.374
IDLE31S	6.3E-04	.003	.012	.241	.809	.776	1.289
CRUISE31	4.4E-03	.001	.364	5.301	.000	.438	2.284

a. Dependent Variable: CO

Figure 7.12: Output from model for the weekends in March 1996

7.4.3 Investigation of the unexplained variance

The model derived for the data from the 15th February 1996 (see Section 7.3 above) accounted for approximately 75% of the measured carbon monoxide levels. This leaves 25% unexplained, which may be due to the effect of the local weather, as rain, wind and temperature are known to affect how pollution disperses. Therefore the analysis was repeated to include meteorological factors as independent variables. The meteorological factors were temperature (°C), relative humidity (%), barometric pressure (mbar), wind direction (degrees from North) and wind speed (m/s), measured at the University of Nottingham Campus (Winter, 1995).

Figure 7.13 shows the result of the analysis. The R^2 value had increased slightly to 0.816, but the coefficients of many of the variables were not statistically significantly different to zero, and the variance inflation factors highlighted collinearity problems between PRE_1_1, PRE_2_1, temperature, barometric pressure and wind direction. However, a Durbin-Watson test showed no evidence of autocorrelation. Next, the SPSS FORWARD REGRESSION procedure was used to identify which of the variables were the most influential. This procedure only includes variables in the equation if they conform to a certain criteria, *ie* that if they are included, then the significance of their *t*-value is less than 0.05. Figure 7.14 shows that, with this criteria, only CRUISE21, ACC21R and TEMP are in the equation, and there are no collinearity problems. The R^2 value of 0.774 is only 0.03 more than for the model shown in Figure 7.5.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.903	.816	.777	.3784	2.050

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	36.129	12	3.011	21.030	.000
Residual	8.160	57	.143		
Total	44.290	69			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	37.053	134.849		.275	.784		
IDLE21R	-1.8E-02	.020	-.130	-.928	.357	.166	6.027
CRUISE21	2.0E-03	.001	.513	3.442	.001	.146	6.866
ACC21R	2.3E-03	.001	.379	3.872	.000	.338	2.957
IDLE31S	1.1E-03	.001	.118	1.408	.164	.459	2.178
CRUISE31	4.6E-04	.000	.111	.941	.351	.234	4.280
PRE_1_1	-.219	.658	-.204	-.333	.741	.009	116.233
PRE_2_1	.537	.625	.496	.859	.394	.010	103.262
TEMP	-.119	.157	-.351	-.756	.453	.015	66.653
HUM	2.1E-02	.041	.068	.523	.603	.191	5.245
PRESS	-3.4E-02	.129	-.101	-.264	.792	.022	45.254
DIRN	-8.4E-03	.007	-.221	-1.182	.242	.092	10.827
SPEED	1.7E-02	.133	.014	.131	.896	.272	3.680

a. Dependent Variable: CO

Figure 7.13: Output from model for the data from 15th February 1996, including meteorological variables

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.880	.775	.765	.4055	1.714

ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	38.438	3	12.813	77.917	.000
Residual	11.182	68	.164		
Total	49.619	71			

Coefficients[a]

	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
(Constant)	1.571	.420		3.741	.000		
TEMP	-.136	.030	-.400	-4.469	.000	.414	2.413
CRUISE21	2.8E-03	.000	.718	6.262	.000	.252	3.973
ACC21R	2.7E-03	.001	.408	4.906	.000	.480	2.084

a. Dependent Variable: CO

Figure 7.14: Output from the FORWARD REGRESSION procedure

A comparison of the results shown in Figure 7.5 with those in Figure 7.14 demonstrates that including meteorological data slightly improved the prediction, but did not account for any substantial amount of the unexplained variation. In view of the fact that the meteorological data had to be collected from a source remote from the monitoring site, it was felt that the large increase in data manipulation resources could not be justified for the small improvement in the prediction.

There are three other possibilities that could help to explain the remaining variation. Firstly, part may be due to the effect of dirty vehicles. Research funded by the Royal Automobile Club (RAC) has found that approximately 10% of vehicles may contribute up to 50% of emissions (Revitt, 1995). These dirty vehicles may well account for the many of the peaks observed in the plots of carbon monoxide levels. However, when the data were averaged over 10 minutes before input into the model, these peaks were smoothed and their effect was not so pronounced.

Secondly, part of the unexplained variation may be due to background levels of carbon monoxide. Figure 7.15 shows a scatterplot of the carbon monoxide values monitored at the University of Nottingham background site against the residuals from the model for the data from the 15th February 1996. There was little correlation.

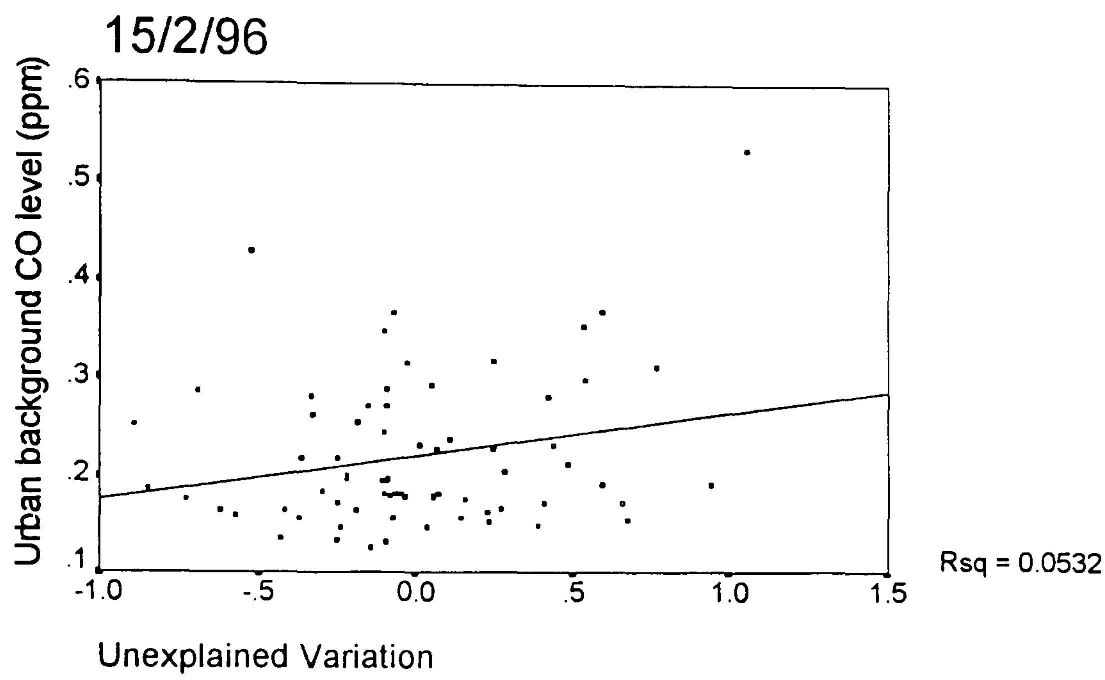

Figure 7.15: Scatterplot of urban background level of carbon monoxide against unexplained variation in model

The third, and final, possibility is that the unexplained variation is statistical variation and therefore it must be accepted that the model accounts for all the variation in kerbside levels of air pollution that is associated with the vehicle driving modes. This possibility needs to be explored further by analysing data for other days and from other locations.

7.5 Discussion

In this chapter a model has been proposed for predicting carbon monoxide levels at a position near to the stopline. The parameters in the model attempt to describe the behaviour of vehicles passing this point on both sides of the road, in terms of whether they are idling, accelerating or cruising.

The parameters in the model were derived from the SCOOT model variables STOPS, DELAY, FLOW, CONGESTION and CYCLE. The ordinary least squares method was used estimate the coefficients of the derived parameters to produce a semi-empirical model to predict the carbon monoxide concentrations.

The model was mainly used to develop predictive relationships for carbon monoxide concentrations measured during March 1996 using the ITEMMS unit on Mansfield Road, Nottingham. Relationships were produced for each day, for the whole month, and for weekdays and weekends separately.

The daily predictive relationships produced showed that in some cases the model explained as much as 87% of the carbon monoxide levels, but in some cases as little as 15%. In many cases one or more coefficients of the parameters were not statistically significantly different from zero and, in some cases, all of the coefficients were not statistically significantly different from zero. On 10 out of 28 days the whole equation became invalid because the residuals were autocorrelated. The autocorrelation occurred despite manipulating the SCOOT parameters to produce the proxies for idling, acceleration and cruising, and applying the model to ten minute rather than five minute averages.

The data for one whole month was used in an attempt to develop a general predictive equation. However, the R^2 value was very low (12%) and the residuals were very autocorrelated. The data was further divided into two datasets - one for the working week (Monday to Friday) and one for the weekends (Saturday and Sunday). This was done because the work described in Section 6.3.2 showed that, on average, the levels at the weekends were found to be 20% lower than during the rest of the week. In addition, it is well known that the traffic flow at weekends has a very different profile to that during the rest of the week. The R^2 value for the working week dataset was found to be very low (9%), but for the weekends it was higher (30%). However, in both cases there was again significant autocorrelation in the residuals.

The residuals were examined to investigate whether this unexplained variance could be due to weather effects or background levels of carbon monoxide. This data was obtained from the background precision pollution and meteorological monitoring station on the University of Nottingham campus. These (urban) background levels of carbon monoxide were found not to correlate well with these residuals and therefore were not included.

Temperature was the only meteorological parameter found to make a difference to the R^2 value and have a coefficient that was not statistically significantly different from zero. Even so, the difference was so small that it was not worth the extra data processing and manipulation necessary to include it at this time. If, however, in the future meteorological variables can be collected in the same way as the SCOOT and kerbside pollution data, then they should be included.

A second possibility considered was that the variation was due to dirty vehicles. Without knowing the emissions from each vehicle it is impossible to know how much pollution is due to dirty, badly maintained vehicles or those with cold engines. Current research at Middlesex University is examining the exhaust emissions from individual vehicles using the FEAT system developed by Steadman (Revitt, 1995). Simultaneous measurements of exhaust pollutant levels and roadside concentrations measured at the kerbside using a precision pollution monitoring system will provide the necessary data to explore the contributions made by dirty vehicles.

Finally, there is the possibility that the model had explained all of the variation in kerbside pollution levels associated with the traffic operating modes. All of these possibilities need to be explored further, and in the next chapter suggestions are made about how this can be achieved.

8. Summary and Discussion

8.1 Overview

The aim of the research described in this thesis was to develop the technology, methodology and analysis procedure to explore relationships between kerbside levels of air pollutants and traffic. The traffic characteristics data were readily available as a by-product of the demand-responsive traffic signal control system known as SCOOT (Split, Cycle and Offset Optimisation Technique) (Hunt, *et al*, 1981). The SCOOT system has been installed in Leicester since 1988 and in Nottingham since 1994. However, at the start of the research the only equipment suitable for kerbside pollution monitoring was either the extremely expensive precision systems such as those used by the Automatic Urban Monitoring Network stations, or the extremely inexpensive diffusion tubes used by environmental health officers. The main disadvantage of the diffusion tubes is that they can only provide an aggregate concentration over a period of time, typically two weeks.

At the start of this research project portable pollution monitoring equipment designed for safety inspections was the only equipment available. These systems had to be constantly supervised and surveys were limited to between four and six hours duration. Subsequently, Siemens and the Engineering and Physical Sciences Research Council acknowledged the need for an inexpensive continuous kerbside pollution monitoring system to support research. This led to the funding of the "Integration of Traffic and Environmental Monitoring and Management Systems (ITEMMS)" project. The other collaborating partners were Leicestershire County Council, Nottinghamshire County Council, the Department of Transport and the County Surveyors Society. The success of this collaborative project provided the infrastructure for most of the work described in this thesis. In this chapter the research carried out will be summarised and discussed, and suggestions for further work will be made where appropriate.

