Environmental RTDI Programme 2000–2006

AIR POLLUTION – Analysis of Air Dispersion Models for Irish Road Conditions

(2000-LS-6.3-M1)

Synthesis Report

(Main Report available for download on www.epa.ie/EnvironmentalResearch/ReportsOutputs)

Prepared for the Environmental Protection Agency

by

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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 (NUI, Galway). The project leader was Bruce Misstear (TCD) assisted by Dr Brian Broderick (TCD) and Prof. Gerard Jennings (NUI, Galway). The monitoring at the Leixlip and Galway sites was overseen by Una Budd (TCD) and Darius Ceburnis (NUI, Galway), 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 (NUI, Galway). The project co-ordinator for the Agency was Dr Frank McGovern.

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1 Introduction

1.1 Background

Ambient air quality measurements in Ireland are largely determined on the basis of the European Union framework directive on ambient air quality assessment and management (Council of the European Union (CEC), 1996; McGettigan, 2001). The directive and its daughter directives (CEC, 1999, 2000) 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, with modelling on its own being deemed sufficient when ambient concentrations fall below the lower assessment threshold level.

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 slow reaction 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.

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 emissions to air from road transport sources and to predict their impacts and dispersion patterns. The specific objectives 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, 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 roadside measurements of air quality, meteorological conditions and traffic flow data;
- make recommendations on the future use of these models in Irish conditions, with particular emphasis on national primary routes.

This project was part of the large-scale integrated project entitled *Air Quality – Transport Impacts and Monitoring Networks*.

1.3 Monitoring Studies

The air quality monitoring studies were carried out at two sites to represent two contrasting situations, one with free-flowing traffic and the second with interrupted traffic flow (Section 2). The main monitoring period was from September 2001 to September 2002. The air pollutants monitored at both sites were carbon monoxide, nitrogen oxides and particulates (Sections 3 and 4). Hydrocarbons associated with vehicle emissions were also measured at one of the sites (Section 3). Meteorological variables such as wind speed and wind direction were recorded at the two sites, and traffic flow data were also collected.

1.4 Dispersion Modelling and Model Validation

The models used for the atmospheric dispersion modelling at the two locations were the UK Department of the Environment, Transport and the Regions (UK DETR) *Design Manual for Roads and Bridges* (DMRB) model (DMRB, 1994, 2000) and the US Environmental Protection Agency (US EPA) model CALINE4 (US EPA www.epa.gov/scram001; Benson, 1992). The main characteristics of all of these models were examined and the effects of employing different emission factors or meteorological conditions were assessed by comparing the results of multiple model runs (Sections 5 and 6).

A model validation exercise was completed, involving the project partners and three consulting firms (AWN Consulting, Envirocon Ltd and Cambridge Environmental Consultants Ltd (CERC)). Each participant produced model predictions of air quality for the first 6 months of the monitoring period at both sites. These predictions were then compared with the measured data (Section 6.1).

1.5 Project Reports

The findings of the project are presented in three reports. The first is the Final Report and contains a full description of the research and the results obtained (Broderick *et al.*, 2004a); it includes an addendum on hydrocarbon modelling, produced as an additional project task (O'Donoghue *et al.*, 2004). The second report is a literature review (Broderick *et al.*, 2004b), which includes a review of air dispersion models and their use in Ireland and elsewhere, while the third report is this Synthesis Report. The Final Report and the Literature Review are both published electronically (www.epa.ie).

2 Description of Study Sites

The project objectives (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 1.3, 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 specific site selection criteria are described in Section 2.1 of the Final Report.

2.1 The M4 Motorway Site at Leixlip

A suitable location to monitor free-flowing traffic was identified along the M4 motorway about 15 km west of Dublin city centre, within the grounds of the Leixlip Water Treatment Works (Figs 2.1 and 2.2). Continuous traffic flow data were available from the National Roads Authority (NRA) for this route.

The M4 motorway at Leixlip has two lanes in each direction, running almost due east–west. The peak traffic flow for an average weekday is 2690 vehicles per hour (vph; Section 3.2). The prevailing wind direction measured at Dublin Airport (18 km north-east of the site) is from the south-west, and therefore emissions from the roadway were expected to influence concentrations at the monitoring unit which was sited to the north of the motorway, 20 m from the nearest kerbside (Fig. 2.1). The

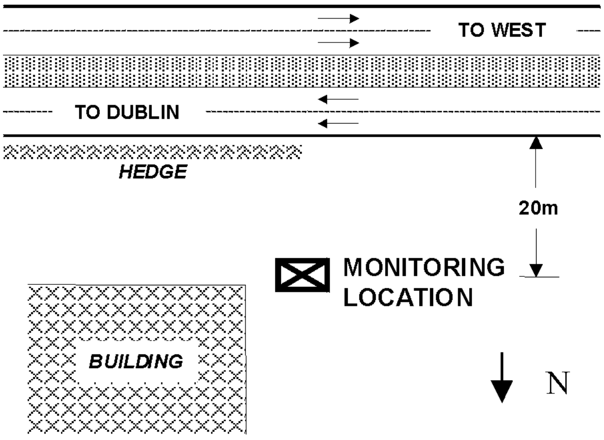

Figure 2.1. Location of monitoring unit beside the M4 at Leixlip.

Figure 2.2. Leixlip site (view east–south-east).

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 95–110 kph. A potential problem with the site was the presence of a large building north-east of the monitoring unit (Fig. 2.2); however, as this was not the direction of the prevailing wind, nor of the main pollution source, it was not considered a major drawback to the site.

2.2 The N6 Roundabout Site in Galway

The second monitoring site was chosen alongside the N6 in Galway, adjacent to a major roundabout (Figs 2.3 and 2.4). Continuous traffic flow data were not available for this site and therefore some data were collected during the project. The roundabout is the second busiest roundabout in Galway City, with the total number of cars peaking at 3900 vph (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–north-east and the N6 road towards Galway City Centre to the south–south-west. Both N6 arms are dual carriageways. The monitoring unit was located 15 m from the southern kerb of the Dublin Road arm, about 25 m from the roundabout.

These two sites presented different modelling challenges. The M4 motorway represented a classical modelling situation – a single line source with simple, 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.

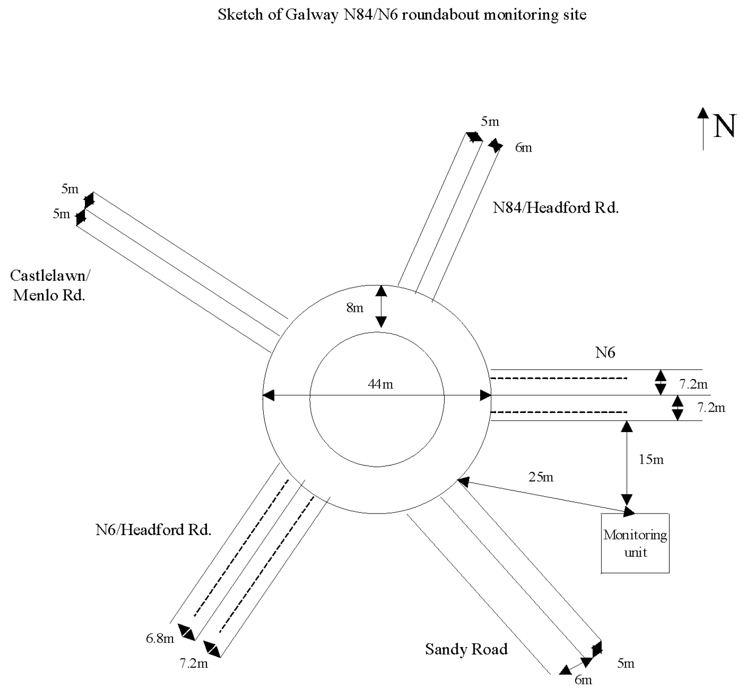

Figure 2.3. Galway roundabout site, showing the junction layout.

Figure 2.4. Galway roundabout (view south-east from Menlo Road direction).

3 Monitoring Results for the M4 at Leixlip

3.1 Air Pollutants Monitored

The contaminants monitored at the M4 monitoring site included carbon monoxide (CO), nitrogen oxides (NO_x, NO and NO_2), particulates (PM_{10}) and selected hydrocarbons. The analysis methods, monitoring periods and sampling intervals are shown in Table 3.1. Further details of instruments, calibration standards and data capture are included in Section 3.1 of the Final Report.

3.2 Traffic Flows

Traffic flow data for the M4 are shown in Fig. 3.1, which compares the average diurnal variation in total flow on weekdays and at weekends. On weekdays, peak flows of approximately 2400 vph were observed between 08:00 and 09:00 h, and approximately 2700 vph between 18:00 and 19:00 h, whereas weekend peak flows averaged 2000 to 2300 vph from 12:00 to 20:00 h. Data for heavy goods vehicles (HGV) showed that HGV flow during weekdays was typically about 10% of total traffic flow, reaching a maximum of 28% between 04:00 and 05:00 h, which corresponds to the hours of lowest total traffic.

3.3 Meteorology

Wind speed, wind direction, temperature and relative humidity were recorded continuously at the monitoring

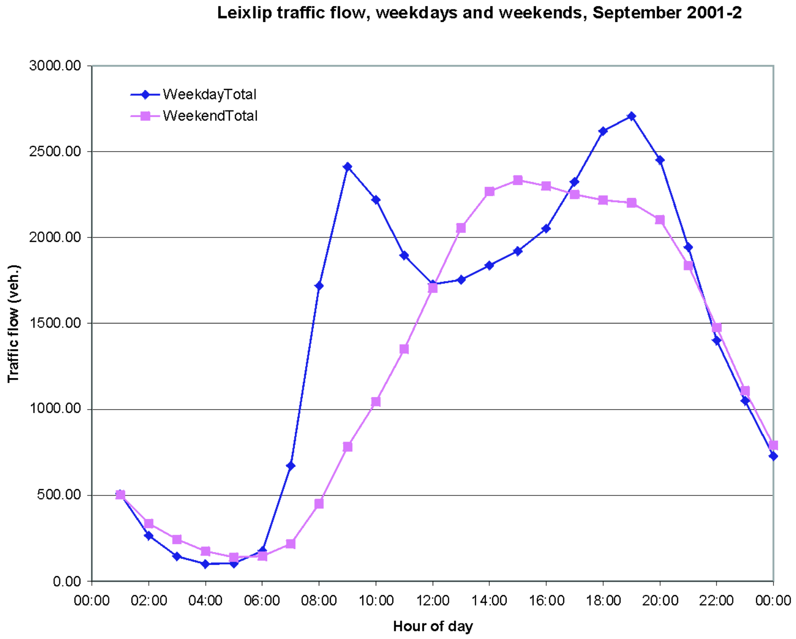

Figure 3.1. Average diurnal variation in total traffic flow on the M4, Leixlip.

