Environmental RTDI Programme 2000-2006

Validation of air pollution dispersion modelling for the road transport sector under Irish conditions (2000-LS-6.3-M1)

FINAL REPORT

Prepared for the Environmental Protection Agency
by
Trinity College Dublin and NUI Galway

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The project was undertaken by the Department of Civil, Structural and Environmental Engineering in Trinity College Dublin (TCD) and the Air Quality Technology Centre at the National University of Ireland, Galway (NUIG). The project leader was Bruce Misstear (TCD) assisted by Dr Brian Broderick (TCD) and Professor Gerard Jennings (NUIG). The monitoring at the Leixlip and Galway sites was overseen by Una Budd (TCD) and Darius Ceburnis (NUIG), respectively. Una Budd undertook the majority of the dispersion modelling. Other members of the project team included Anne Desmond (TCD), Roland O'Donoghue (TCD) and Carsten Junker (NUIG). The project co-ordinator for the Agency was Dr Frank McGovern.

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Contents

ACRONYMS AND NOTATION

AAVF	Annual Average Vehicle Flow
API	Advanced Pollution Instrumentation
CEC	Council of the European Union
CERC	Cambridge Environmental Research Consultants Ltd
CO	carbon monoxide
CO_2	carbon dioxide
COPERT	Computer Programme to calculate Emissions from Road Transport
CPC	condensation particle counter
DETR	Department of the Environment, Transport and the Regions (UK)
DMRB	Design Manual for Roads and Bridges
DoELG	Department of the Environment and Local Government
EFD	Emission Factor Database
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
EU	European Union
FAC2	Factor of two
FB	Fractional bias
FS	Fractional variance
HC	hydrocarbon(s)
HDV	heavy duty vehicle
HGV	heavy goods vehicle
IR	infrared
km	kilometre(s)
kph	kilometres per hour
LAT	Lower Assessment Threshold (cf. UAT)
m	metre(s)
mph	miles per hour
NMSE	normalised mean square error
NO	nitric oxide
NO_x	oxides of nitrogen
NO_2	nitrogen dioxide
NRA	National Roads Authority
NUIG	National University of Ireland, Galway
PSC	Pasquill Stability Class
PM	Particulate matter
R	Pearson correlation coefficient
SO_2	sulphur dioxide
TCD	Trinity College Dublin
TEOM	Tapered Element Oscillating Microbalance
TRL	Transport Research Laboratory, formerly the TRRL
TRRL	Transport and Road Research Laboratory, now named TRL
UAT	Upper Assessment Threshold (cf. LAT)
UCC	University College Cork
vph	vehicles per hour

1 Introduction

1.1 Background

Ambient air quality measurements in Ireland are determined on the basis of the European Union framework directive on ambient air quality assessment and management (CEC 1996, McGettigan 2001). The directive and its daughter directives outline the monitoring, modelling and objective assessment activities to be performed in areas of different air quality.

The daughter directives define limit values and upper and lower assessment threshold values for each pollutant, including carbon monoxide, nitrogen oxides, particulate matter and benzene, which are all components of traffic emissions. While the limit values are of most relevance in assessing air quality compliance, it is the assessment threshold values that determine the extent to which both monitoring and modelling need to be performed. In particular, when ambient concentrations exceed the lower assessment threshold level, at least some monitoring is required. Below this level, modelling or objective estimation techniques alone suffice. It is clear, therefore, that there is a need for reliable atmospheric dispersion modelling techniques for all sectors, including road transport, to meet ambient air quality monitoring obligations.

In addition to its role within a national air quality monitoring strategy, air dispersion modelling also forms a key element of Environmental Impact Assessment studies for dual carriageway and motorway projects in Ireland. Numerical models are used to predict the impacts on ambient air quality that might arise from the construction of these roads. Most of these models simulate non-reactive pollutants such as carbon monoxide, although some incorporate chemical reactions such as the photochemical transformation of nitrogen oxides. The models in most common use in Ireland originate from the USA and the UK. They are applied here using Irish meteorological data (generally from regional stations rather than from the site itself), UK or European Environment Agency vehicle emissions databases and predictions of future traffic flows.

This project represents the first systematic attempt to validate the use of these models under Irish conditions. It was carried out under the Environmental Research Technological Development and Innovation Programme funded by the National Development Plan 2000-2006. Labelled project 2000-LS-6.3-M1, it formed the third of four projects that made up the large-scale integrated project 2000-LS-6-M1 entitled “Air Quality - Transport Impacts and Monitoring Networks”.

1.2 Project Objectives

The aim of this project was to carry out a validation study of models that are currently used in Ireland to determine the levels of emission to air from road transport sources and to predict their impacts and dispersion patterns. The specific objectives identified at the outset of the project were to:

- assess the utility of current air pollution dispersion models in determining the impacts on ambient air quality of emissions arising from road traffic on national primary routes;
- generate new air quality data for improved management of the environment, through the measurement of ambient air quality levels in the vicinity of dual carriageway or motorway sections of national primary routes;
- validate predictions of selected air pollution models using comprehensive roadside measurements of air quality, meteorological conditions and traffic flows;
- develop recommendations on the applications of these models in Irish conditions, with particular emphasis on national primary routes;
- make recommendations with regard to optimum model selection and measurement of specified key air emission species for the future.

1.3 Project Tasks and Work Programme

The main project tasks were as follows:

Task 1 Review of available models.
Task 2 Definition of standards for validation of models.
Task 3 Selection of monitoring sites.
Task 4 Monitoring of air quality, traffic and meteorological conditions.
Task 5 Compilation of databases for the model validation study, and development of recommendations on dispersion modelling in Ireland.

The project commenced in December 2000. Tasks 1 and 2 were substantially completed in May 2001 with the submission of the draft Literature Review. The draft Literature Review was updated and revised at the end of the study (see Section 1.4 below for details of this report).

Task 3 was completed in May 2001 with the selection of two monitoring sites, one beside the M4 motorway at Leixlip and the other alongside the N6 dual carriageway in Galway. Air quality monitoring (Task 4) was carried out at these two locations over a 16-month period between May 2001 and September 2002.

The data analysis and modelling activities (Task 5) were undertaken throughout the project up to the submission of this project report. Additional hydrocarbon studies were carried out at the end of the project, and the results are included in an Addendum to this Final Report.

1.4 Literature Review

The Literature Review (Broderick *et al.*, 2004a) is available as a companion document to this Main Report. It contains:

- a description of the emissions from road transport;

- a review of the dispersion models currently available that are suitable for emissions from road transport sources;
- a summary of previous model validation studies, both national and international;
- a review of the air dispersion models used in Environmental Impact Assessments for road schemes in Ireland between 1989 and 1999;
- recommendations on the models that were to be used in this project.

1.5 Monitoring Studies

The air quality monitoring studies were carried out at two sites to represent two contrasting situations. The site near the M4 motorway at Leixlip was chosen to investigate air pollution where the traffic was free-flowing. The N6 site in Galway was located adjacent to a roundabout and therefore represented a situation with interrupted traffic flow. The Leixlip and Galway sites also differed in their meteorological conditions, being located in the east and west of Ireland, respectively.

The air pollutants monitored at both sites were carbon monoxide, nitrogen oxides and particulates. At Leixlip, a number of hydrocarbons associated with vehicle emissions were also monitored, including benzene, ethyl benzene, xylene and toluene. At Galway condensation particles were counted. In addition to air quality, meteorological variables such as wind speed and wind direction were recorded at the two sites. The National Roads Authority (NRA) provided traffic flow data for the N4 near Leixlip throughout the monitoring period. At the Galway roundabout, Abacus Transportation Surveys carried out a one-day detailed traffic survey for this project. Also, the NRA was able to provide one month of continuous traffic flow data for the N6 at the Galway roundabout.

1.6 Dispersion Modelling and Model Validation

Atmospheric dispersion modelling was undertaken for the two sites. At Leixlip, the models used were the UK Department of the Environment, Transport and the Regions (UK DETR) Design Manual for Roads and Bridges model (DMRB, 1994; DMRB, 2000) and the US Environmental Protection Agency (US EPA) model CALINE4 (Benson, 1992; US EPA www.epa.gov/scram001/). For the roundabout site in Galway, the US EPA model CAL3QHCR was applied during the validation exercise, in addition to the DMRB model. A comparison of the performance of the simpler DMRB model with that of the more complex US EPA models was carried out, by comparing model predictions with measured concentrations. The main characteristics of all of these models were identified and the effect of employing different emission factors and meteorological conditions was assessed by comparing the results of multiple model runs.

A model validation exercise was completed in which the project partners and three consulting firms (AWN Consulting, Envirocon Ltd and Cambridge Environmental Consultants Ltd (CERC)) - who regularly perform dispersion modelling - each produced model predictions of air quality for the first six months of the monitoring period at both

sites. These predictions were then compared with the measured data. A workshop on the model validation studies was held at TCD on 16th October 2002.

1.7 Layout of Report

The findings of the project are presented in three volumes. This first volume is the Final Report and contains a description of the research and the results obtained; there is also an Addendum containing the results of additional hydrocarbon studies (O'Donoghue *et al.*, 2005). The second volume comprises the Literature Review (Broderick *et al.*, 2005a) described in Section 1.4, while the third volume is the Synthesis Report (Broderick *et al.*, 2005b).

The next three sections of this Main Report present the monitoring results. The study sites are described in Chapter 2, and the results obtained for the M4 site at Leixlip and the N6 site in Galway are included in Chapters 3 and 4, respectively. Additional data for these chapters are presented in Appendices A, B and C.

The results of the dispersion modelling at both sites are given in Chapter 5, while the model validation and evaluation are described in Chapter 6. Additional data for Chapter 5 are presented in Appendix D.

The conclusions of the project are presented in Chapter 7, along with recommendations for further research.

2 Description of Study Sites

2.1 Site Selection

The project brief (Section 1.2) required that air quality monitoring should be carried out in the vicinity of dual carriageway or motorway sections of national primary routes. As explained in Section 1.5, the broad strategy adopted for site selection was to identify one monitoring site with relatively free-flowing traffic and a second site with congested, interrupted-flow traffic conditions.

The following specific criteria were also used in the site selection:

a) The traffic flows and therefore emissions should be sufficiently high to provide a source effect capable of being monitored.
b) The traffic flows should be quantifiable.
c) It should be possible to position the monitoring equipment close to the side of the road downwind of the prevailing wind direction.
d) There should be no buildings or other large structures between the road and the monitoring unit.
e) There must be a power supply and reasonable security for the equipment.
f) Permission to locate the equipment should be available from the site owners.
g) The sites should be easily accessible to the project partners based in Dublin and Galway, to facilitate regular checking and maintenance of equipment and downloading of data.

To select the site where it was intended to monitor free-flowing traffic, a survey was carried out along the National Route roads and motorways radiating from Dublin. A suitable location was identified along the M4 motorway about 15 km west of Dublin city centre, within the grounds of the Leixlip Water Treatment Works (Figures 2.1 to 2.4). This location met all the requirements noted above and had the major advantage that continuous traffic flow data were available from the National Roads Authority.

The second monitoring site was chosen alongside the N6 in Galway, close to a major roundabout (Figures 2.5 to 2.8). This also satisfied the desired site selection criteria except that traffic flow data were not available and therefore would have to be collected during the project.

In terms of modelling, the two sites presented different challenges. The M4 motorway represents a classical modelling situation – a single line source with simple, well-defined traffic conditions. In contrast, the N6 roundabout represents a more complex situation – a number of distinct line sources with variable traffic conditions, including queues.

2.2 The M4 Motorway Site at Leixlip

The M4 motorway at Leixlip has two lanes in each direction, running almost due east-west. The NRA's automatic traffic counter on this section of the M4 showed a peak traffic flow for an average weekday of 2690 vehicles per hour (vph; see Section 3.2). The prevailing wind direction measured at Dublin Airport (18 km northeast of the site) is from the southwest, and therefore emissions from the roadway were expected to influence concentrations at the monitoring unit which was sited to the north of the motorway. The monitoring unit was located at a distance of 20 m from the nearest kerbside, as shown in Figures 2.1 and 2.4. The road alignment is straight for a distance of 1.25 km to both the east and west of the monitoring location. Typically, vehicle speeds are in the range 60-70 mph.

Figure 2.1: Monitoring site by the M4 motorway at Leixlip (view north). The unit is the white caravan at the south western corner of the group of buildings in the centre of the aerial photograph, which appeared in Volume 3 (Summer 2002) of Base Magazine.

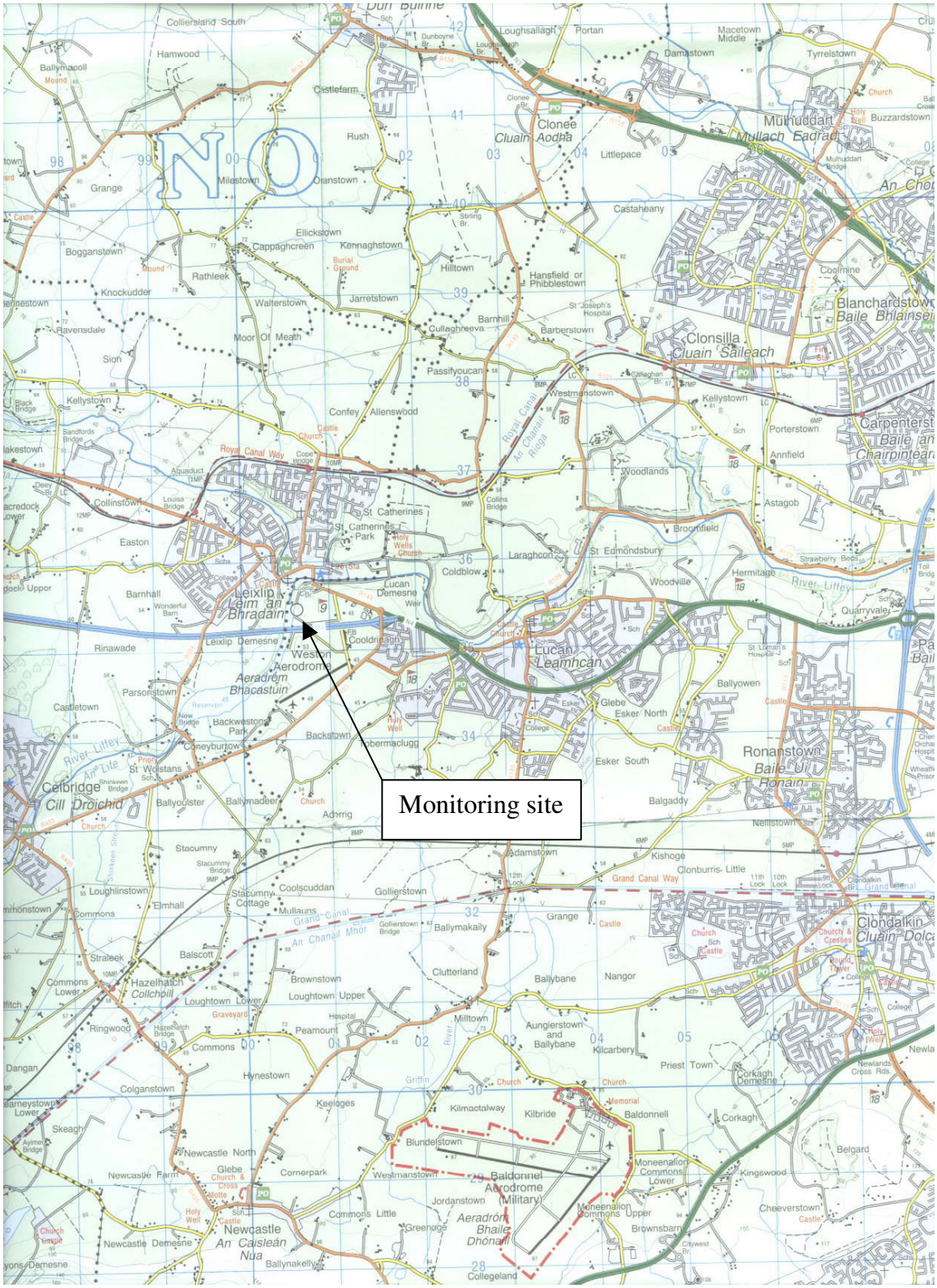


Figure 2.2: Location of monitoring site on M4 at Leixlip

Figure 2.3a): Leixlip site (view east south east) and 2.3b): interior of monitoring unit.

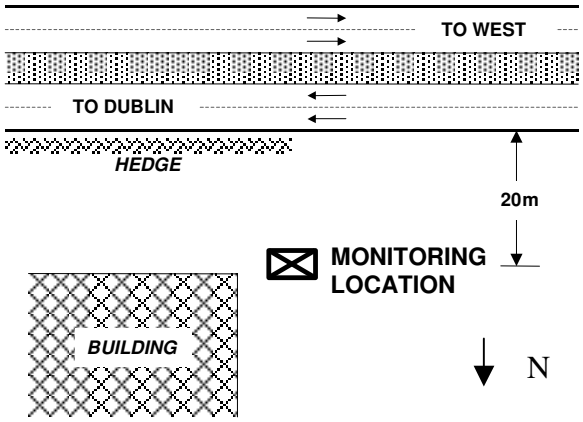


Figure 2.4: Location of monitoring unit by the M4 at Leixlip

Fingal County Council gave permission to locate the monitor within the site of the water treatment works and also provided the power supply.

There is a small aerodrome immediately to the south of the M4 and the town of Leixlip is centred about 1 km to the north of the site. Meteorological data were available from Casement Aerodrome and Dublin Airport for comparison with data recorded at the site (Section 3.3).

A second NO_x analyser was calibrated against the first analyser, from 13th March to 16th May 2002, in the monitoring unit. It was then moved to the south of the M4, approximately 500 m to the east south east of the unit, where monitoring continued until 15th September 2002. Comparisons between the data from the two NO_x analysers are given in Appendix A.

2.3 The N6 Roundabout Site in Galway

The air pollutant monitoring instrumentation was located beside the N6 in Galway, adjacent to the Headford Road roundabout (Figure 2.6). The roundabout is the second busiest roundabout in Galway city with the total number of cars peaking at 3900 vph (see Section 4.2). There are five arms to the roundabout, the three main ones being the N6 Dublin Road to the east, the N84 Headford Road to the north-northeast and the N6 road towards Galway city centre to the south-southwest. Both N6 arms are dual carriageways. The detailed layout of the road network at the roundabout is shown in Figure 2.7. The monitoring unit was located 15 m from the southern kerb of the Dublin Road arm, about 25 m from the roundabout.

Permission for the monitoring site was given by Galway Corporation, and Barry Motors supplied the power.

The nearest source of regional meteorological data was Shannon airport, 70 km to the south. Some meteorological data were also available from the NUI Galway campus, about 2 km southwest of the site, and these data were also used for comparison with site data (see Section 4.3).

Figure 2.5a): Galway monitoring unit and 2.5b): view south from Dublin N6 road centre

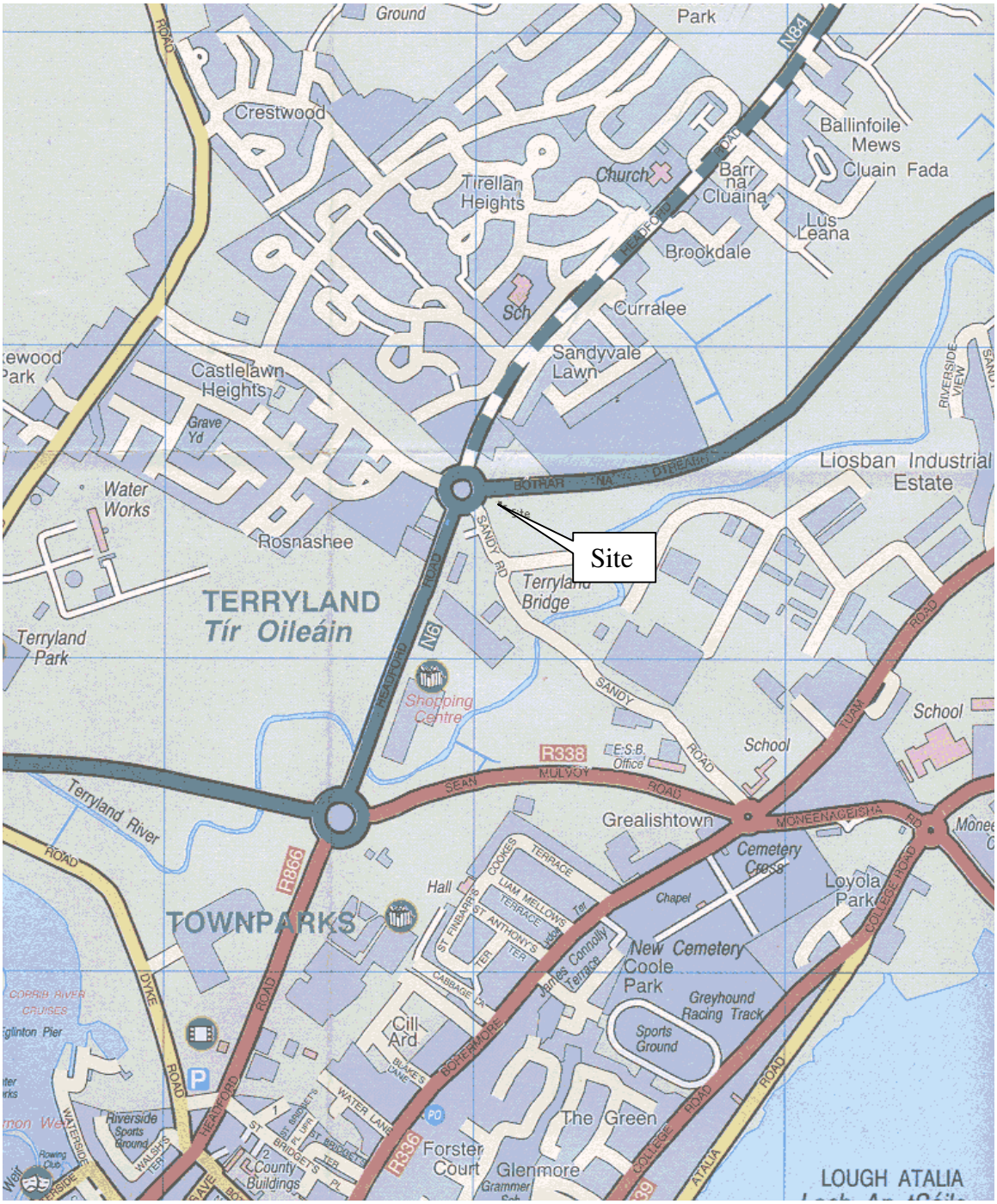


Figure 2.6: Location of the Galway roundabout site on the N6/N84 road

Sketch of Galway N84/N6 roundabout monitoring site

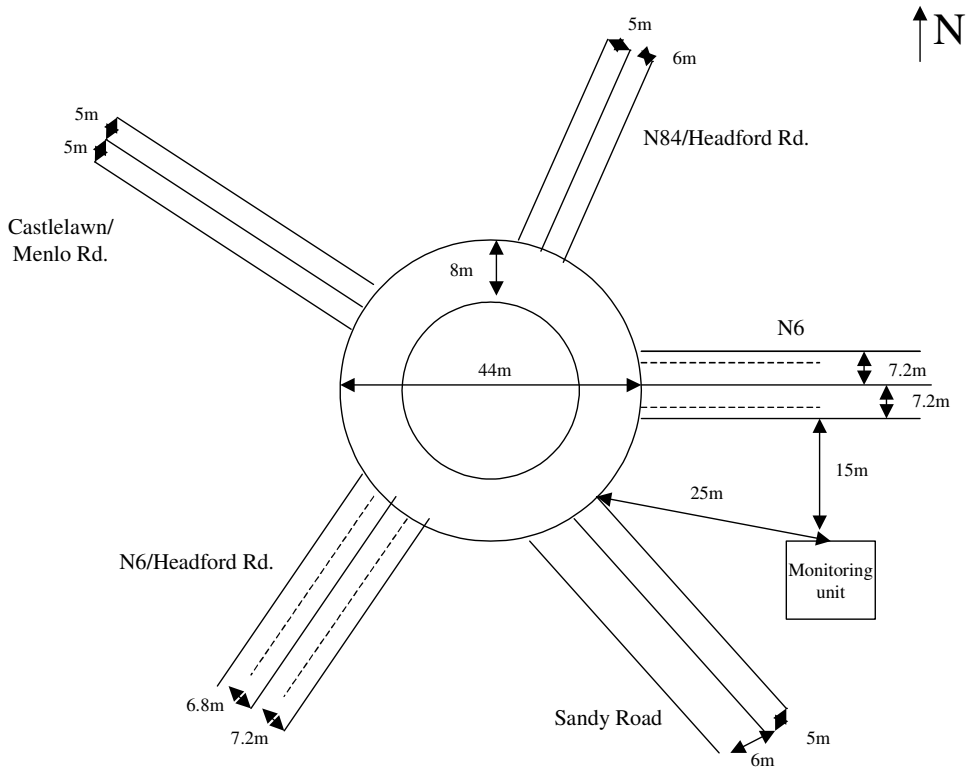


Figure 2.7: Galway roundabout site, showing the junction layout

Figure 2.8: Galway roundabout (view southeast from Menlo)

3 Monitoring Results for the M4 at Leixlip

3.1 Air Pollutants Monitored

Table 3.1 identifies the contaminants monitored at the M4 monitoring site. The sampling intervals and instrumentation employed are also given. Hydrocarbon monitoring is detailed in Appendix C.

Table 3.1: Air pollutants monitored at the M4 site

Pollutant	**Instrument**	**Method**	**Monitoring period**	**Sampling interval**
CO	API Model 300	Infrared absorption	May 01-Sept.02	1 hour, 15 minutes
NO_x, NO, NO_2 2^{nd} NO_x	API Model 200A	Chemiluminescence	May 01-Sept.02 March-Sept. 02	1 hour, 15 minutes
PM_{10}	TEOM	Oscillation frequency	June 01-Sept.02	30 minutes
PM_{10}	Partisol	Gravimetric	June 01-Sept.02	24 hours
Hydrocarbons	ATD400	Gas chromatography	Feb. 02-Sept.02	1 hour

Carbon monoxide (CO)

CO was measured with an Advanced Pollution Instrumentation (API) Gas Filter Correlation CO Analyser Model 300. With this system, the sample is pulled across a critical flow orifice at a rate of 800 cm^3 per minute. A high energy heated element generates broad band infrared light (IR), which passes through a rotating gas filter wheel. The rotation of the wheel sends the IR alternately through a reference cell (REF) and a measurement cell (MEAS) at 30 cycles per second. The reference cell contains a CO/nitrogen mix and therefore the CO absorbs the IR. The pulse from the reference cell is therefore unaffected by any CO in the sample as the IR has already been absorbed in the reference cell. The measurement cell contains only nitrogen and therefore has no effect on the beam of IR as it passes through the wheel. The beam passes through the sample cell and is filtered for conversion to a voltage signal. The two DC voltages generated, CO MEAS and CO REF, are proportional to the light intensity striking the detector during the measurement pulse and reference pulse respectively.

Oxides of nitrogen (NO_x), nitrogen dioxide (NO_2) and nitric oxide (NO)

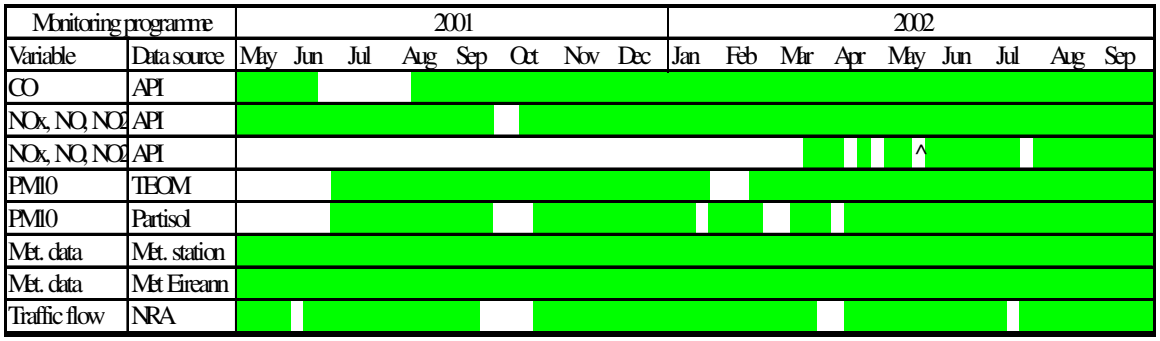
Nitric oxide (NO) and total NO_x were measured with an API Model 200A NO_x Analyser, which calculates nitrogen dioxide (NO_2) as the difference between these. In this system NO is measured from the light intensity of the chemiluminescent gas phase reaction of NO and ozone (O_3). NO reacts with O_3, producing oxygen (O_2) and electronically excited NO_2 molecules. The energy from these excited molecules is released as photons, whose light intensity is directly proportional to the concentration of NO. Any NO_2 in the sample is then converted to NO by heated molybdenum and the total NO_x is measured. The difference between NO_x and NO concentrations is assumed to be due to the presence of NO_2.

Particulate matter (PM_{10})

Two different instruments, both designed by Rupprecht and Patashnik, were used to monitor PM_{10}: the Partisol Plus Model 2025 Sequential Air Sampler and the Tapered Element Oscillating Microbalance (TEOM) Series 1400a Ambient Particulate Monitor. The Partisol draws the sample through a filter at a constant rate of 16.7 litres per minute (1 m^3/hour) (Rupprecht and Patashnik, 1998). The difference between the mass of the filter before and after sampling is taken to be the mass of PM_{10} within the sample volume. The TEOM records the mass concentration of PM_{10} as an average over 30 minutes, one hour and 24 hours. The TEOM flowrate is also 16.7 litres per minute (1 m^3/hour) of which 3 litres per minute is sampled by the mass transducer. The TEOM heats the sample to 50°C before measurement, to eliminate the effects of changes in humidity (cf. Galway TEOM, which operates at 40°C, in Chapter 4). Since this burns off some of the volatile component of the PM_{10}, the TEOM results are expected to be lower than those from the Partisol. The TEOM is a hollow tapered element with a filter cartridge at one end. It is fixed on one side and free to vibrate at its natural frequency at the other. Particles accumulate on the filter as the sample is drawn through, which decrease the frequency of vibration. The change in frequency is proportional to the mass on the filter.

Monitoring programme

Monitoring commenced on the 11th of May 2001, and continued until September 2002. CO and NO_x were monitored from the 15th May 2001. The CO instrument was calibrated nightly from the 8th August 2001. The NO_x instrument was calibrated manually every fortnight from the 9th October 2001. The TEOM and Partisol were operational from the 29th May and the microbalance for weighing the Partisol filters was calibrated. Figure 3.1 illustrates the monitoring programme in more detail, including periods where instruments were non-operational due to repair and servicing requirements. The period from the 15th of September 2001 to the 15th of September 2002 is regarded as the core period for which annual average data values are calculated.



^=Second NOx analyser moved from Leixlip Water Treatment Works (2ndNOxNorth) to site south of M4 (2ndNOxSouth)

Figure 3.1: Monitoring programme

3.2 Traffic Flows

Traffic flows on the M4 were monitored continuously throughout the monitoring period using induction loops located on the motorway, between the interchanges to the east and

west of the monitoring point. The induction loops were installed and operated by the National Roads Authority, who made the data available to this project. The following data were recorded hourly:

- total flow in each lane;
- percentage heavy goods vehicles (HGV) in each lane.

Figure 3.2 compares the average diurnal variation in total flow on weekdays and at weekends. On weekdays, peak flows were observed of approximately 2,400 vehicles per hour (vph) between 08:00 and 09:00, and approximately 2,700 vph between 18:00 and 19:00, whereas weekend peak flows averaged 2,000 to 2,300 vph from 12:00 until 20:00.

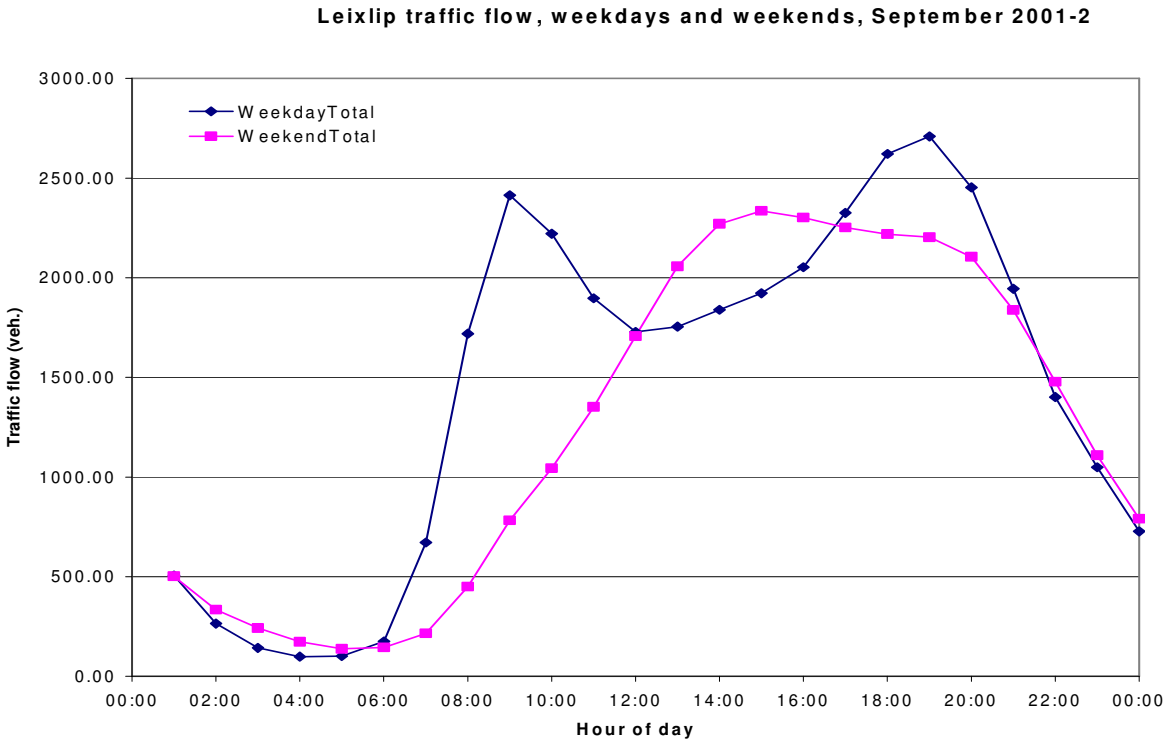


Figure 3.2: Average diurnal variation in total traffic flow on the M4

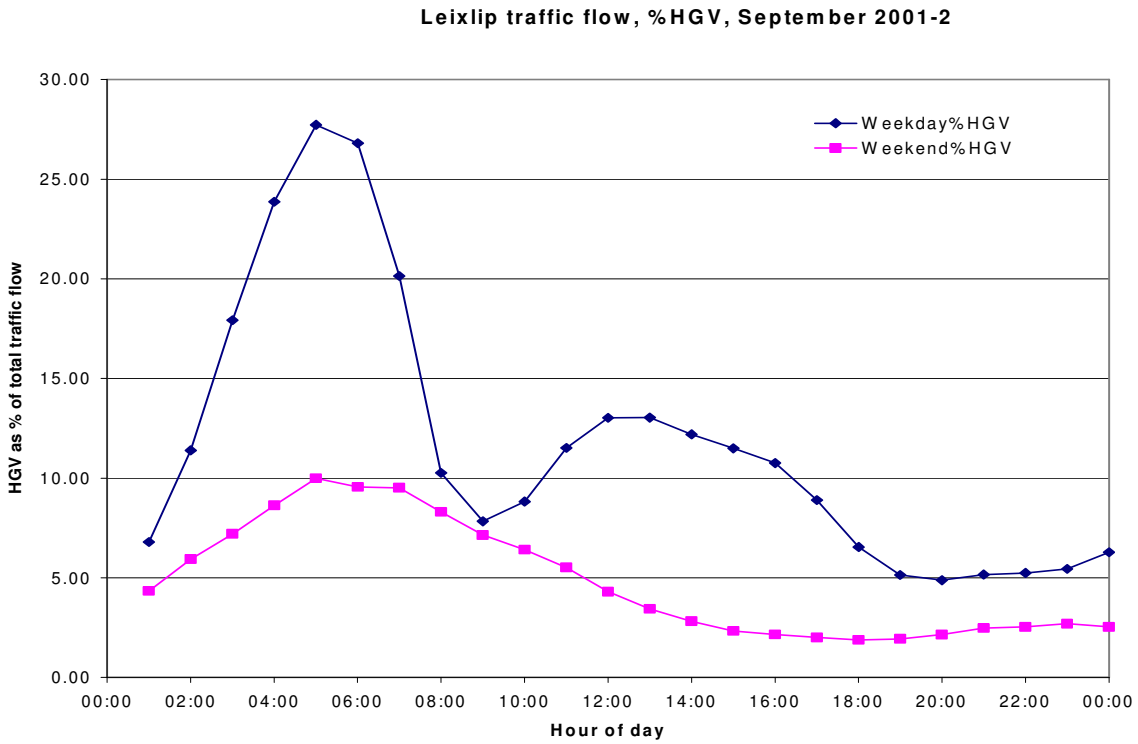


Figure 3.3: Average diurnal variation in percentage HGV content of traffic flow on the M4

Figure 3.3 illustrates the diurnal variation in the percentage HGV content of the flow, for weekends and weekdays. Weekday HGV flow reaches its maximum of 28% of total traffic between 04:00 and 05:00, which corresponds to the hours of lowest total traffic, which occur between 02:00 and 07:00 (28 HGV: 100 vehicles in total). It has a peak at 13 % of the total traffic between 11:00 and 13:00, again corresponding to the lunchtime trough in total traffic (227 HGV: 1,728 vehicles in total).

3.3 Meteorology

Wind speed, wind direction, temperature and relative humidity were recorded continuously at the monitoring site. Sensors were located 6m above ground level, on a mast extending above the monitoring unit. Data were recorded at 15 minute intervals, and these are combined to give hourly values. Wind speed and direction at an altitude of 10 m were measured by Met Eireann at Casement Aerodrome, located approximately 6 km to the south-southeast of the monitoring site. Atmospheric stability and cloud cover were recorded hourly at Casement. Radiation was monitored at Met Eireann's Dublin Airport synoptic station.

Table 3.2 presents the mean monthly values of the measured variables for the period September 2001 – September 2002.

Table 3.2 Monthly mean and maxima of meteorological variables measured at the motorway site, and by Met Eireann at Casement Aerodrome and Dublin Airport.

	MetStation						Met Eireann					
	Temperature Degrees C.		Humidity %		Wind speed m/s		Wind speed m/s		Radiation Joules/cm^2		Cloud cover Octa	
	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.	mean	max.
HOURLY												
Sep-01	12.7	19.3	49	68	1.5	8.3	7.2	25	39.1	229	5.5	8
Oct-01	12.5	19.4	49	71	2.3	7.3	12.4	30	25.2	201	5.2	8
Nov-01	8.6	17.0	52	67	1.8	7.0	10.6	25	12.5	126	6.2	8
Dec-01	5.0	13.6	47	70	1.9	10.8	9.3	35	9.4	86	4.7	8
Jan-02	7.6	14.1	47	98	2.6	9.7	13.7	35	9.7	101	5.7	8
Feb-02	7.2	13.5	44	61	3.2	10.4	16.5	36	21.2	177	5.8	8
Mar-02	7.8	14.8	43	61	2.3	8.6	11.3	31	37.3	234	5.4	8
Apr-02	9.1	18.8	31	62	2.3	6.6	10.1	27	56.0	283	5.7	8
May-02	11.4	19.5	43	65	2.1	7.2	9.6	34	67.0	302	6.1	8
Jun-02	13.1	20.4	46	64	2.0	7.0	10.1	26	68.1	335	6.6	8
Jul-02	13.0	18.2	37	64	1.7	5.2	7.6	18	60.1	291	6.7	8
Aug-02			18	40	1.4	7.2	6.8	25	54.7	285	6.2	8
Sep-02			17	18	1.3	3.9	6.9	19			5.2	8
Year	9.5	20.4	41	98	2.1	10.8	10.4	36	38.5	335	5.8	8
24 HOUR (DAILY)												
Sep-01	12.8	17.0	49	56	1.5	4.0	7.2	18.5	39.2	58.8	5.5	7.1
Oct-01	12.5	15.8	49	63	2.3	4.7	12.4	24.7	25.2	51.9	5.2	7.0
Nov-01	8.6	13.3	52	61	1.8	3.7	10.6	20.0	12.5	25.0	6.2	7.8
Dec-01	5.0	12.3	47	62	1.9	6.5	9.3	23.5	9.4	14.9	4.7	7.2
Jan-02	7.6	11.3	47	57	2.6	4.7	13.7	24.1	9.7	20.4	5.7	7.4
Feb-02	7.2	11.0	44	53	3.2	6.6	16.5	24.8	21.2	33.5	5.8	7.7
Mar-02	7.9	11.4	43	51	2.3	5.9	11.4	25.8	37.2	71.5	5.5	8.0
Apr-02	9.0	14.4	31	58	2.3	4.3	10.0	20.1	56.6	87.7	5.7	7.9
May-02	11.4	15.8	43	59	2.1	4.3	9.7	23.4	67.0	104.1	6.1	7.8
Jun-02	13.1	15.7	46	60	2.0	3.7	10.1	18.1	68.1	100.3	6.6	7.8
Jul-02	13.0	13.9	37	51	1.6	2.6	7.6	13.7	60.1	91.0	6.7	7.8
Aug-02			18	25	1.4	3.6	6.8	14.7	54.7	98.1	6.2	8.0
Sep-02			17	18	1.3	2.4	7.0	14.2			5.2	7.5
Year	9.8	17.0	40	63	2.0	6.6	10.2	25.8	38.4	104.1	5.8	8

The mean temperature was just less than 10°C. The mean wind speed was 2 m/s at the monitoring unit, compared to 10 m/s recorded at Casement Aerodrome, suggesting localised turbulence due to the terrain, in addition to the difference in the height of instrumentation. The temperature was not reported from August 2002 as the instrument was undergoing maintenance.

Figure 3.4 compares the wind direction frequency observed at the monitoring site during the monitoring period with that observed at Casement Aerodrome. The prevailing winds are from the SW in both cases. The wind shadow effect caused by the building to the NE of the monitoring unit (Figure 2.1) can be seen, although the Met Eireann data show few winds from between 300º and 60º. Local effects would have more impact at the monitoring unit than at Casement Aerodrome since the sensor is lower (6 m compared to Met Eireann's standard 10 m).

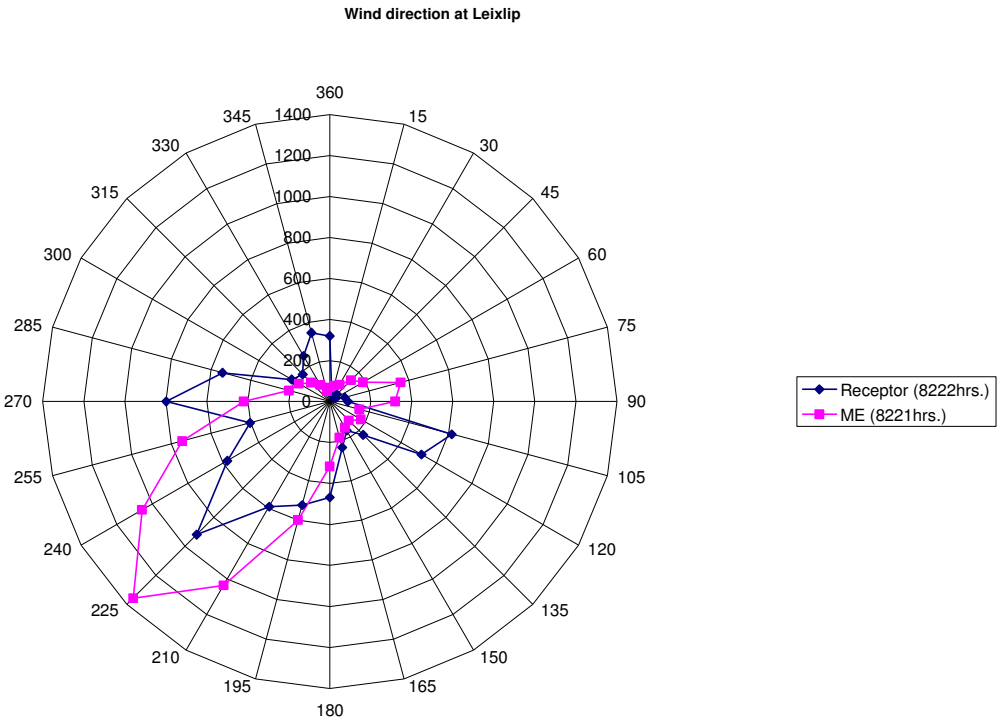


Figure 3.4: Wind direction frequency at monitoring site (Receptor) and at Casement Aerodrome (ME)

Figure 3.5 presents the mean wind speed from each direction observed at the monitoring site, while Figure 3.6 compares the wind speeds measured at the monitoring site with those measured at Casement Aerodrome. The highest wind speeds occur when winds are from the S and SSE. The wind shadow effect of the building to the NE of the monitoring unit is again clear in Figure 3.5.

The wind speed measured at Casement is consistently higher than that recorded at Leixlip, which is as expected, due to the difference in the height of measurement (10 m compared to 6 m), and due to the wind shadow effect of the building at Leixlip.

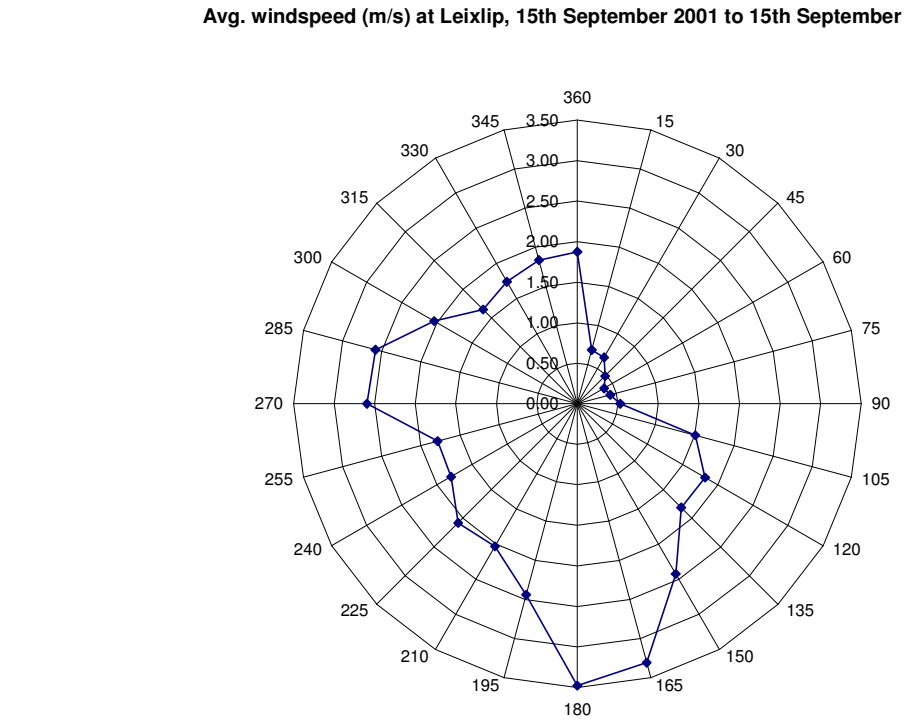


Figure 3.5: Mean wind speeds at monitoring site

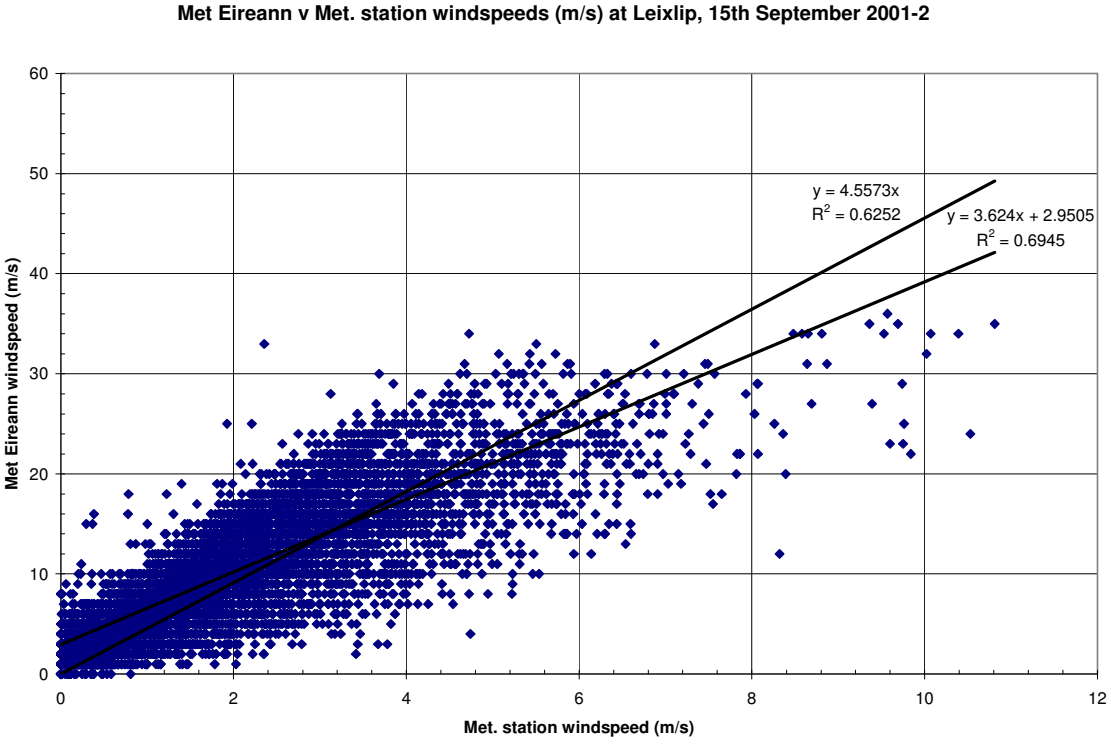


Figure 3.6: Comparison of wind speeds measured at monitoring site and at Casement Aerodrome .

Figure 3.7 shows the relative frequency of stable atmospheric conditions (i.e., stability class E or F) associated with different wind directions, while Figure 3.8 shows the

relative frequency of stable atmospheric conditions at different times of day. Stable conditions occurred with winds from NE and east and at night. Winds from the E and ENE correspond to stable conditions (Pasquill Stability Index E, F or G) for up to 64% of the time, from the NE up to 43%, from the SE up to 33% and less than 25% for all other wind directions. No stable conditions were observed between the hours of 08:00 and 16:00. Stable conditions occur about 35% of the time for the hours between 21:00 and 05:00. Plots showing the variation of mean temperature and relative humidity with wind direction are provided in Appendix A (Figures A.4a) and A.4b)).

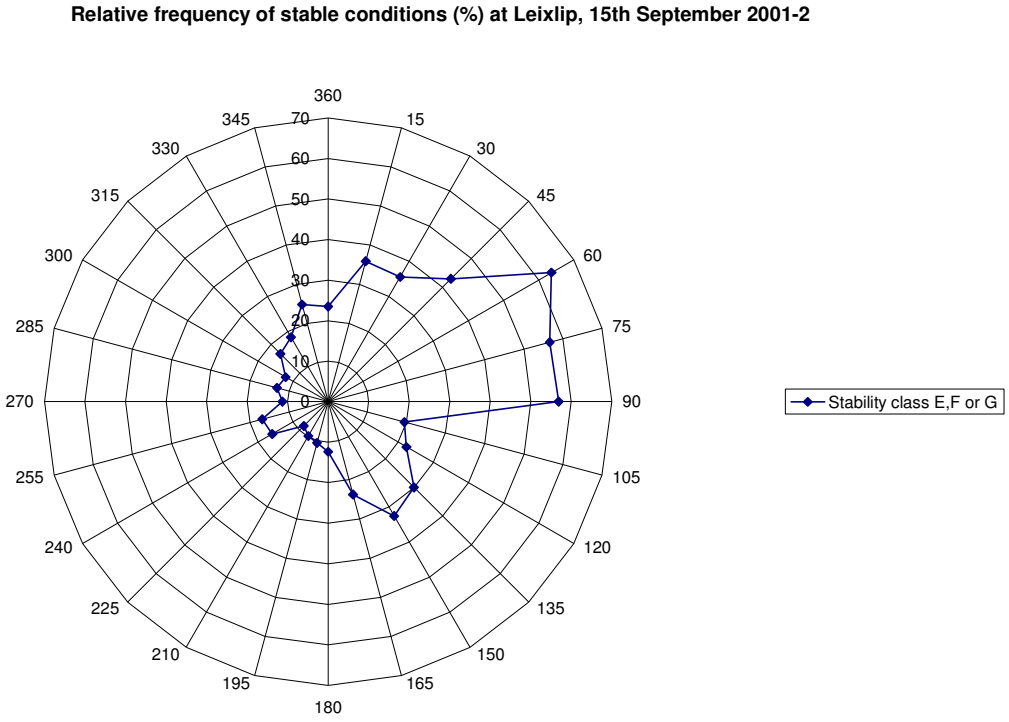


Figure 3.7: Relative frequency of stable atmospheric conditions for different wind directions.

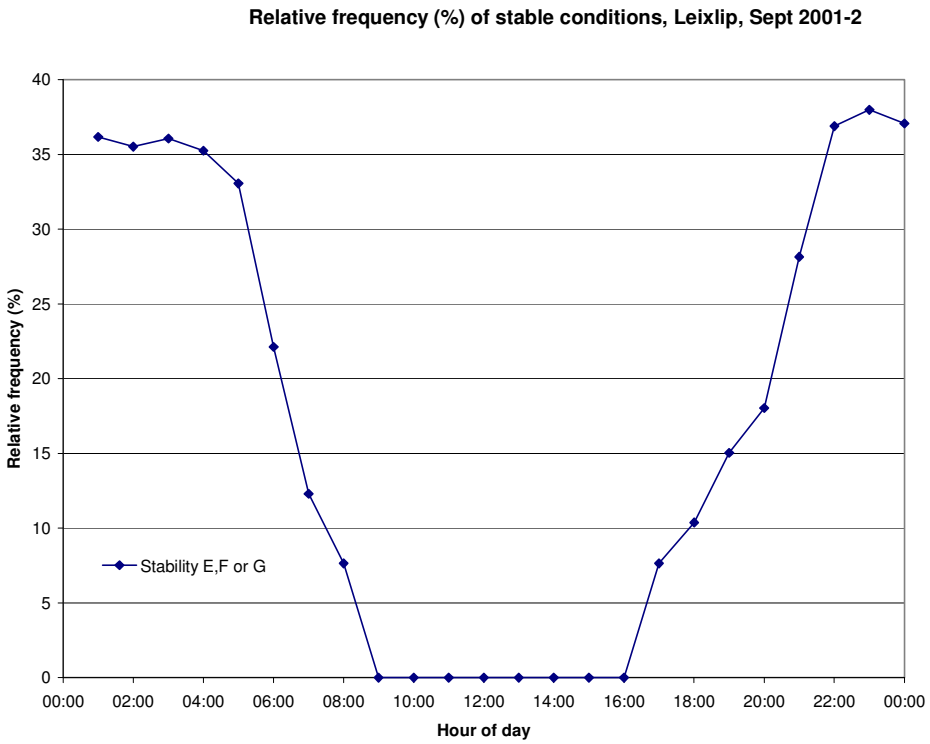


Figure 3.8: Relative frequency of stable atmospheric conditions for different times of day.

3.4 Air Pollutant Concentrations

Table 3.3 presents the mean, maximum, 5th percentile and 95th percentile concentrations of CO, NO, NO_2, NO_x, and PM_{10} for the period September 2001 – September 2002. Mensual pollutant statistics and data from the second NO_x analyser are included in Appendix A (Tables A.1 and A.2).

Table 3.3: Pollutant statistics (ppm CO; ppb NO_2, NO and NO_x; $\mu g/m^3 PM_{10}$)

HOURLY CONCN		NOx			2NOxN/S				
	CO	NO2	NO	NOx	NO2	NO	NOx	TEOM	
Mean	0.27	9.91	10.72	20.50	6.70	4.97	11.64	15.50	
Max	2.6	53.7	320.4	351.1	48.2	165.7	186.1	112.4	
Date of maximum	15/12/2001	12/09/2002	05/01/2002	05/01/2002	21/08/2002	26/03/2002	26/03/2002	05/01/2002	
Time (drivers')	02:00	22:00	23:00	23:00	17:00	08:00	08:00	02:00	
5th %ile	0.1	1.8	0.1	2.1	0	0	0	5.1	
95th %ile	0.6	25.4	38.5	62.9	23.4	20.6	42.4	31.7	
98th %ile	0.9	30.3	71.6	95.7	28.8	37.6	63.7	43.6	
Data capture	0.99	0.96			1.00			0.90	
No. of TEOM values p.a. exceeding 50 ug/m^3 over ONE hour								88	
24 HOUR (DAILY)									
	CO	NO2	NO	NOx	NO2	NO	NOx	TEOM	Partisol
Mean	0.27	9.90	10.68	20.45	6.75	4.96	11.67	15.50	16.80
Max	1.18	29.16	122.80	149.19	26.19	35.49	53.57	47.27	92.50
Date of maximum	09/12/2001	31/12/2001	06/01/2002	06/01/2002	29/03/2002	26/03/2002	26/03/2002	12/09/2002	30/03/2002
5th %ile	0.12	3.77	1.10	5.42				8.09	4.58
95th %ile	0.57	19.50	27.90	46.23				29.20	39.50
98th %ile	0.74	21.70	38.86	64.06				34.60	49.17
Data capture								0.93	0.94
No. of PM10 values p.a. exceeding 50ug/m^3 over 24 hours								0	6

2NOxN/S: second NOx analyser, located north (N) and then south (S) of the M4

Figures 3.9 – 3.11 present the variation in the 24-hour average concentration of each of these pollutants during the same period. Peaks are observed in CO, NO and PM_{10} concentrations during December and early January: in this period, CO concentrations average c.1 ppm rather than the usual peak of ≤0.4 ppm; NO concentrations average at least 60 ppb rather than the usual peak of ≤30 ppb; PM_{10} concentrations average c.40 $\mu g/m^3$ rather than the usual peak of ≤20 $\mu g/m^3$. A second set of peaks towards the end of March is much more pronounced in CO and PM_{10} than in NO_2. Mean concentrations are 0.27 ppm CO, 10.61 ppb NO, 9.99 ppb NO_2, 15.70 $\mu g/m^3$ PM_{10} measured by TEOM, and 17.14 $\mu g/m^3$ PM_{10} measured by Partisol. The TEOM result is, as expected, lower than that of the Partisol (by 8%), since the TEOM burns off the volatile component of the particulate matter.

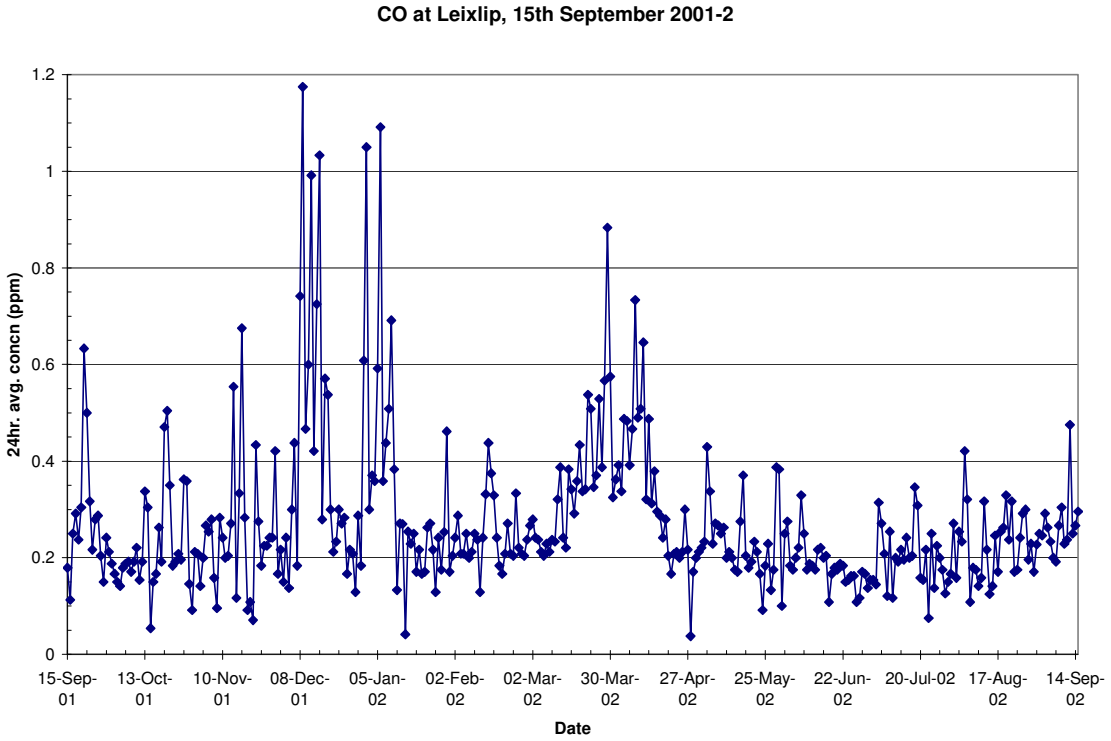


Figure 3.9: 24 hour average CO concentrations

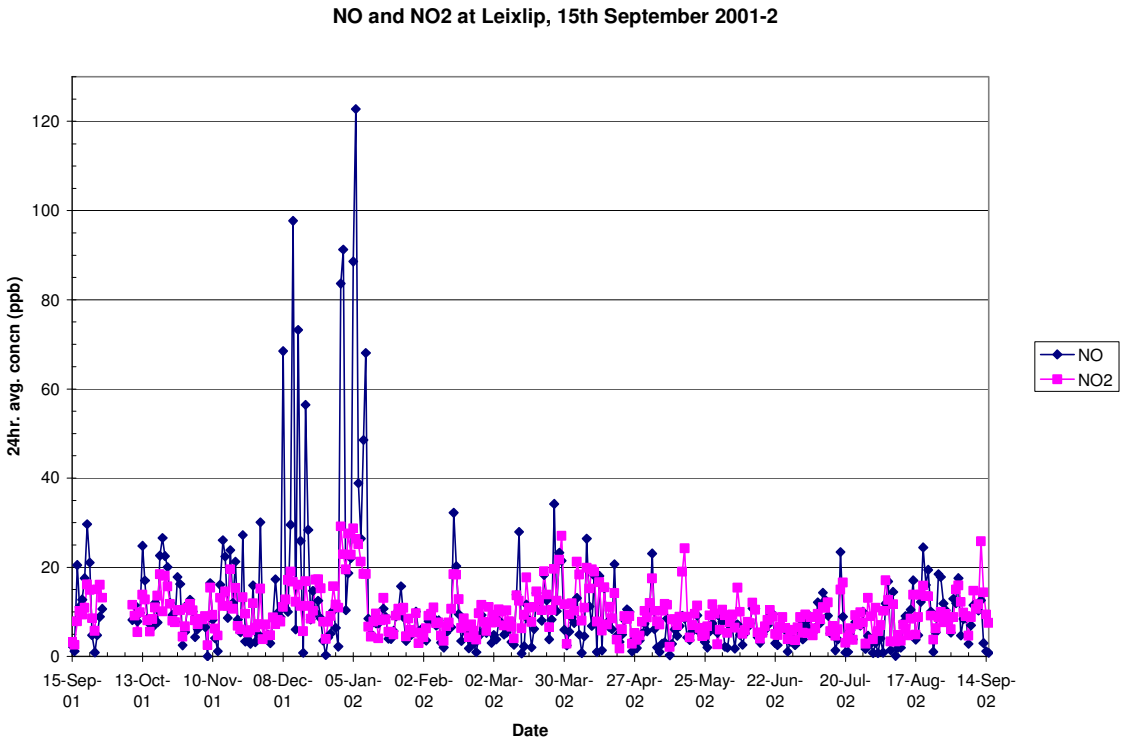


Figure 3.10: 24 hour average NO and NO_2 concentrations

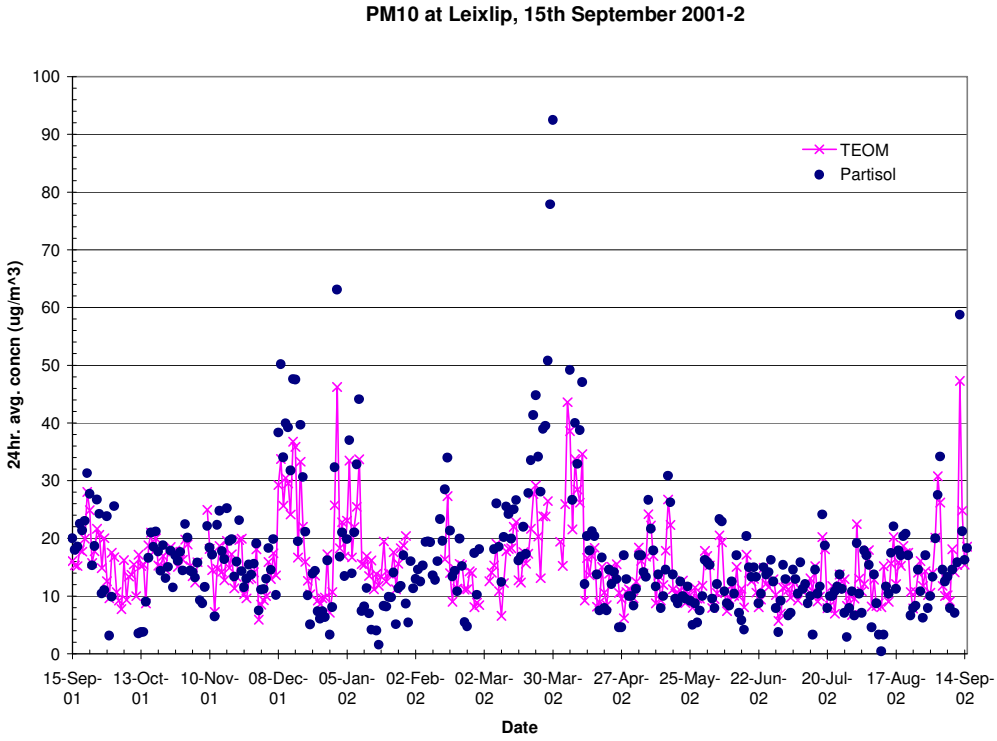


Figure 3.11: 24 hour average PM_{10} concentrations, measured using TEOM and Partisol

Figure 3.12 presents the variation in the 24-hour average concentration of benzene for the period from 7th February 2002 to 22nd September 2002. The mean concentration of benzene is 0.16 ppb and the maximum hourly concentration is 2.09 ppb. These can be compared with the EU Ambient Standard for the annual average concentration, which is 1.52 ppb (5 µg/m^3). Details of the other hydrocarbons are given in Appendix C.

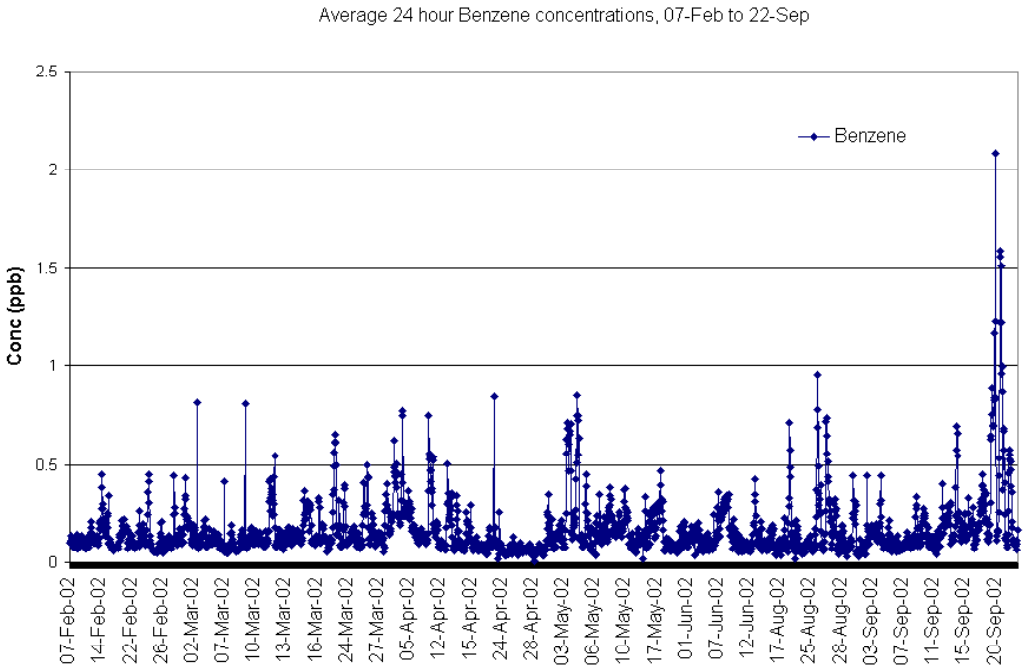


Figure 3.12: 24 hour average benzene concentrations

3.5 Analysis of Monitoring Results

3.5.1 Diurnal variation in pollutant concentrations

The variation in traffic flows described in Section 3.2 is reflected in the diurnal variation in pollutant concentrations. Figures 3.13- 3.17 present the average diurnal variation in the hourly concentrations of CO, NO, NO_2, PM_{10} and benzene. These plots are calculated by averaging all the concentrations observed for each hour of the day. Figures 3.13- 3.16 also show the effect of stable atmospheric conditions on pollutant concentrations, when the influence of the local source is reduced.