8.2 State of art review

The state of art review presented in Chapters 2 and 3 concentrated on three of the primary traffic-related pollutants - carbon monoxide, nitrogen dioxide and sulphur dioxide. The mechanism of their production, their effect on human health and national standards were described in Chapter 2. Understanding the health effects and interrelationships between pollutants are essential when attempting to optimise traffic flows to reduce pollutant levels. However, at the moment doctors are unable to state which pollutant is the most harmful, nor are they able to state whether the health effects are worsened by the mixing of the pollutants into a "cocktail" of gases.

The Government's Automatic Urban Monitoring Network has also been described. The number of reports produced by the Government in the past three years reflects the growth in the public's awareness of environmental issues both nationally and internationally. A document is expected shortly from the Department of the Environment which sets out standards and advice upon which professional must act over the next few years.

Chapter 3 reviewed the monitoring carried out by researchers and the Government. This has been fairly limited because of technological constraints and financial resources. The methodology for the research described in this thesis has been based on previous kerbside monitoring surveys (Koushki, 1988, 1989, 1991).

The early research into emissions modelling was mainly based on the assumption that a Gaussian probability distribution could be used to describe the dispersion of the pollutants emitted from vehicles. The emissions from the vehicles themselves were usually modelled using data collected from laboratory tests of exhaust gases from a representative sample of vehicles. The obvious drawback to this kind of model is that the nature of the exhaust emissions in the laboratory tests may not be truly representative of the actual vehicle fleet at any one time. In addition, in the absence of long-term continuous monitoring of roadside pollution levels many models have not been adequately calibrated and validated.

Early research by Bell and Lear (1990) used TRANSYT (Robertson, 1969) and SATURN (Van Vliet, 1982) to show that, in an undersaturated network, link emissions could be reduced by around three percent by signal co-ordination in networks. Similarly, it was shown that if critical junctions became oversaturated then pollutant emissions could increase by as much as 40% in the network studied. It was this work that demonstrated that traffic signal control and traffic management has an important role to play in the protection of our environment. However, this model could not be calibrated or validated because of the lack of any real 'on-street' data. The recognition of this deficiency led directly to the funding of the research described in this thesis.

8.3 Development of the kerbside pollution monitoring equipment

Chapter 4 contained two main parts. Firstly the Leicester and Nottingham study areas were described, along with UNTRG's dedicated telecommunication links with the traffic management computers of the two county councils. It was these links which made this research possible. The ability to collect and store raw SCOOT data is a virtually unique facility available to UNTRG through the funding of the "Instrumented City" facility (Bennett, 1992) by the Engineering and Physical Sciences Research Council. The "Instrumented City" facility also means that the air pollution data collected during the course of this research, and beyond, is available to academic researchers across the country, and has already enhanced the research of three researchers (Namdeo, 1995; Pearce, 1995; Revitt, 1995).

The second part of Chapter 4 described the surveys carried out using the basic portable carbon monoxide monitoring equipment loaned to UNTRG by Siemens. This equipment was designed for monitoring pollutant concentrations to give safety warnings to employees working in confined spaces. This portable equipment was not suitable to be left unattended at the kerbside. A meteorological monitoring system, which also required constant supervision, was used at the same time.

A preliminary investigation was carried out in Nottingham to establish the best kerbside location to carry out the surveys and to develop a survey methodology. The object of the research was to investigate traffic-related carbon monoxide levels in the *congested* urban area, therefore it was decided that the monitoring should be carried out near the stopline. The preliminary survey showed that the monitoring system could be placed anywhere up to 10 metres upstream of the stopline. Five metres was chosen as the standard distance, as it is approximately one car length. The methodology used by other researchers, most notably Koushki (1988, 1989, 1991), influenced the choice of the monitoring height (1.5 metres) and distance from the kerbside (1 metre). Subsequently, these distances were used in all the surveys carried out.

A set of surveys were then carried out in Leicester using the portable carbon monoxide and meteorological monitoring system. Although considerable resource and effort was expended in carrying out the surveys, it was concluded that they were too short (no survey was longer than six hours) to produce statistically significant results. Furthermore, no useful inferences could be drawn about the form of a relationship between carbon monoxide levels and traffic characteristics. The analysis of the data did, however, define much of the data processing methodology used later in the research.

8.4 ITEMMS - Integration of Traffic and Environmental Monitoring and Management Systems

An important conclusion of the work carried out during the early surveys was that it was necessary to carry out continuous monitoring of pollutant levels and climatic conditions simultaneously with traffic characteristics over long periods of time, *ie* weeks or months, before substantial progress could be made with the research. The lack of a suitable kerbside monitoring system which was able to withstand the harsh street environment, was vandal-proof and of reasonable cost, made it necessary to persuade an industrial company to develop a prototype system. This company was Siemens Environmental Systems Ltd. The advantage of this company was that their sister company, Siemens Traffic Controls Ltd, manufactured and installed both Leicestershire and Nottinghamshire County Councils' traffic management systems. This meant that it would be relatively straightforward to integrate the kerbside pollution monitors with the SCOOT demand-responsive traffic signal control system.

Chapter 5 described how, when the ITEMMS project was originally funded, it was hoped that it would be possible to monitor carbon monoxide, sulphur dioxide, nitrogen dioxide and hydrocarbons. However, it soon became clear that no suitable technology existed to monitor hydrocarbons at reasonable cost in a kerbside cabinet. Consequently, the pollution monitoring units were developed for the three other pollutants, using electrochemical sensors. The existing designs of street furniture for traffic signal control were used to house the monitoring system so that the sensor equipment was inconspicuous.

Two versions of this equipment were developed. The first was a 'stand-alone' version which could be left at the kerbside for extended periods of time, but could be moved from site to site. These research units contained the sensors, a battery and a datalogger. The second was a permanently sited version which was linked directly into the urban traffic control infrastructure.

Siemens Environmental Systems Ltd initially constructed four transportable research units. One of these systems had a meteorological monitoring system attached to it. Three research units were moved regularly to various sites in a SCOOT controlled sub-area of Leicester between December 1993 and October 1995. The fourth research unit and meteorological unit was installed on the roof of a three storey building approximately one mile from this sub-area. The purpose of this unit was to provide 'urban background' pollution data as well as meteorological data. It would have been preferable to monitor the local climate at each roadside site, but the meteorological monitoring equipment could not be left unattended.

In addition to the transportable prototype systems, three permanently installed units (known as ITEMMS units), linked to the urban traffic control systems, were installed in June 1995. One was installed in Leicester and two in Nottingham. The data from these units was captured and transmitted to computers at the UNTRG's laboratory along with the SCOOT traffic data.

The data from the research and ITEMMS units were processed in the same way. Tables of summary statistics for each of the variables were produced, and then the pollution data was merged in a file with the traffic characteristics data available from the SCOOT M02 message, *ie* STOPS, DELAY, FLOW, CONGESTION, to allow further statistical analysis to take place.

Unfortunately, there were many technical problems to overcome in the development and use of these units. It is now believed that the nitrogen dioxide and sulphur dioxide cells used never worked properly, and the data from the carbon monoxide cells has to be interpreted with care. This is due to several reasons. Firstly, electrochemical cells exhibit cross-sensitivities with gases other than the target gas. Secondly, when Siemens Environmental Systems Ltd were developing their commercial prototypes of the research units they found that the air flow across the cells in the research units was insufficient. Finally, it was found that rapid changes in temperature affected the stability of the cells and the cells used in the research units were unable to compensate for this effect. These problems have now been solved for the commercially available units, but it was not possible to "retro-fit" the research units.

Despite being installed in June 1995, the ITEMMS units have also suffered reliability problems which has meant that comparatively little data was available for the analysis described in this thesis. It was found that the initial conversion formulae, to translate electrical signals into pollutant concentrations, derived by Siemens Environmental Systems Ltd were incorrect. These were updated and the units re-calibrated in December 1995. During January 1996 there were problems with the link with Nottinghamshire County Council's traffic management computer which meant that there were many gaps in the data.

The link with the ITEMMS unit in Leicester was very different to the link with the ones in Nottingham. The data from the ITEMMS unit in Leicester was collected on a VAX computer before being combined with the SCOOT data from the PDP-11 computer and then transmitted to UNTRG's lab. It is only very recently that this link has become reliable.

8.5 Statistical analysis of data

In Chapter 6 a representative sample of the carbon monoxide data collected from the research units in Leicester was analysed along with the traffic characteristics data in an attempt to derive an empirical relationship. Initially, basic summary statistics were calculated to give an appreciation of the average values, the spread and the range of levels being measured. It became obvious that the distribution of carbon monoxide levels were very skewed, as the average value was closer to the minimum than the maximum. The concentrations measured at the background site were significantly lower, and did not appear to be skewed to the same extent.

Next, the diurnal variation in the data was examined. There were obvious peaks in the data which corresponded with the morning and evening traffic rush hours. When the distribution of the data was plotted, the long tail was very pronounced due to high concentrations which were measured during the peak periods.

The skewed nature of the distribution meant that it did not conform to a Gaussian, or normal, distribution. It was shown, using the Kolmogorov-

Smirnov test, that the distribution was often *log*normal, to a 95% confidence level. This finding means that statistical tests which rely on assumptions of normality have to be used with care. The background data was, however, shown to be normally distributed.

It was expected that when the carbon monoxide data was plotted against the traffic data it would be shown that as the flow of vehicles increase, then the levels of carbon monoxide would increase. However, no such simple linear relationship was found. This confirmed the results of the early work carried out in Leicester using the portable systems and described in Chapter 4. However, in the early work it was thought that the lack of correlation was simply due to the fact that there was insufficient data to provide a statistically significant result.

Multiple linear regression analysis was explored as a mechanism to develop the empirical relationship. Many researchers, such as Richardson (1982) and Linkaritakis (1983, 1988), have used the technique which is straight forward to use and easy to interpret. The carbon monoxide and traffic data analysed in Chapter 6 using this technique appeared to produce a consistent, unbiased equation until the residual series was analysed and found to be autocorrelated, *ie* there is a relationship between the values in the residual series. This meant that the tests used in the regression analysis (the F- and t-tests) were invalid. The Cochrane-Orcutt method (Montgomery and Peck, 1992) was shown to eliminate autocorrelation, but the resulting model could not be expressed in terms of the original parameters.

As a result, the more complicated time series analysis technique known as ARIMA (AutoRegressive Integrated Moving Average) was investigated. This technique was developed by Box and Jenkins (1972) to analyse the time varying data collected by manufacturing and process control engineers to forecast whether or not a process will go outside control limits in the very near future, so that appropriate adjustments could be made. Using this technique it was found that it was possible to fit an ARIMA model to the data with a very high correlation coefficient, but that only very short-term predictions were possible. In addition, the models could only be developed for those links with monitoring units, since no account could be taken of factors such as traffic characteristics and meteorological variables.

Through the analysis carried out two important issues had emerged. Firstly, it was concluded that the traffic on the opposite side of the road could not be ignored as it seemed to make a contribution to the concentrations measured. Secondly, it was found that the levels of carbon monoxide were up to 20% lower at weekends than during the rest of the week, which meant that it may be necessary to have two separate predictive relationships. This was not wholly unexpected because the traffic at weekends has a very different flow profile, with significantly less congestion.