Table 3.1. Air pollutants monitored at the M4 site.

Pollutant	Method	Monitoring period	Sampling interval
CO	Infrared absorption	May 01–September 02	15-min & 1-h averages
NO_x, NO, NO_2 **2nd NO_x analyser**	Chemiluminescence	May 01–September 02 March–September 02	15-min & 1-h averages
PM_{10}	Oscillation frequency	June 01–September 02	30-min average
PM_{10}	Gravimetric	June 01–September 02	24 h
Hydrocarbons	Gas chromatography, flame ionisation	February 02–September 02	1-h average

site. Sensors were located 6 m above ground level on a mast extending above the monitoring unit. Data were recorded at 15-min intervals, and these were combined to give hourly values. Wind speed and direction at an altitude of 10 m were measured by Met Éireann at Casement Aerodrome, located approximately 6 km to the south–south-east of the monitoring site. Hourly data on atmospheric stability and cloud cover were also available from Casement Aerodrome.

Figure 3.2 compares the wind direction frequency observed at the monitoring site with that observed at Casement Aerodrome. The prevailing winds are from the south-west in both cases. The wind shadow effect caused by the building to the north-east of the monitoring unit (Fig. 2.1) can be seen, although the Met Éireann data also show few winds from between 300° and 60°. The highest wind speeds at the M4 site occur when winds are from the south and south–south-east.

Figure 3.3 shows the relative frequency of stable atmospheric conditions (i.e. Pasquill stability class E, F or G) associated with different wind directions. Stable conditions occurred with winds from the north-east and east, and most often at night.

3.4 Air Pollutant Concentrations

Table 3.2 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 to September 2002.

Figure 3.4 shows the variation in the 24-h average concentration of one of the pollutants, CO, over the entire monitoring period. Peaks in CO concentration were observed during December 2001 and early January 2002, and also towards the end of March 2002. Broadly similar patterns are shown by the data for NO and PM_{10}.

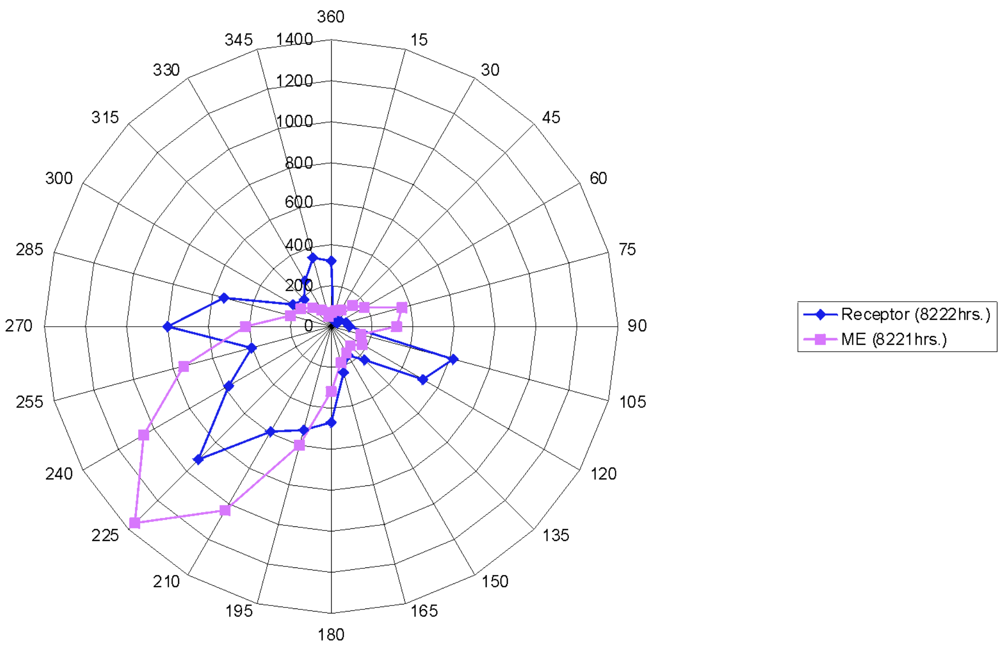

Figure 3.2. Wind direction frequency measured at the M4 monitoring site (Receptor) and by Met Éireann (ME) at Casement Aerodrome.

Table 3.2. Pollutant statistics (ppm CO; ppb NO_2, NO and NO_x; µg/m^3 PM_{10}).

	CO	NO_2	NO	NO_x	PM_{10}-TEOM	PM_{10}-Partisol
Mean	0.27	9.9	10.7	20.4	15.5	16.8
Maximum	1.18	29.16	122.80	149.19	47.27	92.50
5th percentile	0.12	3.77	1.10	5.42	8.09	4.58
95th percentile	0.57	19.50	27.90	46.23	29.20	39.50

TEOM, Tapered Element Oscillating Microbalance.

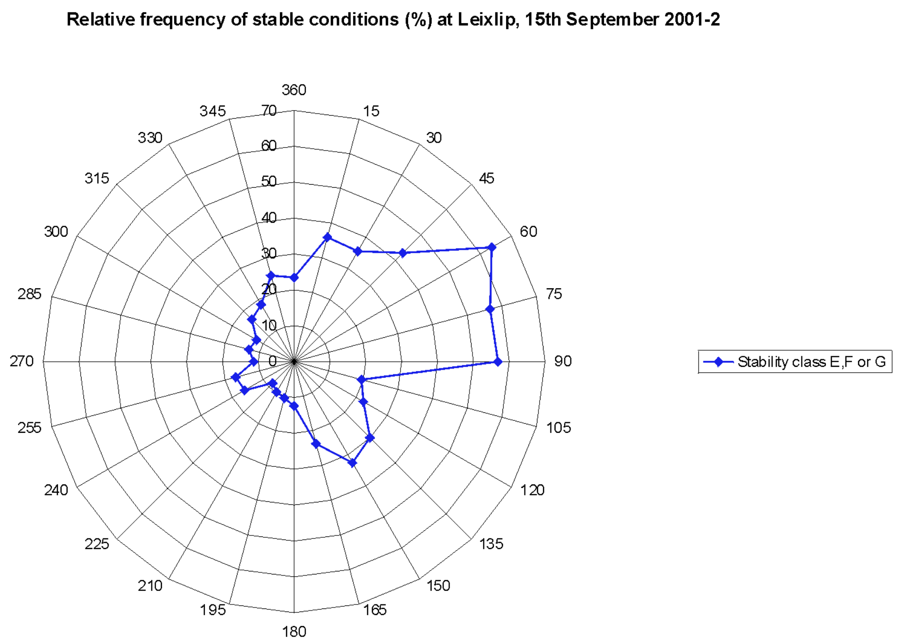

Figure 3.3. Relative frequency of stable atmospheric conditions for different wind directions at the M4 site.

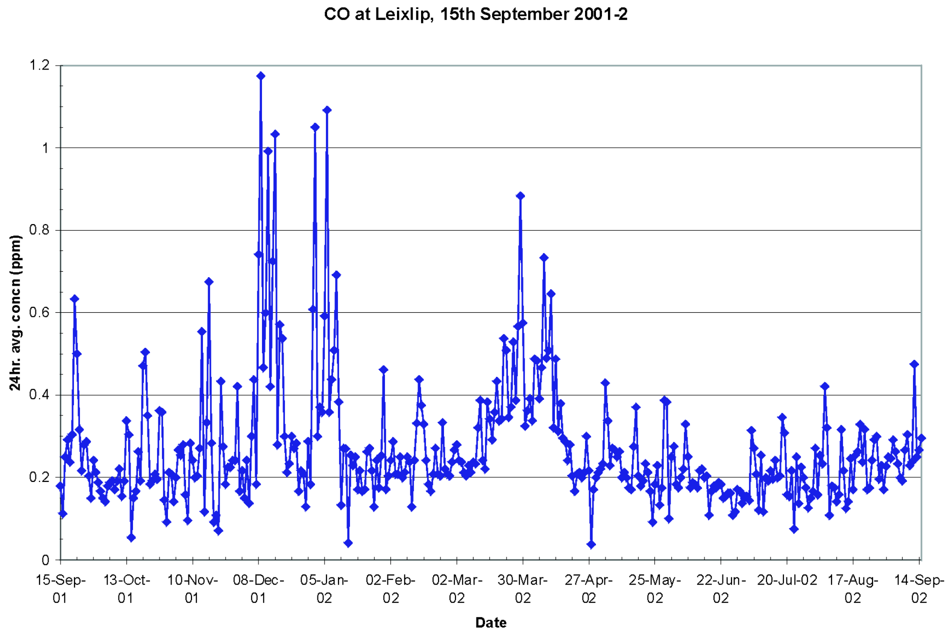

Figure 3.4. 24-h average CO concentrations at the M4 site.

3.5 Analysis of Monitoring Results

The variation in traffic flows described in Section 3.2 is reflected in the diurnal variation in the concentrations of each of the pollutants. Figures 3.5 and 3.6 present the average weekday variation in the hourly concentrations of CO and PM_{10}. They show rises in pollutant concentration corresponding to the morning and evening peak traffic flows. They also show the effect of stable atmospheric conditions on pollutant concentrations at night, when the influence of the local source is reduced.