CO, NO, NO_2 and PM_{10} all show peaks between 08:00 and 09:00. Concentrations then decrease to a relative trough between 13:00 and 14:00, before rising towards 18:00, which reflects the weekday traffic flows. Benzene concentrations show a peak at the hour ending 23:00 and a nadir at the hour ending 11:00, with a minor peak at the hour ending 09:00. These reflect the morning traffic flow, the daytime dispersion due to unstable conditions, and the combination of evening traffic with stable conditions.

No stable conditions occurred between 08:00 and 16:00. The effect of stable conditions is reflected in higher overnight concentrations, for example CO for the hour 23:00 to 24:00 (0.32 ppm A-G, 0.23 ppm A-D), NO for 03:00 to 04:00 (5.42 ppb A-G, 1.29 ppb A-D), NO_2 for 00:00 to 01:00 (8.00 ppb A-G, 5.14 ppb A-D) and PM_{10} for 22:00 to 23:00 (17.52 µg/m^3 A-G, 14.35 µg/m^3 A-D).

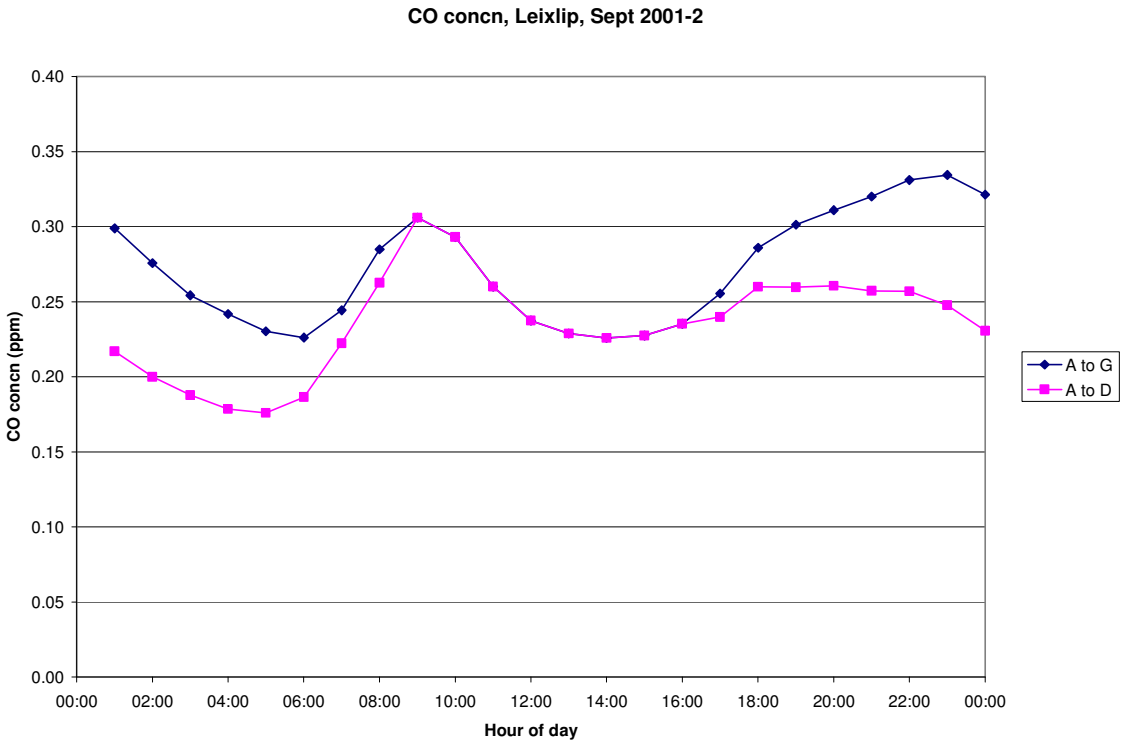


Figure 3.13: Average diurnal variation of hourly CO concentrations with stability class

CO concentrations reduce at a similar rate after 23:00 regardless of stability, therefore it is the increase during stable conditions that results in higher overnight concentrations despite the lack of traffic. The morning peak is greater than the afternoon peak for unstable and neutral stability classes, but the afternoon peak is greater than the morning peak when all classes are included. Stable conditions can influence the afternoon peak (occurs after 16:00) but not the morning peak (occurs after 08:00), except in the case of NO_2, which shows a small influence. Overnight, when traffic flow drops to as low as 100 vph, so CO concentrations approach a minimum of 0.17 ppm, which represents one estimate for the average background concentration.

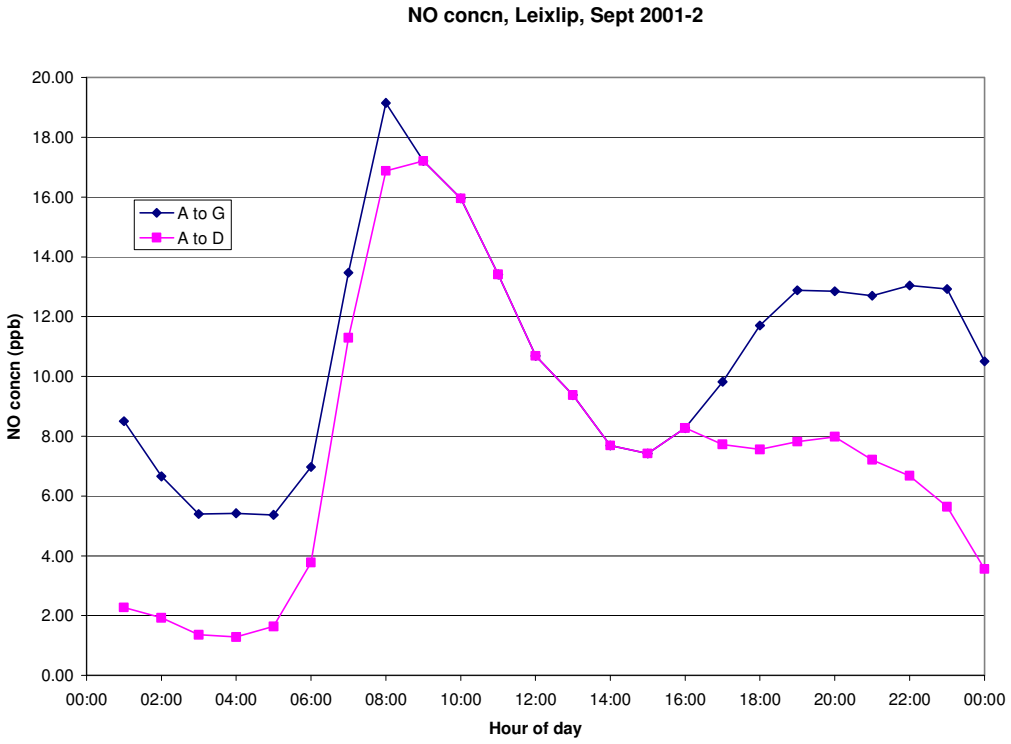


Figure 3.14: Average diurnal variation of hourly NO concentrations

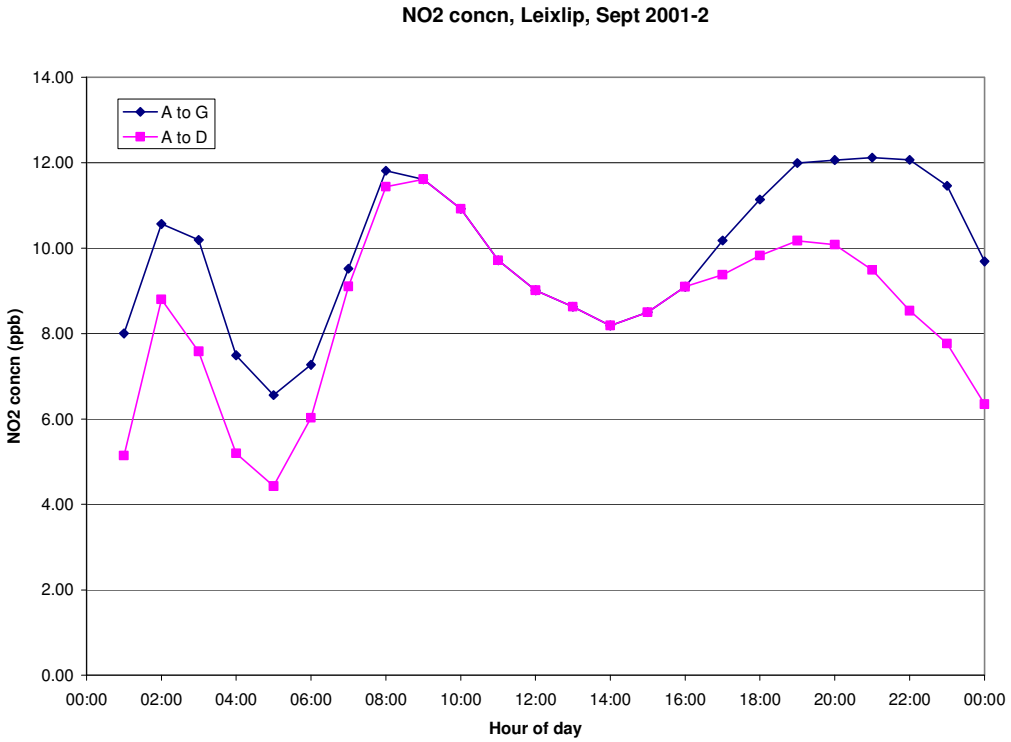


Figure 3.15: Average diurnal variation of hourly NO_2 concentrations

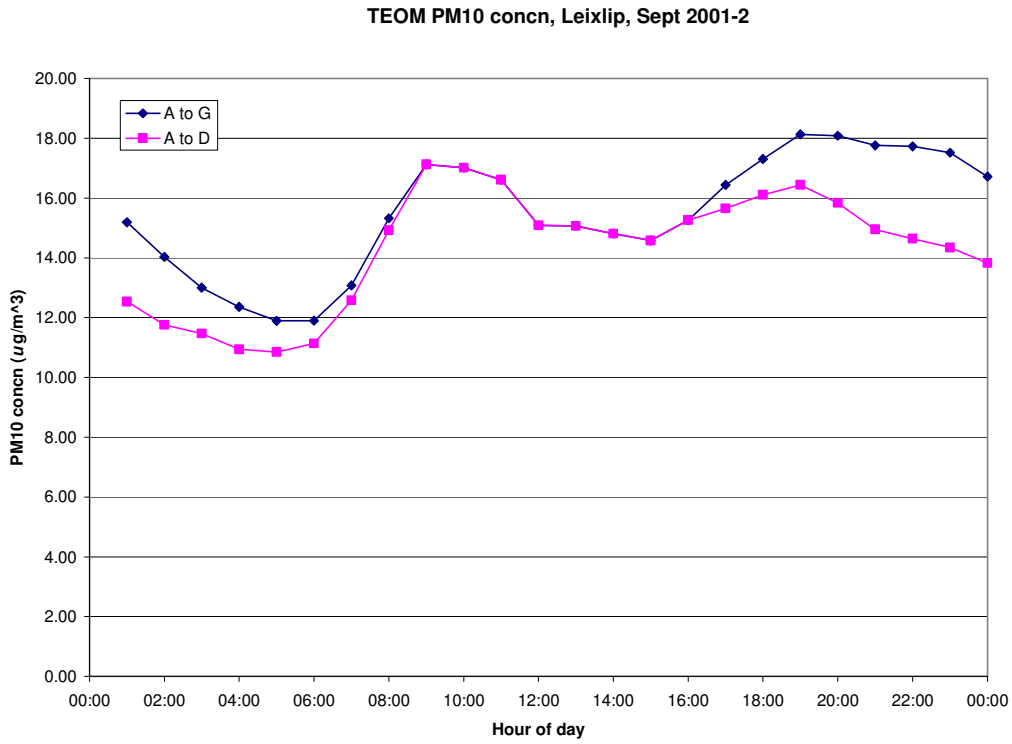


Figure 3.16: Average diurnal variation of hourly PM_{10} concentrations

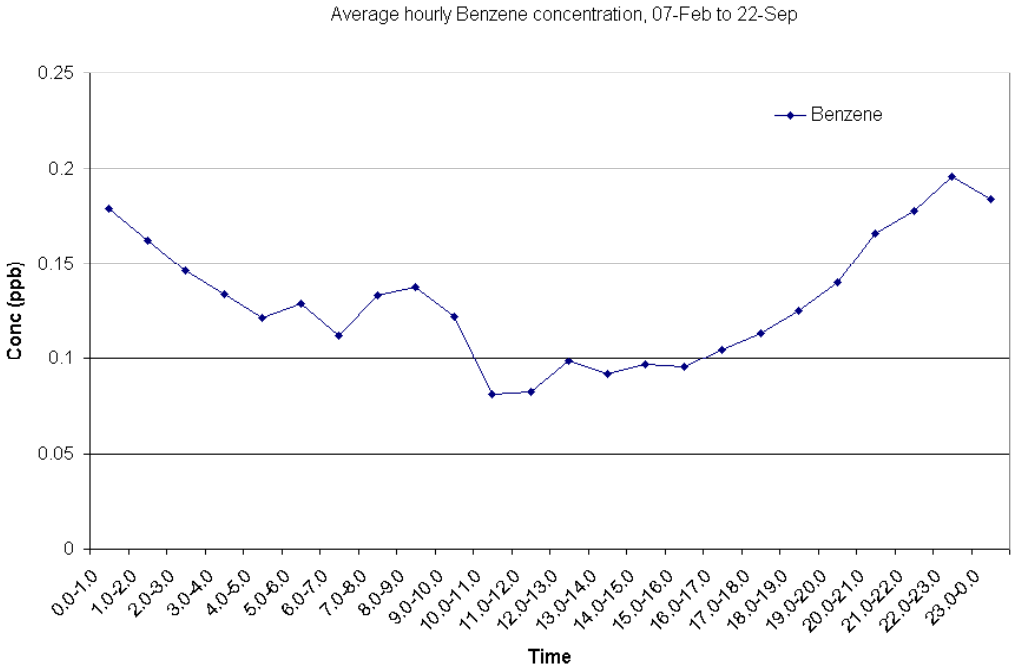


Figure 3.17: Average diurnal variation of hourly benzene concentrations

3.5.2 Variation of pollutant concentration with wind direction

The measured pollutant concentrations were observed to be influenced by wind direction. This influence is shown in Figures 3.18–3.21, which present pollution concentration roses for CO, NO, NO_2, PM_{10} and benzene. These plots show the average

hourly concentration observed for each wind direction. It appears from these plots that winds from the south (S; in the range 90 – 270°), which bring air containing emissions from vehicles on the M4 to the monitoring site, did not always give rise to the highest observed concentrations. This is due to the influences of wind speed and atmospheric stability.

Figure 3.5 showed that there was considerable variation in the observed mean wind speeds for different wind directions. As pollution concentrations can be expected to be inversely proportional to wind speed, directions with low mean wind speeds will tend to display higher concentrations. For the monitoring data collected at Leixlip, the lowest mean wind speeds are from the north-east (NE), as are the highest observed mean concentrations. In addition, Figure 3.4 showed that the wind is very rarely from the NE quadrant.

It appears therefore that the higher concentrations observable in Figures 3.18-3.21 are the product of a low number of measurements obtained during periods of mainly low wind speeds. This effect can be examined by plotting the variation with wind direction of the product of the mean concentration and mean wind speed. This is illustrated in Figures 3.22 – 3.25, which show the highest products when winds are from the S and SSE, i.e. from the M4, reflecting the higher speeds of southerly winds. The apparent peaks in concentrations for NE winds, which are due to low wind speeds and a very low incidence of NE winds, are thus reduced.

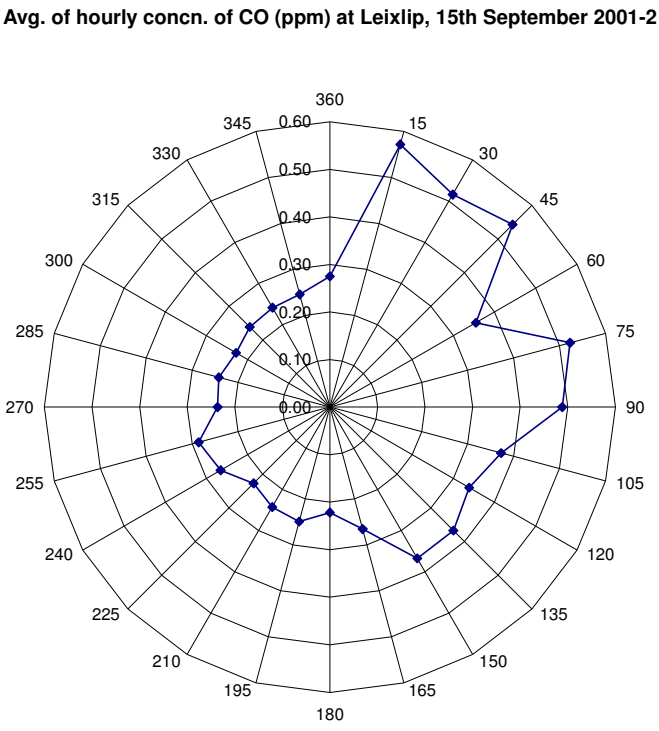


Figure 3.18: Variation of CO concentration with wind direction

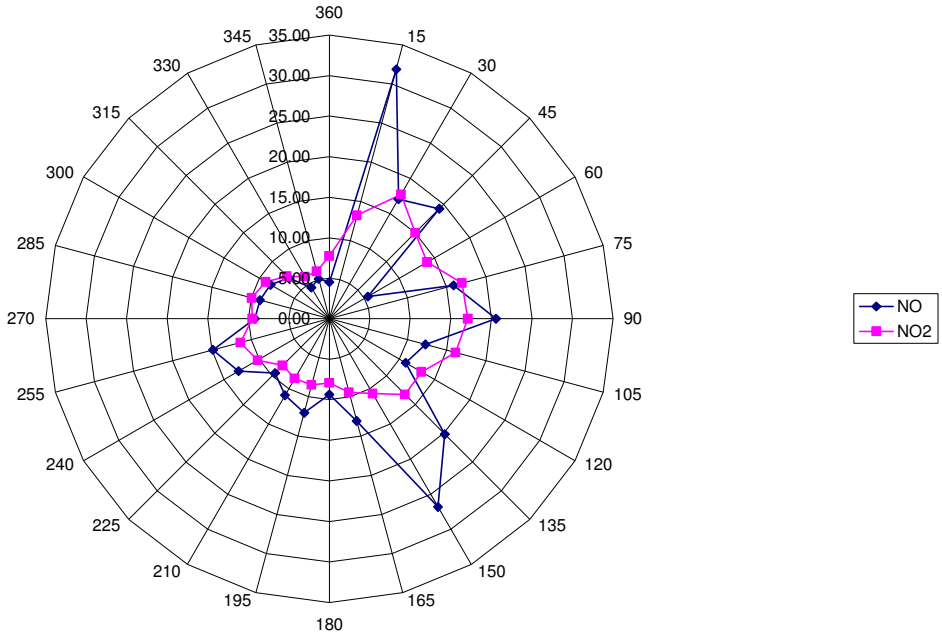


Figure 3.19: Variation of NO and NO_2 concentrations with wind direction

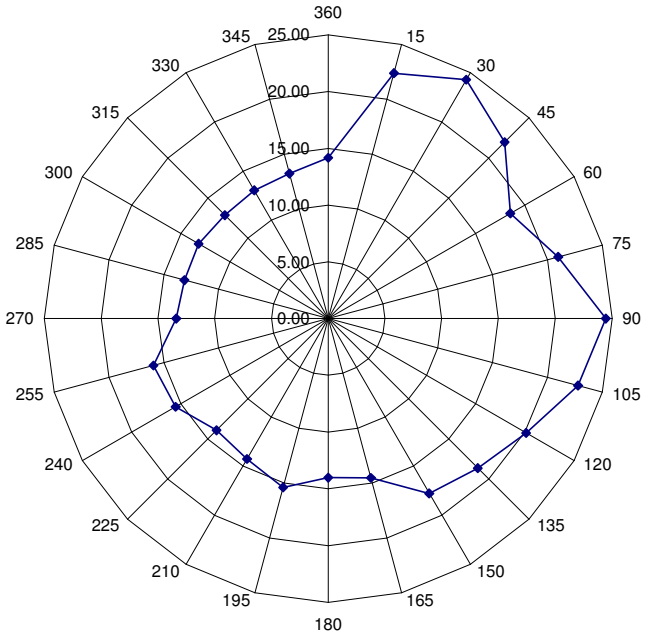


Figure 3.20: Variation of PM_{10} concentration with wind direction

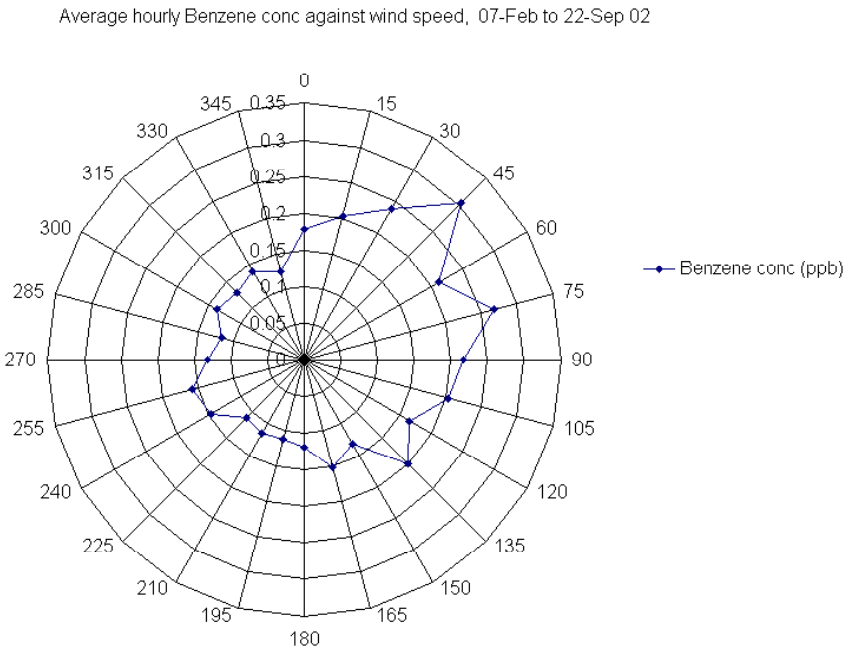


Figure 3.21: Variation of benzene concentration with wind direction

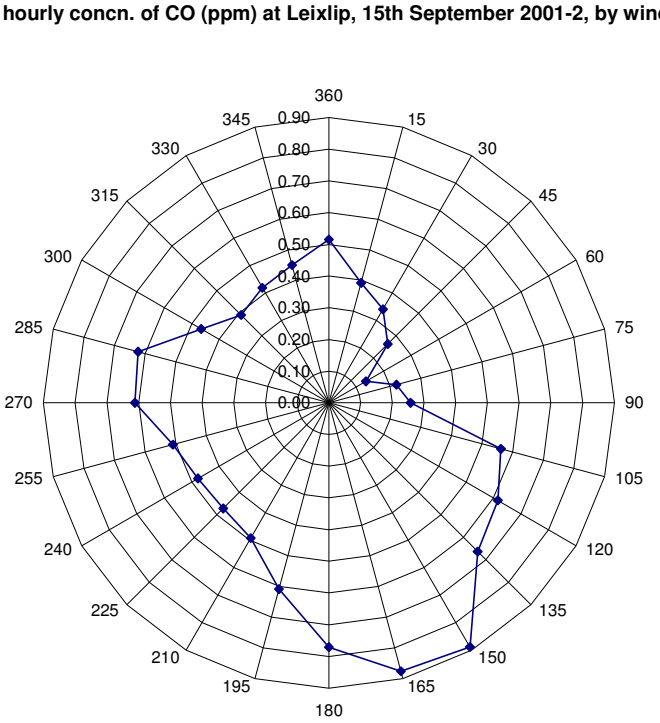


Figure 3.22: Variation with wind direction of the product of the mean CO concentration and mean wind speed

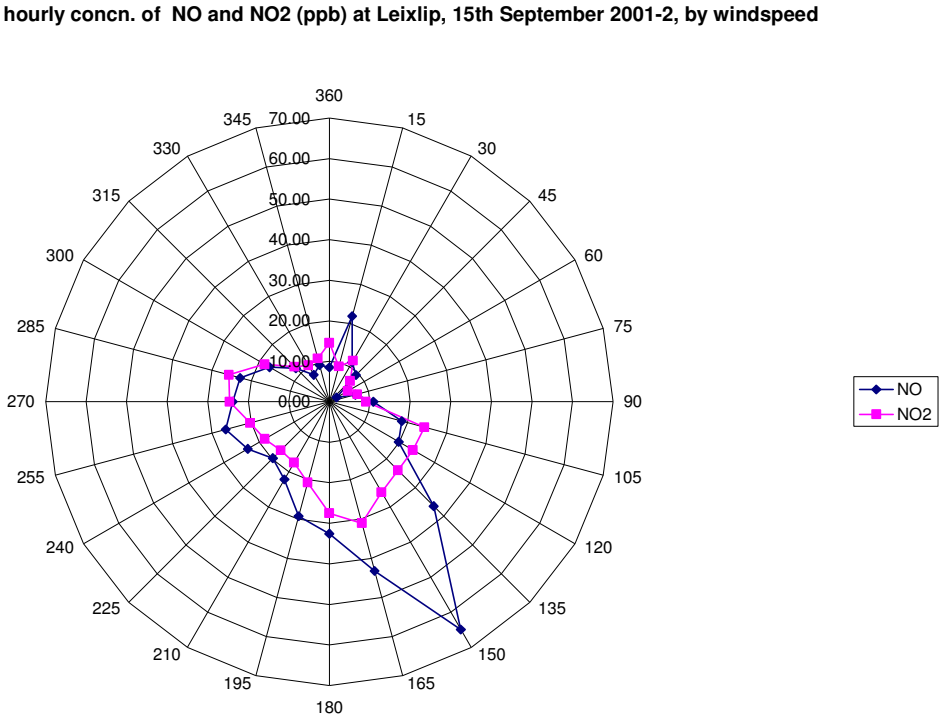


Figure 3.23: Variation with wind direction of the product of the mean NO and NO_2 concentrations and mean wind speed

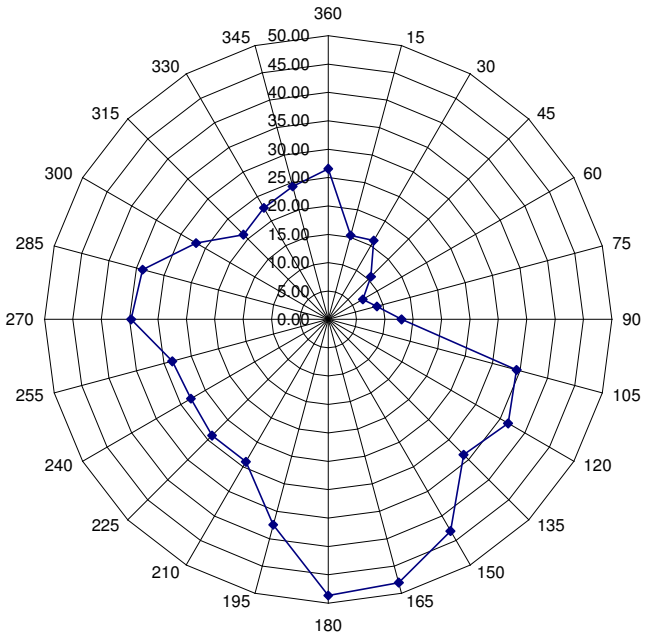


Figure 3.24: Variation with wind direction of the product of the mean PM_{10} concentration and mean wind speed

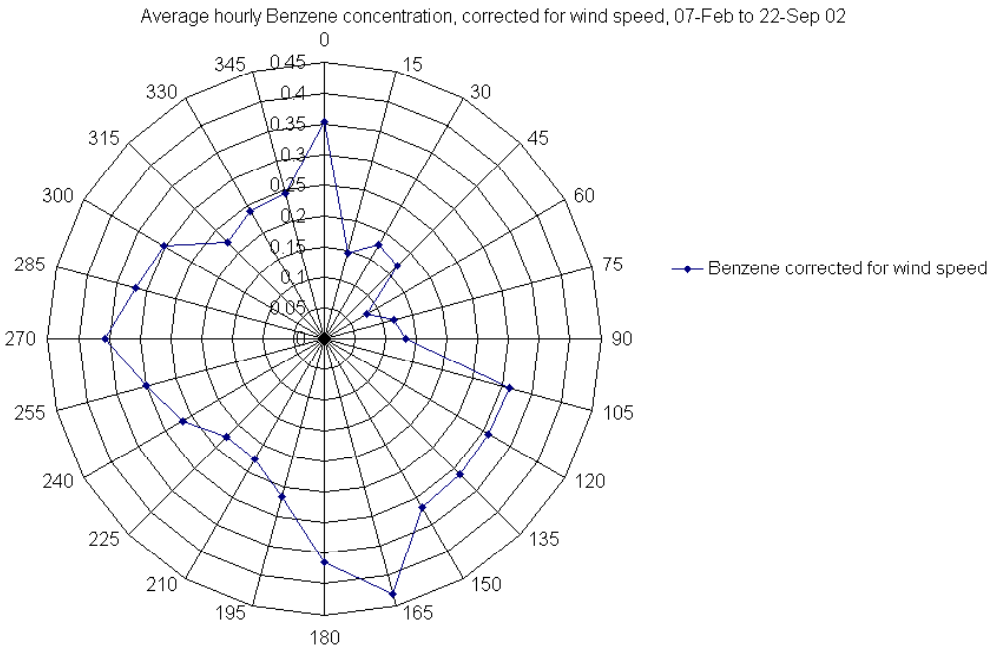


Figure 3.25: Variation with wind direction of the product of the mean benzene concentration and mean wind speed

3.5.3 Seasonal variation in pollutant concentrations

Figures 3.26 to 3.29 compare the variations in mean concentrations with wind direction during the winter and summer periods. The winter mean is higher than the summer for each pollutant. Significantly elevated mean winter concentrations are observed for the NE, E and, to a lesser extent, the SE. However, from Figures 3.4 and 3.5, these may be due to the very low incidence of winds from the NE and the relatively low wind speeds from the NE, and, to a lesser extent, the SE. This holds true for both winter and summer, as shown in Appendix A. The shadowing effect of the building seems to be apparent in all these figures (3.26-3.29).

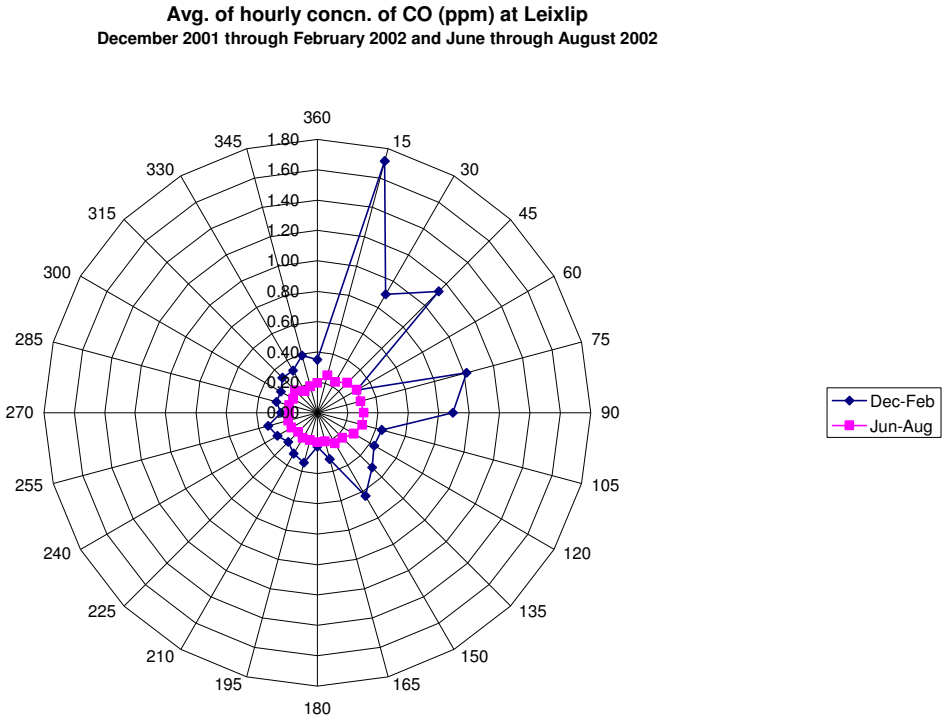


Figure 3.26: Comparison of CO concentration roses for summer and winter

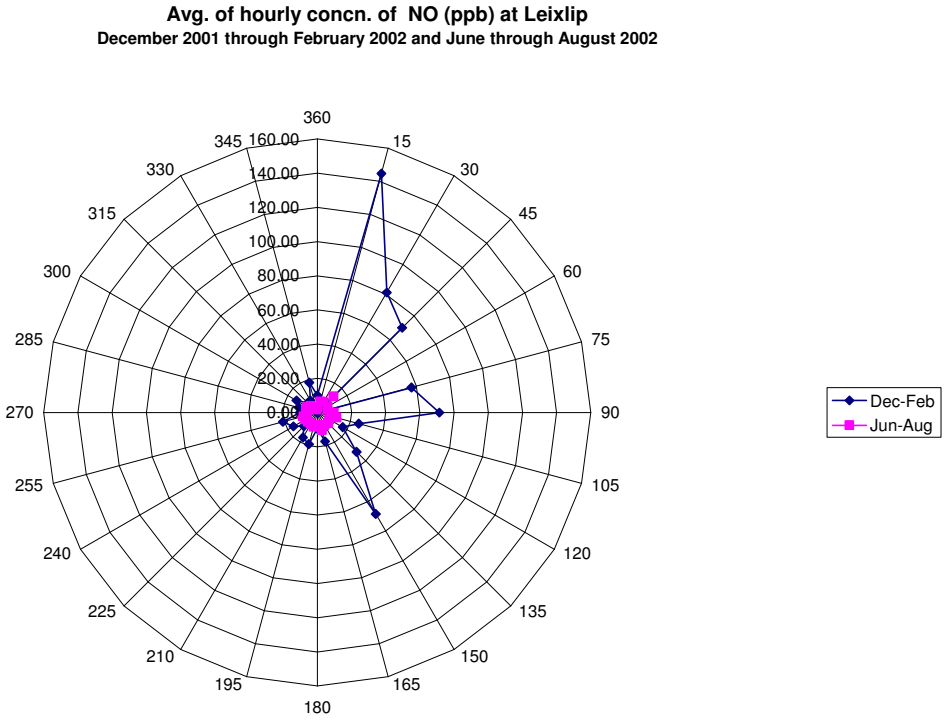


Figure 3.27: Comparison of NO concentration roses for summer and winter

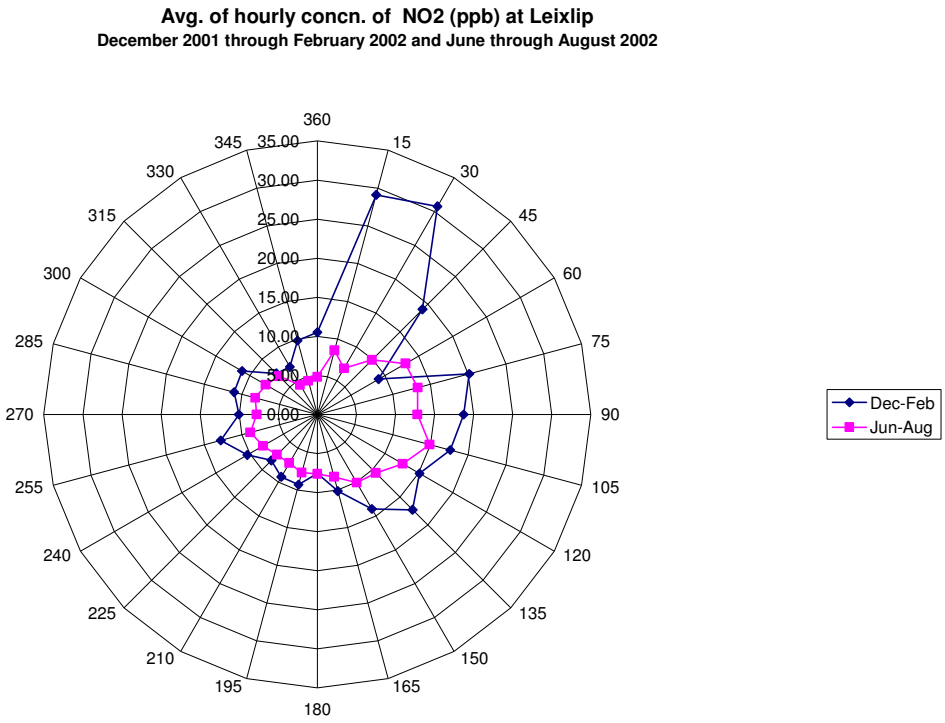


Figure 3.28: Comparison of NO_2 concentration roses for summer and winter

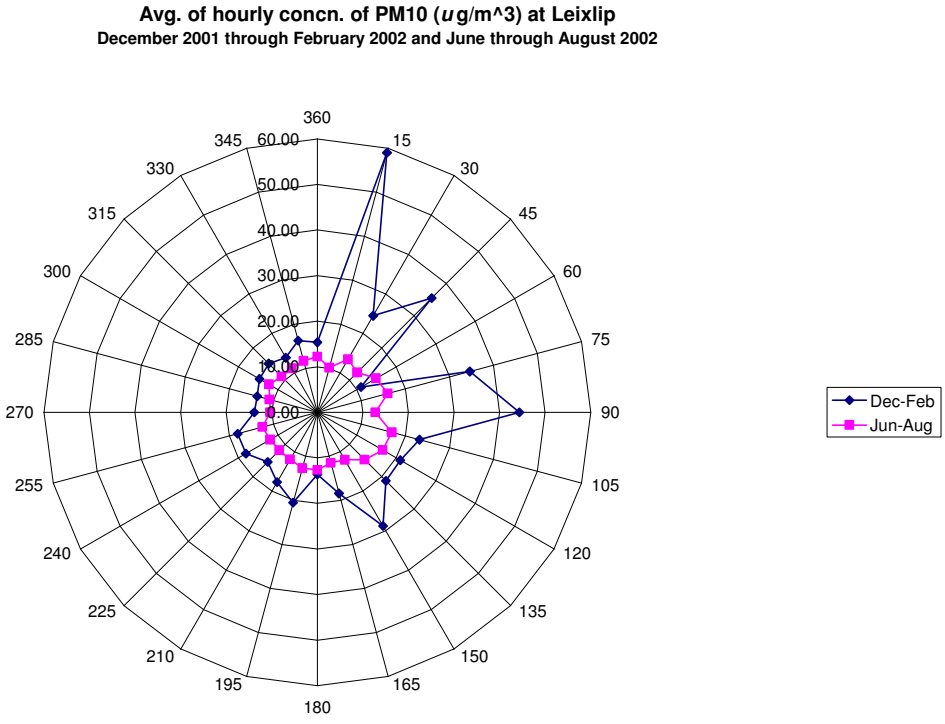


Figure 3.29: Comparison of PM_{10} concentration roses for summer and winter

Figures 3.30 to 3.35 show the diurnal variation in pollutant concentrations, comparing winter with summer, and including a comparison between weekdays and weekends for CO (Figures 3.31 and 3.32); plots of weekday and weekend mean concentrations of NO, NO_2 and PM_{10} can be found in Appendix A (Figures A.8 to A.10).

The average concentrations are higher in winter than summer for all pollutants and at any time of day, except for NO_2 between 02:00 and 06:00. Winter concentrations show a greater diurnal range than summer concentrations. The effects of the diurnal variation in the traffic source can be seen more clearly in winter, with the morning and evening peaks separated by the lunchtime trough, when conditions are never stable. The winter minimum is significantly higher than the summer minimum suggesting a seasonal variation in background levels.

The diurnal variation in CO and PM_{10} is similar, suggesting that once background levels have been established for each, modelling of one could be sufficient to indicate concentrations of the other, allowing for the differences in dispersion and in resuspension of particulate matter. NO and NO_2 differ from CO and PM_{10} due to the diurnal photochemistry. NO_2 decreases overnight in the absence of sunlight; some being converted to HONO. At sunrise HONO can be converted (with sunlight) to NO, therefore NO levels increase before the traffic becomes a significant source. In summer, photochemical conversion of NO to NO_2 leads to a suppression of the evening peak in NO concentration.

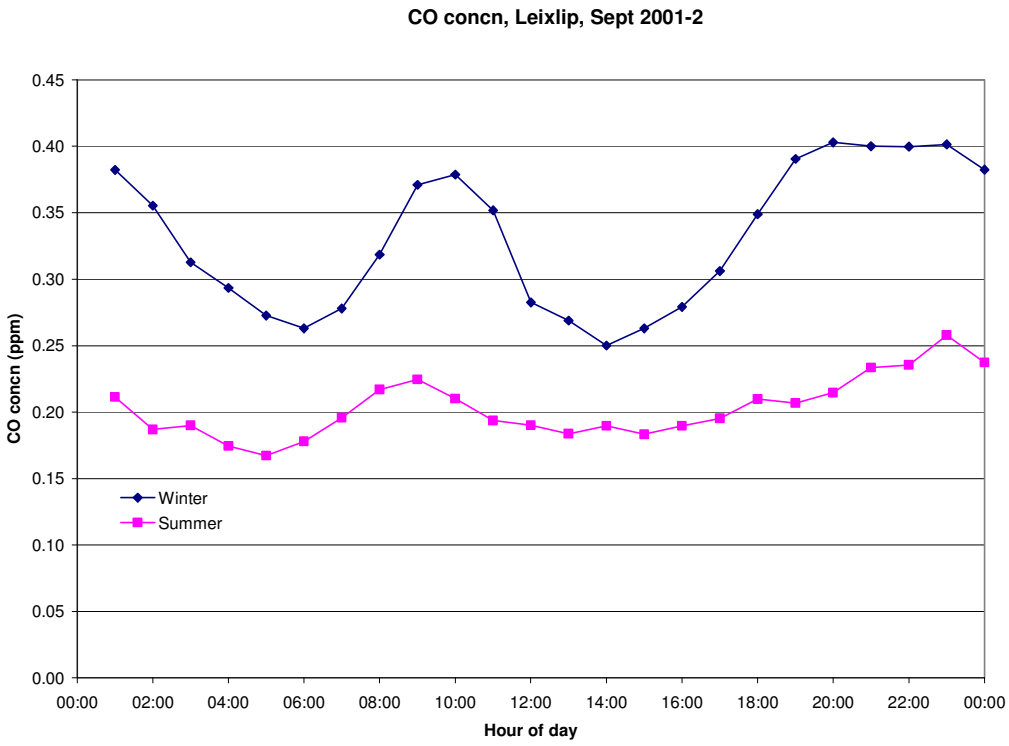


Figure 3.30: Diurnal variation of CO concentration during summer and winter

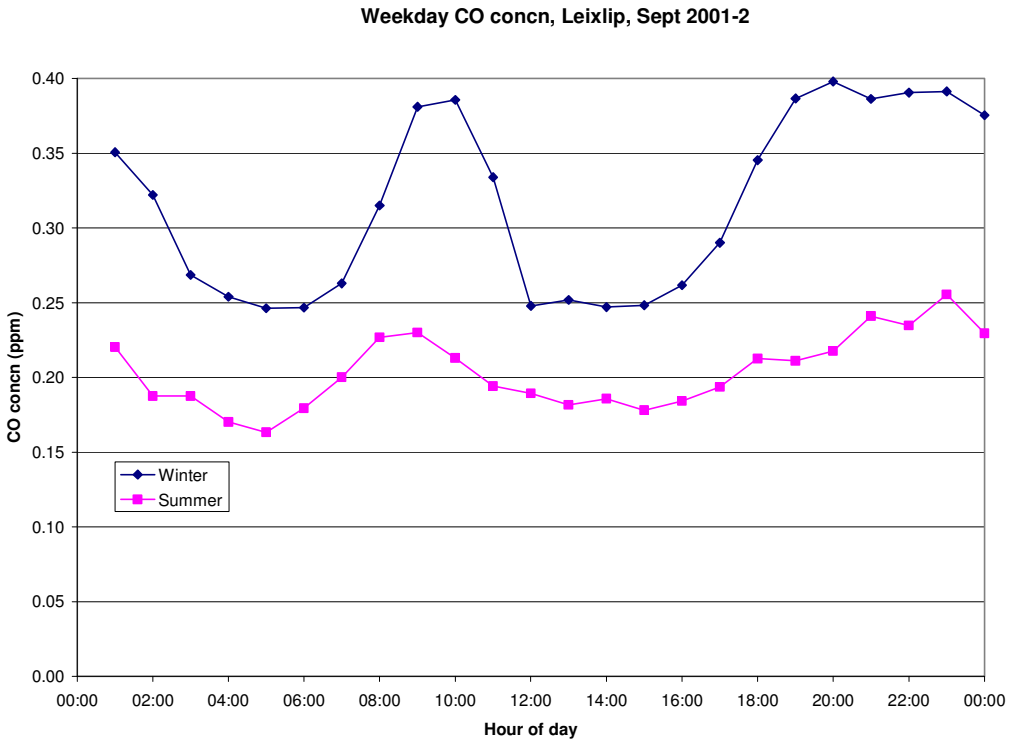


Figure 3.31: Diurnal variation of weekday CO concentration during summer and winter

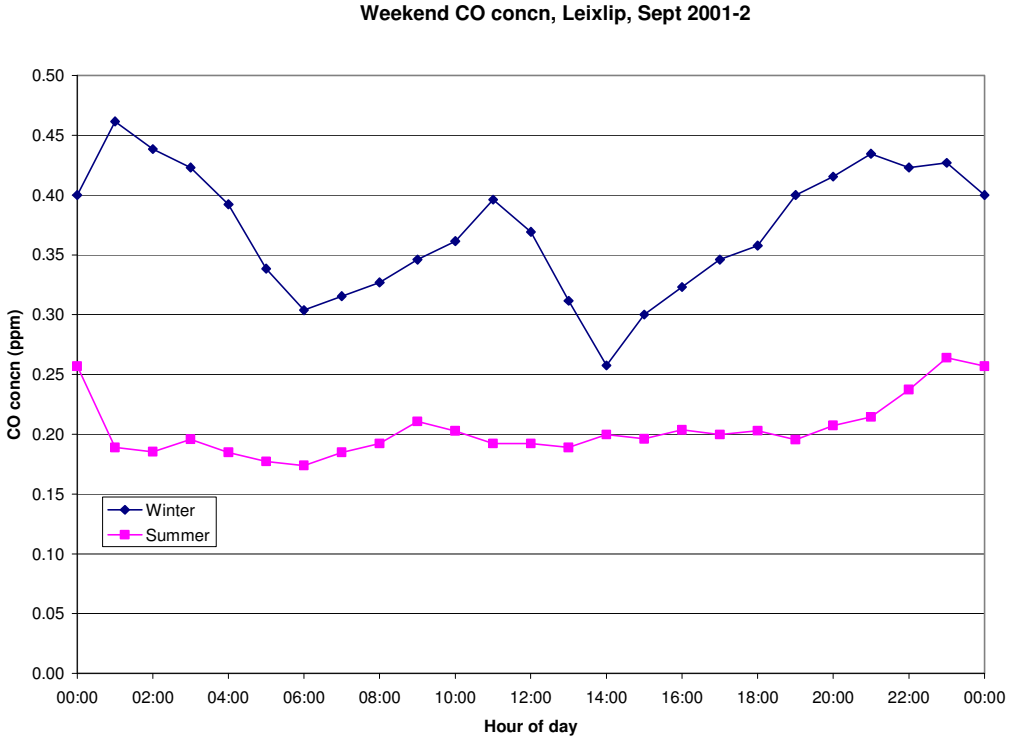


Figure 3.32: Diurnal variation of weekend CO concentration during summer and winter

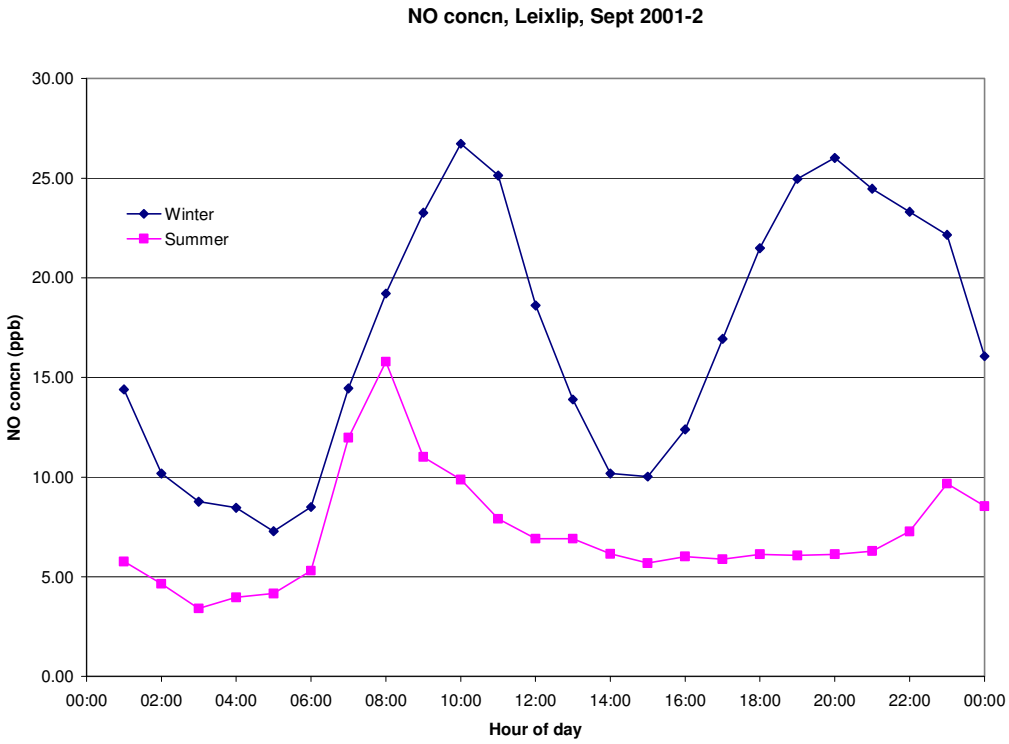


Figure 3.33: Diurnal variation of NO concentration during summer and winter

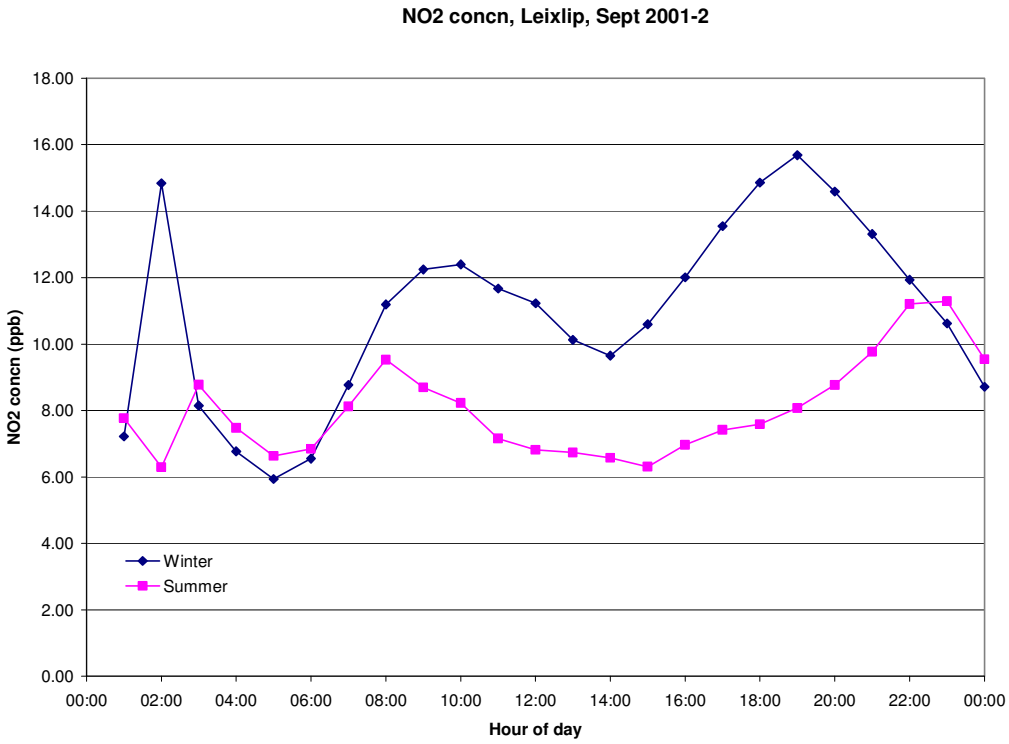


Figure 3.34: Diurnal variation of NO_2 concentration during summer and winter

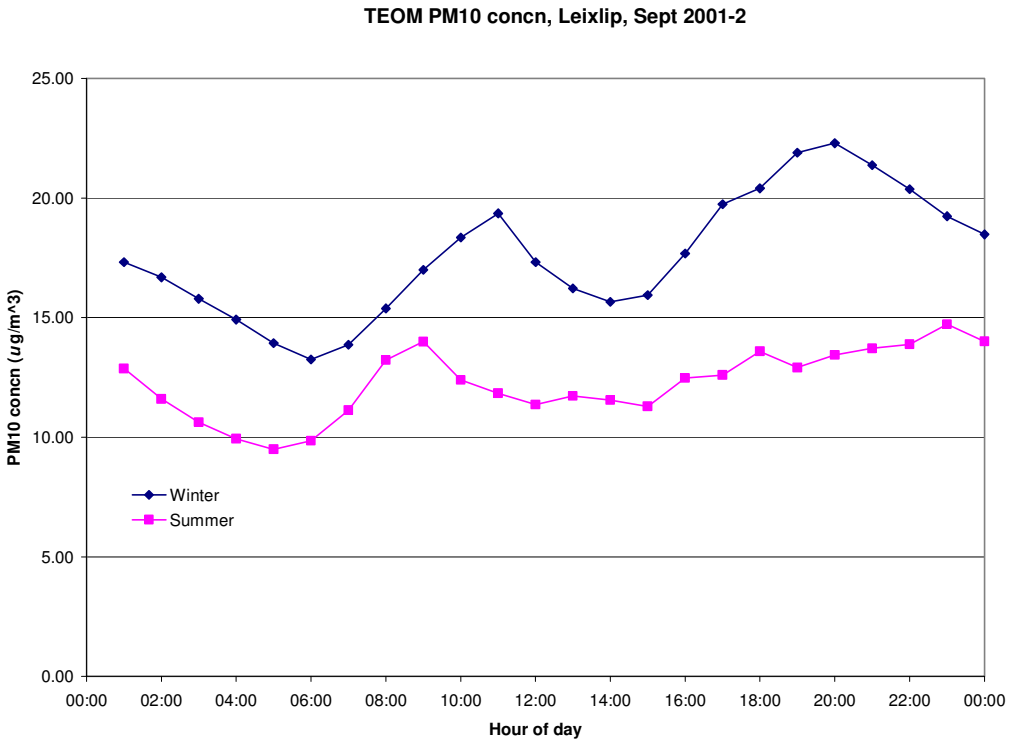


Figure 3.35: Diurnal variation of PM_{10} concentration during summer and winter

4 Monitoring Results for the N6 Roundabout in Galway

4.1 Air Pollutants Monitored

The air pollutants monitored at the Galway roundabout site were: carbon monoxide (CO), nitrogen gases (NO, NO_2, NO_x), particulates (PM_{10}) and CPC counts (condensation particle counter counts, referred to as the total number of aerosol particles per unit volume). Table 4.1 summarises the instrumentation, sampling frequency and monitoring period for each pollutant.

Table 4.1: Air pollutants monitored at the N6 roundabout site

Air Pollutant	Instrument	Monitoring period	Sampling frequency	Comments
CO	Gas Filter Correlation Analyzer, API model 300	June 2001 – September 15 2002	15min and 1hour averages	June-August 2001 data are not validated
NO	Chemiluminescent analyzer, API model 200A	September 15 2001 - September 15 2002	30min and 1hour averages	
NO_2	Chemiluminescent analyzer, API model 200A	September 15 2001 - September 15 2002	30min and 1hour averages	
NO_x	Chemiluminescent analyzer, API model 200A	September 15 2001 - September 15 2002	30min and 1hour averages	
PM_{10}	TEOM	May 2001- September 15 2002	30min average	
PM_{10} (24h)	Partisol, gravimetric	May 2001- September 15 2002	24 hour	
CPC	TSI 3010	May 2001- December 2001	1hour average	

Carbon monoxide concentration was monitored with a gas filter correlation analyzer (API, model 300). The operating principle is based on infrared light absorption by CO molecules. The reliability of measurements was ensured by calibrating the instrument with a standard CO calibration gas from an external cylinder. Autocalibration was performed everyday at midnight, while manual calibrations were carried out every two weeks.

Nitrogen gases – NO, NO_2 and NO_x – were monitored by a chemiluminescent analyzer (API, model 200A). Its operating principle is based on the reaction of NO with ozone, producing NO_2 and light and hence a chemiluminescent reaction. NO_2 gas is calculated as the difference between NO_x and NO. NO_x is measured after conversion of existing NO_2 into NO. The reliability of measurements was ensured by calibrating the instrument with a standard calibration gas from an external cylinder, as for CO.

Measurements of PM_{10} particulate mass concentrations were carried out using a Tapered Element Oscillating Microbalance (TEOM) ambient particulate monitor (Rupprecht & Patashnik Co. Inc., Series 1400a). The basic component of the TEOM consists of a hollow tapered element with a filter cartridge on top, which is clamped at one end but free to move at the other. The crystal element vibrates at its natural frequency. When sample air is drawn through the filter element, particles are deposited on the filter, which decreases the frequency of vibration. The change in frequency of vibration is indirectly proportional to the accumulated mass on the filter. It has been found that semi-volatile aerosol material (e.g. ammonium nitrate, organic carbon compounds) can be lost from the heated sample filter employed in the TEOM and results can be reduced by up to 30% compared to gravimetric samplers (Ayers *et al.*, 1999). At the roundabout site, the TEOM was operated at 40°C to minimise these losses, rather than at the standard 50°C (cf. Leixlip TEOM, which operates at 50°C, in Chapter 3).

PM_{10} particulate mass concentration over a 24-hour period was measured with a medium flow Partisol PM mass monitor, operated by the Public Analyst's Laboratory, University College Hospital, Galway.

4.2 Traffic Flows

The roundabout site is described in Section 2.3. As shown in Figure 2.7, there are five roads leaving the roundabout: the N6 to Dublin, the N84 to Headford (here referred to as Headford Road (N)), the N6 to Galway city centre (Headford Road (S)), Sandy Road connecting to an industrial estate and Castlelawn (Menlo) Road connecting to a residential area. Information on traffic flows was obtained from two sources: a 13 hour detailed survey of all turning movements at the roundabout, and a one month continuous recording of vehicles entering and leaving the roundabout on the N6.

One day detailed traffic survey at the roundabout

A one day survey of traffic flows (and queues) at the roundabout was carried out on Thursday 30th May 2002 by Abacus Transportation Surveys Ltd (Abacus, 2002). The survey hours were from 07:00 to 20:00 hours. Surveillance cameras were installed at different points to cover all traffic entering and leaving the roundabout.

There were two major peaks observed at the junction during the day, a morning peak at 08.30 and an evening peak at about 17.00. A small peak was also observed at lunchtime. The peak flow through the roundabout was close to 4000 vehicles per hour (vph). During the morning peak, the Headford Road (S), Sandy Road and Castlelawn Road approaches were generally free of queues, or experienced only a few minor delays. Between 07:30 and 08:30, Headford Road (N) and the N6 experienced intermittent queues, which were quick to disperse. However, between 08:30 and 09:30, queues were more constant on these two approaches and delays slightly longer. Queue lengths were about 200 m for much of this peak hour, but traffic was moving at the entrance to the roundabout.

Outside the peak periods, traffic at the roundabout generally flowed well, with only occasional small, short-term queues. During the midday/lunchtime period, some queues developed; for example, queues of 100 to 150 m were seen on the Sandy Road approach to the roundabout.

The worst congestion occurred in the evening, between 16:00 and 18:30, on the Headford Road (S) approach. The demand on this approach is often very high, with stationary traffic common at distances of 50 to 75 m back from the yield line. This stationary traffic backs up to the Galway Shopping Centre roundabout further up the road, which is highly congested for much of the late afternoon and early evening peak.

Continuous traffic flow survey for the N6 Dublin Road

The National Road Authority (NRA) carried out a longer survey of traffic flows entering and leaving the roundabout on the N6 Dublin Road. The monitoring period was 18th October to 15th November 2002. These NRA data enabled further analysis of the diurnal variations in traffic and also gave some indication of the differences between weekdays and weekends (Figure 4.1).

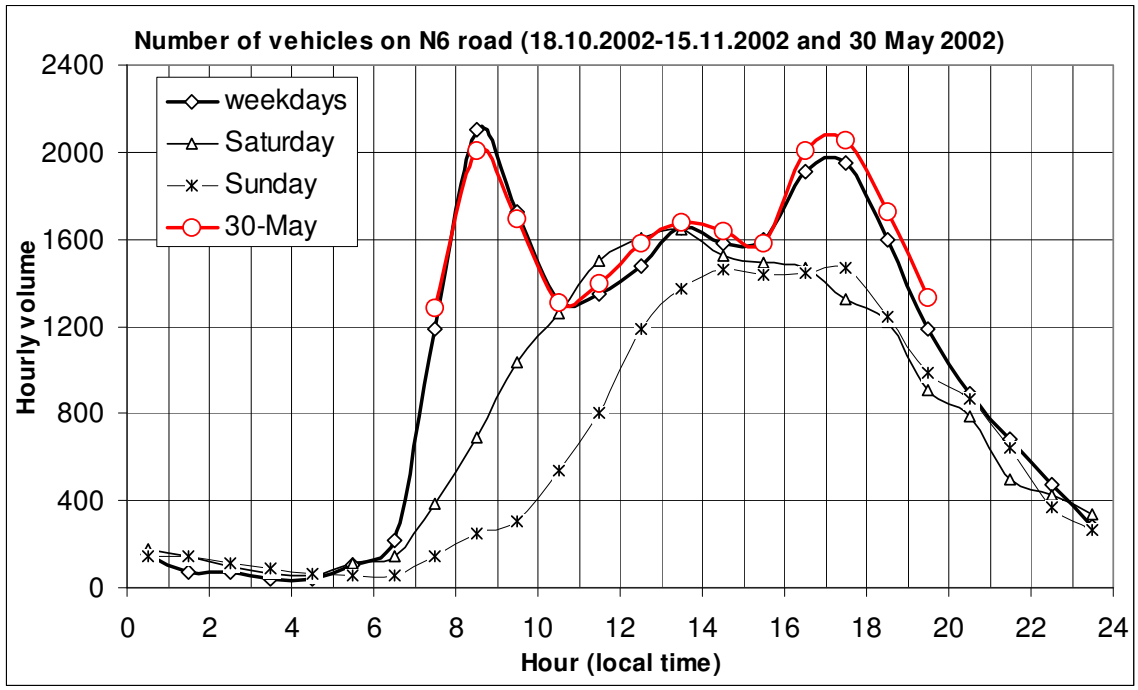


Figure 4.1: Diurnal variations in traffic density (vehicles/hour) on the N6 Dublin road. Abacus survey was performed on a single day, 30 May, 2002.

The morning, afternoon and evening weekday peaks noted in the one-day survey are clearly evident in the NRA results. During Saturdays and Sundays there was a single broad peak (appearing later on Sundays). There is remarkable consistency between the one-day survey and the longer NRA study, especially when it is remembered that the two surveys were separated by an interval of five months. Indeed, some discrepancy would be expected due

to seasonal variation and to the difference in the survey methods: the NRA counted traffic on the N6 Dublin road in both directions for four weeks, while Abacus only counted traffic during a single day, but in full detail on every arm of the roundabout.

4.3 Meteorology

Wind direction and wind speed were monitored on site from May 2001 to December 2002 (data presented in graphs are for the period September 2001 to September 2002). The sensor was set at approximately 5 m above ground level. The data have been analysed for overall patterns and for seasonal variations, distinguishing between cold (December-February) and warm (June-August) seasons. The site data were also compared with wind sensor data collected on the roof of a 15 m high building in the National University of Ireland, Galway (NUIG) campus, about 2 km from the site, close to the city centre. The data from these two Galway sites were also compared with regional data from Shannon airport, located about 70 km from Galway city. Figures 4.2 and 4.3, and Figure B.1 in Appendix B, show the wind direction patterns and Figures 4.4 and 4.5, and Figure B.2 in Appendix B, show wind speeds at the different locations.

The dominant wind direction at all three sites was southwesterly. However, the Shannon Airport data differ significantly from the N6 Road and the NUIG data, both in the frequency of wind direction and the wind speed pattern. Differences in wind direction and wind speed may be partly attributable to the Shannon site being in a different region. In addition, it is likely that the city of Galway has an influence on local wind direction and especially on wind speed due to the built-up areas.

The N6 site data and the NUIG data agree well. Differences in wind speed are probably mainly a result of the different heights of the wind sensors (5 m at the N6 site, 15 m at the NUIG campus). Differences in wind direction in the southeast quadrant (Figure 4.3) might be explainable by the location of the monitor at the N6 site: the site is shielded in the southeasterly direction by the industrial building of Barry Motors Ltd and therefore the wind pattern is somewhat distorted in the SSE direction. Another noticeable difference in the wind directions is the presence of a northeasterly peak in the N6 site data, most likely due to the same reason.

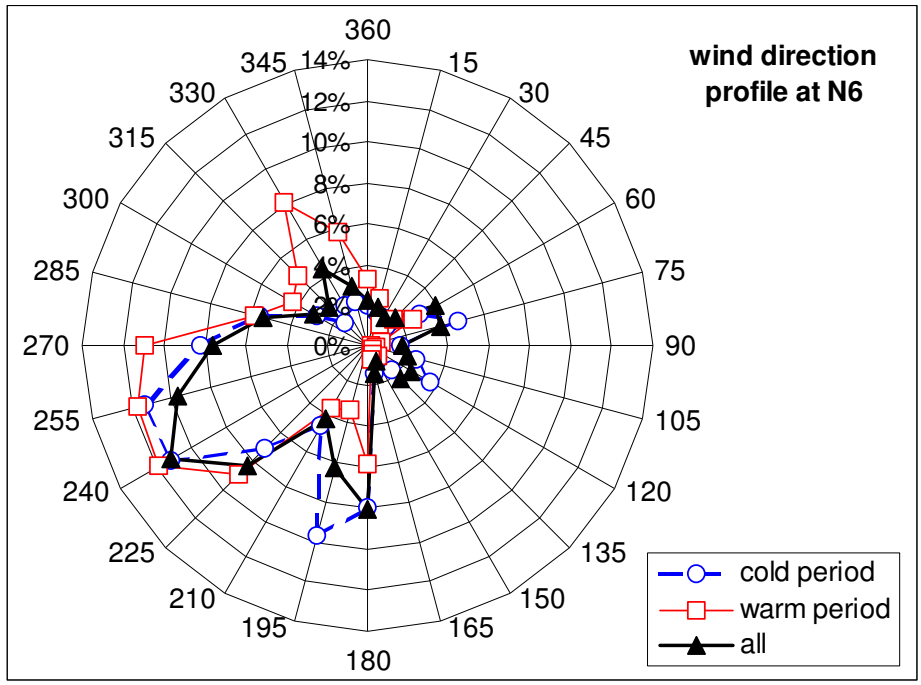


Figure 4.2: Frequency of wind direction at the N6 monitoring site.