At this point in the research it was decided not to continue with developing empirical relationships, but instead to take an alternative approach and develop a *semi*-empirical model. It was proposed to develop a linear model which used SCOOT parameters to provide estimates of the vehicle operating mode, *ie* whether the vehicles passing a point were idling, accelerating, decelerating or cruising.

8.6 The development of a semi-empirical model

In Chapter 7 a semi-empirical model was developed to predict carbon monoxide levels at a position near to the stopline. The parameters in the model attempted to describe the behaviour of the vehicles passing this point on both sides of the road, and included terms to account for the "lingering" of pollution over time as it dispersed.

The definitions of the SCOOT parameters STOPS, DELAY, FLOW, CONGESTION and CYCLE were used to derive estimates for accelerating, cruising and idling vehicles. Data from the ITEMMS unit on Mansfield Road, Nottingham and the corresponding SCOOT links were then used to estimate the coefficients of these "proxies" for each day in March 1996, and for the whole of this month, using the ordinary least squares estimation method.

It was found that, for the daily model predictions, the correlation coefficient (R^2) value varied from 15% to 87%. However, there was no obvious pattern in the results, although it had been initially thought that the prediction would be poorer at weekends. Unfortunately, there were three main problems with the predictive equations. Firstly, many of the parameter coefficients were found not to be statistically significantly different from zero. Secondly, several variables were found to be collinear. Thirdly, and more importantly, nearly two-thirds of the equations had, or were suspected to have, autocorrelated residuals, which meant that the *F*- and *t*-tests were invalid anyway.

Similarly, for the whole month's data the residual series was highly autocorrelated, and the R^2 value was very low (12%). The data was then split into two sections - one for the weekends and one for the rest of the week. The R^2 value for the weekend dataset was higher (30%), but again there was significant autocorrelation for both datasets.

Weather and background carbon monoxide levels, from a monitoring station on the University of Nottingham campus, were collected and analysed to try to explain some of the residual variation. It was found that including temperature did improve the model prediction marginally. If it had been possible to monitor the climate at the kerbside, a correlation with wind speed or wind direction may also have been found. Two other suggestions about this unexplained variation were given. Firstly, that it may be due to dirty, badly maintained vehicles which produce a disproportionate amount of pollution. Secondly, that the model had explained all of the variation in kerbside pollution levels due to the vehicle operating modes.

8.7 Current research

Now that the links with the ITEMMS units have been reliably established, the data will be continued to be collected, as part of the "Instrumented City" facility. During 1996 the number of ITEMMS units in Leicestershire is going to be extended considerably to 13 units. These systems will be funded by two grants from the European Fourth Framework programme. These are called EMMA (Integrated Environmental Monitoring, Forecasting and Warning Systems in Metropolitan Areas) and EFFECT (Environmental Forecasting For the Effective Control of Traffic). In May 1996, Leicestershire County Council upgraded their traffic management system to the latest version of SCOOT which runs on a VAX computer. This means that the data from the ITEMMS units is collected in exactly the same way as the data from the Nottingham units. This data will be processed and information passed on to the public via several routes such as Radio Leicester broadcasts and newspaper articles. A questionnaire will then be used to assess whether this information makes the public change their travel habits.

It is acknowledged that there are two main drawbacks to the approach taken in this research. Firstly, the use of SCOOT data as the basis of the model means that currently there can be no differentiation of vehicle type, *ie* whether the vehicles passing the monitoring/prediction point are cars, buses or HGVs, or whether they are petrol or diesel engined. The second drawback is that the model is specific to one position, rather than being applicable to any point on the link. These two issues are being addressed by another PhD research programme being carried out at UNTRG (Marsden, 1995). A model suite called VEPRODEF (VEhicle PROgression from DEtector Flows) is being developed which consists of a queuing model which takes network parameters and selected SCOOT messages as input. This model then seeks to predict the types and proportions of vehicles travelling in each of the four operating modes at discrete time intervals and a different positions along a link. Time-distance diagrams are produced for each individual vehicle and standard emission factors are used to calculate the emissions. These will then be dispersed using a suitable model. The difference between this model and the one developed by Matzoros and Van Vliet is that the VEPRODEF model will operate in real-time. Monitoring will be carried out using ITEMMS units to provide the calibration and validation of this model.

Another project, currently being undertaken at UNTRG, uses a second generation of research unit (with most of the technical problems solved) to attempt to quantify the benefit to the environment of installing demand-responsive signal control (Winter, 1995). It is hoped to be able to confirm the results of the early work carried out by Bell using TRANSYT which were described in Section 8.2 above.

8.8 Discussion and suggestions for future work

The research described in this thesis was based on two separate projects which were very ambitious. Although other researchers had carried out limited, short-term traffic and pollution monitoring exercises, no-one had had access to the wealth of data available from the SCOOT traffic model. Also, the equipment used in this research had to be specifically designed and developed. As a result these Roadside Pollution Monitors are now available for local authorities to buy to complement their traffic and pollution monitoring capabilities. In addition, throughout the course of the research various macros and programs were written to facilitate the quick and easy processing of the data. In the future, these will be useful to support other "Instrumented City" research projects.

The research has demonstrated that there is no straightforward link between carbon monoxide levels and traffic characteristics. It has been shown that the distribution of kerbside levels of carbon monoxide is highly skewed and that this distribution usually conforms to a lognormal, rather than a normal distribution. This is in contrast to urban background levels, which are usually normally distributed. This result has important implications when statistical tests which rely on the normality of the data are used.

The major obstacle in the application of statistical techniques to develop the empirical relationship in this research has been the fact that, more often than not, the residual series was autocorrelated. This made many of the tests invalid. Montgomery and Peck (1992) stated that the primary cause of autocorrelation is the failure to include one or more important regressors in the model. Consequently, it is important to investigate other factors which affect the air pollution levels measured on-street. One obvious consideration is how the prevailing climatic conditions affect the dispersion of the pollution.

Wind speed and wind direction will both influence the dispersion and transport of air pollution particles. Wind direction is an especially important factor as it determines the path of the pollution particles, which may not be towards the location of the monitoring unit and consequently the concentrations measured may not be representative of the actual pollution emitted. In the specific case of urban street canyons, the presence of turbulent eddies adds to the complexity of the wind field. Figure 8.1 represents the circulation of pollution in a street canyon when the prevailing wind direction is across the axis of the road (after Namdeo, 1995).

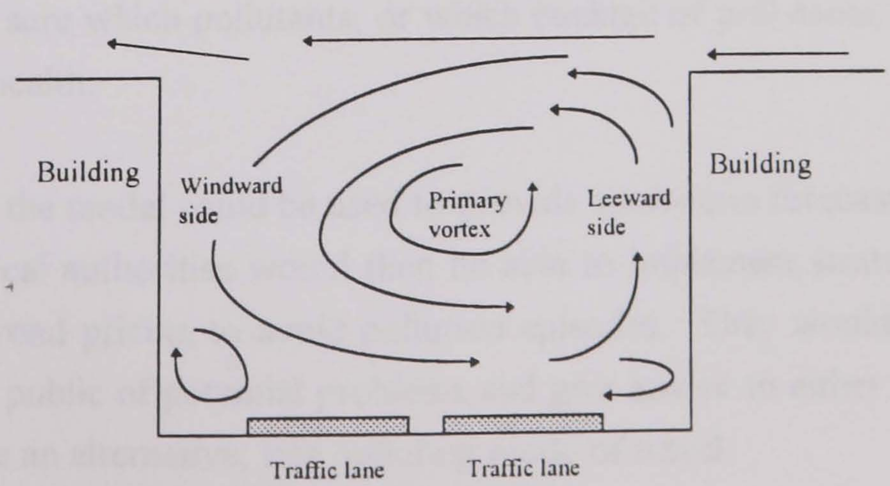

Figure 8.1: Pollutant circulation in a street canyon (after Namdeo, 1995)

Differences between air temperature and ground temperature are also important factors in the ability of pollution particles to disperse. When the ground is cooler than the air, the atmosphere is said to be *stable*. Conversely, when the ground is warmer than the air, the atmosphere is said to be *unstable*. Oke (1987) stated that pollution will disperse more readily in the unstable conditions typical of sunny, daytime conditions. The worst conditions for dispersion occur when there is a temperature inversion (due to warm air overlying cooler air) and the atmosphere is stable.

An attempt was made to include meteorological variables in the semi-empirical model. However, the data used was obtained from a monitoring site which was over three miles from the roadside pollution monitor, and located on an open site. Ideally the meteorological variables should be measured at the roadside to give accurate values. However, this is difficult to achieve in practice as the equipment would be vandalised or stolen if left unattended.

Once an adequate model has been developed it should be validated by using the data collected from the other ITEMMS units installed on Bentinck Road, Nottingham and Waterloo Way, Leicester. These two locations have very different road layouts to the Mansfield Road site and would provide an excellent test of the predictive model. Finally, attention should be turned to the other two pollutants measured by the ITEMMS units - nitrogen dioxide and sulphur dioxide.

There are several potential uses for this type of model. Traffic signal control optimisation techniques could be developed to specifically minimise levels of pollutants rather than delay. The model could also be used to assess the impact of traffic schemes. However, these applications will be difficult to achieve until doctors are sure which pollutants, or which cocktail of pollutants, are the most harmful to health.

In addition, the model could be used to provide short-term forecasts of poor air quality. Local authorities would then be able to implement strategies such as gating and road pricing to avoid pollution episodes. They would also be able to warn the public of potential problems and give advice to either stay at home or to choose an alternative, less polluting mode of travel.

In the meantime, the research described in this thesis has led to the development of a unique kerbside pollution monitoring system which is relatively inexpensive. This means that local authorities will be able to purchase several units and install them across a city. The data collected can be used historically to assess the air quality in the city, and to provide information to the public. This thesis has shown how the development of these systems has already led to an increased understanding of the nature of the relationships between kerbside carbon monoxide concentrations and traffic characteristics. The data collected in the future will support the on-going research, especially into the links with health.

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APPENDIX 1

RESULTS FROM THE PRELIMINARY SURVEYS IN LEICESTER

A1.1 London Rd/Granville Rd (N0215J) - 29/4/92

Table A1 shows the summary statistics for this survey. The number of observations was 19.

Table A1: Summary Statistics from 29/4/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	12.79	1.86	0.19
Wind speed	1.16	0.20	-0.05
Wind direction	241.54	82.41	-0.04
Relative humidity	60.16	5.49	-0.27
Cars	119.11	17.96	0.48
HGV	1.16	0.96	-0.10
Bus	2.00	1.67	-0.23
Carbon monoxide	13.11	6.71	

A1.2 London Rd/Granville Rd (N0215J) - 15/5/92

Table A2 shows the summary statistics for this survey. The number of observations was 49.

Table A2: Summary Statistics from 15/5/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	21.51	3.89	0.10
Wind speed	1.07	0.25	-0.07
Wind direction	262.96	16.84	-0.25
Relative humidity	37.39	12.90	-0.14
Cars	76.88	33.28	-0.05
HGV	2.12	1.73	-0.03
Bus	1.74	1.34	0.02
Carbon monoxide	9.82	13.74	

The carbon monoxide levels measured included one extreme value of 90 ppm, and this explains the large standard deviation in Table A2. The statistics were recomputed without this peak value and the output is shown in Table A3. The number of observations was now 48.