The measured pollutant concentrations are influenced by wind direction. This influence is illustrated by Fig. 3.7, which shows the average hourly CO concentration observed for each wind direction. It appears that winds

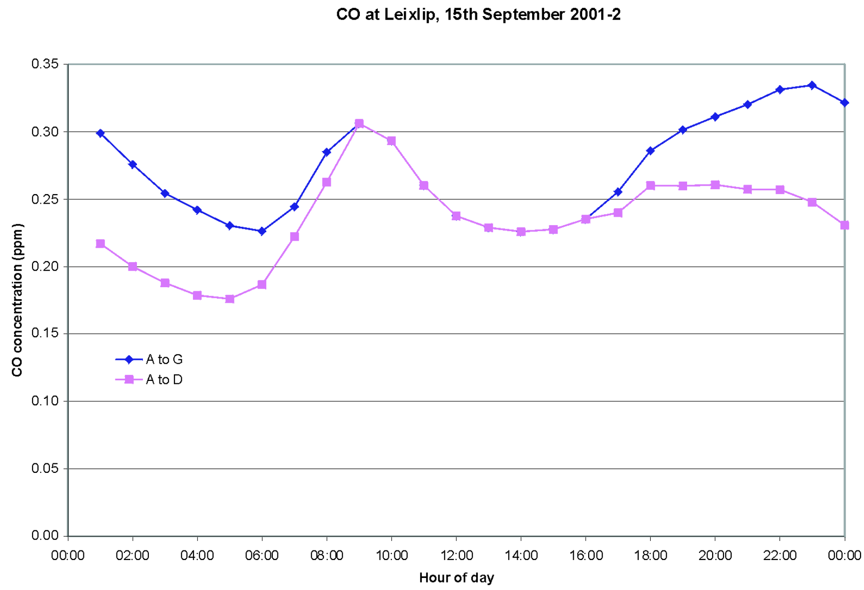

Figure 3.5. Average diurnal variation of hourly CO concentrations with stability class (A–G) at the M4 site.

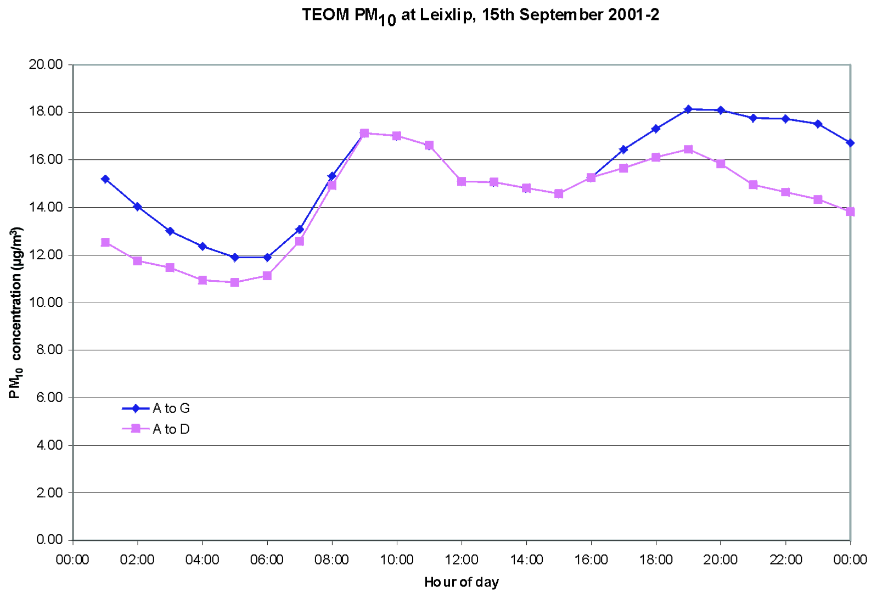

Figure 3.6. Average diurnal variation of hourly PM_{10} concentrations with stability class (A–G) at the M4 site.

from the south (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 attributed to the lower mean wind speeds and more frequent stable atmospheric conditions observed for some other directions.

The average concentrations were found to be higher in winter than in summer for all pollutants. Winter concentrations also showed 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 was significantly higher than the summer minimum, suggesting a seasonal variation in background levels.

The diurnal variations in CO and PM_{10} were 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

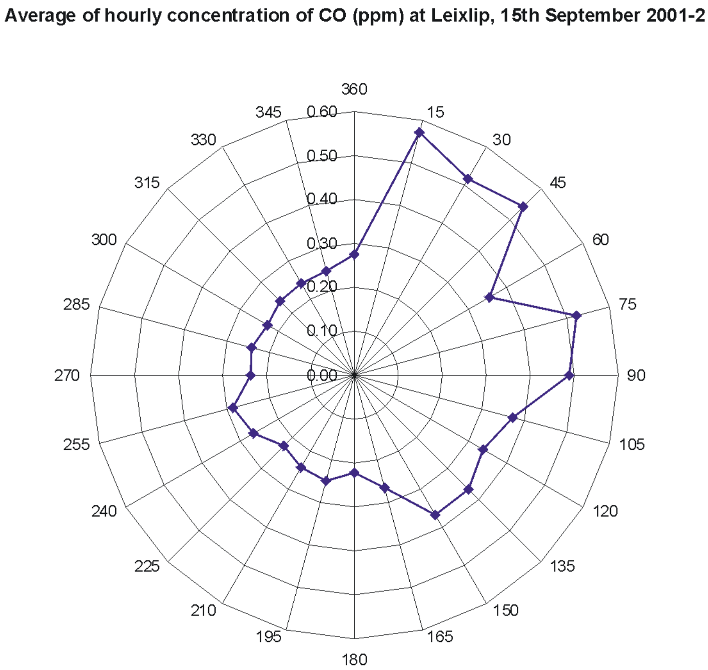

Figure 3.7. Variation of CO concentration with wind direction at the M4 site.

differences in dispersion and in resuspension of particulate matter. However, NO and NO_2 differ from CO and PM_{10} in that their distribution is influenced by diurnal photochemical effects. NO_2 decreases overnight in the absence of sunlight, some being converted to nitrous acid (HONO). At sunrise, HONO can be converted (with sunlight) to NO; therefore NO levels can increase before the traffic becomes a significant source.

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 (condensation particle counter) counts, referred to as the total number of aerosol particles per unit volume. Table 4.1 summarises the analysis method, monitoring period and sampling frequency for each pollutant. Details of instruments and calibration standards are included in Section 4.1 of the Final Report.

4.2 Traffic Flows

The N6 roundabout site in Galway is described in Section 2.2. Information on traffic flows was obtained from two sources: a 13-h detailed survey of all turning movements at the N6 roundabout (carried out on 30 May 2002; Abacus Transportation Surveys Ltd, 2002), and a 1-month continuous recording of vehicles entering and leaving the roundabout on the N6 Dublin Road (18 October to 15 November 2002). The results are summarised in Fig. 4.1.

Table 4.1. Air pollutants monitored at the N6 roundabout site.

Pollutant	Method	Monitoring period	Sampling interval
CO	Infrared absorption	June 01–September 02	15-min & 1-h averages
NO_x, NO, NO_2	Chemiluminescence	May 01–September 02	30-min & 1-h averages
PM_{10}	Oscillation frequency	May 01–September 02	30-min average
PM_{10}	Gravimetric	May 01–September 02	24 h
CPC	Supersaturation	May 01–December 01	1-h average

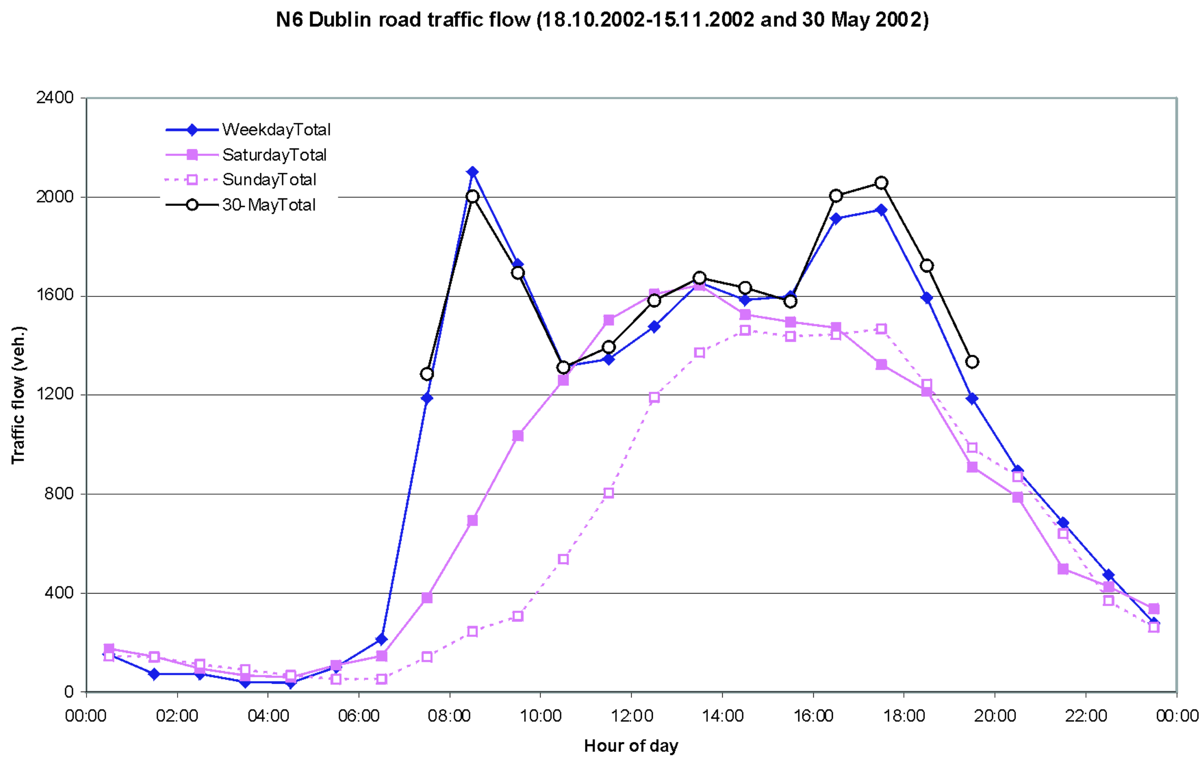

Figure 4.1. Diurnal variations in traffic density (vehicles/hour) on the N6 Dublin road. The Abacus survey was performed on a single day, 30 May 2002.