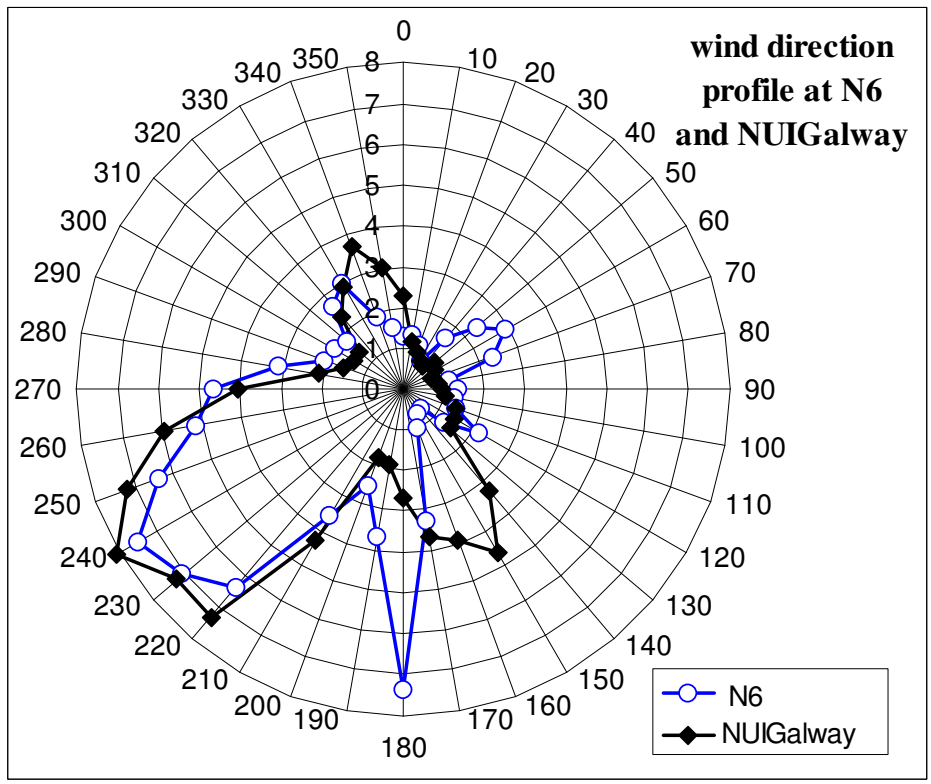


Figure 4.3: Frequency of wind direction at the N6 monitoring site and at NUI Galway.

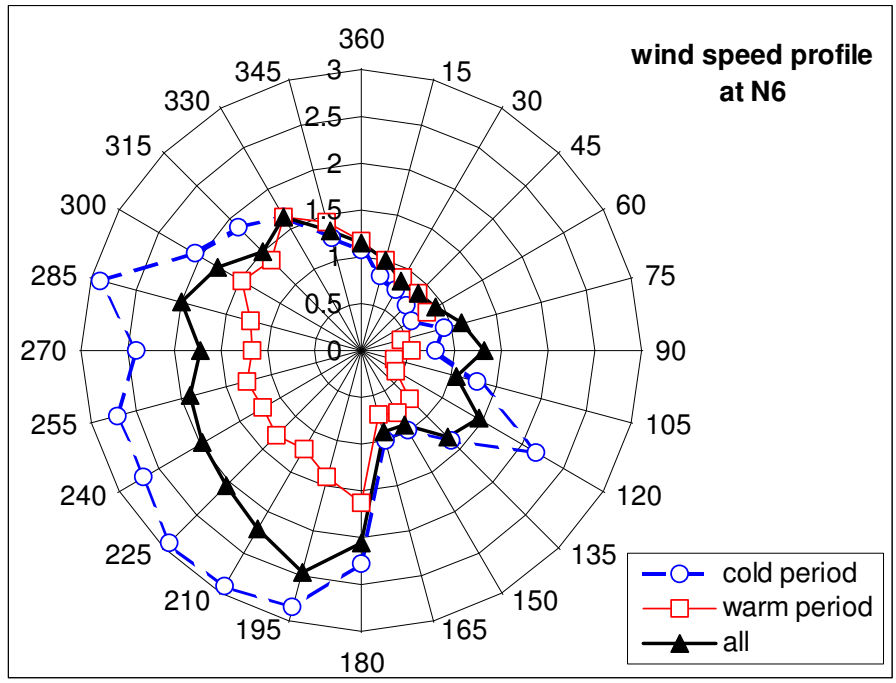


Figure 4.4: Wind speed pattern in m/s at the monitoring N6 site.

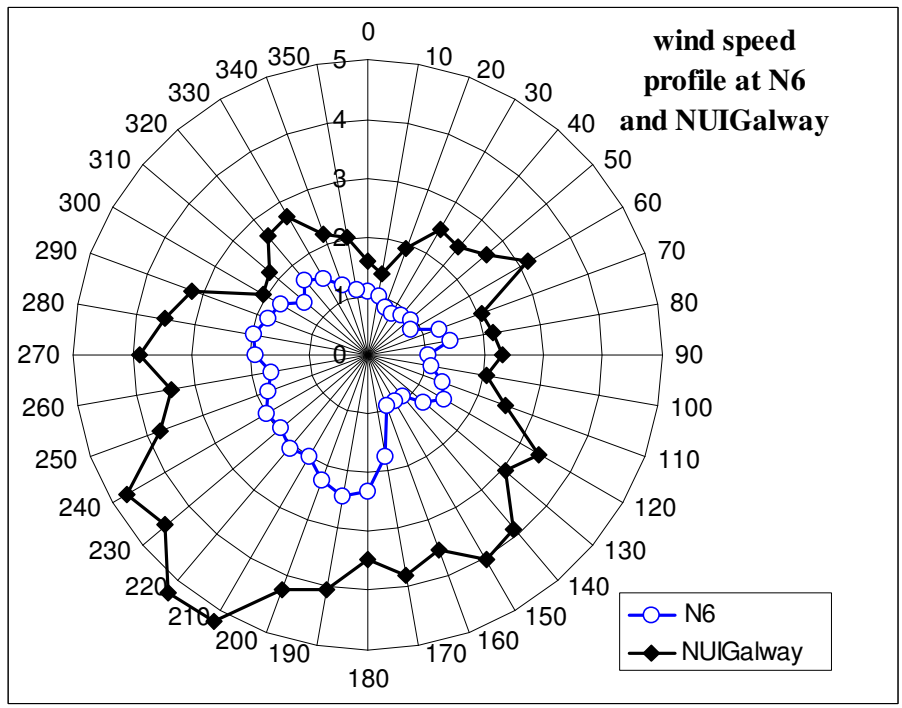


Figure 4.5: Wind speed pattern at the monitoring (N6 road) site and at NUI Galway.

From the above, it is clear that distant and/or regional meteorological data may poorly represent specific localities, especially localities in or near to cities. The usefulness of regional meteorological data for modelling air pollution at individual sites is therefore limited.

Futher analysis was carried out on the wind speed data from the monitoring site: Figures B.3 and B.4 in Appendix B represent wind speed patterns after filtering low values (<0.5 m/s) and higher values (>3 m/s). Low values were filtered because at low wind speeds, wind direction may be poorly determined, thereby distorting the wind speed pattern. Higher wind speeds usually occur in winter.

As can be seen in Figures B.3 and B.4, the general pattern did not change after filtering the low and high wind speed values. The wind speed pattern for wind speeds over 3 m/s was clearly westerly, as expected. High winds during winter usually occurred from a southwesterly direction, and during the summer period from a northwesterly direction. The analysis indicates that low and high wind speeds were rather infrequent and equally distributed. Indeed, wind speed values between 0.5 and 3 m/s accounted for 73% of the total values.

4.4 Air Pollutant Concentrations

The monitoring data presented in this section were collected during the period 15 September 2001 to 15 September 2002. Table 4.2 summarises the monthly statistics of the monitored pollutants including monthly means, maxima, 5^{th} and 95^{th} percentile concentrations. Figures 4.6 to 4.9 show time series of 24-hour average pollutant concentrations for the full year period starting 15^{th} September 2001. It is evident from the graphs that the highest concentrations occurred in winter and the lowest in summer, consistent with the expected seasonal pattern. The highest concentrations were generally observed in November 2001, with some maxima in December 2001. The month of November 2001 was characterised by generally dry weather, clear skies and low wind speed - the absence of rain and the low wind speed resulting in increased PM_{10} concentrations. Clear skies are characteristic of anticyclonic activity bringing air from continental Europe. Moreover, clear skies usually cause temperature inversions during morning and evening hours, when pollution is most intensive. All those conditions favoured increased pollution. Figure 4.8 displays good agreement between the days on which high concentrations of the primary pollutants, CO and NO, were observed.

Table 4.2 Monthly mean, maxima, 5th and 95th percentile concentrations of pollutants at the N6 site in Galway between the period 15/09/2001 and 15/09/2002

HOURLY CONCN												
	NOx	ppb										
	NO2	NO2	NO2	NO2	NO	NO	NO	NO	NOx	NOx	NOx	NOx
	mean	max.	5%ile	95%ile	mean	max.	5%ile	95%ile	mean	max.	5%ile	95%ile
Sep-01	7.8	46	0	25	14.1	117	0.2	58	21.9	155	0.03	80
Oct-01	9.4	44	0	28	15	143	0.08	60	24.3	178	0	85
Nov-01	15.2	56	0	36	32.8	438	0.54	122	48	494	0.3	147
Dec-01	13.9	62	0.21	35	31.5	294	0.4	127	45.4	341	0.84	158
Jan-02	9.7	44	0	27	12.2	147	0.01	52	21.9	184	0.11	76
Feb-02	9.5	39	0	24	13.4	155	0.09	47	22.9	194	0	71
Mar-02	10.1	39	0.29	24	11.9	119	0.6	37	22	145	1.11	60
Apr-02	9.7	36	0	24	11.5	131	0.75	41	21.2	164	0.93	64
May-02	10.5	41	0.95	25	10.9	116	0	38	21.4	144	1.33	63
Jun-02	8	31	0	20	11.9	73	1.01	36	19.8	98	1.06	56
Jul-02	9.1	31	0.9	20	15.1	76	1.1	42	24.2	107	2.39	61
Aug-02	8.2	26	0.46	18	14.1	85	1.25	37	22.3	101	2.01	54
Sep-02	8.1	27	0.32	19	11.8	99	0.6	38	19.8	120	1.66	56
Full year*	10.1	27	3.37	19	16.1	92	2.4	43	26.2	119	5.8	62
HOURLY CONCN					24 HOUR (DAILY)				24 HOUR (DAILY)			
	CO	ppm			TEOM	(ug/m^3)			Partisol	(ug/m^3)		
	CO	CO	CO	CO	PM10				PM10			
	mean	max.	5%ile	95%ile	mean	max.	5%ile	95%ile	mean	max.	5%ile	95%ile
Sep-01	0.38	1.63	0.11	0.96	26.2	45.6	13.6	43.7	24.5	42	10.3	41.4
Oct-01	0.38	1.92	0.09	0.98	23.2	42.8	12.7	37.4	22.3	43	10.5	38.5
Nov-01	0.61	4.39	0.12	1.69	32.9	89.9	10.3	79.5	35	93	11	85
Dec-01	0.64	3.67	0.12	1.62	35.6	104.5	8.8	92.6	42.6	110	9.4	103.9
Jan-02	0.42	2.52	0.11	1	26.4	61.2	14	50.1	28.1	67	16.7	46.3
Feb-02	0.47	3.05	0.11	0.97	25.1	39.6	15.5	37.6	24.9	39	14.4	38
Mar-02	0.47	1.47	0.14	1.02	29.3	50.6	13.4	44.9	29.7	68	12	44.8
Apr-02	0.46	1.73	0.14	0.92	25.9	52.4	12.6	45.5	26.6	68	12	54.8
May-02	0.43	1.4	0.11	0.86	20.8	46.2	11.3	32.2	22.5	41	11.4	39
Jun-02	0.38	1.04	0.1	0.72	21.3	39.8	9.9	32.2	19.5	38	8.5	29
Jul-02	0.41	1.04	0.12	0.72	19.3	36.1	11.4	36.1	16.1	32	25.5	26.6
Aug-02	0.42	1.21	0.11	0.84	19.3	31.8	11	30.5	16.7	35	7.4	27
Sep-02	0.42	1.7	0.12	0.85	23.9	35.7	15.8	33.1				
Full year*	0.46	1.27	0.24	0.87	25.5	105	11.2	46.8	25.6	110	10	53

*Full year statistics based on 24 hour averages.

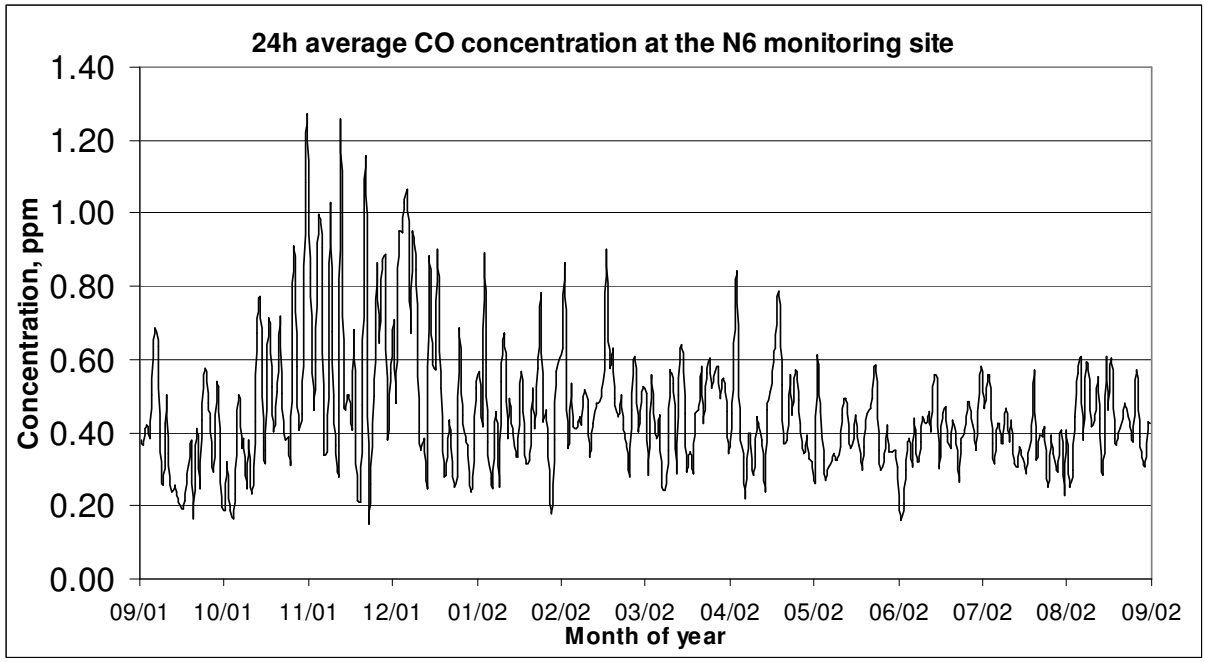


Figure 4.6: 24-hour average CO concentrations at the N6 site in Galway over the period 15/09/2001 to15/09/2002

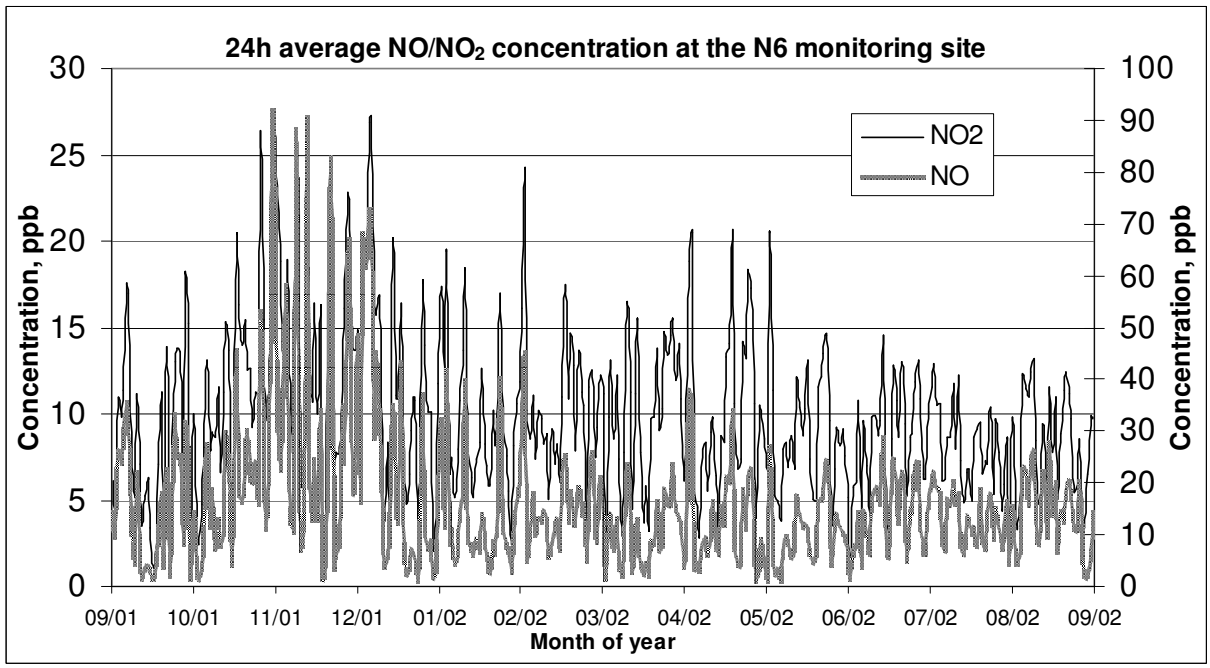


Figure 4.7: 24-hour average NO and NO_2 concentrations at the N6 site in Galway over the period 15/09/2001 to15/09/2002

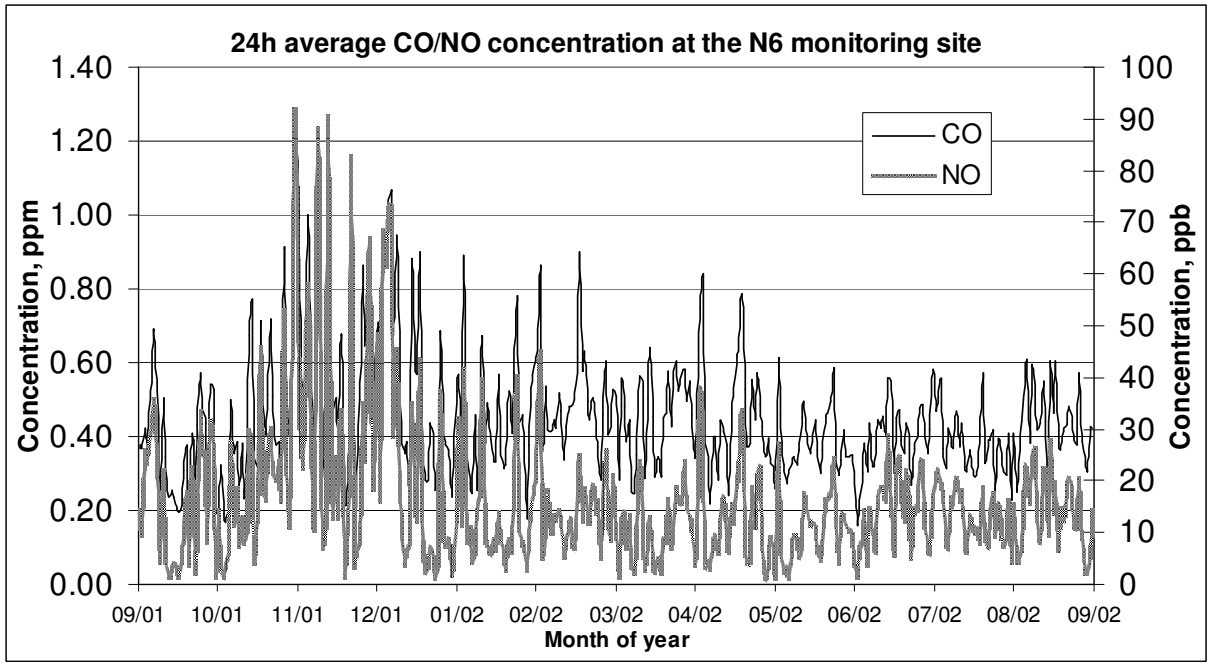


Figure 4.8: Comparison of 24-hour average CO and NO concentrations at the N6 site over the period 15/09/2001 to15/09/2002

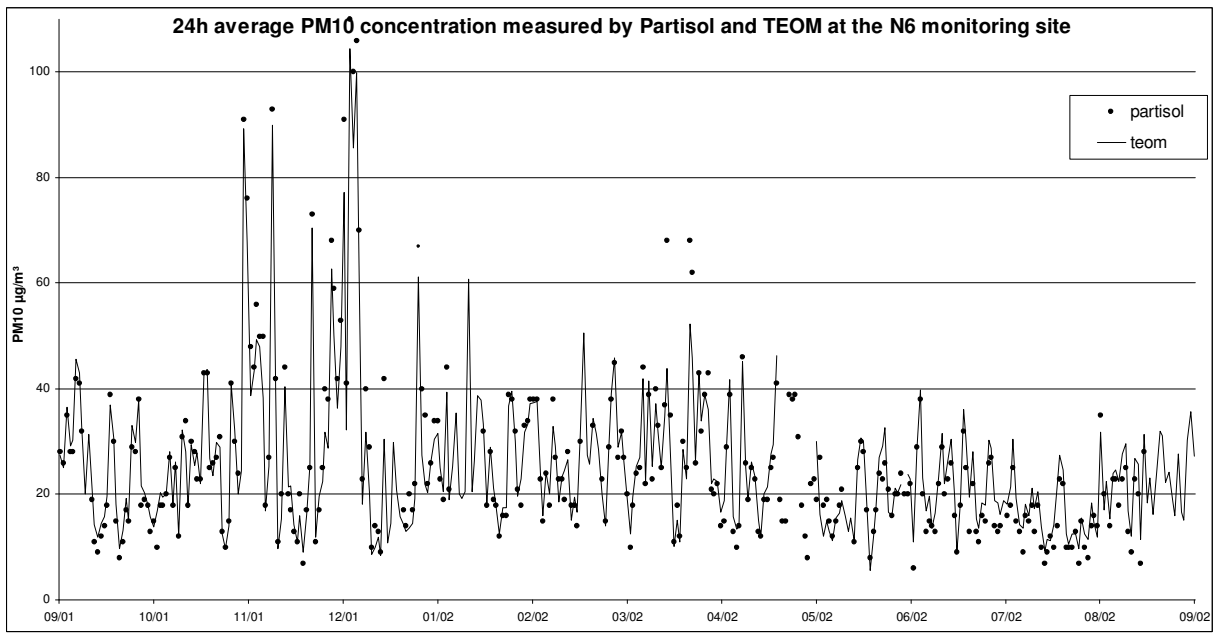


Figure 4.9: 24-hour average PM_{10} concentrations monitored by TEOM and gravimetric (Partisol) methods at the N6 site

Carbon monoxide and nitrogen oxides

Monitoring of gaseous pollutants at the N6 site showed, that highest concentrations occurred in the months of November and December (Table 4.2). Maximum concentrations never reached limit values, and the 95th percentile concentrations were usually less than 1 ppm, 50 ppb and 30 ppb for CO, NO and NO_2, respectively.

Particulates

As noted in Section 4.1, particulates at the N6 site in Galway were monitored by two methods: gravimetric and the TEOM. Gravimetric measurements provided 24-hour averages, while TEOM data were processed for averaging periods of 30 minutes and one hour (the latter is used in all graphs presented here). There is reasonably good agreement between the TEOM and Partisol PM_{10} measurements (r^2=0.94, Figure 4.10).

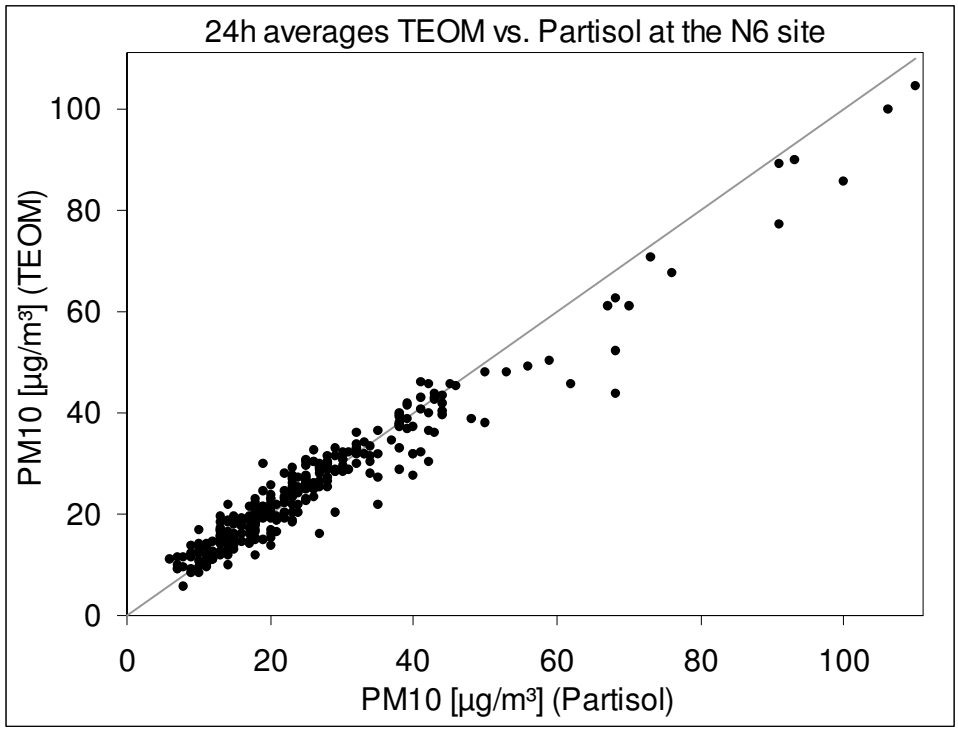


Figure 4.10: Plot of PM_{10} concentrations measured by the TEOM versus the Partisol

The annual average concentration of 25.5 µg/m³ measured by the TEOM agrees very well with that of 25.6 µg/m³ measured by the Partisol. Within the range 20 to 30 µg/m³ there was an excellent agreement (see, for example, the data for October 2001 and February 2002 in Table 4.2). This agreement is quite different from the general finding elsewhere that the TEOM causes significant losses (up to ~30%) [Ayers *et al.*, 1999]. In this regard, it is worth

repeating that the TEOM at the N6 site was operated at 40°C, thus probably minimising losses.

The values measured by the TEOM tend to be slightly lower than the Partisol measurements when concentrations are high, and slightly above the Partisol when concentrations are low (Figure 4.10). It is very likely that when PM_{10} concentrations are high there are more organic volatile species in aerosols, which are partially lost by the TEOM. When PM_{10} concentrations are low, it seems that gravimetric measurements suffer from lack of sensitivity, e.g. when PM_{10} concentrations are less than about 10 µg/m³, there is only ≤ 240 µg of particulate mass collected on the filter, making it difficult to weigh precisely.

The 95th percentile mass concentrations were usually below the EU Directive 24 hour limit value of 50 µg/m³. There were fewer than 35 days over the year when PM_{10} concentrations exceeded the limit value, suggesting that PM_{10} pollution may not be a significant problem in Galway even at congested sites such as roundabouts and junctions. The yearly average of 25 µg/m³ is also well below the limit value (40 µg/m³).

4.5 Analysis of Monitoring Results

The data presented in the previous section indicated that pollution levels at the N6 site were generally low. Inspection of the monitoring results shows that the major part of this pollution comes from vehicular traffic. Figures 4.11 to 4.22 illustrate the average diurnal variation of pollutant concentrations at the N6 site.

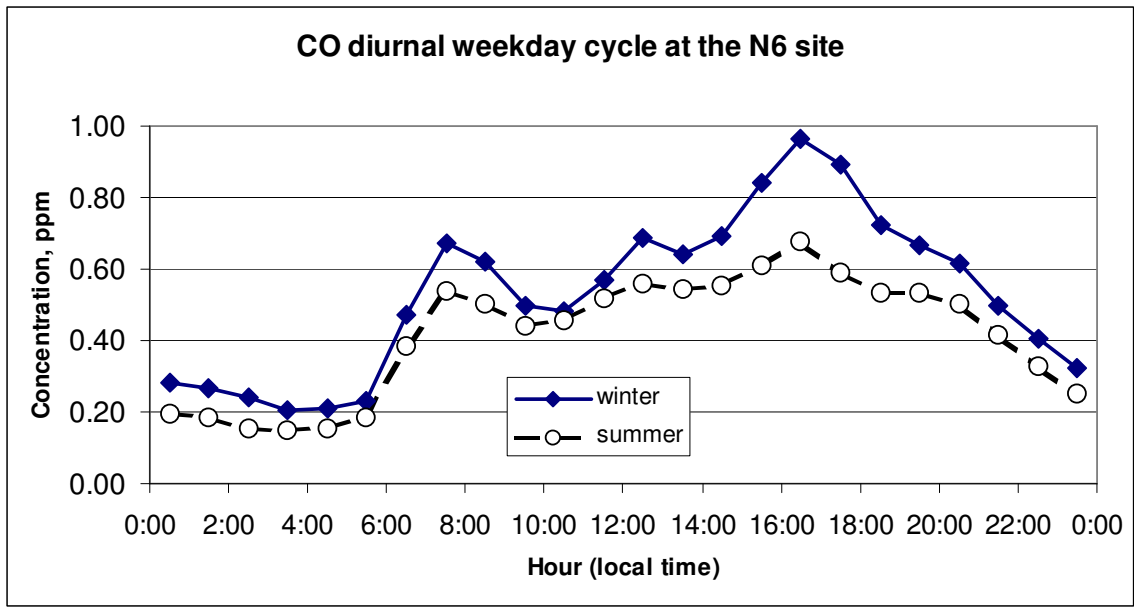


Figure 4.11: Average diurnal variation of CO at the N6 site on weekdays.

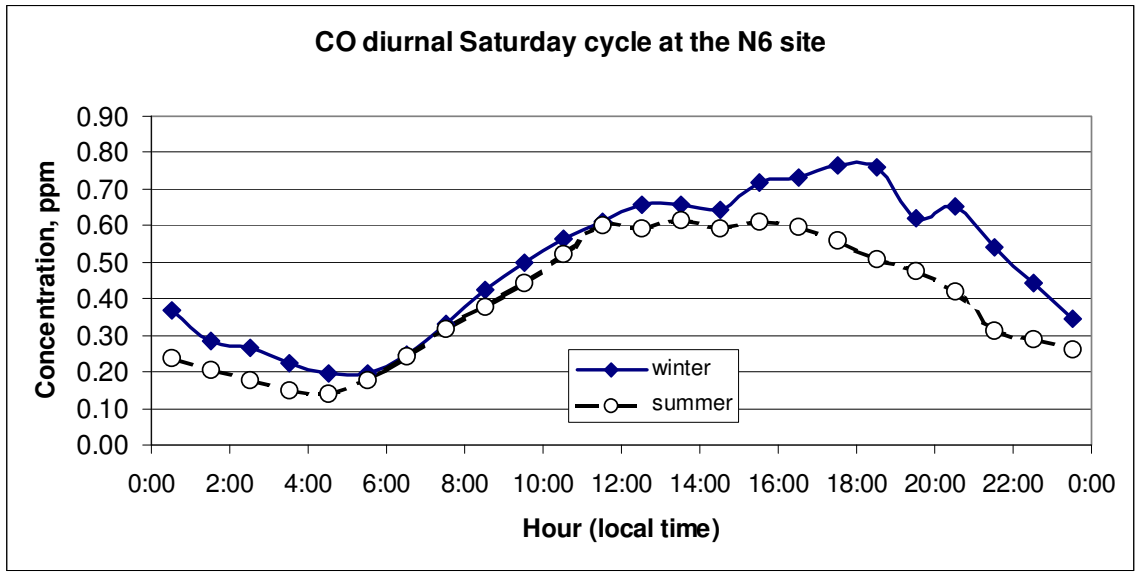


Figure 4.12: Average diurnal variation of CO at the N6 site on Saturdays

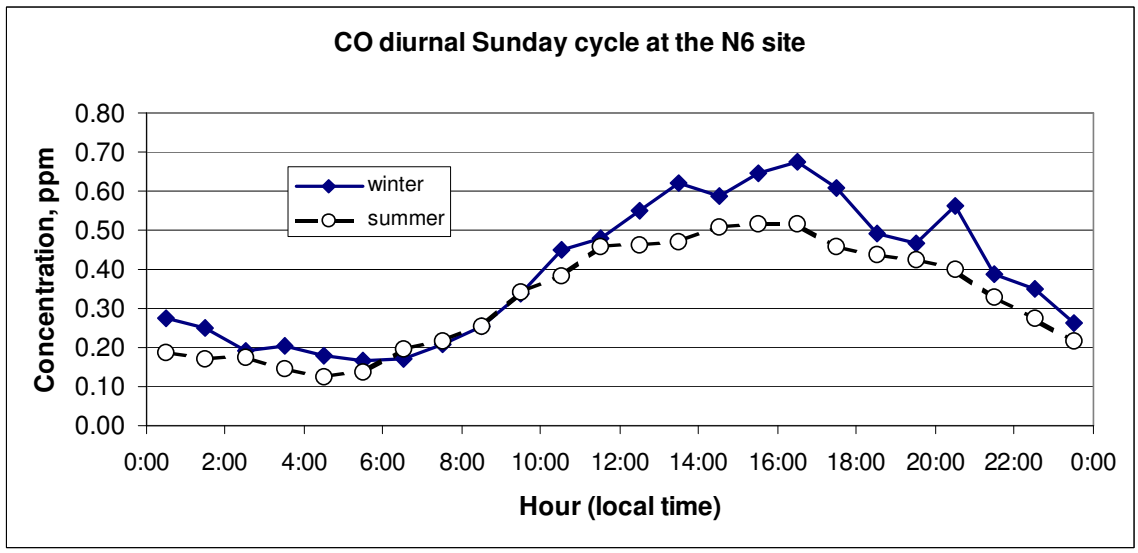


Figure 4.13: Average diurnal variation of CO at the N6 site on Sundays

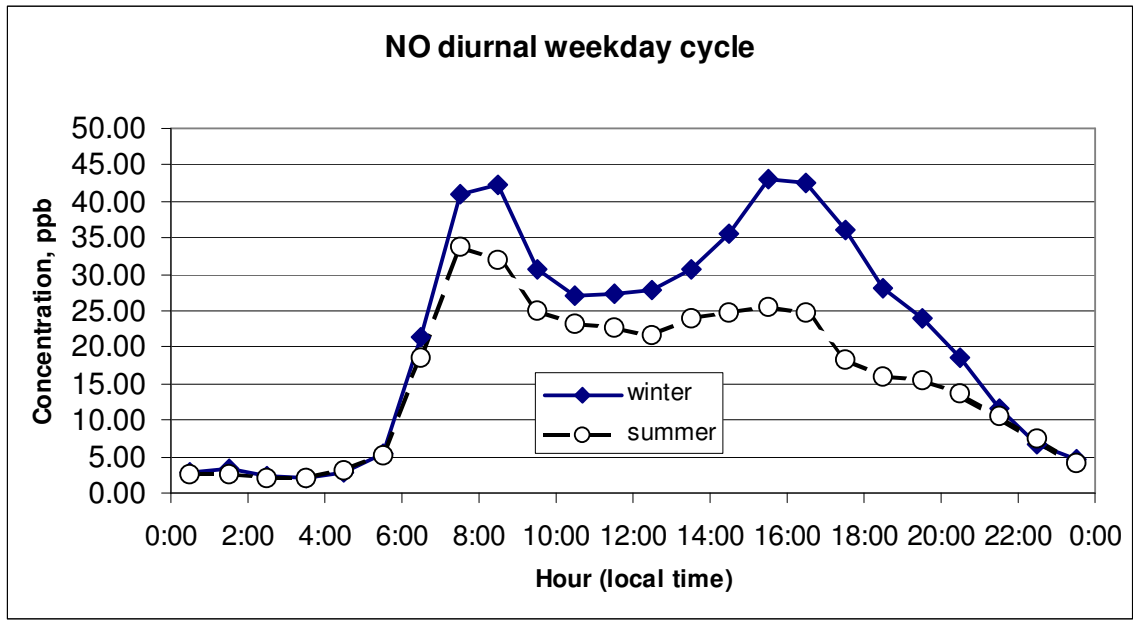


Figure 4.14: Average diurnal variation of NO at the N6 site on weekdays

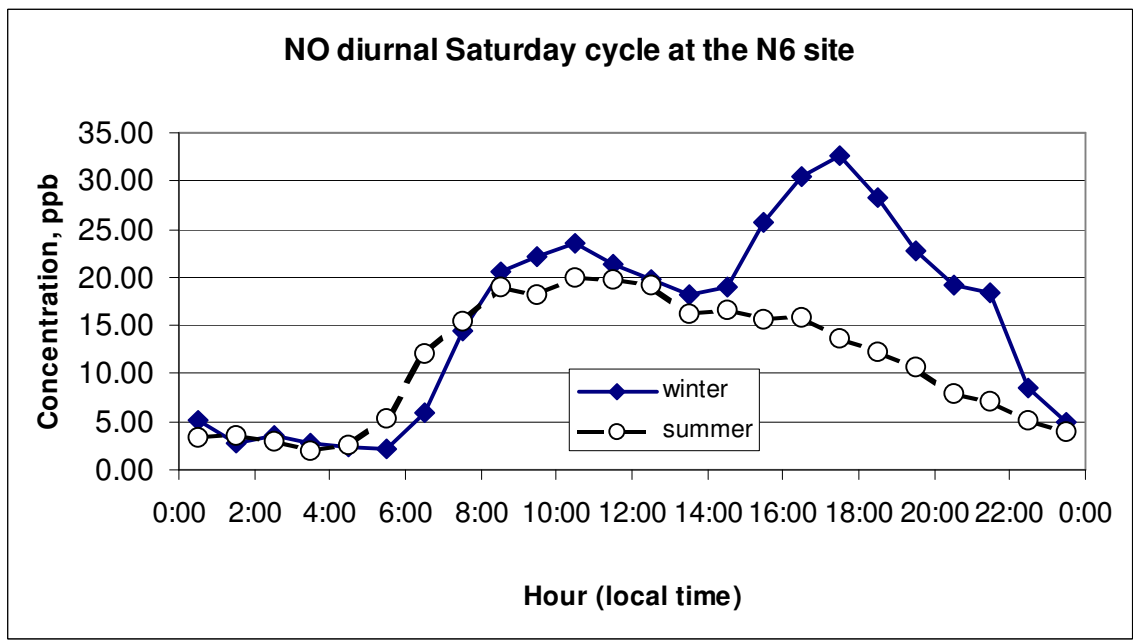


Figure 4.15: Average diurnal variation of NO at the N6 site on Saturdays

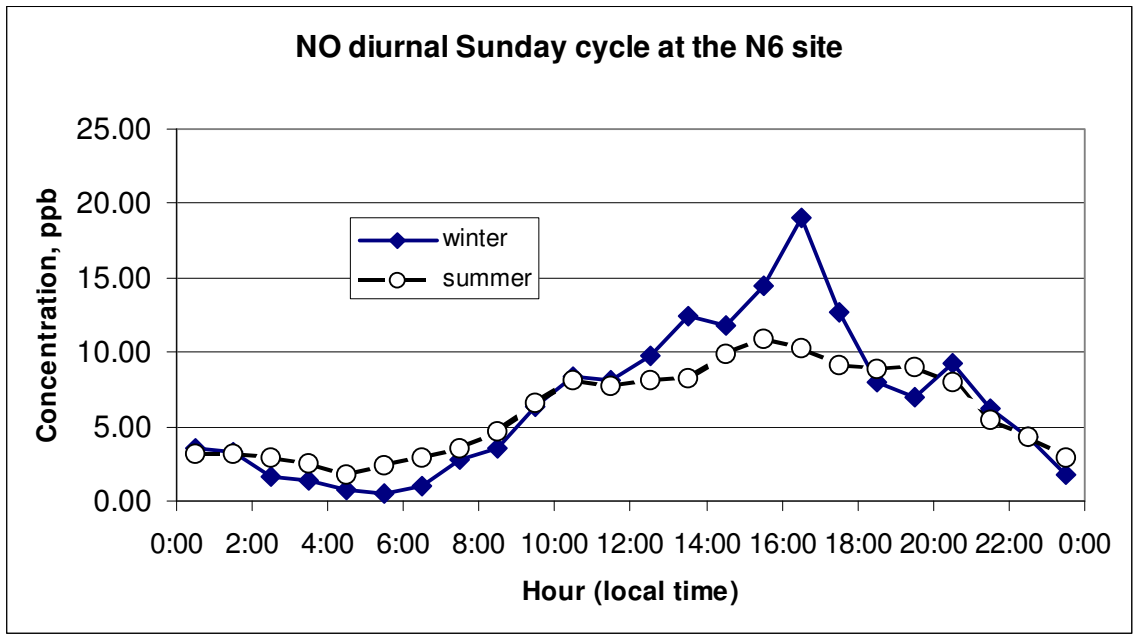


Figure 4.16: Average diurnal variation of NO at the N6 site on Sundays

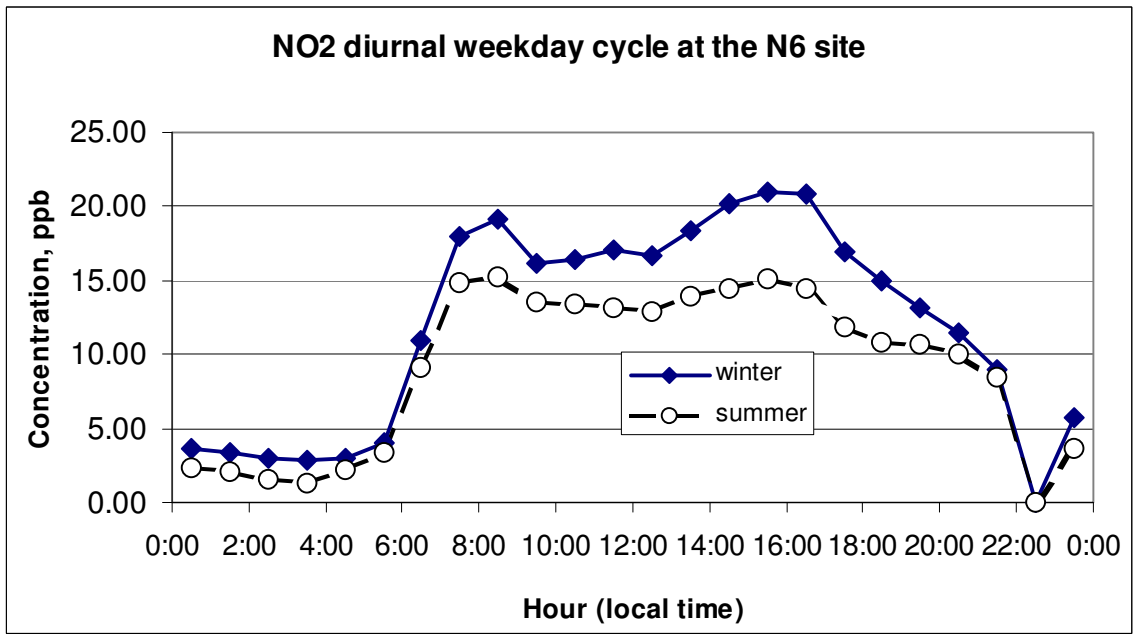


Figure 4.17: Average diurnal variation of NO_2 at the N6 site on weekdays

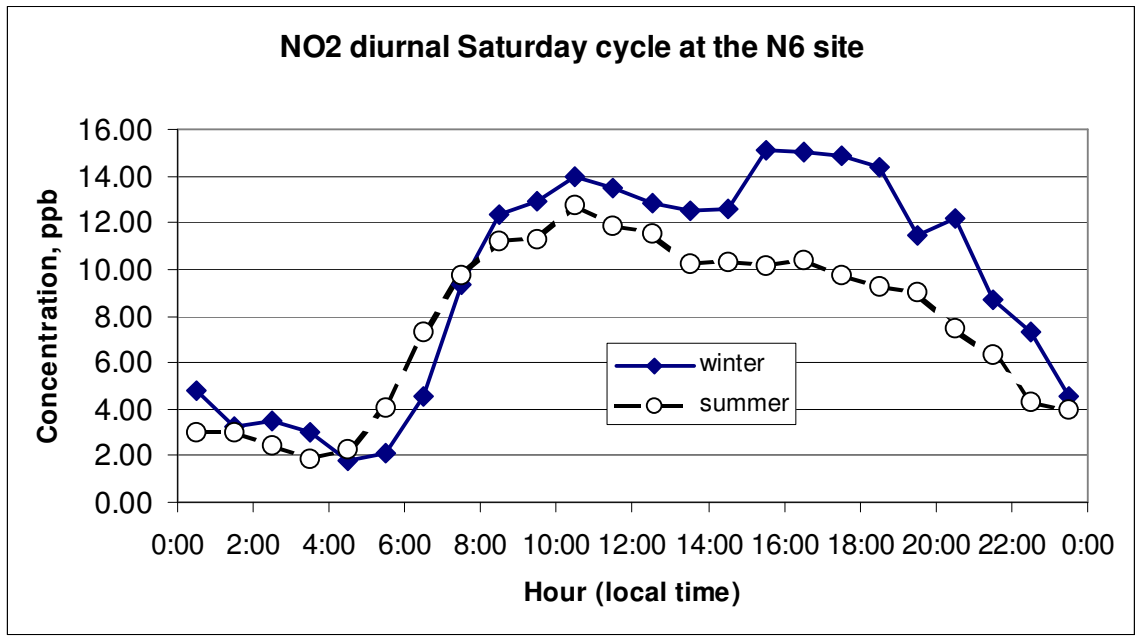


Figure 4.18: Average diurnal variation of NO_2 at the N6 site on Saturdays

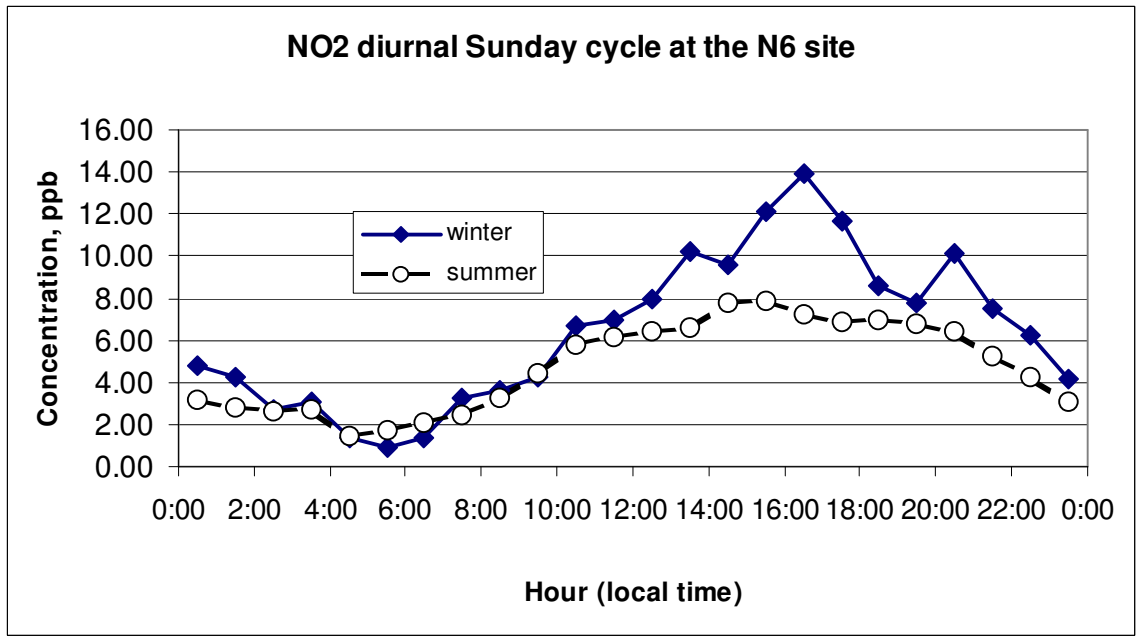


Figure 4.19: Average diurnal variation of NO_2 at the N6 site on Sundays

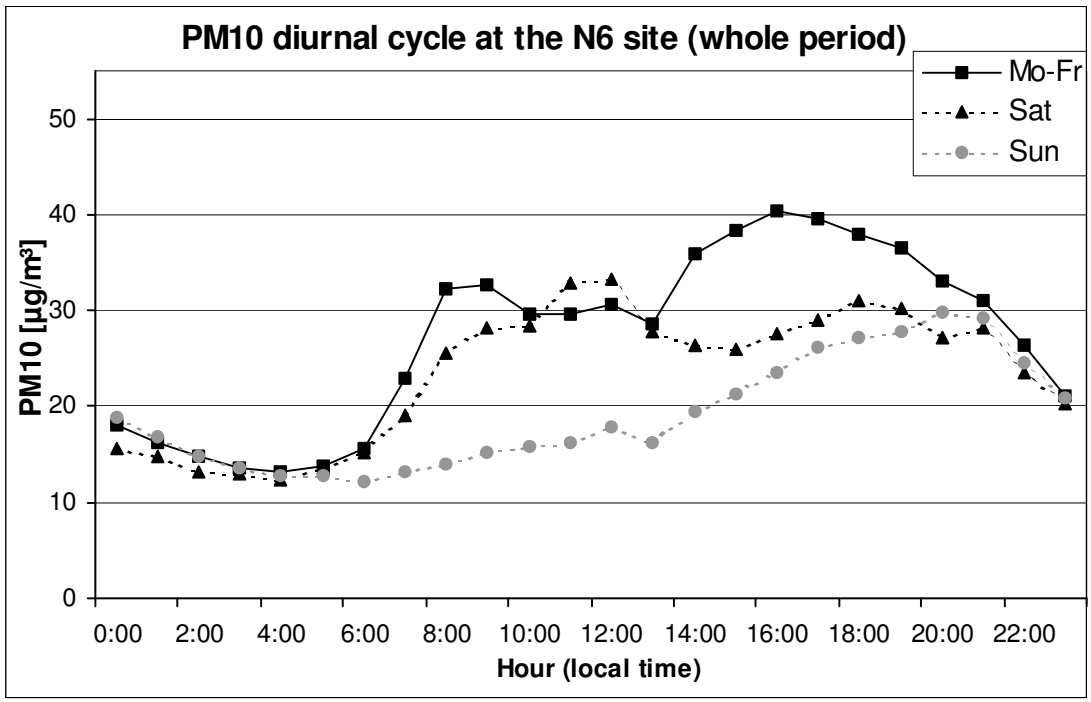


Figure 4.20: Average diurnal variation of PM10 at the N6 site over the whole period

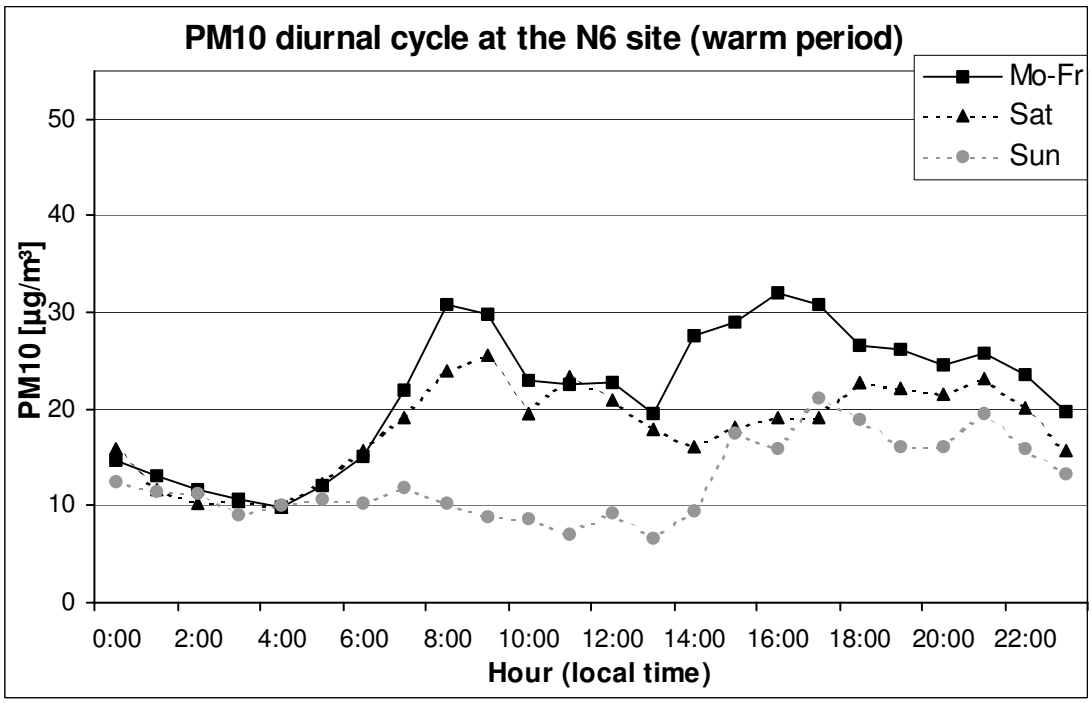


Figure 4.21: Average diurnal variation of PM10 at the N6 site during the warm period

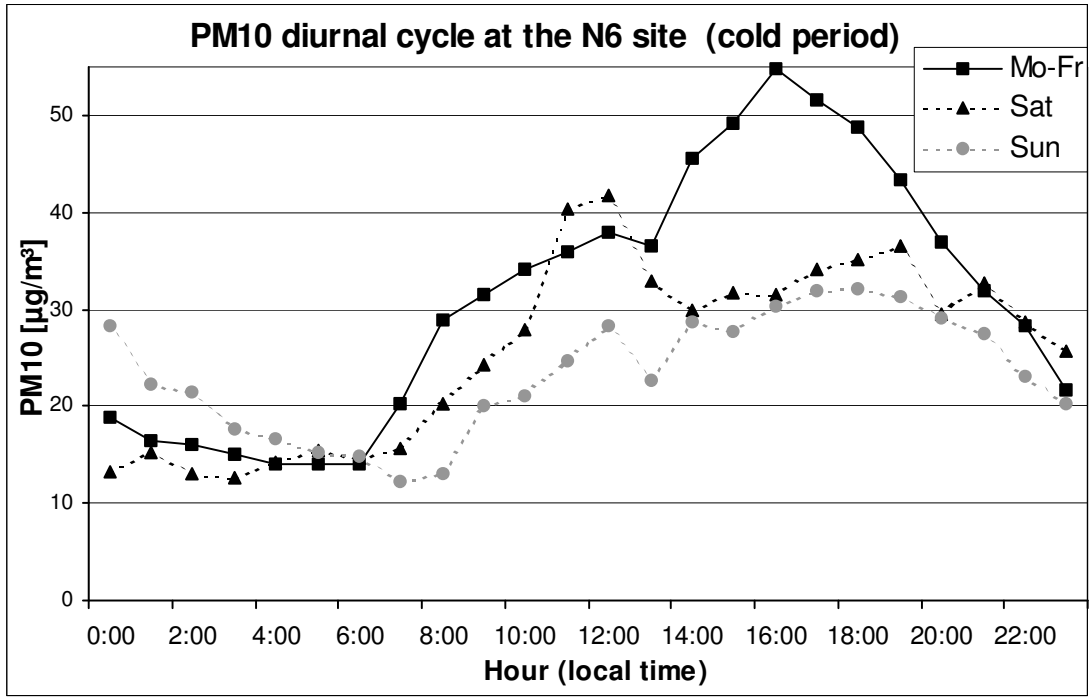


Figure 4.22: Average diurnal variation of PM10 at the N6 site during the cold period

The graphs for CO, NO and PM_{10} all indicate a pronounced morning and evening peak in weekdays, as well as a small lunchtime peak for CO and PM_{10}. The morning peak occurs at 08:30, the evening peak at 17:00 and the lunchtime peak at 12:30. These peaks agree well with the peaks in traffic flows illustrated in Figure 4.1, suggesting that most of the pollution is traffic-related. There are some differences in the detailed diurnal patterns for the different pollutants. For example, NO and NO_2 concentrations decline to nearly zero during the night, indicating that nitrogen compounds derive entirely from local sources. Between 03:00 and 04:00, the concentrations of NO and NO_2 at Leixlip (Figures 3.33 and 3.34) are higher than those at Galway. For CO and PM_{10}, on the other hand, there is an enhanced evening peak and an apparent background during the night, which was observed at both sites. For NO_x the enhanced evening peak and apparent background during the night were only observed at the motorway site but not at the roundabout.

The diurnal variation during the weekend (Figures 4.12, 4.13, 4.15, 4.16, 4.18, 4.19, 4.21 and 4.22) is very different from the weekday pattern, and there are also differences between the patterns observed on Saturdays and Sundays. Similar variations can be seen in the traffic flows (Figure 4.1). However, the NO diurnal cycle on Saturday is slightly different from the traffic flow pattern. It is likely that such a difference is caused by the nature of traffic. On Saturday people drive to the city and spend some time there, then drive back. Therefore, engines cool down during their stay. Cool engines always produce more NO until they become hot (this is the nature of the engine), thus two distinct peaks appear. CO and PM emissions are not so dependent on engine temperature.

Separate analysis of pollutant concentrations was carried out involving wind direction and speed. An association with wind direction can provide an insight into the principal sources of pollutants, while wind speed is generally responsible for dispersing and diluting airborne pollutants. The directional analysis of pollutants at the N6 site is presented in Figures 4.23 to 4.25 and Figures B.5 to B7. The results show that there were two distinct sectors from where highest concentrations appeared, corresponding to northwesterly and more especially northeasterly wind directions. Figure 2.3 shows that the N6 roundabout is located to the northwest of the monitoring location, while the N6 Dublin Road runs to the northeast. Winds from the NE are in a narrow band (40-70°) and associated with low wind speeds. This is further confirmation that the pollutant pattern is strongly dependent on traffic emissions. During cold periods, pollutant concentrations were significantly higher, but exhibited the same pattern as for the whole period.

Correlation analysis between CO and NO concentration is presented in Figure 4.26. The correlation coefficient was high, with $r^2 = 0.86$. Allowing for the number of data points (roughly 9000), this correlation is considered to be very good. However, there is always an "excess" of CO concentration; in other words, when NO concentration is close to zero, CO concentration always has a value above zero (generally of the order 0.2-0.4 ppm). This phenomenon is most likely the result of additional sources of pollution other than local traffic, i.e. background concentration.

The strong influence of wind speed on CO concentration is illustrated on Figure 4.27. The data used for this figure were filtered in such a way that values from only the evening peak were selected for examination. The reason for this was that the evening peak is broader than the morning peak, and so the dependence on wind speed may be more clearly pronounced. Figure 4.27 exhibits an interesting feature, which is that every particular wind speed may be characterised by a maximum and minimum concentration. There are, of course, parameters other than wind speed that influence pollutant concentrations, namely wind direction, air mass history and vertical turbulence caused by surface temperature. Nevertheless, it appears from this analysis that wind speed has the largest and best defined influence on CO concentration, while other parameters perhaps are of secondary importance. Figure 4.27 also shows the potential for making simple forecasts: knowing only the wind speed, one can forecast the maximum concentration at the site.

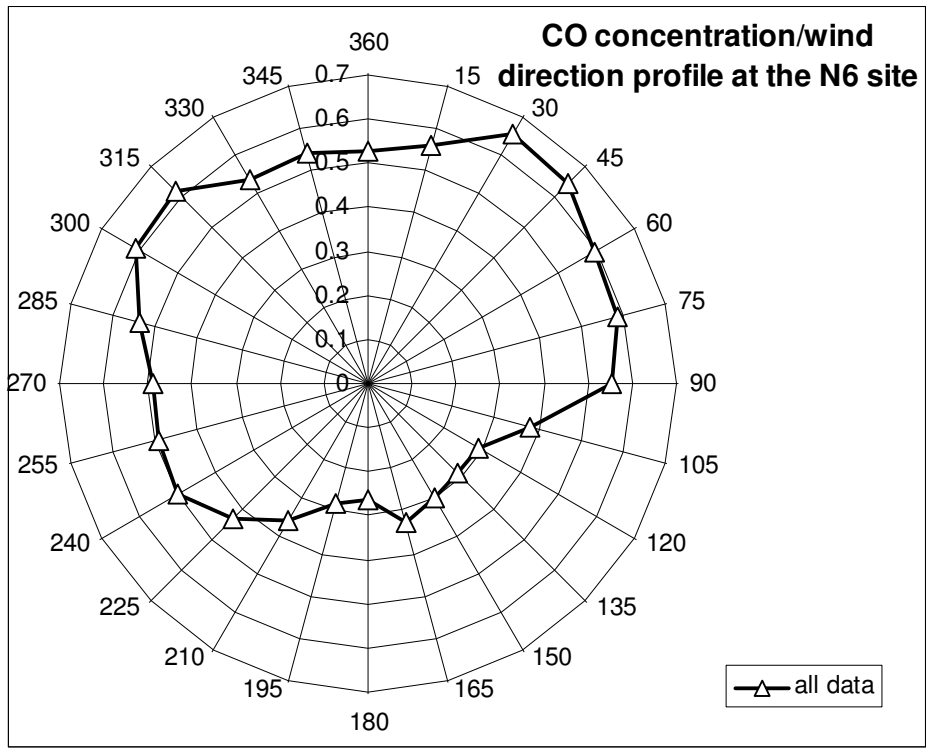


Figure 4.23: Distribution of CO concentration at the N6 site as a function of wind direction

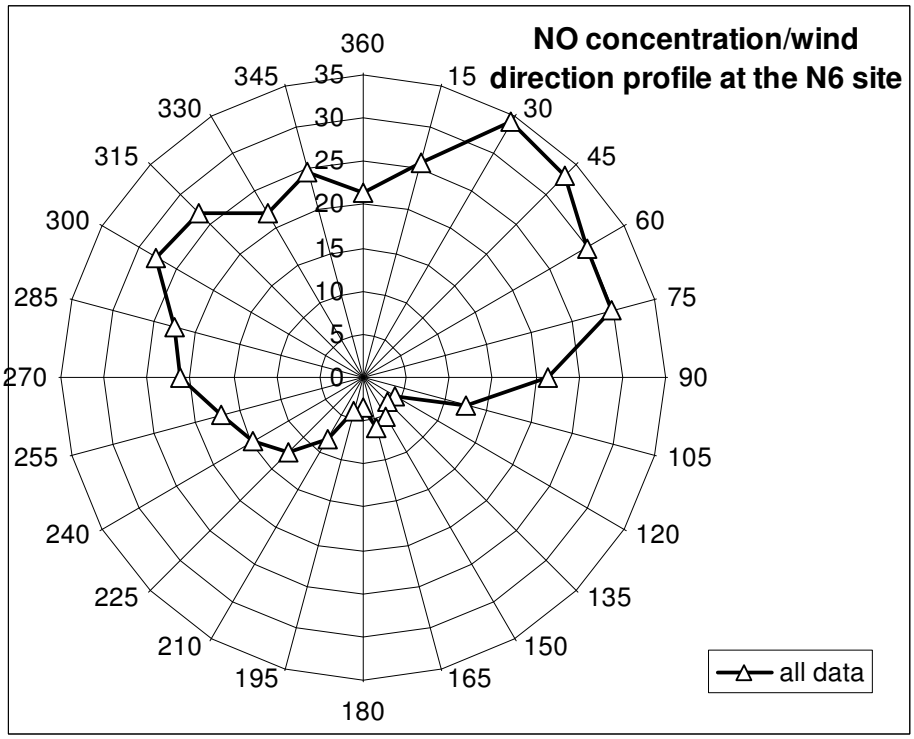


Figure 4.24: Distribution of NO concentration at the N6 site as a function of wind direction

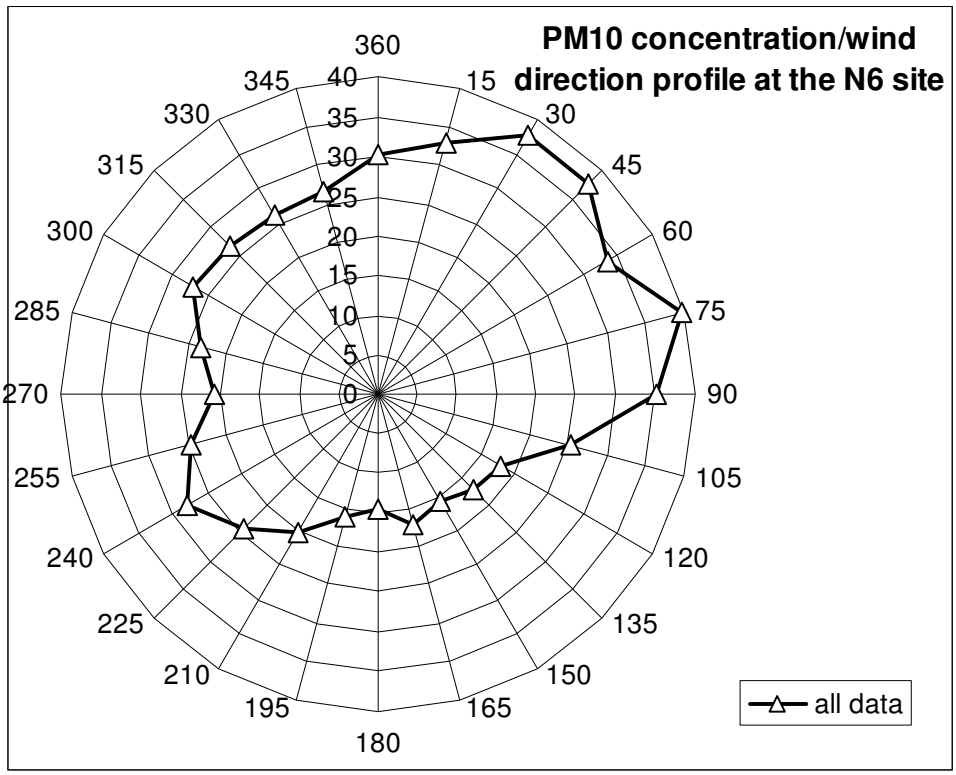


Figure 4.25: Distribution of PM10 concentration (mesasured by TEOM) at the N6 site as a function of wind direction.

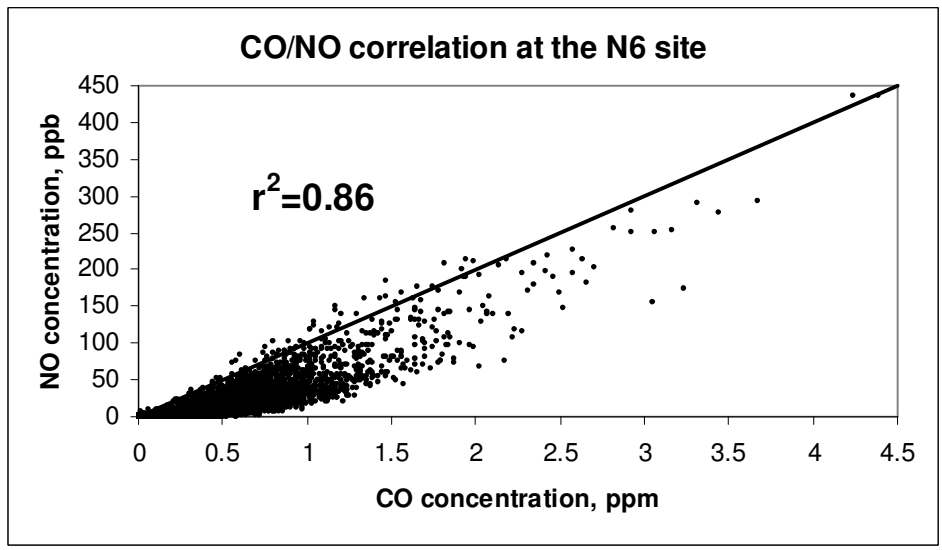


Figure 4.26: Correlation between NO and CO concentrations at the N6 site.