Table A3: Summary Statistics from 15/5/92 for CO less than 90 ppm

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	21.48	3.93	0.10
Wind speed	1.07	0.25	-0.17
Wind direction	263.34	16.81	-0.22
Relative humidity	37.57	12.97	-0.10
Cars	77.44	33.39	0.11
HGV	2.13	1.75	-0.03
Bus	1.73	1.35	-0.02
Carbon monoxide	8.15	7.29	

A1.3 Waterloo Way/Lancaster Rd - 27/5/92

Tables A4 and A5 show the summary statistics for this survey. The total number of observations was 41, however cars, buses and HGVs were only recorded for 21 cases and SCOOT data was available for 23 cases. Consequently there are two sets of tables - the first for the manual counts and the second for the SCOOT data.

Table A4: Summary Statistics from 27/5/92 (n = 21)

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	15.66	1.84	0.01
Wind speed	2.12	0.45	-0.24
Wind direction	266.54	9.44	0.34
Relative humidity	69.31	7.76	0.05
Cars	25.33	5.97	0.32
HGV	1.24	1.00	-0.12
Bus	0.10	0.30	0.10
Carbon monoxide	10.00	6.89	

Table A5: Summary Statistics from 27/5/92 (n = 23)

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	20.83	1.30	0.27
Wind speed	2.26	0.51	-0.16
Wind direction	270.47	10.62	0.15
Relative humidity	46.98	5.42	-0.20
STOPS	218.65	44.95	0.18
FLOW	264.48	57.21	-0.02

Variable	Mean	Standard Deviation	Correlation with CO
DELAY	20.22	4.09	0.16
Carbon monoxide	13.74	6.76	

A1.4 University Road/Regent Rd - 16/6/92 and 17/6/92

In order to investigate the variation of carbon monoxide levels over the whole day it was decided to conduct two surveys on the same link. The first lasted from 7.35 until 12.00, and the second from 12.05 to 17.55. However the two surveys took place on consecutive days so that the surveyors were not asked to count traffic for more than six hours. The two sets of data were amalgamated into one with 125 cases. The manual count and classification was done for each side of the road.

Table A6: Summary Statistics from 16/6/92 and 17/6/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	21.18	3.99	0.10
Wind speed	0.94	0.25	-0.20
Wind direction	269.53	11.88	0.05
Relative humidity	42.45	15.74	-0.10
Cars (near)	17.03	6.58	0.49
HGV (near)	0.18	0.45	0.04
Bus (near)	0.73	0.82	-0.01
Cars (off)	20.18	8.25	0.02
HGV (off)	0.31	0.53	0.07
Bus (off)	0.75	0.82	0.10
STOPS	244.86	96.02	0.17
FLOW	260.80	96.58	0.18
DELAY	19.54	11.98	0.01
Carbon monoxide	23.88	32.01	

After this initial analysis of the data it was decided to split the data up into three sections to investigate variations over the peaks and off-peak periods. The morning peak was identified as being the period from 7.35 to 9.30 (n = 24), the off-peak started at 9.35 and continued until 15.55 (n = 77), and the evening peak finished at 17.55 (n = 24). The data was described in a similar way to previously.

Table A7: Summary Statistics from 16/6/92 morning peak

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	15.81	0.75	0.29
Wind speed	1.07	0.20	-0.09
Wind direction	264.42	12.08	-0.15
Relative humidity	67.04	3.82	-0.18
Cars (near)	16.08	6.79	0.27
HGV (near)	0.17	0.38	-0.24
Bus (near)	0.67	0.76	0.42
Cars (off)	32.58	8.48	0.44
HGV (off)	0.25	0.44	0.26
Bus (off)	0.67	0.82	0.19
STOPS	339.79	128.84	0.42
FLOW	355.75	125.56	0.42
DELAY	34.75	16.09	0.38
Carbon monoxide	19.25	13.23	

Table A8: Summary Statistics from 16/6/92 and 17/6/92 off-peak

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	22.34	3.42	0.23
Wind speed	0.96	0.25	-0.19
Wind direction	269.84	12.33	-0.05
Relative humidity	36.94	12.16	-0.17
Cars (near)	14.75	4.45	0.09
HGV (near)	0.22	0.48	0.10
Bus (near)	0.73	0.84	-0.08
Cars (off)	16.82	4.90	-0.05
HGV (off)	0.38	0.59	0.11
Bus (off)	0.78	0.85	-0.02
STOPS	208.03	63.34	-0.01
FLOW	219.82	61.39	-0.04
DELAY	16.04	7.08	-0.06
Carbon monoxide	13.65	17.36	

Table A9: Summary Statistics from 17/6/92 evening peak

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	22.85	3.0	-0.22
Wind speed	0.77	0.20	0.22
Wind direction	273.66	8.16	-0.07
Relative humidity	35.52	7.10	0.18
Cars (near)	25.29	5.71	0.36
HGV (near)	0.08	0.41	0.33
Bus (near)	0.79	0.83	-0.11
Cars (off)	18.58	3.89	-0.04
HGV (off)	0.17	0.38	0.45
Bus (off)	0.75	0.74	0.36
STOPS	268.13	73.03	0.10
FLOW	297.33	75.17	0.002
DELAY	15.54	7.11	0.22
Carbon monoxide	61.33	50.18	

A1.5 Regent Rd/De Montfort St (N0224J) - 13/8/92

Table A10 shows the summary statistics for this survey. The number of observations was 26.

Table A10: Summary Statistics from 13/8/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	19.15	0.57	0.31
Wind speed	0.85	0.35	0.54
Wind direction	287.16	31.15	-0.32
Relative humidity	50.67	5.62	-0.55
Cars (near)	30.71	4.56	-0.05
HGV (near)	0.54	0.72	0.20
Bus (near)	0.29	0.46	0.20
Cars (off)	33.08	6.96	0.29
HGV (off)	0.63	0.71	0.02
Bus (off)	0.21	0.42	-0.07
STOPS	295.08	62.71	-0.20
DELAY	6.25	1.57	-0.11
FLOW	392.13	60.47	-0.26
Raw	2.00	7.64	-0.12
Carbon monoxide	11.92	8.81	

A1.6 Regent Rd/De Montfort St (N0224J) - 18/8/92

Table A11 shows the summary statistics for this survey. The number of observations was 71.

Table A11: Summary Statistics from 18/8/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	24.66	1.76	-0.01
Wind speed	0.53	0.20	0.35
Wind direction	190.67	34.01	-0.08
Relative humidity	29.42	6.11	-0.01
Cars (near)	31.39	6.31	0.07
HGV (near)	0.47	0.79	-0.02
Bus (near)	0.28	0.45	-0.17
Cars (off)	42.51	13.08	0.09
HGV (off)	0.45	0.73	-0.05
Bus (off)	0.28	0.45	-0.06
STOPS	227.85	73.50	0.03
DELAY	5.80	3.08	-0.01
FLOW	391.70	86.03	-0.03
Raw	1.86	7.21	0.02
Carbon monoxide	11.24	9.27	

A1.6 Regent Rd/De Montfort St (N0224J) - 20/8/92

Table A12 shows the summary statistics for this survey. The number of observations was 38.

Table A12: Summary Statistics from 20/8/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	19.16	1.65	0.04
Wind speed	0.49	0.10	0.09
Wind direction	236.65	75.07	0.18
Relative humidity	68.62	6.88	-0.002
Cars (near)	33.37	11.21	0.21
HGV (near)	0.53	0.73	-0.16
Bus (near)	0.24	0.43	0.48
Cars (off)	32.00	7.72	0.04
HGV (off)	0.71	0.77	-0.25

Variable	Mean	Standard Deviation	Correlation with CO
Bus (off)	0.32	0.57	0.03
STOPS	304.08	102.75	-0.17
DELAY	7.76	3.26	-0.11
FLOW	457.79	109.32	-0.16
Raw	2.84	7.61	0.01
Carbon monoxide	24.95	21.96	

A1.7 London Rd/University Rd (inbound) (N0213A) - 3/9/92

Table A13 shows the summary statistics for this survey. The number of observations was 35.

Table A13: Summary Statistics from 3/9/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	14.14	1.57	-0.23
Wind speed	1.33	0.37	-0.20
Wind direction	219.50	122.07	0.15
Relative humidity	63.69	6.59	0.34
Cars	94.63	32.73	0.27
HGV	2.86	1.31	0.13
Bus	2.63	1.57	-0.18
STOPS	994.74	321.11	0.30
DELAY	65.89	70.24	-0.05
FLOW	1104.91	304.27	0.33
Congestion	8.23	18.58	0.11
Raw	13.71	23.85	0.11
Carbon monoxide	18.17	15.52	

A1.8 London Rd/University Rd (outbound) (N0213C) - 10/9/92

Table A14 shows the summary statistics for this survey. The number of observations was 27.

Table A14: Summary Statistics from 10/9/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	19.30	1.65	-0.34
Wind speed	1.38	0.33	-0.41
Wind direction	257.01	26.60	-0.19
Relative humidity	58.04	4.17	0.29

Variable	Mean	Standard Deviation	Correlation with CO
Cars	62.22	9.55	-0.21
HGV	3.07	2.32	-0.24
Bus	2.44	1.25	0.07
STOPS	405.00	118.17	-0.25
DELAY	14.56	5.52	-0.19
FLOW	798.63	106.47	-0.31
Raw	0.44	2.31	0.17
Carbon monoxide	5.89	3.67	

A1.9 De Montfort St/Regent Rd (N0224I) - 14/9/92

Table A15 shows the summary statistics for this survey. The number of observations was 66.

Table A15: Summary Statistics from 14/9/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	19.39	2.52	0.20
Wind speed	1.67	0.28	-0.12
Wind direction	152.25	65.21	-0.02
Relative humidity	53.96	12.31	-0.21
Cars	22.06	6.64	0.53
HGV	0.27	0.54	-0.08
Bus	0.03	0.17	-0.01
STOPS	110.77	56.21	-0.20
DELAY	3.88	2.22	-0.19
FLOW	136.64	64.80	-0.22
Raw	3.27	10.21	-0.04
Carbon monoxide	8.42	15.18	

A1.9 Evington Rd/London Rd (N0215I) - 16/9/92

Table A16 shows the summary statistics for this survey. The number of observations was 46.

Table A16: Summary Statistics from 16/9/92

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	14.52	1.91	-0.07
Wind speed	0.56	0.18	0.15
Wind direction	160.84	118.04	0.22

Variable	Mean	Standard Deviation	Correlation with CO
Relative humidity	61.44	10.03	0.05
Cars	83.22	20.48	0.13
HGV	3.07	2.52	-0.08
Bus	3.35	2.25	0.02
STOPS	166.91	92.28	0.09
DELAY	7.96	6.93	0.12
FLOW	194.07	88.53	0.11
Raw	2.09	8.87	-0.05
Carbon monoxide	28.52	28.16	

A1.10 Regent Rd/Waterloo Way - 21/9/92

Tables A17 and A18 shows the summary statistics for this survey. The number of observations was 45, however SCOOT data was only available for 22 of these cases.