Both surveys showed similar peaks for weekday mornings and afternoons. During Saturdays and Sundays there was a single broad peak (appearing later on Sundays). There is remarkable consistency between the 1-day survey and the longer NRA study, which were separated by an interval of 5 months.

4.3 Meteorology

Wind direction and wind speed were monitored on site throughout the project. The sensor was set at approximately 5 m above ground level. The data were 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 (NUI), Galway Campus, about 2 km from the site. The data from these two Galway sites were also compared with data from Shannon Airport, located about 65 km from Galway City.

Figure 4.2 shows the wind direction patterns at the two Galway sites. The dominant wind direction at both sites is south-westerly. However, the Shannon Airport data differed significantly from the Galway data, indicating that it may not be appropriate to use such regional data for predictive modelling.

Figure 4.3 shows the wind speed pattern at the roundabout site. The highest wind speeds are associated with the prevailing south-westerly wind direction, especially in winter.

4.4 Air Pollutant Concentrations

Table 4.2 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 to September 2002.

Figure 4.4 shows the 24-h average concentrations of the primary pollutants CO and NO for the full 1-year monitoring period. There is generally good agreement between the days on which high concentrations of CO and NO were observed. It is also evident that the highest concentrations occurred in winter and the lowest in summer, consistent with the expected seasonal pattern.

As noted in Table 4.1, particulates were monitored by two methods: gravimetric (using a Partisol instrument) and by an oscillation frequency method (using a Tapered Element Oscillating Microbalance, or TEOM). Gravimetric measurements provided 24-h averages, while TEOM data were processed for averaging periods of 30 min and 1 h. There was generally good agreement between the TEOM and Partisol PM_{10} measurements, and the annual average concentrations derived from the two instruments

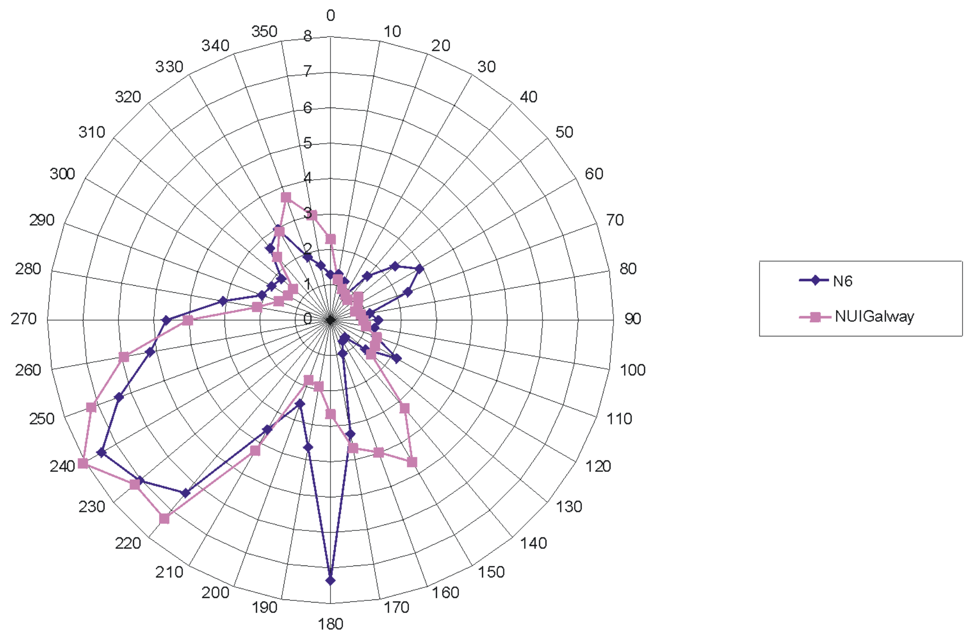

Figure 4.2. Frequency of wind direction at the N6 monitoring site and at NUI, Galway.

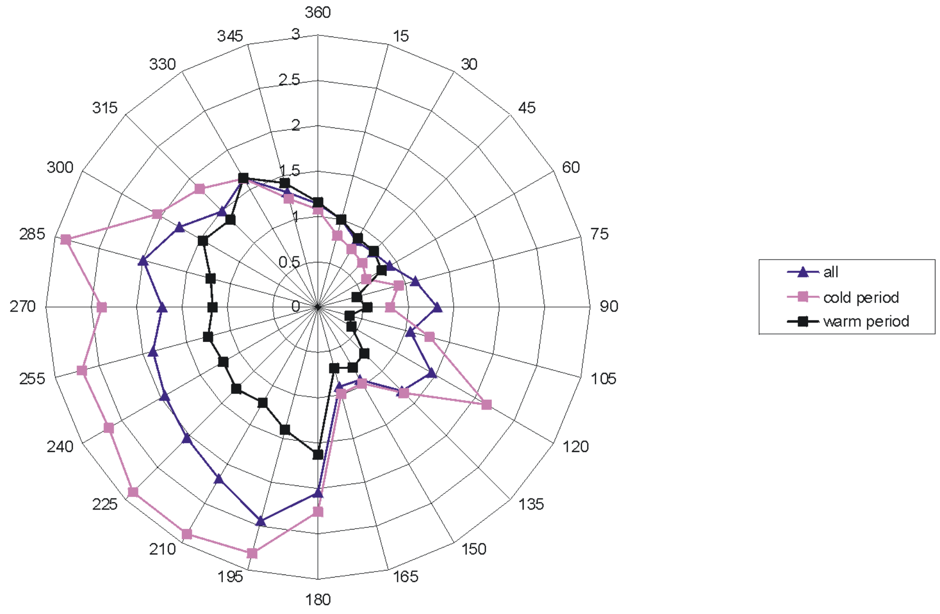

Figure 4.3. Wind speed rose in m/s at the N6 roundabout site.

Table 4.2. Pollutant statistics (ppm CO; ppb NO_2, NO and NO_x; µg/m^3 PM_{10}).

	CO	NO_2	NO	NO_x	PM_{10}-TEOM	PM_{10}-Partisol
Mean	0.46	10.1	16.1	26.2	25.5	25.6
Maximum	1.27	27	92	119	105	110
5th percentile	0.24	3.37	2.4	5.8	11.2	10
95th percentile	0.87	19	43	62	46.8	53

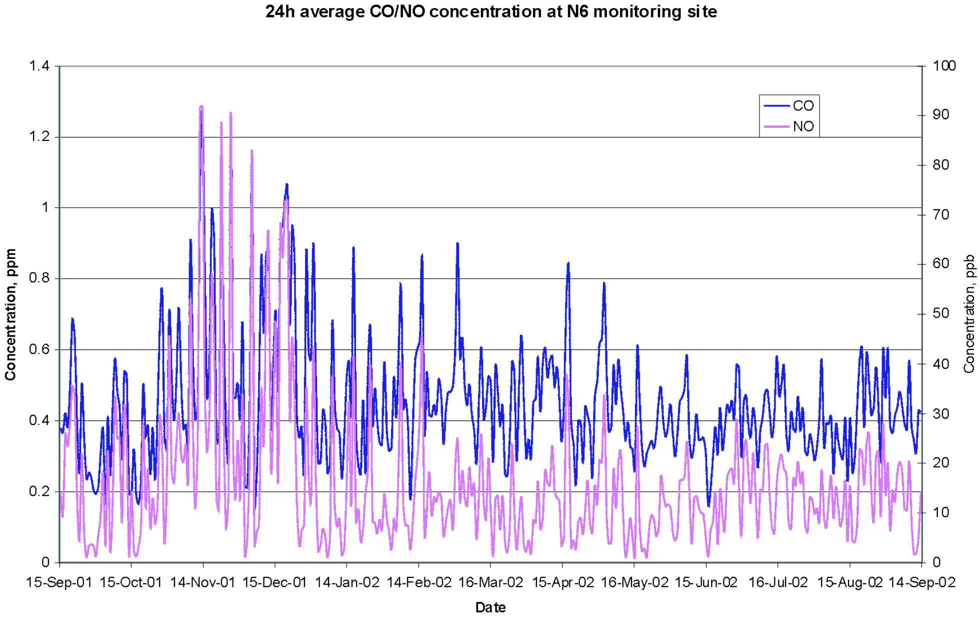

Figure 4.4. Comparison of 24-h average CO and NO concentrations at the N6 roundabout site.

were almost identical (25.5 µg/m³ and 25.6 µg/m³ for the TEOM and Partisol, respectively).

The 24-h PM_{10} mass concentrations exceeded the EU Directive 24-h limit value of 50 µg/m³ on fewer than 35 days per year, as required by the Directive. The yearly average of 25 µg/m³ is also well below the limit value (40 µg/m³). (See McGettigan (2001) for a summary of air quality limit values and assessment thresholds.)

4.5 Analysis of Monitoring Results

Figures 4.5 and 4.6 illustrate the average weekday diurnal variation of CO and NO pollutant concentrations at the N6 site. The figures indicate pronounced morning and evening peaks on weekdays, as well as a small lunchtime peak for CO. The morning peak occurs at 08:30 h and the evening peak at 17:00 h. These peaks agree well with the peaks in traffic flows illustrated in Fig. 4.1, suggesting that

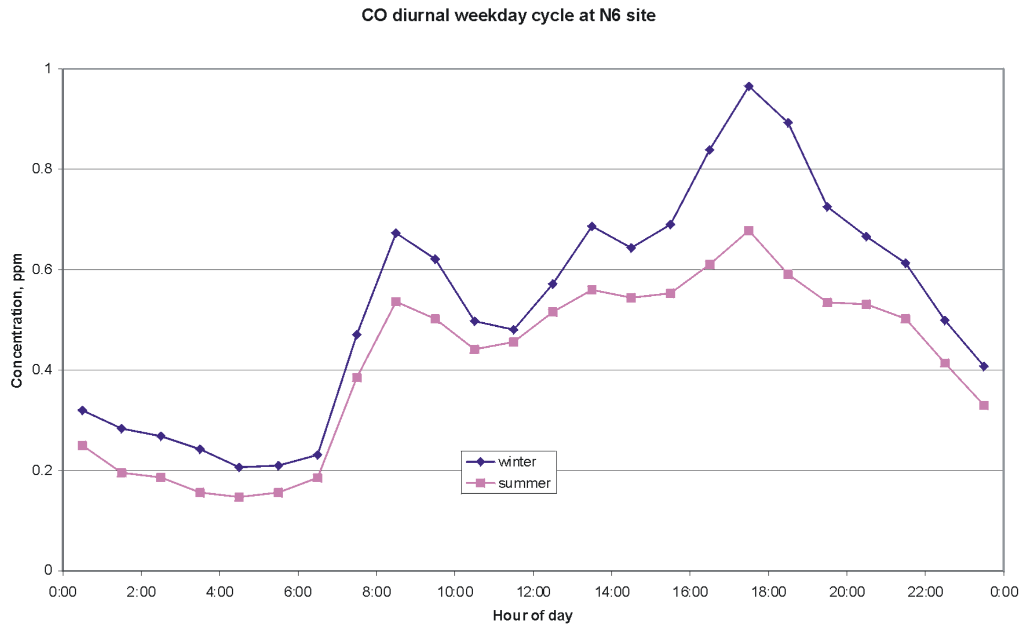

Figure 4.5. Average diurnal variation of CO at the N6 roundabout site on weekdays.