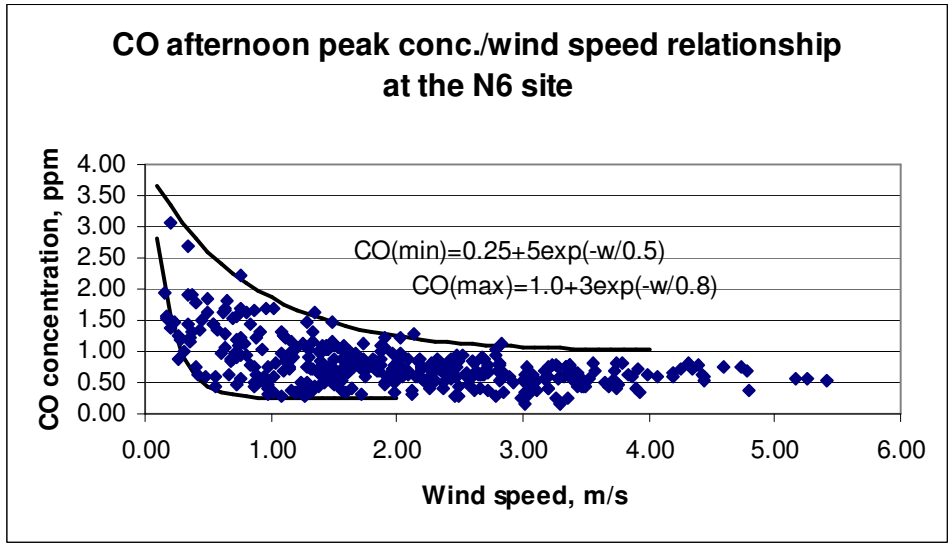


Figure 4.27: Dependence between CO concentration and wind speed.

4.6 Comparison of monitoring results from Leixlip and Galway

The average CO concentrations are generally higher at Galway than at Leixlip (Figures 3.31 and 4.11). The minima are similar at both sites: 0.2 ppm CO occurring at 04:00.

The maximum average NO concentrations (peaks) are generally higher at Galway than at Leixlip, though the minima are higher at Leixlip (Figures 3.33 and 4.14). The summer evening peak is suppressed in both cases.

The average NO_2 concentrations are slightly higher at Galway than at Leixlip (Figures 3.34 and 4.17). The proportion of NO_2 to NO is higher at Leixlip (1:1 compared to 2:3 at Galway).

While the diurnal profiles of average PM_{10} concentrations are similar, the average concentrations are higher at Galway than at Leixlip (Figures 3.35 and 4.20).

5 Dispersion Modelling

5.1 Overview of Atmospheric Dispersion Modelling

Atmospheric dispersion modelling involves the following three steps:

1. Representation of source emissions.
2. Modelling of pollutant transport, dispersion, transformation and removal.
3. Calculation of the impact on ambient concentrations.

In the case of the road transport sector, the following need to be considered:

- source modelling of the number and type of vehicles on the roads being assessed, and of the unit emissions expected from each vehicle;
- the transport of the pollutant downwind;
- the dispersion of the pollutant due to convective and thermal turbulence which, close to the roadway, will be affected by the passage of vehicles;
- the transformation of nitrogen oxides by reaction with other emitted and ambient pollutants;
- the removal of particulate matter from the atmosphere by deposition;
- the presence of background ambient concentrations.

In this context, highway dispersion models fulfil two roles. Firstly, they provide standard representations of the physical and chemical processes outlined above. These representations are normally semi-empirical and simplified. They include information such as the rate at which pollutants disperse under different conditions. Secondly, dispersion models facilitate the execution of large numbers of repetitive calculations. Models differ in the amount of input they require from modellers. For example, the DMRB model requires only information on vehicle flow, and assumes emission rates from this, whereas CALINE4 requires the modeller to calculate a composite emission factor, on which source emissions are based. The DMRB and CALINE4 models are described in the following section.

The purpose of the dispersion modelling described in this chapter is to evaluate the accuracy of model results through comparison with the monitoring data presented in Chapters 3 and 4. Three relevant questions are considered:

1. Do model results predict high ambient concentrations for the times and conditions during which high concentrations were measured?
2. Do the magnitudes of the model concentrations agree with those measured?
3. Do statistical variables determined from the model results compare well with those determined from the monitoring data?

5.2 Selection of Models: DMRB and CALINE4

5.2.1 Requirements

The dispersion models to be evaluated are required to address the pollutants of concern in Ireland. These can be identified as the pollutants addressed under EU directives and which are known to be present in concentrations close to limit values. Hence, models which allow NO_2 and PM_{10} concentrations to be calculated are of most interest.

Two types of dispersion model are used in environmental assessments. Screening models calculate conservative estimates of key statistical concentrations, in an efficient manner that places minimum demands on modellers. Often, the role of screening models is to determine whether more accurate modelling or monitoring is required. Short-term models seek to calculate the hour-by-hour variation in ambient concentrations due to corresponding variations in meteorological and traffic conditions. One model of either type has been chosen for investigation. The models are described briefly below. Further details of these and other atmospheric dispersion models can be found in Chapter 5 of the Literature Review (Broderick *et al.*, 2004a).

5.2.2 The Design Manual for Roads and Bridges (DMRB) model

The DMRB model is a screening model derived from a Gaussian dispersion model developed by the UK Transport and Roads Research Laboratory (TRRL - now Transport Research Laboratory, TRL) (DMRB, 1994; DMRB, 2000). It consists of a number of charts and tables that allow ambient concentrations to be determined at distances downwind of a road or roundabout. Carbon monoxide, nitrogen dioxide, PM_{10} and total hydrocarbon concentrations can be calculated. Only traffic data are required, as standard vehicle emission factors have already been employed to produce the ambient concentration charts, and the results correspond to worst-case meteorological conditions. The model was developed to produce approximate pollutant concentrations from new and improved road schemes, and thus indicate whether further air quality assessments are required. Spreadsheet-based versions have also been developed.

5.2.3 CALINE4

CALINE4 is one of two versions of the CALINE (California Line Source) dispersion model currently in use (Benson, 1992; US EPA www.epa.gov/scram001/). It can predict hour-by-hour concentrations of pollutants using data files containing sequences of hourly meteorological and traffic data. Concentrations of CO (or any other inert pollutant), NO_2 and PM_{10} can be determined, and intersections may be modelled, by including sub-models for reactive plume chemistry, particle deposition and modal emissions.

The model uses a semi-empirical solution to the Gaussian dispersion equation. It follows a conventional Gaussian formulation but uses improved vertical and horizontal dispersion curves modified for the effects of surface roughness, averaging time and vehicle-induced turbulence. Horizontal dispersion coefficients are estimated from the wind-speed standard deviation, using a method developed by Draxler (1976).

The model divides roadway links into a series of elements from which incremental concentrations are computed and summed. Each segment is modelled as an equivalent finite line source, positioned normal to the wind direction. The finite line source formulation requires solution by numerical integration. The atmosphere immediately above the roadway is modelled as a mixing zone in which the vertical distribution of concentrations depends on the crossroad wind speed.

The plume chemistry model for NO_2 operates separately to the dispersion model, using the concept of a discrete parcel. According to Benson (1992) this model is valid only when the assumptions of fully mixed initial reactants and short travel times are satisfied, and its use is questionable under parallel wind or strongly convective conditions.

5.3 Emission Factors

5.3.1 Unit vehicle emissions

The following pollutants emitted from motor vehicles are considered in this project: carbon monoxide (CO), oxides of nitrogen (NO_x), including nitric oxide (NO) and nitrogen dioxide (NO_2), PM_{10}, and hydrocarbons (HC) including benzene (see Section 3.1 and Section 4.1 for more information on the air pollutants monitored). Most emissions are from vehicle exhausts, but evaporative emissions of fuel hydrocarbons also occur, as do particulate emissions due to wear and resuspension.

Pollutant emission rates are highly dependent on vehicle operation mode. The highest emission rates for CO and HC occur at the low average speeds typical of urban driving in which frequent starts and stops, accelerations and decelerations occur. At higher average speeds, engine efficiency improves and emission rates reduce on a distance-travelled basis. However, as engine temperature increases at these higher average speeds (when fuel consumption per unit time is high), the rate of formation of oxides of nitrogen also increases. The contribution of individual vehicles to overall pollution levels can be expressed in terms of emission factors. These seek to quantify the mass of a pollutant emitted by a given vehicle under set operating conditions, and are combined with vehicle activity information to obtain emissions inventories. The effects of some operational factors are better understood than others, and most research has concentrated on the relationship between emission rates and vehicle speed for different pollutants.

5.3.2 Emission factor databases: UK EFD and COPERT III

Quantitative information on emission rates from vehicles is obtained in tests that measure the pollutant emitted from a single vehicle travelling at a known average speed. By sampling a large number of similar vehicles, and testing at a range of speeds, the velocity-emission rate characteristic of a particular class of vehicle may be determined. Databases of such characteristics have been established, and these can be used to develop the source emission input data required by dispersion models. For Ireland, two suitable databases are available: the UK Emission Factor Database (UK EFD) and COPERT III. These can be viewed at *http://www.naei.org.uk/emissions/index.php* *and* *http://www.epa.gov/scram001/* respectively.

COPERT III was developed under the European Environment Agency, within the framework of the CORINAIR programme (http://www.aeat.com). Published in 2000, it is the second update of the original version produced in 1989. The latest revision is based on the results of a large number of EU research and collaboration projects completed in the late 1990s. The latest version of the UK EFD was published in 2003, and reflects a review of emission factors for more recent vehicles carried out by the Transport Research Laboratory in 2001. For application to this project, both databases provide emission factors for CO, NO_x and PM_{10}. The UK EFD also provides emission factors for benzene and 1,3-butadiene while COPERT III covers these and about 20 other hydrocarbons.

Figures 5.1 and 5.2 illustrate the type of information provided by these databases, and compare their outputs for the case of petrol cars with engine capacities between 1.4 and 2.0L. The CO emission rates for vehicles of different ages (i.e. complying with different emission control legislation), travelling at an average speed of 100 kph, are shown in Figure 5.1. The large reduction in emission rates from the pre-ECE class (pre-1971) to EURO II (current) vehicles is evident. There is broad agreement between the two databases, but with COPERT III predicting higher rates for EURO II-IV vehicles. Figure 5.2 considers one vehicle type, EURO I, but displays how the emissions from these vehicles are expected to vary with mean vehicle velocity. The two databases agree on the range of emission rates displayed, and also on the general trend, but can differ at specific velocities.

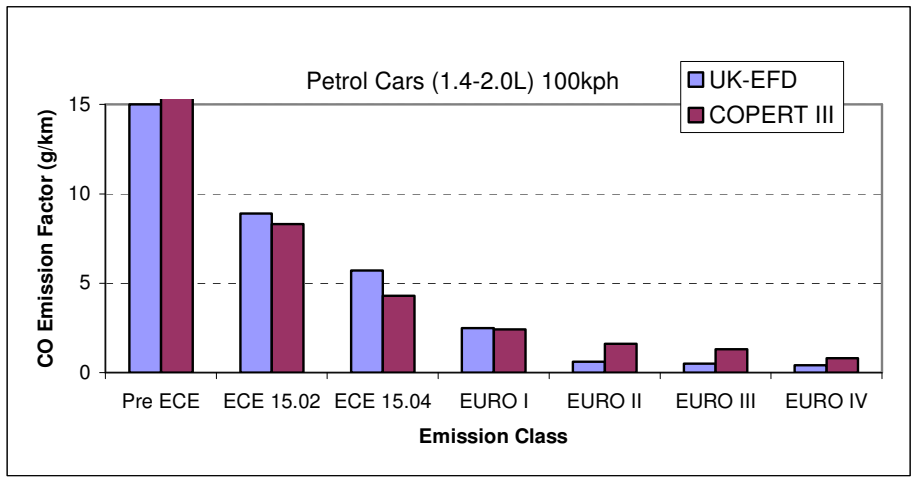


Figure 5.1: UK-EFD and COPERT III CO emission rates for 1.4-2.0L petrol cars by emission control legislation (V_{mean} = 100 kph)

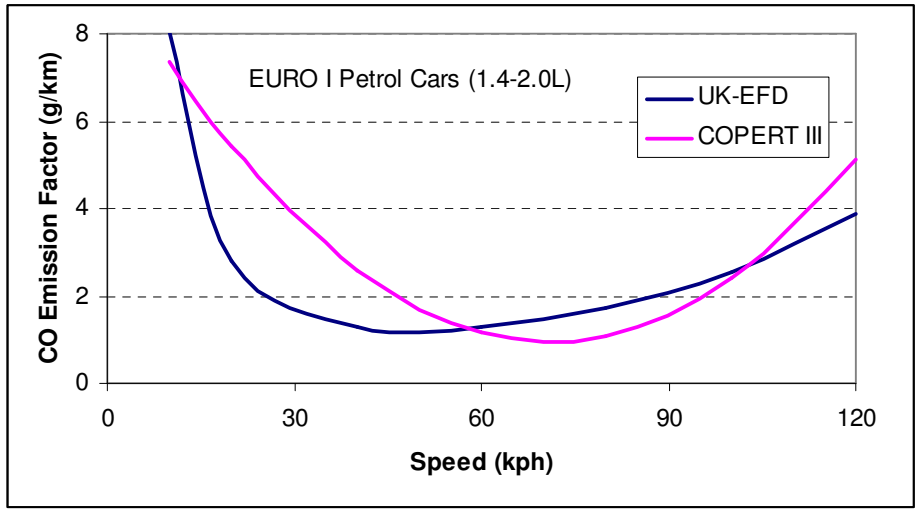


Figure 5.2: UK-EFD and COPERT III CO emission rate functions

5.3.3 National fleet composition

Table 5.1: Assumed national fleet composition (source: DoELG, 2000)

Vehicle Type	Fuel Type	Size	Emission Control	% of Fleet	km per annum
Cars	Petrol	< 1.4L	Pre EURO I	13.7	19.5
			EURO I	18.8	24.4
			EURO II	21.8	24.4
		1.4-2.0L	Pre EURO I	4.7	19.4
			EURO I	6.4	24.4
			EURO II	7.4	24.4
		> 2.0L	Pre EURO I	0.3	19.0
			EURO I	0.6	23.9
			EURO II	0.6	23.9
	Diesel	< 2.0L	Pre EURO I	0.4	13.1
			EURO I	4.2	18.1
			EURO II	2.2	18.1
		> 2.0L	Pre EURO I	0.3	13.1
			EURO I	2.8	18.1
			EURO II	1.5	18.1
LDVs	Petrol	All	Pre EURO I	0.3	25.0
			EURO I	0.3	25.0
			EURO II	0.3	25.0
	Diesel	All	Pre EURO I	1.7	27.0
			EURO I	2.1	27.0
			EURO II	1.2	27.0
HGVs	Diesel	3.5-7.5t	Pre EURO I	0.5	30.0
			EURO I	0.9	30.0
			EURO II	1.2	30.0
		7.5-16t	Pre EURO I	0.2	30.0
			EURO I	0.3	30.0
			EURO II	0.4	30.0
		16-32t	Pre EURO I	0.9	40.0
			EURO I	1.5	40.0
			EURO II	2.2	40.0
		>32t	Pre EURO I	0.1	40.0
			EURO I	0.2	40.0
			EURO II	0.2	40.0

Data are available from the Department of the Environment and Local Government (DoELG) giving the number of vehicles in Ireland which fall into different categories of vehicle type, fuel type and engine size or laden weight (DoELG, 2000). The percentages of the national fleet in each sub-class are included in Table 5.1. The assumed average number of kilometres travelled annually by vehicles in each sub-class is also given. Allowance can also be made for the proportions of distance travelled by different vehicle types in urban, rural and highway conditions.

5.3.4 Composite emission factors

Combining the unit vehicle emission factors (for mean speeds of 30 and 100 kph) from the UK EFD and COPERT III with the assumed fleet characteristics presented in Table 5.1 produces the composite emission factors given in Table 5.2. While the CO values obtained with both databases are in good agreement, the NO_x composite emission factors obtained using COPERT III are both much lower than those obtained with the UK-EFD. This reflects the large difference in the unit emission factors for HGVs given by the two databases.

Table 5.2a): Composite emission factors (g/km) – UK EFD

Pollutant	Motorway CEF (100 kph)	Urban CEF (30 kph)
CO	2.57	3.70
NO_x	3.65	1.12
PM_{10}	0.121	0.054

Table 5.2b): Composite emission factors (g/km) – COPERT III

Pollutant	Motorway CEF (100 kph)	Urban CEF (30 kph)
CO	2.24	3.94
NO_x	1.56	0.78
PM_{10}	0.114	0.051

The CALINE4 modelling results presented in this chapter have been determined using composite emission factors of 4.14 g/km CO (6.62 g/mile CO) and 1.4 g/km NO_x (2.24 g/mile NO_x) at both sites, 0.12 g/km PM_{10} (0.19 g/mile PM_{10}) at the motorway site and 0.06 g/km PM_{10} (0.09 g/mile PM_{10}) at the roundabout site, which were derived from the UK EFD of 2001. The difference in the composite emission factors given by the two databases is addressed in the parametric study described in Chapter 6.

5.4 Model Results for M4 Motorway at Leixlip

5.4.1 DMRB input data

The data requirements of the DMRB are shown in Table 5.3 together with the values used at the motorway site. The year, site geometry, the traffic flow, its basic profile and speed, are combined with information on background

concentrations, to give predictions of pollutant concentrations in the formats shown in Table 5.4.

Table 5.3: DMRB input data – motorway

Receptor and link data	Receptor name	Leixlip WTW
	Year to be modelled	2001
	Link number (1-20)	1
	Description of link	M4, Leixlip
	Distance to receptor (from centre of road) (m)	30
	Distance to receptor (from kerbside) (m)	20
	Annual average vehicle flow (veh/hr)	1400
	%HDV	20
	Average speed (km/hr)	90
Background concentrations (year adjusted)	CO (mg/m^3)	0.27
	Benzene ($\mu g/m^3$)	0.40
	NO_x ($\mu g/m^3$)	11.73
	PM_{10} ($\mu g/m^3$) gravimetric	11.90

5.4.2 DMRB model results and measurements

Background concentrations of CO, benzene and PM_{10} are high relative to concentrations due to the road traffic source, and therefore are highly significant in the total concentrations predicted using the DMRB, presented in Table 5.4.

Table 5.4: DMRB results – motorway

	CO (mg/m^3)	**Benzene** ($\mu g/m^3$)	**NO_x** ($\mu g/m^3$)	**PM_{10}** ($\mu g/m^3$)
Contribution from all roads	0.10	0.59	130.32	3.93
Background contribution	0.27	0.40	11.73	11.90
Total annual mean (incl. background)	0.37	0.99	142.05	15.83
Maximum 8-hr mean	3.69	*	*	*
Maximum running annual mean	*	1.09	*	*
Annual mean NO_2	*	*	58.27	*
90^{th}%ile of daily means	*	*	*	28.34

5.4.3 CALINE4 input data

The input data required for CALINE4 are shown in Table 5.5. These are more comprehensive than the data for the DMRB modelling since hourly variations in traffic and meteorological conditions may be modelled for different terrain types and up to 20 receptors. As shown in Table 5.6, hourly and 8-hour average concentrations are predicted for varying wind directions including the worst-case wind angle. Table 5.5 can be compared with the simplified input data for the CL4 interface, which is given in Table 5.11 for the Galway roundabout site.

Table 5.5: CALINE4 input data – motorway

	Parameter	**Units**	**Notes**
Job	Job title		
Pollutant	Pollutant type (1-4)		e.g. 1 = CO, 2 = NO_2
	Pollutant name		
Site	Aerodynamic roughness coefficient	cm	
	Molecular weight	g/mol	N.A. for PM
	Settling velocity	cm/s	
	Deposition velocity	cm/s	
	Number of receptors		
	Number of links		converts roadway geometry to m
	Scale factor		
	Link title option		
	Receptor title option		
	Altitude	m	above sea level
Receptor	Receptor name		
	x-,y-,z-coordinates		
Link	Link name		
	Link type (1-6)		e.g. 1 = At-grade, 2 = Depressed
	x-,y-,z-coordinates (startpoint)		
	x-,y-,z-coordinates (endpoint)		
	Roadway height		
	Mixing zone width		min. 1 lane plus 3m either side
	Mixing width left		0 = no horizontal obstruction
	Mixing width right		
	Continuation code (0,1)		1 if Link A endpoint is Link B startpoint
Run	Run type (1-4,9)		e.g. 1 = standard
	Traffic volume code (0,1)		0 = unchanged, 1 = changed
	Emission factor code (0,1)		0 = unchanged, 1 = changed
	Intersection parameter code (0,1)		0 = unchanged, 1 = changed
	Meteorology code (0,1)		0 = unchanged, 1 = changed
	Run title		
Traffic	Hourly traffic volume	vph	
	Composite emission factor by link	g/v-mile	
Met.	Wind direction	deg.	
	Wind speed	m/s	
	Atmospheric stability class (A-G)	1 to 7	A = 1 to G = 7
	Mixing height	m	
	Wind direction standard deviation	deg.	
Ambient	Ambient concentration	ppm	for CO, inert gas & particulates
	Temperature	˚C	
	Ambient concentration O_3	ppm	for NO_2 (Pollutant type 2, above)
	Ambient concentration NO	ppm	
	Ambient concentration NO_2	ppm	
	NO_2 photolysis rate constant	/s	

5.4.4 CALINE4 modelled annual concentrations

CALINE4 predicts hourly and 8-hour average concentrations. It can also anticipate the worst case wind direction, and the 8 hour average for the worst-case wind direction. The measured concentrations are compared with predictions for each of these run types in Table 5.6. The standard run hourly concentrations generally overestimate the measured concentrations. The worst-case wind angle option exacerbates this. For example, the 18:00 prediction is 0.23 ppm, which is entirely due to the background CO since the wind was from receptor to source (12.7˚). When this hour is modelled for the worst-case wind direction (255˚) the concentration is predicted to be 1.23 ppm, three times the measured value of 0.4 ppm. The 8-hour averaged concentrations also overestimate the measured concentrations somewhat, with the worst-case wind direction option higher again.

Run-types: 1 = Standard (hourly)
2 = Multi-run (8-hr average)
3 = Worst-case wind angle (hourly, wind direction given)
4 = Multi-run/worst-case (8-hr average)

Table 5.6: CALINE4 results – motorway CO (ppm)

3.i.2002	Measured		Modelled					
Hour	Hourly	8hr average	Hourly			8hr average		
			S	W	W(θ˚)	S	W	S*
07:00	0.3	0.3	0.33	0.33	249˚			
08:00	0.4	0.33	0.53	0.53	249˚			
09:00	0.5	0.35	0.53	0.53	249˚			
10:00	0.5	0.38	0.53	0.53	249˚			
11:00	0.4	0.38	0.53	0.53	249˚			
12:00	0.3	0.39	0.83	0.83	251˚			
13:00	0.4	0.4	0.43	0.53	249˚			
14:00	0.4	0.41	0.73	0.83	250˚	0.53	0.53	0.5
15:00	0.4	0.41	0.43	0.43	249˚	0.53	0.63	0.5
16:00	0.4	0.4	0.53	0.53	249˚	0.53	0.63	0.5
17:00	0.4	0.39	0.43	0.53	248˚	0.53	0.63	0.5
18:00	0.4	0.38	0.23	1.23	255˚	0.53	0.63	0.5
19:00	0.3	0.39	0.93	1.03	250˚	0.53	0.73	0.5
20:00	0.4	0.38	0.53	0.53	249˚	0.53	0.73	0.5
21:00	0.3	0.38	0.33	0.33	249˚	0.53	0.73	0.5
22:00	0.4	0.38	0.43	0.43	250˚	0.53	0.63	0.5

S: Standard model run
W: Worst case wind direction model run
W(θ˚): Wind direction for worst case concentration
S*: Standard run with model input background concentration ≠ 0 ppm CO. This was modelled with the same background concentration of 0.23 ppm CO as all previous runs, but with the background concentration included as an input variable in modelling. For all previous runs the background concentration was added after modelling. Since CO is inert, the difference is due only to the limit on decimal places in the model output, highlighting the low level of the concentrations measured at the motorway site.
See Appendix D for other input data.

5.4.5 CALINE4 results - motorway: sample hourly and 24 hour averages

Hour-by-hour variation

Figures 5.3-5.5 compare the hour-by-hour variation in measured and modelled concentrations for a sample week. The week shown is that in which the highest eight-hour CO concentration was observed. In these figures, background concentrations of 0.23 ppm CO, 6 ppb NO_2 and 11.9 $\mu g/m^3$ PM_{10} have been added to the model results, as explained later in this section.

In Figure 5.3, large increases in both measured and modelled CO concentrations are observable for the latter hours of 31st December 2001. However, while elevated measured concentrations persist well into the following day, the modelled episode lasts only a few hours, until the traffic flow reduces. In general, model results do not predict well overnight periods of several hours during which elevated concentrations persist due to stable atmospheric conditions. Elsewhere in Figure 5.3, a number of number of much smaller and shorter term increases in measured concentrations are displayed, and these are mostly matched by increases in modelled concentrations. While the range of values in both sets of data agree, large differences between individual contemporary pairs can be observed. Absolute values, however, are all low compared to legislative and instrumental limit values (see Section 5.4.10).

The NO_2 concentrations shown in Figure 5.4 show more variation than the CO values in Figure 5.3. Peaks in measured concentrations occur at three distinct times: overnight (during stable conditions), and during the morning and evening peak travel periods. The model results predict the times and magnitudes of the concentration increases during peak travel periods, for example the evenings of 31st December 2001, 2nd and 3rd January 2002. Modelled NO_2 concentrations equal zero for some hours since, unlike CO or PM_{10}, the background concentration is included in the model calculations. (CO and PM_{10} are modelled as inert pollutants, with the background concentration being superimposed on the model output.)

The measured and modelled PM_{10} concentrations shown in Figure 5.5 generally agree well, especially in the latter half of the sample week. As for CO, however, CALINE4 predicts neither the magnitude nor the persistence of the large overnight concentration episode in the middle of the week.

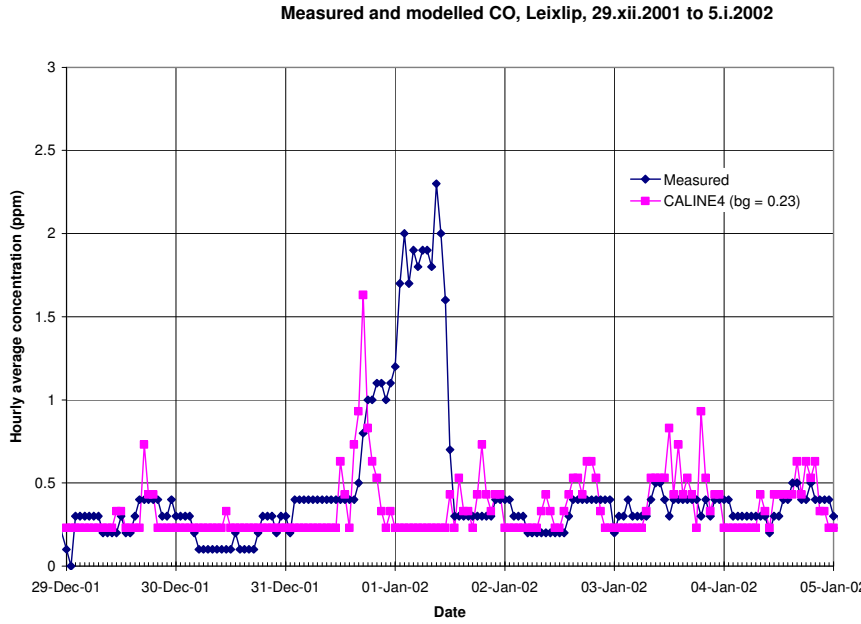


Figure 5.3: Sample week of modelled and measured hourly CO concentrations.

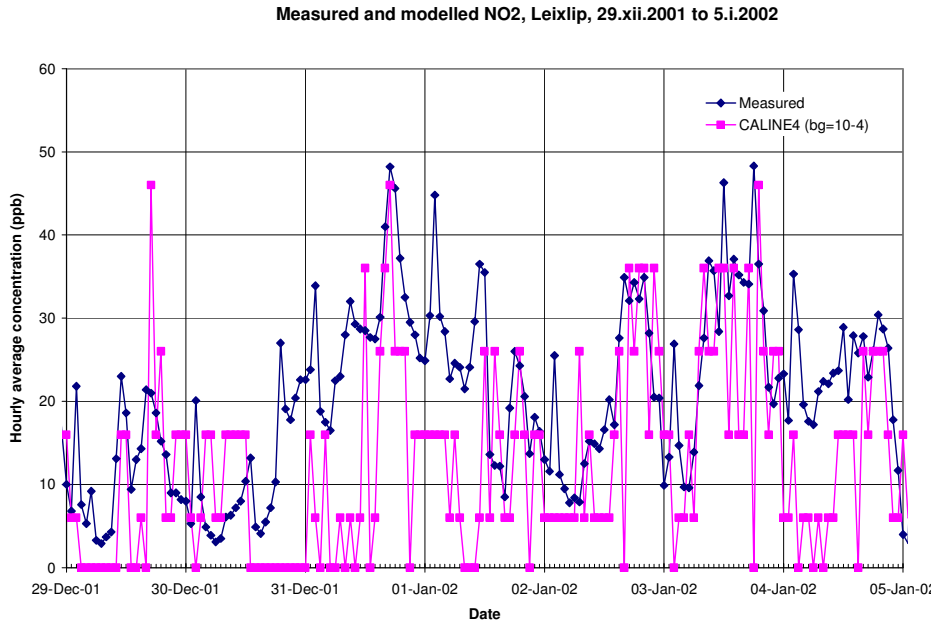


Figure 5.4: Sample week of modelled and measured hourly NO_2 concentrations

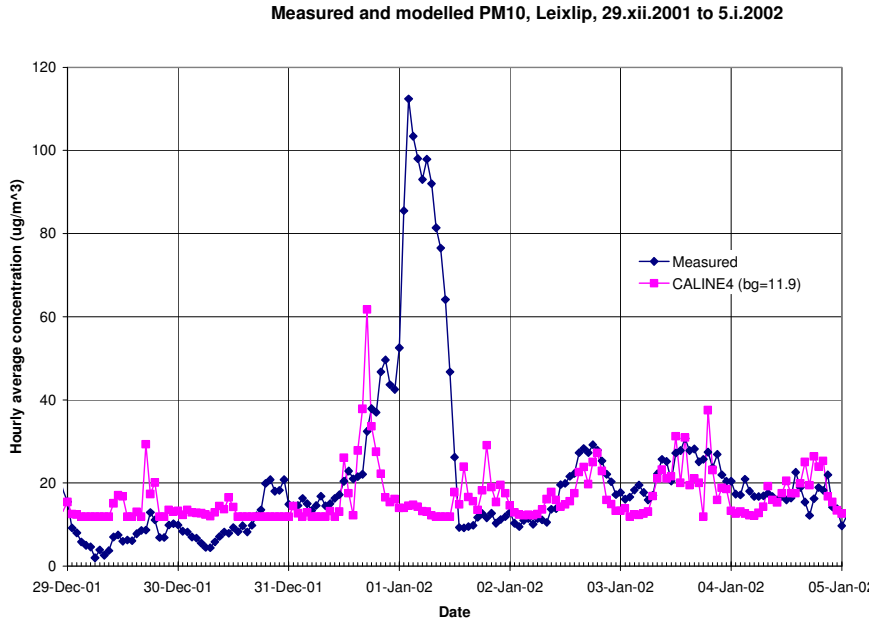


Figure 5.5: Sample week of modelled and measured hourly PM_{10} concentrations.

Variation in 24-hour average

Figures 5.6-5.8 compare measured and modelled 24-hour average concentrations over an eight-week period in mid-winter. For all three pollutants, the highest measured concentrations occur at the start and middle of this period. However, individual peaks in the measured and modelled values do not always occur on the same days. While the modelled peaks in the CO and PM_{10} concentrations are lower than the corresponding measured values (Figures 5.6 and 5.8), the modelled NO_2 peaks are close to the measured values, slightly over-estimating and under-estimating at the start and middle of the period, respectively (Figure 5.7).

The agreement between PM_{10} concentrations measured by the TEOM and Partisol is clear in Figure 5.8 (see also Section 3.4). The Partisol peaks and troughs are higher and lower respectively than those for the TEOM, due to the difference in the measurement methods. Scatter plots comparing measured and modelled CO, NO_2 and PM_{10} are of poor resolution due to the overlap of data points on the limited scale but may be seen in Appendix D.

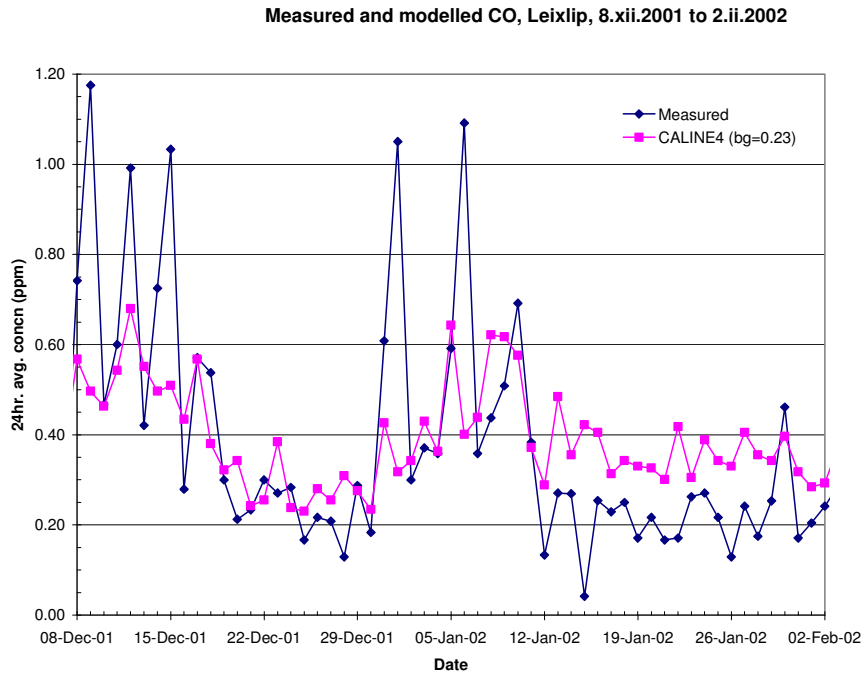


Figure 5.6: Comparison of measured and modelled 24-hour CO averages

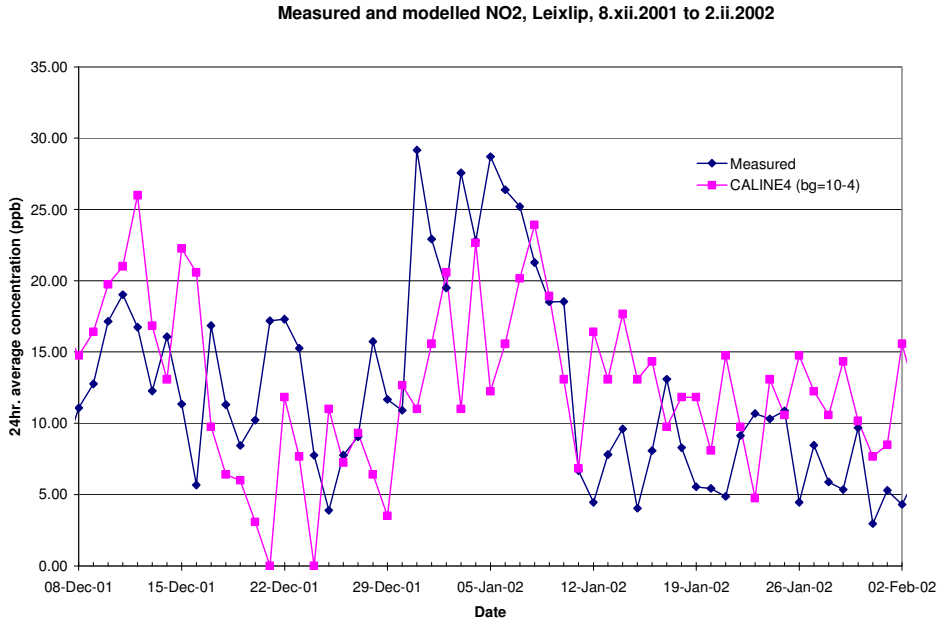


Figure 5.7: Comparison of measured and modelled 24-hour NO_2 averages

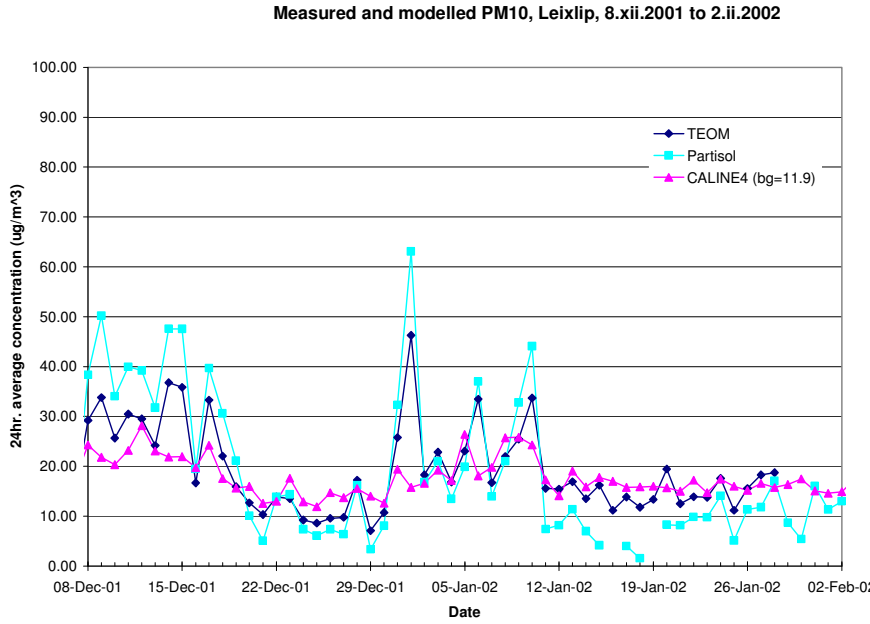


Figure 5.8: Comparison of measured and modelled 24-hour PM_{10} averages

5.4.6 CALINE4 results – motorway: diurnal variation

Rather than examining individual hours or days of data, it is useful to consider the average variation in measured and modelled pollutant concentrations throughout an average day. Figures 5.9-5.11 compare the average diurnal variations of the measured and modelled concentrations of CO, NO_2, and PM_{10} over the whole monitoring period. In Figure 5.9, two modelled CO profiles are shown: one which shows the average model result at each hour of the day, and another in which a constant background concentration of 0.23 ppm has been added. This background value was chosen as the lowest value on the measured diurnal profile, which occurs in early morning when traffic flows are lowest. Similarly, background values of 6 ppb and 11.9 $\mu g/m^3$ are obtained and employed for NO_2 and PM_{10}, respectively. For NO_2, the background concentration is employed in CALINE4's photochemical module, but this requires concentrations to be input in multiples of 10 ppb. Hence Figure 5.10 includes two modelled profiles: one which shows the results obtained with a background concentration of 10 ppb, and another in which those values have been reduced by 4 ppb (to reflect the more accurate background of 6 ppb).

With all three pollutants, the measured and modelled profiles reflect the diurnal variation in traffic flow and, hence, source emissions. Figure 5.9 shows that the peak annual average hourly CO concentration is 0.33 ppm at 23:00, whereas the modelled peak is 0.53 ppm at 20:00. The model does not predict the high CO concentrations observed after 20:00, which are generally due to stable conditions rather than the immediate traffic source, but the morning peak hour concentrations are in closer agreement. The observed NO_2 peak (Figure 5.10: 12.12 ppb at 21:00) is also lower and occurs later than the predicted peak (18.19 ppb at 19:00). The morning peaks coincide (08:00) though again the predicted concentration (14.61

ppb) is higher than that observed (11.81 ppb). Of the three pollutants, PM_{10} displays the best agreement between the measured and modelled concentrations (Figure 5.11), with the predicted morning and evening peaks being within 10% to 20% of the observed values. The diurnal maximum is predicted to be 22.52 $\mu g/m^3$ at 20:00, compared to the observed maximum of 18.13 $\mu g/m^3$ at 19:00. The consistent overestimation represented in the model results of Figures 5.9-5.11 is addressed in Chapter 6, when the composite emission factors are considered further.

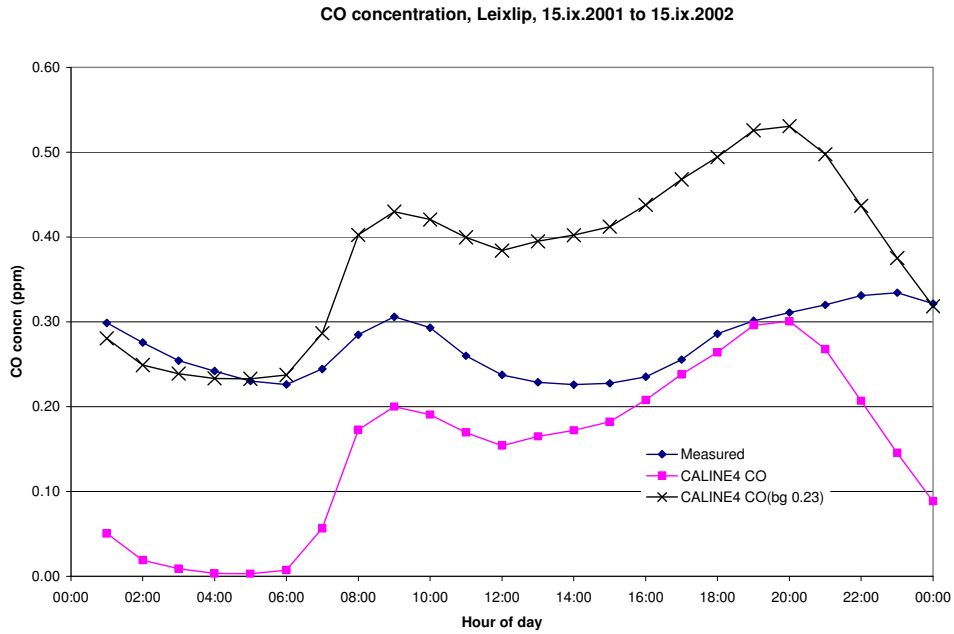


Figure 5.9: Measured and modelled average diurnal profiles for CO

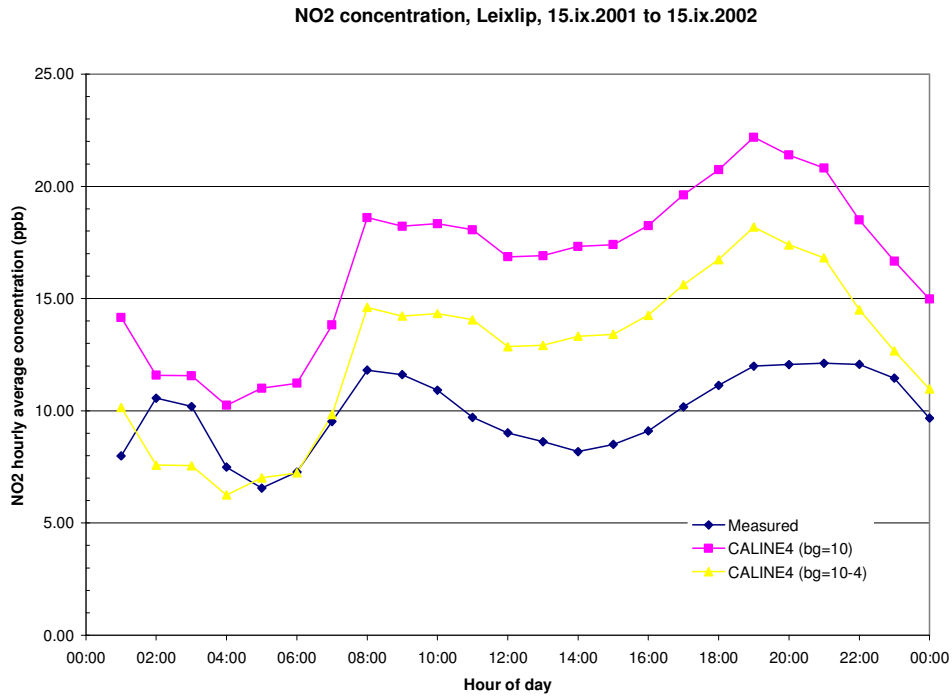


Figure 5.10: Measured and modelled average diurnal profiles for NO_2

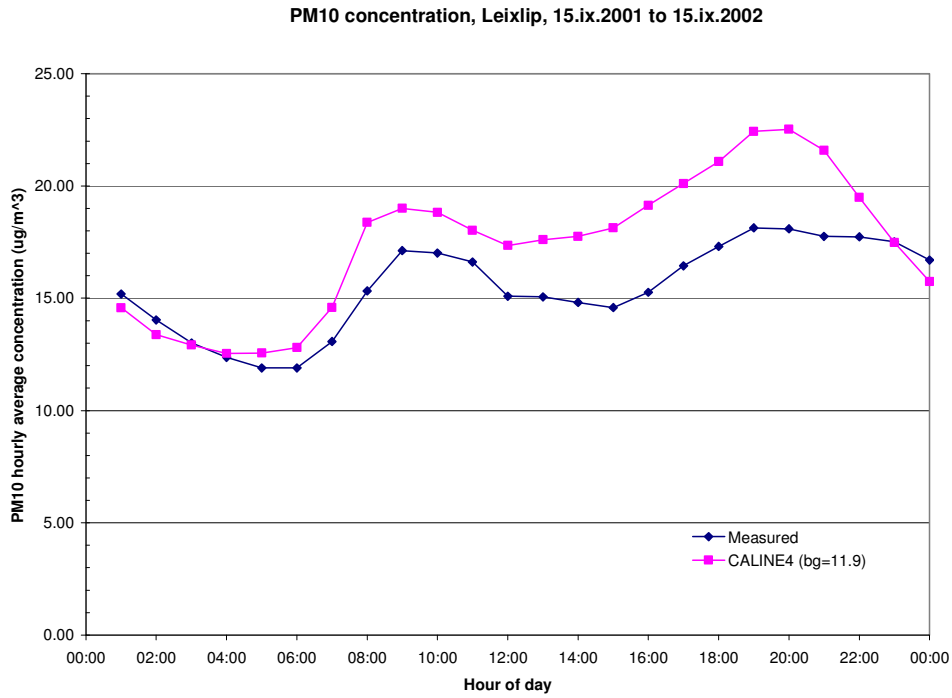


Figure 5.11: Measured and modelled average diurnal profiles for PM_{10}

5.4.7 CALINE4 results – motorway: variation with wind direction

Figures 5.12-5.14 compare the variations in measured and modelled pollutant concentrations with wind direction. As discussed in Chapter 3, the maximum observed concentrations occur with winds from the northeast, which are rare and of low speed. For all three pollutants, the highest predicted concentrations occur when winds are near parallel to the road, or from the south. In particular, considering a wind direction range of 165-180º, the measured and modelled NO_2 and PM_{10} values are very close. For wind directions closer to that of the road, poorer agreement is observed, especially for NO_2. Previous studies on CALINE4 have also observed the tendency of the model to overestimate for near-parallel winds, and the NO_2 photochemical module is known to perform especially poorly in these circumstances when pollutant travel time is greatest (Broderick *et al.*, 2004a). This feature is especially relevant at the Leixlip monitoring site where westerly winds were frequently observed.

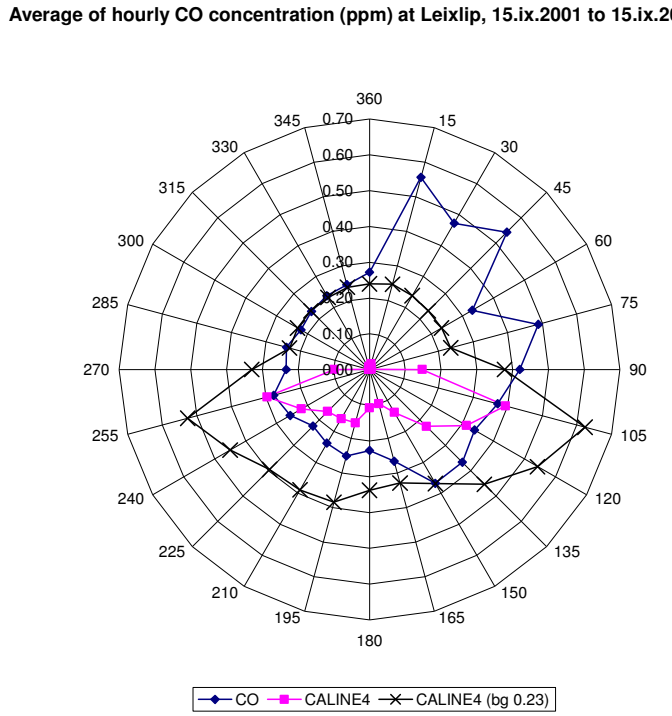
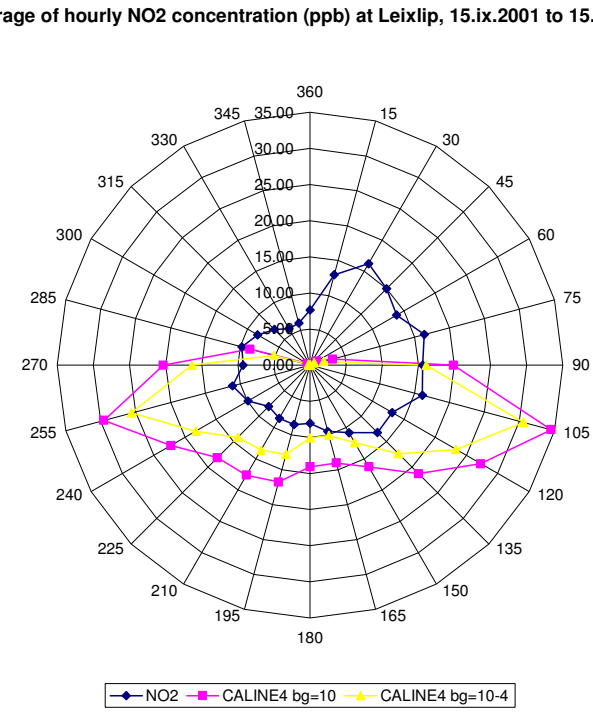
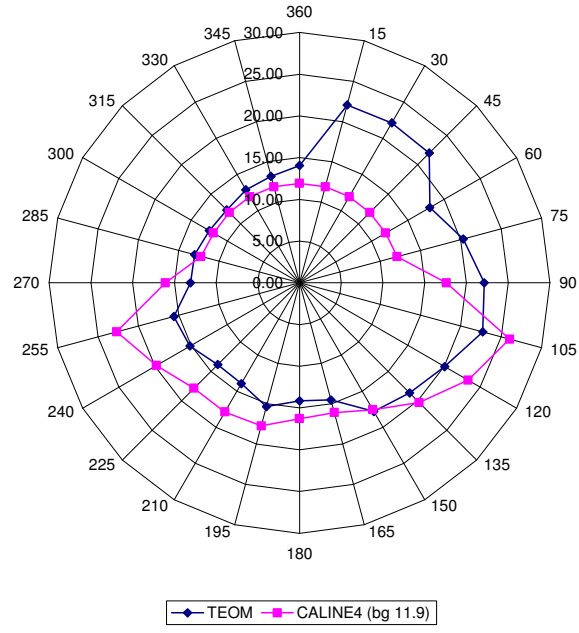


Figure 5.12: Measured and modelled CO pollution roses



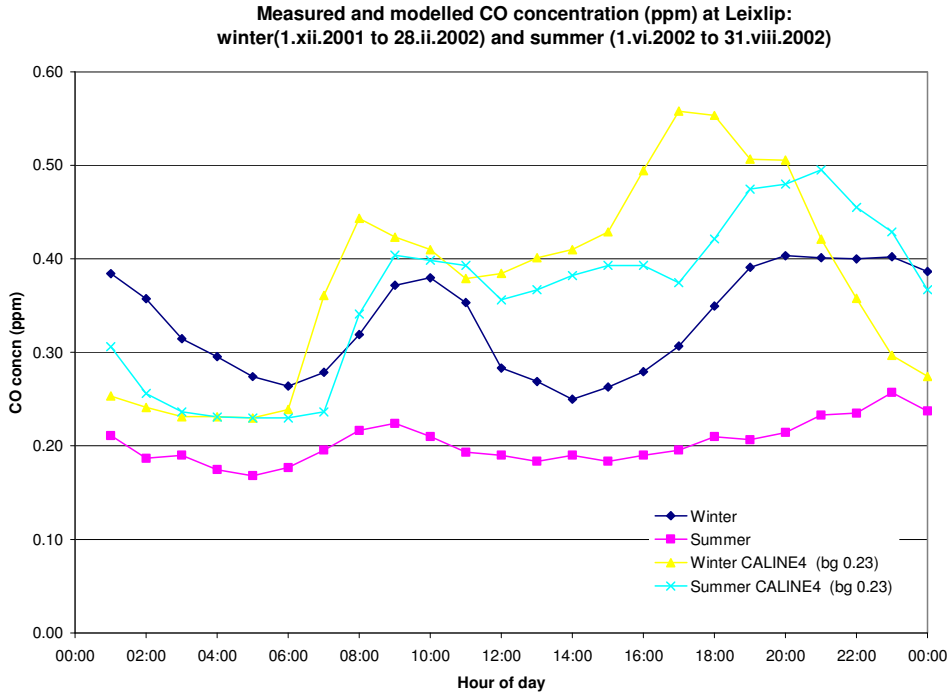
Figures 5.13: Measured and modelled NO_2 pollution roses



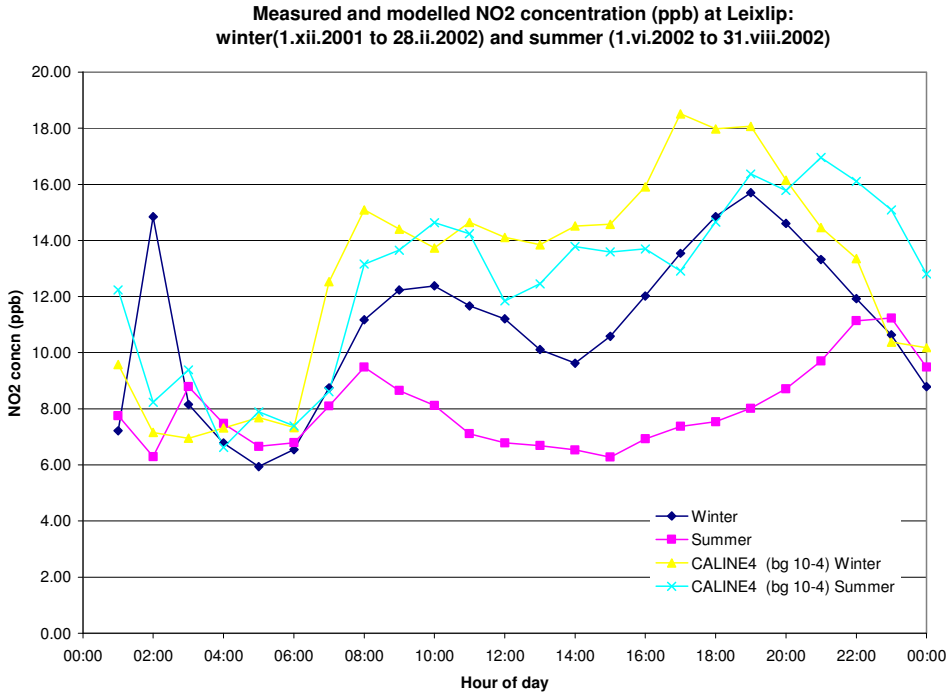
Figures 5.14: Measured and modelled PM_{10} pollution roses

5.4.8 CALINE4 results – motorway: winter and summer seasons

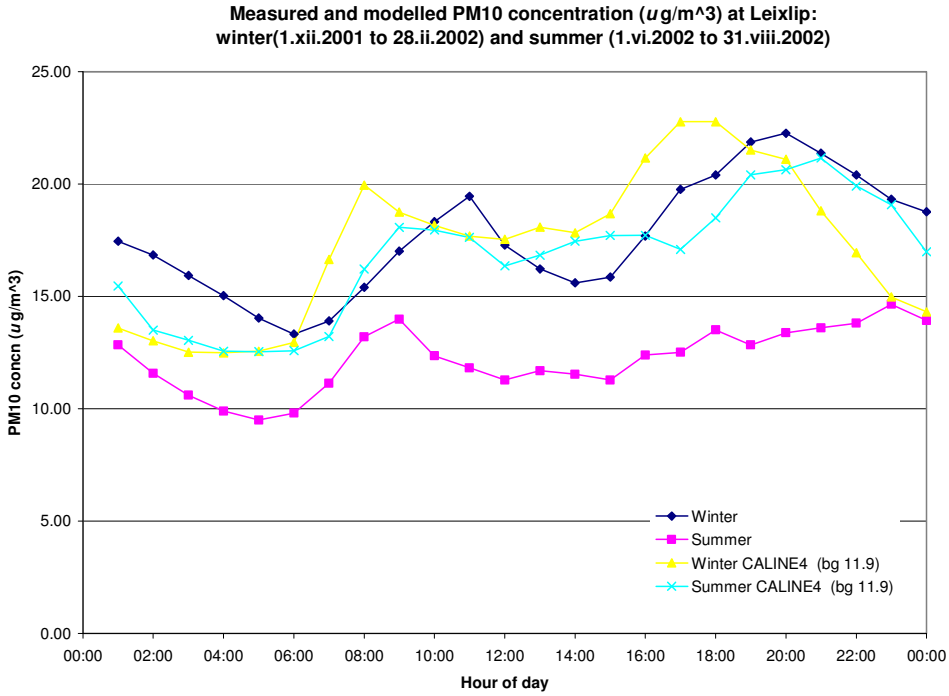
Figures 5.15-5.17 show measured and modelled diurnal profiles for separate winter and summer periods. The same background concentrations have been used for both seasons. For all pollutants, winter concentrations are both observed and predicted to be higher than summer concentrations. The modelled values are more sensitive to variations in traffic than the measured values, but are less sensitive to seasonal variations. For CO and NO_2, the concentrations predicted for the summer months are generally higher even than those observed in the winter months (Figures 5.15 and 5.16). Overall, better agreement between the measured and modelled profiles is achieved with the winter data, and the best agreement is observed for wintertime NO_2.



Figures 5.15: Modelled and measured average diurnal profiles for CO in winter and summer



Figures 5.16: Modelled and measured average diurnal profiles for NO_2 in winter and summer



Figures 5.17: Modelled and measured average diurnal profiles for PM_{10} in winter and summer

5.4.9 CALINE4 results – motorway: leeward concentrations

The monitoring programme at the Leixlip motorway site was designed to determine the impact of emissions from the M4 on ambient air quality. Clearly, this impact is only measured when the wind direction is such that pollutants emitted on the road are blown towards the receptor/monitoring point located 20m north of the motorway. This occurs when the wind direction is in the range 80-280º, approximately.

Figures 5.18-5.20 show average measured and modelled diurnal profiles for two wind direction ranges: between 100 and 280º and between 280 and 360º. Data for wind directions in the range 0-100º are not included due to the influence of a nearby building. For all three pollutants, higher daytime concentrations are observed for winds between 100 and 280º, reflecting the influence of the M4 source. However, the 280-360º profile also displays concentration peaks during high travel demand times – indicating a probable traffic source north of the monitoring site. The measured concentrations of all three pollutants (Figures 5.18-5.20) were only marginally higher (in the afternoon and evening) for winds directly from source to receptor (100-280º) than when all wind directions (0-360º) are considered, because the predominant wind directions lie in the 100-280º range.

The model correctly predicts higher concentrations for the leeward case. However, the difference in the modelled profiles for the two wind direction ranges is much greater than that observed. In general, agreement between the modelled and measured profiles is no better for the leeward cases in Figure 5.18-5.20 than for the general cases in Figures 5.9-5.11.

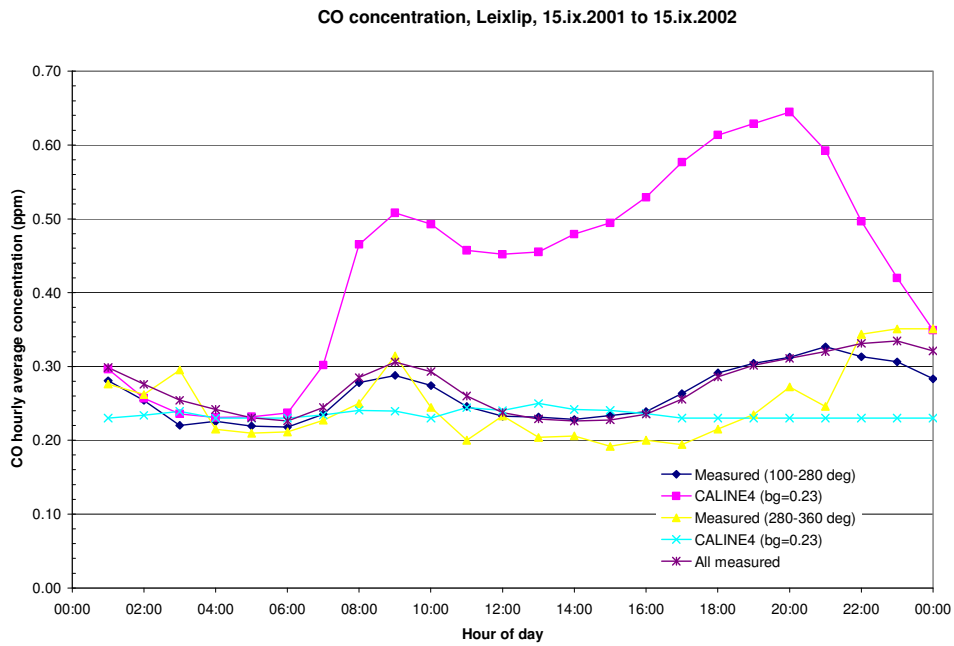


Figure 5.18: Modelled and measured average diurnal profiles for CO with different wind directions.

The difference between modelling inert and reactive pollutants is reflected in the results obtained. For winds from 280-360º, the CO and PM_{10} concentrations are almost always equal to the assumed background concentrations, whereas NO_2 is predicted to be lower than the its background concentration, due to low concentrations of the primary pollutant NO.

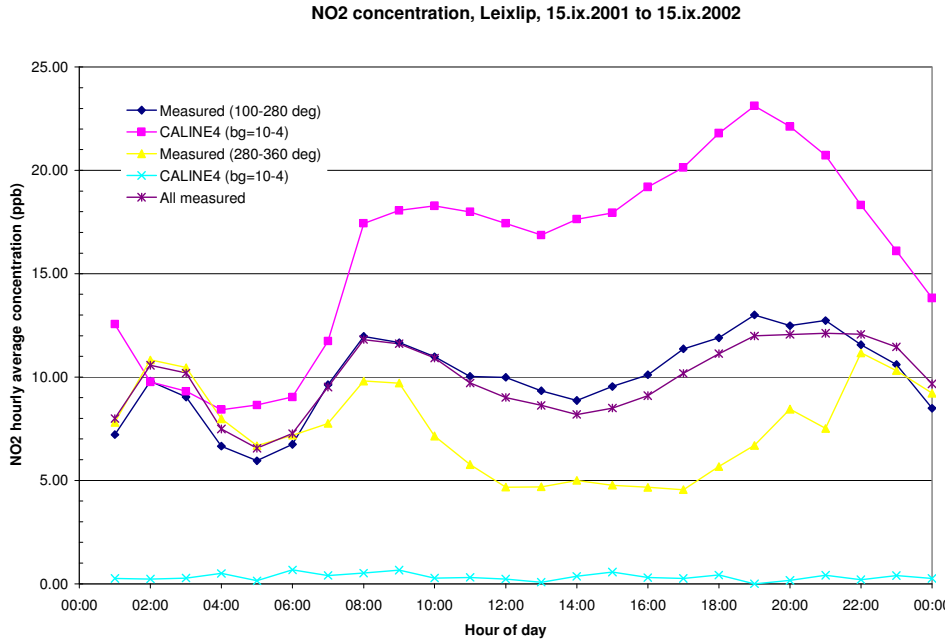


Figure 5.19: Modelled and measured average diurnal profiles for NO_2 with different wind directions.

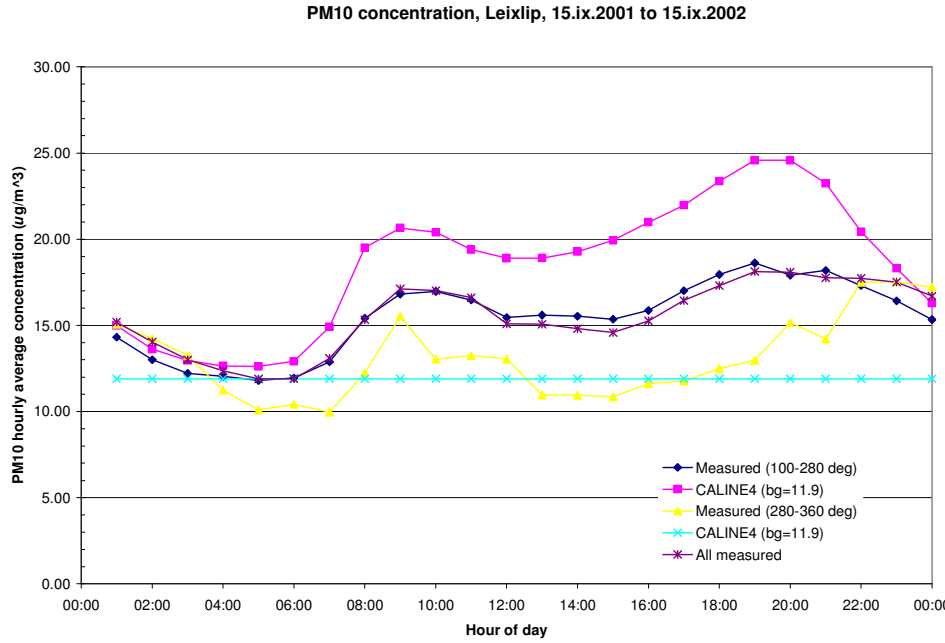


Figure 5.20: Modelled and measured average diurnal profiles for PM_{10} with different wind directions.

5.4.10 CALINE4 results – motorway: summary statistics

Two different sets of statistical values are used to evaluate model performance: a set of values related to legislative limit values and a set of model evaluation parameters.

Limit Values

EU directives on air quality specify limit values for CO, NO_2 and PM_{10}, but use different statistical variables for each (CEC 1999, CEC 2000, McGettigan 2001). In Table 5.7 equivalent modelled and measured values are presented for four cases: annual (September - September), winter (December-February), summer (June-August) and leeward (wind directions between 100 and 280º). The actual limit values and lower assessment thresholds (LATs) are also shown. Background values of 0.23 ppm CO, 6 ppb NO_2 and 11.9 µg/m^3 PM_{10} are included. All pollutant concentrations are expressed as µg/m^3 for comparison with the limit values.

For CO the maximum 8-hour rolling average must not exceed 10,000 µg/m^3. For NO_2 the hourly average must not exceed 200 µg/m^3 more than 18 times in one year (hence Table 5.7 shows the 19th highest value) which is equivalent to the 99.8th%ile. For NO_2 the annual mean must not exceed 40 µg/m^3. For PM_{10} the 24-hour average must not exceed 50 µg/m^3 more than 35 times in one year (hence the table shows the 36th highest value). These limit values must be attained by 1st January 2010 in the case of NO_2 and 1st January 2005 for both CO and PM_{10}. For PM_{10} the permissible number of exceedances of the limit value will be reduced to 7 times in one year by 1st January 2010. Rather than comparing the 8th highest value, the more stringent 4th highest is considered since the data for winter and summer obviously comprise less than the full year's data.

Table 5.7: CALINE4 – motorway: prediction of limit values

Pollutant	Measure	Limit Value µg/m^3	Measured (Modelled using CALINE4)			
			Annual	Winter	Summer	Leeward
CO	Max 8-hr rolling ave	10,000 LAT 5,000	2559(4007)	2559(3531)	640(2624)	2559(3531)
NO_2	19th highest hourly ave	200 LAT 100	84.46(89.93)	90.52(89.93)	63.54(89.93)	83.67(89.93)
	Annual mean	40 LAT 26	19.37(26.20)	21.39(25.13)	15.61(24.61)	19.44(31.21)
PM_{10} [Partisol]	36th highest 24-hr ave	50 LAT 20	22.83(22.63) [28.08]	30.46(22.89) [30.46]	17.54(21.12) [17.92]	20.34(21.12) [25.50]
	4th highest 24-hr ave	(50 for 8th)	38.58(26.70) [58.75]	46.24 (26.39) [14.01]	20.55(24.28) [23.33]	33.77(26.34) [50.21]
	Annual mean	40	15.49(17.42) [16.79]	17.67(17.29) [17.96]	12.20(16.78) [11.84]	14.75(17.30) 15.78

Note: Values are in green when the predicted and observed values both increase (or decrease) from the annual, and in red when only one increases (or decreases). Hourly NO_2 predicted values are limited to increments of 20 µg/m^3.

For CO, the maximum 8-hour rolling averages predicted by the model all exceed the measured values by a large amount. However, the model data do correctly predict that no measured values exceed either the limit value or the LAT.