Table A17: Summary Statistics from 21/9/92 (n = 22)

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	14.273	0.407	-0.005
Wind speed	0.418	0.096	-0.308
Wind direction	155.455	41.906	0.250
Relative humidity	85.386	2.052	-0.132
Cars	62.864	9.573	0.190
HGV	2.136	1.320	-0.170
Bus	0.591	0.796	0.091
STOPS	91.545	54.198	-0.167
DELAY	5.955	4.123	-0.218
FLOW	122.455	53.110	0.081
Carbon monoxide	35.727	25.995	

Table A18: Summary Statistics from 21/9/92 (n = 45)

Variable	Mean	Standard Deviation	Correlation with CO
Temperature	15.320	1.899	-0.119
Wind speed	0.629	0.565	0.075
Wind direction	156.704	42.016	-0.013
Relative humidity	81.322	7.074	0.104
Cars	65.756	15.608	0.142

Variable	Mean	Standard Deviation	Correlation with CO
HGV	1.778	1.259	-0.007
Bus	0.556	0.785	0.026
Carbon monoxide	37.889	29.805	

Table B1: Multiple regression analysis results

Date	Period	R2	Temp	Wind speed	Wind dirn	RH (%)	Cars (Near)	HGV (Near)	Bus (Near)	Cars (Off)	HGV (Off)	Bus Off	Cars (Total)	HGV (Total)	bus (Total)	Others	FLOW	STOPS	DELAY	CONG	Constant
28/4/92	7.40 - 9.15	0.668	-4.399	-29.627	-0.002	-1.411	0.371	0.893	-1.220												146.545
15/5/92	7.30 - 9.06	0.170	-5.295	-20.702	-0.170	-1.914	0.047	-0.640	-0.176												260.198
	7.30 - 9.06	0.492	-2.973	-14.809	0.029	-1.431	-0.052	-0.415	-0.804												147.641
	9.36 - 11.56	0.222	-7.177	-18.115	-0.236	-3.232	-0.238	-0.929	0.689												371.283
27/5/92	7.33 - 9.13	0.365	4.937	-1.443	0.316	1.391	0.306	-1.044	0.822												-251.288
	9.03 - 10.53	0.243	3.070	-1.783	0.072	0.317											-0.035	0.109	-0.639		-82.252
16&17/6/92	7.35 - 17.55	0.282	1.920	-10.478	-0.058	0.494	2.467	5.434	-0.792	-0.109	8.361	2.995									-57.219
		0.093	0.308	-18.691	-0.043	-0.035											-0.003	0.125	-0.555		29.216
		0.178	-1.130	-15.772	-0.118	-0.448							1.153			2.822	-0.042	0.081	-0.653		69.155
	7.35 - 9.30	0.574	14.232	-5.026	-0.344	2.347	0.400	-2.957	6.966	0.327	5.953	1.680									-290.547
		0.406	33.786	4.467	-0.187	5.898											-0.318	0.317	0.165		-865.934
		0.570	34.026	14.967	-0.322	5.445							0.460			3.609	-0.347	0.329	-0.110		-827.581
	16.00 - 17.55	0.681	-42.455	-4.454	-0.175	-17.185	4.145	53.691	-2.636	0.797	52.724	8.400									1555.711
		0.303	-60.057	-1.126	-1.082	-25.964											0.179	-0.565	6.867		2644.294
		0.526	-64.751	-37.675	-0.288	-27.001							1.265			22.243	0.218	-0.716	6.453		2539.546
	9.30 - 16.00	0.121	2.643	-8.083	-0.062	0.503	0.307	2.805	-1.508	-0.089	4.270	-0.108									-43.599

Date	Period	R2	Temp	Wind speed	Wind dirn	RH (%)	Cars (Near)	HGV (Near)	Bus (Near)	Cars (Off)	HGV (Off)	Bus Off	Cars (Total)	HGV (Total)	bus (Total)	Others	FLOW	STOPS	DELAY	CONG	Constant
		0.113	3.162	-9.629	-0.125	0.619											-0.146	0.146	0.117		-37.072
		0.112	2.873	-9.959	-0.113	0.530							0.014			0.187	-0.148	0.137	0.127		-28.929
	9.30 - 13.00	0.242	8.717	-4.792	-0.131	1.603							0.123			0.154	-0.001	0.058	-0.578		-199.660
	13.00 - 16.00	0.099	0.384	-11.137	-0.060	-0.560							0.000			0.938	-0.238	0.182	-0.085		60.721
18/08/92	12.10-18.00	0.243	0.930	20.176	-0.046	0.361	0.382	0.372	-3.244	0.128	-0.359	-0.229					-0.038	0.028	-0.502		-28.911
		0.166	0.512	18.869	-0.050	0.178											-0.017	0.016	-0.328		-1.930
		0.165		17.415	-0.026	0.141										-0.758					-1.470
20/08/92	8.05-12.15	0.509	15.349	52.071	0.045	3.356	0.338	-6.713	20.902	-0.144	-8.716	2.344					-0.089	-0.031	1.607		-502.938
		0.251	4.857	14.461	-0.030	0.656	0.357	-6.182	16.848	0.359	-7.632	7.329									-135.243
		0.210	16.011	67.127	0.056	3.990											-0.068	-0.143	4.064		-560.870
		0.083	3.975	5.142	-0.032	0.512							0.420			-1.226					-106.670
3/9/92	7.55-10.45	0.446	6.772	-4.701	0.050	2.277							-0.204	1.849	-2.931		0.055	-0.014	-0.026		-247.466
		0.353	8.075	-3.241	0.044	2.889							-0.009	2.209	-1.772						-286.156
		0.362	6.963	-3.519	0.052	2.232											-0.003	0.024	-0.067		-248.312
10/09/92	12.20-14.30	0.412	-1.636	-4.223	-0.024	-0.397							-0.068	-0.361	0.467						76.744
		0.425	-2.086	-4.220	-0.275	-0.580											-0.008	0.002	-0.014		98.451
		0.455	-2.045	-3.714	-0.026	-0.588							0.013	-0.211	0.508		-0.012	0.003	-0.019		98.175
	12.20-18.00	0.183	-2.057	-6.467	-0.028	-0.565							0.028	-0.032	0.028						95.005

Date	Period	R2	Temp	Wind speed	Wind dirn	RH (%)	Cars (Near)	HGV (Near)	Bus (Near)	Cars (Off)	HGV (Off)	Bus Off	Cars (Total)	HGV (Total)	bus (Total)	Others	FLOW	STOPS	DELAY	CONG	Constant
14/09/92	12.15-17.40	0.349	0.954	-7.295	0.025	-0.129							1.190	-1.110	1.046						-20.761
		0.156	-2.054	-14.511	0.044	-0.858											-0.086	0.091	-1.250		118.278
		0.390	0.882	-9.573	0.026	-0.148							1.184	-1.199	7.543		-0.029	0.058	-1.982		-9.768
16/09/92	8.15-12.00	0.118	-10.731	6.757	0.065	-1.801							0.161	-1.582	0.229						271.462
		0.120	-13.037	8.272	0.049	-2.536											0.142	-0.138	1.059		348.626
		0.142	-13.691	5.025	0.057	-2.912							0.128	-1.615	-0.133		0.081	-0.062	0.879		377.085
21/09/92	9.15-12.55	0.054	-0.946	11.087	0.051	0.679							0.189	-0.563	1.499						-30.023
		0.257	7.813	-73.854	0.006	0.706											0.335	-0.154	-2.017		-121.030
	9.15-11.30	0.404	3.652	-103.127	-0.060	-2.178							-0.383	-3.085	16.797		0.573	-0.239	-1.865		205.537

APPENDIX 2

SIEMENS' ROADSIDE POLLUTION MONITOR TECHNICAL DATA SHEET

SIEMENS

RPM – Roadside Pollution Monitor

- Continuous monitoring of traffic pollutants CO, SO_2, NO_2 to highlight hot spots and trends
- Robust design for kerbside environment
- System configured for simple installation and operation
- System integration with urban traffic control systems
- Networked to automatic central air quality monitoring stations

General Description

The levels of traffic pollution at the kerbside have been causing increasing concern. Monitoring sites are often a compromise between the need to monitor typical urban and/or residential areas and to measure the specific kerbside environment.

Siemens has recognised the need to develop a 'Guideline' monitoring system which will be able to measure the kerbside levels to within acceptable tolerances. This instrument, called the Roadside Pollution Monitor (RPM), is able to measure nitrogen dioxide (NO_2), sulphur dioxide (SO_2) and carbon monoxide (CO) concentration levels.

Electro-chemical cells are used to measure the pollutant concentration levels. Automatic correction techniques are employed to compensate for changes in the cell performance characteristics owing to temperature and cross-gas sensitivity effects.

The air sample is pumped at a constant flow rate of approximately two litres per minute through a filter and humidity exchanger, and then over the cells. NO_2 and SO_2 measurement compatible materials are used in the air sampling line.

A terminal can be plugged into the technician interface to monitor the concentration levels being measured and change the set up parameters.

The RPM is able to store data locally and, via a UTC system or PSTN line, data can be uploaded to a database system for reporting. The logged data is stored at user defined intervals (once every 2 to 60 minutes). Up to one month's data is stored in the monitor. All logged data is time stamped and the RPM real time clock is backed up by a battery.

The RPM has low operational costs (just a weekly filter change) and a six monthly gas calibration. The electro-chemical cells will need replacing every 18 months.

Technical Summary

Environmental

Operating -10°C to 40°C
Intermittent -15°C to 55°C
Humidity 90% at 40°C

Power Supply

110V/230V 1.2A/0.6A 47 to 63Hz

Standards

BS EN60950 - Safety of IT equipment
BS EN50081 - 1 EMC Emission
BS EN50082 - 1 EMC Immunity

Measurement Range

NO_2	0 to 2000 ppb
SO_2	0 to 2000 ppb
CO	0 to 120 ppm

Lowest Detectable Level

NO_2	30 ppb
SO_2	30 ppb
CO	0.1 ppm

Dimensions

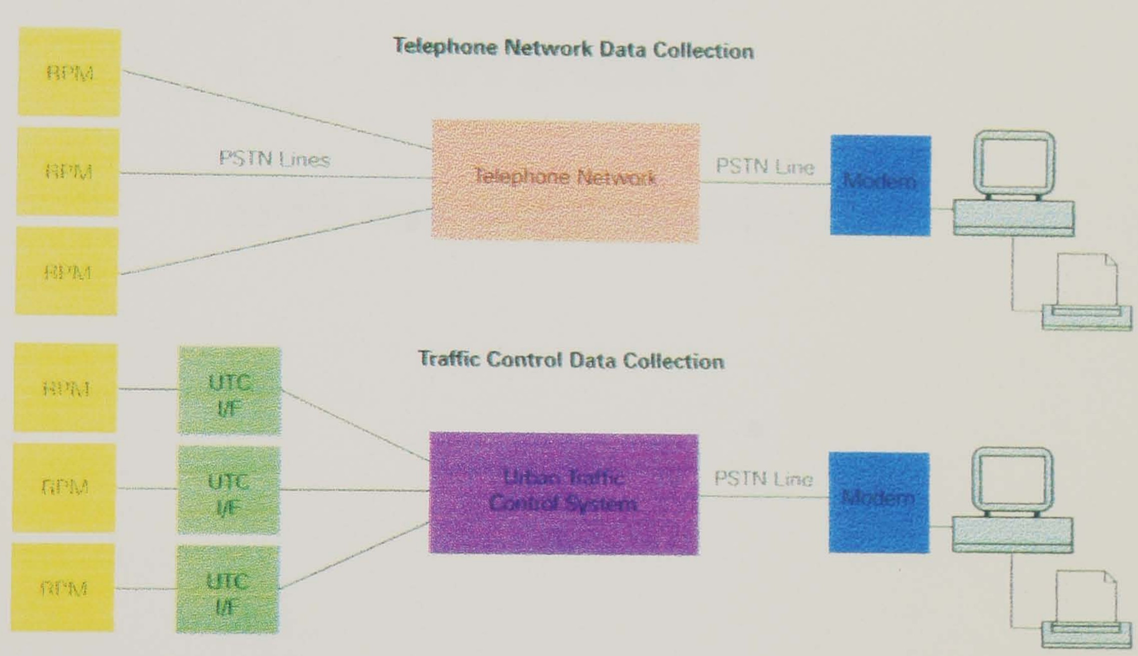
Height	680mm + stand
Width	390mm
Depth	300mm
Stand Height	800mm (above ground)

Options

Environmental Measurement Database – PC based software package to read the RPM pollution data and generate standard daily, weekly, monthly and annual reports.