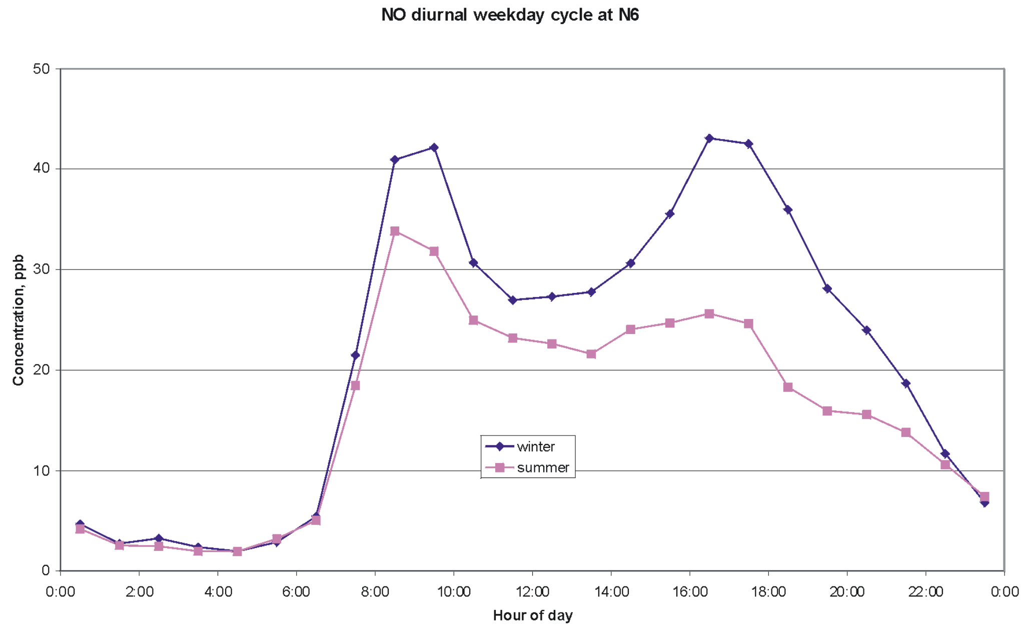

Figure 4.6. Average diurnal variation of NO at the N6 roundabout site on weekdays.

most of the pollution is traffic related. Comparison of Fig. 4.5 with Fig. 3.5 indicates that the average CO concentrations are generally higher at Galway than at Leixlip, while the minima are similar at both sites (0.2 ppm CO occurring at 04:00 h).

The air pollutant data were also examined in relation to wind direction and wind speed. The results show that winds from the north-west and north-east gave rise to the highest concentrations (Fig. 4.7). Figure 2.3 shows that the N6 roundabout is located to the north-west of the monitoring location, while the N6 Dublin Road runs to the north-east. Winds from the north-east are in a narrow band (40–70°) and associated with low wind speeds (Figs 4.2 and 4.3). 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.

The strong influence of wind speed on CO concentration is illustrated in Fig. 4.8. The figure exhibits an interesting feature, which is that a particular wind speed may be characterised by a maximum and minimum concentration. This is discussed further in Section 4.5 of the Final Report.

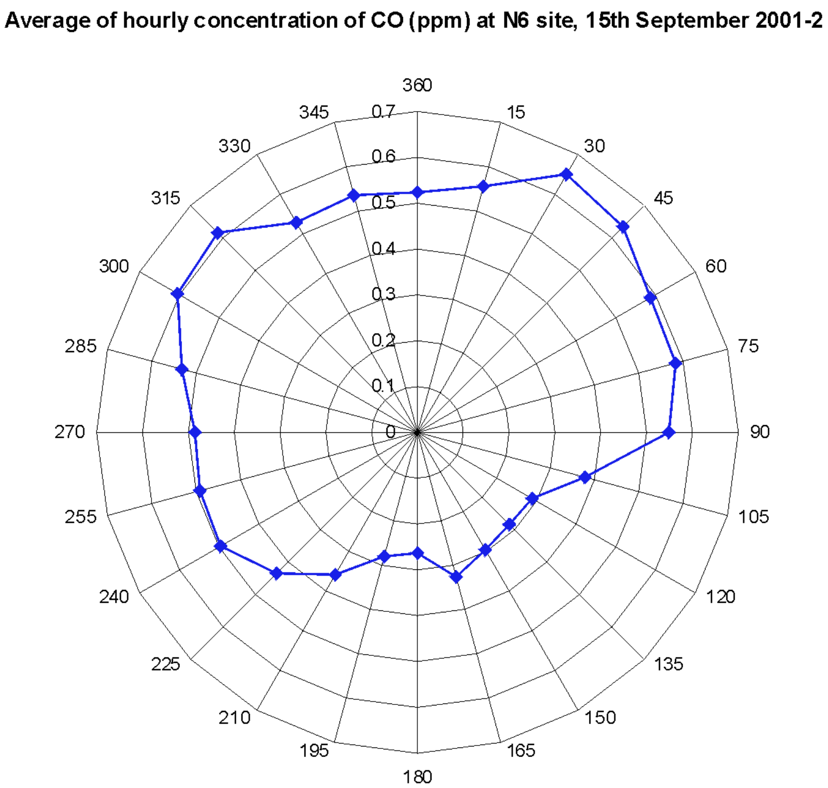

Figure 4.7. Variation of CO concentration with wind direction at the N6 site.

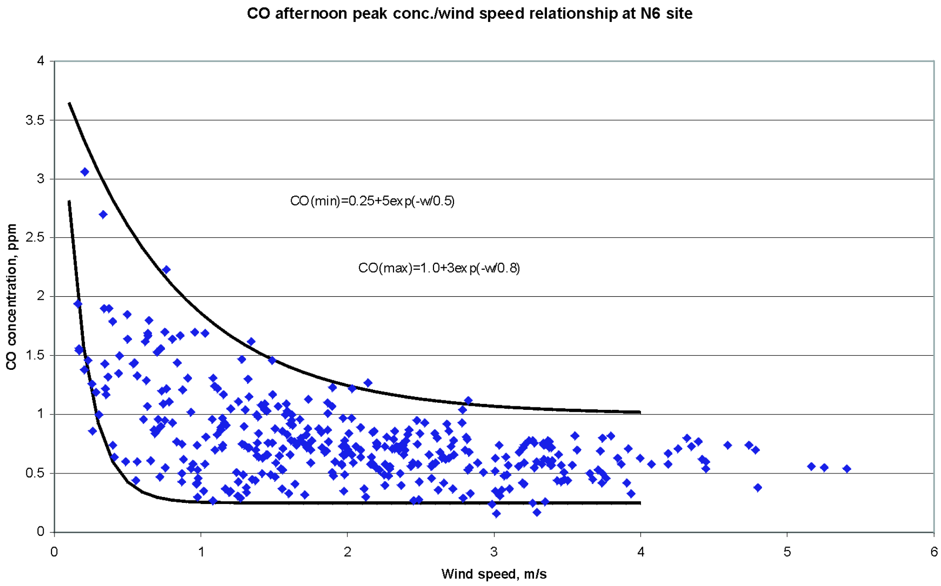

Figure 4.8. Relationship between CO concentration and wind speed at the N6 site.

5 Dispersion Modelling

5.1 Model Selection

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 was selected for investigation in this project.

The Design Manual for Roads and Bridges (DMRB) model is a screening model derived from a Gaussian dispersion model developed by the UK Transport Research Laboratory (DMRB, 1994, 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 concentrations of the hydrocarbon compounds benzene and 1,3-butadiene can be calculated. Only background concentrations and 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.

CALINE4 is one of two versions of the CALINE (California Line Source) dispersion model currently in use (www.epa.gov/scram001; Benson, 1992). The model uses a semi-empirical solution to the Gaussian dispersion equation. It can predict hour-by-hour concentrations of CO (or any other inert pollutant), NO_2 and PM_{10} from meteorological and traffic data.

Further details of these and other atmospheric dispersion models, and model selection for this project, can be found in Chapter 3 of the Literature Review (Broderick et al., 2004b).

5.2 Emission Factors

Most emissions of CO, NO_x, PM_{10}, and hydrocarbons (HC) 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.

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. Databases of velocity-emission rate characteristics for particular classes of vehicle 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.

Data are available from the Department of the Environment, Heritage and Local Government (DoELG, 2000) giving the number of vehicles in Ireland which fall into different categories of vehicle type, fuel type and engine size or laden weight (although updates are needed as the number of passenger cars has increased substantially in recent years). Combining the assumed fleet characteristics with the unit vehicle emission factors (for mean speeds of 30 kph at the roundabout and 100 kph at the motorway) from the UK EFD and COPERT III, composite emission factors can be derived.

The CALINE4 modelling results presented in this section 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 Section 6.2, which includes a comparison between the UK EFD of 2001 and the 2002 update. (It should be noted that the current DMRB v1.01 is based on the EFT2e database released in February 2003.)

5.3 Model Results for the M4 Motorway at Leixlip

The results of predictive modelling using the DMRB screening model are summarised in Table 5.1 (for the year 2001). Background concentrations of CO and PM_{10} were taken as the concentrations when the traffic flows were lowest, and were high relative to concentrations due to the road traffic source.