For NO_2, good agreement on the highest hourly concentrations (equivalent to the 99.8^{th}%ile) is achieved for the annual, winter and leeward cases, while the summer value is overestimated. The model results overestimate the annual average concentration, but not by as much as with CO. The predicted concentrations indicate that some monitoring of NO_2 is required whereas the measured values are below the LAT.

For PM_{10}, two short-term variables are considered: the 36^{th} and 4^{th} highest 24-hour average concentrations. There is good agreement on the 36^{th} highest 24-hour average concentrations for the annual and leeward cases. The model produces a slight overestimate for summer and a large underestimate for winter. Agreement is much worse when considering the 4^{th} highest value. The model correctly predicts the exceedance of the LAT and the non-exceedance of the limit value (and the upper exceedance threshold). The annual mean is well predicted in the winter case, but over-estimated in the other cases.

Across all pollutants, the model correctly anticipates a reduction in average concentrations over the summer months, and an increase for winds from the road. The modelled increase in concentrations during winter months is less than that observed, as seen in the graphs of diurnal variation in Figures 5.15-5.17.

Model evaluation parameters

Table 5.8: CALINE4 – motorway: model evaluation parameters

	Parameter	**Mean**	**R**	**NMSE**	**FAC2**	**FB**	**FS**
	Minimum	0	-1	0	0	-2	-2
	Maximum	∞	1	∞	1	2	2
	Ideal	1	±1	0	1	0	0
CO	annual	1.68	0.24	0.77	0.59	0.33	0.03
	winter	1.50	0.21	0.93	0.55	0.12	-0.34
	summer	1.92	0.35	0.80	0.79	0.56	0.71
	leeward	1.81	0.30	0.72	0.57	0.43	0.11
NO_2	annual	2.25	0.39	0.87	0.67	0.30	0.45
	winter	2.00	0.38	0.71	0.58	0.16	0.23
	summer	2.42	0.41	1.11	0.81	0.45	0.72
	leeward	2.26	0.45	0.72	0.55	0.46	0.38
PM_{10}	annual	1.51	0.33	0.46	0.48	0.12	-0.25
	winter	1.32	0.33	0.64	0.51	-0.02	-0.51
	summer	1.78	0.34	0.38	0.76	0.31	0.13
	leeward	1.53	0.38	0.42	0.80	0.18	-0.22

The use of a set of common parameters allows model performance to be compared with the results of other assessment studies. They also help identify the conditions under which models perform best. Marmur and Mamane (2003) give a comprehensive explanation of the statistical parameters used in Tables 5.8 and 5.14. The mean, Pearson's correlation coefficient (R), normalised mean square error (NMSE), factor of two (FAC2), fractional bias (FB and fractional variance (FS) are calculated for annual, winter, summer and leeward datasets of predicted and observed hourly concentrations.

Mean: The mean of the modelled and measured values confirms that the predictions tend to overestimate the observed values, and that the predictions are closest to the observed concentrations in winter. The PM_{10} ratios are closest to the ideal value of 1.0, and the NO_2 values furthest away. Considering leeward values only does not suggest better model performance.

Pearson correlation coefficient (R): The Pearson correlation coefficient indicates whether variations in predicted hourly concentrations coincide with variations in observed hourly concentrations. By this assessment, the model performs somewhat better in summer and for NO_2, which contrasts with the above comparison of means. Considering leeward values leads to only a slight improvement. The best correlation is for leeward NO_2 (0.45) and the worst for winter CO (0.21).

Normalised mean square error (NMSE): Whereas the R-value compares hour-by-hour changes in values, the NMSE compares the absolute numerical values for each hour. If the predicted and observed values agree perfectly, the NMSE is zero. The PM_{10} values are in closest agreement, as shown graphically in the diurnal and directional plots (Figures 5.11 and 5.14). Summer PM_{10} concentrations agree best (0.38) and summer NO_2 worst (1.11), possibly reflecting the uncertainty in the modelling of photochemical transformations. For all three pollutants, considering the leeward case leads to closer agreement. CO concentrations are closest for the leeward situation and furthest apart for the winter.

Factor of two (FAC2): The FAC2 is the fraction of data for which the ratio of predicted to observed hourly concentrations is at least 0.5 and no more than 2. A FAC2 of 1 means that all of the predicted values are within a factor of two of the observed values, whereas a FAC2 of 0 means that none are. For all pollutants and all cases considered, between 50 and 80% of the modelled values lie within a factor of two of the observed values. Summer predictions perform much better than those in winter. Only for PM_{10} do the leeward predictions show a significant improvement on the annual values (80% compared to 48%), whereas for NO_2 a disimprovement is observed (55% compared to 67%).

Fractional bias (FB) and fractional variance (FS): FB measures the correlation between the averages of the predictions and observations, whereas the FS measures the correlation between the variances (standard deviations). Both vary from –2 for under prediction to +2 for over prediction, with 0 for perfect agreement. Compared to the annual value for all three pollutants, the FB suggests a lower over-prediction in winter and a greater over-prediction when only leeward

conditions are considered. The FB values agree with the comparison of means, suggesting that the PM_{10} prediction is closer to observed values than either CO or NO_2. The FS values suggest that modelled NO_2 values show more variance than the observed values, but that PM_{10} model values show less. For CO, the variance is underestimated in summer. For all pollutants, summer FS values are greater than those in winter. Considering leeward values only does not change the FS values significantly.

5.5 Model Results for N6 Roundabout, Galway

5.5.1 DMRB input data

The data requirements of the DMRB for the roundabout site are shown in Table 5.9. The major difference between modelling the roundabout compared to the motorway is the use of five links rather than one (see Table 5.3).

Table 5.9: DMRB input data – roundabout

Receptor and link data	Receptor name	Roundabout
	Year to be modelled	2001
	Link number (1-20)	5
	Description of link	Bothar na dTreabh Sandy Road N6 Headford Road Menlo N84
	Distance to receptor (from centre of road) (m)	15 15 35 45 45
	Distance to receptor (from kerbside) (m)	10 10 30 40 40
	Annual average vehicle flow (vph)	2480 1070 2760 1200 1790
	%HDV	7
	Average speed (kph)	15
Background concentrations (year adjusted)	CO (mg/m^3) Benzene ($\mu g/m^3$) NO_x ($\mu g/m^3$) PM_{10} ($\mu g/m^3$) gravimetric	0.21 0.40 11.73 12.90

5.5.2 DMRB Model Results & Measurements

Table 5.10 shows the annual mean concentrations predicted for the roundabout using the DMRB. Benzene was not measured at this site. The background value for benzene is that estimated for the motorway, though concentrations at the roundabout are expected to be higher. Clearly this low value has much less significance in the total concentration than at the motorway site, where the background was almost half of the total (see Table 5.4). Predictions decrease from 2001 to 2002 and 2003 since improved vehicle technology is expected to reduce unit emissions of all the pollutants modelled (see Tables D.3a and D.3b in Appendix D).

Table 5.10: DMRB results – roundabout

2001	**CO** (mg/m^3)	**Benzene** ($\mu g/m^3$)	**NO_x** ($\mu g/m^3$)	**PM_{10}** ($\mu g/m^3$)
Contribution from all roads	1.88	12.14	763.22	32.01
Background contribution	0.21	0.40	11.73	12.90
Total annual mean (incl. background)	2.09	12.54	774.95	44.91
Maximum 8-hr mean	20.93	*	*	*
Maximum running annual mean	*	13.79	*	*
Annual mean NO_2	*	*	193.95	*
90^{th}%ile of daily means	*	*	*	80.38

5.5.3 CALINE4 input data

The main difference between the CALINE4 modelling at the roundabout compared to that at the motorway, is the use of five links rather than one (see Table 5.5). A single separate link is employed to represent traffic flow in both directions on each of the five arms of the roundabout (Figure 2.7). Vehicles on all links are assumed to travel at an average velocity of 30 kph. In Table 5.11 the CALINE4 input data are presented under the categories of the CL4 interface programme: job parameters, link geometry, link activity, run conditions and receptor conditions.

Table 5.11: CALINE4 input data for CL4 interface - roundabout

	Parameter	**Options/units**
Job parameters	Job title	
	Run type	Standard
		Multi-run
		Worst-case wind angle
		Multi-run worst-case hybrid
	Aerodynamic roughness coefficient	Rural
		Suburban
		Central business district
		Other (cm)
	Model information	Link/receptor geometry units
		Altitude above sea level (m)
Link geometry	Link name	
	Link type	At-grade
		Depressed
		Fill
		Bridge
		Parking lot
	Endpoint 1 Coordinate X1	
	Endpoint 1 Coordinate Y1	
	Endpoint 2 Coordinate X2	
	Endpoint 2 Coordinate Y2	
	Link height	
	Mixing zone width	
	Canyon/bluff mix left	
	Canyon/bluff mix right	
Link activity	Link/run	
	Traffic volume (vph) Hour 1	
	Emission factor (g/mile) Hour 1	
Run conditions	Wind speed	(m/s)
	Wind direction	(degrees)
	Wind direction standard deviation	(degrees)
	Atmospheric stability class	(1-7)
	Mixing height	(m)
	Ambient temperature	(degrees C)
	Ambient pollutant concentration	(ppm)
Receptor conditions	Receptor name	
	X	
	Y	
	Z	

5.5.4 CALINE4 modelled annual concentrations

CALINE4 models the effect on air quality of emissions from each link separately, and these are summed to give the total predicted concentration. As at the motorway (see Table 5.6) predictions for the worst-case wind direction

overestimate the measured concentrations, given in Table 5.12. The 8-hour averages agree well with the measured concentrations.

Run-types: 1 = Standard (hourly)
2 = Multi-run (8-hr average)
3 = Worst-case wind angle (hourly, wind direction given)
4 = Multi-run/worst-case (8-hr average)

Table 5.12: CALINE4 results – roundabout CO (ppm)

3.i.2002 Hour	Measured		Modelled					
	Hourly	8hr average	Hourly			8hr average		
			S	W	W(θ˚)	S	W	S*
07:00	0.19	0.19	0.18	0.18	299˚			
08:00	0.23	0.20	0.18	0.28	299˚			
09:00	0.29	0.21	0.28	0.38	298˚			
10:00	0.35	0.23	0.38	0.48	299˚			
11:00	0.33	0.25	0.28	0.38	298˚			
12:00	0.33	0.26	0.38	0.48	298˚			
13:00	0.36	0.28	0.38	0.48	298˚			
14:00	0.37	0.31	0.18	0.38	298˚	0.28	0.38	0.2
15:00	0.31	0.32	0.18	0.38	298˚	0.28	0.38	0.2
16:00	0.33	0.33	0.28	0.38	298˚	0.29	0.38	0.2
17:00	0.33	0.34	0.38	0.58	298˚	0.31	0.48	0.2
18:00	0.37	0.34	0.38	0.58	298˚	0.31	0.48	0.2

S: Standard model run
W: Worst case wind direction model run
W(θ˚): Wind direction for worst case concentration
S*: Standard run with model input background concentration ≠ 0 ppm CO. This was modelled with the same background concentration of 0.18 ppm CO as all previous runs, but with the background concentration included as an input variable in modelling. For all previous runs the background concentration was added after modelling.
See Appendix D for other input data.

5.5.5 CALINE4 results – roundabout: sample hourly and 24 hour averages

Hour-by-hour variation

Figures 5.21-5.23 compare the hour-by-hour variation in measured and modelled concentrations for a sample week. The week shown is that discussed in Section 5.4.5. At the roundabout site, background concentrations of 0.18 ppm CO, 6 ppb NO_2 and 12.9 $\mu g/m^3$ PM_{10} have been added to the model results, using the same procedures as for the motorway site (Section 5.4.6).

In Figure 5.21, increases in the model CO concentrations are observed at the same times as most of the measured peaks, but the observed concentrations are usually underestimated, especially for the lage peaks. The times of the peaks in the modelled and measured NO_2 concentrations shown in Figure 5.22 also agree well, and in this case there is better agreement on the peak concentrations, with small overestimates generally observable. The differences in values are generally within the 10 ppb precision to which the model results are reported. In Figure 5.23, the variation in the modelled PM_{10} concentrations is much less than that in the

measured values. For the high measured concentration episode observed in midweek, there is a noticeable contemporary increase in the modelled profile, but the peak concentration is underestimated. However, at the other times when the measured concentrations increase, only slight variations in the modelled values occur.

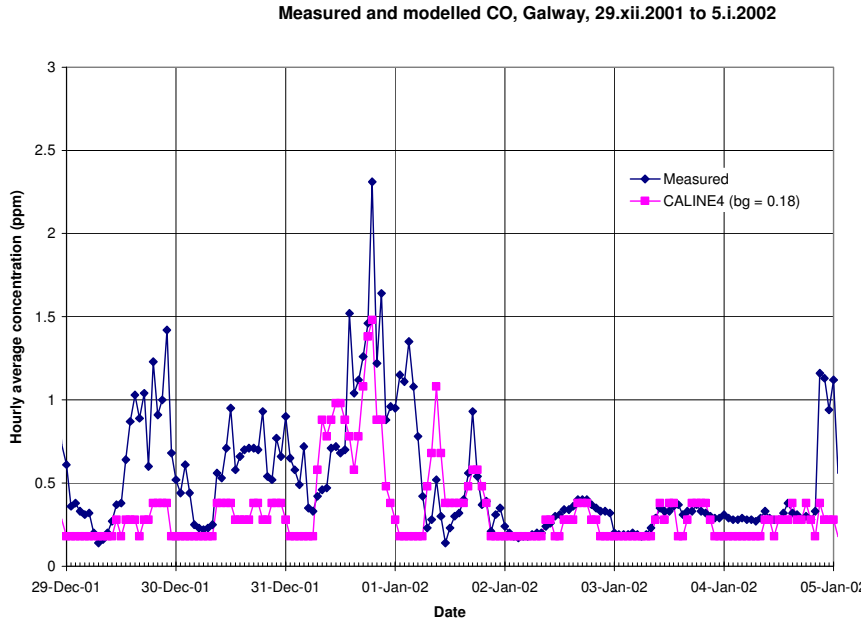


Figure 5.21: Sample week of modelled and measured hourly CO concentrations

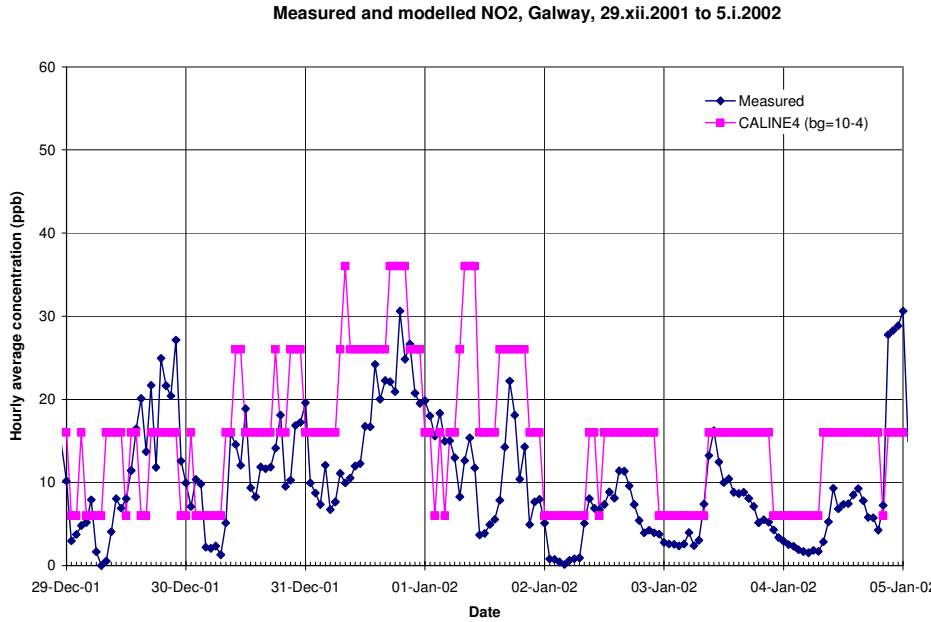


Figure 5.22: Sample week of modelled and measured hourly NO_2 concentrations

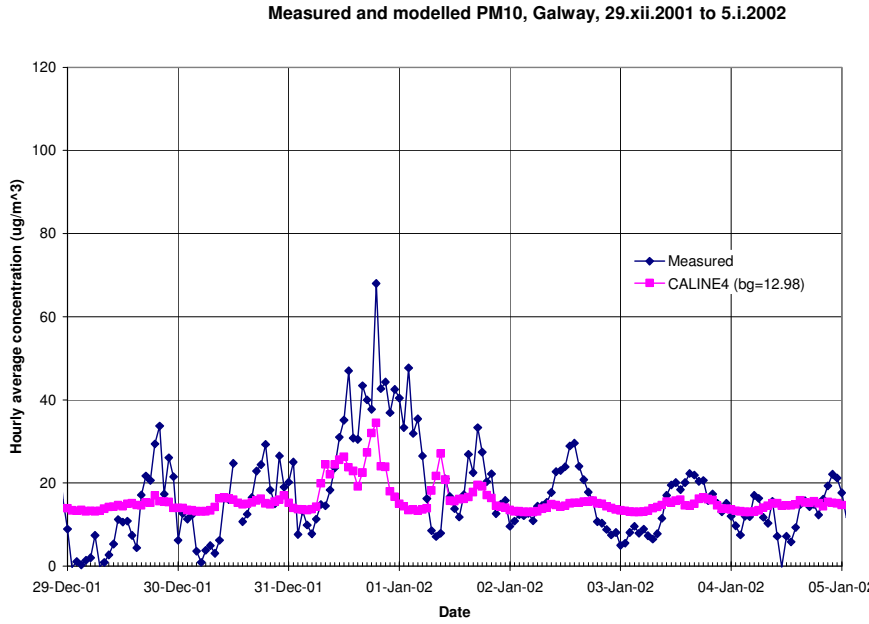


Figure 5.23: Sample week of modelled and measured hourly PM_{10} concentrations.

Variation in 24-hour average

Figures 5.24-5.26 compare measured and modelled 24-hour average concentrations over an eight-week period in mid-winter. In Figure 5.24, the high CO concentrations observed at the start of the period are not predicted by the model, but some of those occurring in the middle of the period are. Generally the model results underestimate the measured CO concentrations. In Figure 5.25, the peaks in the modelled NO_2 concentrations match the observed peaks well, both in time and magnitude. The comparison of modelled and measured NO_2 data in this figure agrees well with that shown in Figure 5.7 for the motorway site. As in the sample week of hourly data, the PM_{10} predictions in Figure 5.26 show little variation, which is in contrast to the significant fluctuations measured by both the TEOM and Partisol. Modelled PM_{10} concentrations are almost always less than those observed.

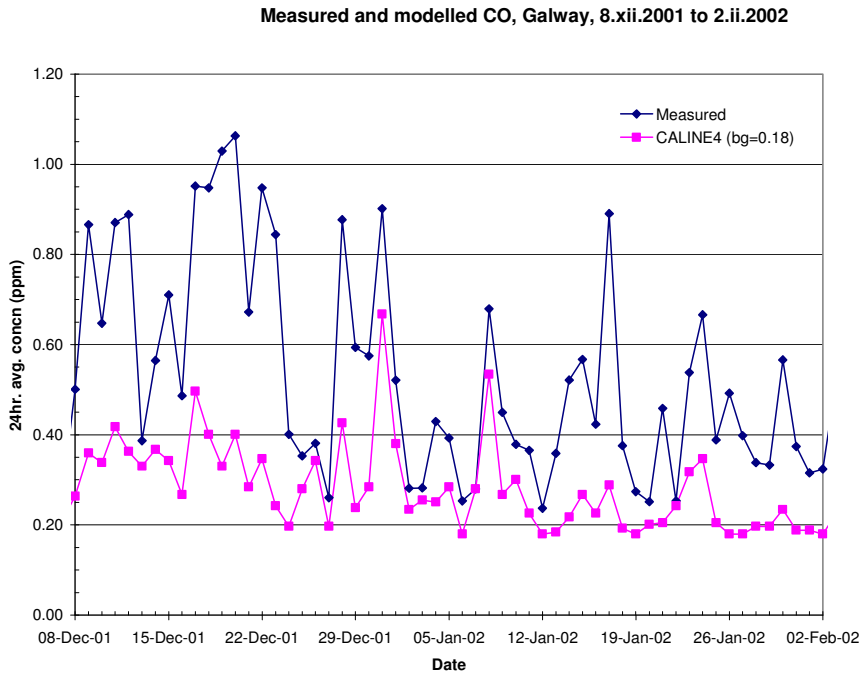


Figure 5.24: Comparison of measured and modelled 24-hour CO averages

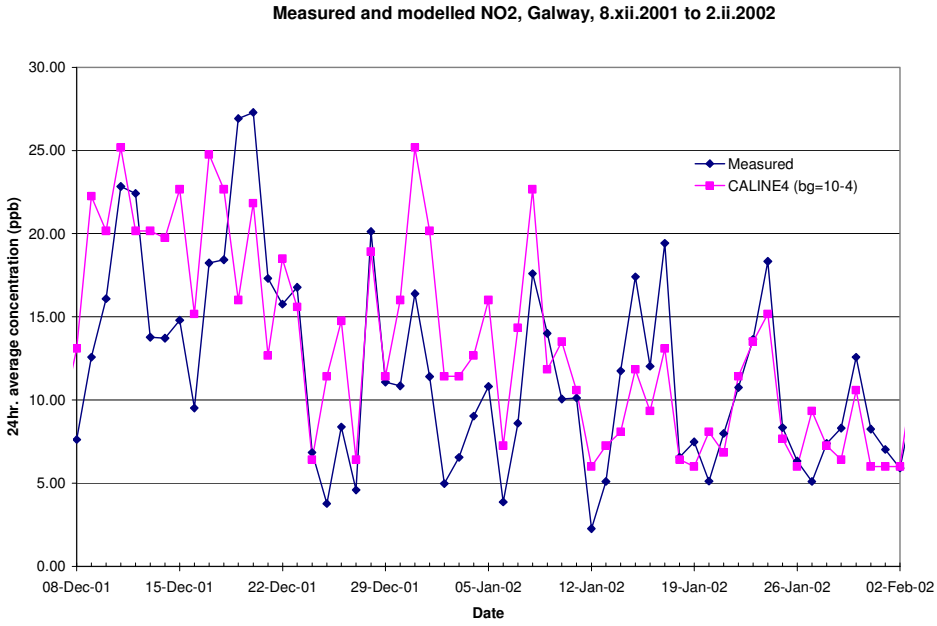


Figure 5.25: Comparison of measured and modelled 24-hour NO_2 averages

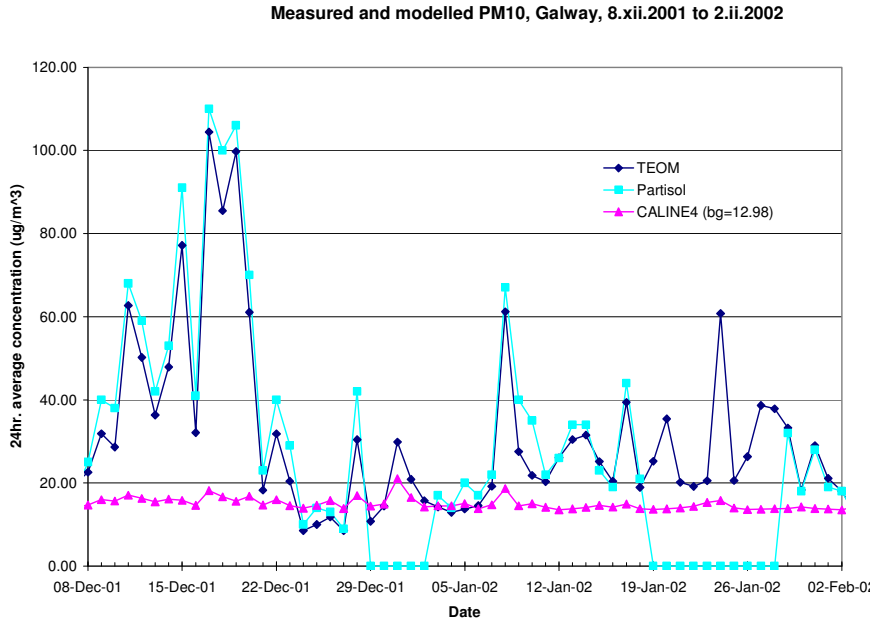


Figure 5.26: Comparison of measured and modelled 24-hour PM_{10} averages

5.5.6 CALINE4 results – roundabout: diurnal variation

Figures 5.27-5.29 compare the average diurnal variations of the measured and modelled concentrations of CO, NO_2, and PM_{10} over the whole monitoring period. With all three pollutants, the measured and modelled profiles both reflect the diurnal variation in traffic flow, but the diurnal range of concentrations is much smaller in the modelled data. For CO, the average difference between the early morning concentration minimum and the evening concentration maximum is 0.57 ppm in the measured data, but only 0.20 ppm in the modelled data. For NO_2, this difference was measured as 14.0 ppb and modelled as 9.6 ppb; while for PM_{10} the measured and modelled differences are 23.2 and 4.1 $\mu g/m^3$, respectively. The maximum CO and PM_{10} concentrations are greatly underestimated by the model, but the measured and modelled NO_2 maxima agree well.

Table 5.13 compares the diurnal concentration ranges at the roundabout and motorway sites. The modelled ranges are all wider at the Leixlip motorway site, but the measured ranges are all narrower. The differences in the modelled ranges at either site agree with the different peak traffic flows and emission factors used. The peak flow on the M4 at Leixlip was 33% higher than that on the N6 (Dublin arm) in Galway. This is reflected in 20-50% wider diurnal concentration ranges for modelled NO_2 and CO. The modelled PM_{10} concentration range is 250% wider at Leixlip, due to the combined effect of the higher traffic flow and the use of a composite emission factor which was twice as high as that used at Galway. The wider diurnal range displayed by the concentrations measured at Galway may be due to diurnal variations in the emission strength of sources other than traffic on the N6 Dublin road.

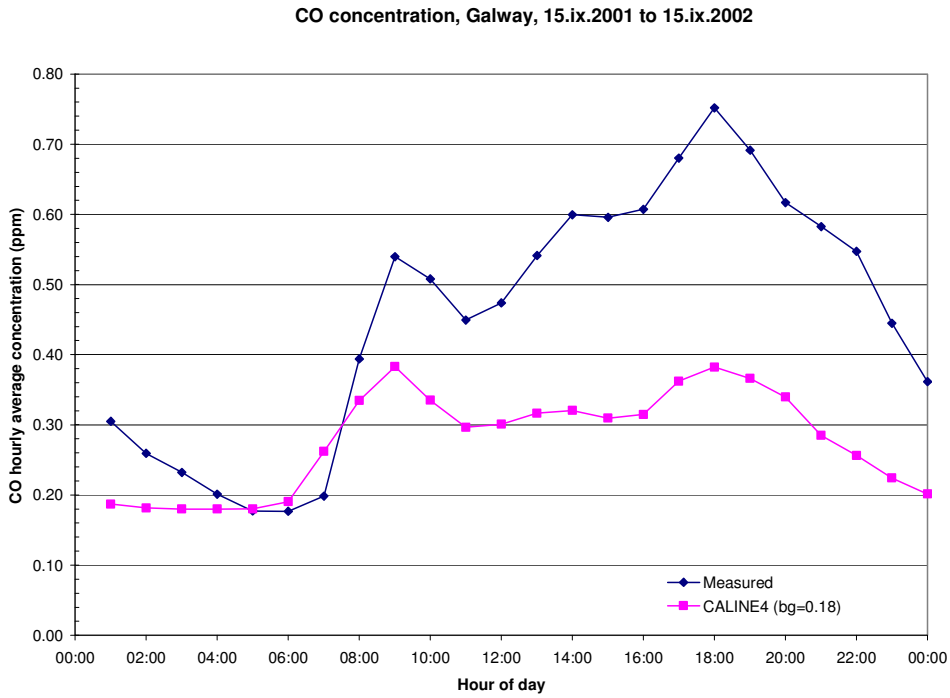


Figure 5.27: Measured and modelled average diurnal profiles for CO

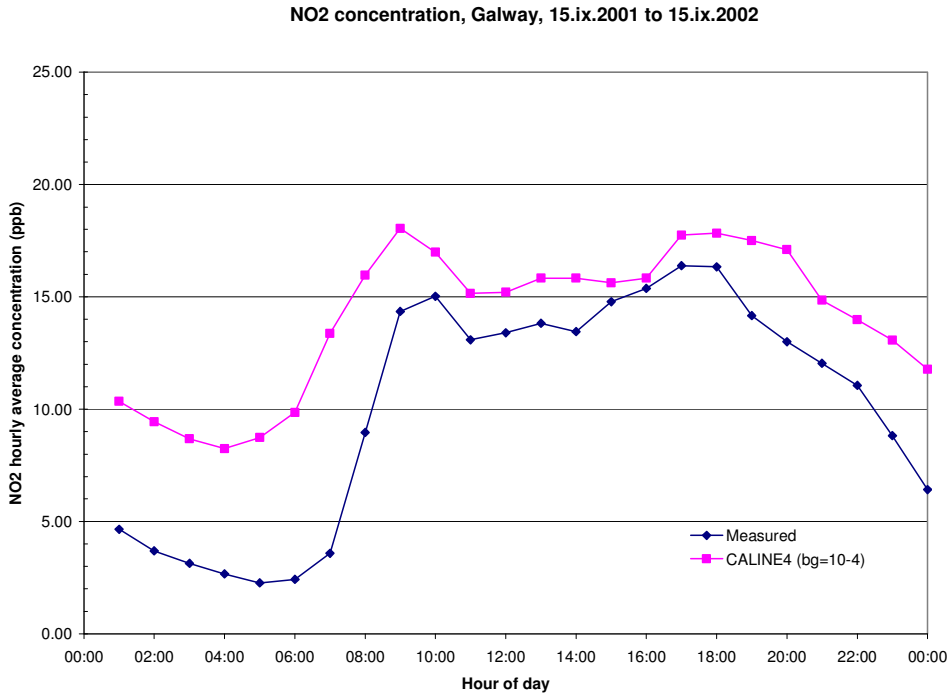


Figure 5.28: Measured and modelled average diurnal profiles for NO_2

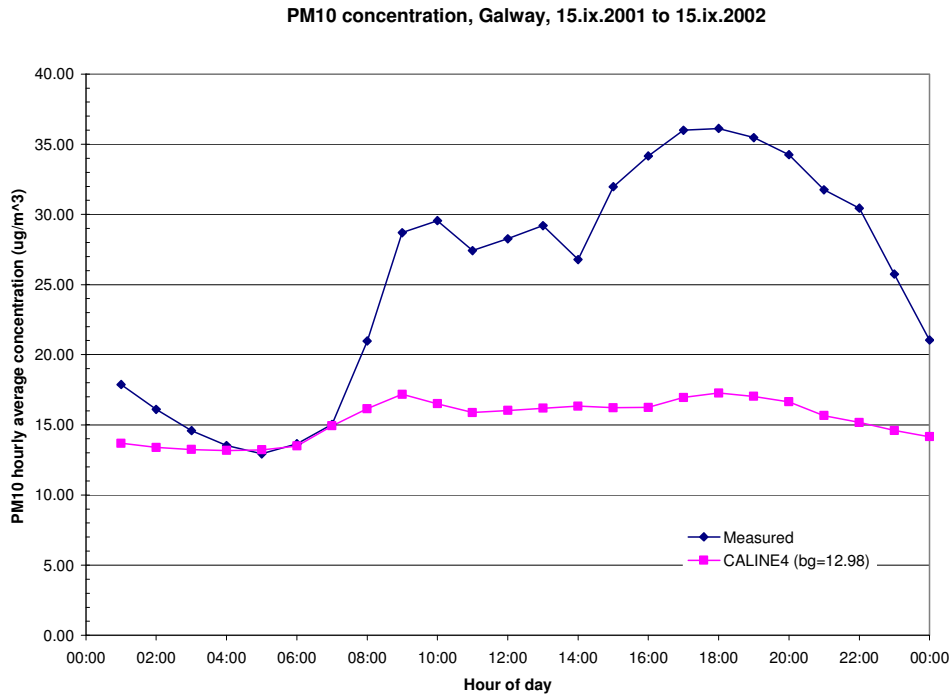


Figure 5.29: Measured and modelled average diurnal profiles for PM_{10}

Table 5.13: Comparison of diurnal concentration ranges at the motorway and at the N6 (Dublin Road) arm of the roundabout.

Site	Peak pm traffic flow (vph)	Diurnal Concentration Range					
		CO (ppm)		NO_2 (ppb)		PM_{10} ($\mu g/m^3$)	
		Modelled	Measured	Modelled	Measured	Modelled	Measured
Motorway	2650	0.30	0.11	12	6	10	6
N6 (Dublin)	2058	0.20	0.57	10	14	4	23

5.5.7 CALINE4 results – roundabout: variation with wind direction

Figures 5.30-5.32 compare the variations in measured and modelled concentrations with wind direction. In Figure 5.30 and 5.32, CO and PM_{10} concentrations are underestimated by the model for all wind directions except those in the SE quadrant. For wind directions between 0 and 190º, modelled NO_2 concentrations overestimate measured values, but for wind directions between 190 and 360º, good agreement is observed, especially for the predominant wind directions between 225 and 270º.

For all pollutants, the highest concentrations are observed with winds from the NE and, for CO, the NW. The model also predicts the highest concentrations for NE winds, which are near-parallel to a long, straight part of the N6 East (Figure 2.6). As at the motorway site, NO_2 concentrations are greatly overpredicted under these conditions. However, modelled CO and PM_{10} concentrations in this wind direction

range are much less than those observed, especially for PM_{10} (Figure 5.32) where the highest observed and modelled concentrations are 44.03 µg/m^3 and 16.85 µg/m^3, respectively.

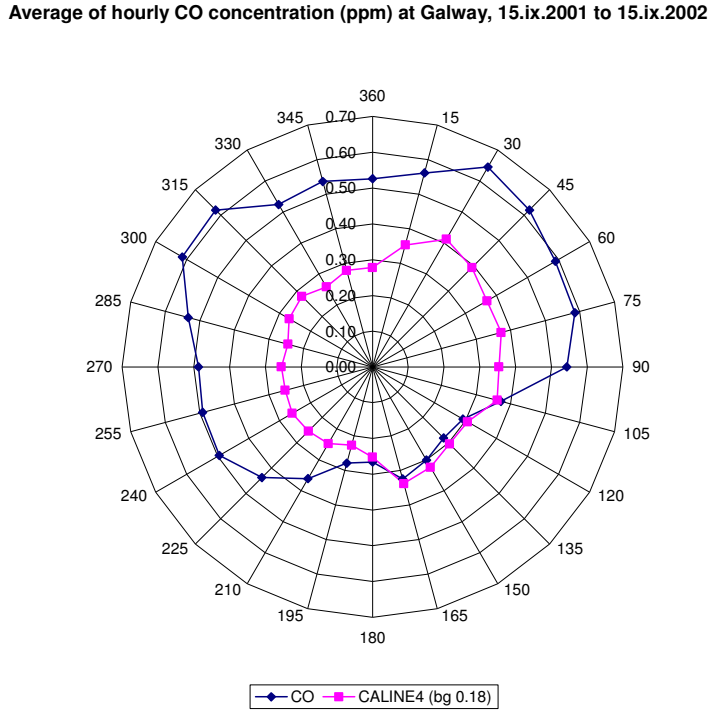


Figure 5.30: Measured and modelled CO pollution roses

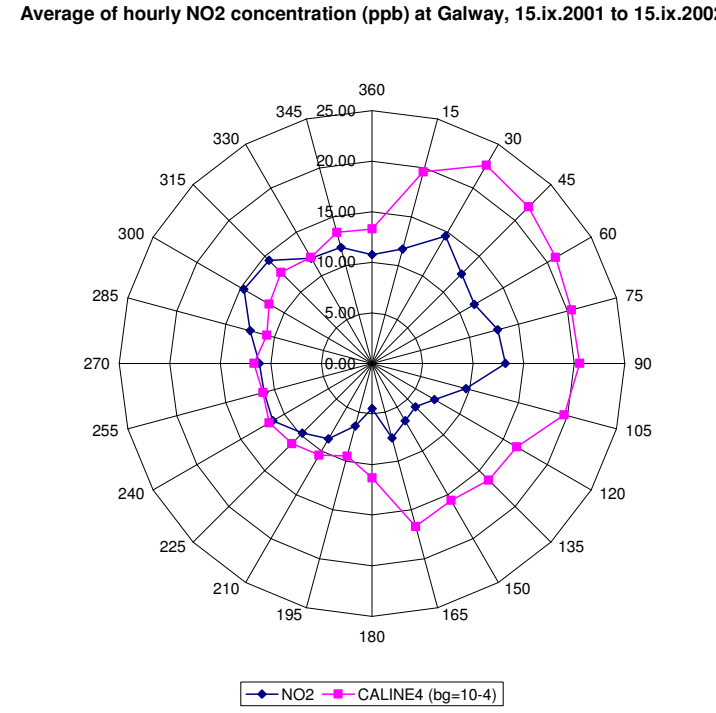


Figure 5.31: Measured and modelled NO_2 pollution roses

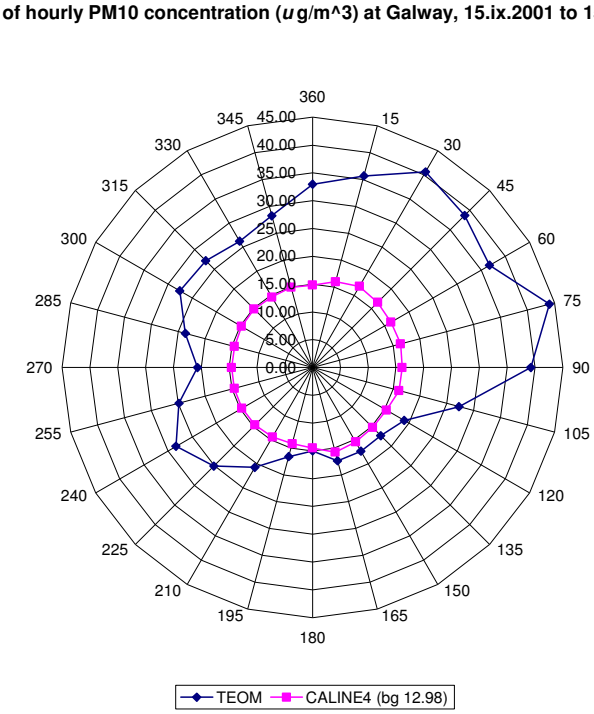
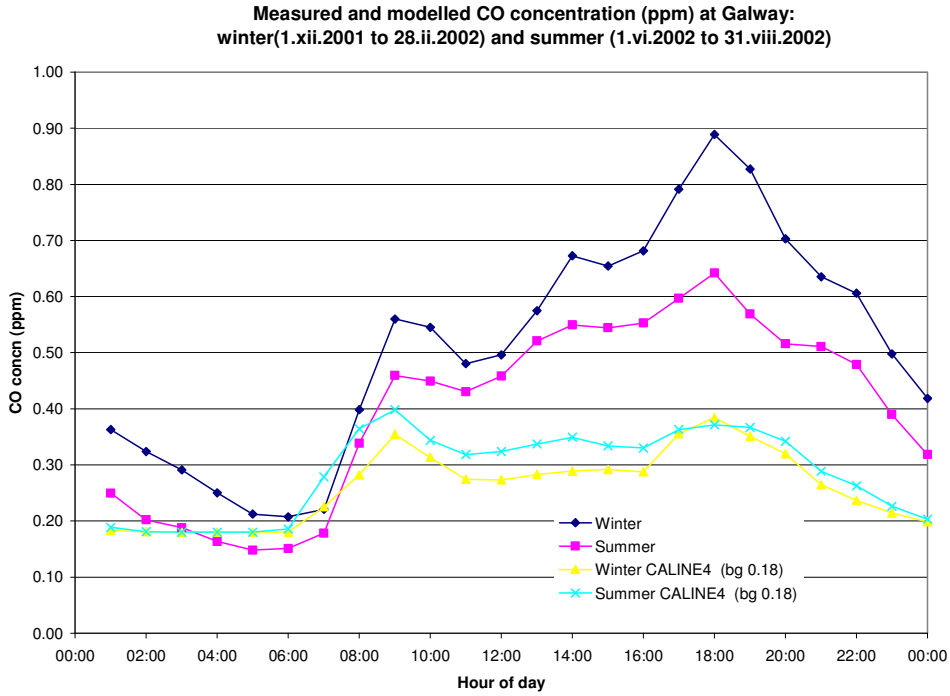


Figure 5.32: Measured and modelled PM_{10} pollution roses

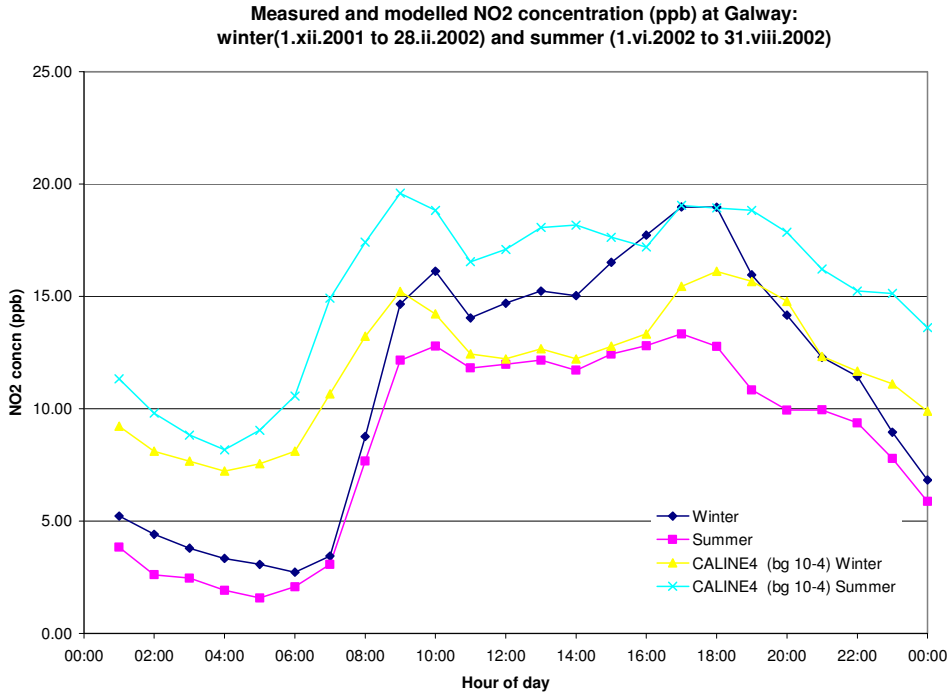
See also pollution roses for 24-hour average concentrations in Appendix B.

5.5.8 CALINE4 results – roundabout: winter and summer seasons

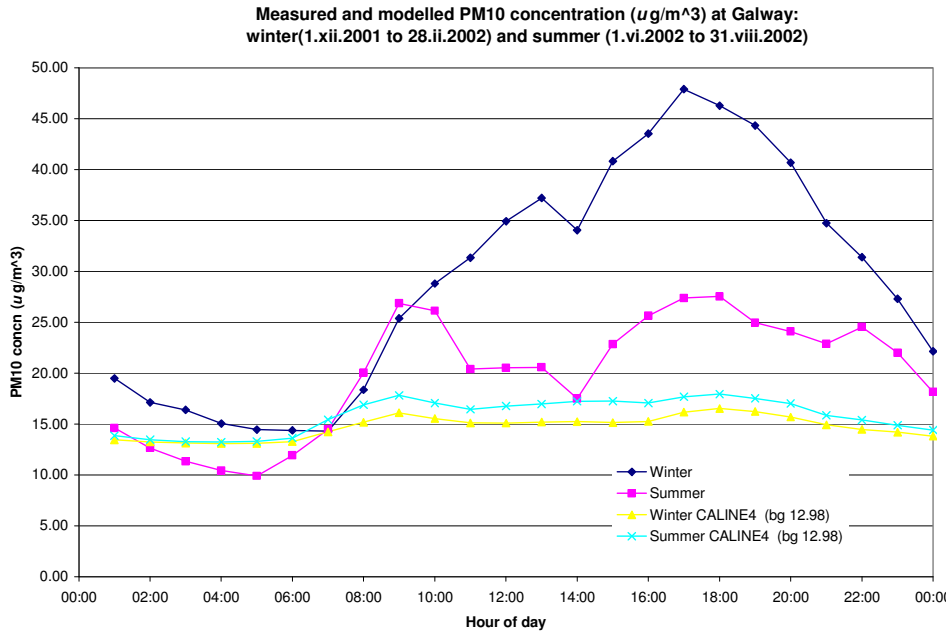
Figures 5.33-5.35 show measured and modelled diurnal profiles for separate winter and summer periods. The same background concentrations have been used for both seasons. For all three pollutants, concentrations measured in winter are greater than those measured in summer. However, for the modelled concentrations, the opposite is the case: summer values exceed winter values, albeit that for CO and PM_{10} the difference between the modelled profile in either season is very small. For NO_2, as at the motorway site, the measured and modelled diurnal profiles agree better in winter than in summer, although the average annual diurnal profiles shown in Figure 5.28 agree best of all.



Figures 5.33: Modelled and measured average diurnal profiles for CO in winter and summer



Figures 5.34: Modelled and measured average diurnal profiles for NO_2 in winter and summer



Figures 5.35: Modelled and measured average diurnal profiles for PM_{10} in winter and summer

5.5.9 CALINE4 results – roundabout: summary statistics

As for the motorway site, two different sets of statistical values are used to evaluate model performance: a set of values related to legislative limit values and a set of model evaluation parameters.

Limit Values

EU directives on air quality specify limit values for CO, NO_2 and PM_{10}, but use different statistical variables for each. In Table 5.14, equivalent modelled and measured values are presented for three cases: annual (September - September), winter (December-February) and summer (June-August). The actual limit values and lower assessment thresholds (LATs) are also shown. These can be compared with the values for the motorway in Table 5.7.

When considering the annual cases, the model correctly predicts that none of the pollutants exceed current limit values. The only exceedance of a limit value (for the protection of human health) is that for the annual average of 24–hour PM_{10}, for which the 50 $\mu g/m^3$ is exceeded more than seven times in the year, but the attainment date for this limit value is not until 1 January 2010.

The maximum eight-hour rolling average concentration of CO is underestimated in all three cases, but the non-exceedance of the LAT is correctly predicted. In contrast, the annual mean NO_2 concentration is overestimated by the model in all three cases. Although good agreement is achieved in the winter data set, an exceedance of the LAT is wrongly predicted due to a large model overestimate in summer. Considering the highest hourly NO_2 concentrations, the annual prediction

is reasonable, but those for winter and summer are under- and over-estimates, respectively.

Annual PM_{10} mean concentrations are underpredicted in every case, with the greatest discrepancy in winter. All model predictions of the highest 24-hour PM_{10} concentrations are also lower than the measured values, with winter model estimates especially low. The model fails to predict the exceedance of the LAT in some cases, but succeeds in others. In fact, considering the 36th highest 24-hour average in the annual case, the measured PM_{10} concentration is above the UAT of 30 $\mu g/m^3$, whereas the modelled value is below the LAT of 20 $\mu g/m^3$.

For CO the model accurately reflects the occurrence of the maximum 8-hour rolling average during the winter, and the lower summer maximum. The winter increases and summer reductions in the measured concentrations of NO_2 and PM_{10} are not matched by the modelled concentrations.

Table 5.14: CALINE4 – roundabout: prediction of limit values

Pollutant	Measure	Limit Value $\mu g/m^3$	Measured (Modelled using CALINE4)		
			Annual	Winter	Summer
CO	Max 8-hr rolling ave	10,000 LAT 5,000	2860(1181)	2860(1181)	1184(824)
NO_2	19th highest hourly ave	200 LAT 100	88.82(70.38)	94.93(70.38)	57.56(70.38)
	Annual mean	40 LAT 26	19.79(27.45)	21.70(23.13)	16.53(29.98)
PM_{10} [Partisol]	36th highest 24-hr ave	50 LAT 20	39.61(17.15) [42]	50.21(16.28) [67]	30.00(20.27) [26]
	8th highest 24-hr ave	50 LAT 20	67.63(24.04) [73]	85.80(18.20) [106]	32.90(24.04) [32]
	Annual mean	40	25.46(15.39) [25.53]	29.17(14.73) [32.32]	19.89(15.86) [17.43]

Note: Values are in green when the predicted and observed values both increase (or decrease) from the annual, and in red when only one increases (or decreases). Hourly NO_2 predicted values are limited to increments of 20 $\mu g/m^3$. LAT: Lower Assessment Threshold.

Model evaluation parameters

Table 5.15 presents model evaluation parameters determined using the measured and modelled data for the roundabout site. These can be compared with those for the motorway site in Table 5.8, where a description of the parameters is given.

Mean: The mean of modelled and measured NO_2 and PM_{10} are again closest in winter, though for CO (for which the mean is underpredicted) they are closest in summer. The mean NO_2 value confirms the overprediction observed in Figures 5.25 and 5.28.

Pearson correlation coefficient (R): According to the R-value, the variations in concentrations in the modelled and measured data agree best in winter. The best

correlation is for winter CO (0.64) and the worst for summer PM_{10} (0.33). These R-values are higher than those determined with the motorway data.

Normalised mean square error (NMSE): From the NMSE, the magnitude of the measured and modelled NO_2 concentrations agree best and those of PM_{10} agree worst. NO_2 predictions are better in winter than in summer, whereas CO and PM_{10} predictions improve in summer. The NMSE for CO is similar to that determined at the motorway site, while those for NO_2 and PM_{10} are much lower and higher, respectively.

Factor of two (FAC2): Across all cases and pollutants, between 50 and 80% of the modelled hourly concentrations lie within a factor of two of their contemporary measured values. This is the same range observed at the motorway site. The modelled PM_{10} and CO results compare slightly better than the NO_2 values, and both PM_{10} and CO improve in summer, whereas NO_2 improves in winter.

Fractional bias (FB) and fractional variance (FS): The fractional bias values confirm Figures 5.33 and 5.35, that CO and PM_{10} are underpredicted, particularly in winter. For NO_2, the FB shows negligible winter overprediction (0.06), but significant overprediction for the summer months (0.58). Overall, the FB values suggest that agreement between modelled and measured data is less good at this site than at the motorway. The large negative fractional variance values for CO and PM_{10} reflect the much greater variation in the measured concentrations of these pollutants, compared to that in the modelled values. The NO_2 values are much better in this regard.

Table 5.15: CALINE4 – roundabout: model evaluation parameters

	Parameter	**Mean**	**R**	**NMSE**	**FAC2**	**FB**	**FS**
	Minimum	0	-1	0	0	-2	-2
	Maximum	∞	1	∞	1	2	2
	Ideal	1	±1	0	1	0	0
CO	annual	0.83	0.58	0.77	0.67	-0.48	-0.78
	winter	0.75	0.64	0.96	0.56	-0.65	-0.91
	summer	0.90	0.54	0.48	0.78	-0.33	-0.51
NO_2	annual	4.63	0.49	0.50	0.55	0.32	-0.08
	winter	3.49	0.63	0.33	0.61	0.06	-0.21
	summer	4.57	0.42	0.69	0.49	0.58	0.20
PM_{10}	annual	1.17	0.35	1.44	0.66	-0.49	-1.52
	winter	1.09	0.56	2.25	0.62	-0.66	-1.74
	summer	1.28	0.33	0.52	0.75	-0.23	-1.09

6 Model Validation and Evaluation

6.1 Introduction

In this chapter, further dispersion modelling results are presented which examine the range of results that can be achieved when different modellers use alternative models, and when different modelling assumptions are employed. In Section 6.2, a model validation exercise is described in which a number of independent modellers calculated pollution concentrations at the motorway and roundabout sites. In Sections 6.3-6.5 model sensitivities to emission factors, background concentrations and link layout are examined. In Section 6.6, proposals are made for the future use of highway dispersion models in Ireland.

6.2 Collaborative Model Validation Exercise

6.2.1 Description of exercise

Environmental consultants known to have relevant experience were invited to use atmospheric dispersion models with suitable input data (traffic, emission factors, meteorological conditions) to determine pollutant concentrations due to vehicle emissions at the two sites. Their calculations were to cover the first six months of the monitoring period. The objective of the exercise was to establish the current state-of-the practice in Ireland, and to improve the evaluation of dispersion model accuracy by employing the modelling results of as many participants as possible. The collated results were presented and discussed at a modelling workshop held in TCD.

6.2.2 Data provided

Site maps provided for Leixlip and Galway showed the location and layout of each. Local hourly meteorological data were presented from both sites for September 2001 to March 2002 inclusive. Some Met Eireann data (such as hourly Pasquill Stability Class and cloud cover) were also provided to participants, where this was necessary to supplement the locally collected data. The NRA supplied hourly lane-by-lane traffic data for the motorway. At the roundabout site, traffic data were limited to manual counts carried out by TCD, NUIG and Galway Corporation. The first 12 days of hourly concentration measurements obtained at both sites for CO, NO, NO_2, NO_x and PM_{10} were included, to aid in the estimation of background concentrations.

6.2.3 Participants and modelling assumptions

The following organisations participated in the exercise, employing the dispersion models stated:

AWN Consulting (CAL3QHCR)
Cambridge Environmental Research Consultants (ADMS Roads)
Envirocon (ADMS Roads)

Trinity College Dublin (CALINE4)

In addition, representatives of Enterprise Ireland and Dublin City Council also participated in the modelling workshop at TCD, as did the project partners from NUI, Galway.

The participants adopted different approaches to the estimation of background concentrations. Two participants based these on the 12 days of monitoring data provided for both sites, while the other two employed historical data from established monitoring sites. The latter approach is the more conventional, and it was felt that employing the 12 days of monitored data would lead to higher values.

To determine composite emission factors, the participants drew on three sources of vehicle emission data: COPERT III, the UK EFD and the DMRB. One modeller made additional allowances for coarse fraction and sea salt at Galway. Only one modeller made explicit allowance for cold starts. One modeller varied the composite emission factor according to the recorded hour-by-hour variation in HGV percentage, whereas the other three took a constant average value.

None of the participants allowed for the gradient of the road at the motorway site. All participants modelled the five approach roads to the Galway roundabout as five straight single links, but two participants also included five more short links to represent the circulatory part of the roundabout. In one case, different mean vehicle speeds were assumed for the five links, although all of these were in the range 20-30 kph.

6.2.4 Results for M4 motorway at Leixlip

The results in Tables 6.1a) and 6.1b) show that the observed mean hourly and eight-hourly CO concentrations were all well predicted, except in the case of Participant B who assumed a low background concentration. However, the higher concentrations were under predicted, especially the limit value-equivalent maximum eight-hour average concentration. It is worth noting that the observed CO concentrations at this location are very low.

Table 6.1a): Carbon Monoxide – Hourly average concentrations (ppm)

	Measured	Participant			
		A	B	C	D
Mean	*0.28*	-	0.04	0.25	0.30
Median	*0.2*	0.30	0.02	0.22	0.20
Maximum	*2.6*	0.47	0.35	0.62	1.40
90^{th} %-ile	*0.5*	0.34	0.11	0.32	0.46
95^{th} %-ile	*0.7*	0.35	0.16	0.39	0.60

Table 6.1b): Carbon Monoxide – 8-hour average concentrations (ppm)

	Measured	Participant			
		A	B	C	D
Mean	*0.28*	-	0.04	0.25	0.30
Median	*0.24*	0.30	0.03	0.23	0.27
Maximum	*1.88*	0.37	0.29	0.46	0.93

In Table 6.2, the mean/median observed NO_2 concentrations are quite well predicted by the modellers, with model results both above and below the measured values. The maximum and limit value-equivalent 9th highest hourly concentrations were well predicted by two participants, but the other two underpredicted by about 50%.

Table 6.2: Nitrogen Dioxide – Hourly average concentrations (ppb)

	Measured	Participant			
		A	B	C	D
Mean	*11.2*	9.3	7.5	10.7	19.8
Median	*9.1*	10.0	5.1	7.4	10.0
Maximum	*49.0*	26.1	27.9	48.3	50.0
90th %-ile	*23.9*	11.0	17.7	26.2	30.0
95th %-ile	*28.0*	12.6	22.7	32.1	40.0
9th highest	*45.4*	20.7	26.9	43.9	50.0

Tables 6.3a) and 6.3b) show that the mean hourly average and 24-hour average PM_{10} concentrations were overpredicted by three participants (by up to 50%), but underpredicted by the other. While the maximum 24-hour average concentration was underpredicted by all four participants, predictions of the limit value-equivalent 17th highest 24-hour average concentration was within 25% of the observed value in three out of four cases.

Table 6.3a): PM_{10} – Hourly average concentrations ($\mu g/m^3$)

	Measured	Participant			
		A	B	C	D
Mean	*16.5*	20.8	12.8	24.5	24.9
Median	*14.9*	19.2	12.4	23.3	19.0
Maximum	*112.4*	35.7	18.9	61.1	82.0
90th %-ile	*26.7*	23.2	14.2	37.5	33.0
95th %-ile	*33.0*	24.4	15.2	42.8	40.0

Table 6.3b): PM_{10} – 24-hour average concentrations ($\mu g/m^3$)

	Measured	Participant			
		A	B	C	D
Mean	*16.4*	20.6	12.9	24.9	24.0
Median	*15*	19.9	12.7	24.9	23.0
Maximum	*46*	23.6	15.9	37.7	35.0
3rd highest	*36*	23.2	14.7	35.5	34.0
17th highest	*25*	21.6	13.7	31.0	30.0

6.2.5 Results for N6 roundabout in Galway

Tables 6.4a) and 6.4b) show that mean/median hourly CO concentrations at the roundabout site were well predicted by two participants, over predicted by one and under predicted by one other. However, the highest hourly concentrations were under predicted by all, as were both the mean and maximum 8-hour average concentrations.

Table 6.4a): Carbon Monoxide – Hourly average concentrations (ppm)

	Measured	Participant			
		A	B	C	D
Mean	*0.41*	-	0.19	0.37	0.36
Median	*0.33*	0.39	0.11	0.28	0.28
Maximum	*3.68*	1.72	0.68	1.69	2.08
90th %-ile	*0.78*	0.69	0.55	0.62	0.58
95th %-ile	*1.05*	0.83	0.64	0.88	0.68

Table 6.4b): Carbon Monoxide – 8-hour average concentrations (ppm)

	Measured	Participant			
		A	B	C	D
Mean	*0.49*	-	0.19	0.37	0.36
Median	*0.43*	0.42	0.12	0.30	0.36
Maximum	*2.40*	1.02	0.68	1.42	1.09

Table 6.5 shows that good predictions of the mean/median NO_2 concentrations were obtained by two participants. Model predictions of the highest hourly concentrations vary greatly; the limit value-equivalent 9th highest hourly concentration includes one over prediction (by about 60%) and two under predictions (by about 40-50%).

Table 6.5: Nitrogen Dioxide – Hourly average concentrations (ppb)

	Measured	Participant			
		A	B	C	D
Mean	*11.2*	5.8	12.5	14.0	-
Median	*9.4*	3.2	8.6	8.6	-
Maximum	*22.8*	34.4	29.7	92.0	-
90th %-ile	*25.3*	10.1	28.2	34.7	-
95th %-ile	*30.6*	12.9	29.2	42.0	-
9th highest	*48.6*	24.1	29.7	79.2	-

Tables 6.6a) and 6.6b) compare the modelled and measured PM_{10} concentrations at the roundabout site. Three of the predicted mean hourly concentrations are within 15% of the measured value, but the other underestimates by nearly 50%. The mean/median 24-hour concentrations show a similar comparison. As with CO, the highest values (for both hourly and 24-hour averages) are underpredicted by all participants. For the limit value-equivalent 17th highest 24-hour average - the measured value is underestimated by between 25 and 50%.

Table 6.6a): PM_{10} – Hourly average concentrations ($\mu g/m^3$)

	Measured	Participant			
		A	B	C	D
Mean	*29.0*	28.4	15.4	24.8	32.1
Median	*21.7*	25.6	14.0	23.8	29.2
Maximum	*339.7*	56.6	25.5	69.0	92.2
90^{th} %-ile	*54.8*	37.5	22.7	35.2	39.7
95^{th} %-ile	*75.7*	41.6	24.7	39.1	43.2

Table 6.6b): PM_{10} – 24-hour average concentrations ($\mu g/m^3$)

	Measured	Participant			
		A	B	C	D
Mean	*34.4*	28.4	15.6	24.9	32.1
Median	*32.8*	27.2	14.7	24.9	32.2
Maximum	*48.2*	38.0	25.4	37.7	41.0
3^{rd} highest	*46.9*	37.3	23.9	35.5	36.9
17^{th} highest	*44.7*	34.3	20.5	31.0	34.2

6.2.6 Summary of workshop discussion

The general comparison of the monitored results with the range of model results obtained showed that at the motorway site, mean CO and PM_{10} values were well predicted, but the highest concentrations were under predicted, and mean and maximum NO_2 concentrations were well predicted. At the roundabout site, CO concentrations were well predicted, mean/median NO_2 concentrations were well predicted, and mean PM_{10} values were well predicted, but the highest concentrations were under predicted.

Most models suggest maximum NO_2 concentrations in the range 30 to 50 $\mu g/m^3$, which is well within the limit value of 200 $\mu g/m^3$. (One model gives a maximum of 90 $\mu g/m^3$ at the roundabout.) In such situations, detailed modelling may not be warranted and a simple screening model such as DMRB may be sufficient. In many cases, however, NO_2 modelling is most important, as this pollutant is most likely to exceed limit values.

Ambient PM_{10} concentrations are mostly attributable to sources other than local traffic. Nevertheless, levels may be close to regulatory limits and as this pollutant is highly significant for health it is therefore very important. However, PM_{10} is probably the least useful parameter for validating models because of the high background levels and

because of the difficulty of accounting for resuspension. In contrast, although CO concentrations are always low when compared to limit values, they are useful for model validation as background levels are low and photochemistry is not relevant.

The broad assumptions on which emission factors are based were contrasted with the higher level of detail in model formulation. Model precision should agree with that of the available input data (traffic, emission factors and meteorological data), so simple modelling is often justified.

It was noted that EURO standard emissions may be underestimated. An Irish regulation emission factor database would be useful. (As MOBILE in the USA, DMRB or UK EFD in the UK). It would also be desirable to have a database of calibrated background concentrations for rural, urban and suburban sites.

There is a lack of traffic data for most air quality modelling exercises associated with roads. In contrast, the traffic data available for this modelling exercise were very good, even in the case of the roundabout study. Environmental Impact Assessment (EIA) traffic predictions are for daily average or peak traffic only, compared to a model resolution of separate hourly lane speed and flows and fleet composition.

Models tend not to reflect the persistence of monitored peaks beyond the duration of modelled peaks, and the occurrence of high concentrations in the absence of the road source. These effects are associated with stable atmospheric conditions.

It was noted that the project final report should indicate the monitoring requirements to facilitate better modelling, particularly in the context of EIAs. The following topics might be addressed: the pollutants and meteorological data to be monitored, the recommended sampling interval, the duration of the monitoring period.

6.3 Emission Factor Sensitivity

The composite emission factors (CEFs) employed in Chapter 5 were largely based on those suggested by the UK EFD in late 2001, when monitoring commenced at both sites. Updated UK EFD emission factors were published in 2002. Table 6.7 compares the resulting CEFs for the motorway and roundabout sites, and shows the equivalent values obtained using COPERT III data. For CO, both the updated UK EFD and COPERT III suggest lower CEFs than those used in Chapter 5 for the motorway site, but all the values for the roundabout are similar. For NO_x, the motorway value used in Chapter 5 agrees with that suggested by COPERT III, but the updated UK EFD value is much higher. In contrast, while both UK EFD NO_x values for the roundabout are similar, that suggested by COPERT III is much lower.

To investigate the significance of these different CEFs, additional model runs were performed, as indicated in Table 6.7. For the motorway site, these concentrated on leeward CO and NO_2 concentrations, as described in Chapter 5, while at the roundabout

separate winter and summer NO_2 modelling was performed. Tables 6.8 and 6.9 examine the results obtained in terms of the model evaluation parameters used in Chapter 5.

Table 6.7: Composite Emission Factors for CALINE4 sensitivity analysis

Pollutant	Motorway CEF (100 km/hr)			Urban CEF (30 km/hr)		
	g/km	g/mile	Modelled	g/km	g/mile	Modelled
CO	4.14[1]	6.62	Y	4.14[1]	6.62	Y
	2.569[2]	4.11	Y	3.696[2]	5.91	N
	2.235[3]	3.58	Y	3.935[3]	6.30	N
NO_x	1.4[1]	2.24	Y	1.4[1]	2.24	Y
	3.649[2]	5.84	Y	1.116[2]	1.79	N
	1.562[3]	2.50	N	0.782[3]	1.25	Y
PM_{10}	0.121[2]	0.19	Y	0.054[2]	0.09	Y

[1:] per UK-EFD (Autumn 2001); [2:] per UK-EFD (Autumn 2002); [3:] per COPERT III

Table 6.8: CALINE4 – Motorway: Model Evaluation Parameters by CEF (g/mile)

		Mean	R	NMSE	FAC2	FB	FS
	Minimum	*0*	*-1*	*0*	*0*	*-2*	*-2*
	Maximum	*∞*	*1*	*∞*	*1*	*2*	*2*
	Ideal	*1*	*±1*	*0*	*1*	*0*	*0*
CO: Leeward	CEF = 6.62	1.81	0.30	0.72	0.57	0.43	0.11
	CEF = 4.11	1.49	0.32	0.50	0.70	0.21	-0.33
	CEF = 3.58	1.44	0.24	0.57	0.71	0.17	-0.34
NO_2: Leeward	CEF = 2.24	2.26	0.45	0.72	0.55	0.46	0.38
	CEF = 5.84	3.66	0.36	1.77	0.29	0.76	0.89

(cf. Table 5.8)

Table 6.9: CALINE4 – Roundabout: Model Evaluation Parameters by CEF

		Mean	R	NMSE	FAC2	FB	FS
	Minimum	*0*	*-1*	*0*	*0*	*-2*	*-2*
	Maximum	*∞*	*1*	*∞*	*1*	*2*	*2*
	Ideal	*1*	*±1*	*0*	*1*	*0*	*0*
NO_2: winter	CEF = 2.24	3.49	0.63	0.33	0.61	0.06	-0.21
	CEF = 1.25	3.18	0.54	0.48	0.55	-0.12	-0.43
NO_2: summer	CEF = 2.24	4.57	0.42	0.69	0.49	0.58	0.20
	CEF = 1.25	3.94	0.34	0.56	0.54	0.35	0.02

(cf. Table 5.15)

At the motorway site, the lower emission factors of 4.11 and 3.58 g/mile lead to closer mean modelled and measured concentrations. The NMSE and FB parameters which largely reflect the magnitude of both sets of data, also improve. The proportion of model results within a factor of two of the contemporary measured value increases from 57% to 70 or 71%. However, the fractional variance (FS) parameter, which compares the spread of the values in the modelled and measured data sets, disimproves. The observed

reduction makes it more likely that the model will underestimate the highest measured concentrations.

The use of the higher NO_x CEF suggested by the most recent UK-EFD for the motorway site (5.84 g/mile) leads to a disimprovement in all six model evaluation parameters compared to those presented in Chapter 5. The CEF suggested by COPERT III value is close to that employed in Chapter 5 and its use would lead to similar parameter values.

In winter at the roundabout site, the use of the higher NO_x CEF of 2.24 g/mile, suggested by the UK-EFD in 2001 leads to better model evaluation parameters. However, in summer, the lower value suggested by COPERT III gives a better comparison. In both winter and summer, however, the observed differences in model evaluation parameters are small relative to the large difference in CEFs.

6.4 Background Concentrations

From mid-May to mid-September 2002, additional NO_x, NO and NO_2 measurements were obtained close to the M4 monitoring site at Leixlip. An additional API 200A monitor was installed in the garage of a private house located approximately 200m south of the M4 motorway, i.e. on the other side of the road to Leixlip Water Treatment Works (WTW) where the main monitoring site was located (see Section 2.2). This site was also approximately 1km east of the WTW. It was expected that ambient concentrations at this supplementary site would be affected by emissions from the M4 whenever winds were from the north, or parallel to the motorway. However, for wind directions between 100 and 260º, the concentrations observed at this site could be regarded as representative of the background concentrations in the local area.

Figures 6.1 and 6.2 compare the average diurnal variation in NO_x concentrations measured at the WTW (NO_x) and at the background site ($bgNO_x$), for all hours when the wind direction (θ) at Casement Aerodrome was in the ranges 100-260º and 280-80º, respectively. For $100< \theta <260$º, the concentration at the WTW was always higher than that at the background site. For $280< \theta <80$º, the two profiles are much closer, with the 'background' site showing slightly higher values. Comparisons of the NO and NO_2 measurements at the two sites show similar trends.