Traffic controller interface – Compatible with Siemens Telecommand 12 series. Pollution data collected at the traffic control centre.

RPM – Data Collection Systems



Siemens Environmental Systems Limited
Sopers Lane
Poole
Dorset UK BH17 7ER

Tel: 01202 782000 International + 44 1202 782000
Fax: 01202 782335 International + 44 1202 782335

SESL/95/83/PPG/06/1K

APPENDIX 3

SPSS FOR WINDOWS MACROS

"12hrsum.sps" macro

```
* run macro from command line at end of file

define getdata (file = !tokens(1)
          / link = !tokens (1)
          / date = !tokens (1)
          / flow = !tokens (1)
          / delay = !cmdend).

* import data from text file and give variables names and labels
GET TRANSLATE
  FILE= !file
 /TYPE=tab /MAP .
EXECUTE .

rename variables (var1 to var16 = time stops delay flow raw cong len  av_no2 min_no2 max_no2
        av_co min_co max_co av_so2 min_so2 max_so2).

formats stops to len (f5.0) / av_no2 to max_so2 (f8.3).

variable labels av_no2 'average NO2 (ppm)'
          / av_co 'average CO (ppm)'
          / av_so2 'average SO2 (ppm)'
          / min_no2 'minimum NO2 (ppm)'
          / min_co 'minimum CO (ppm)'
          / min_so2 'minimum SO2 (ppm)'
          / max_no2 'maximum NO2 (ppm)'
          / max_co 'maximum CO (ppm)'
          / max_so2 'maximum SO2 (ppm)'
          / stops 'STOPS (veh/hr)'
          / delay 'DELAY (1/10 veh.h/h)'
          / flow 'FLOW (veh/hr)'
          / raw 'RAW'
          / cong 'CONGESTION'.

*produce summary statistic tables for each pollutant
TABLES
  /BOXCHARS = SYSTEM
  /FORMAT LIGHT VBOX FRAME SPACE BLANK MARGINS(1,110) LENGTH(1,30)
    CWIDTH(15,11,15) INDENT(2) MISSING('.') WRAPCHARS(',/-') LLAYER
 /OBSERVATION= av_no2 to max_so2
 /GBASE=CASES
 /TABLE=av_no2 + min_no2 + max_no2 + av_co + min_co + max_co + av_so2
      + min_so2 + max_so2  BY (STATISTICS)
 /STATISTICS
 mean( av_no2 'Mean')
 stddev( av_no2 'Std Deviation')
 minimum( av_no2 'Minimum')
 maximum( av_no2 'Maximum')
 median( av_no2 'Median')
 ptile 98( av_no2 '98Percent')
 validn( av_no2( F5.0 ) 'Valid N')
```

```
mean( min_no2 'Mean')
stddev( min_no2 'Std Deviation')
minimum( min_no2 'Minimum')
maximum( min_no2 'Maximum')
median( min_no2 'Median')
ptile 98( min_no2 '98Percent')
validn( min_no2( F5.0 ) 'Valid N')
mean( max_no2 'Mean')
stddev( max_no2 'Std Deviation')
minimum( max_no2 'Minimum')
maximum( max_no2 'Maximum')
median( max_no2 'Median')
ptile 98( max_no2 '98Percent')
validn( max_no2( F5.0 ) 'Valid N')
mean( av_co 'Mean')
stddev( av_co 'Std Deviation')
minimum( av_co 'Minimum')
maximum( av_co 'Maximum')
median( av_co 'Median')
ptile 98( av_co '98Percent')
validn( av_co( F5.0 ) 'Valid N')
mean( min_co 'Mean')
stddev( min_co 'Std Deviation')
minimum( min_co 'Minimum')
maximum( min_co 'Maximum')
median( min_co 'Median')
ptile 98( min_co '98Percent')
validn( min_co( F5.0 ) 'Valid N')
mean( max_co 'Mean')
stddev( max_co 'Std Deviation')
minimum( max_co 'Minimum')
maximum( max_co 'Maximum')
median( max_co 'Median')
ptile 98( max_co '98Percent')
validn( max_co( F5.0 ) 'Valid N')
mean( av_so2 'Mean')
stddev( av_so2 'Std Deviation')
minimum( av_so2 'Minimum')
maximum( av_so2 'Maximum')
median( av_so2 'Median')
ptile 98( av_so2 '98Percent')
validn( av_so2( F5.0 ) 'Valid N')
mean( min_so2 'Mean')
stddev( min_so2 'Std Deviation')
minimum( min_so2 'Minimum')
maximum( min_so2 'Maximum')
median( min_so2 'Median')
ptile 98( min_so2 '98Percent')
validn( min_so2( F5.0 ) 'Valid N')
mean( max_so2 'Mean')
stddev( max_so2 'Std Deviation')
minimum( max_so2 'Minimum')
maximum( max_so2 'Maximum')
median( max_so2 'Median')
```

```
ptile 98( max_so2 '98Percent')
validn( max_so2 'Valid N')
/TTITLE=LEFT !link  !date  " " .

*produce summary statistic tables for each SCOOT variable
TABLES
/BOXCHARS = SYSTEM
/FORMAT LIGHT VBOX FRAME SPACE BLANK MARGINS(1,110) LENGTH(1,59)
      CWIDTH(15,11,15) INDENT(2) MISSING('.') WRAPCHARS('./-') LLAYER
/OBSERVATION= stops delay flow cong raw
/GBASE=CASES
/TABLE=stops + delay + flow + cong + raw  by (statistics)
/STATISTICS
mean( stops 'Mean')
maximum( stops 'Maximum')
minimum( stops 'Minimum')
median( stops 'Median')
ptile 98( stops '98Percent')
validn( stops 'Valid N')
mean( delay 'Mean')
maximum( delay 'Maximum')
minimum( delay 'Minimum')
median( delay 'Median')
ptile 98( delay '98Percent')
validn( delay 'Valid N')
mean( flow 'Mean')
maximum( flow 'Maximum')
minimum( flow 'Minimum')
median( flow 'Median')
ptile 98( flow '98Percent')
validn( flow 'Valid N')
mean( cong 'Mean')
maximum( cong 'Maximum')
minimum( cong 'Minimum')
median( cong 'Median')
ptile 98( cong '98Percent')
validn( cong 'Valid N')
mean( raw 'Mean')
maximum( raw 'Maximum')
minimum( raw 'Minimum')
median( raw 'Median')
ptile 98( raw '98Percent')
validn( raw 'Valid N') .

* recode times to produce hourly summaries
IF (time >= '07:30:00' & time < '08:30:00') hour = 1 .
IF (time >= '08:30:00' & time < '09:30:00') hour = 2.
IF (time >= '09:30:00' & time < '10:30:00') hour = 3 .
IF (time >= '10:30:00' & time < '11:30:00') hour = 4 .
IF (time >= '11:30:00' & time < '12:30:00') hour = 5 .
IF (time >= '12:30:00' & time < '13:30:00') hour = 6 .
IF (time >= '13:30:00' & time < '14:30:00') hour = 7.
IF (time >= '14:30:00' & time < '15:30:00') hour = 8 .
IF (time >= '15:30:00' & time < '16:30:00') hour = 9 .
```

```
IF (time >= '16:30:00' & time < '17:30:00') hour = 10 .
IF (time >= '17:30:00' & time < '18:30:00') hour = 11 .
IF (time >= '18:30:00' & time < '19:30:00') hour = 12 .

execute.
formats hour (f1.0).

value labels hour 1 '07:30 - 08:25'  2 '08:30 - 09:25'  3 '09:30 - 10:25'
          4 '10:30 - 11:25'  5 '11:30 - 12:25' 6 '12:30 - 13:25'
          7 '13:30 - 14:25'  8 '14:30 - 15:25'  9 '15:30 - 16:25'
          10 '16:30 - 17:25'  11 '17:30 - 18:25' 12 '18:30 - 19:25'.

formats hour (f5.0).

!let !list = !concat(av_no2, ' ', av_co, ' ', av_so2, ' ', stops, ' ',
          delay, ' ', flow).
!do !p !in (!list).

* produce hourly summary statistics tables
 TABLES
 /BOXCHARS = SYSTEM
 /FORMAT LIGHT VBOX FRAME SPACE BLANK MARGINS(1,110) LENGTH(1,30)
    CWIDTH(15,11,15) INDENT(2) MISSING('.') WRAPCHARS('./-') LLAYER
 /OBSERVATION= !p
 /GBASE=CASES
 /TABLE=hour  BY !p
 /corner !date
 /STATISTICS
 mean( !p 'Mean')
 stddev( !p 'Std Deviation')
 minimum( !p 'Minimum')
 maximum( !p 'Maximum')
 median( !p 'Median')
 ptile 98( !p '98Percent')
 validn( !p( F5.0 ) 'Valid N') .
!doend.

*calculate correlation matrix
CORRELATIONS
 /VARIABLES=av_no2 av_co av_so2 stops delay flow
 /PRINT=TWOTAIL SIG
 /MISSING=PAIRWISE .

*produce line graphs of pollutants and SCOOT variables
GRAPH
 /LINE(MULTIPLE)= VALUE( av_no2 av_co av_so2 ) BY time
 /TITLE= !date !link.
GRAPH
 /LINE(MULTIPLE)= VALUE( stops delay flow ) BY time
 /TITLE= !date !link.

*produce scatterplots of pollutants against SCOOT variables
!let !list1 = !concat(av_no2, ' ', av_co, ' ', av_so2).
!do !v !in (!list1).
```

```
GRAPH
 /SCATTERPLOT(OVERLAY)=stops flow  WITH !v !v (PAIR)
 /MISSING=LISTWISE
 /template = !flow
 /TITLE= !date !link.
GRAPH
 /SCATTERPLOT(OVERLAY)=delay  WITH !v (PAIR)
 /template = !delay
 /MISSING=LISTWISE
 /TITLE= !date !link.
!doend.

!enddefine.

*command line
getdata file = 'c:\itemms\n0224l\260594.msp' link = 'N0224L'  date = '26/05/94'
        flow = 'c:\itemms\flow.cht' delay = 'c:\itemms\delay.cht' .
```

Written by Shirley Reynolds for the EPSRC-funded ITEMMS project June 1994.