CALINE4 predicts hourly and 8-h average concentrations for varying wind directions. It was found that the average variation in measured and modelled pollutant concentrations throughout the day reflected the variation in traffic flow and, hence, in source emissions. This can be seen in Fig. 5.1, which compares the average diurnal variations of the measured and modelled concentrations of CO over the whole monitoring period. 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.

Figure 5.1 indicates that the peak annual average hourly CO concentration is 0.33 ppm at 23:00 h, whereas the modelled peak is 0.53 ppm at 20:00 h. The model does

Table 5.1. DMRB results – motorway.

	CO (mg/m^3)	NO_x ($\mu g/m^3$)	PM_{10} ($\mu g/m^3$)
Contribution from all roads	0.10	130	3.93
Background contribution	0.27	11.7	11.9
Total annual mean (incl. background)	0.37	142	15.8
Maximum 8-h mean	3.69	–	–
Maximum running annual mean	–	–	–
Annual mean NO_2	–	58.3	–
90th percentile of daily means	–	–	28.3

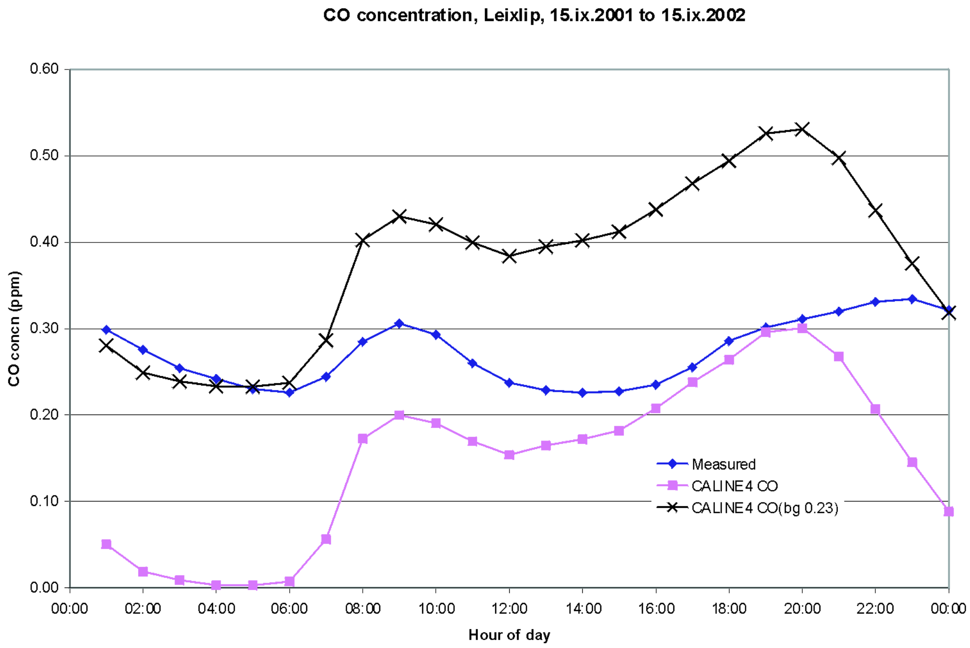

Figure 5.1. Measured and modelled average diurnal profiles for CO at the M4 site.

not predict the high CO concentrations observed after 20:00 h, which are generally due to stable atmospheric conditions rather than the immediate traffic source, but the morning peak-hour concentrations are in closer agreement (0.30 ppm measured compared to 0.43 ppm modelled, both occurring at 09:00 h).

Modelled pollutant concentrations are highly dependent on wind direction, with the highest predicted concentrations occurring when winds are near parallel to the road, or from the south. Figure 5.2 shows the relationship for NO_2 as an example. In particular, considering a wind direction range of 165–180°, the measured and modelled NO_2 values are very close. For wind directions closer to that of the road, poorer agreement is observed. 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 when pollutant travel time is greatest (Broderick *et al.*, 2004b). This feature is particularly relevant at the Leixlip monitoring site where westerly winds were frequently observed.

Seasonal effects were examined with the CALINE4 model. For all pollutants, winter concentrations were both observed and predicted to be higher than summer concentrations. Overall, using annual average background values, better agreement between the measured and modelled profiles was achieved with the winter data, as can be seen by the results for PM_{10} in Fig. 5.3.

The performance of the CALINE4 model can also be evaluated by looking at some summary statistics. At the motorway site, CALINE4 was used to predict 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-h average CO concentration was also predicted to within 4%. Similar performance was observed for PM_{10}, for which the annual mean concentration was predicted to within 12%, while the 36th highest 24-h average was predicted to within 1% of the measured value. While the annual mean concentration of NO_2 was overpredicted by 30%, the 99.8th percentile hourly average concentration was overpredicted by only 6%. The Final Report includes further evaluation of model performance in terms of statistical parameters such as Pearson correlation coefficient, normalised mean square error and fractional bias (Broderick *et al.*, 2004a). Between 50 and 80% of the modelled hourly concentrations lay within a factor of two of the observed values for this site, and also for the Galway roundabout site described below.

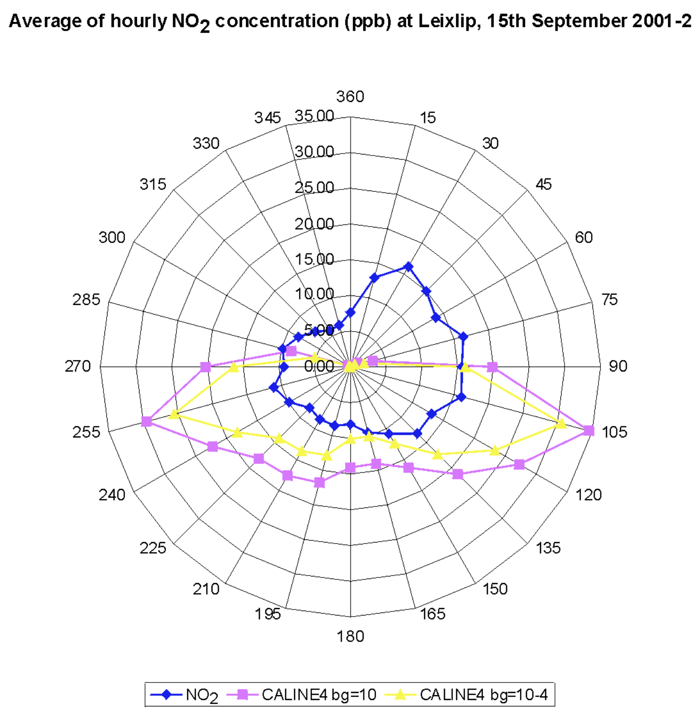

Figure 5.2. Measured and modelled NO_2 pollution rose at the M4 site.

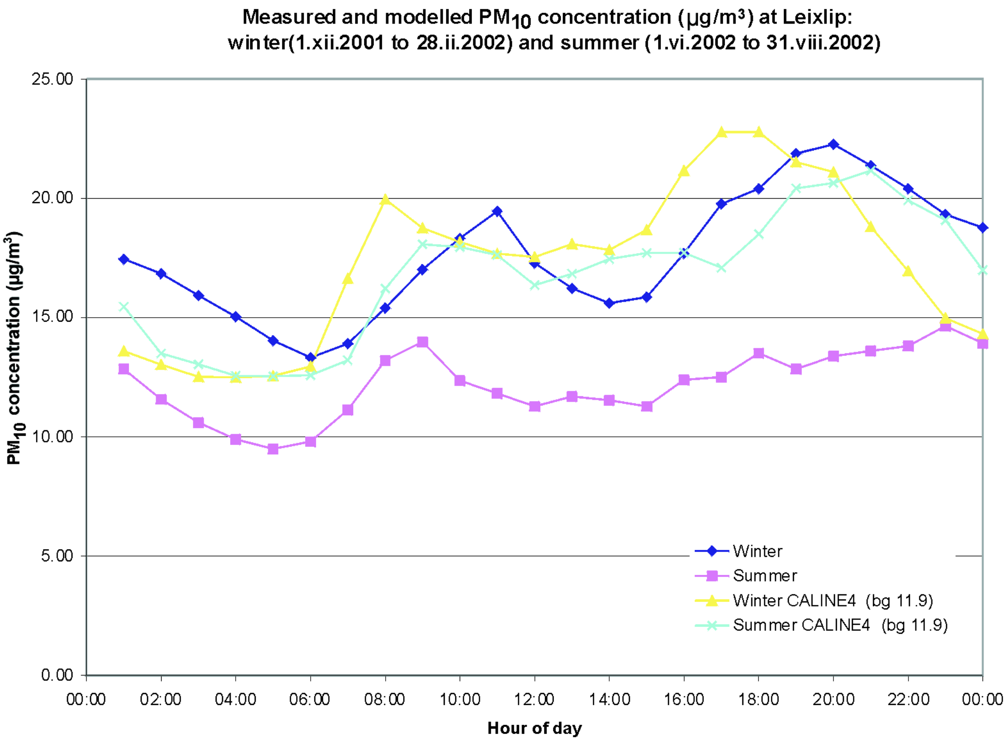

Figure 5.3. Modelled and measured average diurnal profiles for PM_{10} in winter and summer at the M4 site.

5.4 Model Results for the N6 Roundabout, Galway

The main difference between the modelling at the roundabout compared to that at the motorway is the use of five links rather than one (Section 2.2). Table 5.2 shows the annual mean concentrations predicted for the roundabout using the DMRB (again for the year 2001).

The measured and modelled diurnal pollution profiles at the roundabout site reflect the diurnal variation in traffic flow, as at the M4 Leixlip site. This is illustrated by the profile for NO_2 in Fig. 5.4. The diurnal range in pollutant concentration between the early morning minimum and the evening maximum is smaller for the modelled data (9.6 ppb modelled compared to 14.0 ppb measured), but the measured and modelled NO_2 maxima agree quite well.