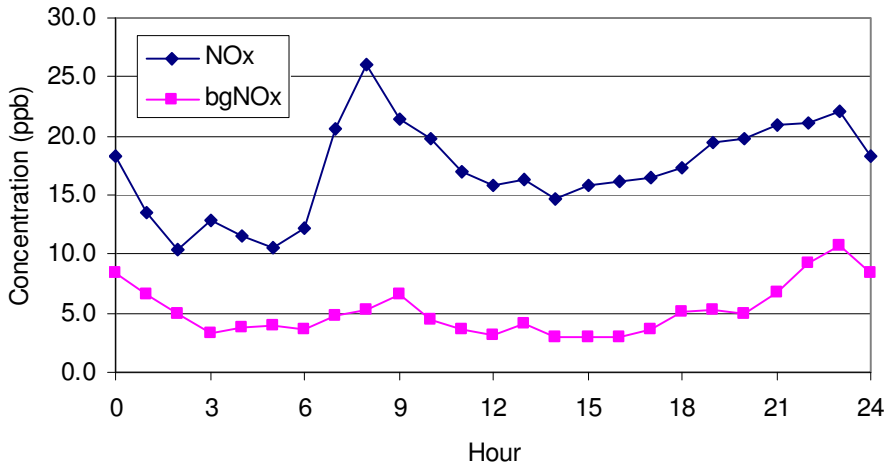


Figure 6.1: Average diurnal variation of NO_x concentrations at monitoring (NO_x) and background ($bgNO_x$) sites for wind directions between 100º and 260º

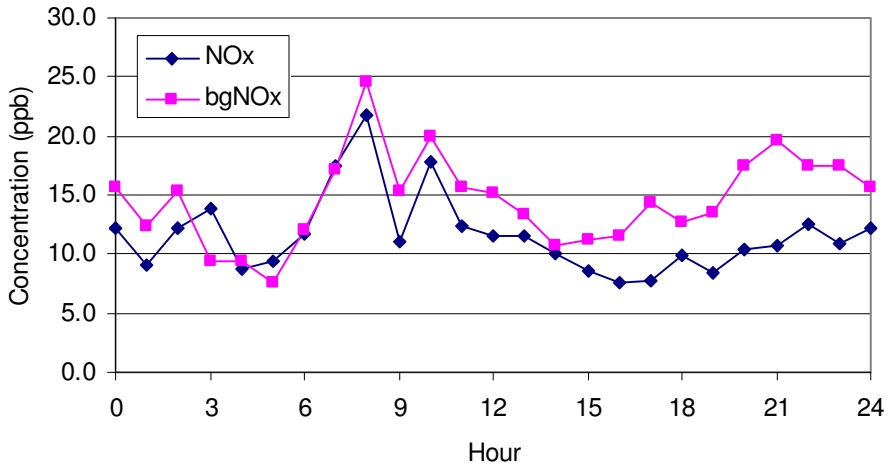


Figure 6.2: Average diurnal variation of NO_x concentrations at monitoring (NO_x) and background ($bgNO_x$) sites for wind directions between 280º and 80º

Although no measurements of CO or PM_{10} concentrations were made at the background site, because background concentrations of most pollutants are affected by the same parameters (such as wind speed, wind direction and atmospheric stability/turbulence), it could be assumed that whenever the NO_x concentration at the background site was high, so too were the CO and PM_{10} concentrations.

To test this hypothesis, the correlations between the CO, NO_x and PM_{10} hourly concentrations observed at the WTW were examined. Table 6.10 presents correlation coefficients determined from the hourly concentration measurements at the WTW, for the entire monitoring period. The relatively high values obtained suggest that the data sets of

all concentration measurements are well correlated on an hour-by-hour basis. Surrogate hourly background concentrations of CO and PM_{10} may therefore be created by scaling the hourly concentrations of NO, NO_2 or NO_x obtained at the background site by the ratio of the mean concentrations of the different pollutants.

Table 6.10: Correlation coefficients for hourly concentrations at Leixlip WTW

	NO	NO_x	CO	PM_{10}
NO_2	0.57	0.71	0.54	0.56
NO		0.98	0.74	0.82
NO_x			0.84	0.74
CO				0.61

Figure 6.3 compares the average diurnal variation in the CO concentration measured at the WTW with a similar profile obtained by scaling the hourly NO_2 concentration measured at the same location by a factor of 0.0275, being the ratio of the mean CO and mean NO_2 concentrations measured at the WTW. The two profiles compare surprisingly well. Figure 6.4 shows a similar comparison for PM_{10} in which good agreement is again obtained. A scaling factor of 1.565 was employed in this case. Less good agreement was obtained when measured NO or NO_x concentrations were scaled instead of NO_2.

Figure 6.5 shows the results of the application of this approach to the modelling of CO concentrations at the monitoring site. Hourly NO_2 concentrations at the background site were factored by 0.0240 to obtain surrogate hourly background concentrations of CO. Only wind directions between 100º and 260º are considered, and the factor of 0.0240 represents the ratio of the mean NO_2 and CO concentrations measured at the monitoring site, for these wind directions during the period of the background monitoring only. These surrogate background CO concentrations are added to the hourly CO concentrations modelled using CALINE4 with the COPERT III CEF of 2.235 g/km. The resulting average modelled diurnal profile is compared with that obtained assuming a constant background concentration of 0.17 ppm, and with the diurnal profile measured at the WTW monitoring site. The use of hourly background values leads to a better estimate of the peak measured concentrations, with especially good agreement observable for the morning peak, but to a poorer estimate of the overnight concentrations between 24:00 and 08:00, when the use of a constant background value produces better results. The minimum observed morning value was taken as the constant background hence good agreement for this period would be expected.

Figure 6.6 compares the modelling results obtained when assuming hour-by-hour or constant background PM_{10} concentrations. The hourly PM_{10} background concentrations were obtained by factoring the hourly NO_2 concentration at the background site by 1.439, and CEF of 0.121 g/km was employed. A similar comparison to that seen for CO in Figure 6.5 is observable, with the hourly background approach producing a better estimate of the peak measured values, but a worse estimate between 24:00 and 08:00.

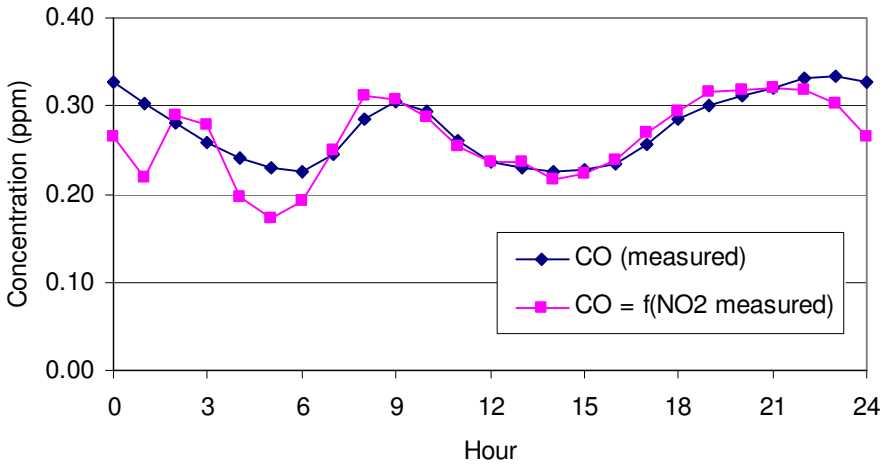


Figure 6.3: Measured and calculated average diurnal variation of CO concentration at LWTW monitoring site.

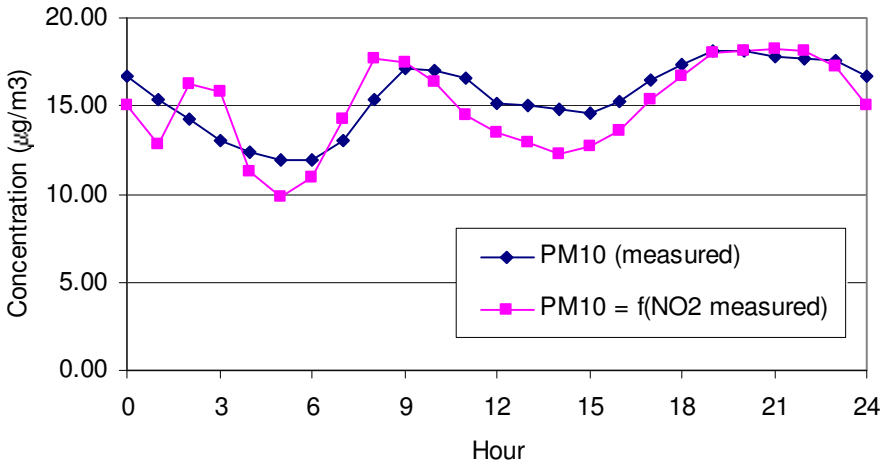


Figure 6.4: Measured and calculated average diurnal variation of PM_{10} concentration at LWTW monitoring site.

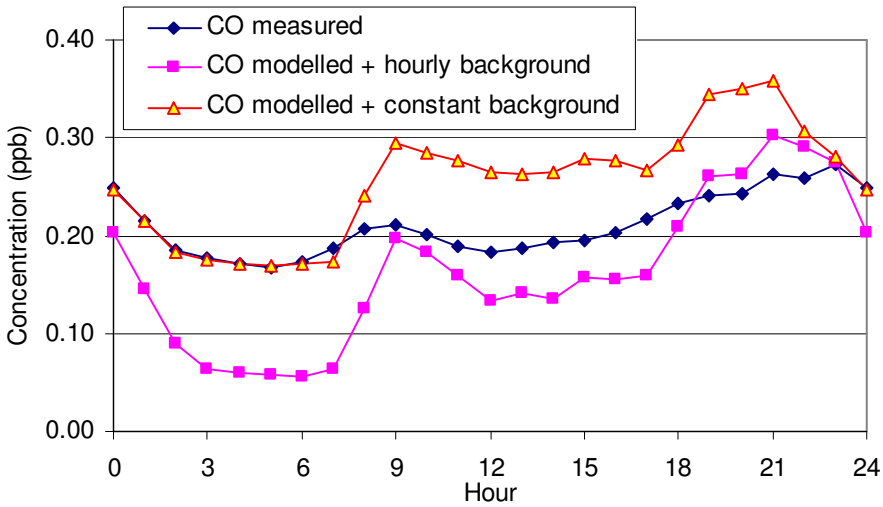


Figure 6.5: Measured and modelled average diurnal variation of CO concentration at LWTW monitoring site.

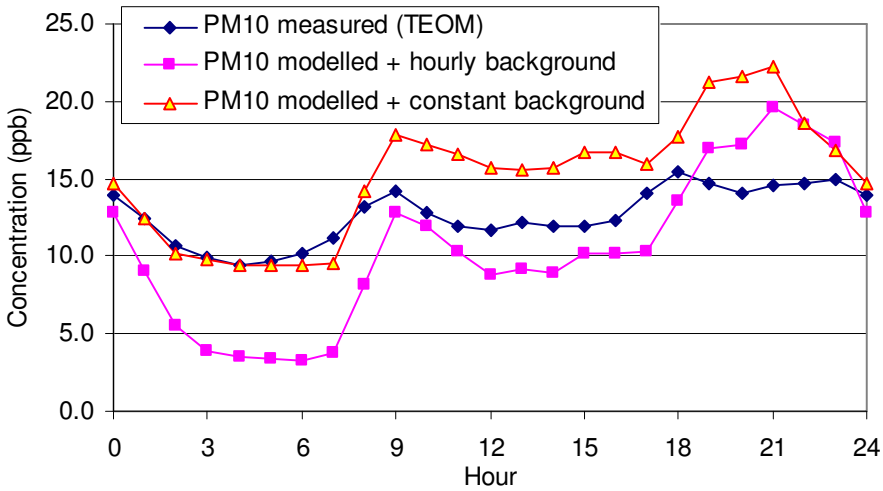


Figure 6.6: Measured and modelled average diurnal variation of PM_{10} concentration at LWTW monitoring site.

Figure 6.7 shows the seasonal variation in CO concentrations. The measured concentration for negligible traffic flow in the early hours of the morning varies from winter to summer. Rather than using one constant value for the background regardless of the time of year, these concentrations are taken to be the seasonal background concentrations. The predictions overestimate the diurnal average concentrations measured in both winter and summer.

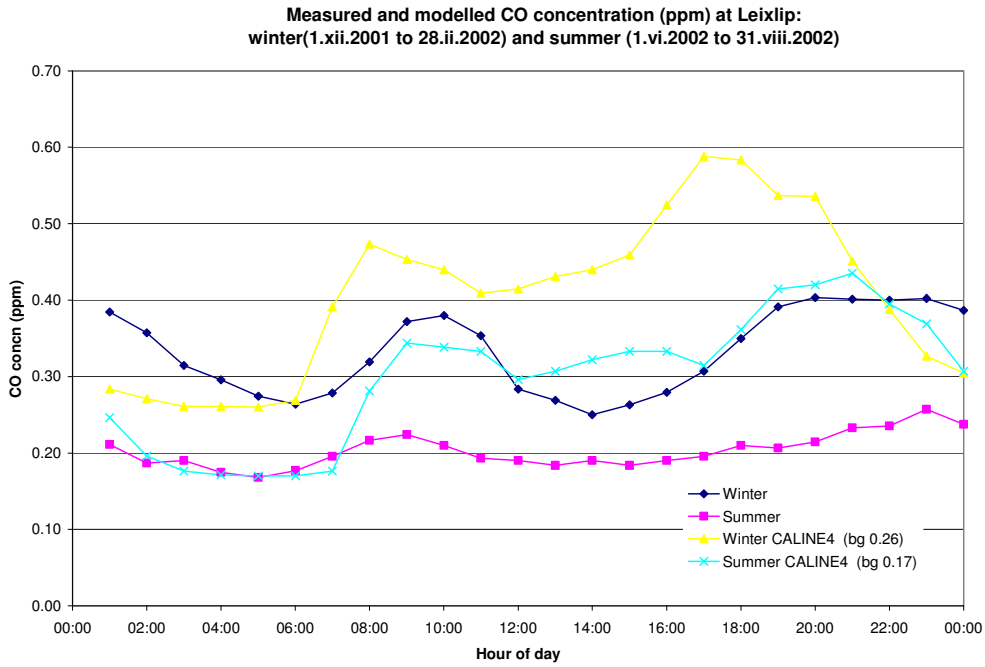


Figure 6.7: Leixlip diurnal CO with winter and summer background concentrations (Cf. Figure 5.15)

6.5 Link Layout, Vehicle Speed and Wind Direction

This section examines the model sensitivity to variations in the input parameters; specifically the link geometry, the average speed of vehicles and the wind direction as measured on site and regionally.

6.5.1 Link layout: motorway

The motorway was initially modelled as a single link, and then as two parallel links with independent traffic flows. Table 6.11 shows examples of the input parameters for the hour ending 09:00 on six days in December 2001. The corresponding concentrations of CO for this hour on these six days are given in Table 6.12, as observed and as predicted by using CALINE4, with and without the interface programme CL4.

Table 6.11: Input data for single and double link layout

09:00 **Date**	**PSC**	**Wind**		**Temp.**	**Traffic**		
		direction	**speed**		**Total**	**Westbound**	**Eastbound**
12.xii.2001	D	120.1	0.3	6.1	2557	802	1755
13.xii.2001	D	104.9	1.7	7.6	2446	791	1655
14.xii.2001	D	115.3	1.1	6.7	2301	741	1560
15.xii.2001	C	202.9	0.3	-2.3	1333	480	853
16.xii.2001	D	107.2	0.6	6.7	505	253	252
17.xii.2001	D	262.1	0.6	1.9	2380	675	1705

Table 6.12: CALINE4 predictions for single and double link layout

09:00	**Observed**	**CL4**			**CALINE4**		
Date	**CO**	**Single**	**Double**	**W/E**	**Single**	**Double**	**W/E**
12.xii.2001	1.5	1.0	0.9	0.2/0.5	1.1	1.1	0.2/0.7
13.xii.2001	0.4	0.7	0.6	0.0/0.3	0.7	0.6	0.0/0.3
14.xii.2001	0.4	0.7	0.6	0.1/0.3	0.7	0.6	0.1/0.3
15.xii.2001	1.0	0.5	0.5	0.0/0.2	0.6	0.6	0.1/0.3
16.xii.2001	0.2	0.4	0.4	0.0/0.0	0.4	0.4	0.0/0.0
17.xii.2001	0.5	0.7	0.6	0.0/0.3	0.7	0.6	0.0/0.3
18:00	**Observed**	**CL4**			**CALINE4**		
Date	**CO**	**Single**	**Double**	**W/E**	**Single**	**Double**	**W/E**
12.xii.2001	0.5	0.9	0.6	0.3/0.2	1.1	1.2	0.2/0.7
13.xii.2001	0.4	0.4	0.3	0.2/0.1	0.5	0.3	0.2/0.1
16.xii.2001	0.3	0.2	0.2	0.0/0.1	0.3	0.2	0.0/0.1
19.xii.2001	0.2	0.0	0.0	0.0/0.0	0.0	0.0	0.0/0.0
20.xii.2001	0.2	0.4	0.3	0.2/0.1	0.5	0.3	0.2/0.1
23.xii.2001	0.3	0.2	0.2	0.1/0.0	0.3	0.2	0.1/0.0
E.f. x10							
18:00	**Observed**	**CL4**			**CALINE4**		
Date	**CO**	**Single**	**Double**	**W/E**	**Single**	**Double**	**W/E**
12.xii.2001	0.5	1.5	5.8	3.3/2.5	11.3	11.6	6.8/4.8
13.xii.2001	0.4	3.7	3.3	1.9/1.4	5.0	3.3	1.9/1.4
16.xii.2001	0.3	2.4	2.2	1.0/1.2	3.2	2.2	1.0/1.2
19.xii.2001	0.2	0.0	0.0	0.0/0.0	0.1	0.0	0.0/0.0
20.xii.2001	0.2	3.6	3.3	1.9/1.4	4.5	3.3	1.9/1.4
23.xii.2001	0.3	2.1	1.9	1.0/0.9	2.6	1.9	1.0/0.9

W/E: predictions for Westbound and Eastbound links.
"Double" = W + E + background
The background concentration = 0.23 ppm for "Single and "Double"

The concentrations in Table 6.12 are predicted for both ways of modelling the link layout. Predictions of evening peak concentrations (for the hour ending 18:00) are also shown and the limitation of the format (in modelling such low concentrations) is highlighted by increasing the emission factor tenfold. The limit of model prediction by the format (F3.1) is clear, for example, at 09:00 on 16.xii.2001: CL4 and CALINE4 concur in predicting the concentration due to Westbound and Eastbound links to be both 0.0 ppm CO, but that their combined total is 0.2 ppm CO. For a background value of 0.23 ppm CO, this suggests that, due to formatting limitations, 0 plus 0 is apparently 0.2.

Figure 6.8 compares the CALINE4 predictions of hourly CO concentration for the single and double link layouts. Of the twelve sample hours only once does the double link prediction exceed that for the single link. That hour also has the highest predicted concentrations.

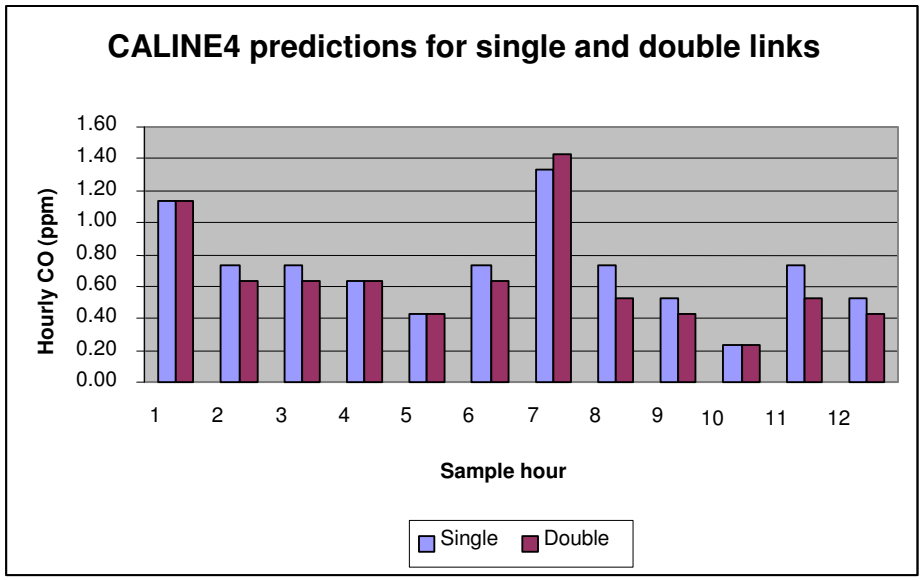


Figure 6.8: CALINE4 predictions for single and double link layout

Table 6.13 shows four variations in DMRB input parameters for the motorway site. Initially the motorway is modelled as one link, 20 metres wide, with an Annual Average Vehicle Flow (AAVF) of 1400 vehicles. When this is divided into four separate traffic flows, with the same overall road width and total traffic flow, there is little impact on the predictions, the most significant being an increase in PM_{10} from 3.93 to 4.00 µg/ m^3.

Table 6.13: DMRB sensitivity; Receptor "Van", Year 2001

Link	Distance (m) from: Road centre	kerbside	AAVF vph	HDV %	Av.speed kph	CO mg/m^3	benzene µg/ m^3	NO_x µg/ m^3	PM_{10} µg/ m^3
M4	30	20	1400	20	90	0.10	0.59	130.32	3.93
EastSlow	22.5	20	350	20	90	0.10	0.60	132.44	4.00
EastFast	27.5	25	350	20	90				
WestSlow	32.5	30	350	20	90				
WestFast	37.5	35	350	20	90				
M4[a]	30	20	3023	8	90	0.22	1.04	162.00	5.15
M4[b]	30	20	3023	4.4	90	0.23	0.98	126.17	4.15

M4[a]: 17.viii.2001 18:00, average %HDV. M4[b]: 17.viii.2001 18:00, actual %HDV.

The third scenario (M4[a] in Table 6.13) reverts to one link but uses the actual traffic flow for the hour ending at 18:00 on 17th August 2001, with the hourly percentage of heavy duty vehicles (HDVs) averaged from several months of monitoring at the site. The increase in total traffic, and relative reduction in HDVs, result in higher predicted concentrations for all pollutants, in decreasing order of significance: CO, benzene, PM_{10} and NO_x. The increase is most significant for CO and benzene, due to the increase in total traffic (i.e. petrol vehicles), whereas PM_{10} is more sensitive to the fleet profile (%HDV) since HDVs are generally diesel fuelled. This is confirmed by the fourth set of predictions. When the actual fleet profile for that hour (4.4% HDV for 18:00 on 17.viii.2001) is used, the reduction in HDVs from 8% (in the third scenario) to 4.4% is

reflected in the reduction in predicted PM_{10}. Since the total traffic is unchanged, the corresponding increase in the predominantly petrol fuelled, non-HDVs is reflected in the increase in CO from 0.22 to 0.23 mg/m^3.

6.5.2 Vehicle speed: roundabout

Table 6.14 shows five variations in DMRB input parameters for the roundabout site. Initially the traffic is modelled with 7% HDVs travelling at an average speed of 15 kph. When the speed is reduced to 10 and then 5 kph, with the same overall road width and traffic flows, all pollutants are predicted to increase by at least 24% and then at least 74% from the predictions at 15 kph. The fourth scenario differs from the third only in the fleet profile. The reduction in HDVs from 7% to 5% results in an increase in CO but reductions in the other three pollutants, particularly NO_x and PM_{10}. The final set of predictions, which can be compared with the initial predictions to show the effect of this same reduction in HDVs from 7% to 5%, but for an average speed of 15 kph, confirms this pattern.

Table 6.14: DMRB Galway; Receptor "Galway roundabout", Year 2001

Link	Distance (m) from: road centre	kerbside	AAVF[a] vph	HDV %	Av. speed kph	CO mg/m^3	benzene µg/ m^3	NO_x µg/ m^3	PM_{10} µg/ m^3
1	15	10	2480	7	15	1.88	12.14	763.22	32.01
2	15	10	1070	7	15				
3	35	30	2760	7	15				
4	45	40	1200	7	15				
5	45	40	1790	7	15				
1-5	As above, per link			7	10	2.47	16.14	942.92	41.63
1-5	As above, per link			7	5	3.94	27.25	1329.69	70.98
1-5	As above, per link			5	5	3.96	25.85	1008.69	55.35
1-5	As above, per link			5	15	1.90	11.72	598.29	26.15

AAVF[a] : Total peak hour flow for each link (a.m. peak, total 9300 vph)

6.5.3 Wind direction

As shown in Figure 6.9, the DMRB predictions are independent of meteorological conditions, and therefore reflect the position of the receptor relative to the source location in terms of distance but not direction. The DMRB "worst case" prediction of 0.2 mg/m^3 is lower than the worst case concentrations predicted by CALINE4 for wind speeds of 2 m/s.

CALINE4 predicts the highest concentrations of pollutants at the receptor for wind directions which are near to parallel with the road. For these wind directions, the area of road upwind of the receptor is maximised. However Noll *et al.* (1978) found that a previous version, CALINE2 overestimated concentrations for parallel winds and underestimated concentrations for oblique and crosswinds. More recently, Shenouda and Schmidt (1997) found that CALINE4 predictions compared satisfactorily with observed values.

The concentrations predicted by CALINE4 show that the worst case concentrations predicted for the Leixlip site will be for wind directions within 40° to the south of the road bearing (i.e. 85-125° and 225-265°), and that wind directions outside the wind sector 85-265° will result in predicted concentrations of zero.

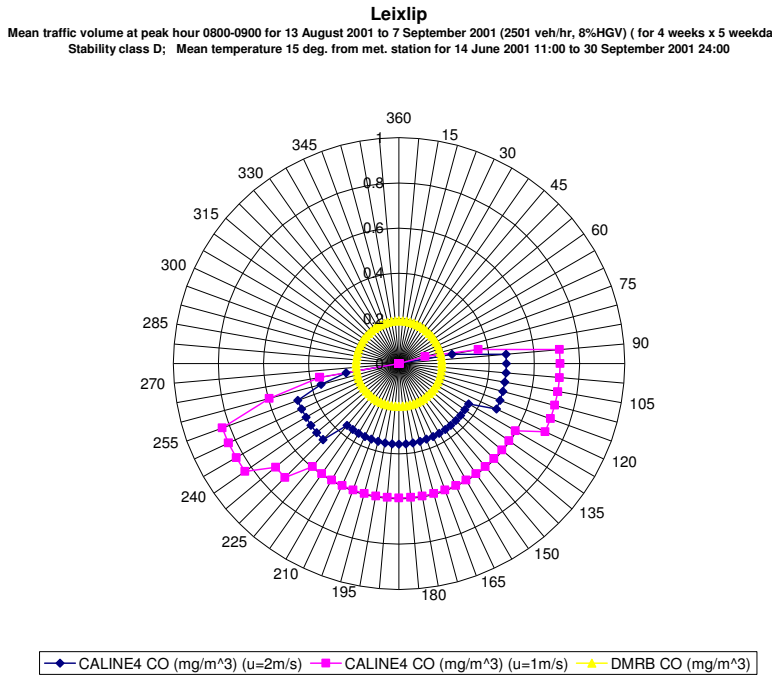


Figure 6.9: CALINE4 prediction at motorway with varied wind speed and direction

6.6 Proposals for Future Use of Models in Ireland

In this section, proposals for future dispersion modelling are given, based on the modelling results presented in Chapters 5 and 6, including the model validation exercise and workshop.

6.6.1 Investigated models

In all, the results of four different dispersion models have been compared with monitoring results obtained at both study sites. The greatest amount of modelling was carried out using CALINE4. The results of the DMRB model were also compared with all 12 months of monitoring data at either site. In the model validation exercise, participants employed CAL3QHCR and ADMS Roads, as well as CALINE4.

The DMRB model calculates predefined concentration statistics only, in formats suitable for comparison with the EU limit values. The DMRB is often regarded as a scoping model. The other investigated models are short-term models that calculate concentrations on an hour-by-hour basis. The use of these models is often invoked where a scoping model or objective assessment indicates ambient concentrations close to a limit value.

A comparison of the results obtained using CALINE4 and the DMRB model at the motorway site (Tables 5.4 and 5.7) suggests a better overall performance by the short-term model. CALINE4's predictions of the annual mean concentrations of CO and NO_2, and of the higher eight-hourly and 24-hourly concentrations of CO and PM_{10} are all closer to the equivalent mean values than are the DMRB predictions. Only in the case of the annual mean concentration of PM_{10} does the DMRB model perform better. At the roundabout site (Tables 5.10 and 5.14), the CALINE4 predictions of mean and highest CO and PM_{10} concentrations underestimate the measured values by 35-60%. For PM_{10}, the predictions using the DMRB model overestimate those measured by 35-55%. The DMRB model's predictions of CO concentrations are much higher than the measured values. The DMRB model also grossly overpredicts the mean NO_2 concentration, whereas the CALINE4 prediction is within 40% of the measured value.

Overall, therefore, the DMRB model was able to predict PM_{10} concentrations just as well as CALINE4, and could be used for this purpose in future. Although the DMRB model's predictions of CO concentration are too high, they may be useful in a scoping context, especially since CO concentrations are least likely to approach limit values. On the basis of its performance in this study, the DMRB model's ability to predict NO_2 concentrations appears to be poor, and it should not be relied upon for this purpose.

The model validation exercise did not indicate that any one of the short-term models employed should be favoured over the others. Considering the range of results obtained for all three pollutants at both sites, no model performed consistently better or worse than others. It appears that for short-term modelling, the modelling practices employed are more important than the formulation of the dispersion model. A more detailed summary of the performance of CALINE4 is given in Section 7.2.

6.6.2 Composite emission factors

Most dispersion models require user-defined composite emission factors (CEFs). Accurate estimation of these should be based on a characterisation of the vehicle fleet, the mean speeds of these vehicles and the unit emission rate of individual vehicles.

National fleet statistics are available to help define the expected fleet composition. Local differences may occur, especially in relation to vehicle age profile and vehicle type distribution. The CEFs of most pollutants of interest are sensitive to these parameters, and for CO, PM_{10} and benzene, this sensitivity will be reflected in the modelled ambient concentrations.

Two databases of vehicle emission factors are freely available: the UK Emission Factor Database (UK EFD) and COPERT III. Generally, their use leads to similar CEFs; however in this study, higher NO_x emission factors were obtained using the UK EFD, especially at the motorway site. In this case, and whenever other smaller differences were observed, model results based on COPERT III values generally displayed better agreement with measured concentrations.

Both COPERT III and the UK EFD provide vehicle speed-dependent emission factors. Their use therefore requires an accurate estimate of average vehicle speeds on the roads of interest. Although vehicle emission rates are known to also depend on other modal parameters such as acceleration, deceleration and queuing time, separate consideration of these is not supported by available emissions data. For free-flowing highways, estimates of average speed can be expected to be reasonably accurate, given the low sensitivity of emission rates at higher speeds. More difficulty will be encountered in urban areas, and the average speed within the study area is likely to vary both spatially and temporally. Driving cycles used in emissions measurements may not reflect conditions at roundabouts such as that investigated in this study.

When modelling emissions from vehicles in future years, the relevant traffic flows, composition, speed and unit emissions must be estimated. It is likely that this will lead to a poorer representation of the required CEFs than could be obtained in this study, with consequences for model result accuracy.

6.6.3 Background concentrations for modelling

In this report, background concentrations are considered to be the ambient concentrations that exist in the absence of traffic on the roads under consideration.

For short-term modelling at both the motorway and roundabout sites, estimating background concentrations was seen to be as important as calculating the impact of local traffic emissions. In future modelling, the amount of resources required to estimate the relevant background concentrations are likely to be similar to that required to perform the dispersion modelling itself.

When considering PM_{10} concentrations at either site, the background concentration was the dominant component, with the local effect being less strong. The modelling question to be considered for this pollutant is whether the local contribution is likely to increase the ambient concentration beyond the limit value. For this purpose, the background concentration existing at the time of maximum local impact will be required. This occurs when traffic volumes are high and atmospheric conditions are stable with low wind speeds.

For NO_2 modelling, background concentrations of NO, NO_2 and O_3 are required, each of which varies with the time of day and year. Regional data on O_3 concentrations are likely to suffice for modelling purposes, but local assessments of the variations in NO and NO_2 concentrations will be required for short-term modelling. Because NO_2 is both a primary and secondary pollutant, it is not simple to identify a limited set of circumstances in which concentrations will be highest. Hence, limited background monitoring, even at carefully elected times, will not provide sufficient information. Continuous short-term monitoring aimed at estimating the local statistical distributions of NO and NO_2 concentrations will be necessary.

In this study, the highest observed CO concentrations were significantly influenced by the background concentration. However, these values were much lower than the limit

values, and it is unlikely that a highly accurate estimate of the background CO concentration will be necessary in most future modelling exercises. Conservative estimates based on historical data obtained at similar locations should suffice.

The availability of a set of agreed background concentrations would have the twin benefits of ensuring that modelling results are acceptable to more parties and reducing the costs of individual modelling projects. Such a database should distinguish between urban, suburban and rural values, and for some pollutants at least, distinguish between different seasons and meteorological conditions. The development of this database would require substantial air quality monitoring; however, background modelling techniques, which would be beyond the scope of individual road projects, could also be employed.

7 Conclusions and Recommendations

7.1 Summary of Completed Research

1) The aim of this project was to carry out a validation study of the models currently used in Ireland to determine the levels of emission to air from road traffic on national primary routes and to predict their impacts and dispersion patterns. The general approach taken was to compare air quality measurements obtained in the vicinity of traffic sources with model results.

2) A review of literature and relevant EISs led to the selection of two models for detailed examination. The literature review also identified useful sources of emission factors and suitable statistical bases for comparing model results and measurements.

3) The air quality monitoring studies were carried out at two sites representing contrasting situations. One site, adjacent to the M4 motorway at Leixlip, was chosen to investigate air pollution where the traffic was free-flowing. The other site, alongside the N6 in Galway, was located close to a roundabout and therefore represented a situation with interrupted traffic flow. Both sites were selected to meet criteria relating to air quality, traffic flows, access and security.

4) In terms of modelling, the investigated sites presented different challenges. The M4 motorway represented a classical modelling situation - a single line source with well defined traffic conditions. In contrast, the N6 roundabout represented a more complex situation – a number of distinct line sources with variable traffic conditions, including queues.

5) The air pollutants monitored at both sites were carbon monoxide, nitrogen oxides and particulates. At Leixlip, a number of hydrocarbons associated with vehicle emissions were also monitored, and at Galway, condensation particles were also counted. Two methods of PM_{10} measurement were compared at both sites: continuous monitoring using TEOM instruments and a gravimetric method using automatic Partisol samplers. At both sites, monitoring commenced in May 2001 and ran continuously until September 2002.

6) In addition to air quality, meteorological variables such as wind speed and wind direction were recorded at the two sites. The National Roads Authority (NRA) provided traffic flow data for the M4 near Leixlip throughout the monitoring period. At the Galway roundabout, one month of continuous traffic flow data was supplemented by a one-day detailed traffic survey.

7) Atmospheric dispersion modelling was undertaken for the two sites. The models used were the UK Department of Transport DMRB model and CALINE4, developed by the US Environmental Protection Agency. The meteorological and traffic data collected at the monitoring sites were employed as model inputs. The results of both

models were compared with air quality measurements through graphical and statistical analyses.

8) A model validation exercise was completed in which the project partners and three consulting firms, who all regularly perform dispersion modelling, each produced model predictions of air quality during the first six months of the monitoring period at both sites. These predictions were then compared with the measured data. A workshop on the model validation studies was held at TCD.

9) The modelling work completed and the results obtained were used to put forward proposals for the future use of models in Ireland. These addressed the investigated models, and the key issues of composite emission factors and background concentrations.

7.2 Main Results

a) At the motorway site, a mean CO concentration of 0.27 ppm was observed (Table 3.3). Mean NO_2 and benzene concentrations were 9.91 ppb and 0.16 ppb, respectively (Tables 3.3 and C.2). TEOM measurements resulted in a mean PM_{10} concentration of 15.5 $\mu g/m^3$, whereas the Partisol/gravimetric measurement gave a slightly higher mean concentration of 16.8 $\mu g/m^3$ (Table 3.3). The maximum eight-hour rolling average CO concentration was 2.56 mg/m^3 and the 99.8^{th} percentile hourly NO_2 concentration was 84.5 $\mu g/m^3$ (Table 5.7). The 90^{th} percentile 24-hour average concentration of PM_{10} was measured as 22.8 $\mu g/m^3$ by the TEOM, but as 28.1 $\mu g/m^3$ using the gravimetric method (Table 5.7). All of these values are well below the corresponding EU limit values. The values for NO_2 are close to the lower assessment threshold (LATs) for that pollutant, and the 90^{th} percentile 24-hour average concentration of PM_{10} exceeds its LAT. For all pollutants, mean winter concentrations were higher than those observed in summer.

b) The mean CO and NO_2 concentrations observed at the roundabout site were 0.46 ppm and 10.1 ppb, respectively (Table 4.2). The NO_2 value is nearly identical to that observed at the motorway, but the CO value is higher. Higher mean PM_{10} concentrations were also observed at the roundabout site, where agreement between the TEOM and gravimetric methods was better. The mean concentration measured by the TEOM was 25.5 $\mu g/m^3$ while a mean value of 25.6 $\mu g/m^3$ was obtained using the gravimetric method (Table 4.2). Differences were observed at higher concentrations, with the 95^{th} percentile 24-hour average TEOM value being 46.8 $\mu g/m^3$, and that for the gravimetric method being 53 $\mu g/m^3$ (Table 4.2). The TEOM instrument at Galway was operated at a lower temperature than that at Leixlip. At 2.86 mg/m^3 and 88.8 $\mu g/m^3$, respectively, the maximum eight-hour rolling average CO concentration and the 99.8^{th} percentile hourly NO_2 concentration were both only slightly higher than the values observed at the motorway site, and no pollutant exceeded its limit value (Table 5.14).

c) At both sites, the average diurnal variations in pollutant concentrations were generally seen to follow that of the local traffic flow. Exceptions to this occurred when stable atmospheric conditions led to the persistence of elevated overnight concentrations when traffic flows were low, and in summer when the evening NO peak was suppressed. Pollutant concentrations were observed to be strongly dependent on wind speed, but not on wind direction. The hourly concentrations of the individual pollutants were usually well correlated with each other.

d) For short-term dispersion modelling at both sites, composite emission factors (CEFs) were determined using both COPERT III and the UK-EFD by applying national fleet statistics, measured HGV content and assumed mean vehicle speeds. Similar CO and PM_{10} CEFs were calculated with both databases, but the UK-EFD suggested significantly higher NO_x emission rates, especially for the motorway site. Overall, the use of the COPERT III values led to slightly better agreement with model results. Previous and current UK-EFD values were compared, and while the use of the current values led to improved CO model results, this was not the case for NO_2.

e) At the motorway site, CALINE4 predicted the annual mean CO concentration to within 4% of the measured value when a composite emission factor derived from the 2002 UK-EFD was employed. The maximum 8-hour average concentration was also predicted to within 4%. Similar performance was observed for PM_{10}, for which the annula mean concentration was predicted to within 12% of the measured value, while the 36^{th} highest 24-hour average was predicted to within 1% of the measured value. For NO_2, both the annual mean concentration and the 99.8^{th} percentile hourly average concentration were overpredicted, albeit the latter by only 6%. Observed benzene concentrations were overpredicted, but the modelled average diurnal concentration profile of some alkane compounds agreed well with that measured (Table C.2).

f) At the roundabout site, CALINE4 predictions compared less well with measurements (Table 5.14). Annual mean CO and PM_{10} concentrations were underpredicted by 30 and 40%, respectively, while the annual mean NO_2 concentration was overpredicted by 40%. Higher concentration statistics were all underpredicted: the maximum eight-hour average CO concentration by 60%, the 99.8^{th} percentile hourly NO_2 concentration by 25% and the 90^{th} percentile 24-hour average PM_{10} concentration by 55%. Unlike at the motorway site, the average modelled diurnal concentration profiles at the roundabout site were much flatter than those measured, especially for CO and PM_{10}. The poorer performance of CALINE4 at this site may be partly attributable to the more complex traffic conditions, which led to vehicles travelling at low speeds for at least part of their journey through the roundabout. Low speeds are associated with higher CO and PM_{10} emission rates, but NO_x emissions are not as sensitive. A large diurnal variation in background concentration may also have played a role.

g) The accuracy of modelling results depends not only on the model, but also on the modelling practices and assumptions employed. The model validation exercise was designed to show the range of modelling results that could be obtained at either site. At the motorway site, the observed mean CO concentrations were generally well

predicted by all participants, but the higher concentrations were underpredicted. Mean observed NO_2 concentrations were also quite well predicted by the modellers, with model results both above and below measured values. Higher concentration statistics were well predicted by two participants, but the other two underpredicted by about 50%. Model estimates of PM_{10} concentrations differed from the measured value by about 50%, but the predicted 90^{th} percentile 24-hour average concentration was within 25% of the observed value in three out of four cases.

h) CO concentrations at the roundabout site were both over- and under-predicted by the participants. However, the maximum 8-hour concentration was underpredicted by all. Good predictions of mean NO_2 concentrations were obtained by two participants, but estimates of the 99.8^{th} percentile hourly concentration varied greatly. Three of the predicted mean hourly PM_{10} concentrations were within 15% of the measured value, but the other underestimated by nearly 50%. As with CO, the higher concentrations were underpredicted by all participants, with the 90^{th} percentile 24-hour average being underestimated by between 25 and 50%.

i) A comparison of modelled and measured results showed that the DMRB model was able to predict PM_{10} concentrations just as well as CALINE4, and could be used for this purpose in future. Although the DMRB model's predictions of CO concentration were too high, they may be useful in a scoping context, especially as CO concentrations are least likely to approach limit values. On the basis of its performance in this study, the DMRB model's ability to predict NO_2 concentrations appears to be poor, and it should not be relied upon for this purpose.

j) A set of model evaluation parameters was used to assess the relative performance of CALINE4 at the two sites, in winter and in summer, and at the motorway site when only leeward concentrations are considered. Of the six parameters, the mean concentration and the fractional bias (FB) were better at the motorway site. The normalized mean square error (NMSE) was better at the roundabout site for NO_2, but at the motorway for PM_{10}. Pearson's correlation coefficient (R) was better at he roundabout as was the fractional variance (FS), except for PM_{10}. At both sites, between 50 and 80% of the modelled hourly concentrations lay within a factor of two (FAC2) of the observed values.

k) Considering both sites together, the mean concentration and the FB were better in winter, as was the NMSE for NO_2. The NMSE for CO and PM_{10} were better in summer. With the exception of NO_2 at the roundabout, the FAC2 was always much better in summer. The R and FS showed no clear winter/summer trends. When only leeward concentrations were considered at the motorway site, only small differences in the evaluation parameters were observed, except that the FAC2 for PM_{10} increased from 48% to 80%.

l) Good agreement was observed between the profiles of the measured average diurnal variation in CO, NO_2 and PM_{10} concentrations. On this basis, NO_2 concentration measured at a background monitoring site was used to estimate background CO and PM_{10} values. This approach led to improved model predictions of CO and PM_{10}

concentrations at peak travel times and throughout the day, but poorer agreement with measured nocturnal values.

m) An examination of 12 sample peak travel hours showed that CALINE4 model predictions at the motorway site are influenced by the number of links used to represent the roadway. Model runs employing separate links for each carriageway consistently produced lower concentrations than those employing a single link only.

7.3 Recommendations for Further Research

1) There is considerable scope for further research into background concentrations for modelling. Two separate studies could be performed. One of these would seek to define default background values for a range of conditions reflecting location and meteorological conditions, based on monitoring and modelling results. The other would seek to set guidelines for local assessments of background concentrations, such as the pollutants to be monitored and the sampling period and frequency required.

2) A model validation study such as that completed in this project would benefit from the availability of local background concentration measurements. A future study might concentrate on a single pollutant, but obtain simultaneous measurements at two or more locations spatially distributed around the source. To this end, measurement methods that support contemporaneous sampling at different locations should be investigated.

3) The use of diurnally varying background concentrations for modelling could be assessed. This would allow for the impact of changes in traffic profile during the course of the day and night, and of the cumulative effects which are dependent on the pollutant type and meteorological conditions.

4) The estimation of composite emission factors for congested or partially congested traffic conditions requires more attention. In particular, it should be established whether the driving cycles used to measure emissions at low mean speeds are a good representation of vehicle movement at large congested roundabouts.

5) Traffic modelling software should be investigated to determine its usefulness in estimating the mean vehicle speeds required for emission rate calculations. The spatial variation of these mean speeds in the vicinity of junctions (including roundabouts) should be considered.

6) The effect of employing regional rather than local meteorological data available in this project should be assessed, as should the minimum modelling period required to establish key statistical concentration variables.

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UK EFD. UK Emission Factor Database, http://www.naei.org.uk/emissions/index.php

US EPA. US Environmental Protection Agency, http://www.epa.gov/scram001/

Appendix A

Appendix to Chapter 3: Monitoring Results for the M4 at Leixlip

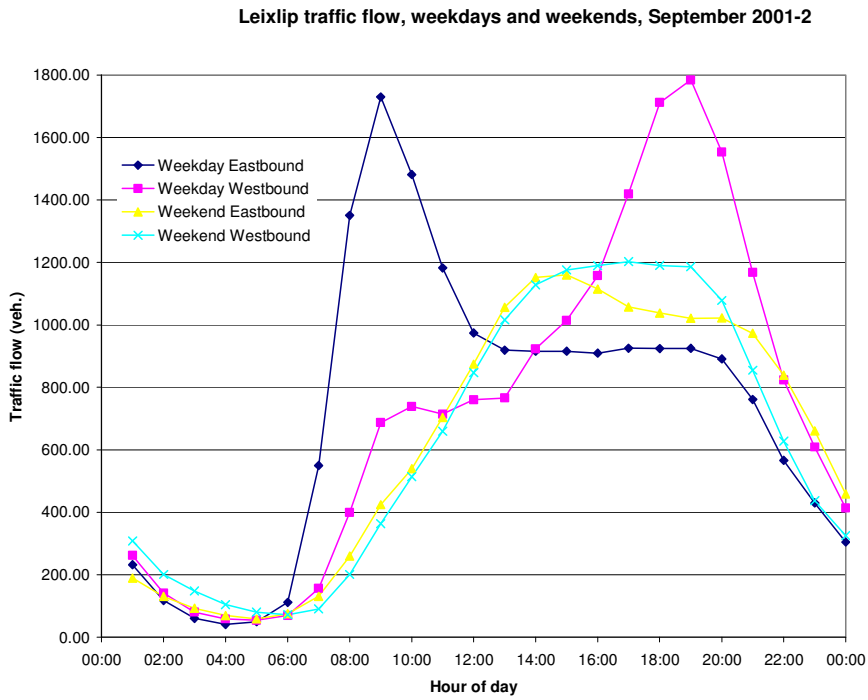


Figure A.1: Diurnal variation by lane

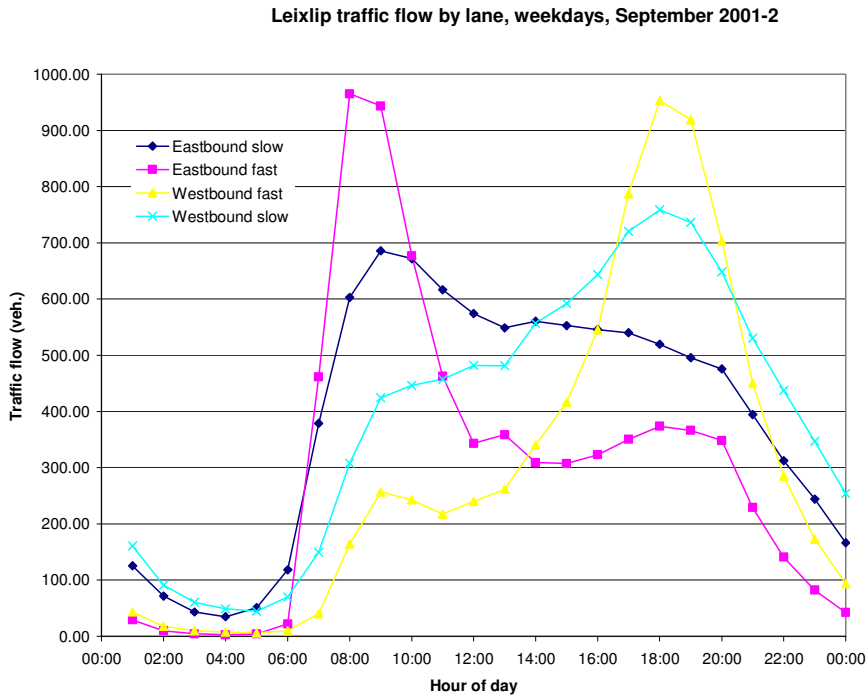


Figure A.2: Traffic flow by lane, weekdays

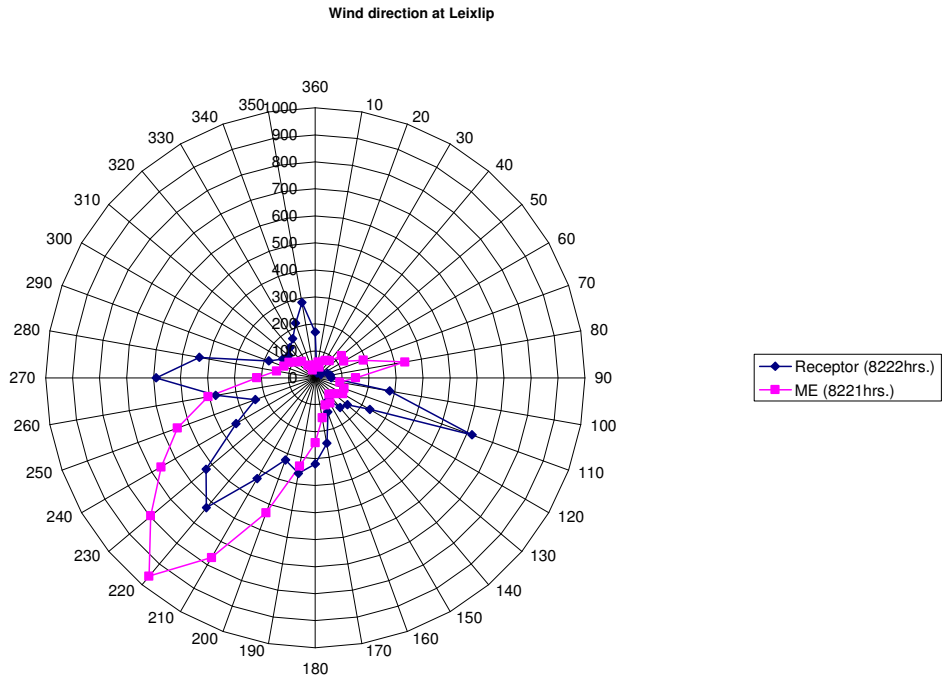


Figure A.3: Wind direction at Leixlip and Casement (as in Chapter 3 Figure 3.4, with 10° intervals)

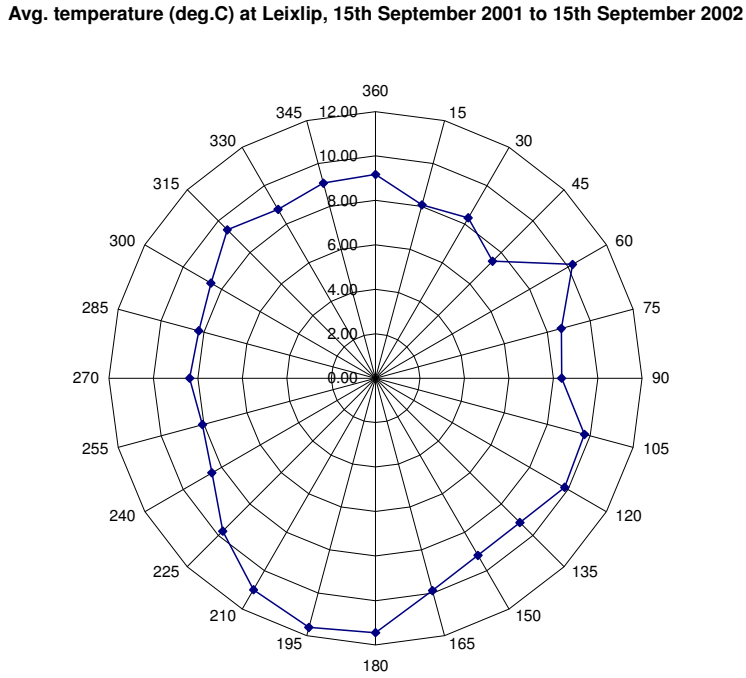


Figure A.4a): Variation in mean temperature with wind direction

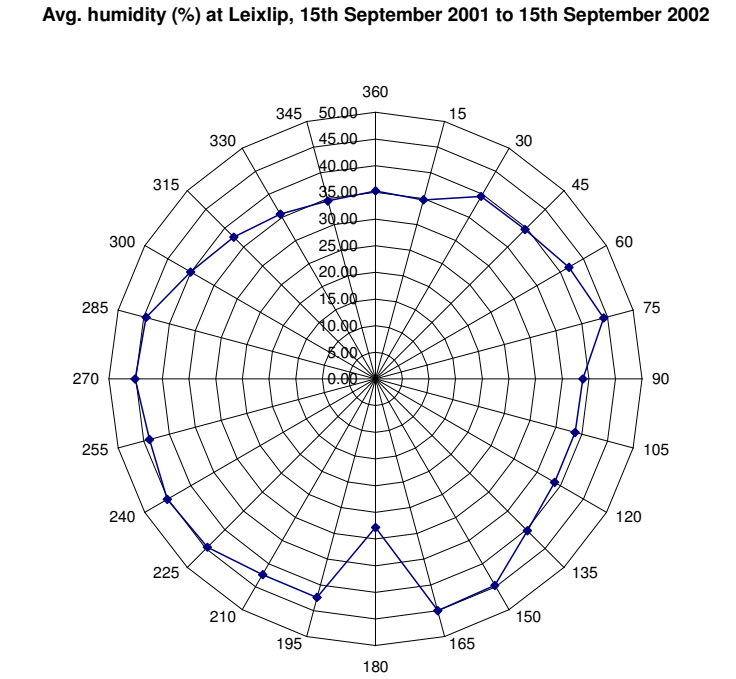


Figure A.4b): Variation in mean humidity with wind direction

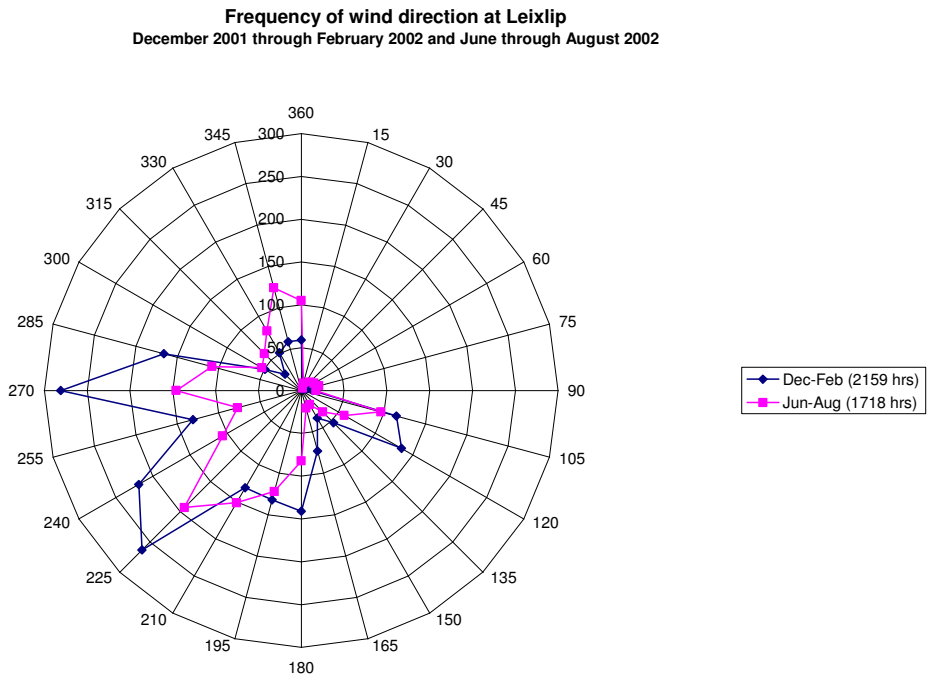


Figure A.5: Seasonal variation in frequency of wind direction

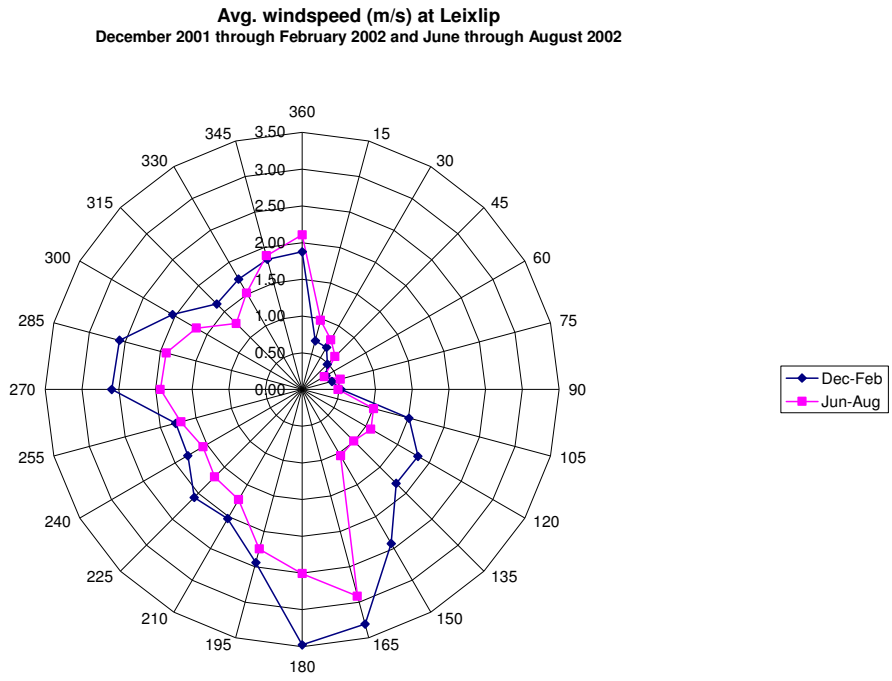
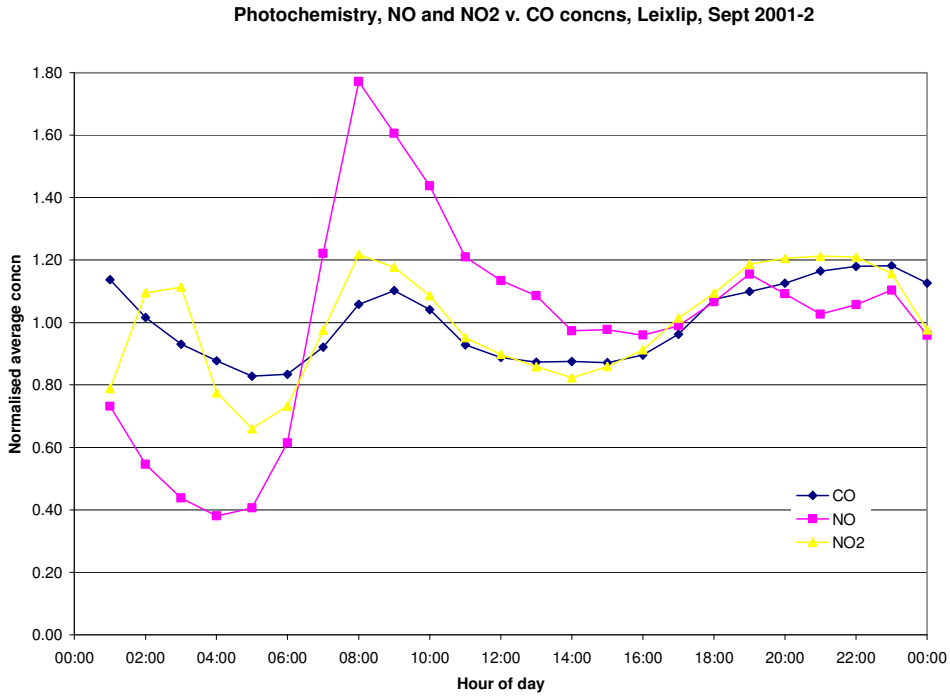


Figure A.6: Seasonal variation in mean wind speeds

Table A.1: Air pollutant concentrations

HOURLY CONCN		NOx			2NOxN/S			
	CO	NO2	NO	NOx	NO2	NO	NOx	TEOM
Mean	0.27	9.91	10.72	20.50	6.70	4.97	11.64	15.50
Mean (2NOxN)	0.34	11.08	8.54	19.62	9.96	8.58	18.52	17.83
Mean (NOxS)	0.21	8.59	7.09	15.67	5.03	3.12	8.12	13.07
Max	2.6	53.7	320.4	351.1	48.2	165.7	186.1	112.4
Date	15/12/2001	12/09/2002	05/01/2002	05/01/2002	21/08/2002	26/03/2002	26/03/2002	05/01/2002
Time (drivers')	02:00	22:00	23:00	23:00	17:00	08:00	08:00	02:00
Max (2NOxN period)	1.7	44.9	161.2	181.6	45.3	165.7	186.1	61.8
Date		11/04/2002	26/03/2002	26/03/2002	11/04/2002	26/03/2002	26/03/2002	
Time (drivers')		00:00	08:00	08:00	00:00	08:00	08:00	
Max (2NOxS period)	1	53.7	98.6	112.7	48.2	76.4	92.7	80.9
Date		12/09/2002	18/07/2002	18/07/2002	21/08/2002	26/08/2002	26/08/2002	
Time (drivers')		22:00	07:00	07:00	17:00	08:00	08:00	
5th %ile	0.1	1.8	0.1	2.1	0	0	0	5.1
95th %ile	0.6	25.4	38.5	62.9	23.4	20.6	42.4	31.7
98th %ile	0.9	30.3	71.6	95.7	28.8	37.6	63.7	43.6
5th %ile (2NOxN period)		1.6	0.2	2.3	0.4	0.1	0.9	
95th %ile (2NOxN period)		28.3	34.1	60.9	27.7	34	60.5	
98th %ile (2NOxN period)		32.3	55.3	83.7	32.3	55	82.4	
5th %ile (2NOxS period)		1.8	0.1	2.2	0	0	0	
95th %ile (2NOxS period)		21.2	22.9	42.1	18	13	30.1	
98th %ile (2NOxS period)		26.4	35.2	56.5	24.3	23	44.5	
Data capture	0.99	0.96			1.00			0.90
Data capture (2NOxN)					0.99			
Data capture (2NOxS)					1.00			
No. of TEOM values p.a. exceeding 50 ug/m^3 over ONE hour								88

24 HOUR (DAILY)		NOx			2NOxN/S				
	CO	NO2	NO	NOx	NO2	NO	NOx	TEOM	Partisol
Mean	0.27	9.90	10.68	20.45	6.75	4.96	11.67	15.50	16.80
Mean (2NOxN)	0.34	10.94	8.42	19.36	9.98	8.45	18.38	17.80	23.31
Mean (2NOxN)	0.21	8.53	7.08	15.59	4.98	3.12	8.06	12.96	12.70
Max	1.18	29.16	122.80	149.19	26.19	35.49	53.57	47.27	92.50
Date	09/12/2001	31/12/2001	06/01/2002	06/01/2002	29/03/2002	26/03/2002	26/03/2002	12/09/2002	30/03/2002
Max (2NOxN period)	0.88	27.06	34.20	53.89	26.19	35.49	53.57		
Date	29/03/2002	29/03/2002	26/03/2002	26/03/2002	29/03/2002	26/03/2002	26/03/2002		
Max (2NOxS period)	0.48	25.80	24.44	40.33	24.00	20.95	36.43		
Date	12/09/2002	12/09/2002	20/08/2002	20/08/2002	17/05/2002	26/07/2002	12/09/2002		
5th %ile	0.12	3.77	1.10	5.42				8.09	4.58
95th %ile	0.57	19.50	27.90	46.23				29.20	39.50
98th %ile	0.74	21.70	38.86	64.06				34.60	49.17
5th %ile (2NOxN period)	0.17	2.85	0.98	5.23	1.57	0.95	4.58		
95th %ile (2NOxN period)	0.65	21.23	23.29	26.41	20.46	24.28	45.65		
98th %ile (2NOxN period)	0.88	27.06	34.20	53.89	26.19	35.49	53.57		
5th %ile (2NOxS period)	0.12	3.65	0.99	4.93	0.43	0.22	0.63		
95th %ile (2NOxS period)	0.35	15.88	17.56	32.63	15.45	13.44	28.89		
98th %ile (2NOxS period)	0.42	24.25	23.41	38.43	22.99	17.08	32.42		
Data capture								0.93	0.94
Data capture (2NOxN)									
Data capture (2NOxS)									
No. of PM10 values p.a. exceeding 50 *u*g/m^3 over 24 hours								0	6



FigureA.7: Diurnal variation in primary and secondary pollutant concentrations

Table A.2: Air pollutant concentrations

HOURLY																
Instrument/units/pollutant			Sep-01	Oct-01	Nov-01	Dec-01	Jan-02	Feb-02	Mar-02	Apr-02	May-02	Jun-02	Jul-02	Aug-02	Sep-02	Sept 01-02
CO	CO	mean	0.28	0.22	0.25	0.41	0.34	0.24	0.36	0.33	0.23	0.19	0.19	0.23	0.27	0.27
ppm	CO	max.	1	1.5	1.2	2.6	2.3	0.8	1.7	1.2	1	0.5	0.6	0.8	0.9	2.60
NOx	NO2	mean	10.14	10.49	9.63	11.72	12.62	8.26	11.67	10.28	9.29	7.41	7.80	8.72	11.89	9.99
ppb	NO2	max.	29.8	36	39.7	48.4	48.3	34.5	42	44.9	37.8	32.5	34.9	39.3	53.7	53.7
	NO	mean	11.24	13.09	10.81	20.43	22.68	7.07	9.84	7.95	6.02	5.38	6.78	9.05	8.27	10.66
	NO	max.	97.5	110.9	124.9	262.1	320.4	95.9	161.2	146.8	71.6	31.5	98.6	84.2	88.2	320.4
	NOx	mean	21.37	23.57	20.17	31.00	35.30	15.33	21.52	18.23	15.29	12.79	14.57	17.77	20.14	20.54
	NOx	max.	119.1	123.9	164.7	291.6	351.1	115.6	181.6	178.1	87.8	64	112.7	102.9	107.2	351.1
2NOxN/S	NO2	mean	*2NOxN*	*May*	*8.42*	*2NOxS*	*May*	*4.03*	12.56	9.25	6.22	2.82	4.94	5.72	9.24	7.25
ppb	NO2	max.	*2NOxN*	*May*	*36.3*	*2NOxS*	*May*	*39.1*	42.2	45.3	39.1	25.4	30.9	48.2	44.2	48.2
	NO	mean	*2NOxN*	*May*	*6.12*	*2NOxS*	*May*	*1.03*	11.90	7.93	3.57	1.11	3.40	4.49	5.87	5.47
	NO	max.	*2NOxN*	*May*	*74.9*	*2NOxS*	*May*	*21.5*	165.7	150.1	74.9	18.7	66.5	76.4	65.7	165.7
	NOx	mean	*2NOxN*	*May*	*14.54*	*2NOxS*	*May*	*5.05*	24.40	17.17	9.78	3.90	8.32	10.14	15.08	12.68
	NOx	max.	*2NOxN*	*May*	*91.4*	*2NOxS*	*May*	*58.8*	186.1	182.7	91.4	38.9	82.1	91.2	92.7	186.1
TEOM	PM10	mean	17.93	15.40	14.57	18.34	18.92	13.43	18.04	18.12	13.70	11.97	11.17	13.49	18.89	15.69
(ug/m^3)		max.	44.7	106.4	53.4	84.6	112.4	44.8	50.2	61.8	39.3	31.9	39.6	45.7	80.9	112.4
24 HOUR (DAILY)																
CO	CO	mean	0.28	0.22	0.25	0.41	0.34	0.24	0.36	0.33	0.23	0.19	0.19	0.23	0.27	0.27
ppm	CO	max.	0.63	0.50	0.68	1.18	1.09	0.44	0.88	0.73	0.43	0.33	0.35	0.42	0.48	1.18
NOx	NO2	mean	10.29	10.51	9.63	11.72	12.49	8.27	11.39	10.42	9.29	7.41	7.80	8.72	11.91	9.99
ppb	NO2	max.	16.16	18.44	19.58	29.16	28.70	18.40	27.06	21.23	24.25	15.45	16.58	17.05	25.80	29.2
	NO	mean	11.25	12.85	10.80	20.43	22.29	7.07	9.60	8.06	6.02	5.38	6.79	9.04	8.30	10.61
	NO	max.	29.65	26.60	30.08	97.71	122.80	32.22	34.20	26.41	23.08	10.73	23.41	24.44	17.56	122.8
	NOx	mean	21.54	23.36	20.16	31.00	34.77	15.34	20.99	18.47	15.29	12.79	14.58	17.75	20.18	20.48
	NOx	max.	45.82	41.05	45.28	113.74	149.19	50.61	53.89	46.28	40.63	22.81	38.40	40.33	38.43	149.2
2NOxN/S	NO2	mean	*2NOxN*	*May*	*8.27*	*2NOxS*	*May*	*3.58*	12.14	9.46	6.25	2.82	4.94	5.72	9.25	7.23
ppb	NO2	max.	*2NOxN*	*May*	*16.69*	*2NOxS*	*May*	*24.00*	26.19	20.46	24.00	15.82	15.45	14.50	22.99	26.2
	NO	mean	*2NOxN*	*May*	*6.05*	*2NOxS*	*May*	*0.95*	11.01	8.03	3.57	1.11	3.39	4.49	5.89	5.36
	NO	max.	*2NOxN*	*May*	*23.65*	*2NOxS*	*May*	*5.64*	35.49	26.43	23.65	5.68	17.08	20.95	14.00	35.5
	NOx	mean	*2NOxN*	*May*	*14.31*	*2NOxS*	*May*	*4.53*	23.01	17.48	9.81	3.90	8.32	10.14	15.10	12.54
	NOx	max.	*2NOxN*	*May*	*40.24*	*2NOxS*	*May*	*29.63*	53.57	45.65	40.24	21.50	32.42	32.41	36.43	53.6
TEOM	PM10	mean	18.00	15.38	14.87	18.37	18.90	13.32	18.07	17.92	13.73	11.96	11.14	13.38	19.07	15.70
(ug/m^3)		max.	28.05	21.00	24.96	36.77	46.24	27.34	29.20	43.59	26.74	20.55	20.21	22.48	47.27	47.3
Partisol	PM10	mean	19.75	14.96	16.01	21.56	14.52	16.30	31.94	19.32	13.24	12.39	10.99	12.16	19.69	17.14
(ug/m^3)		max.	31.29	25.58	25.25	50.21	63.08	34.00	92.50	49.17	30.83	23.33	24.17	22.08	58.75	92.50