"model.sps" Macro

```
*calculate the variables in the model from the SCOOT M02 message parameters
COMPUTE idle21r = 3600/cycle .
EXECUTE .
COMPUTE cruise21 = flow21r - stops21r .
EXECUTE .
COMPUTE acc21r = stops21r - (3600/cycle) .
EXECUTE .
COMPUTE idle31s = (flow31s * cong31s) / 900 .
EXECUTE .
COMPUTE cruise31 = (flow31s * (900 - cong31s)) / 900 .
EXECUTE .

*select data for one day
USE ALL.
COMPUTE filter_$=(date = DATE.DMY(31,03,96)).
FILTER BY filter_$.
EXECUTE .

*estimate the coefficients of the model using the REGRESSION procedure
REGRESSION
 /MISSING pairwise
 /STATISTICS COEFF OUTS R ANOVA
 /CRITERIA=PIN(.05) POUT(.10)
 /NOORIGIN
 /DEPENDENT co
 /METHOD=ENTER idle21r cruise21 acc21r idle31s cruise31
 /SAVE PRED.
CREATE
 /pre_1_1=LAG(pre_1 1).
REGRESSION
 /MISSING pairwise
 /STATISTICS COEFF OUTS R ANOVA
 /CRITERIA=PIN(.05) POUT(.10)
 /NOORIGIN
 /DEPENDENT co
 /METHOD=ENTER idle21r cruise21 acc21r idle31s cruise31 pre_1_1
 /SAVE PRED.
CREATE
 /pre_2_1=LAG(pre_2 1).
REGRESSION
 /MISSING pairwise
 /STATISTICS COEFF OUTS R ANOVA
 /CRITERIA=PIN(.05) POUT(.10)
 /NOORIGIN
 /DEPENDENT co
 /METHOD=ENTER idle21r cruise21 acc21r idle31s cruise31 pre_1_1 pre_2_1
 /residuals=durbin
 /SAVE PRED RESID.

**Written by Shirley Reynolds for the EPSRC-funded ITEMMS project March 1996.**
```

APPENDIX 4

MSPD DATA TABLES

Five minute averages of MSPD variables on link N0215J 17/12/93 to 16/3/94 (maximum count = 52)

time	Avg Of STOPS	Avg Of DELAY	Avg Of FLOW	Avg Of av_no2	Avg Of av_co	Avg Of av_so2	Count
07:30:00	358.947	20.842	534.553	0.022	1.003	-0.114	38
07:35:00	460.675	26.825	653.050	0.021	1.608	-0.103	40
07:40:00	582.500	34.800	784.675	0.021	1.865	-0.098	40
07:45:00	746.400	44.525	923.925	0.020	2.231	-0.093	40
07:50:00	788.821	48.923	968.846	0.021	2.464	-0.089	39
07:55:00	784.625	47.025	942.450	0.021	2.282	-0.091	40
08:00:00	750.659	47.098	927.049	0.020	2.541	-0.088	41
08:05:00	796.293	50.732	971.415	0.020	2.813	-0.085	41
08:10:00	923.122	62.122	1041.317	0.020	3.075	-0.079	41
08:15:00	939.707	69.683	1071.463	0.018	3.279	-0.078	41
08:20:00	1012.073	82.927	1129.463	0.017	3.724	-0.072	41
08:25:00	1030.000	92.049	1150.805	0.016	3.431	-0.075	41
08:30:00	1024.714	104.619	1153.857	0.015	3.238	-0.081	42
08:35:00	1038.857	117.024	1145.333	0.013	3.270	-0.079	42
08:40:00	1114.182	122.136	1214.250	0.013	3.770	-0.073	44
08:45:00	1197.196	142.870	1288.022	0.011	3.579	-0.072	46
08:50:00	1153.109	142.130	1265.043	0.012	3.824	-0.068	46
08:55:00	1169.000	141.326	1259.696	0.011	3.661	-0.071	46
09:00:00	1077.977	142.932	1172.000	0.009	3.563	-0.072	44
09:05:00	1002.159	126.182	1119.750	0.009	3.558	-0.070	44
09:10:00	874.273	84.205	1047.545	0.008	3.245	-0.069	44
09:15:00	796.349	71.674	987.930	0.009	2.914	-0.077	43
09:20:00	723.864	59.045	942.841	0.008	2.597	-0.078	44
09:25:00	756.512	55.767	956.907	0.009	2.367	-0.079	43
09:30:00	655.444	45.289	873.489	0.009	1.926	-0.085	45
09:35:00	694.217	46.891	895.804	0.007	2.027	-0.085	46
09:40:00	632.217	39.478	877.370	0.006	1.712	-0.087	46
09:45:00	715.413	44.957	914.022	0.005	1.762	-0.086	46
09:50:00	675.563	42.896	874.292	0.001	1.721	-0.087	48
09:55:00	671.347	39.878	900.265	0.001	1.641	-0.089	49
10:00:00	657.788	39.096	874.000	-0.005	1.646	-0.087	52
10:05:00	607.784	34.294	852.020	-0.006	1.575	-0.089	51
10:10:00	656.373	38.176	863.490	-0.007	1.574	-0.089	51
10:15:00	662.647	38.078	847.059	-0.009	1.618	-0.084	51
10:20:00	714.725	41.412	917.235	-0.011	1.687	-0.084	51
10:25:00	706.854	41.313	907.542	-0.012	1.621	-0.084	48
10:30:00	664.143	37.327	852.796	-0.016	1.500	-0.087	49
10:35:00	643.571	36.694	840.633	-0.017	1.575	-0.086	49
10:40:00	610.021	36.542	804.188	-0.015	1.490	-0.085	48
10:45:00	623.708	36.854	822.104	-0.016	1.508	-0.085	48
10:50:00	653.896	38.604	858.854	-0.018	1.387	-0.086	48
10:55:00	648.146	37.646	839.083	-0.023	1.504	-0.081	48
11:00:00	605.674	35.130	798.239	-0.020	1.660	-0.077	46
11:05:00	612.711	35.622	822.000	-0.024	1.499	-0.078	45
11:10:00	598.087	35.239	782.739	-0.027	1.426	-0.078	46
11:15:00	623.149	37.362	821.787	-0.028	1.659	-0.073	47
11:20:00	674.826	40.109	857.935	-0.033	1.720	-0.067	46

time	Avg Of STOPS	Avg Of DELAY	Avg Of FLOW	Avg Of av_no2	Avg Of av_co	Avg Of av_so2	Count
11:25:00	634.729	37.083	824.542	-0.034	1.573	-0.069	48
11:30:00	616.880	36.160	803.920	-0.038	1.616	-0.070	50
11:35:00	623.200	37.080	813.880	-0.039	1.528	-0.068	50
11:40:00	645.098	38.471	832.196	-0.036	1.590	-0.063	51
11:45:00	675.923	39.154	864.923	-0.037	1.566	-0.064	52
11:50:00	665.077	39.250	859.615	-0.038	1.706	-0.059	52
11:55:00	668.500	42.423	843.635	-0.041	1.671	-0.057	52
12:00:00	631.840	38.620	832.500	-0.044	1.520	-0.059	50
12:05:00	676.769	42.577	845.231	-0.043	1.711	-0.053	52
12:10:00	644.750	39.808	823.808	-0.043	1.955	-0.047	52
12:15:00	662.385	40.712	850.385	-0.044	1.807	-0.047	52
12:20:00	700.673	42.577	870.962	-0.044	2.017	-0.043	52
12:25:00	680.824	40.510	861.157	-0.043	1.942	-0.042	51
12:30:00	647.392	39.098	819.667	-0.044	2.057	-0.040	51
12:35:00	631.020	38.078	804.490	-0.044	1.829	-0.041	51
12:40:00	653.294	39.804	824.176	-0.044	1.722	-0.041	51
12:45:00	684.192	43.000	851.769	-0.043	1.836	-0.040	52
12:50:00	655.808	40.327	834.192	-0.042	1.897	-0.037	52
12:55:00	710.135	44.962	876.673	-0.043	2.013	-0.035	52
13:00:00	663.750	41.154	835.885	-0.041	2.172	-0.031	52
13:05:00	704.942	42.250	869.346	-0.040	2.037	-0.033	52
13:10:00	666.788	40.212	837.904	-0.040	2.012	-0.032	52
13:15:00	649.615	39.654	823.019	-0.039	1.842	-0.034	52
13:20:00	701.569	43.980	865.863	-0.038	1.911	-0.032	51
13:25:00	753.196	44.745	930.549	-0.037	1.781	-0.033	51
13:30:00	685.255	39.255	869.471	-0.036	1.779	-0.033	51
13:35:00	673.863	42.706	878.824	-0.035	1.786	-0.033	51
13:40:00	768.240	47.680	946.580	-0.032	1.868	-0.032	50
13:45:00	778.163	47.592	976.449	-0.030	1.856	-0.035	49
13:50:00	875.592	57.000	1038.653	-0.029	1.999	-0.034	49
13:55:00	802.286	48.612	980.531	-0.028	2.013	-0.034	49
14:00:00	781.360	47.720	966.040	-0.025	1.918	-0.033	50
14:05:00	739.451	44.882	914.961	-0.022	2.046	-0.029	51
14:10:00	724.118	45.510	899.353	-0.019	1.911	-0.033	51
14:15:00	753.686	46.922	913.412	-0.017	1.927	-0.033	51
14:20:00	747.520	48.300	913.560	-0.017	1.911	-0.030	50
14:25:00	695.490	44.373	880.000	-0.016	1.813	-0.035	51
14:30:00	660.440	43.260	849.620	-0.015	1.654	-0.040	50
14:35:00	643.673	42.061	835.653	-0.014	1.765	-0.038	49
14:40:00	650.620	40.960	825.260	-0.012	1.800	-0.039	50
14:45:00	638.100	39.040	813.840	-0.011	1.690	-0.039	50
14:50:00	637.404	40.096	810.635	-0.009	1.695	-0.040	52
14:55:00	585.115	37.673	761.808	-0.009	1.672	-0.041	52
15:00:00	601.481	36.231	783.212	-0.008	1.734	-0.040	52
15:05:00	587.615	36.077	753.885	-0.007	1.802	-0.040	52
15:10:00	577.627	36.176	756.451	-0.006	1.883	-0.039	51
15:15:00	535.922	32.804	711.353	-0.004	1.649	-0.043	51
15:20:00	598.102	36.408	757.306	-0.002	1.874	-0.043	49
15:25:00	606.489	36.723	782.447	0.001	1.996	-0.042	47
15:30:00	593.213	36.468	763.936	0.001	1.766	-0.046	47
15:35:00	630.479	38.646	798.625	0.003	1.971	-0.043	48