For all pollutants, the highest concentrations were observed with winds from the north-east and, for CO, the north-west. The model also predicted the highest concentrations for north-easterly winds, which are near-parallel to a long, straight part of the N6 Dublin Road (Fig. 2.3). As at the motorway site, NO_2 concentrations are greatly overpredicted under these conditions (Fig. 5.5). However, for wind directions between 190° and 360°, good agreement is observed, especially for the predominant wind directions between 225° and 270°.

Table 5.2. DMRB results – roundabout.

	CO (mg/m^3)	NO_x (µg/m^3)	PM_{10} (µg/m^3)
Contribution from all roads	1.88	763	32.0
Background contribution	0.21	11.73	12.90
Total annual mean (incl. background)	2.09	775	44.9
Maximum 8-h mean	20.9	–	–
Maximum running annual mean	–	–	–
Annual mean NO_2	–	194	–
90th percentile of daily means	–	–	80.4

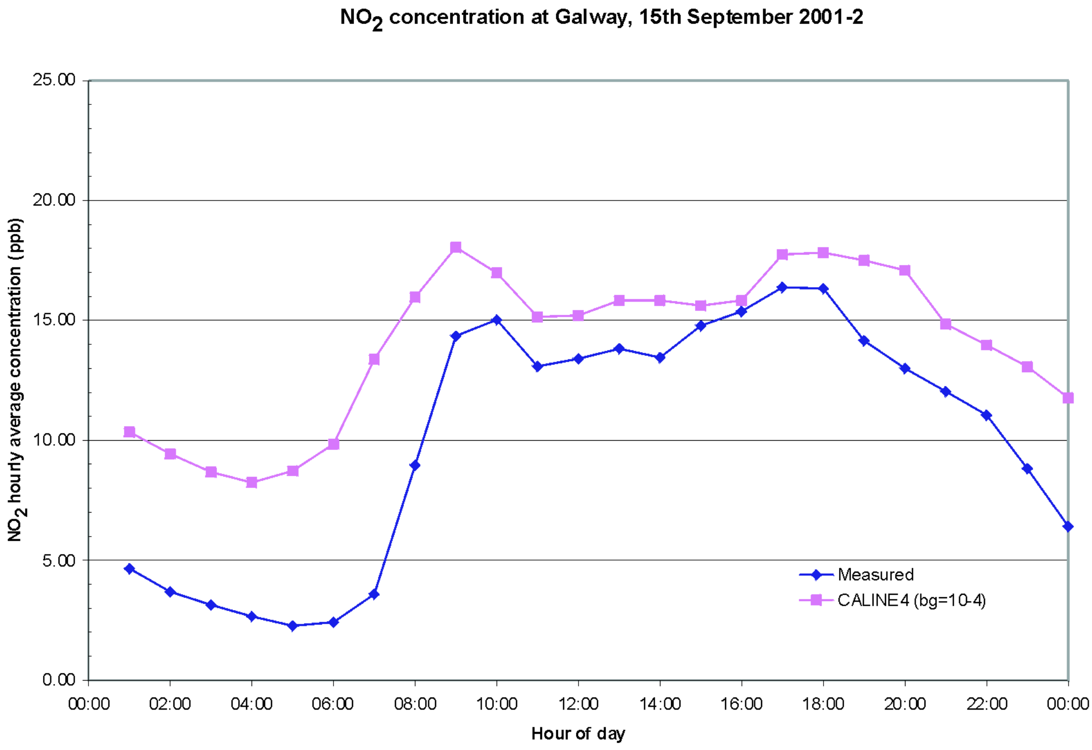

Figure 5.4. Measured and modelled average diurnal profiles for NO_2 at the N6 site.

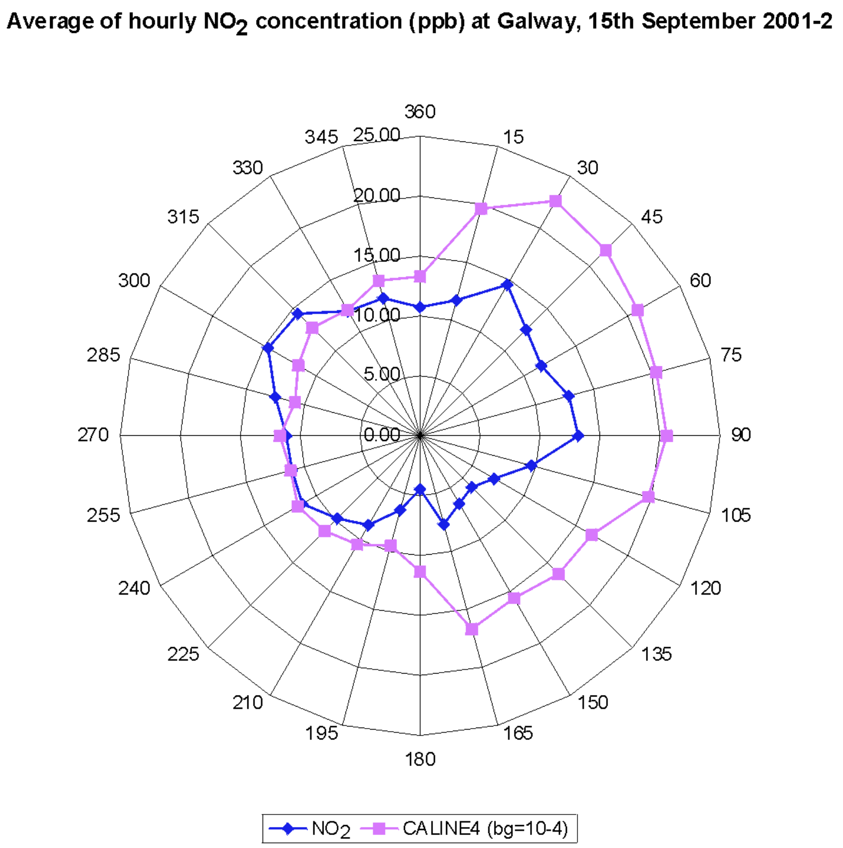

Figure 5.5. Measured and modelled NO_2 pollution rose at the N6 site.

An analysis of diurnal profiles for separate winter and summer periods showed that the pollutant concentrations measured in winter were greater than those measured in summer. However, for the modelled concentrations, the opposite is the case: summer values exceeded winter values, albeit for CO and PM_{10} the difference between the modelled profile in either season is very small. For NO_2, the measured and modelled diurnal profiles agreed better in winter than in summer.

Sets of statistical values were used to evaluate model performance at the roundabout site, as for the motorway site. In the statistical evaluation, CALINE4 predictions compared less well with measurements at the roundabout than at the motorway. 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 8-h average CO concentration by 60%, the 99.8th percentile hourly NO_2 concentration by 25% and the 90th percentile 24-h 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 significant diurnal variation in background concentration may also have played a role (see Section 5.5 of the Final Report).

6 Model Validation and Evaluation

6.1 Collaborative Model Validation 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 covered the first 6 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 participants were provided with meteorological and site data for the motorway and roundabout sites, and were then free to choose an appropriate air dispersion model and to make their own assumptions on parameters such as background concentrations and emission factors. The collated results were presented and discussed at a modelling workshop held in TCD in October 2002.

The following organisations participated in the exercise, employing the dispersion models included in parentheses: AWN Consulting (CAL3QHCR), Cambridge Environmental Research Consultants (ADMS Roads), Envirocon (ADMS Roads) and 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.

At the motorway site, the observed mean CO concentrations were generally well predicted by all participants, but the peak 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 NO_2 concentration statistics were well predicted by two of the participants, but the other two underpredicted by about 50%. Model estimates of mean PM_{10} concentrations differed from the measured value by about 50%, but the predicted 90th percentile 24-h average concentration was within 25% of the observed value in three out of four cases.

At the roundabout site, mean CO concentrations were both overpredicted and underpredicted by the participants. However, the maximum 8-h concentration was underpredicted by all. Good predictions of mean NO_2 concentrations were obtained by two participants, but estimates of the 99.8th 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 PM_{10} concentrations were underpredicted by all participants, with the 90th percentile 24-h average being underestimated by between 25 and 50%.

6.2 Emission Factor Sensitivity

The composite emission factors (CEFs) used in the modelling work described in Section 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 6.1 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 Section 5 for the motorway site, but all the values for the roundabout are similar. For NO_x, the motorway value used in Section 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 fairly similar, that suggested by COPERT III is much lower.

Additional model runs were performed to investigate the significance of these different CEFs. At the motorway site, the lower emission factors of 4.11 and 3.58 g/mile for CO lead to closer mean modelled and 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 the statistical parameters used for model evaluation (Section 5.3).

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

Table 6.1. Composite emission factors (CEF) for CALINE4 sensitivity analysis.

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

EF databases: 1, UK EFD (Autumn 2001); 2, UK EFD (Autumn 2002); 3, COPERT III.

parameters in winter at the roundabout site. However, in summer, the lower value suggested by COPERT III gave 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 (see Section 6.6.2 below).

6.3 Background Concentrations of the Air Pollutants

Additional NO_x, NO and NO_2 measurements were obtained close to the M4 monitoring site at Leixlip for a 4-month period in 2002. An additional monitor was installed in a private house located approximately 200 m 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 unit was located (Section 2.1). It was expected that ambient concentrations at this supplementary site would be representative of the background concentrations in the local area whenever winds were from the south and, as was most frequent, south-west, i.e. for wind directions between 100° and 260° (Figure 6.1).

Although no measurements of CO or PM_{10} concentrations were made at the background site, it was considered reasonable to assume that whenever the NO_x concentration at the background site was high, so too were the CO and PM_{10} concentrations, since background concentrations of most pollutants are affected by the same parameters (such as wind speed, wind direction and atmospheric stability/turbulence). To test this hypothesis, the correlations between the CO, NO_x and PM_{10} hourly concentrations observed at the WTW were examined, and the relatively high correlation coefficients obtained suggested that the data sets of all concentration

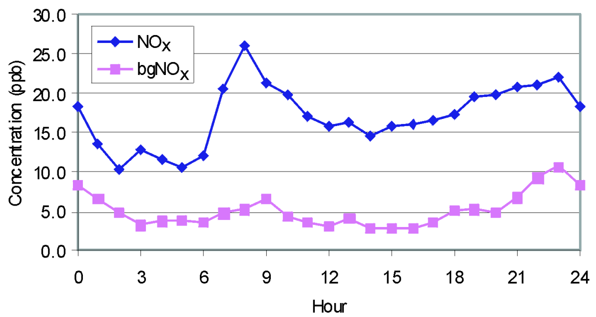

Figure 6.1. Average diurnal variation of NO_x concentrations at the M4 monitoring (NO_x) and background ($bgNO_x$) sites for wind directions between 100° and 260°.

measurements were well correlated on an hour-by-hour basis. Surrogate hourly background concentrations of CO and PM_{10} could 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.