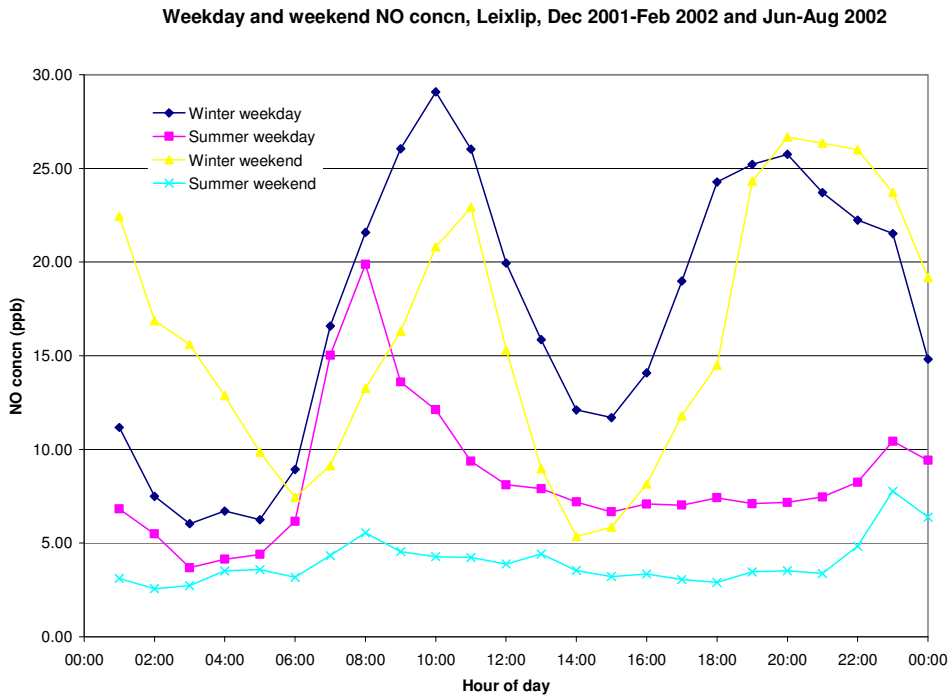


Figure A.8: Seasonal diurnal variation in weekday and weekend mean concentration of NO

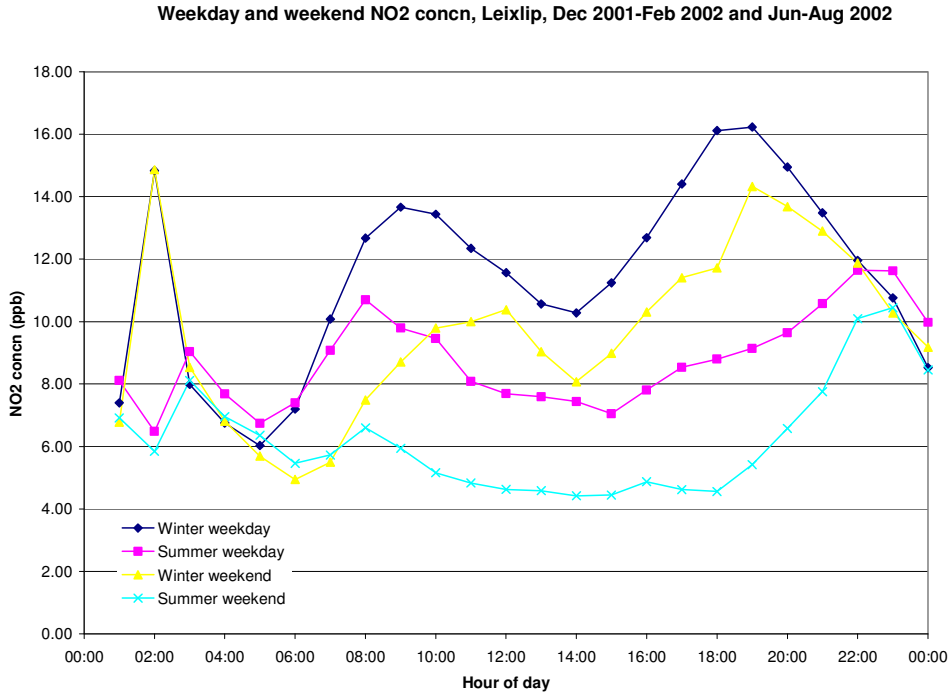


Figure A.9: Seasonal diurnal variation in weekday and weekend mean concentration of NO_2

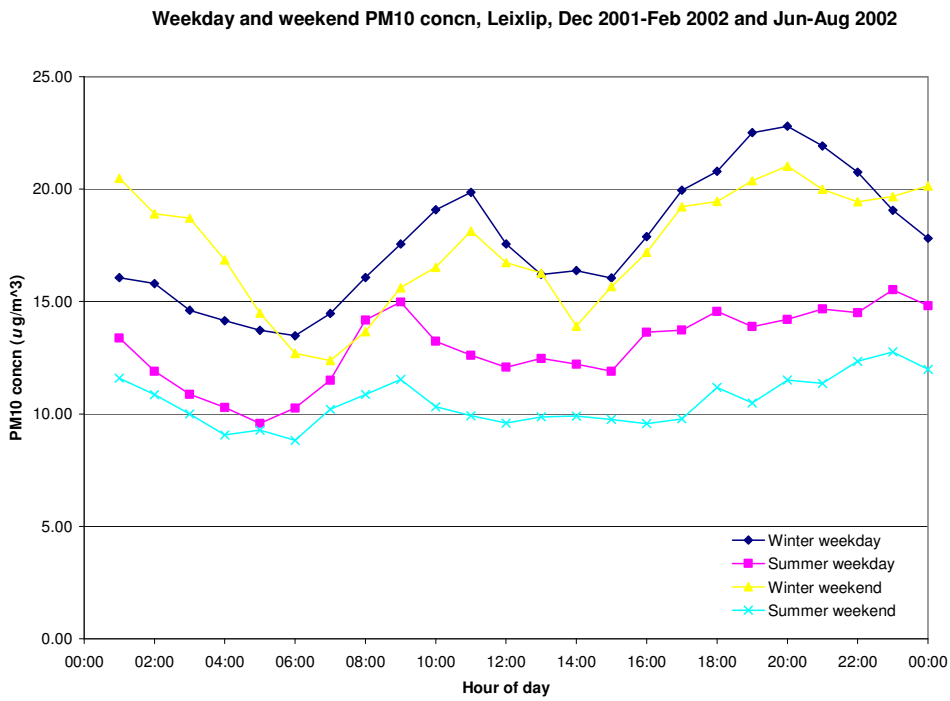


Figure A.10: Seasonal diurnal variation in weekday and weekend mean concentration of PM_{10}

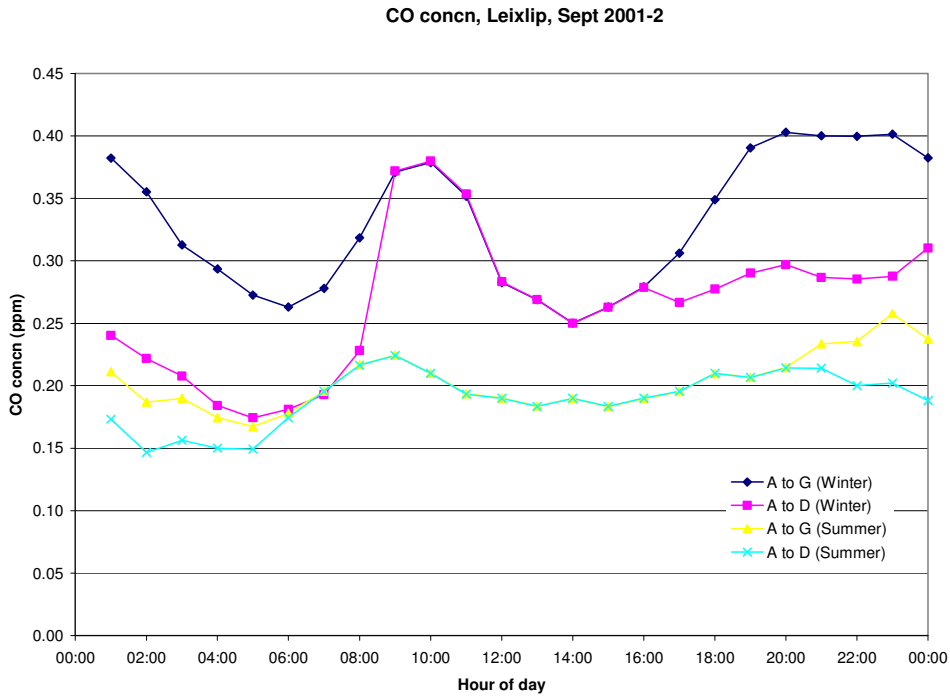


Figure A.11: Diurnal variation in CO with season and stability class

Appendix B

Appendix to Chapter 4: Additional Monitoring Results for the N6 Roundabout in Galway

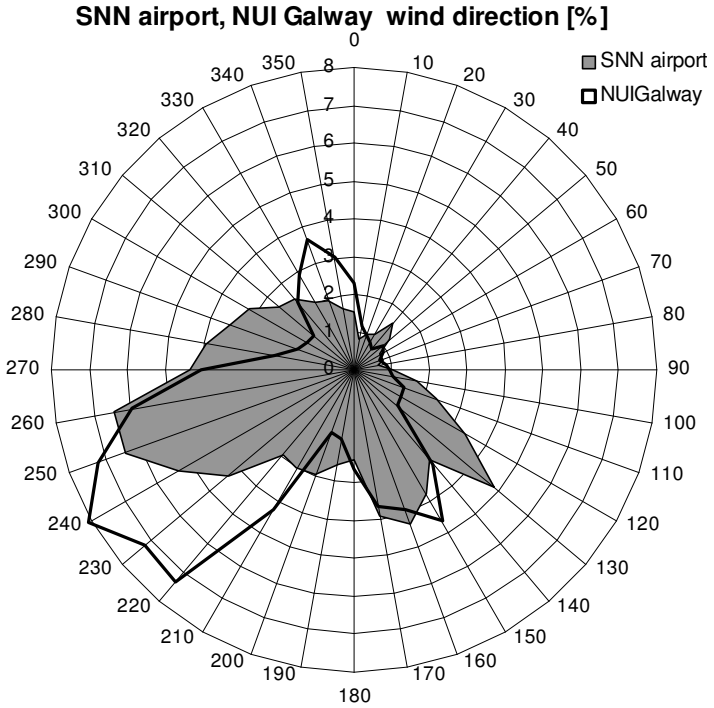


Figure B.1: Frequency of wind direction at the Shannon airport and at NUI Galway

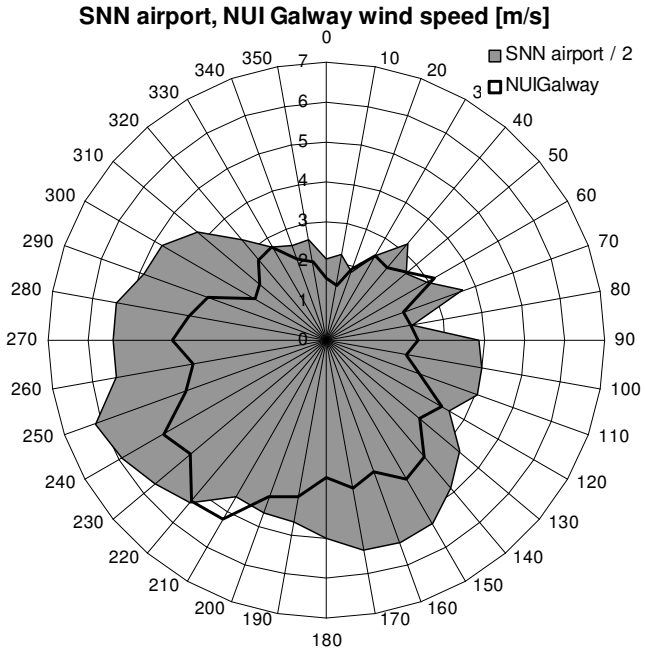


Figure B.2: Wind speed pattern at NUI Galway and at Shannon airport

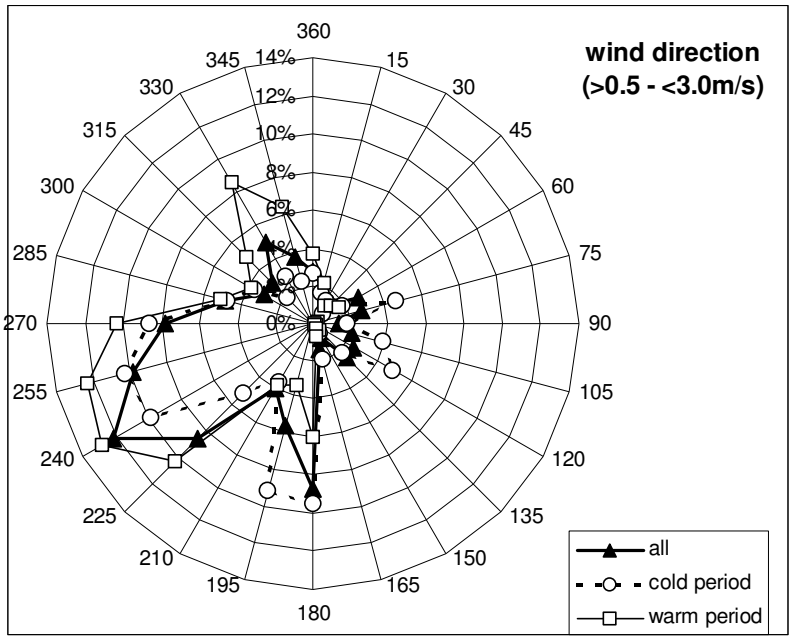


Figure B.3: Frequency of wind direction for wind speeds between 0.5 and 3 m/s at the N6 site

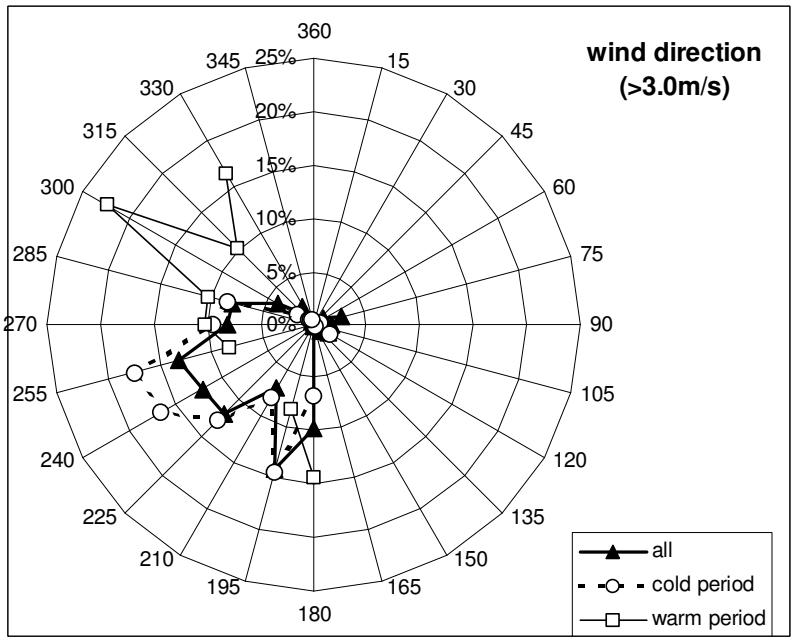


Figure B.4: Frequency of wind direction for wind speeds over 3 m/s at the N6 site

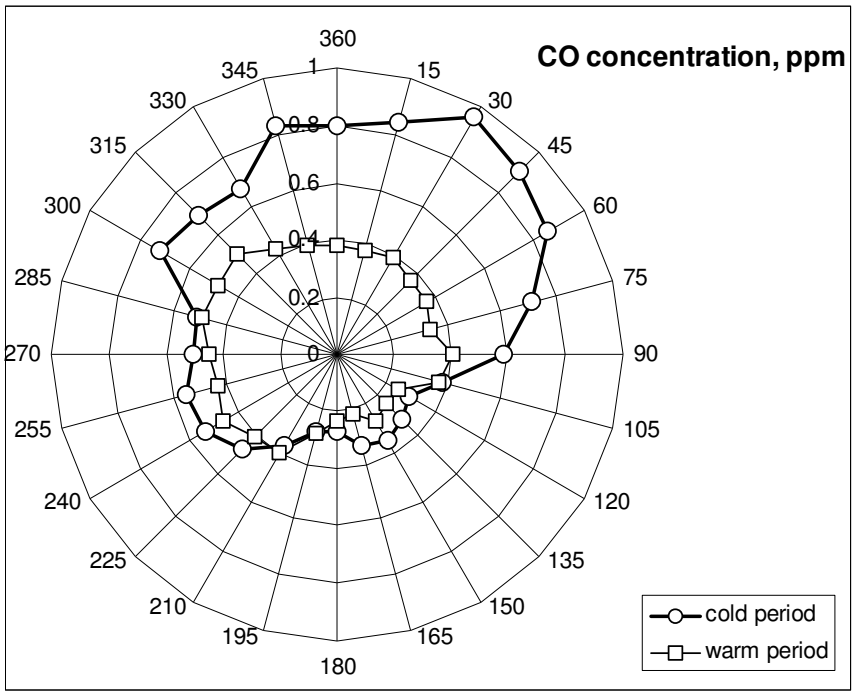


Figure B.5: Distribution of CO concentration during cold and warm periods, as a function of wind direction

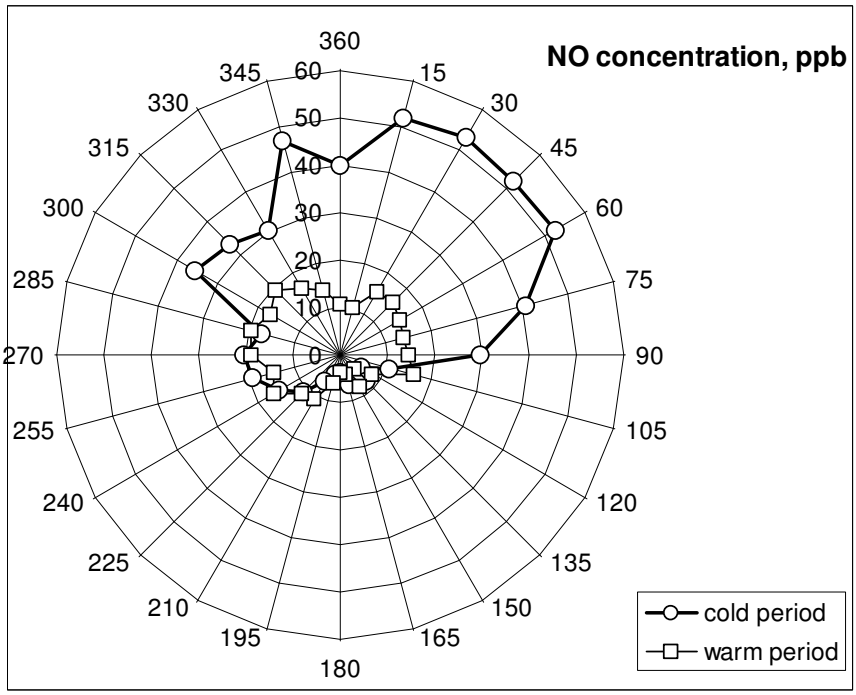


Figure B.6: Distribution of NO concentration during cold and warm periods, as a function of wind direction

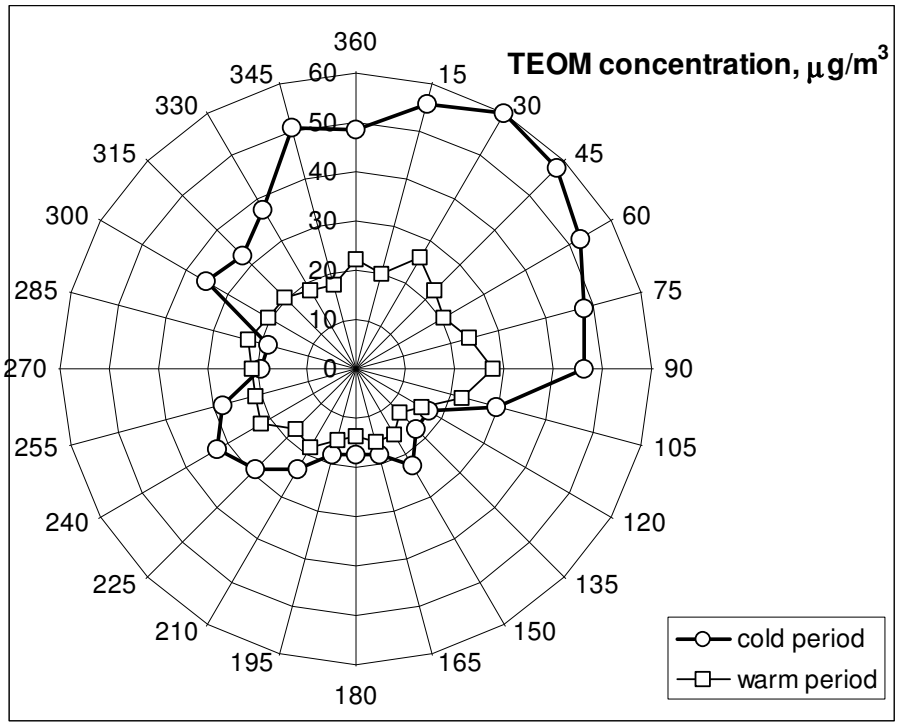


Figure B.7: Distribution of PM10 concentration during cold and warm periods, as a function of wind direction

Appendix C: Hydrocarbon Monitoring at M4 Motorway Site

C.1 Introduction

This appendix describes the monitoring of hydrocarbon concentrations at the M4 monitoring site near Leixlip. Hourly average concentrations of more than 20 different hydrocarbons were measured over an eight-month period. Details of the sampling and measurement equipment employed, and the results obtained, are given. The influences of local traffic flow and meteorological conditions on the measured concentrations are analysed.

C.2 Monitoring Equipment

C.2.1 System overview

The hydrocarbon monitoring system employed in this project is composed of several components. The system is housed in a mobile laboratory along with other air quality monitoring equipment and a meteorological station. The principal components of the on-line hydrocarbon monitoring system are an air sampler, an ATD400, an Autosystem Gas Chromatograph, a 900 series interface and a PC with Turbochrom analytical software. The relationships between these components are illustrated in Box C.1.

The Perkin-Elmer Ozone Precursor System is an adaptation of the standard Automated Thermal Desorber Model ATD 400 to include a special means for introduction of ambient air samples. This is achieved via a modified internal standard valve mounted at the rear of the ATD 400, which incorporates a dehumidifying system (the air sampler). The ATD 400 desorber is connected to the gas chromatograph via a heated transfer line. Carrier and combustion gases and dry zero air supplies are obtained from gas cylinders and generators. Separation of the target analytes is achieved through the use of a dual-column system with column switching. The system includes two flame ionization detectors (FIDs) for signal detection. Voltage signals from the detectors are collected by a dual-channel buffered digital-to-analog interface, which supplies data to a personal computer running the Turbochrom® data handling software.

C.2.2 Sampling

The Automated Thermal Desorber, Model ATD 400, is a system for the pre-concentration of a gaseous sample using solid sorbents and the subsequent injection of that sample into the inlet of a gas chromatograph (GC). In this specific application, many of the standard features of the ATD are not used (the autosampling capability and the sample tube, for example). The ATD 400 incorporates a small glass trap packed with two sorbent materials, one of which is a form of graphite and the other is carbon molecular sieve. During sampling, 600 cc of ambient air or standard gas is drawn through this trap by a small vacuum pump. The trap is cooled electrically to -30°C and this causes the volatile organic compounds (VOCs) in the air to adsorb strongly onto the surface of the sorbents. At the end of the sampling period, the flow is stopped. A valve in the ATD then operates to reverse the direction of flow. The trap is heated, causing the VOCs to be

desorbed and swept into the transfer line and onto the analytical columns of the GC system. This procedure is followed for both ambient air samples and standard samples used for calibration.

ATD400 method parameters:

Mode	2	Oven temp	250°C
First tube	1	Desorb time	1.0 min
Last tube	1	Valve temp	175°C
Inj/tube	99	Trap low	-30°C
Trap fast	YES	Trap high	325°C
Cycle time	60min	Trap hold	5.0 min
Inlet split	NO	Line temp	200°C
Outlet split	YES	Min PSI	43psig
Recycle	NO	Std inj	40min

Outlet split flow = 3 to 5ml/min
Desorb flow = 15 to 20ml/min
Inlet split (not used) – needle valve fully anti-clockwise (open)

Sample collection rate (adjusted using mass flow controller) set to 15 ml/min.

Box C.1: ATD400 method parameters

C.2.3 Analysis

The Autosystem GC is a dual-channel, temperature programmable, gas chromatograph (Box C.2). For on-line measurements, the sample is provided to the GC via the heated transfer line from the ATD400. The GC incorporates 2 FID detectors and an oven which houses the capillary columns used to separate the compounds of interest. The two columns used in this study are a 50 metre PLOT column and a 50 metre BP-1 column.

Autosystem GC method parameters

Oven temp 1	45°C	Oven temp 2	170°C	Oven temp 3	200°C
Oven time 1	15min	Oven time 2	0 min	Oven time 3	6min
Oven rate 1	5°C/min	Oven rate 2	15°C/min	Oven rate 3	END
Det 1 temp	250°C	Det 1 range	1	Det 1 attenuation	1
Det 2 temp	250°C	Det 2 range	1	Det 2 attenuation	1
Int output 1	FID 1	Autozero 1	ON	FID 1 offset	10
Int output 2	FID 2	Autozero 2	ON	FID 2 offset	10
Carrier 2	17.0 psig	Valve 2 (initial)	ON		
Events	9.5min	Valve 2	OFF		

Box C.2: *Autosystem GC method parameters*

C.2.4 Data acquisition and control

900 Series Interface: The 900 series interface is an analogue-to-digital interface which acquires analytical data (dual FID response) from the Autosystem GC and transfers these to the host computer.

Turbochrom Analytical Software: Turbochrom software processes the raw data transferred to the PC from the GC detectors via the 900 interface. The software is also used to write analysis "sequences" which provide instructions to ATD400, the air sampler and the GC on forthcoming sampling and analyses runs. This feature allows the system to then operate unattended with regular calibrations at predetermined intervals.

C.3 Monitoring Programme

Table C.1: Monitored Hydrocarbon Compounds

Classification	**Compounds**
Alkanes	ethane propane n-butane iso-butane n-pentane iso-pentane n-heptane n-hexane
Olefins	ethene propene 1-butene trans-2-butene cis-2-butene 1,3 butadiene trans-2-pentene cis-2-pentene
Aromatics	benzene toluene o-xylene m+p-xylene ethylbenzene
Alkyne	ethyne (acetylene)

Table C.1 lists the individual hydrocarbons monitored, and identifies the classification of each. The system was calibrated weekly, using a NIST traceable calibration gas mixture containing all of the compounds listed in Table C.1.

The on-line system was first put into use for this project on the 22nd November 2001. Various set-up and initialisation problems were encountered over the following 2 months, central to which were the inclusion of a new zero air generator, carrier gas (helium) leaks and a delay in obtaining a suitable calibration standard. Smaller problems such as the GC intermittently shutting itself on and off (due to overheating) were also encountered, all of which had to be remedied before reliable monitoring results could be obtained.

The monitoring period extended from the 8th February 2002 to the 23rd September 2002. During this eight-month period, measurements were made for 3096 out of a possible 5450 hours, equivalent to a sampling rate of 57%. Examples of the issues which led to breaks in monitoring are: instrument methods for the Turbochrom software had to be re-written, problems were encountered with analytical column switching on the GC (Dean's switch) and the ATD400 sporadically giving "bus errors". This latter issue meant that new internal processor boards had to be obtained for the instrument, and resulted in no data being obtained in July or the first half of August. Notwithstanding these problems, the total number of HC measurements exceeded that planned at the beginning of the project.

C.4 Meteorology and traffic flows

In this appendix, only meteorological data obtained during hours in which hydrocarbon measurements were made are considered. Figure C.1 shows that on a clear majority of occasions, the wind came from the direction of the M4 motorway. The most common wind directions were those nearly parallel to the motorway and the southwest. Figure C.2 shows that there was little difference between the wind directions observed during unstable atmospheric conditions only (stability classes A-D) and those observed for all stability conditions (classes A-F). Figure C.3 shows that high average wind speeds are associated with wind directions from the motorway. The lowest speeds are seen to come from the sector 15° to 90°, where an adjacent building is a contributory factor.

Details of the traffic flow on the M4 motorway are given in Chapter 3. It is assumed that the average diurnal traffic flow during the hydrocarbon monitoring period is the same as that observed during the whole monitoring campaign (September 15th 2001 – September 15th 2002).

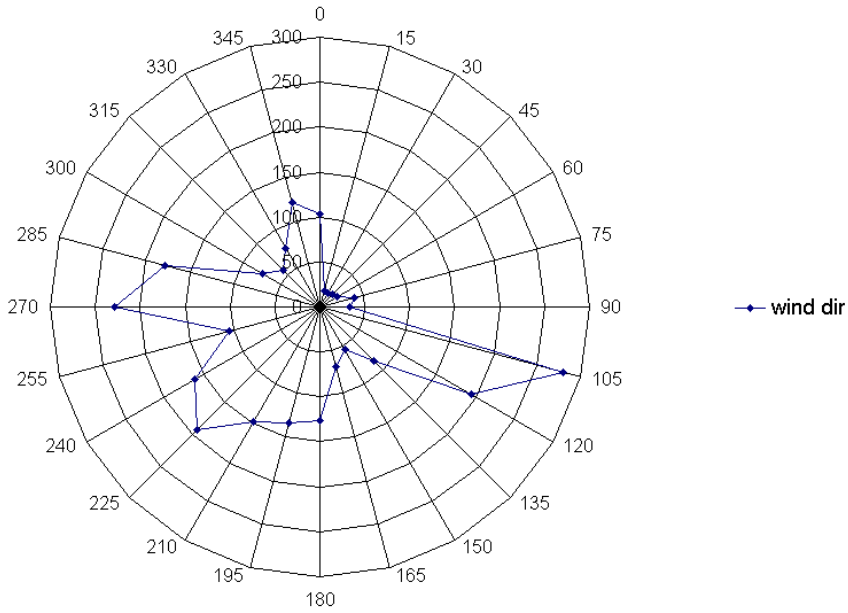


Figure C.1: Wind direction frequency for all hydrocarbon measurements.

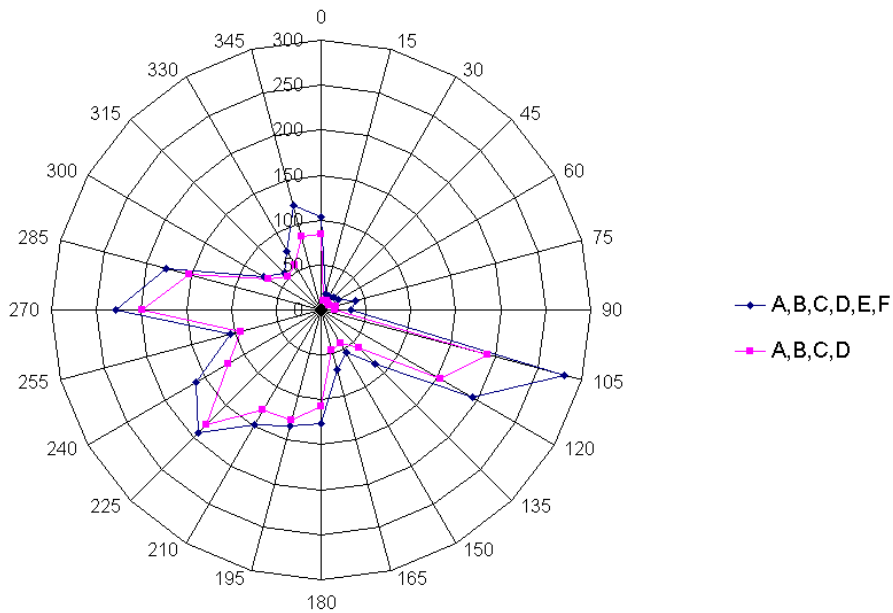


Figure C.2: Wind direction frequency for different stability classes.

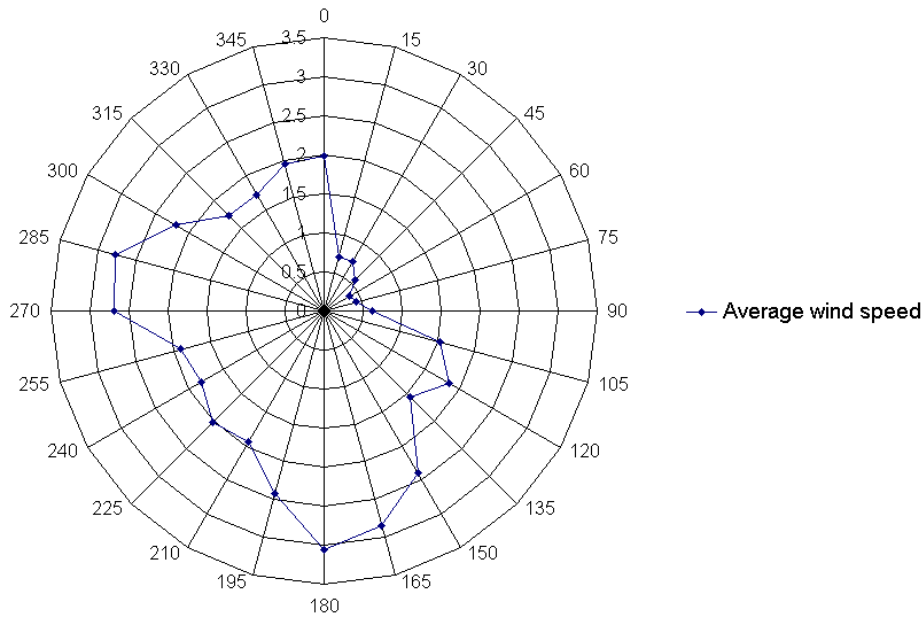


Figure C.3: Average wind speed for all hydrocarbon measurements.

C.5 Measured hydrocarbon concentrations

Table C.2 presents a statistical summary of the measured hydrocarbon concentrations. Ethane displayed the highest mean observed concentration, followed by ethene, propane, acetylene and n-butane. Ethane, propane, ethene, and toluene displayed the highest maximum concentrations. The relative standard deviation of the measured ethane concentrations is low compared to that of many of other compounds – indicating a relatively constant concentration. The highest relative standard deviations are displayed by n-heptane, toluene, n-hexane and m+p xylene, indicating that the concentrations of these compounds varied most during the monitoring period.

On average, the maximum concentration of each compound is more than twice the 98th percentile concentration of that compound, indicating that the maximum concentrations reflect rare events. This effect is most noticeable for the aromatics. The median (98th percentile) concentrations are, on average, 30% lower than the mean concentration of each compound. The average relative standard deviations of the aromatics and alkanes are similar, but that of the olefins is much lower, indicating that the olefins tend to display relatively constant concentrations.

The mean observed benzene concentration was 0.16 ppb, and the maximum hourly concentration was 2.09 ppb. These values can be compared with the EU Ambient Air Standard of an annual average of 1.52 ppb (5 µg/m^3). The mean observed 1,3-butadiene concentration was 0.24 ppb, and the maximum hourly concentration was 0.71 ppb. For

comparison, the UK National Air Quality Strategy has as an objective that, by 2005, the annual running mean concentration of 1,3-butadiene should not exceed 1 ppb.

Table C.2: Statistical summary of measured hydrocarbon concentrations

Classification	Compound	Max (ppb)	Mean (ppb)	Std Deviation (ppb)	Relative Std Dev (%)	98th %-ile (ppb)	50th %-ile (ppb)
Alkanes	Ethane	6.98	1.43	0.86	60.50	3.72	1.44
	Propane	8.59	0.72	0.68	94.76	2.65	0.56
	N-butane	4.41	0.46	0.53	114.89	2.09	0.28
	Isobutane	3.12	0.28	0.33	119.48	1.29	0.17
	N-pentane	1.13	0.31	0.15	49.32	0.68	0.32
	Isopentane	3.35	0.28	0.34	120.41	1.42	0.16
	N-hexane	1.43	0.09	0.13	142.77	0.50	0.05
	N-heptane	2.64	0.19	0.28	150.28	1.15	0.10
Olefins	Ethene	7.25	0.78	0.85	109.14	3.43	0.49
	Propene	1.59	0.22	0.21	91.80	0.92	0.15
	1-butene	0.53	0.12	0.06	51.93	0.34	0.11
	Isoprene	0.24	0.04	0.03	63.19	0.12	0.04
	1,3 butadiene	0.71	0.24	0.13	53.51	0.54	0.21
	Trans-2-but	0.31	0.10	0.05	46.79	0.21	0.09
	Cis-2 butene	0.20	0.05	0.02	45.93	0.12	0.05
	Trans-2 pent	0.29	0.06	0.04	68.77	0.17	0.05
	Cis-2 pentene	0.13	0.04	0.02	58.21	0.10	0.04
Aromatics	Toluene	6.83	0.31	0.45	145.47	1.67	0.16
	0-xylene	1.58	0.11	0.12	113.17	0.48	0.07
	M+p xylene	4.35	0.21	0.28	134.31	1.04	0.12
	Benzene	2.09	0.16	0.15	89.63	0.65	0.12
	Ethylbenzene	1.15	0.09	0.09	98.54	0.38	0.07
Alkyne	Acetylene	4.01	0.52	0.43	82.08	1.98	0.41

For further analysis of the hydrocarbon data, the monitored compounds are considered within the different chemical classifications listed in Table C.1. The variation, throughout the monitoring period, in the 24-hour average concentration of one compound in each classification is shown in Figures C.4 to C.7. It is evident that the compounds selected all experienced peak episodes on the same days, and that the general profiles of all graphs are similar. The main difference relates to toluene, whose profile does not vary quite as

much as the other three compounds. For propane, ethene and acetlyene, summertime peaks are lower than those obtained in winter, possibly due to a greater boundary layer depth, and/or increased photochemical activity. For these compounds, the lower bound on 24-hour average concentrations also appears to reduce in summertime.

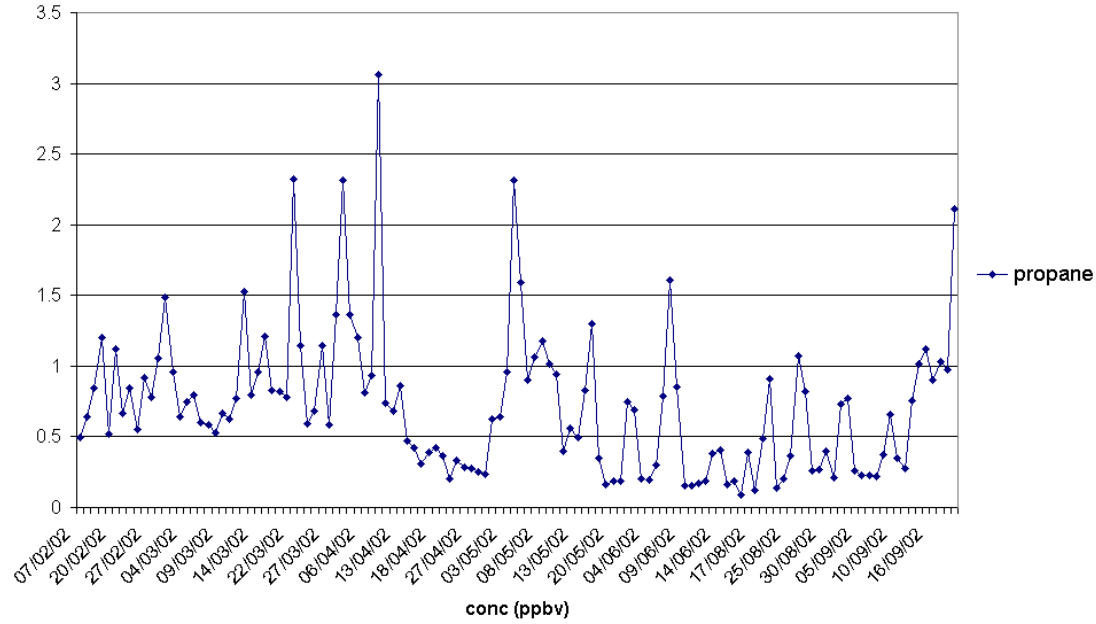


Figure C.4: Variation in the 24-hour average concentration of propane

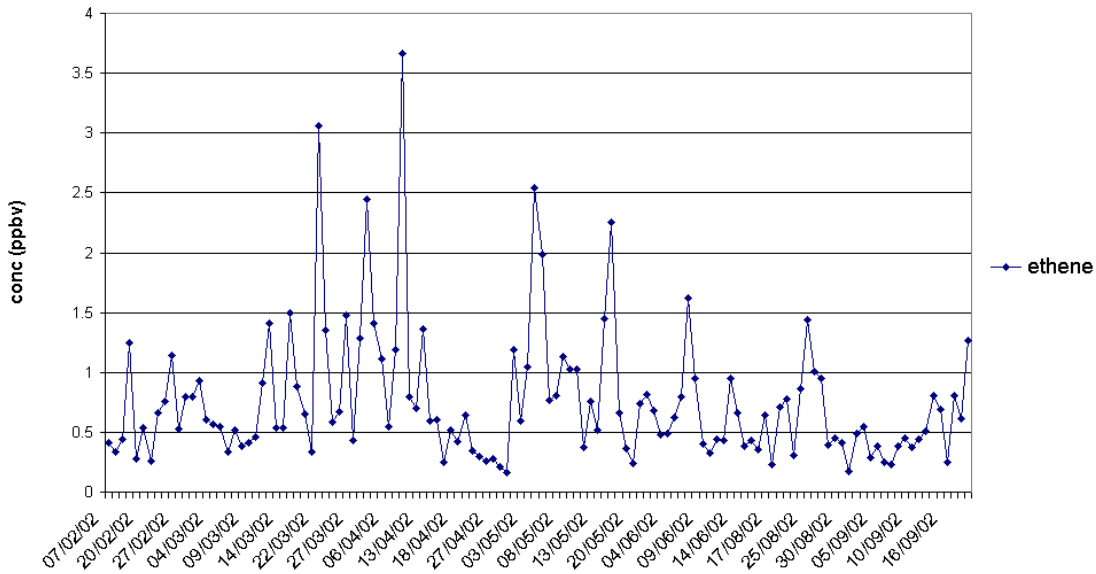


Figure C.5: Variation in the 24-hour average concentration of ethene

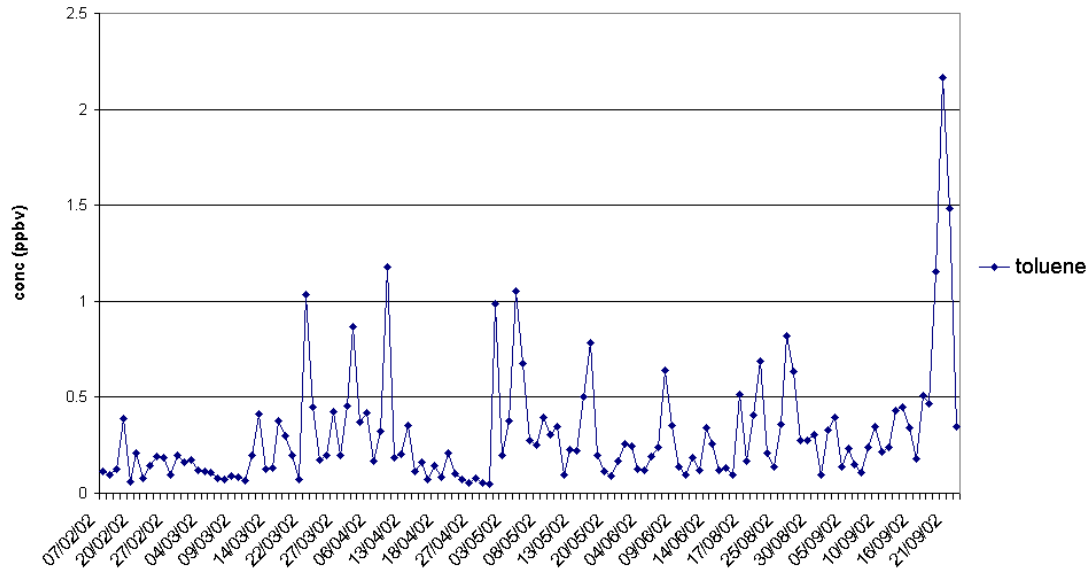


Figure C.6: Variation in the 24-hour average concentration of toluene

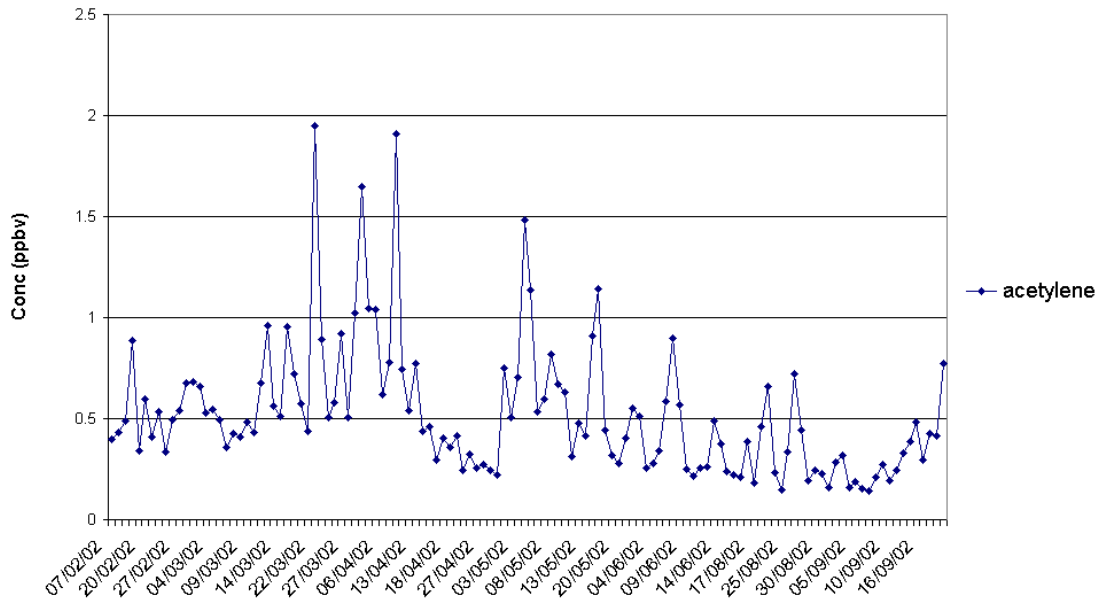


Figure C.7: Variation in the 24-hour average concentration of acetylene.

Figures C.8 to C.12 present scatter plots which compare the concentrations of two hydrocarbons measured in the same hour. Figure C.8 and C.12 compare the concentrations of two alkanes, Figure C.9 compares two olefins, Figure C.10 compares two aromatics, while Figure C.11 compares the only alkyne monitored with an olefin.

With the exception of Figure C.12, good agreement is generally observed between pairs of contemporary values, and a high concentration of one compound implies a high concentration of the other. Figure C.12 illustrates the unusual behaviour of n-pentane, for which concentrations are weakly correlated with that of another alkane, iso-butane.

Table C.3 is a matrix of correlation coefficients for the monitored compounds. It is clear that n-pentane is poorly correlated with many compounds. In general, the aromatics are well correlated with each other, and with acetylene and isopentane. The correlation between pairs of olefins and pairs of alkanes is less strong.

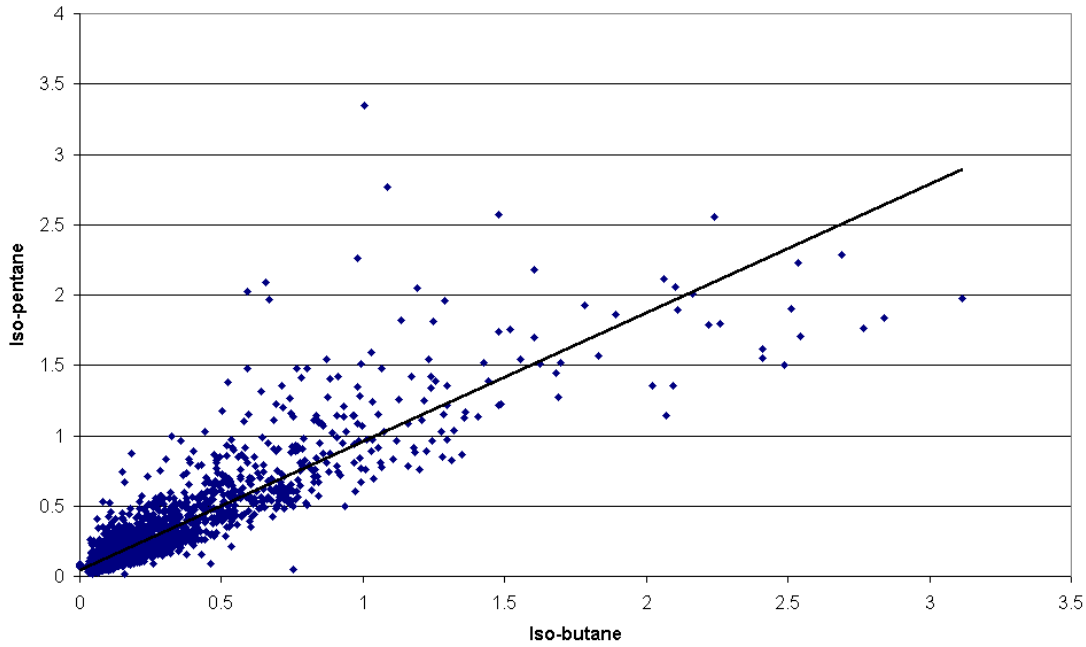


Figure C.8: Scatter plot of iso-butane and iso-pentane concentrations (ppb)

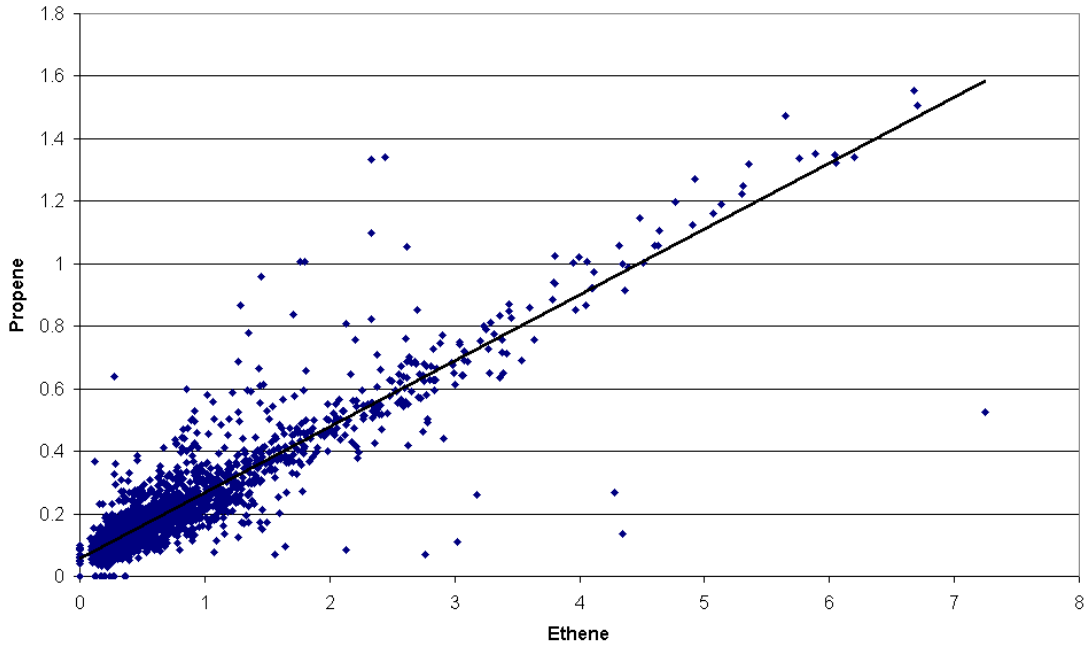


Figure C.9: Scatter plot of ethene and propene concentrations (ppb)

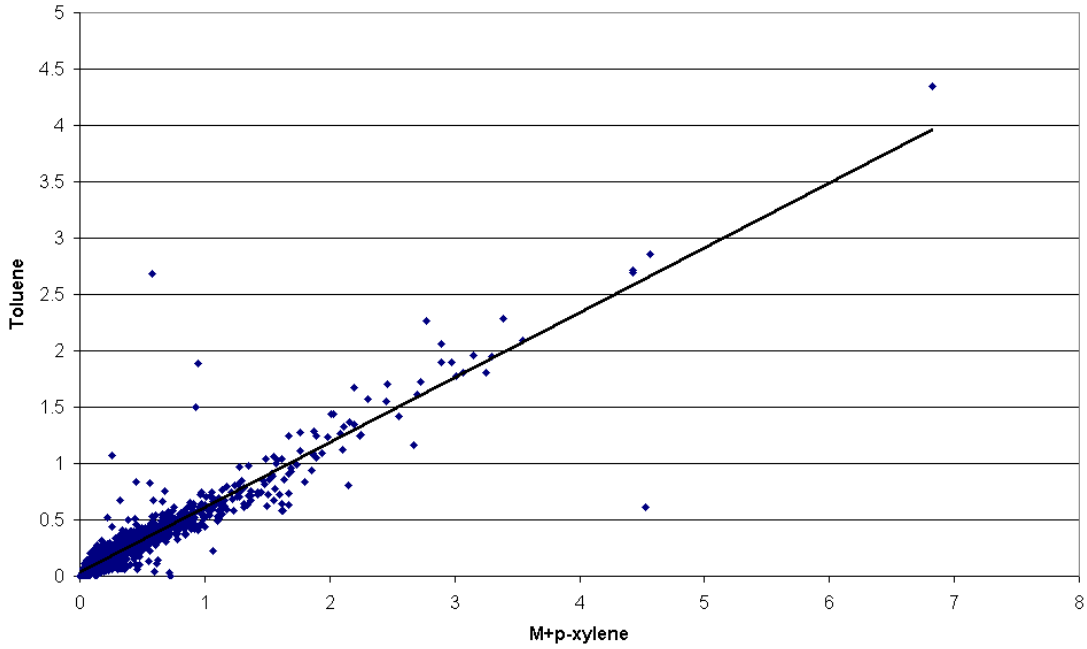


Figure C.10: Scatter plot of toluene and m+p xylene concentrations (ppb)

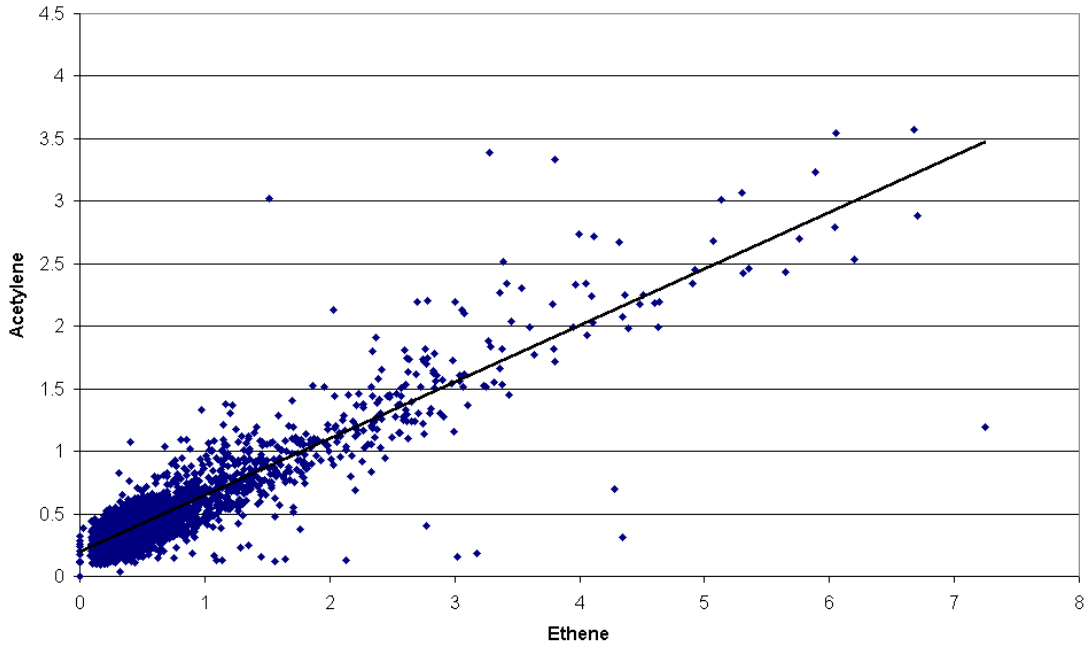


Figure C.11: Scatter plot of ethene and acetylene concentrations (ppb)

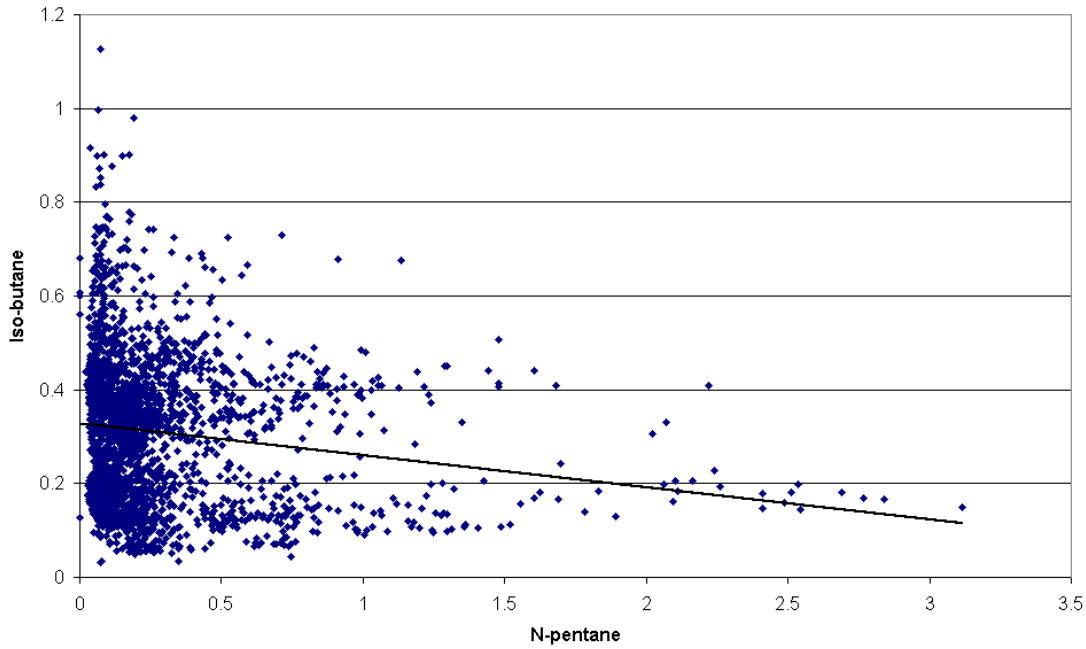


Figure C.12: Scatter plot of iso-butane and n-pentane concentrations (ppb)

Table C.3: Correlation matrix for all compounds monitored

	eth	prop	n-but	I-but	n-pen	isopen	n-hex	n-hep	Ethe	Prope	1-bute	1,3 but	trns-2	cis 2	trns 2	cis 2	tol	0-xyl	m+p xyl	benz	ethylb	acet
Ethane	1.00																					
propane	0.71	1.00																				
n-butane	0.69	0.88	1.00																			
isobutane	0.69	0.86	0.97	1.00																		
n-pentane	-0.04	-0.19	-0.10	-0.15	1.00																	
isopentane	0.59	0.76	0.92	0.88	0.00	1.00																
n-hexane	0.37	0.33	0.43	0.35	0.11	0.39	1.00															
n-heptane	0.25	0.43	0.42	0.41	-0.06	0.63	0.17	1.00														
Ethene	0.59	0.75	0.83	0.83	-0.14	0.81	0.24	0.45	1.00													
Propene	0.54	0.71	0.82	0.79	-0.01	0.85	0.26	0.47	0.91	1.00												
1-butene	0.46	0.56	0.71	0.69	0.15	0.79	0.28	0.44	0.74	0.84	1.00											
1,3 butadiene	0.39	0.20	0.21	0.24	-0.03	0.21	-0.03	0.25	0.29	0.27	0.38	1.00										
trns-2-but	0.46	0.33	0.36	0.40	-0.03	0.33	0.07	0.30	0.40	0.38	0.48	0.90	1.00									
cis 2 butene	0.50	0.50	0.59	0.64	0.05	0.59	0.20	0.44	0.64	0.65	0.65	0.60	0.72	1.00								
trns 2 pent	0.48	0.63	0.81	0.75	0.02	0.79	0.23	0.38	0.71	0.81	0.78	0.39	0.45	0.71	1.00							
cis 2 pentene	0.27	0.46	0.60	0.54	0.08	0.69	0.19	0.34	0.52	0.64	0.67	0.34	0.45	0.60	0.73	1.00						
toluene	0.55	0.71	0.84	0.80	0.03	0.90	0.42	0.49	0.80	0.88	0.81	0.20	0.31	0.59	0.84	0.72	1.00					
0-xylene	0.55	0.66	0.78	0.72	0.06	0.86	0.42	0.48	0.70	0.83	0.82	0.31	0.40	0.63	0.77	0.72	0.89	1.00				
m+p xylene	0.46	0.61	0.75	0.70	0.15	0.83	0.33	0.47	0.71	0.82	0.78	0.16	0.25	0.54	0.79	0.70	0.88	0.92	1.00			
benzene	0.58	0.75	0.84	0.80	-0.05	0.84	0.35	0.45	0.85	0.89	0.76	0.20	0.31	0.58	0.81	0.65	0.86	0.85	0.81	1.00		
ethylbenzene	0.55	0.64	0.75	0.70	0.06	0.82	0.32	0.44	0.69	0.81	0.78	0.33	0.41	0.62	0.78	0.69	0.87	0.91	0.96	0.82	1.00	
acetylene	0.63	0.81	0.85	0.85	-0.27	0.78	0.28	0.43	0.89	0.82	0.68	0.28	0.41	0.60	0.72	0.49	0.77	0.67	0.65	0.82	0.66	1.00

C.6 Analysis of Monitoring Data

C.6.1 Diurnal variation in hydrocarbon concentrations

Figures C.13 to C.16 present the average diurnal concentration profiles of each of the monitored compounds, by classification. These profiles are determined using all measurements obtained. In most cases, the diurnal profiles do not follow the diurnal variation in traffic flow, and concentration peaks are not noticeable during the morning and evening peak travel periods. For most alkanes and olefins, one of two typical concentrations profiles are displayed: one which the concentration varies little throughout the twenty-four hour period, or one in which higher concentrations are observed during night time hours. This latter case is attributable to the influence of stable nocturnal conditions. However, for two olefins (ethene and propene), the aromatics and acetylene, noticeable increases in concentration during the morning peak travel period are observable. For these compounds, increases also occur in early evening, but this trend does not reverse when traffic levels fall.

It is clear that for most compounds, the variation in background concentration is as strong or stronger than that of the local traffic impact. To investigate the local traffic effect more closely, a 'filtered' dataset is examined from which concentrations observed during hours with low wind speeds, or stable atmospheric conditions, or wind directions from the monitor to the road, were removed. The resulting diurnal profiles are shown in Figures C.17 to C.20. Only those compounds which show a diurnal profile resembling that of traffic flow on the motorway are represented. Of the alkanes, isobutane and isopentane now show a local traffic influence. Three or four olefins and aromatics, and acetylene also display the expected pattern. Elevated nocturnal concentrations are no longer present, and many compounds display very similar profiles.