time	Avg Of STOPS	Avg Of DELAY	Avg Of FLOW	Avg Of av_no2	Avg Of av_co	Avg Of av_so2	Count
15:40:00	616.021	37.625	788.958	0.005	2.154	-0.042	48
15:45:00	624.383	36.936	799.723	0.005	2.108	-0.040	47
15:50:00	659.872	40.255	819.043	0.006	2.113	-0.041	47
15:55:00	642.340	39.787	799.745	0.007	2.093	-0.042	47
16:00:00	607.000	37.333	755.042	0.008	2.117	-0.041	48
16:05:00	585.000	37.979	723.417	0.009	2.273	-0.040	48
16:10:00	563.833	36.333	704.229	0.010	2.235	-0.040	48
16:15:00	549.417	35.417	700.646	0.011	2.199	-0.041	48
16:20:00	547.500	37.229	694.563	0.011	2.394	-0.040	48
16:25:00	549.061	37.714	697.490	0.014	2.265	-0.040	49
16:30:00	525.061	36.571	680.245	0.014	2.356	-0.039	49
16:35:00	491.447	34.851	629.489	0.015	2.296	-0.040	47
16:40:00	547.085	40.574	686.915	0.015	2.735	-0.035	47
16:45:00	516.875	39.938	670.167	0.017	2.392	-0.039	48
16:50:00	545.667	41.000	701.563	0.018	2.440	-0.040	48
16:55:00	538.327	42.918	693.816	0.021	2.552	-0.038	49
17:00:00	536.688	40.917	687.188	0.021	2.718	-0.034	48
17:05:00	542.438	43.042	673.021	0.022	3.305	-0.028	48
17:10:00	493.277	38.660	644.638	0.023	2.922	-0.030	47
17:15:00	506.178	41.111	645.356	0.025	3.121	-0.027	45
17:20:00	505.413	39.043	659.022	0.024	3.134	-0.029	46
17:25:00	442.319	34.702	600.064	0.025	2.747	-0.032	47
17:30:00	469.170	36.234	612.255	0.026	2.694	-0.031	47
17:35:00	463.957	35.426	608.085	0.026	2.913	-0.032	47
17:40:00	445.447	34.191	603.979	0.027	2.929	-0.032	47
17:45:00	504.826	38.239	649.217	0.028	2.737	-0.038	46
17:50:00	445.851	34.277	609.872	0.028	2.776	-0.035	47
17:55:00	415.660	31.319	578.234	0.029	2.702	-0.034	47
18:00:00	410.340	30.617	576.723	0.030	2.400	-0.039	47
18:05:00	410.065	28.109	564.391	0.031	2.381	-0.039	46
18:10:00	417.957	29.522	564.543	0.031	2.366	-0.038	46
18:15:00	399.391	25.913	549.413	0.032	2.079	-0.044	46
18:20:00	400.578	24.867	554.511	0.032	1.936	-0.047	45
18:25:00	400.891	24.848	534.478	0.032	1.871	-0.048	46
18:30:00	385.370	23.696	516.674	0.033	1.830	-0.048	46
18:35:00	431.152	26.413	576.087	0.033	1.787	-0.050	46
18:40:00	423.543	25.500	576.978	0.033	1.793	-0.049	46
18:45:00	454.826	29.065	609.370	0.033	1.787	-0.052	46
18:50:00	479.761	29.087	647.304	0.033	2.269	-0.046	46
18:55:00	543.021	32.234	710.362	0.033	1.837	-0.052	47
19:00:00	502.000	29.065	670.609	0.033	1.849	-0.052	46
19:05:00	533.304	30.457	689.978	0.033	1.912	-0.053	46
19:10:00	508.745	27.723	675.745	0.033	1.919	-0.053	47
19:15:00	535.553	29.298	703.596	0.034	1.876	-0.054	47
19:20:00	494.128	27.149	656.298	0.033	1.785	-0.056	47
19:25:00	454.455	25.591	614.318	0.032	1.628	-0.059	44
19:30:00	484.435	26.261	630.696	0.034	1.926	-0.064	23

APPENDIX 5

RESULTS FROM SEMI-EMPIRICAL MODEL

Date	Day	R^2	F	sig F	idle21r	cruise21	acc21r	idle31s	cruise31s	$pre_{(t-2)}$	$pre_{(t-1)}$	const	n	DW	d_L	d_U
01/03/96	Fri	0.8737	10.8735	0.0004	0.1986	0.0046	0.0034	-0.0013	-0.0020	0.0463	0.7375	-11.9940	19	2.2046	0.75	2.02
				sig t	0.0040	0.0356	0.1908	0.4963	0.1935	0.8897	0.0337	0.0066				
02/03/96	Sat	0.3585	4.6572	0.0008	0.0574	-0.0019	-0.0017	0.0025	0.0049		-0.0327	-1.0525	57	1.2425	1.38	1.77
				sig t	0.3124	0.1777	0.2335	0.3431	0.0002		0.9180	0.7983				
03/03/96	Sun	0.7562	32.5714	0.0000	0.0380	0.0032	0.0036	0.0007	0.0016		0.1592	-1.7945	70	1.4415	1.46	1.77
				sig t	0.0782	0.0000	0.0009	0.5595	0.0448		0.3306	0.1866				
04/03/96	Mon	0.2787	1.6741	0.1673	0.0325		0.0025	0.0032	0.0008	-0.5006	0.0714	2.1433	33	1.4342	1.13	1.81
				sig t	0.5831		0.0312	0.2722	0.2881	0.2035	0.2592	0.5019				
05/03/96	Tues	0.6136	13.1593	0.0000	-0.0826	0.0004	-0.0007	0.0026	0.0007	0.2510	0.4081	5.3052	66	1.3862	1.44	1.77
				sig t	0.0861	0.6512	0.5962	0.4995	0.4241	0.5608	0.2467	0.1260				
06/03/96	Wed	0.5963	13.0807	0.0000	-0.0287	0.0031	0.0049	0.0048	0.0013	0.0729	0.6862	-1.1430	70	1.2218	1.46	1.77
				sig t	0.5220	0.0330	0.0034	0.0210	0.2122	0.8220	0.0183	0.6815				
07/03/96	Thurs	0.5454	10.6252	0.0000	0.0376	0.0041	0.0051	0.0030	0.0023	-0.1800	0.5659	-4.4872	70	2.1574	1.46	1.77
				sig t	0.1554	0.0000	0.0000	0.0090	0.0001	0.6788	0.1905	0.0075				
08/03/96	Fri	0.3507	4.7834	0.0002	0.0034	0.0018	0.0038	0.0016	0.0009	1.7247	-1.7973	1.1460	70	2.2221	1.46	1.77
				sig t	0.8901	0.0076	0.0000	0.2319	0.0428	0.5196	0.5002	0.4656				
09/03/96	Sat	0.6220	17.2802	0.0000	-0.1092	0.0036	0.0071	0.0009	0.0051		0.0458	7.1602	70	1.9377	1.46	1.77
				sig t	0.2316	0.0742	0.0007	0.8349	0.0259		0.8206	0.2746				
10/03/96	Sun	0.4740	7.9828	0.0000	-0.2378	0.0040	0.0097	-0.0033	0.0000	-1.0687	0.8504	16.5680	70	1.6452	1.46	1.77
				sig t	0.0036	0.0673	0.0004	0.5152	0.9899	0.4620	0.5420	0.0013				
11/03/96	Mon	0.4392	6.9353	0.0000	-0.0400	0.0039	0.0064	0.0077	0.0051	-3.5026	3.8210	0.1660	70	1.5436	1.46	1.77
				sig t	0.5813	0.0728	0.0082	0.0878	0.0341	0.0051	0.0023	0.9681				
12/03/96	Tues	0.4523	7.3129	0.0000	-0.0018	0.0018	0.0045	0.0076	0.0021	1.0452	-0.1929	-2.2236	70	1.5786	1.46	1.77
				sig t	0.9637	0.2205	0.0205	0.1504	0.1393	0.0166	0.5434	0.4293				
13/03/96	Wed	0.3176	4.8869	0.0004	-0.0647	0.0013	0.0037	-0.0008	0.0017		-0.0584	5.6203	70	2.2304	1.46	1.77
				sig t	0.1232	0.2161	0.0037	0.7722	0.0401		0.8300	0.0718				

Date	Day	R^2	F	sig F	idle21r	cruise21	acc21r	idle31s	cruise31s	$pre_{(t-2)}$	$pre_{(t-1)}$	const	n	DW	d_L	d_U
14/03/96	Thurs	0.1638	1.7351	0.1172	0.0613	-0.0001	0.0022	0.0008	0.0002	-0.8007	0.4388	1.6882	70	1.4117	1.46	1.77
				sig t	0.0716	0.9104	0.0612	0.5960	0.7514	0.4616	0.6715	0.4779				
15/03/96	Fri	0.3996	5.6569	0.0001	0.0464	0.0005	0.0024	0.0039	0.0020		0.1728	-0.9766	58	1.4022	1.40	1.77
				sig t	0.1421	0.6768	0.0786	0.1221	0.0173		0.5048	0.6661				
16/03/96	Sat	0.7559	10.3221	0.0000	0.2080	0.0047	0.0060	-0.0008	0.0033		-0.0191	-12.1575	27	0.9984	1.01	1.86
				sig t	0.0002	0.0028	0.0008	0.9234	0.0094		0.9183	0.0012				
17/03/96	Sun	0.4949	15.9202	0.0000				0.0805	0.0286	-34.5205	32.6192	0.5304	70	1.3555	1.46	1.77
				sig t				0.0074	0.0000	0.0000	0.0000	0.6585				
18/03/96	Mon	0.3496	3.6089	0.0034	0.1437	-0.0045	-0.0049	0.0079	0.0034	0.1039	0.4085	-4.5544	55	1.2179	1.38	1.77
				sig t	0.0624	0.1266	0.1322	0.4832	0.2622	0.8958	0.5649	0.3435				
19/03/96	Tues	0.1981	2.5932	0.0261	-0.0077	0.0038	0.0050	0.0037	0.0034		0.0049	0.6255	70	1.2572	1.46	1.77
				sig t	0.8705	0.0238	0.0056	0.4304	0.0147		0.9886	0.8634				
20/03/96	Wed	0.4774	8.0898	0.0000	-0.0411	0.0031	0.0050	0.0086	0.0007	0.3070	0.2530	0.5735	70	1.8078	1.46	1.77
				sig t	0.2068	0.0035	0.0000	0.4803	0.4063	0.3699	0.4481	0.7870				
21/03/96	Thurs	0.2457	3.4194	0.0055	-0.0254	0.0023	0.0052	0.0090	-0.0003		-0.0144	4.3382	70	1.6524	1.46	1.77
				sig t	0.5436	0.0274	0.0002	0.0644	0.7845		0.9517	0.1243				
22/03/96	Fri	0.7649	5.1120	0.0085	0.0865	0.0029	0.0067	0.9251	0.0003	0.8025	0.1328	-7.6073	19	1.2684	0.75	2.02
				sig t	0.2505	0.3135	0.0194	0.0712	0.9217	0.1570	0.7215	0.2028				
23/03/96	Sat															
24/03/96	Sun															
25/03/96	Mon	0.4956	8.1411	0.0000	-0.0118	0.0020	0.3005	0.0087	0.0005	0.1400	0.2835	0.3443	66	1.6748	1.44	1.77
				sig t	0.5902	0.0174	0.0010	0.0172	0.4523	0.7775	0.5497	0.8145				
26/03/96	Tues	0.4290	6.6537	0.0000	-0.0114	0.0017	0.0039	0.0098	0.0006	-0.2929	0.5466	0.8915	70	1.9032	1.46	1.77
				sig t	0.5676	0.0210	0.0000	0.0100	0.4101	0.7205	0.5046	0.5691				
27/03/96	Wed	0.1571	1.6501	0.1383	-0.0396	0.0011	0.0039	0.0002	0.0005	-2.1182	2.3938	3.3690	70	1.6130	1.46	1.77
				sig t	0.4258	0.4964	0.0495	0.9420	0.6443	0.1683	0.0997	0.4267				

Date	Day	R^2	F	sig F	idle21r	cruise21	acc21r	idle31s	cruise31s	$pre_{(t-2)}$	$pre_{(t-1)}$	const	n	DW	d_L	d_U
28/03/96	Thurs	0.5394	10.3742	0.0000	-0.0546	0.0008	0.0006	0.0007	-0.0002	0.1777	0.8635	2.1878	70	1.7102	1.46	1.77
				sig t	0.2603	0.4678	0.6613	0.6705	0.8487	0.6783	0.0045	0.4791				
29/03/96	Fri	0.4023	5.2882	0.0001	-0.0706	-0.0010	0.0022	-0.0018	-0.0002	-1.2102	1.6106	5.5576	63	1.5860	1.41	1.77
				sig t	0.1785	0.4550	0.1707	0.4096	0.8084	0.0818	0.0161	0.1070				
30/03/96	Sat															
31/03/96	Sun	0.3438	2.1710	0.0671	0.1104	0.0005	0.0016	-0.6896	0.0029	1.2820	-0.1731	-8.3073	37	1.9699	1.19	1.80
				sig t	0.5704	0.9057	0.7944	0.3413	0.4584	0.0211	0.6566	0.5034				