Figure 6.2 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 6.3 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 0.024 to obtain surrogate hourly background concentrations of CO. Only

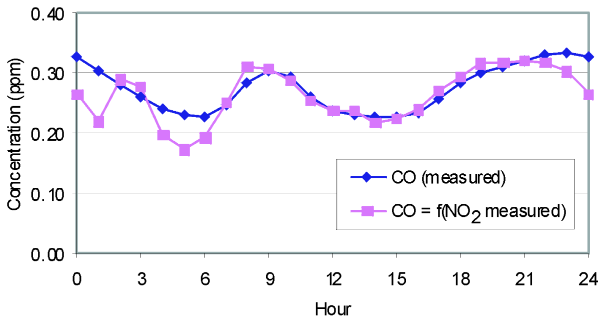

Figure 6.2. Measured and calculated average diurnal variation of CO concentration at the M4 monitoring site.

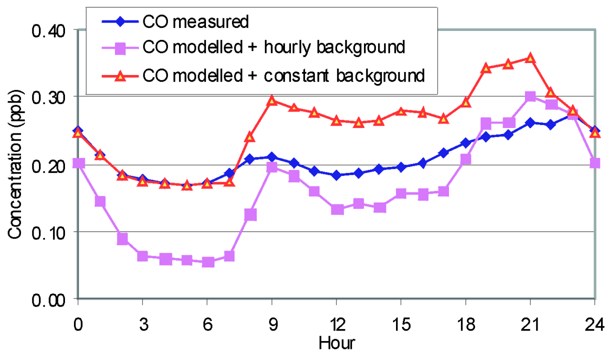

Figure 6.3. Measured and modelled average diurnal variation of CO concentration at the M4 monitoring site.

wind directions between 100° and 260° were considered, and the factor of 0.024 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 were 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 was 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 h and 08:00 h, when the use of a constant background value produces better results. Similar results were obtained for PM_{10}.

6.4 Link Layout and Wind Direction

The sensitivity of the models to variations in the input parameters, including the link geometry and the wind direction as measured on site and regionally, was examined. With respect to link layout, it was found that CALINE4 model predictions at the motorway site were influenced by the number of links used to represent the roadway. Model runs employing separate links for each carriageway usually produced lower concentrations than those employing a single link only.

The DMRB predictions are independent of wind direction, and therefore reflect the position of the receptor relative to the source location in terms of distance but not of direction (Fig. 6.4). 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.

6.5 Hydrocarbon Modelling

As an additional project task, described in the Addendum to the Final Report, dispersion modelling procedures for highway sources were further validated for a number of individual hydrocarbon compounds associated with vehicle emissions. The following hydrocarbons were investigated: ethene, propene, acetylene, benzene, isopentane, *n*-pentane and 1,3-butadiene. A CEF for each of these was determined using COPERT procedures and data, and details of the local vehicle fleet. The CEFs obtained for benzene and 1,3-butadiene agreed with those suggested by the UK EFD.

These CEFs were employed to model the temporal variation of hydrocarbon concentrations at the M4 motorway site. The individual hydrocarbons were modelled as inert pollutants, and the modelling procedures previously employed for carbon monoxide were followed. Agreement between measured and modelled diurnal profiles and long-term averages was better with the hydrocarbon data than with the carbon monoxide results. Short-term evaluation parameters suggest similar performance for hydrocarbon and carbon monoxide modelling. These results suggest that confidence in CALINE4 hydrocarbon results should be at least as strong as that for carbon monoxide.

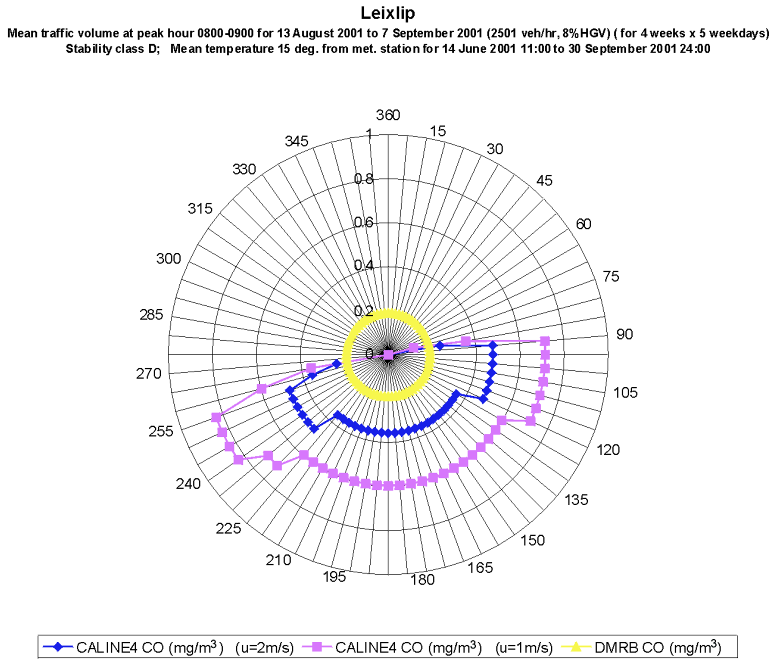

Figure 6.4. CALINE4 prediction with varied wind speed and direction at the M4 site.

Hydrocarbon measurements obtained at three points upwind and three points downwind of a site on the M50 motorway west of Dublin were used to further evaluate the performance of CALINE4. The availability of contemporaneous upwind concentration observations allowed the observed downwind concentrations to be corrected for background concentrations. The measured data set represented an excellent basis on which to evaluate dispersion model performance. The concentrations of compounds with no significant evaporative emissions (ethene, propene and 1,3-butadiene) were most accurately predicted by CALINE4. The model was found to predict average concentrations very well: the ratios of the average modelled to average measured values were 0.9, 1.01 and 1.05 at distances of 25 m, 120 m and 250 m downwind of the motorway, respectively.

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 described in Sections 5 and 6, including the model validation exercise and workshop.

6.6.1 Investigated models

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 also employed CAL3QHCR and ADMS Roads.

The DMRB model calculates predefined concentration statistics only, in formats suitable for comparison with the EU limit values. It is 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 an objective assessment indicates ambient concentrations close to a limit value.

Comparison of the results obtained using CALINE4 and the DMRB model at the motorway site suggests a better overall performance by CALINE4 as expected, since it is a short-term model requiring much more input data than a screening model such as the DMRB. CALINE4 predictions of the annual mean concentrations of CO and NO_2 and of the higher 8-hourly and 24-hourly concentrations of CO and PM_{10} are all closer to the equivalent measured 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, the CALINE4 predictions of mean and highest CO and PM_{10} concentrations underestimated the measured values by 35–60%. For PM_{10}, the predictions using the DMRB model overestimated those measured by 35–55%. The DMRB model's predictions of CO concentrations were much higher than the measured values. The DMRB model also grossly overpredicted the mean NO_2 concentration, whereas the CALINE4 prediction is within 40% of the measured value.

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.

6.6.2 Composite emission factors

The use of two emission factor databases (UK EFD and COPERT III) leads to similar CEFs. However, in this study, higher NO_x emission factors were obtained using the UK EFD, especially at the motorway site. For NO_x, the 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. 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 flow data, 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 ozone (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 selected 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, as recommended in Section 7.2.

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.

7 Conclusions and Recommendations

7.1 Conclusions

1. At both sites, the average diurnal variation in pollutant concentrations was 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.

2. For short-term dispersion modelling at both sites, 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 measured results.

3. 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 used. The maximum 8-h average CO concentration was also predicted to within 4%. Good model performance was also observed for PM_{10}, and for a number of hydrocarbon compounds. For NO_2, both the annual mean concentration and the 99.8th percentile hourly average concentration were overpredicted, albeit the latter by only 6%.

4. At the roundabout site, CALINE4 predictions compared less well with measurements. 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 poorer performance of CALINE4 at this site may be partly attributable to the variation in vehicle speeds at 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 influenced results.

5. 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. Mean pollutant concentrations were generally well predicted, but the higher concentrations were often underestimated. The predictions were found to be sensitive to a number of input variables, including the assumed background concentrations and the vehicle emission factors.

6. 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.

7.2 Recommendations for Further Research

To improve the accuracy of model predictions, further research is needed into a number of issues, especially background concentrations and emission factors:

1. Background concentrations, including:

   - default background values for a range of conditions reflecting location and meteorological conditions

   - guidelines for local assessments of background concentrations, such as the pollutants to be monitored, sampling period, sampling location/site selection criteria, quality assurance/quality control procedures and sampling frequency required

   - use of diurnally varying background concentrations for modelling

- use of methods for estimating a long-term average pollutant concentration from a short term measurement.

2. Estimation of composite emission factors for congested or partially congested traffic conditions. 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, taking into account the effects of cold start emission factors, tyre and brake wear, and evaporative emissions.

3. The use of traffic modelling software for 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.

4. The effect of employing regional rather than local meteorological data in predictive modelling exercises, and the required length of data sets that are necessary.

5. Standardisation of model verification procedures for all assessments.

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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/

Acronyms and Notation

CEC	Council of the European Union
CO	carbon monoxide
CO_2	carbon dioxide
COPERT	COmputer Program to calculate Emissions from Road Transport
CPC	condensation particle counter
EFD	Emission Factor Database
HC	hydrocarbon(s)
HGV	heavy goods vehicle
kph	kilometres per hour
NO	nitric oxide
NO_x	oxides of nitrogen
NO_2	nitrogen dioxide
NRA	National Roads Authority
PM	particulate matter
SO_2	sulphur dioxide
TEOM	Tapered Element Oscillating Microbalance
vph	vehicles per hour