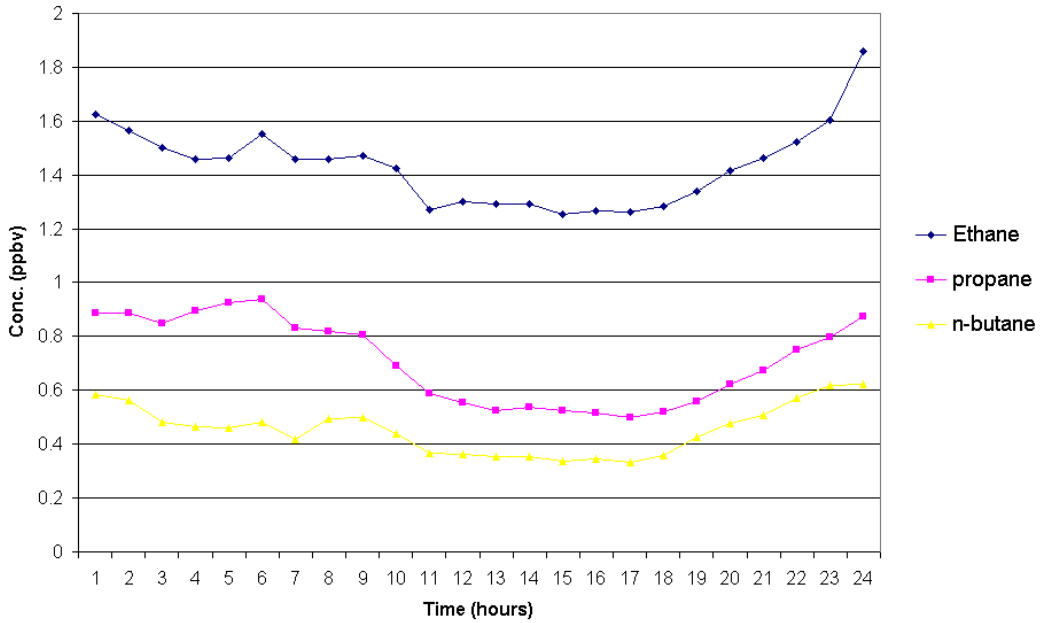


Figure C.13a): Average diurnal variation in the concentrations of three alkanes

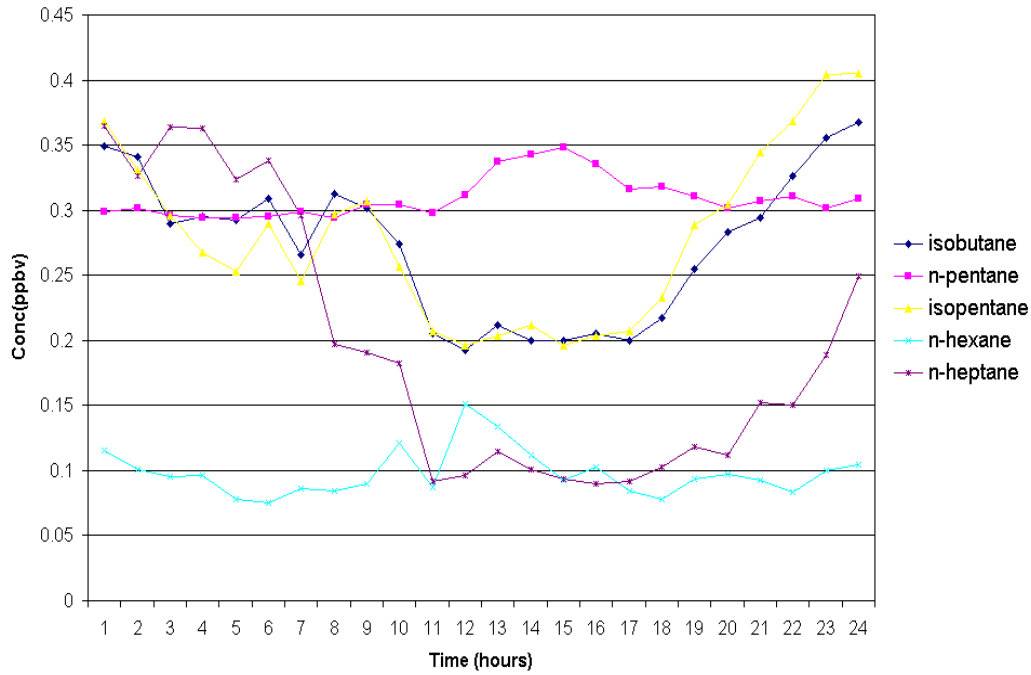


Figure C.13b): Average diurnal variation in the concentrations of five alkanes

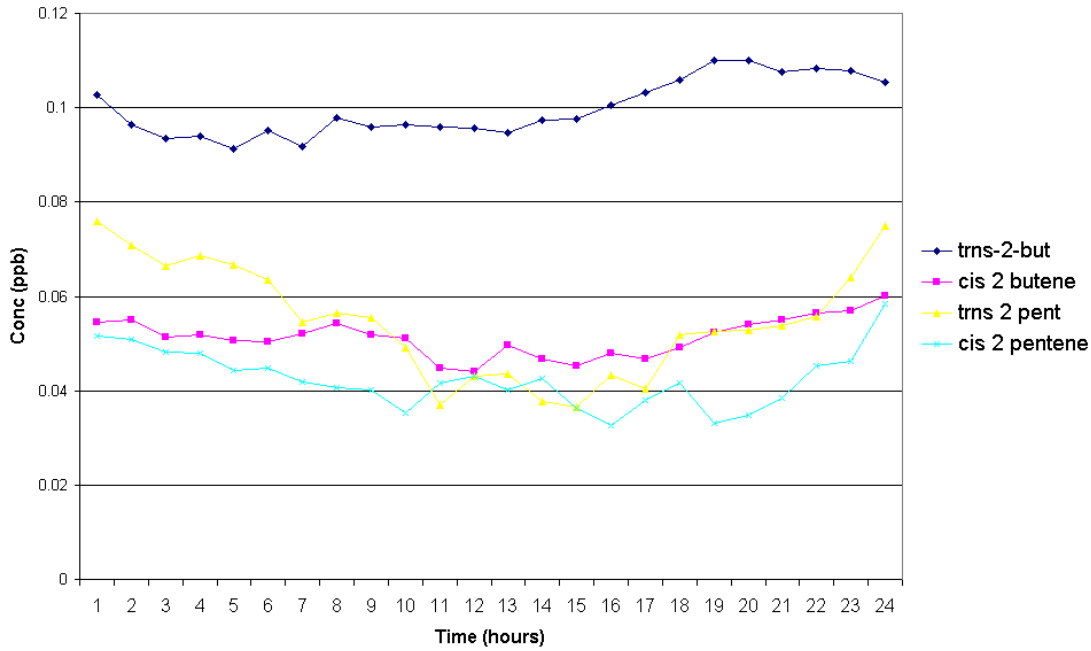


Figure C.14a): Average diurnal variation in the concentrations of four olefins

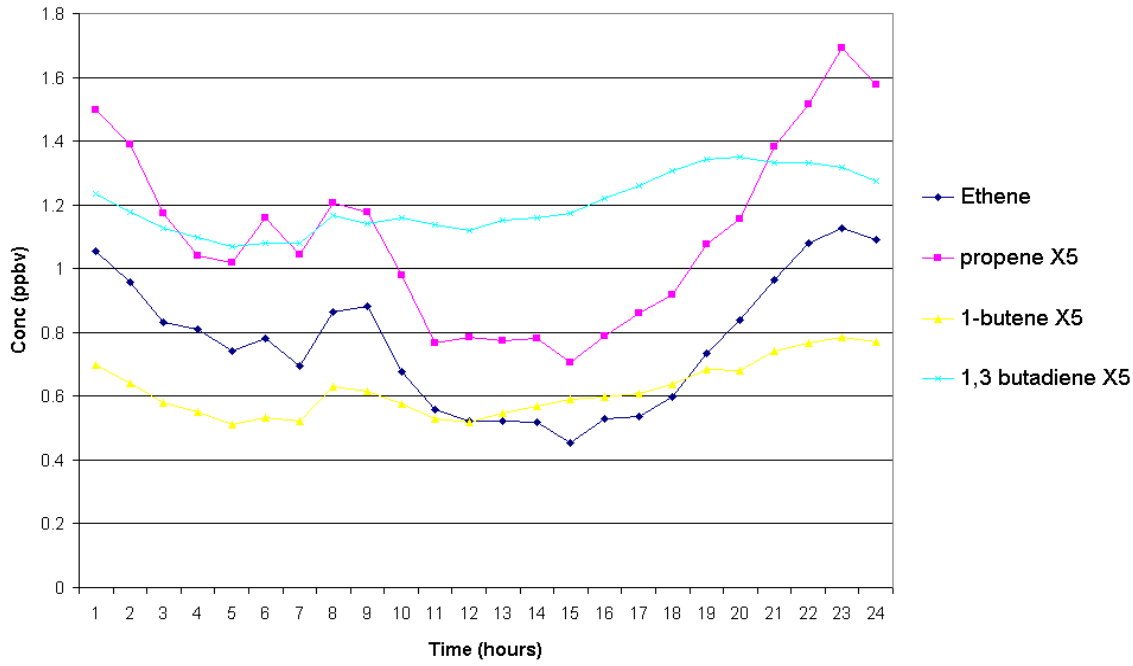


Figure C.14b): Average diurnal variation in the concentrations of four olefins

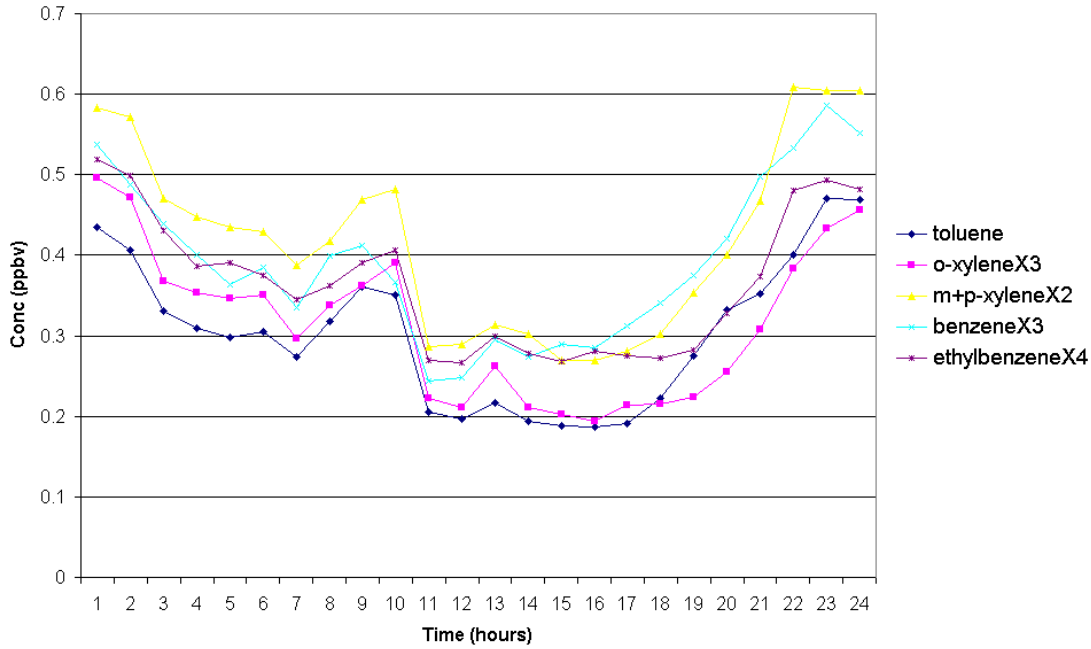


Figure C.15: Average diurnal variation in the concentrations of all five aromatics

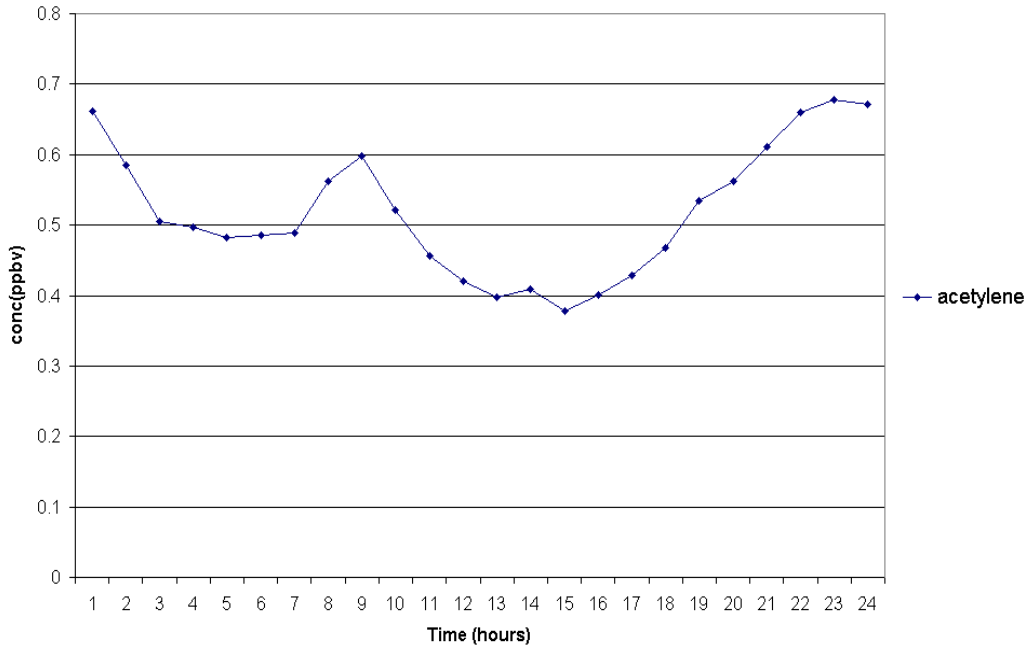


Figure C.16: Average diurnal variation in the concentration of acetylene

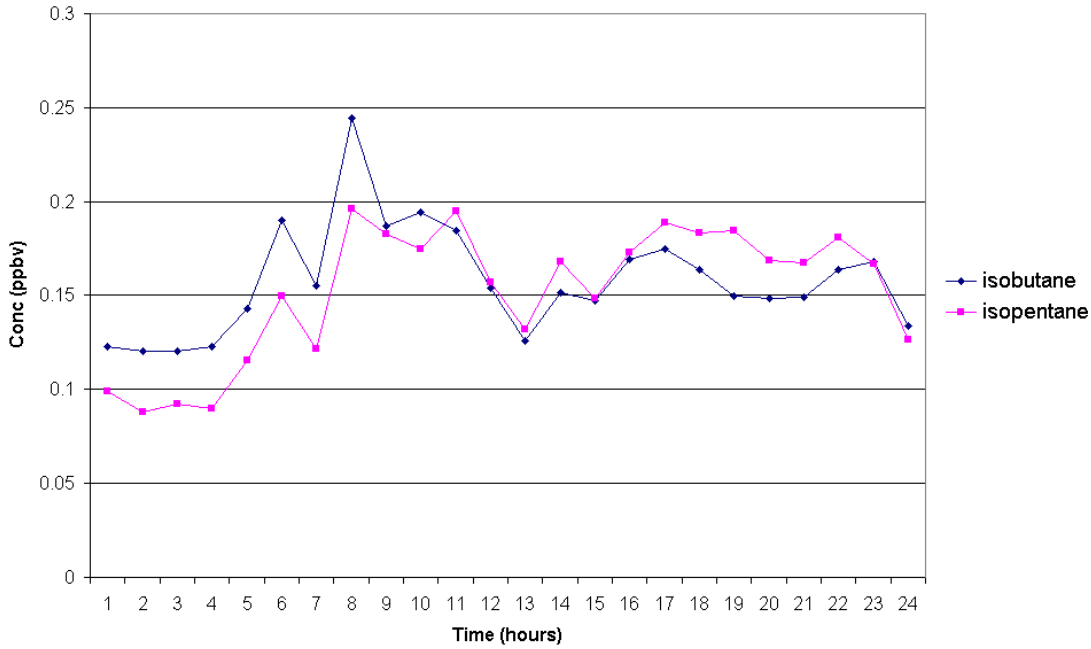


Figure C.17: Average diurnal variation in the concentrations of two alkanes (wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D)

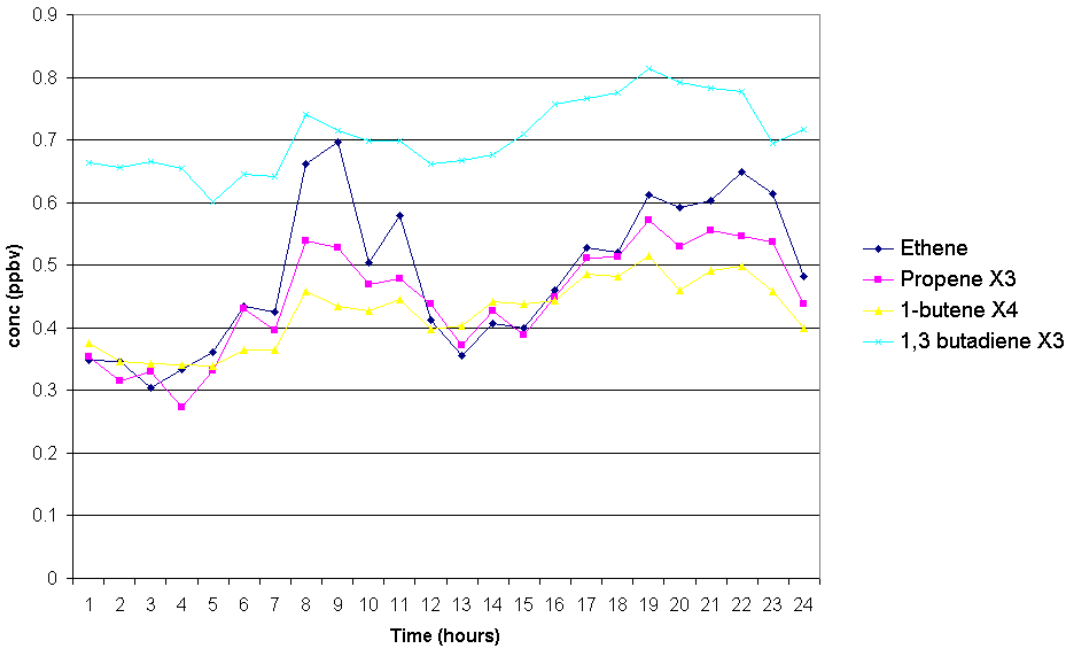


Figure C.18: Average diurnal variation in the concentrations of four olefins (wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D)

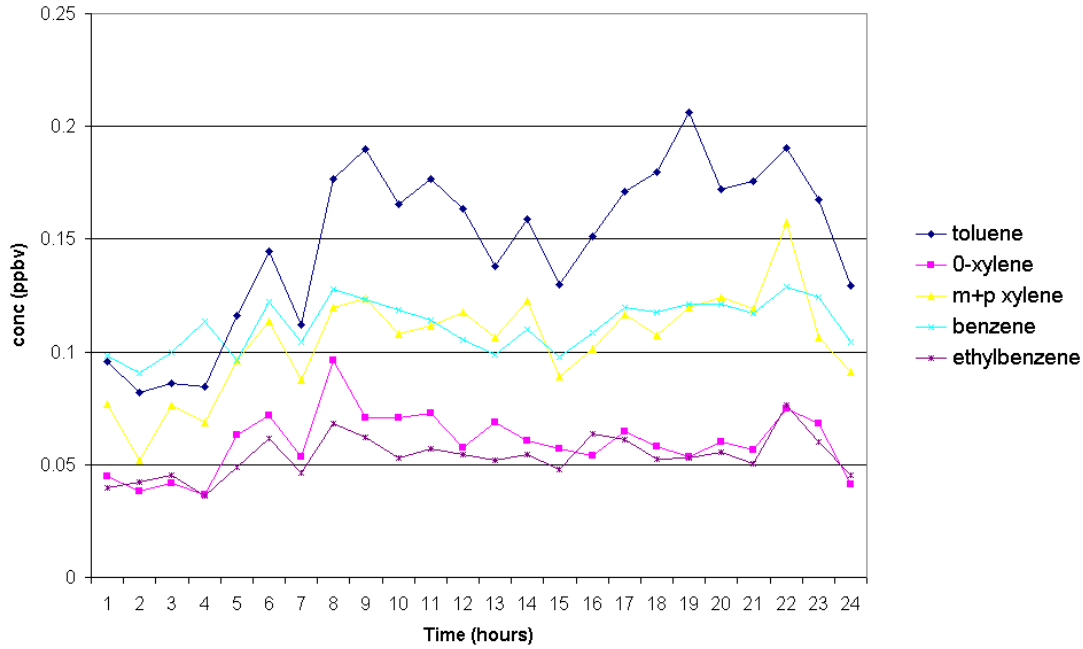


Figure C.19: Average diurnal variation in the concentrations of five aromatics (wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D)

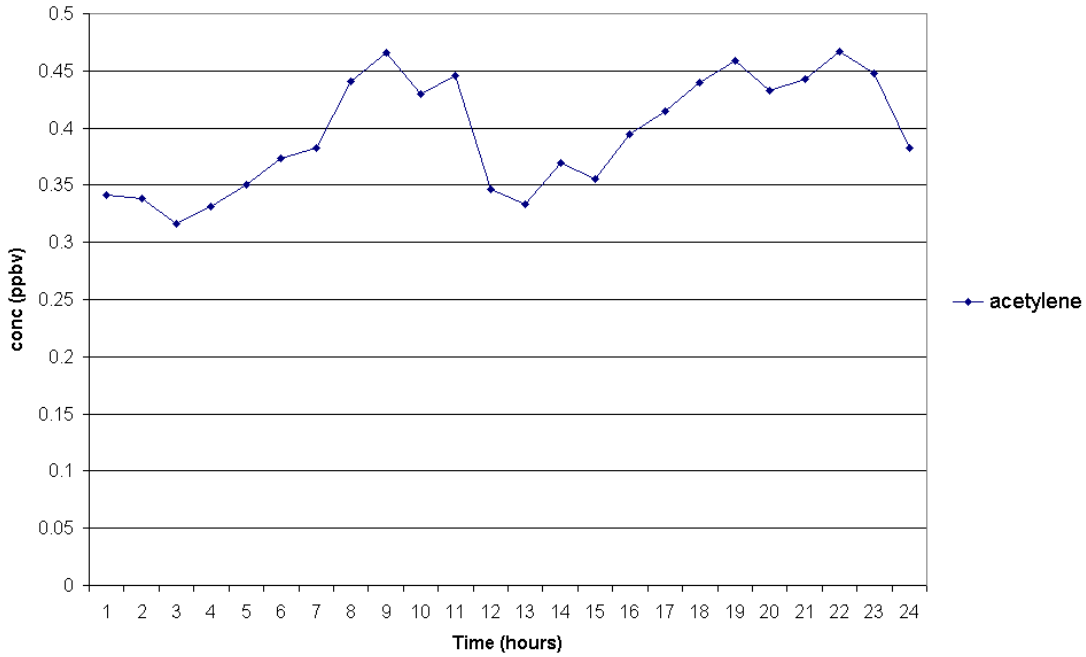


Figure C.20: Average diurnal variation in the concentrations of acetylene (wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D)

C.6.2 Variation of hydrocarbon concentrations with wind direction

Figures C.21a) and b) present pollution roses for one compound in each class. In Figure C.21a) the highest concentrations are observed with winds from the NE, and not from the road. This occurs because winds from the NE were rare, and were associated with low wind speeds, the effect of which is illustrated in Figure C.21b) which plots the product of the mean concentration and mean wind speed for each direction.

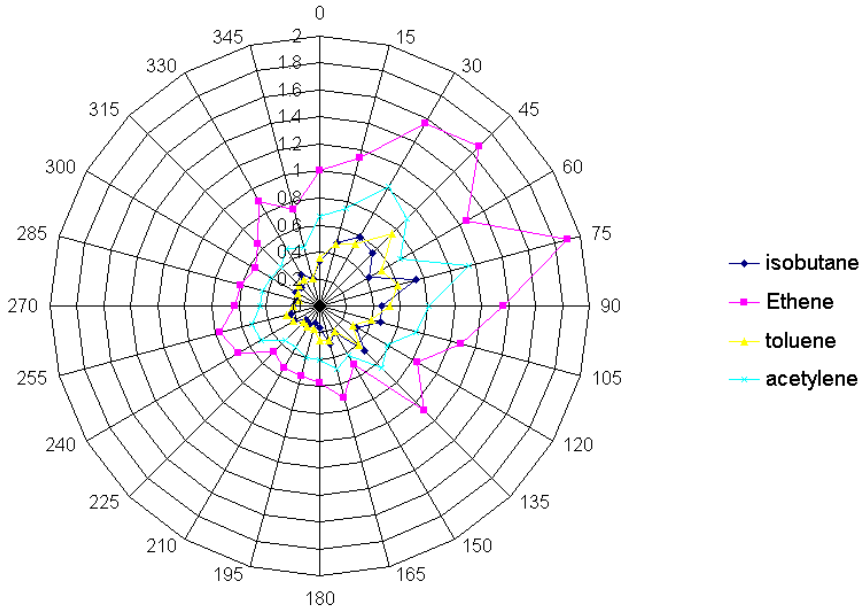


Figure C.21a): Pollution roses for one compound in each class

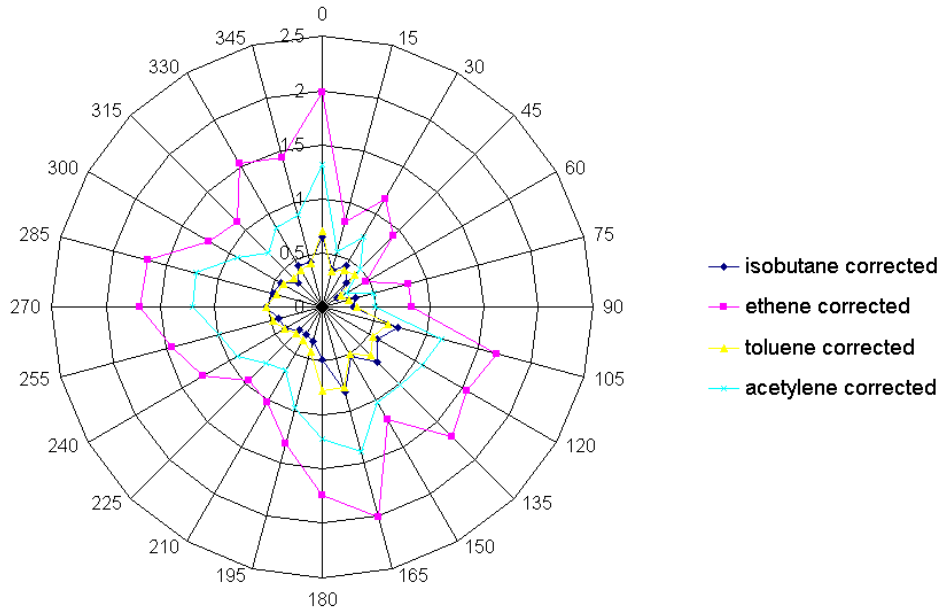


Figure C.21b): Pollution roses adjusted for mean wind speed

C.6.3 Variation of hydrocarbon concentrations with wind speed

Figures C.22 – C.25 show the dependence on wind speed of the concentrations of one compound in each class.

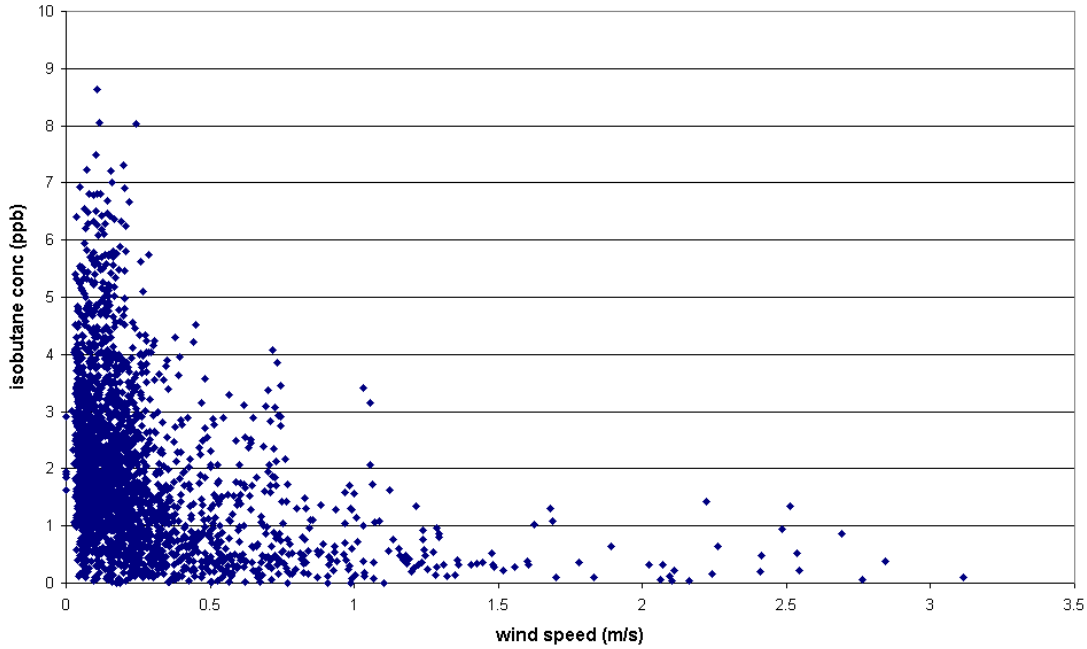


Figure C.22: Variation of iso-butane concentration with wind speed

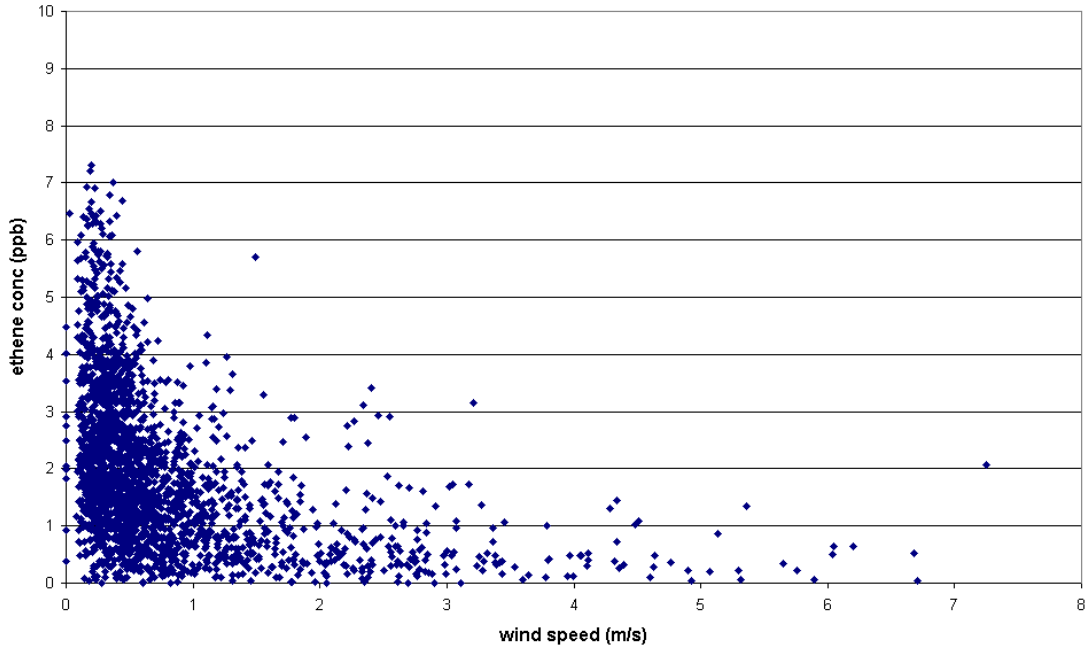


Figure C.23: Variation of ethene concentration with wind speed

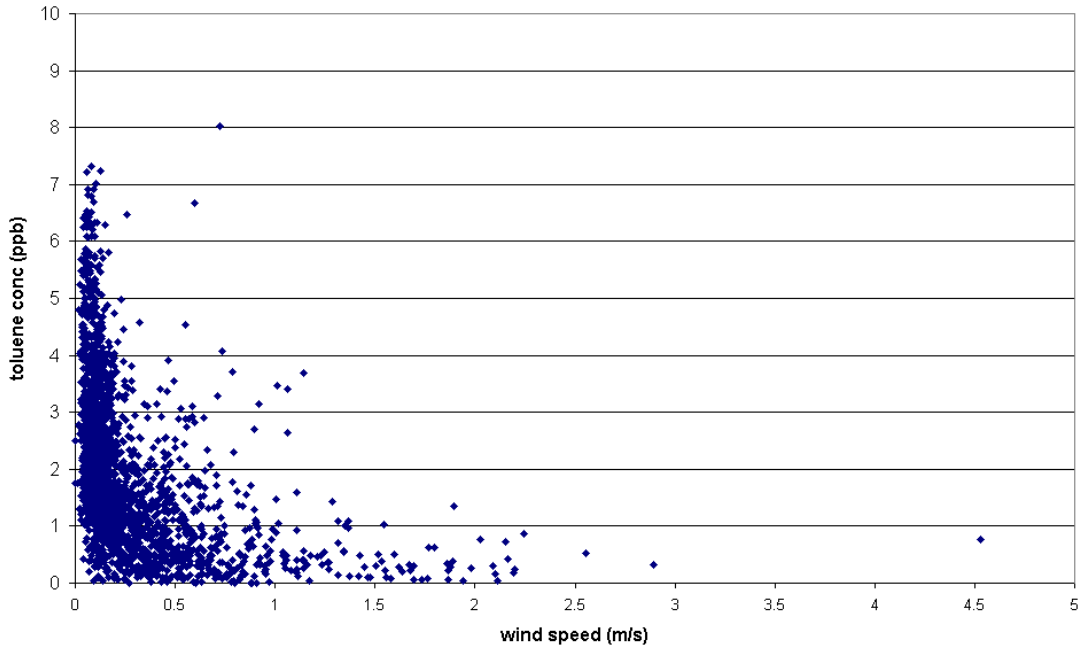


Figure C.24: Variation of toluene concentration with wind speed

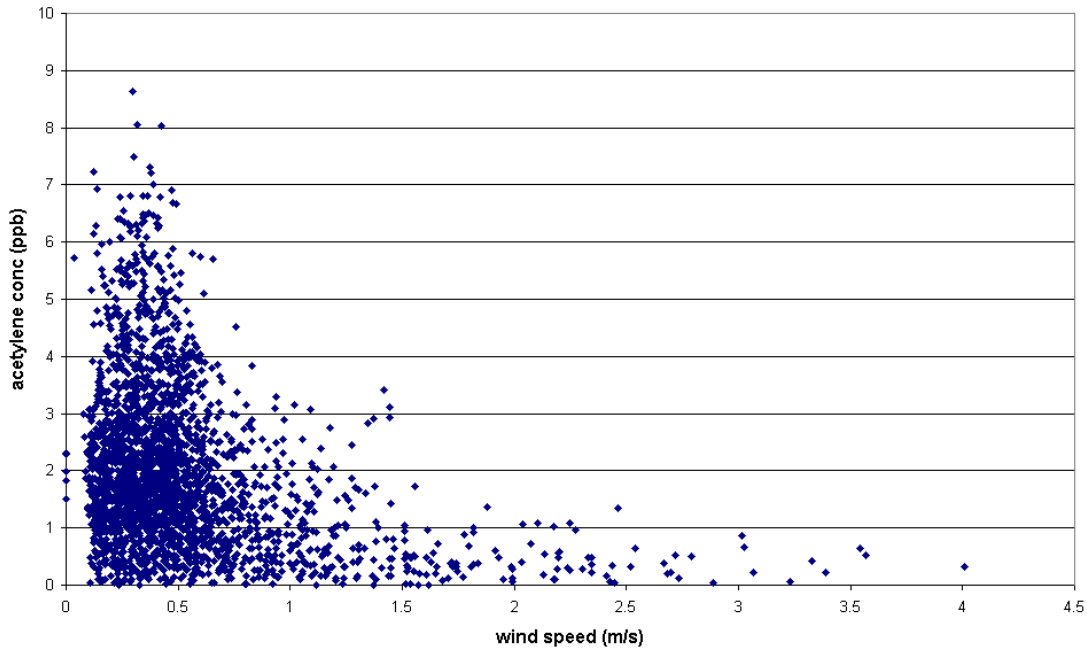


Figure C.25: Variation of acetylene concentration with wind speed

C.7 CALINE4 Modelling of Hydrocarbon Concentrations

COPERT III presents speed-dependent emission functions for total VOC emissions by vehicle and fuel type. It also presents data on the percentage contribution of individual hydrocarbons to the total VOC emission rate. These data allow composite emission factors (CEFs) for the M4 motorway to be determined for most of the individual hydrocarbons monitored there.

If it is assumed that the hydrocarbons are unaffected by chemical or physical transformations during their travel time from the road source to the sampling point, then CALINE4 results for CO (which is modelled as an inert pollutant) can be scaled to obtain model results for the individual hydrocarbons. This scaling needs to allow for the difference in emission rates (CEF_{CO}:CEF_{HC}) and relevant ppb to $\mu g/m^3$ conversions.

Background concentrations are identified, as for CO, as the minimum concentration on the average diurnal profile for each compound. A constant background is assumed.

For a selection of compounds, Figures C.26 – C.28 compare the resulting diurnal concentration profiles ('compound + bg') with measured values. For the two alkanes shown in Figure C.26, reasonable agreement can be observed, however, agreement is less good for the olefins and aromatics shown in Figures C.27 and C.28.

In Figures C.29 to C.31, the same comparison of measured and modelled data is made, except the filtered data set described in Section C.6.1 is employed. For the alkanes, the agreement observed in Figure C.26 has improved in Figure C.29. In Figures C.30 and C.31, the shape of the modelled profiles for the olefins and aromatics shown agrees more closely with the measured profiles (compared with Figures C.27 and C.28), but there the modelled concentrations overestimate the measured values by up to 200%.

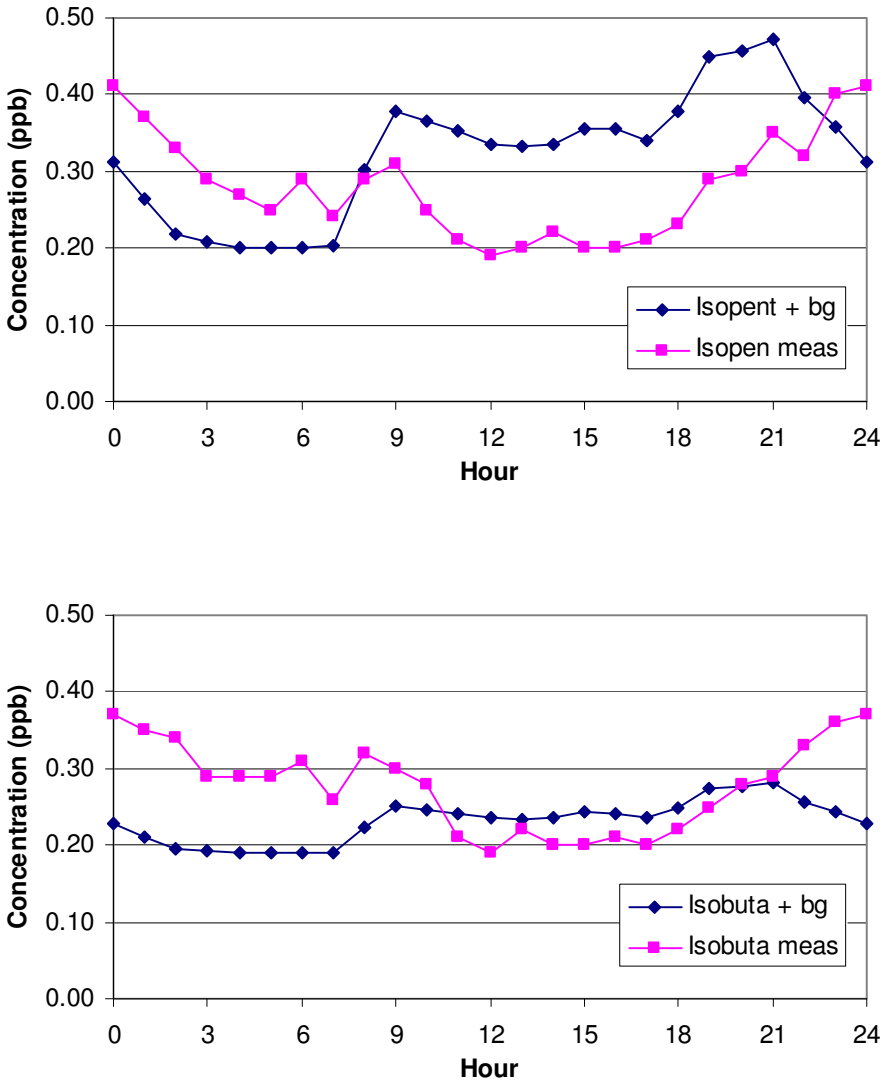


Figure C.26: Measured and modelled diurnal concentration profiles of two alkanes (isopentane and isobutane)

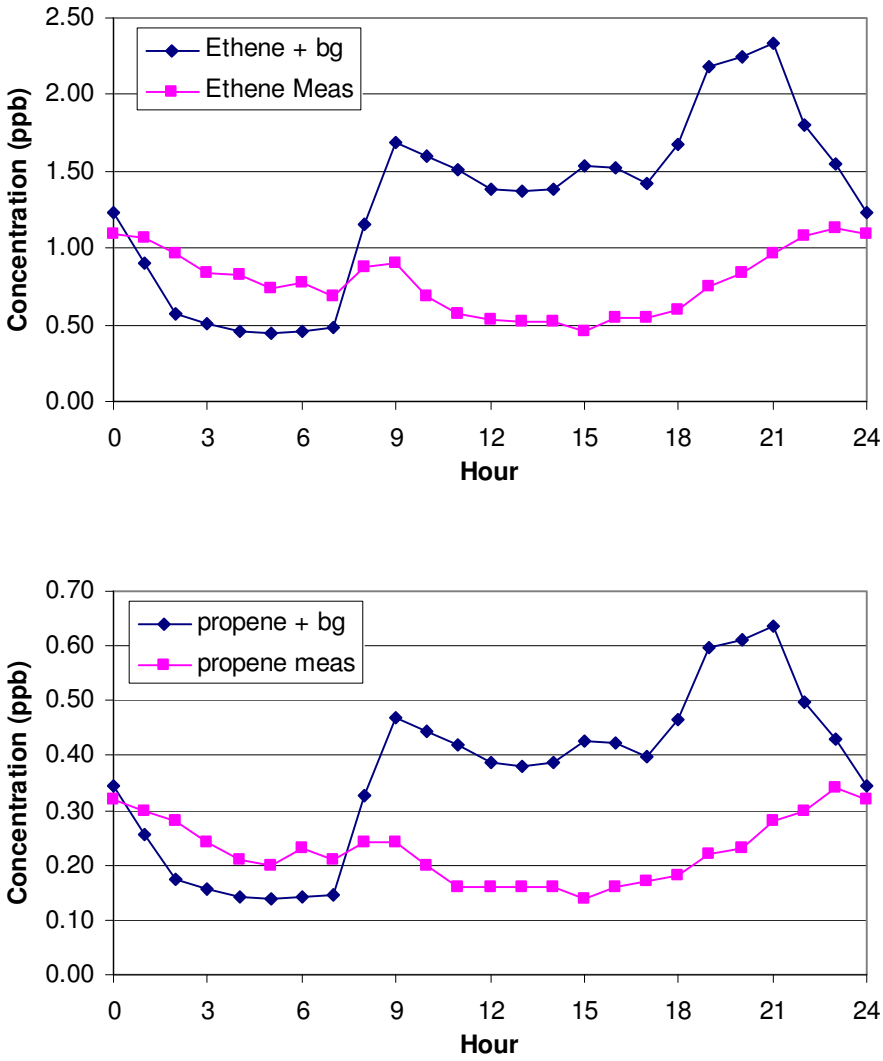


Figure C.27: Measured and modelled diurnal concentration profiles of two olefins (ethene and propene)

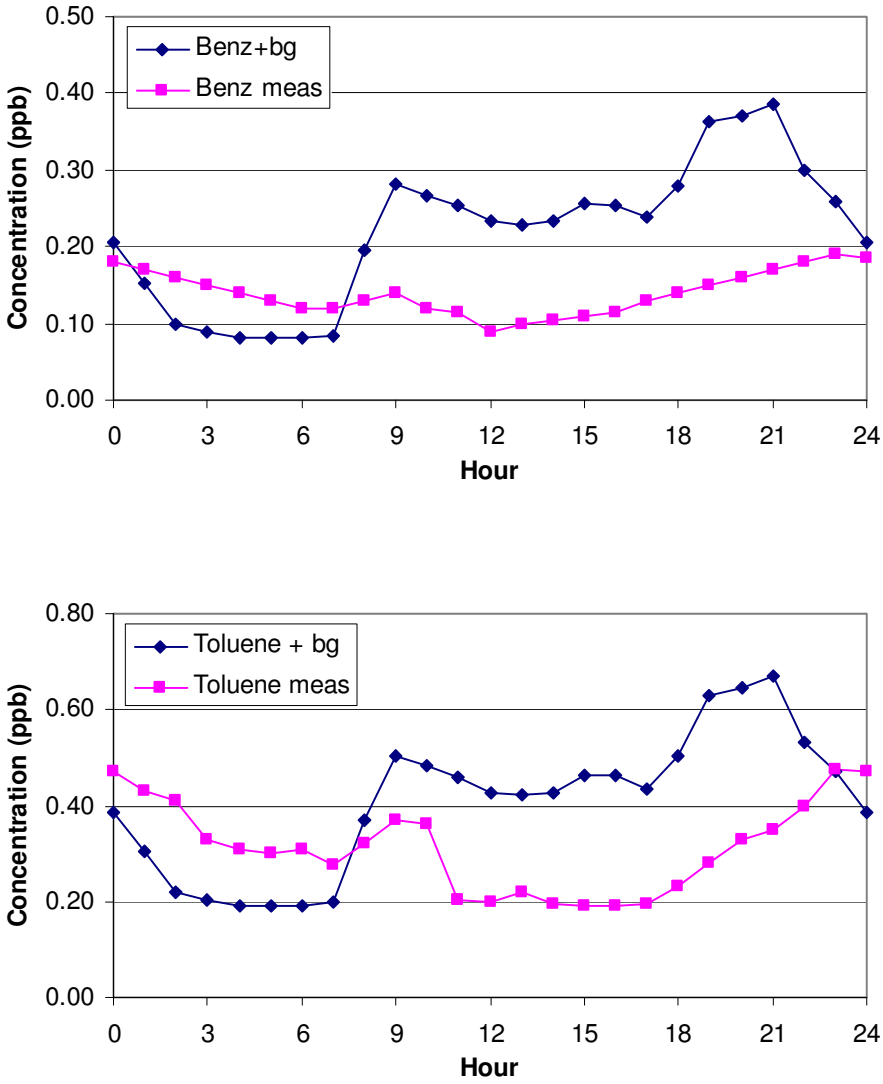


Figure C.28: Measured and modelled diurnal concentration profiles of two aromatics (benzene and toluene)

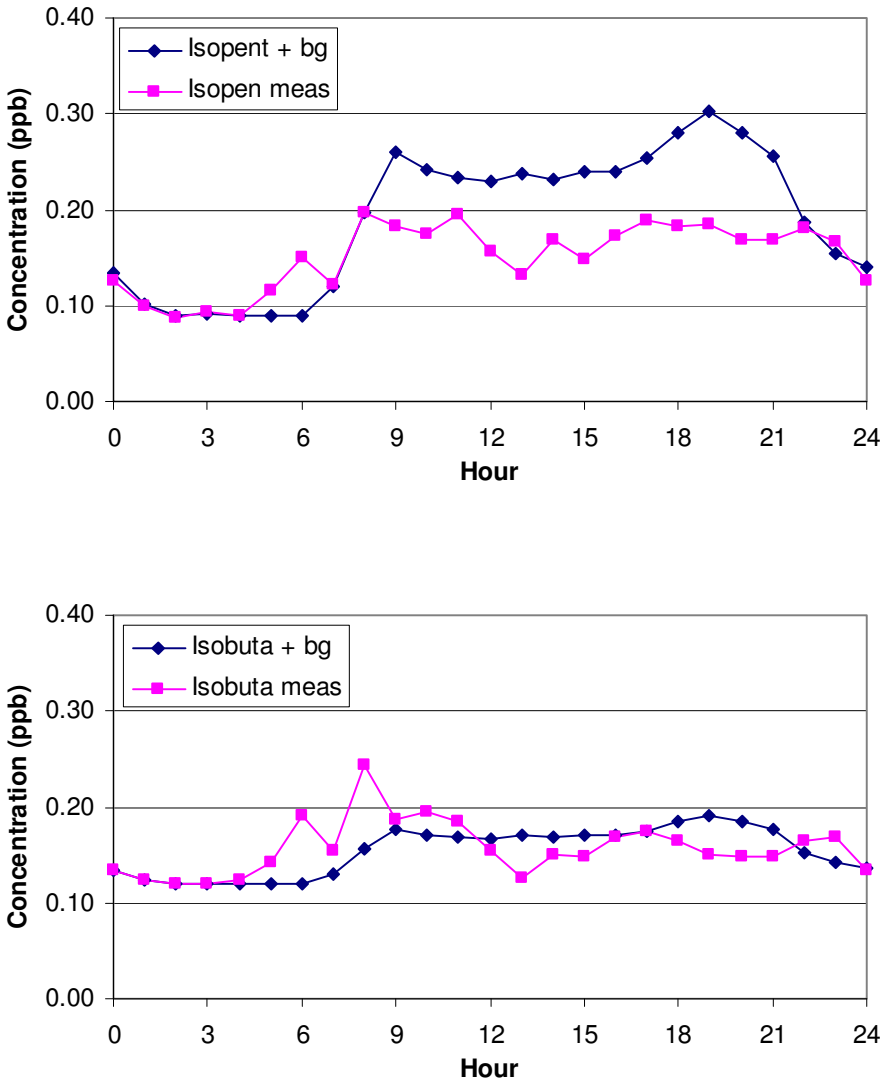


Figure C.29: Measured and modelled diurnal concentration profiles of two alkanes (isopentane and isobutane). Wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D.

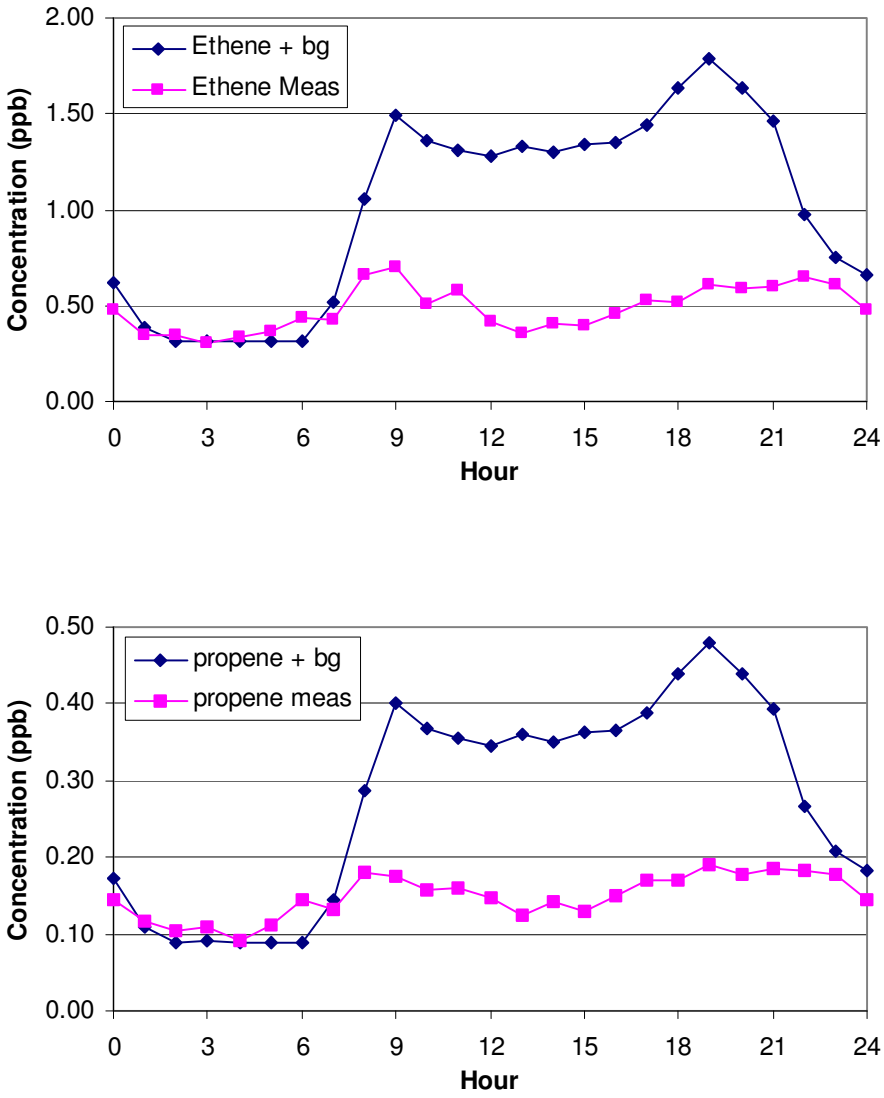


Figure C.30: Measured and modelled diurnal concentration profiles of two olefins (ethene and propene). Wind speed > 1 m/s, wind direction between 105° and 285°, stability class A to D.

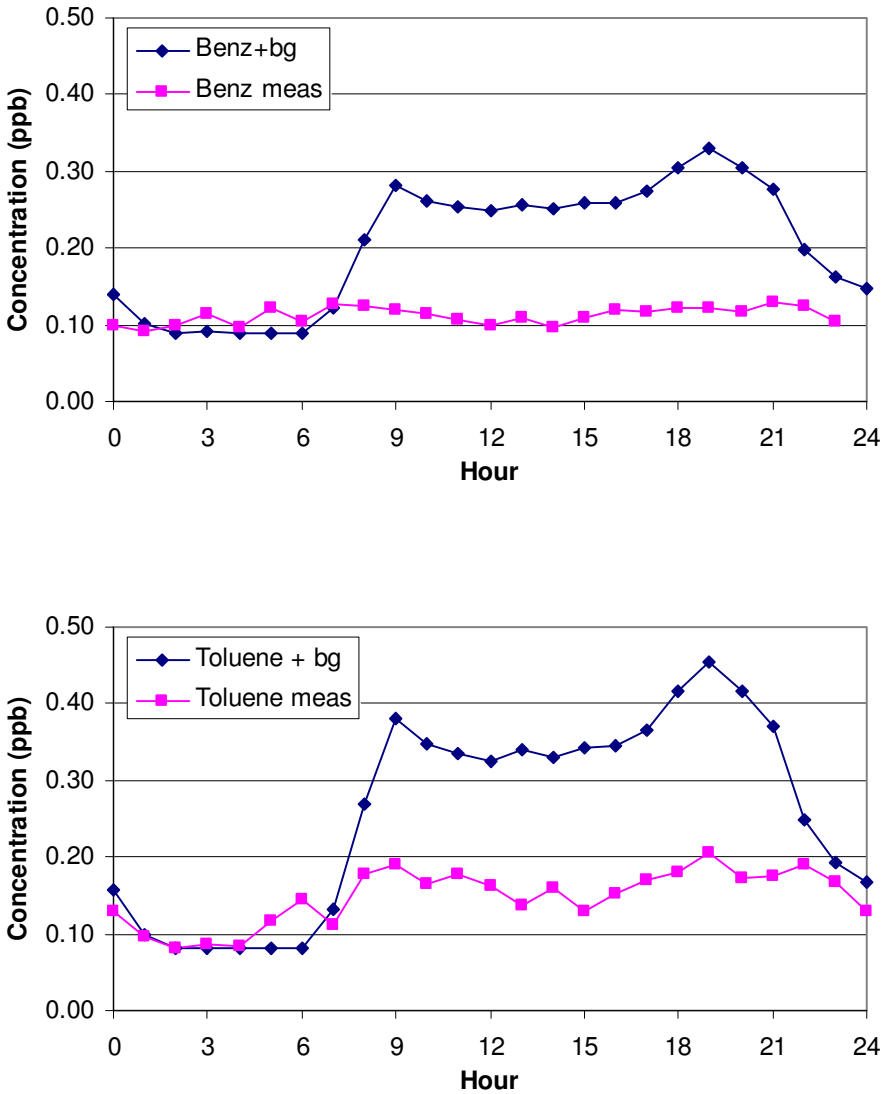


Figure C.31: Measured and modelled diurnal concentration profiles of two aromatics (benzene and toluene). Wind speed > 1 m/s, wind direction between 105 ° and 285 °, stability class A to D.

Appendix D

Appendix to Chapter 5: Dispersion Modelling

Table D.1: CALINE4 Input Data for CL4 interface – Motorway

	Parameter	**Options/units**
Job parameters	Job title	
	Run type	Standard
		Multi-run
		Worst-case wind angle
		Multi-run worst-case hybrid
	Aerodynamic roughness coefficient	Rural
		Suburban
		Central business district
		Other (cm)
	Model information	Link/receptor geometry units
		Altitude above sea level (m)
Link geometry	Link name	
	Link type	At-grade
		Depressed
		Fill
		Bridge
		Parking lot
	Endpoint 1 Coordinate X1	
	Endpoint 1 Coordinate Y1	
	Endpoint 2 Coordinate X2	
	Endpoint 2 Coordinate Y2	
	Link height	
	Mixing zone width	
	Canyon/bluff mix left	
	Canyon/bluff mix right	
Link activity	Link/run	
	Traffic volume (vph) Hour 1	
	Emission factor (g/mile) Hour 1	
Run conditions	Wind speed	(m/s)
	Wind direction	(degrees)
	Wind direction standard deviation	(degrees)
	Atmospheric stability class	(1-7)
	Mixing height	(m)
	Ambient temperature	(degrees C)
	Ambient pollutant concentration	(ppm)
Receptor conditions	Receptor name	
	X	
	Y	
	Z	

Table D.2: Input data for CL4 - motorway

3.i.2002 Hour	PSC	Wind direction	Wind speed	Temp.	Traffic
07:00	D	104.4	3.0	5.8	1055
08:00	D	102.2	3.0	5.5	1976
09:00	D	103.2	2.2	5.8	1931
10:00	C	104.3	2.4	6.5	1690
11:00	D	104.3	2.0	6.4	1554
12:00	D	103.5	0.8	7.8	1717
13:00	D	114.6	2.6	8.3	1844
14:00	D	101.7	1.0	7.9	1884
15:00	D	110.3	3.2	8.7	1884
16:00	D	120.3	2.3	8.5	2081
17:00	D	110.5	4.0	8.4	2472
18:00	E	12.7	0.7	6.8	2512
19:00	D	104.5	0.8	7.3	2354
20:00	D	106.8	2.2	7.1	2004
21:00	D	113.7	4.1	6.9	1282
22:00	D	103.9	1.7	6.5	951

Table D.3a): DMRB results – roundabout for 2002

2002	**CO** (mg/m^3)	**Benzene** ($\mu g/m^3$)	**NO_x** ($\mu g/m^3$)	**PM_{10}** ($\mu g/m^3$)
Contribution from all roads	1.68	10.27	691.81	27.92
Background contribution	0.21	0.40	11.73	12.90
Total annual mean (incl. background)	1.89	10.67	703.54	40.82
Maximum 8-hr mean	18.88	*	*	*
Maximum running annual mean	*	11.74	*	*
Annual mean NO_2	*	*	181.27	*
90^{th}%ile of daily means	*	*	*	73.06

Table D.3b): DMRB results – roundabout for 2003

2003	**CO** (mg/m^3)	**Benzene** ($\mu g/m^3$)	**NO_x** ($\mu g/m^3$)	**PM_{10}** ($\mu g/m^3$)
Contribution from all roads	1.50	8.68	629.03	24.43
Background contribution	0.21	0.40	11.73	12.90
Total annual mean (incl. background)	1.71	9.08	640.76	37.33
Maximum 8-hr mean	17.13	*	*	*
Maximum running annual mean	*	9.99	*	*
Annual mean NO_2	*	*	169.79	*
90^{th}%ile of daily means	*	*	*	66.82

Table D.4: Input data for CL4 - roundabout

3.i.2002 Hour	PSC	Wind direction	Wind speed	Temp.	Traffic (total)
07:00	D	111	2.42	5.8	2403
08:00	D	111	3.20	5.5	4202
09:00	D	113	3.50	5.8	7010
10:00	C	117	2.04	6.5	6894
11:00	D	113	1.82	6.4	5556

12:00	D	128	1.44	7.8	5994
13:00	D	130	1.43	8.3	6438
14:00	D	120	3.27	7.9	6852
15:00	D	119	3.49	8.7	6890
16:00	D	129	2.39	8.5	6758
17:00	D	153	1.60	8.4	7522
18:00	E	143	1.56	6.8	7824

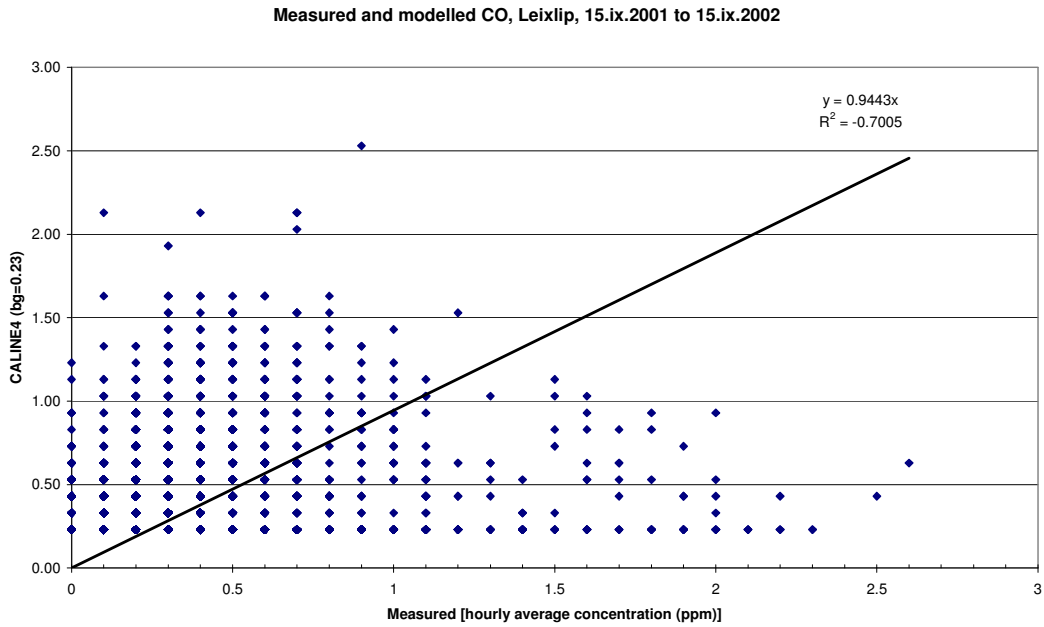


Figure D.1: Scatter Plot CO

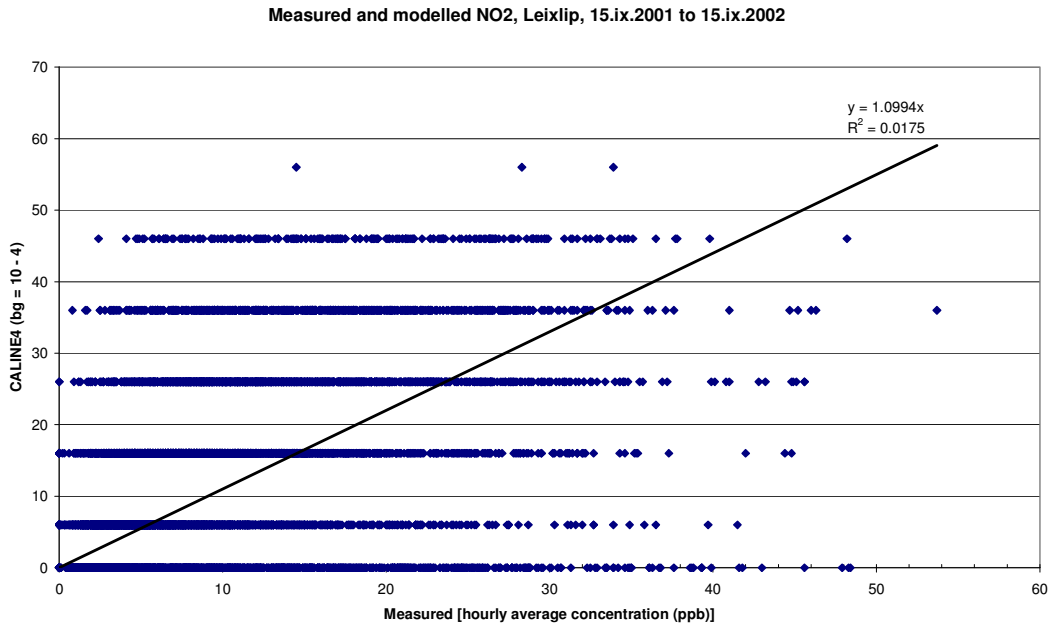


Figure D.2: Scatter Plot NO_2

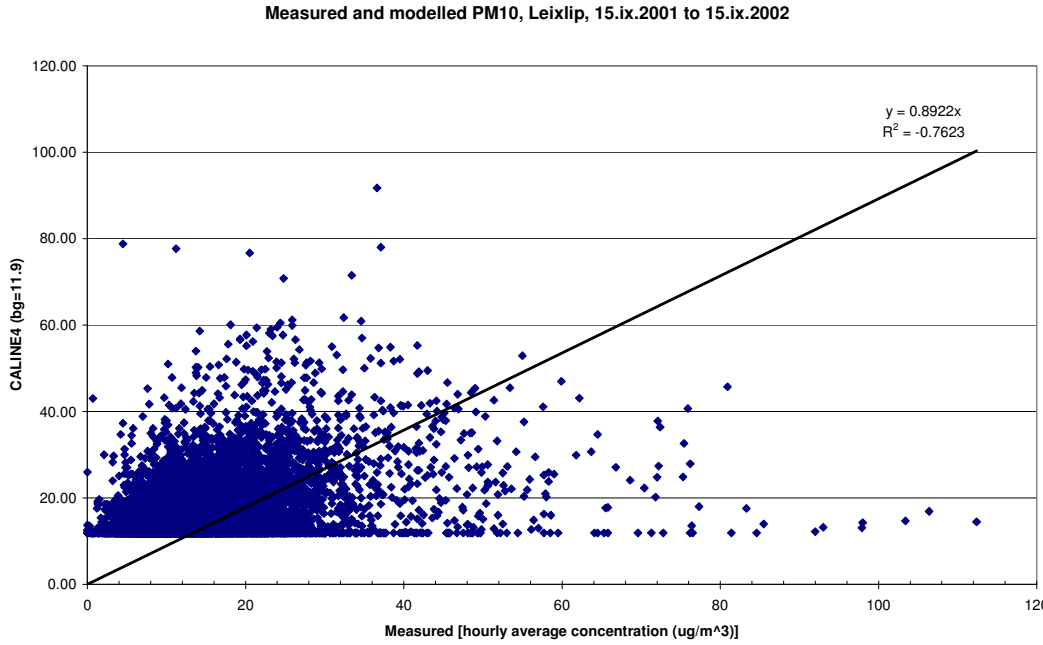


Figure D.3: Scatter Plot PM_{10}

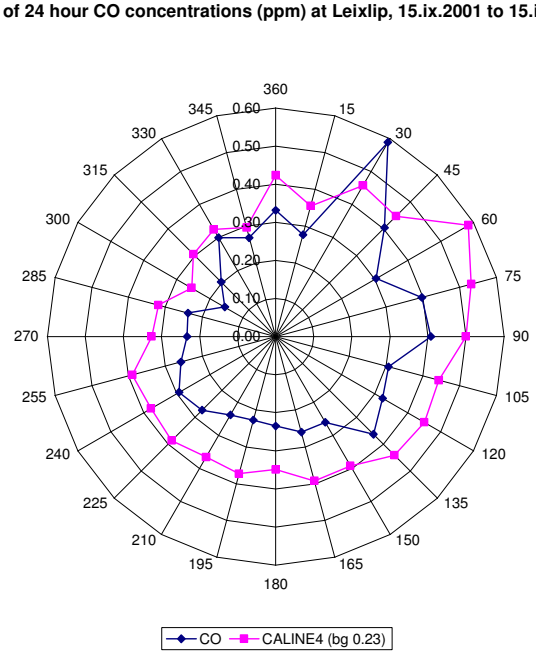


Figure D.4: Measured and modelled CO pollution roses

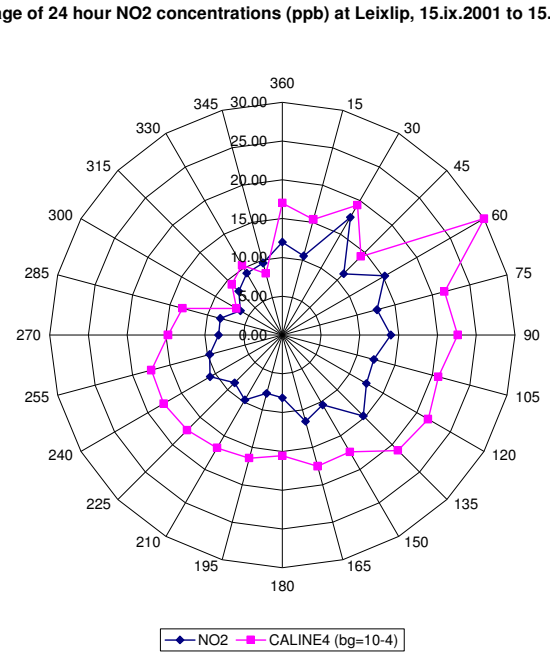


Figure D.5: Measured and modelled NO_2 pollution roses

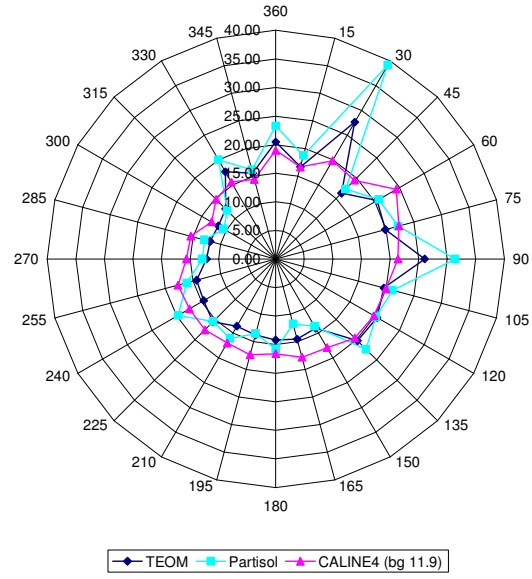


Figure D.6: Measured and modelled PM_{10} pollution roses